Geological Monitoring

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2009

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Cover: Speleothems located at the bottom of a shaft (known as the “National Geographic Ladder Pit”) that drops down from the Big Room into Lower Cave section of Carlsbad Cavern, Carlsbad Caverns National Park, New Mexico, USA. Photo by Ronal C. Kerbo, 2006. Back cover, counterclockwise from top left: Great Sand Dunes National Park (National Park Service [NPS] photo); stream gage monitoring (U.S. Geological Survey photo); repeat photography of glaciers at Denali National Park and Preserve (NPS photo taken by G.W. Adema); scuba diving in Carmen, Agusan del Norte (Wikimedia Commons photo taken by Historianurian, 2008, Creative Commons, http://creativecommons.org/licenses/by-sa/3.0/); fossil wasp, Palaeovespa florissantia at Florissant Fossil Beds National Monument (NPS photo); Furnace Creek, Death Valley National Park (NPS photo taken by Dave Steensen); stone rings, Svalbard (Wikimedia Commons photo taken by Hans Grobe, 2007, Creative Commons, http://creativecommons.org/licenses/by-sa/2.5/); lava flow at Hawaii Volcanoes National Park (NPS photo); Geoscientist-in-the-Park participant Cherith Janes monitoring at Sleeping Bear Dunes National Lakeshore (NPS photo); cave formations at Carlsbad Caverns National Park (NPS photo); geothermal features at Yellowstone National Park (NPS photo); Hebgen Lake, Montana earthquake, August 1959 (U.S. Geological Survey photo).

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Introduction

The Geologic Resources Division of the National Park Service initiated and funded the development of this manual to provide guidance for resource managers seeking to establish the status and trends of geologic resources and processes within the National Park System, and to further the understanding of how geologic processes impact ecosystem dynamics. This book is not intended to guide the inventory of geological resources, but rather to provide selected methods for the monitoring of long-term changes in those resources. In light of the reality of continuing global change, it is particularly important that land and resource managers have some perspective on the rate and nature of change within the physical environments they are managing. While the ultimate goal of most resource managers is to protect individual species, communities, or ecosystems, this cannot be done effectively without understanding the physical changes within the geological environment that may drive long-term ecosystem change.

Extensive input from geoscientists in a variety of federal agencies and educational institutions was included in each of the chapters in this manual. The purpose of the manual is to inform non-specialists on a range of techniques for monitoring the spectrum of geologic features and processes in the world around them; aid in the design and implementation of geologic monitoring programs on local, state, and federal lands; and provide a reference text for students studying and monitoring geologic processes. Many of the monitoring methods described in this book could also be used by teachers at all levels who are interested in involving their classes in monitoring the changes in a local geological resource (e.g., a stream near their school).

This book represents an effort to provide a variety of methodologies for use in monitoring important geologic resources; however, the methodologies provided within are not meant to be comprehensive. Quite the opposite, they have been selected from the pool of possible methodologies by a panel of subject experts. Our goal is to provide monitoring advice and support to managers and scientists who may not have geological expertise, but who have a need for geological monitoring. The volume includes chapters dedicated to specific critical geological resources (e.g., caves, glaciers, coastal areas). Within each chapter, you will find a justification for monitoring the resource, a listing of items that could be monitored (vital signs), and several possible methods for monitoring those vital signs. Where possible, we have provided methodologies that can meet all capabilities: from low-cost, low-expertise-required methods (level 1) to higher cost, higher expertise, detailed monitoring methods (level 3). Case studies are also presented, and each chapter includes a summary table of vital signs, methods, and costs that can be used as an easy reference for selecting monitoring methods.

This volume does not include methodologies for the monitoring of groundwater resources or chemistry, nor does it include any biological or ecosystem monitoring. Furthermore, due to space constraints, we have not attempted to detail each methodology within this book. Where details are not presented, references are provided to other published sources so that a methodology can be explored in more detail or so that additional case studies may be reviewed. Resources included in the book are:

- Aeolian resources
  - Frequency and magnitude of dust storms
  - Rate of dust deposition
  - Rate of sand transport
  - Wind erosion rate
  - Changes in total area occupied by sand dunes
  - Area of stabilized and active dunes
  - Dune morphology and morphometry
  - Dune field sediment state
  - Rates of dune migration
  - Erosion and deposition patterns on dunes
- Cave resources
  - Cave meteorology
  - Airborne sedimentation
  - Direct visitor impacts
  - Permanent or seasonal ice
  - Cave drip and pool water
  - Microbiology
  - Stability (e.g., breakdown)
  - Mineral growth
  - Surface expressions and processes
  - Groundwater levels and quality
  - Fluvial processes
- Coastal resources
  - Shoreline change
  - Coastal dune geomorphology
  - Coastal vegetation cover
  - Topography and elevation
  - Composition of beach material
  - Coastal wetland position and acreage
  - Coastal wetland accretion
- Fluvial resources
  - Watershed landscape
  - Hydrology
  - Sediment transport
  - Channel: cross section
  - Channel: planform
  - Channel: longitudinal profile
- Geothermal resources
  - Thermal feature location
  - Thermal feature extent
  - Temperature and heat flow
  - Thermal water discharge
  - Fluid chemistry
- Glacial resources
  - Glacier mass balance
  - Glacier terminus position
  - Glacier area
  - Glacier velocity
- Marine resources
  - Bathymetry
  - Hydrography
  - Barriers: reefs
  - Barriers: other
  - Substrate
  - Water column
- Paleontological resources
  - Erosion (geologic factors)
  - Erosion (climatic factors)
  - Catastrophic geohazards
  - Hydrology and bathymetry
  - Human access and public use
- Permafrost
  - Thermal state
  - Physical conditions
- Seismic resources
  - Monitoring earthquakes
  - Earthquake activity
  - Historical and prehistoric earthquake activity
  - Earthquake risk estimation
  - Geodetic monitoring, ground deformation
  - Geomorphic and geologic indications of active tectonics
- Slope movements
  - Types of landslides
  - Landslide triggers and causes
  - Geologic materials in landslides
  - Measurement of landslide movement
  - Assessing landslide hazards and risks
- Volcanic resources
  - Earthquake activity
  - Ground deformation
  - Gas emission at ground level
  - Emission of gas plumes and ash clouds
  - Hydrologic activity
  - Slope instability

Local, state, and national land managers are tasked with recognizing, observing, and understanding the ecological changes that are taking place on the lands they manage and using that information to modify their actions and to advance sustainable practices. The key is to begin with a good natural resource inventory and then develop an ecological monitoring program to detect the critical elements or indicators of change in the natural systems. Yet too often, the driver of the ecosystem change (changes in the physical environment) is not monitored. Monitoring geological change is a critical part of adaptive management. The only way that an effective land manager can develop strategies for preserving key ecological assets is to understand how physical landscape changes are impacting those resources.

For example, through biological monitoring we know that the number of Piping Plovers is decreasing along U.S. barrier island shorelines. In order to preserve the bird, one needs to know the rate of change of the particular physical environment—the overwash fan—within which these Plovers flourish. These areas have been strongly impacted by both human activities and global change (sea-level rise). The only way that a resource manager can hope to protect and manage this threatened species, is to understand the rate and nature of change of the geologic environment upon which the bird is dependant.

Geological monitoring can be carried out for a number of reasons beyond the protection of biological resources. Of particular interest these days is the monitoring of geological hazards. A number of the chapters in this book cover geological aspects that could be considered both a resource and a hazard (e.g., volcanoes, fluvial systems, coasts). Geological hazards can impact both human infrastructure and ecosystem dynamics and pose safety hazards, making them particularly important targets for monitoring.

Geological monitoring can also be critical for managing important geological heritage sites (the Old Faithful geyser, or the fossils of Dinosaur National Monument). Finally, geological monitoring activities can be an excellent way to introduce students at all grade levels to the scientific method and to the tools scientists use to understand global change. We hope that this manual will prove a useful tool for all of the above.

How to Use This Manual

The book is arranged to be a relatively "rapid" reference. In other words, we don't expect that many people will read the entire volume from cover to cover, although we would be thrilled for you to do so. Rather, we anticipate that users will turn directly to the chapter that interests them. All chapters have identical formatting to make them easy to use. Each chapter contains an overview of the resource and provides some background on the benefits of monitoring that particular resource.

The bulk of each chapter contains recommended methodologies for monitoring the vital signs listed above. Therefore, one can use this manual to gain the technical information necessary to plan the implementation of a monitoring program for documenting the impacts, for example, of global warming on a geologic resource such as the glaciers in Glacier National Park. Or, a resource manager may already know that he or she would like to monitor glacier mass balance. In that case, the user may simply turn directly to the section on that vital sign to find a detailed description of the vital sign, a variety of monitoring methodologies requiring varying costs and staff expertise, and references to case studies. In either case, we hope that you will find this a useful guide to the monitoring of geological resources on multiple levels.

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Aeolian features and processes

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INTRODUCTION

Aeolian processes, involving erosion, transportation, and deposition of sediment by the wind, occur in a variety of environments, including the coastal zone, cold and hot deserts, and agricultural fields. Common features of these environments are a sparse or nonexistent vegetation cover, a supply of fine sediment (clay, silt, and sand), and strong winds. Aeolian processes are responsible for the emission and/or mobilization of dust and the formation of areas of sand dunes. They largely depend on other geologic agents, such as rivers and waves, to supply sediment for transport.

Areas of sand dunes occur in inland and coastal settings, where they often provide a distinctive environment that provides habitats for endemic and rare or threatened species. In both coastal and inland settings, dune migration and sand encroachment may impact neighboring ecosystems and resources, as well as infrastructure.

Transport of fine sediment by wind may cause **dust storms**, events in which visibility is reduced to less than 1 km by blowing dust. Dust storms impact air quality in their immediate vicinity as well as in areas downwind. Deposition of dust may have a significant effect on the composition and nature of soils in arid regions and beyond. Far-traveled dust from distant sources may have a significant effect on soil chemistry and nutrient status (e.g., Farmer, 1993).

Aeolian Processes, Landforms, and Deposits

This section provides a brief introduction to aeolian processes and landforms and their deposits. For more detailed information and an in-depth discussion of the topic, see Lancaster (1995) for desert dunes, and Nordstrom et al. (1990) for coastal dunes. Goudie and Middleton (2006) provide an excellent review of desert dust processes, while Goudie et al. (1999) provide a good short overview of aeolian processes in general.

Transport of Particles by Wind

Movement of particles by the wind takes place by a combination of direct wind shear stress and atmospheric turbulence. There are three modes of sediment transport by wind: **creep** or reptation; **saltation**, and **suspension** (Fig. 1). The mode of transport depends primarily on the ratio between particle settling velocity, and hence particle size, and wind shear stress and turbulence intensity. Very small particles (<20 microns) are transported in suspension (tens of km or greater) and are kept aloft by turbulent eddies in the wind. True suspension occurs when the particle settling velocity is very small compared to the turbulence intensity of the wind. Larger particles (20–70 microns) undergo short-term suspension for distances of tens to hundreds of meters; material of sand size (70–1000 microns) is transported mainly in a series of short hops (saltation), in which the vertical component of wind velocity (turbulence) has a minimal effect on particle trajectories. Material coarser than 500 microns in diameter (coarse sand) is transported on surface by reptation and creep. The modes of transport are interdependent: saltating sand particles eject silt- and

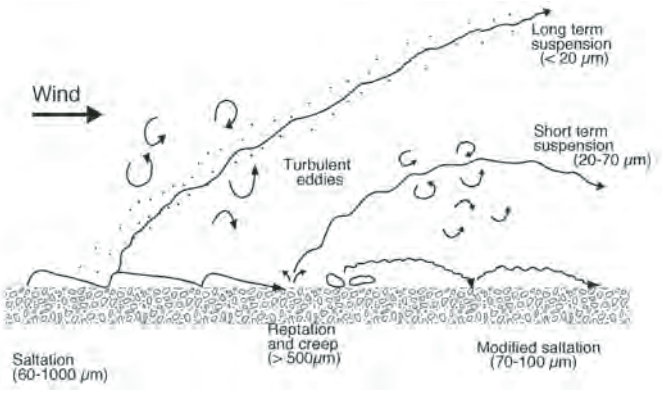


Figure 1. Modes of sediment transport by the wind (after Pye, 1987).

Lancaster, N., 2009, Aeolian features and processes, *in* Young, R., and Norby, L., Geological Monitoring: Boulder, Colorado, Geological Society of America, p. 1–25, doi: 10.1130/2009.monitoring(01). For permission to copy, contact editing@geosociety.org. ©2009 The Geological Society of America. All rights reserved.

clay-sized particles into the wind and impact coarse grains that are rolled along the bed.

Grains begin to move and sediment is entrained by the wind when fluid forces (lift, drag, moment) exceed the effects of the weight of the particle, and any cohesion between adjacent particles as a result of moisture, salts, or soil crusts. The threshold wind speed at which grains begin to move is strongly dependent on particle size (Fig. 2A). For quartz sand, the minimum threshold velocity is associated with fine sand (~100 microns diameter). The mass flux or transport rate of sand has been determined by numerous laboratory wind tunnel and field studies to be proportional to the cube of wind shear velocity above a threshold value (Fig. 2B). For any wind shear velocity, there is a potential rate of sand transport or transport capacity, which is only reached when

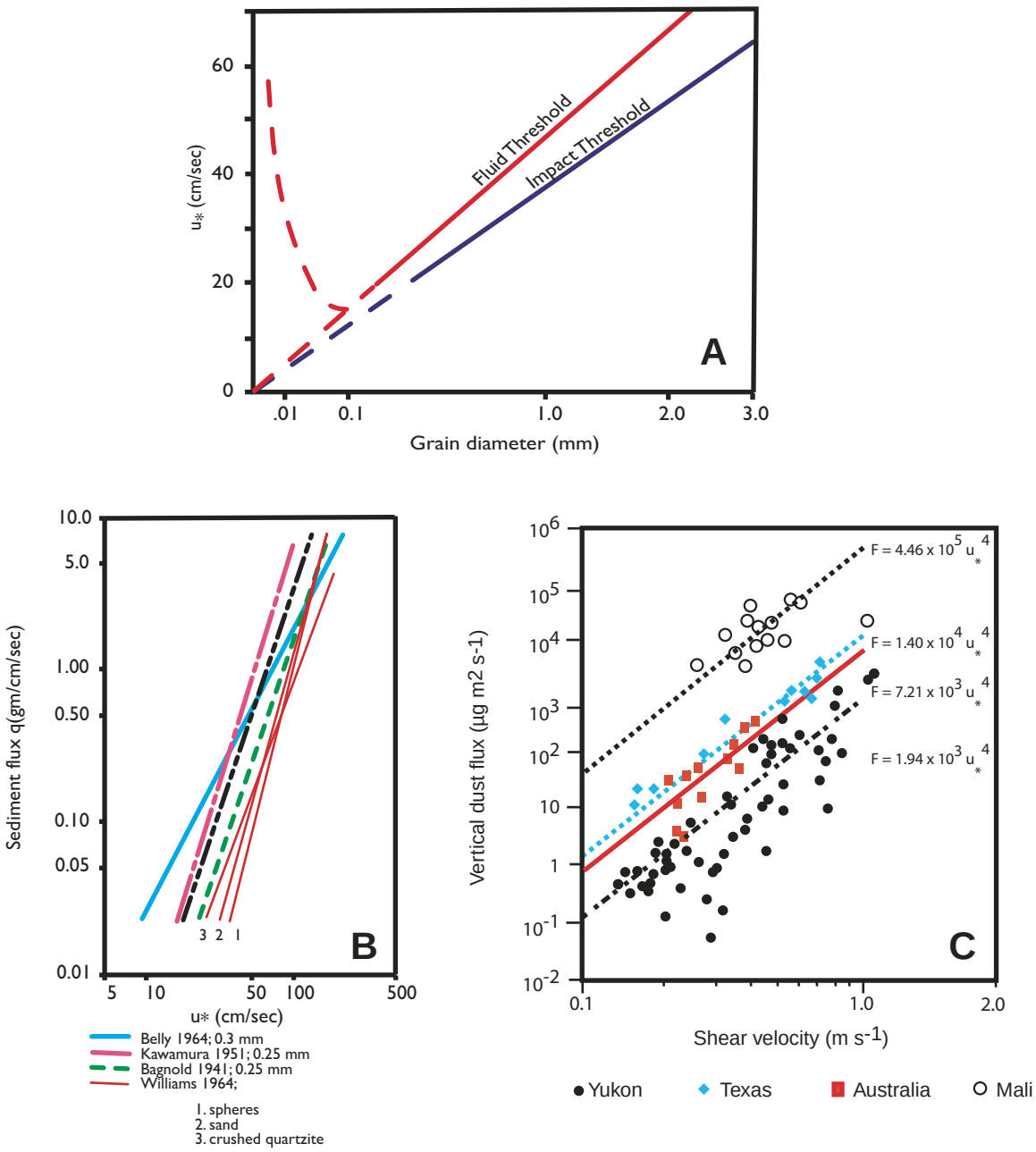


Figure 2. Transport of sediment by the wind: (A) Relation between threshold wind shear velocity and particle size (from (Bagnold, 1941). (B) Mass flux of sand as a function of wind shear velocity (from Lancaster, 1995). Data from laboratory wind tunnel experiments. (C) Relations between horizontal flux of sand-sized particles and vertical flux of dust (from Nickling et al., 1999). Data from field experiments. Figure from Lancaster (2005).

the availability of sediment is unrestricted (e.g., most loose sand surfaces). In these conditions, the wind is saturated with respect to transport capacity.

Very fine grains (silt and clay size) are inherently resistant to entrainment, yet are readily transported by the wind. Recent studies have shown the critical role of impacting sand grains in the mobilization of silt- and clay-size particles and demonstrated the close relations between the horizontal flux of sand-size particles and the vertical flux of fine particles. In these situations, the horizontal mass transport rate is directly related to shear velocity (Fig. 2B), so dust emissions scale to the fourth power of wind shear velocity (Fig. 2C). Where there is a limited supply of particles able to abrade soil clods or playa crusts, dust emissions are limited by the supply of particles rather than the wind shear velocity, and the vertical flux of dust is almost independent of wind shear velocity.

Wind Erosion

Erosion by wind involves two linked processes: **abrasion** (mechanical wearing of coherent materials, including playa crusts and clods created by tillage) and **deflation** (removal of loose material). Considerable attention has been devoted to the processes and rates of wind erosion because of their impact on agriculture, especially in semi-arid regions, and the implications of dust emissions for air quality. Wind erosion abrades crops, removes organic matter, nutrients and fertilizer, and changes soil texture. The products of wind erosion (especially dust particles) impact air quality, atmospheric radiative properties, and human health, causing respiratory illnesses. Rates of wind erosion vary widely and for a given wind shear velocity are dependent on soil or sediment texture and the degree of crusting and cohesion. The highest emission rates for fine-grained sediment are associated with soils of loamy texture, especially those that have been disturbed by vehicular traffic and/or animals.

Aeolian Deposits

Aeolian deposits include sand seas and dune fields, deposits of silt (loess), and fine-grained material that forms a significant component of desert margin and other soils.

Aeolian deposits—silt and clay size. Deposits of wind-transported, silt-sized quartz particles, termed **loess**, cover as much as 10% of Earth's land surface. Loess deposits are widespread in areas of northern China, southern central Asia, central Europe, Argentina, Alaska, and the central United States. Much of the material was thought to be derived from silt particles produced by glacial grinding and supplied to aeolian processes by glacial outwash ("glacial loess"), but other processes, including frost shattering, salt weathering, reduction in size during transport by rivers, and aeolian abrasion are important, especially in the formation of "desert loess."

Silt- and clay-sized material of aeolian origin is also an important component of many desert margin soils. Deposition of silt plays a role in the formation of many stone pavement surfaces in desert regions (desert pavement). These surfaces are characterized by a surface layer of gravel or larger **clasts** (particles) that overlie fine-grained materials. Detailed studies of these surfaces show that the surface layer of gravel rests on a layer of soil-modified dust that may be a meter or more thick and mantles bedrock or materials deposited by other processes (e.g., alluvial sediments). The dust is trapped by the clasts and deposited between them. The fine material is incorporated into the mantle by the shrinking and swelling of clay minerals so that the clasts remain at the surface as they inflate over periods of thousands of years.

Aeolian deposits—sand dunes. Aeolian dunes form part of a hierarchical system of self-organizing bedforms which comprises: (1) wind ripples (spacing 0.1–1 m); (2) individual simple dunes or superimposed dunes on compound and complex dunes (spacing 50–500 m); and (3) compound and complex (mega-) dunes or **draa** (spacing more than 500 m). Dunes occur wherever there is a sufficient supply of sand-sized sediment, winds to transport that sediment, and conditions that promote deposition of the transported sediment. These requirements are satisfied in two main environments: (1) coastal areas with sandy beaches and onshore winds; and (2) desert areas. Most dunes occur in contiguous areas of aeolian deposits called sand seas (>100 km^2) or **dune fields**.

Wind ripples (Fig. 3) typically have a wavelength of 0.05–0.2 m and an amplitude of 0.005–0.010 m. They are ubiquitous on sand surfaces, except those undergoing very rapid erosion or deposition, and form because a flat sand surface over which sand transport by saltation and reptation occurs is dynamically unstable.

Aeolian dunes occur in a self-organized pattern that depends on the wind regime (especially its directional variability) and the supply of sand. Sand dunes occur in four main morphologic types (Fig. 4): **Crescentic** (transverse), **linear**, **star**, and **parabolic**. The simplest dunes form in areas characterized by a narrow

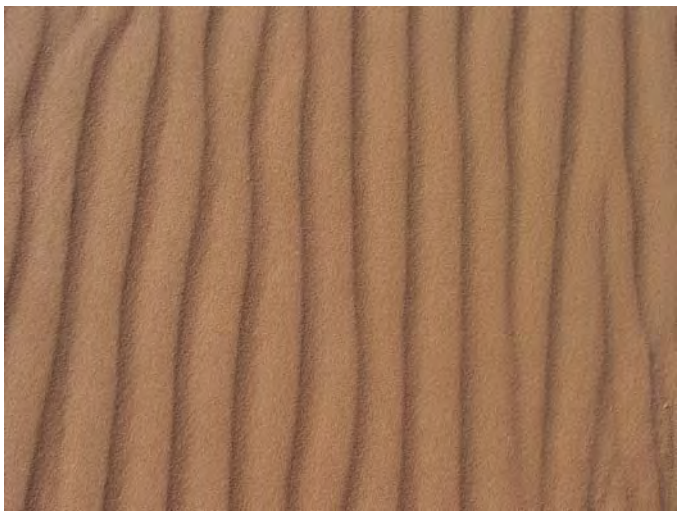


Figure 3. Wind ripples, Gran Desierto, Mexico. Wind direction from left to right.

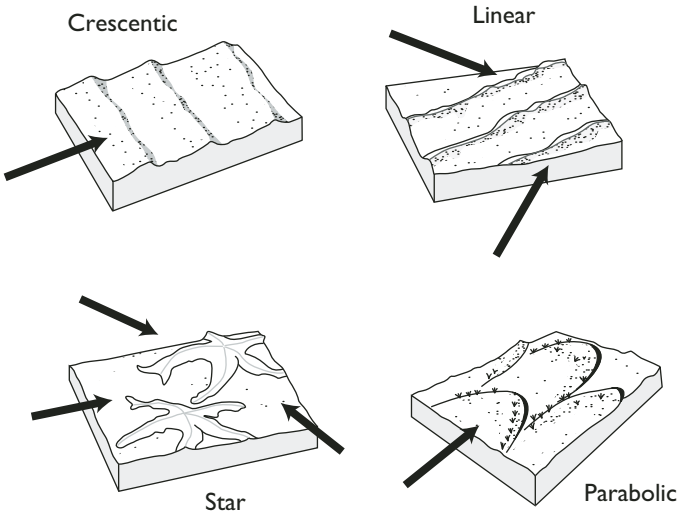


Figure 4. Major dune types (after McKee, 1979b).

range of wind directions. In the absence of vegetation, **crescentic** dunes will be the dominant form. Isolated crescentic dunes or barchans occur in areas of limited sand supply, and coalesce laterally to form crescentic or barchanoid ridges as sand supply increases (Figs. 5A and 5B). **Linear** dunes are characterized by their length (often more than 20 km) sinuous crestline, parallelism, and regular spacing (Figs. 5C and 5D). They form in areas of bimodal or wide unimodal wind regimes. **Star** dunes have a pyramidal shape, with three or four sinuous sharp-crested arms radiating from a central peak and multiple avalanche faces (Fig. 5E). Star dunes occur in multidirectional or complex wind regimes and are the largest dunes in many sand seas, reaching heights of more than 300 m. **Parabolic** dunes (Fig. 5F) are characterized by a U or V shape with a "nose" of active sand and two partly vegetated arms that trail upwind. They are common in many coastal dune fields and semi-arid inland areas, and they often develop from localized blowouts in vegetated sand surfaces. Other important dune types include nebkhas, or hummock dunes, anchored by vegetation (common in many coastal dune fields); lunettes (often composed of sand-sized clay pellets) that form downwind of small playas; and a variety of topographically controlled dunes (climbing and falling dunes, echo dunes).

Relations between dune types and wind regimes indicate that the main control of dune type is the direction of the wind (Fig. 6). Grain size, vegetation cover, and sediment supply play subordinate roles in desert areas. In semi-arid and coastal areas, vegetation cover plays a major role in aeolian dynamics.

STRESSORS AND POSSIBLE CHANGES

The state of an aeolian geomorphic system is controlled by the supply of sediment of a size suitable for transport by the wind; the mobility of the supplied sediment, which is controlled by wind conditions; and the availability of sediment for transport, determined by vegetation cover and soil moisture (Kocurek and Lancaster, 1999). Changes in these external drivers can be the result of climate or human impacts. Climate change and variability affects the mobility of sediment through variations in wind strength; vegetation cover and soil moisture are directly influenced by the amount of precipitation; the supply of sediment may be affected by changes in wave energy, beach sediment budgets, or river discharge. Changes to aeolian systems that can be attributed to the effects of climate variability on annual to decadal time scales include changes in the magnitude and frequency of dust storms (Middleton, 1989), sand transport rates (Lancaster and Helm, 2000), and activation or stabilization of areas of sand dunes (Wolfe, 1997). Such changes are a good indication of the response of a landscape to drought periods. In addition, human impacts may affect vegetation cover by grazing pressure or trampling by animals or people, and increase sediment availability of soils due to disturbance by animals or off-road vehicles. Humans can also directly or indirectly affect sediment supply from rivers or the coastal zone.

VITAL SIGNS

Three main groups of vital signs for aeolian features and processes have been identified. First, rates of sediment movement by the wind give an indication of the magnitude and frequency of aeolian transport events in an area, as well as changes in time and space in response to stressors. Measurements or estimates of rates of sediment transport (sand and/or dust) by the wind provide information on the quantity of sediment transported in this manner and therefore the likely contribution of wind action to erosion and deposition. Second, dune field dynamics provide information on how areas of dunes are responding to external and internal stressors, including disturbance, changes in sediment supply, and climate change and variability. Lastly, dune dynamics provide information on how individual dunes or groups of dunes are responding to stressors.

The level of effort and cost for each monitoring method are summarized in Table 1.

VITAL SIGN 1: FREQUENCY AND MAGNITUDE OF DUST STORMS

The magnitude and frequency of dust storms is an index of rates of wind erosion in the immediate vicinity of a defined location. Reduction of visibility by blowing dust may also indicate an influx of dust from neighboring upwind sources. In addition to the methods described below, some information may also be obtained from the visibility monitoring programs maintained by the Air Resources Division of the National Park Service and its cooperators, available at http://www2.nature.nps.gov/air/monitoring/.

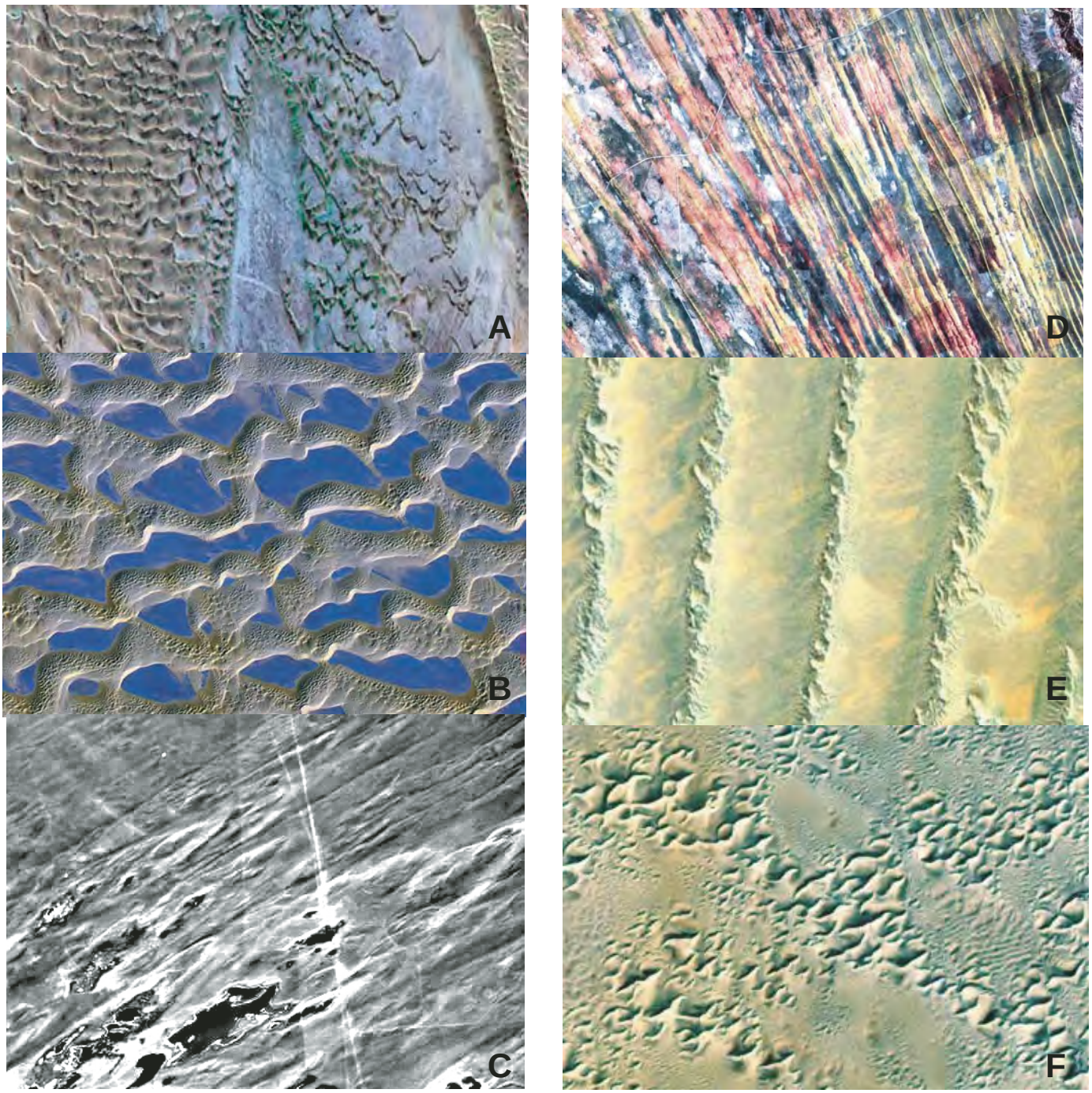


Figure 5. Satellite images and aerial photographs of major dune types: (A) barchans and crescentic dunes, Namib Sand Sea; (B) compound crescentic dunes (Liwa, United Arab Emirates); (C) parabolic dunes, Casper, Wyoming; (D) simple linear dunes (Kalahari Desert); (E) complex linear dunes (Namib Sand Sea); (F) star dunes (Gran Desierto, Mexico). Figure from Lancaster (2005).

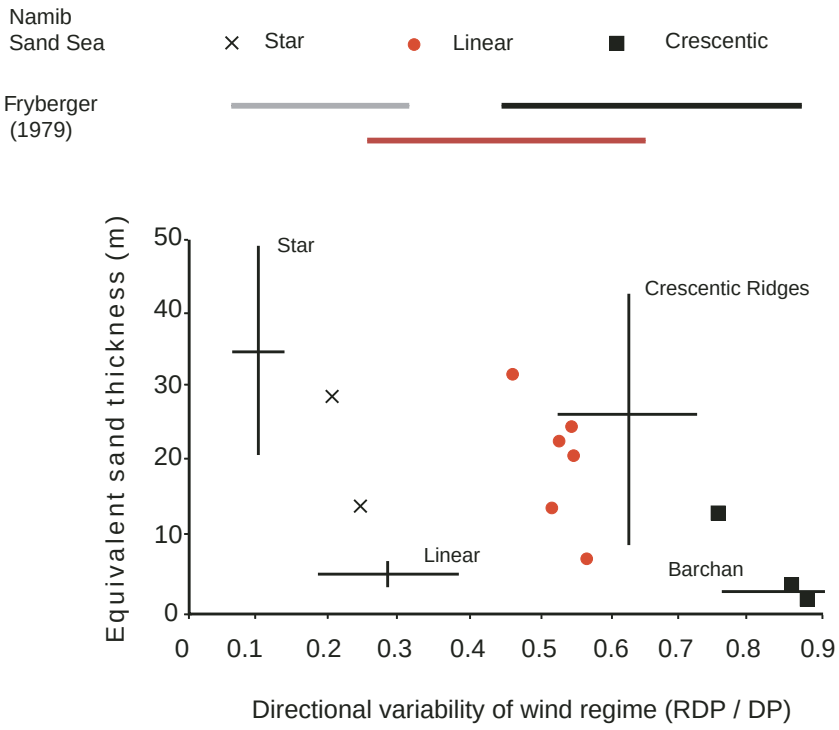


Figure 6. Relations between dune types and wind regimes. Figure from Lancaster (2005).

Monitoring Methods

Level 1: Visual Observation of Dust Storms

Dust storms (Fig. 7) are defined as severe weather conditions in which visibility is reduced to 1 km or less by blowing dust. The frequency of dust storms is measured by the number of such events in a given time period. The magnitude of dust storms can be assessed by the duration of such conditions. Dust events (also known as dust haze) are conditions when visibility is reduced to 11.3 km or less by dust suspended in the air. Blowing dust is a situation where dust is raised to a height of 2 m or more by strong winds, but does not reduce visibility to less than 1 km. Figure 8 provides an example of visibility reduction as a result of a dust storm.

First order meteorological stations may record these conditions as part of their normal schedule of hourly observations. Such data have been used to assess the frequency of dust storms in relation to climatic parameters, such as annual and seasonal precipitation (e.g., Bach et al., 1996; Brazel, 1989; Goudie, 1983; Goudie and Middleton, 1992; MacKinnon et al., 1990; Middleton, 1989). In many areas, dust storm frequency increases in the period following years of lower than average rainfall, although direct correlation between drought conditions and dust storm frequency is not always evident.

Equipment required. No equipment is required.

Complexity. The complexity of this method is very low; it can be conducted by a single observer

Cost. The cost is very low. No instrumentation is required, except for wind speed measurements.

Methodology. Monitoring of dust storms can be undertaken at selected locations where dust storms are known to occur and suitable landmarks exist for visibility determinations. Landmarks at 1 km and 11.3 km distance from the observation point should be identified, and the time and date of dust conditions should be recorded, as well as any relevant meteorological conditions (such as wind speed) and site conditions (such as vegetation cover). The number of dust events and their duration should be recorded on a monthly and annual basis and compared to rainfall and antecedent vegetation conditions.

Timing. Timing is event driven.

Level 2: Camera Stations (Still and Video)

Remotely activated camera stations can be used to image the time, location, and characteristics of dust plumes.

Equipment required. A camera station is required.

Cost. The cost is moderate—around $3,000 to $4,000 per station. (All amounts listed herein are U.S. dollars.)

Complexity. Stations are moderately complex to set up and maintain. Technical assistance is required for set up.

Methodology. Video cameras can be used as they are at Owens Lake, California, by the Great Basin Unified Air Pollution Control District, but their resolution and data capacity are limited. For real-time images see http://www.gbuapcd.org/dustcam.htm. Digital still camera stations have been used to monitor dust storms in the Mojave National Preserve since 2000 (Tigges et al., 2001). The stations automatically acquire digital color images of dust storms, with the cameras triggered by wind speeds above a predetermined threshold. The images are used to

TABLE 1. VITAL SIGNS: AEOLIAN PROCESSES AND FEATURES

Indicator	Methods	Expertise	Technical needs	Cost	Labor
Vital sign 1: Frequency and magnitude of dust storms	Level 1: Visual observation of dust storms	SCA/volunteer	None	Low	1 person
	Level 2: Camera stations (still and video)	Scientist/SCA	Needed for set up	Medium	1 person
	Level 3: Visibility sensors	Scientist	Needed for set up	High	1 person
Vital sign 2: Rate of dust deposition	Level 1: Dust traps	SCA/volunteer	None	Low	1 person
Vital sign 3: Rate of sand transport	Level 1: Estimate rate from wind data	Scientist/SCA	None	Low	1 person
	Level 1: Abrasion stakes	SCA/volunteer	None	Low	1 or 2 people
	Level 2: Sand traps	Scientist/SCA	Needed for set up	Medium	1 or 2 people
	Level 3: Electronic sand transport sensors (e,g., Sensit)	Scientist	Needed for set up	High	1 person
Vital sign 4: Wind erosion rate	Level 1: Lowering of affected surfaces (erosion pins)	SCA/volunteer	None	Low	1 or 2 people
	Level 2/3: Dust concentration measurements	Scientist	Needed for set up	High	1 person
Vital sign 5: Changes in total area occupied by sand dunes	Level 1: Sketch area on topographic map	SCA/volunteer	None	Low	1 person
	Level 2: GPS Survey	Scientist/SCA	GPS	Low	1 or 2 people
	Level 2/3: Aerial photographs and/or satellite images	Scientist	GIS required	Moderate	1 person
Vital sign 6: Area of stabilized and active dunes	Level 1: Delineate areas on topographic map	Scientist/SCA	None	Low	1 person
	Level 2: GPS Survey	Scientist/SCA	GPS	Low	
	Level 3: Aerial photographs and/or satellite images	Scientist	GIS	Moderate	1 person
Vital sign 7: Dune morphology and morphometry	Level 1: Describe major dune types and their characteristics	Scientist/SCA	None	Low	1 person
	Level 2: Aerial photographs or satellite images	Scientist	GIS	Moderate to high	1 person
	Level 3: Digital elevation models	Scientist	GIS	Moderate to low	1 person
Vital sign 8: Dune field sediment state (supply, availability, mobility)	Level 1/2: Identify and describe sources of sediment using existing geologic and sedimentary information	Scientist/SCA	None	Low	1 person
	Level 3: Satellite image processing and modeling	Scientist	GIS	High	1 person
Vital sign 9: Rates of dune migration	Level 1: Field survey	SCA/volunteer	None	Low	1 or 2 people
	Level 2: GPS Survey	Scientist/SCA	GPS	Low	1 or 2 people
	Level 3: Aerial photographs or satellite images	Scientist	GIS	Moderate to low	1 person
Vital sign 10: Erosion and deposition patterns on dunes	Level 1: Repeat photography	SCA/volunteer	None	Low	1 or 2 people
	Level 1: Erosion pins	SCA/volunteer	None	Low	1 person
	Level 3: Topgraphic survey	Scientist/SCA	Surveying/GPS	Moderate	1 or 2 people

Note: GPS—Global Positioning System; SCA—Student Conservation Association.



Figure 7. Dust Storm, Iraq.



Figure 8. Reduced visibility from major dust storm in West Texas, 15 December 2003. Compare with normal clear day (inset). Photographs by Jeff Lee, Texas Tech University.

identify the locations from which dust particles become airborne, the direction and intensity of the dust event, and the meteorological conditions at the time, in conjunction with Climate Impact Meteorological (CLIM-MET) sites (http://climchange.cr.usgs.gov/info/sw/clim-met/) in the area. The system is placed on top of a mountain to provide views to sites of dust emission at distances of 9–20 km. This system is made up of several off-the-shelf components, and several components that were designed and built in-house. Together they perform the task of automatically recording digital images from an unmanned remote location, with recording triggered by wind speed sensors, controlled by a data logger. Images are recorded on a compact flash card with date and time information, for subsequent correlation of images and meteorological data.

The number of dust events and their duration should be recorded on a monthly and annual basis and compared to rainfall and antecedent vegetation conditions.

Timing. Timing is event driven.

Level 3: Visibility Sensors

Automated sensors can be used to estimate the reduction in visibility due to blowing dust, and therefore provide information on the timing, magnitude, and frequency of dust events.

Equipment required. A visibility sensor and a data logger are needed. The instrument should be co-located with other meteorological instruments, including anemometers, to establish the conditions for dust generation and transport.

Complexity. This method requires technical assistance to set up; it is simple to maintain thereafter.

Cost. This method is expensive. Sensors cost $10,000 (Vaisala), plus $2,000 to $3,000 for setting up the station.

Methodology. A variety of visibility sensing devices measure visibility automatically using the forward scattering of infrared light in air over a range of 10–50,000 m. Normally used at airports and other locations at which visibility measurements are made for safety monitoring, such instruments are commercially available, automated, and self contained. Applications specific to dust monitoring are rare, but a visibility sensor has been deployed in association with a U.S. Geological Survey/Desert Research Institute Desert Winds site at Jornada Experimental Range, New Mexico, for several years, and has routinely collected information on visibility reduction resulting from increased dust content in the air.

Timing. The number of dust events and their duration should be recorded on a monthly and annual basis and compared to rainfall and antecedent vegetation conditions.

VITAL SIGN 2: RATE OF DUST DEPOSITION

The rate of dust deposition can indicate the rate of wind erosion in areas that are upwind of a specific site. Wind-blown dust may be derived from local sources, such as **playas** (dry or ephemerally flooded lake beds), and/or more distant sources, like far-traveled dust from the Sahara and Asia. The rate of dust deposition is measured as mass/area/time.

Wind-blown dust is an important long-term contributor of fine material and ions to soils in arid regions and adjacent areas, where it also affects water quality and human health.

Deposition of dust may have a significant effect on the composition and nature of soils in arid regions and beyond. Far-traveled dust may have a significant effect on soil chemistry and nutrient status (Farmer, 1993). Rates of dust deposition can be measured using a variety of active and passive samplers (Goossens and Offer, 2000).

Monitoring Methods

Level 1: Dust Traps

A convenient and practical method of passive sampling of atmospheric dust deposition has been developed by Marith Reheis of the U.S. Geological Survey (USGS) (Reheis, 1997, 2003; Reheis and Kihl, 1995) and utilized in extensive networks for sampling dust input to soils in the southwestern United States. Similar techniques have been used to monitor dust deposition rates in the Dry Valleys of Antarctica (Lancaster, 2002).

Equipment required. A dust trap and field and laboratory supplies for cleaning the dust trap and collecting samples are needed.

Complexity. The complexity is low.

Cost. The cost is low. Each trap costs less than $50 to set up.

Methodology. The method consists of installing a simple, robust passive dust trap, which is cleaned and emptied periodically. The trap is a coated angel-food cake pan painted black on the outside and mounted on a post ~2 m above the ground (Fig. 9). Glass marbles rest on a circular piece of metal mesh that is fitted into the pan 3–4 cm below the rim. The 2-m height eliminates most saltating sand-sized particles. The marbles simulate the effect of a gravelly surface and prevent dust that has filtered or washed into the bottom of the pan from being blown away. The dust traps are fitted with two metal straps looped in an inverted basket shape, and the top surfaces of the straps are coated with a sticky material to discourage birds from roosting. At the chosen monitoring interval, the deposited particles are removed by rinsing the pan, the screen, and the marbles in de-ionized water into a 1 L plastic bottle (see Reheis [2003] for full details of trap construction and field procedures).

In the laboratory, the sample is slowly dried at ~35 °C in large evaporating dishes or beakers; coarse organic material is also removed during this process. The mineral matter remaining can then be weighed. Subsequent physical and chemical analyses on dust samples include: (1) moisture content, (2) organic matter, (3) soluble salts, (4) total carbonate (calcite plus dolomite), and (5) grain size. Other chemical analyses such as phosphorus fractions, strontium and other isotopes, elemental and mineralogical composition, and magnetic properties can be performed on selected samples, depending on sample size and monitoring or research needs.

Following the definitions of Reheis and Kihl (1995), **total aeolian flux** is defined as the rate of deposition of material in



Figure 9. U.S. Geological Survey Reheis Dust Trap. Photo by Marith Reheis, USGS.

grams per square meter per year (g $m^{-2}yr^{-1}$). This can be divided into two components: "dust" flux, which comprises material <50 μm in diameter (silt and clay size), and "sand," which is material >50 μm in diameter. The rate of aeolian deposition is calculated as follows: aeolian deposition rate (g $m^{-2}yr^{-1}$) = mass of dust retained on filter (g) * 1/area of dust pan (m^2) * time exposed (yr).

Timing. Measurement frequency should be annual or semi-annual (to distinguish seasonal changes in dust flux).

VITAL SIGN 3: RATE OF SAND TRANSPORT

The rate of sand transport on sandy surfaces is an indicator of the activity of aeolian processes in an area. Rates of sand transport in relation to wind speed have been determined empirically in wind tunnel studies (Lancaster, 1995). Measurements of sand transport rates in natural settings are much less common (except perhaps in coastal areas), and long-term monitoring studies of sand transport rates are rare.

Monitoring Methods

Level 1: Estimate Sand Transport from Available Climatological Data

Providing that quality wind data are available, sand transport rates may be estimated from wind speed data measured at meteorological stations using one of a number of empirical and theoretical equations (see reviews in Pye and Tsoar, 1990; Sarre, 1987). These rates are, however, *potential* rates, because actual sand transport rates may be reduced by the availability of suitable sediment for transport, presence of vegetation or other elements, surface moisture, crusting, and cohesion of the surface.

Equipment required. This method requires access to pre-existing wind records.

Complexity. The complexity is low.

Cost. The cost is low.

Methodology. One of the most widely used equations for estimating potential sand transport from wind data is the one developed by the USGS (Fryberger, 1979), with modifications and cautions discussed by Bullard (1997). The "Fryberger method" also provides classification schemes for characterizing the energy and directional variability of wind regimes. The method has been widely used to characterize aeolian sand transporting conditions (e.g., Sweet et al., 1988).

The Fryberger method only considers winds above a threshold velocity for sand movement and weights these winds in recognition of the fact that stronger winds are proportionately more effective in transporting sand than weaker winds. Thus:

$$q \propto V^2(V - V_t)/100$$

where q is the rate of sand transport, V is the wind velocity at 10 m height and V_t is the impact threshold for transport measured at 10 m. This weighting equation is then calculated for all wind speed categories above the threshold and applied to the percentage frequency of these wind speed categories so that:

$$Q \propto V^2(V - V_t)t$$

where Q is the rate of sand drift (expressed in vector units), and t is the percentage frequency of winds in that wind speed category.

The total Q for each wind direction and the total for a station are obtained by summation to give the sand "drift potential," or **DP**; and the vector sum or resultant sand drift (RDP) magnitude and direction are obtained by vectoral summation. The DP is a measure of the total wind energy of a location, whereas the ratio between RDP and DP is a measure of the directional variability of the wind regime, which has been widely noted as a major control of the type of sand dune in an area (Fig. 6). Full details of the methods are contained in Fryberger (1979). The original method was based on the use of wind speeds recorded in knots. Bullard (1997) cautions the user and provides information on the use of the weighting factors for winds recorded in other units. Saqqa and Saqqa (2007) provide a simple computer program for estimating sand transport potential. Figure 10 shows an example of a "sand rose" calculated using the Fryberger method, as well as an example of monthly changes in drift potential.

Timing. This method should be performed annually or monthly.

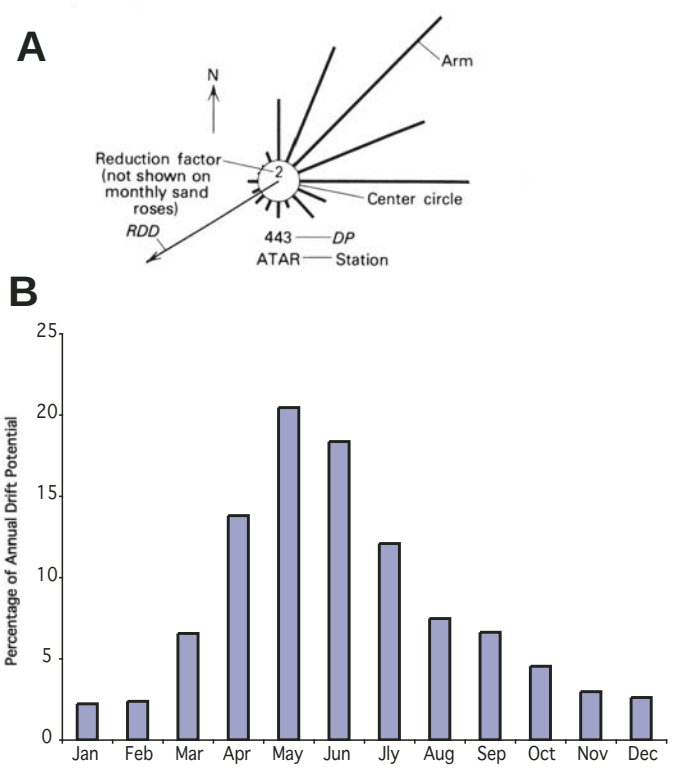


Figure 10. (A) Example of a "sand rose" developed using the Fryberger (1979) method. (B) Monthly variations in drift potential, Palm Springs, California.

Level 1: Abrasion Stakes

An estimate of the rate of wind transport of sand from different directions can be derived from observations of the removal of layers of paint from wooden or aluminum stakes, as used in Pangnirtung National Park, Baffin Island, Canada (McKenna Neuman and Gilbert, 1986).

Equipment required. 1–2-m-high aluminum or wooden poles are needed.

Complexity. The complexity of this method is low.

Cost. The cost of this method is low.

Methodology. The poles should be set up in areas known to experience sand transport. Each pole is painted with eight layers of exterior enamel paint of different colors. Exposure of paint of different colors at different heights and orientation on the stake gives a relative estimate of the intensity of sand transport by different wind directions. This method will work best when sand transport is at a high intensity and thus able to scour paint off the poles.

Timing. Timing should be annual or seasonal.

Level 2: Sand Traps

A wide variety of sand traps have been developed to measure rates of sand transport in laboratory and field settings. See Goossens et al. (2000) and Nickling and McKenna Neuman (1997) for a review of different trap designs.

Equipment required. Sand traps, a balance for weighing sand, and collection bags are needed.

Complexity. The complexity is low to moderate.

Cost. The cost is low. Each Fryrear trap costs approximately $80 (see below).

Methodology. Long-term monitoring of sand transport rates using traps requires that the traps be robust and self-orienting into winds from different directions. Although many different types of traps have been developed, few can withstand long-term exposure and maintain collection efficiency. An efficient and robust passive sand trap was designed by the U.S. Department of Agriculture (Fryrear, 1986) (Fig. 11). (See http://www.fryreardustsamplers.com/BSNE.html.) This type of trap has been used extensively for time-integrated measurements of sand-size particles moving in saltation in harsh environments (Gillette et al., 1997b; Gillette, 1999; Gillette and Chen, 2001) and for long-term monitoring (Lancaster and Helm, 2000; Tigges et al., 1999). These passive collectors maintain a collection efficiency of ~90% for a wide range of wind speeds (Shao et al., 1993).

The traps can be exposed at a single height (typically 10 cm) or at multiple heights (spaced logarithmically, as in Fig. 11). They may be emptied of sand at any desired interval, taking care that the trap is not filled completely, and the contents weighed. The total horizontal flux of sand can be calculated using the approach of Gillette and Chen (2001). The sand traps should be co-located with wind speed and direction sensors.

Timing. Timing should be weekly or monthly, depending on the rates of sand transport to be expected.



Figure 11. The Big Spring Number Eight sand trap (from http://www.fryreardustsamplers.com/bsne.html).

Level 3: Electronic Sand Transport Sensors

Electronic sand transport sensors have been developed to allow remote monitoring of sand transport rates in conjunction with measurements of wind speed and other parameters. The devices operate on a piezo-electric principle, in which sand grains impact a protected crystal, which sends a signal recording the number and kinetic energy of grain impacts (Gillette and Stockton, 1986). One device is the Sensit™ (http://www.sensit.com/). In practice, the kinetic energy signal from this device has been difficult to interpret. The particle count signal is calibrated by the manufacturer or in a wind tunnel with a known mass flux of sand.

Equipment required. A sand transport sensor, data logger, anemometer, and wind vane are needed.

Complexity. The complexity is moderate to high. Technical knowledge is needed to install and maintain devices and interpret data.

Cost. The cost is moderate to high; Sensits are about $2,000 each, Safires about $700 each. A data logger and associated instrumentation (e.g., anemometer and wind vane) are required, adding a further $2,000–$3,000 to the cost.

Methodology. The Sensit device has been widely used for sand transport monitoring (Fig. 12). Examples include the USGS Desert Winds (Tigges et al., 1999) and CLIMET programs (http://climchange.cr.usgs.gov/info/sw/clim-met/) and the Great Basin Unified Air Pollution Control District at Owens Lake, California. Sensits should be co-located with anemometers and wind vanes to ensure sand transport is monitored in conjunction with relevant wind data. A newly developed alternative to the Sensit are the Saltation Flux Impact Responders (Safires). Baas (2004) evaluated the performance of these piezoelectric crystal type instruments. He found that the Safire presents a minimal obstruction to the wind flow and provides high-frequency omnidirectional measurements at a relatively low cost compared with other piezoelectric type sensors. Although Safires have been used in coastal dune settings in the Netherlands (Arens, 1997), they have not been used for long-term monitoring.



Figure 12. Sensit sand transport sensor at Owens Lake, California. Senor is mounted so that height of crystal above surface can be adjusted if surface changes.

Timing. Data should be downloaded monthly.

VITAL SIGN 4: WIND EROSION RATE

The action of wind on exposed sediments and friable rock formations causes erosion (abrasion) and entrainment of sediment and soil particles. Wind erosion physically removes the lighter, less dense soil constituents such as organic matter, clays, and silts. Thus it removes the most fertile part of the soil and lowers soil productivity (Leys, 1999). The rate of wind erosion of a given area is a direct measure of the loss of the surface soil and its contained nutrients, seeds, and soil materials. In addition to lowering of the surface, some authors have noted changes in soil texture as a result of wind erosion. Although these mainly apply to agricultural fields, some coarsening of natural surfaces may occur as a result of wind erosion.

Monitoring Methods

Level 1: Lowering of Affected Surfaces

Equipment required. Erosion pins (e.g., rebar) and a measuring tape are needed.

Cost. The cost is low.

Complexity. The complexity level is low.

Methodology. The rate of lowering of affected surfaces, such as sand sheets, playa surfaces, and alluvial flats may be monitored using erosion pins at strategically located sites. Monitoring of erosion using erosion pins can be as simple as using lengths of rebar hammered into the ground and measuring the exposure of the pin relative to the ground surface at regular intervals. Such methods have been used to monitor wind erosion rates at Jornada Experimental Range and Owens Lake (Fig. 13). When placing the pins, care should be taken to choose a representative sample of the area. Multiple pins per site are useful to estimate local variability in rates. The resolution of this method is relatively low; it is difficult to measure surface changes of less than 10 mm.

In addition, qualitative estimates of wind erosion can be made via the degree of exposure of roots and creation of residual pedestals of soil by wind erosion.

Timing. Timing should be monthly or annually.



Figure 13. Erosion pins for monitoring dune dynamics, Namib Desert.

Level 2 and 3: Measurements of Dust Concentration Downwind of Affected Area

Measurements of dust concentration in the air downwind of an eroding area can provide information on the mass of fine material eroded from that area.

Equipment required. Dust concentration measuring devices (e.g., DustTrak) are needed.

Cost. Costs are very high. MiniVol is $3,500; DustTrak is $3,000 to $4,000; TEOM is $25,000 or more.

Complexity. The complexity level is high to very high. Skilled technical support is required to install and maintain TEOM instruments. DustTrak can be operated with minimal training.

Methodology. The vertical profile of dust concentration above the surface is a measure of the amount of fine particulate matter being emitted from a surface (the vertical flux of dust). Typically, dust concentration shows an exponential decrease in height above the emitting surface, due to dispersion of the dust by atmospheric turbulence. The gradient (slope) of the profile is proportional to the rate of emission. Measurements of concentration profiles require sophisticated instrumentation and are a research, rather than a monitoring, technique. They apply only to the conditions being studied (Gillette et al., 1997a; Gillette et al., 1997b; Nickling et al., 1999).

An estimate of dust emission rates can be obtained via measurements of particle concentrations downwind of the eroding area. Such measurements are made using one of a wide variety of devices used to measure ambient air quality and are usually targeted toward a specific particle size (e.g., PM10, or 10 µm). Such devices employ a pump, which draws air at a precisely calibrated rate through a filter, on which the dust collects for subsequent weighing and analysis. Typical examples of these devices are the HiVoL and MiniVol samplers used to collect dust to ensure compliance with federal (Environmental Protection Agency) and state air quality standards (Chow, 1995). Newer devices include the DustTrak (Fig. 14), which employs a laser beam to measure dust concentrations in a chamber within the instrument (http://www.tsi.com/Product.aspx?Pid=11). The TEOM, Tapered Element Oscillating Microbalance, (http://www.rpco.com/products/ambprod/amb1400/index.htm) is another, more costly device, and it is the only real-time particulate monitor that directly and continuously measures the mass of particulates collected on a filter and provides continuous particulate concentration data. Such devices can be installed in critical areas (such as Owens Lake, California). They also provide information on the magnitude and frequency of dust storms via changes in dust concentration over time.

Timing. Timing should be event based, or data can be downloaded weekly.

VITAL SIGN 5: CHANGES IN TOTAL AREA OCCUPIED BY SAND DUNES

The total area occupied by sand dunes is an indication of the long-term supply of sediment to an area. Changes in the total area and location covered by dunes will, over time, reflect the long-term sediment budget of an area, as well as the degree to which the dune field as a whole is migrating. Decreases in the area covered by dunes as well as the size of dunes (see below) reflect a negative sediment budget in which sediment is being lost from the dune field faster than it is supplied. Conversely, an increase in dune size or area of dunes may indicate a positive sediment budget in which the supply of sediment exceeds losses.



Figure 14. DustTrak monitoring device deployed at Jornada Experimental Range, NM. (Photograph by W.G. Nickling.)

Monitoring Methods

Level 1: Delineation on a Map of Area Occupied by Dunes

Measurements or estimates of the area occupied by dunes are necessary steps to establishing a baseline for monitoring changes in dune fields.

Equipment required. Maps and/or orthophotograph quads and a planimeter are needed.

Cost. The cost is low.

Complexity. The complexity level is low.

Methodology. The most straightforward method of assessing changes in dune area is to delineate the area(s) covered by dunes on published topographic maps or similar products. The total area(s) covered by dunes can be estimated using a planimeter or by measuring dune field width and length. If maps compiled at different dates are available, then comparisons of dune field area and position can be made. In many cases, however, the area(s) of dunes depicted on USGS 7.5′ quad (1:24,000 scale) topographic maps is very generalized. A more accurate estimate of dune field area can be obtained from the digital orthophoto quarter-quadrangles (DOQQ), which are compiled directly from aerial photographs. It should be noted that this method can only provide information on dune field area for the dates when the maps were compiled, which may be irregular or infrequent. If a more frequent assessment of dune field area is required, then Level 2 or Level 3 methods should be used.

Timing. Intervals should be determined by available maps and frequency of revision.

Level 2: Global Positioning System (GPS) Survey

In recent years, low-cost, handheld GPS units have provided a simple, rapid, and accurate way to document geographical areas. Field traverses of the margins of dune fields can provide an accurate outline of the area.

Equipment required. A handheld GPS unit and maps and/or orthophotograph quads are needed.

Cost. The cost of this method is low.

Complexity. The complexity level is low to moderate.

Methodology. Field traverse of the perimeter of the area of dunes are conducted. Coordinates of key points are determined by GPS. The coordinates of these points can then be transferred to a topographic map base or geographic information system (GIS). This method may be time-consuming for larger dune fields and is best suited to small areas of dunes where an accurate mapping of the area of dunes is required at a frequency greater than that of map revisions or new aerial photograph or satellite coverage.

Timing. This method can be performed at annual or longer intervals.

Levels 2 and 3: Comparison of Areas of Dunes on Aerial Photographs and/or Satellite Images

In many areas, a long history (as much as 70 years) of dune field dynamics can be compiled by comparing the area and position of dune field margins on vertical aerial photographs or satellite images taken at different times.

Equipment required. Aerial photographs, a scanner, access to a GIS application are needed.

Cost. The cost is moderate to high, depending on the cost of aerial photograph coverages.

Complexity. The complexity level is high; this method requires knowledge of GIS applications.

Methodology. At the simplest level, transparency sheets (made of mylar, for example) are laid over the photographs. The area can be delineated on the transparency, and the information transferred to a topographic map using visual comparison to features common to both. More accurate and more valuable information can be gained by scanning the images, correcting their geometry in a GIS and compiling coverages of dune field area at different times. Geometric corrections are necessary to co-register the images in a common geographic reference frame. The GIS can then be used to generate dune areas and to estimate changes in area and/or position over time (Lancaster, 1997; Lancaster et al., 2001).

Satellite image data (e.g., Landsat) can also be used to generate data on dune field dynamics. Because their spatial resolution is in tens of meters, they are best used for larger dune areas.

High-resolution satellite image data are available, but these data are expensive and have a limited temporal and spatial availability. Landsat satellite data are also only available back to 1973, so information from this source is only relevant to the past 30 years or so. Despite these limitations, satellite data have been used to provide a long-term view of the dynamics of some dune fields, such as Great Sand Dunes (Janke, 2002; Marîn et al., 2005).

Timing. Intervals should be determined by dates of aerial photograph coverages.

VITAL SIGN 6: AREA OF STABILIZED AND ACTIVE DUNES

The active area of dunes, bare sand surfaces or migrating (mobile) dunes, compared to the inactive area (stabilized by vegetation) is a valuable indicator of the response of both inland and coastal dunes to changes in sediment supply and mobility. In coastal dune areas, the primary control of dune activity is the supply of sediment, because many coastal dunes are located in areas where the climate permits growth of vegetation. Thus, many coastal dunes are very active close to the supply of sediment at the coast and become progressively less active inland as sediment supply decreases.

In inland dune areas, the primary control of dune activity is climatic. Dune mobility can be characterized by the ratio between wind energy (W) and the effective precipitation (P/PE) (Lancaster and Helm, 2000). Thus, dunes can be active in areas that are characterized by windy conditions, although precipitation can be quite high. The relations between wind energy and effective precipitation for dune areas in the western United States are shown in Figure 15.

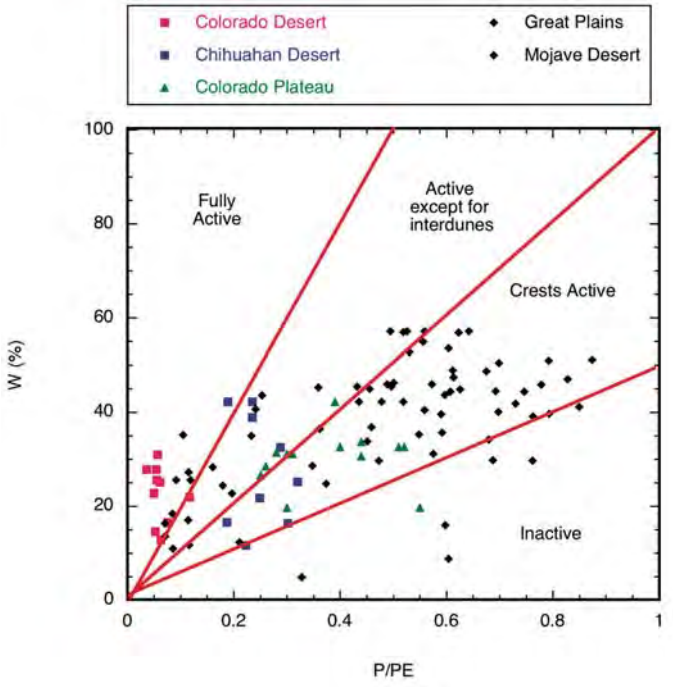


Figure 15. Dune mobility index values for locations in the western United States compiled from data provided by author and D. Muhs (U.S. Geological Survey).

Monitoring Methods

Level 1: Delineation of Area Occupied by Active and Inactive Dunes on Topographic Maps

Equipment required. Aerial photographs and topographic maps are needed.

Cost. Costs are low to moderate, depending on the cost of aerial photograph coverages.

Complexity. The complexity level is moderate.

Methodology. The areas covered by active and vegetation-stabilized dunes can be interpreted from aerial photographs or field survey and transferred to a topographic map base. On most aerial photographs, bright tones indicate bare (active) sand, whereas progressively darker tones indicate vegetation-stabilized dunes and sand surfaces. Field checking is desirable to develop accurate classification of areas. These methods have been used to map areas of active and inactive dunes in many areas (Forman et al., 2006; Lancaster, 1997; Paisley et al., 1991)

In some cases, historical records of dune conditions developed by land surveys and explorations can be a valuable source of information on very long-term trends (Muhs and Holliday, 1995).

Timing. Timing should be determined by the dates of aerial photograph coverages.

Level 2: GPS Survey

Equipment required. A handheld GPS unit is required.

Cost. The cost of this method is low.

Complexity. The complexity level is low to moderate (assuming that a GPS unit is available).

Methodology. Field traverses of the margins of active and inactive dune areas can provide an accurate outline of the area of dunes in different states, once the coordinates of key points are determined by GPS survey transferred to a topographic map base. This method may be time-consuming for larger dune fields and is best suited to small areas of dunes where an accurate mapping of the area of dunes is required at a frequency greater than that of map revisions or new aerial photograph coverage.

Timing. Intervals should be annual or decadal.

Levels 2 and 3: Comparison of Aerial Photographs and/or Satellite Images

Equipment required. Aerial photographs or satellite images and access to GIS application are needed.

Cost. The cost of this method is moderate, depending on the cost of aerial photograph coverages and satellite images.

Complexity. This method is highly complex; it requires knowledge of GIS applications and image analysis.

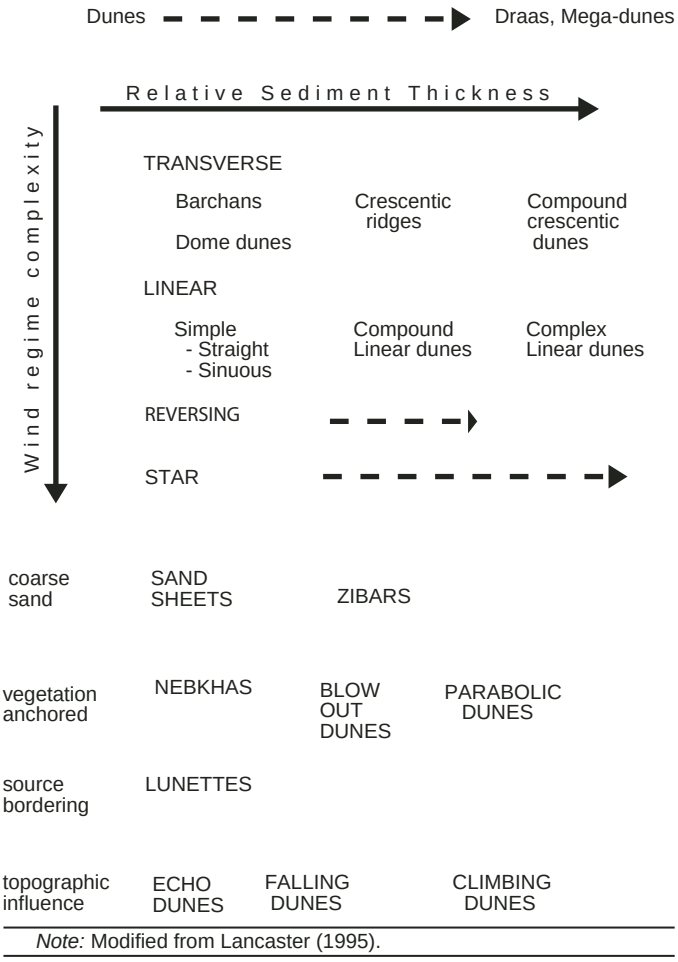
Methodology. In many areas, a long history (as much as 60 years) of dune field dynamics can be compiled by comparing the area and position of areas of active and inactive dunes on vertical aerial photographs. At the simplest level, transparency sheets (made of mylar, for example) are laid over the photographs. The area can be delineated on the transparency, and the information transferred to a topographic map using visual comparison to features common to both. More accurate and more valuable information can be gained by scanning the images, correcting their geometry in a GIS and compiling coverages of dune field area at different times. Geometric corrections are necessary to co-register the images in a common geographic reference frame. The GIS can then be used to generate dune areas and to estimate changes in area and/or position over time. Satellite image data can also be classified to develop information on vegetation and land cover characteristics and to determine changes in the area of active and inactive dunes. For example, Janke (2002) was able to show that dune grasses were being replaced by semi-desert scrub on the west side of Great Sand Dunes, thereby reducing sand mobility.

Timing. Intervals are determined by dates of aerial photograph and/or satellite image coverages.

VITAL SIGN 7: DUNE MORPHOLOGY AND MORPHOMETRY

Dunes occur in a variety of morphological types in self-organized patterns as a response to the wind regime (especially its directional variability) and the supply of sand. Parabolic dunes and nebkhas are controlled by the presence of vegetation. Sand dunes occur in four main morphologic types (Figs. 5 and 6; Table 2): Crescentic (transverse), linear, star, and parabolic. The type of dune is therefore an indicator of the characteristics of the wind regime and the amount of sand available for dune construction. Changes in dune morphology over time can provide valuable information about the long-term response of the dune field to climate and sediment supply. For example, a change from parabolic to crescentic dunes could indicate a reduction in vegetation cover, whereas development of parabolic dunes from crescentic types is indicative of increased vegetation cover, as in coastal areas of Israel (Tsoar and Blumberg, 2002). Changes in dune size are a clear indication of increases or decreases in sediment supply and changes in sediment budgets.

TABLE 2. MORPHOLOGICAL CLASSIFICATION OF DUNES



Note: Modified from Lancaster (1995).

Monitoring Methods

Level 1: Describe Major Dune Types and Their Characteristics

Equipment needed. Maps, aerial photographs, and satellite images of the dune area are needed, as well as access to any previously published work.

Cost. The cost of this method is low.

Complexity. The level of complexity is low.

Methodology. Identification and description of the major dune types occurring in a dune field is a necessary first step to understanding the dynamics of a dune system. The different dune types present should be identified using well-accepted classification schemes (e.g., McKee, 1979a) (Fig. 5, Table 2), and described in terms of their height, width, and spacing. There are numerous studies of dune morphology done in this way (see Lancaster, 1995, for examples), but many dune fields in the United States have not been systematically described.

Timing. This method should be used as needed. Most dune types do not change significantly over time periods of years to decades, and many have remained similar for thousands of years.

Level 2: Map Dune Types and Their Distribution using Aerial Photographs or Satellite Images

Equipment required. Maps, aerial photographs, and satellite images of the dune area are needed.

Cost. Costs are moderate to high, depending on the cost of aerial photograph coverages or satellite images.

Complexity. The complexity level is moderate to high; this method requires knowledge of GIS applications.

Methodology. The goal at this level is to accurately map the different dune types using aerial photographs or satellite images,

using a classification scheme as above. In this way, the area occupied by different dune types can be estimated, and changes in dune distribution and/or morphology can be assessed using sequential aerial photograph series. There are numerous examples of the application of these techniques (Andrews, 1981; Lancaster, 1990, 1993; McKee and Moiola, 1975; Sweet et al., 1988).

Timing. Intervals are determined by dates of aerial photograph coverages.

Level 3: Use Digital Elevation Models (DEMs) to Estimate Dune Size and Sediment Volumes

Equipment required. Computing resources and GIS applications are needed.

Cost. Costs are low to moderate, depending on the cost of image data.

Complexity. This method is highly complex; it requires knowledge of GIS applications and data processing.

Methodology. DEMs can be used to estimate dune size, spacing, and sediment volume using GIS software. With these data, it is possible to accurately monitor changes in sand volume that may be occurring as a result of changes in sediment supply. Data may include online digital data (e.g., http://seamless.usgs.gov/) or high-resolution LIDAR (light detection and ranging) data, which may be available from state or local governments, or specifically commissioned.

Timing. Intervals are determined by the dates of DEM or LIDAR coverages.

VITAL SIGN 8: DUNE FIELD SEDIMENT STATE

Dune fields form part of the well-defined regional- and local-scale sediment transport systems in which sand is moved by wind from source areas (e.g., distal fluvial deposits, sandy beaches) via transport pathways to depositional sinks. Dune fields accumulate downwind of source zones at points where wind speed and directional variability change, so that the influx of sand exceeds outflux, resulting in deposition and growth of a dune field. Over long periods of time (decades to centuries and longer) the dynamics of the system are determined by changes in the supply of sediment of a size suitable for transport by the wind; the availability of this sediment for transport, determined by vegetation cover and soil moisture; and the mobility of this sediment, controlled by wind strength. The interactions between these variables can be evaluated in terms of the state of the aeolian system and the limiting factors identified (Kocurek and Lancaster, 1999). Monitoring of the current and past sediment state of a dune field is an aid to understanding how it is responding to stressors.

Monitoring Methods

Level 1 and 2: Identify and Describe the Sources, Transport Pathways, and Depositional Sinks of the System

Equipment required. Maps, aerial photographs, and published reports are needed.

Cost. The cost is moderate to low, depending on the cost of image data. Google Earth is also a good source of data.

Complexity. The complexity level is moderate to high. Some expert knowledge may be required for interpretation of data.

Methodology. Monitoring of basic parameters and how they change over time is essential to assessing the state of any system. A regional survey of the primary and secondary sources of sediment, the transport pathways, and the sinks for sediment (depositional areas) is also valuable for addressing impacts on the system. For example, knowledge of these parameters in the Coachella Valley, California, was a necessary prerequisite for developing a habitat conservation plan for the Coachella fringe-toed lizard (Griffiths et al., 2002).

The sources of sediment, transport pathways and sediment sinks can be identified from published literature and maps, field survey, and aerial photographs, supplemented by mineralogical analyses of sand. Good examples of this approach are Griffiths et al. (2002) and Sharp, (1966).

Timing. This method should be used at decadal intervals.

Level 3: Use Remote Sensing Data to Identify and Track Sand Sources, Transport Pathways and Sinks

Especially in large, complex dune fields, it may be difficult to assess sand sources, transport pathways, and sinks using published studies and limited field surveys. Recent advances in both remote sensing technologies and methods of analysis allow the identification and monitoring of aeolian systems remotely, thus saving many months of field research. These approaches were pioneered in the Gran Desierto of Mexico (Blount and Lancaster, 1990; Blount et al., 1990), and have been followed by more detailed studies of sand sources for Kelso dunes, California (Ramsey et al., 1999) and the Coachella Valley, California (Katra et al., 2009).

Equipment required. Satellite image data, computing resources, and image analysis software are needed.

Cost. Costs are moderate, assuming image data are available.

Complexity. This method is highly complex; expert knowledge is required for image analysis and interpretation.

Methodology. Primary minerals have distinctive characteristics that can be identified in multispectral image data (such as Landsat). This approach uses spectral information on the sub-pixel scale to identify mineral composition and the relative abundance of different primary minerals. Formerly, this was a research technique, but some available image analysis software applications (such as ENVI) include these techniques as part of their suite of image analysis routines. Care should be taken with interpretation of results.

Timing. This method should be performed at decadal intervals.

VITAL SIGN 9: RATES OF DUNE MIGRATION

The rate of dune migration is inversely proportional to dune height and directly proportional to wind speed and sand transport rates. Monitoring rates of dune migration provides valuable

and easily understood information on the dynamics of the aeolian system. If the potential exists for dunes to move into areas of concern (by crossing roads or migrating into critical habitats, for example), then monitoring of migration rates can provide valuable information for resource management. There is a long history of studies of dune migration rates and several well-established methodologies, as discussed below.

Monitoring Methods

Level 1: Field Survey of Dune Position Over Time

Equipment required. Marker stakes and a tape measure are needed.

Cost. The cost is very low.

Complexity. The complexity level is low.

Methodology. Where dunes are well defined, rates of migration may be monitored by comparing their position relative to fixed markers, such as stakes driven into the ground. These markers may be placed around the perimeter of isolated dunes or adjacent to the lee face of transverse or parabolic dunes. The position of the dune can be compared to the original stake positions and rates of change determined on a seasonal or annual basis. Such methods have been used at White Sands, New Mexico (McKee and Douglass, 1971), and in Namibia (Bristow and Lancaster, 2004), and elsewhere. The disadvantage of field surveys is the need to continually revisit the monitored dune over the years, and the probability that monitoring stakes may be buried or left behind as the dune advances.

Timing. This should be done annually.

Level 2: GPS Survey of Dune Positions

Equipment required. A differential GPS unit is needed.

Cost. Costs are low, providing that a GPS unit is available.

Complexity. This method is moderately complex; training in use of GPS units is required.

Methodology. Dune migration rates can be determined and monitored very easily with high-precision GPS surveys using a differential GPS unit. Using this methodology, the coordinates (latitude and longitude or UTM coordinates) of the leading edge of a dune (usually the base of a slip face) can be determined with a precision of less than 1 m, which is more than sufficient for annual surveys of dune migration rates. The coordinates for the position of the dune in successive years can then be compared to determine any advance. This methodology has been used to determine dune migration rates in Egypt (Stokes et al., 1999). The outline of the dune can be also surveyed using this method, providing a record of changes in dune morphology over time.

Timing. This should be done annually.

Level 3: Comparison of Dunes on Aerial Photographs or Satellite Images of Different Dates

Equipment required. Aerial photographs and topographic maps are needed.

Cost. Costs are low to moderate, except for computing resources.

Complexity. This method is highly complex; it requires specialist knowledge of GIS and data processing.

Methodology. In this method, the position of dunes at different times is compared using aerial photographs taken at selected intervals. At the simplest level, transparency sheets (made of mylar, for example) are laid over the photographs. The area can be delineated on the transparency, and the information transferred to a topographic map using visual comparison to features common to both. The change in position of the dunes can then be measured on the map and divided by the number of years between the aerial photograph coverages to provide an estimate of dune migration rates. This method has been used extensively in southern California (Haff and Presti, 1995; Long and Sharp, 1964; Sweet et al., 1988) and elsewhere (Finkel, 1959; Hastenrath, 1967; and Slattery, 1990). It works best when the dunes are well-defined and moving fairly rapidly. In general, dune migration rates vary inversely with dune size.

More precise and more valuable information can be gained by scanning the images, correcting their geometry in a GIS and compiling coverages of the position of the dunes at different times. The GIS can then be used to generate maps of dunes at different times and to estimate migration rates. This methodology was used to examine dune and dune field migration rates in the Christmas Valley, Oregon, in support of management of this area by the Bureau of Land Management (Lancaster et al., 2001), and at Great Sand Dunes, where changes in dune migration rates were compared to climate data (Marîn et al., 2005).

Timing. Intervals are determined by the dates of the aerial photographs.

VITAL SIGN 10: EROSION AND DEPOSITION PATTERNS ON DUNES

The pattern of erosion and deposition on dunes provides a record of the response of the dune to airflow patterns and vegetation. Valuable information on the dynamics of the dunes and their response to changes in climate and vegetation can be generated in this way.

Monitoring Methods

Level 1: Repeat Photography

Many changes in the topography and morphology of dunes are complex, and require careful, quantitative topographic survey. A qualitative monitoring of seasonal, annual, or multi-annual changes in dunes can be achieved using repeat photography from fixed camera stations (Livingstone, 1987).

Equipment required. A digital camera and a GPS unit are needed.

Cost. The cost of this method is low.

Complexity. The complexity level is low.

Methodology. Critical areas of dunes, such as advancing dune fronts, are identified, and a camera station with an unob-

structed view is established. The camera station is permanently marked and its GPS location recorded. Clear information is needed on the date and time of the photographs, the camera system and focal length of lens used. Photographs or panoramas are repeated on a regular basis.

Timing. This method should be repeated annually.

Level 2: Erosion Pins

Transect lines or grids of erosion pins can be set up across dunes to measure erosion and deposition patterns at certain points on the dunes (Fig. 13). These patterns can then be compared to winds and, if relevant, vegetation cover. This method has been used to monitor changes on a dune in Namibia for over 20 years (Livingstone, 1989, 1993, 2003). Other examples include studies of coastal dune systems (e.g., Arens et al., 2004; Gares, 1990; Gares and Nordstrom, 1995; Jungerius and Verheggen, 1981).

Equipment required. Erosion pins (or stakes) and tape measure(s) are needed.

Cost. The cost is low (after initial set up).

Complexity. The complexity level is low to moderate.

Methodology. Grids or transects of erosion pins are set up across the dune using pins at intervals of 5 or 10 m (or at critical points, such as the base of the slip face). If possible, positions of pins should be surveyed. Measurements from tip of pin to surface should be recorded, as well as the height (exposure) of pin. Changes in the exposure of the erosion pins (less exposure = deposition; increased exposure = erosion) provide a record of dune dynamics.

Timing. This method can be used weekly, monthly, or annually. Shorter intervals provide more precise information and are easier to relate to winds and vegetation conditions.

Level 3: Topographic Survey

Detailed topographic surveys, with a contour interval of 1 m or less can provide very useful data for monitoring dune changes and dune dynamics. These techniques have been used to assess dune changes in several studies, in Oman (Warren, 1988), Namibia (Livingstone, 2003; Ward and von Brunn, 1985); and in coastal blowout dunes in the Netherlands (Arens, 1997; Arens et al., 2004).

Equipment required. Survey instruments (total station) or a differential GPS unit are needed.

Cost. The cost is moderate, assuming that equipment can be borrowed or rented.

Complexity. The level of complexity is moderate to high. Training in surveying is required; analysis of results requires a GIS expert.

Methodology. This type of survey can be carried out using a **total station**, which downloads coordinates to a computer for subsequent plotting in a contouring and mapping program such as Surfer. If a differential GPS unit is available, then similar, but slightly less precise, data can be generated from a detailed GPS topographic survey. Either type of survey can generate data for a digital elevation model, or DEM. Changes can be assessed quantitatively by comparing digital elevation models for different time periods, generating information on areas where changes have occurred and on the volumes and rates of erosion and deposition in these areas.

Timing. This data can be generated at seasonal to annual intervals.

SUMMARY AND RECOMMENDATIONS FOR MONITORING OF VITAL SIGNS

This section provides a statement of the most effective methods for monitoring of the vital signs identified for aeolian processes and landforms.

Vital Sign 1: Frequency and Magnitude of Dust Storms

Providing that personnel are available to record visibility reduction caused by blowing dust, visual observation and recording is the preferred and most cost effective method for monitoring of dust events. In cases where the site is remote, then automated camera systems are the preferred methodology.

Vital Sign 2: Rate of Dust Deposition

The USGS dust trap method is reliable and simple, and provides a valuable record of dust deposition over periods of years to decades.

Vital Sign 3: Rate of Sand Transport

Estimation of potential sand transport rates from wind data is a necessary first step for monitoring of sand transport rates. This also provides data that can be compared with other areas. Long-term field monitoring of transport rates using the Big Spring Number Eight (BSNE) trap provides a valuable record, if the site(s) are carefully chosen.

Vital Sign 4: Wind Erosion Rate

Use of erosion pins and other topographic data can provide a good documentation of wind erosion rates for specific areas.

Vital Sign 5: Changes in Total Area Occupied by Sand Dunes

Although more complex and expensive, a GIS approach is far superior to other methods for estimation of dune field changes, providing quantitative data that can be used in conjunction with climate records to understand long-term aeolian dynamics.

Vital Sign 6: Area of Stabilized and Active Dunes

Mapping of active and stabilized dunes using satellite image data is an excellent method. When used in combination with a

GIS, this approach is far superior to other methods for estimation of dune field changes, providing quantitative data that can be used in conjunction with climate records to understand long-term aeolian dynamics.

Vital Sign 7: Dune Morphology and Morphometry

Use of aerial photographs and/or satellite images is the preferred method for describing dune morphology and documenting any changes that may occur. Although more complex and expensive, a GIS approach is far superior to other methods, providing quantitative data to understand long-term aeolian dynamics.

Vital Sign 8: Dune Field Sediment State

Valuable data on sediment state can be obtained using a descriptive approach, with limited analyses of samples for bulk mineralogy.

Vital Sign 9: Rates of Dune Migration

Rates of dune migration are best determined using repeated GPS surveys, or if a long-term historical record is needed, by comparison of dune positions on aerial photographs or satellite images. In either case, a GIS approach for data recording and synthesis is desirable.

Vital Sign 10: Erosion and Deposition Patterns on Dunes

Repeat photography and simple field surveys can provide valuable information and are simple to set up and repeat.

STUDY DESIGN

General Principles

Any study design should consider the goals of the monitoring, and therefore what process or landform will be studied, why it should be monitored, and for how long. Short-term observations of change are useful, but long-term monitoring is very valuable, though it involves a long-term commitment of resources. The personnel and other resources available will largely determine the methods employed. In general, simple methods regularly applied will yield good results. As far as possible, monitoring programs should strive for quantitative and reproducible results. All data gathered should be assessed critically after two or three measurement intervals to determine: (1) whether changes can be detected; and (2) whether the data can be explained and understood using knowledge of the process or landform being monitored. Adjustments to the monitoring program then can be made as needed, but radical changes should be avoided. It is always useful to have an outside "expert" to act as a consultant.

An Example Program to Monitor Movement of Small- to Moderate-Size Inland Dunes

Monitoring of the rates of movement of inland dunes can provide a sensitive overall assessment of the activity of an aeolian sand system and its response to natural and anthropogenic stressors. An ideal program will combine both short-term (months to years) and long-term (years to decades) monitoring of dune migration rates. Migration rates should be compared to climatic data on all time scales.

Major Project Milestones

1. Determine resources available for monitoring and select appropriate methods to be used. As discussed above, the best techniques for short-term monitoring are field survey using fixed markers or a differential GPS survey; for long-term measurements, use aerial photographs or satellite images taken on different dates.
2. Ensure that relevant hourly wind speed and direction data are available for the monitoring site. Upgrade existing weather stations or install new equipment for the monitoring program.
3. For short-term measurements: select dunes to be monitored. Dunes should be selected to be representative of the size and morphological type found in the study area. If dune types vary significantly, then choose measurement sites for each type. Ensure that monitoring sites are easy to access and not likely to be disturbed by animals or people. Set up fixed points and benchmarks. Allocate resources for monthly or seasonal measurements.
4. For long-term monitoring: Acquire baseline image data and incorporate into a GIS system.
5. For short-term monitoring: make monthly or seasonal measurements and enter these data into a database. Produce graphics showing changes over time.
6. For long-term monitoring: compare dunes on images acquired annually. Produce maps of changes from year to year.
7. After one year, assess short-term monitoring data (if data are collected monthly). Compare rates of movement to wind and other climate data. Determine trends. Are there seasonal differences in migration rates? Do these relate to variations in wind speed and/or direction over the year? Determine optimal timing of measurements and adjust program accordingly. It may be that dune movement is slow enough that annual or seasonal measurements are sufficient. Report results to scientific and management communities. Provide public outreach.
8. After 5 years, assess long-term monitoring data on migration rates by comparing image data from different years. Determine trends, if any. Are there inter-annual differences in migration rates? Do these relate to variations in wind speed and/or direction, or to changes in precipitation (and therefore vegetation cover)? Report results to scientific and management communities.

CASE STUDIES

There are relatively few long-term monitoring studies of aeolian processes and landforms, in part because of the remote nature of many desert regions, and in part because of the perception that geomorphic change is slow in deserts. Good examples include the USGS Desert Winds project (now in part administered by the Desert Research Institute), the USGS dust trap–monitoring study in the southwestern United States, and a decades-long monitoring of cross-sectional and morphologic change on a Namibian linear dune. Common to the latter two projects is a relatively simple and robust methodology. This simplicity ensures that ongoing costs of monitoring are low, using a clearly targeted process or landform and a dedicated principal investigator, who has maintained the monitoring network over many years. Many of the problems encountered by the Desert Winds project stem from the overabundance of data collected and the lack of a clearly defined purpose for the monitoring.

Long-Term Monitoring of Sand Transport and Climatic Parameters: The Desert Winds Project

The Desert Winds Project was set up by the USGS in the early 1970s and was designed to permit remote monitoring of aeolian processes (McCauley et al., 1984). Goals of the monitoring network were: (1) to provide a long-term database for understanding the range of environmental conditions that can be expected to occur normally in arid and semiarid areas of the desert southwest; (2) to acquire baseline data to assess changes in the desert such as changes in vegetation, migration of sand, and increased dust storms that may occur due to climate change in desert regions; and (3) to acquire data for field-checking remotely sensed image data of various surfaces, so that regional models can be developed for monitoring land surface changes over time.

Each station was equipped with anemometers at three heights (1.2, 2.7, and 6.1 m), a wind vane at 6.1 m, temperature and humidity sensors at 1.2 and 6.1 m, and a tipping bucket rain gauge. Transport of sediment by wind is monitored by BSNE sand traps (Fryrear, 1986) mounted at 0.05 or 0.15 m, 0.50 m, and 1.0 m, together with a Sensit piezo-electric sand transport sensor at 0.05 or 0.15 m above the surface. Full details of the instrumentation and operation of the stations are given in Tigges et al. (1999). With the exception of the BSNE traps, all sensors are scanned at one-second intervals with 6-minute averages of the anemometer, wind vane, and Sensit readings, together with 12-minute average temperature, as well as hourly humidity, and precipitation. Data were uploaded via the GOES satellite each hour until the mid 1990s, when the original equipment was replaced by data loggers, which are downloaded on a monthly basis. Currently, only two of the original stations are operating: Gold Spring, Arizona, and Jornada, New Mexico. In addition to the meteorological data, there is repeat photography for the sites at a series of marked camera stations, which provides an indication of changes in vegetation cover over time.

Some preliminary results of the project are discussed in Breed and Reheis (1999), but most of the data have never been analyzed in a systematic fashion. An example of the application of this unique monitoring network to understanding variability of sand transport rates in relation to climatic parameters is documented in (Lancaster and Helm, 2000). The data on long-term variations in sand transport rates provide a record of the response of sand transport rates to external stressors, including drought periods and changes in the composition of vegetation communities over a period of two decades at Gold Spring and Jornada (Fig. 16). The Gold Spring data show the effects of heavy rainfall on vegetation cover and sand transport rates in the period 1992–1993 and subsequent droughts, while the Jornada data show an order of magnitude increase in sand flux since the mid 1990s, likely as a result of the change from a grassland to a mesquite-dominated landscape.

Dust Deposition in the Southwestern United States

This is a good example of a monitoring project that provides quantitative information on an important geologic process, as well as data that lead to a greater understanding of how the process responds to stressors. The project is ongoing and is designed to monitor dust deposition rates in areas of the Great Basin and Mojave deserts of the southwestern United States. Goals of the project are to determine the rate and composition of dust inputs to soils, and to relate dust accumulation to climatic patterns, especially the amount and seasonal distribution of rainfall, as it affects different dust source areas, including playas and alluvial areas. Results of the project are summarized in Reheis, (1997, 2003, 2006) and Reheis and Kihl (1995). The methodology used is briefly described above under Vital Sign 2, and discussed in detail in Reheis (1999, 2003).

Thirty-five dust trap sites in the eastern Mojave Desert and southern Great Basin have been monitored since 1984. Rates of deposition of silt and clay, clay, carbonate, and soluble salts have been determined on an annual or two-year basis, and compared to data on annual and seasonal precipitation at nearby weather stations (Fig. 17). Additional data on the chemical and mineral composition of the deposited dust were also generated.

The data show that generation and accumulation of dust is affected by the amount and seasonal distribution of rainfall. However, different source types (alluvium, dry playas, and wet playas) respond in different ways. A major factor in determining dust generation is the condition of surface sediments, especially their moisture content. For example, the flux of silt and clay and soluble salt increased following the El Niño events of 1987–1988 and 1997–1998 at sites close to playas with a shallow depth to groundwater. In this case, evaporative concentration of salts disrupted surface crusts and increased the susceptibility of surface sediment to wind erosion. The silt and clay flux increased during drought periods at sites downwind of alluvial sources and playas with deeper groundwater. This was the result of reduced vegetation cover on alluvial sediments, and local runoff events that

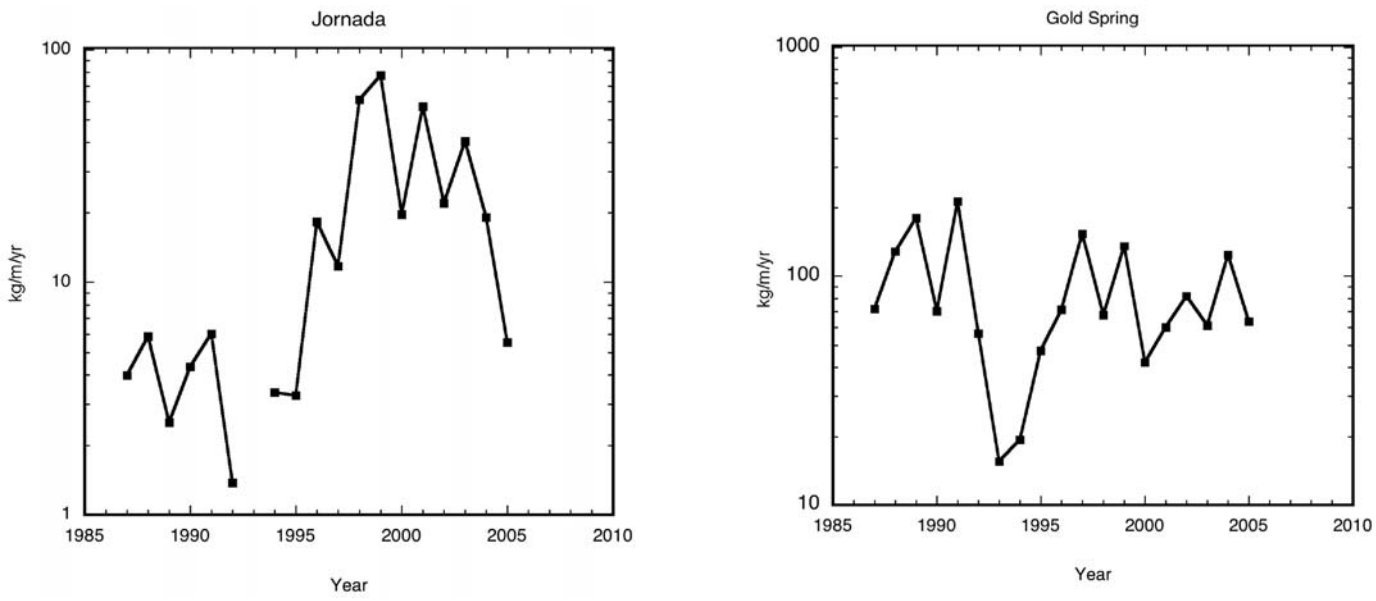


Figure 16. Changes in sand flux over time at Gold Spring and Jornada Desert Winds sites. Sand flux measured using Big Spring Number Eight traps.

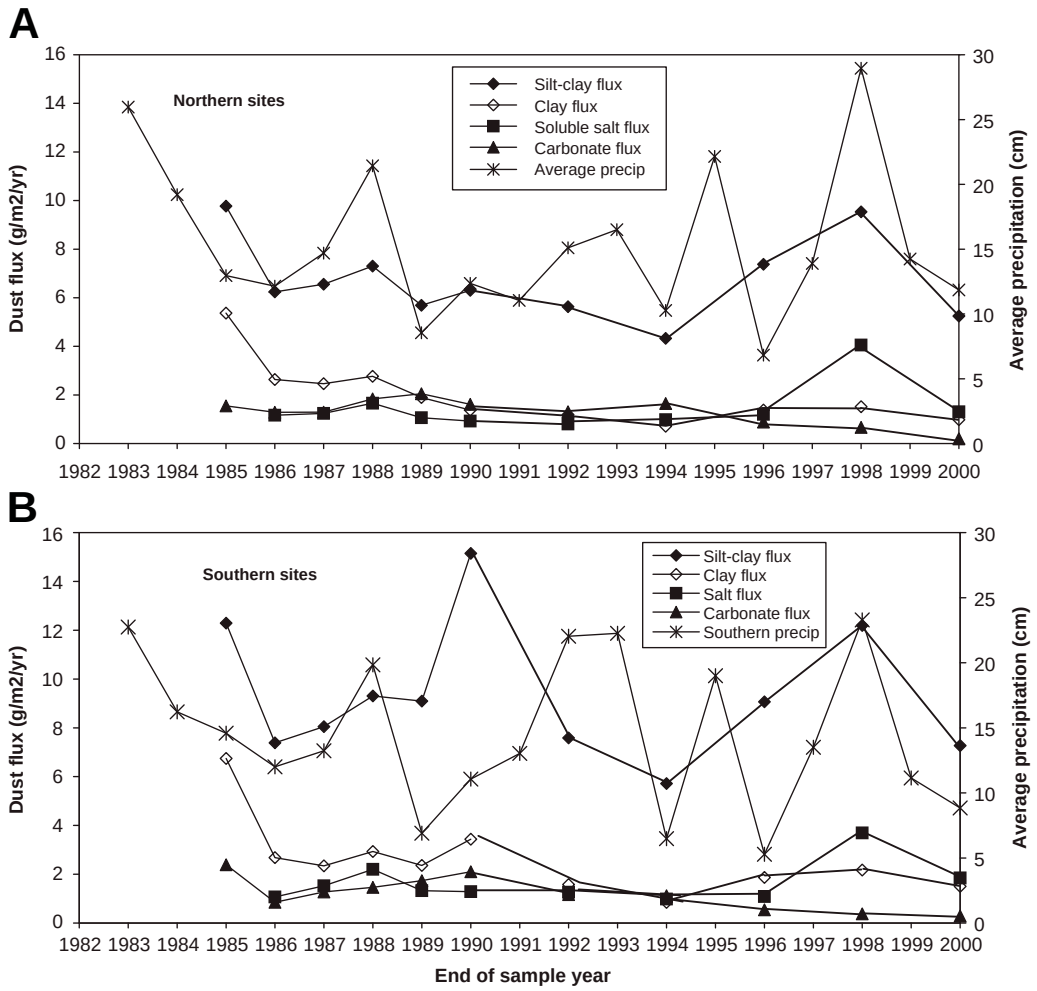


Figure 17. Changes in dust flux in the Mojave and Great Basin deserts (after Reheis, 2006). (A) Dust flux and precipitation at northern sites. (B) Dust flux and precipitation at southern sites.

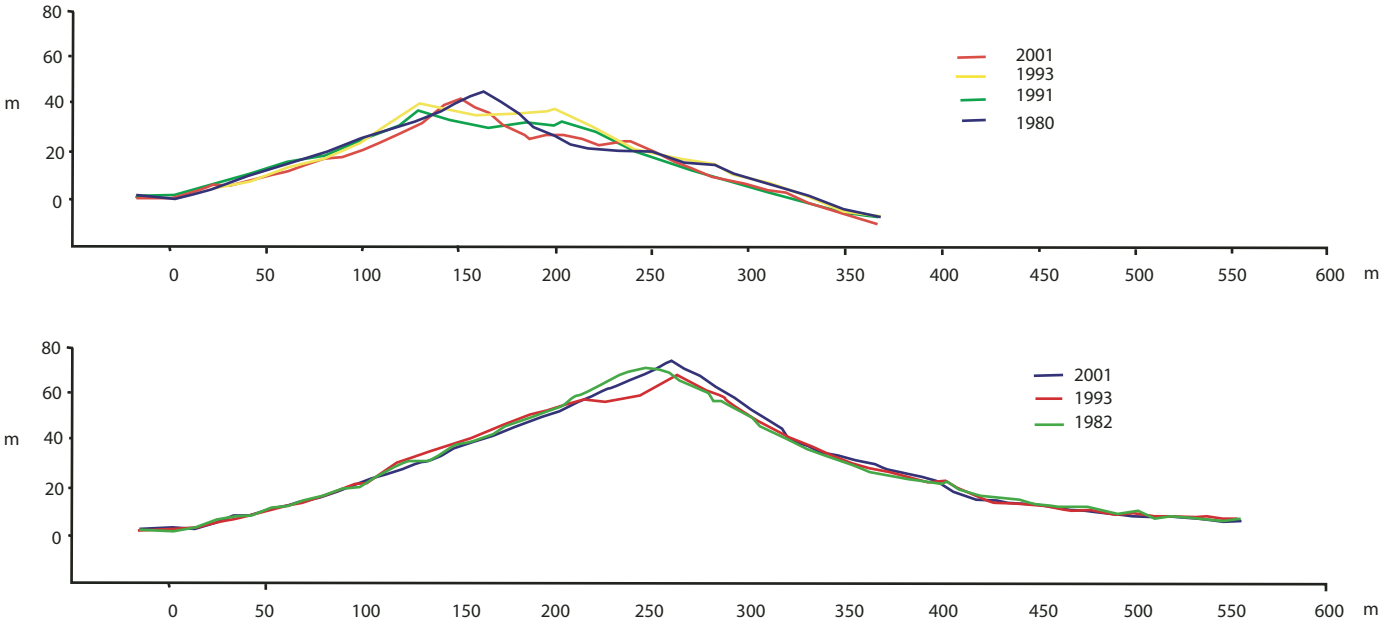


Figure 18. Changes in linear dune morphology (simplified from Livingstone, 2003).

delivered fresh sediment to playa margins and the distal portions of alluvial fans (Reheis, 2003, 2006). Reheis (2006) also noted geographical differences in the response of dust sources to precipitation variability, with a greater range of dust fluxes noted in southern (mostly Mojave Desert) sites.

Topographic Change on a Namibian Linear Dune

Most long-term studies of desert dunes have concentrated on monitoring rates of movement of small crescentic or barchan dunes via comparison of the position of dunes on aerial photographs taken at different time intervals. Studies of the dynamics of individual dunes are relatively rare. This project has monitored surface topographic change on a large linear dune in the central Namib Desert since 1980. Erosion pins were set up in 1980 and monitored weekly for the first four years (Livingstone, 1989). Subsequently, the dune was resurveyed in 1993, providing information on dune change over a decade (Livingstone, 1993), and again in 2001 (Livingstone, 2003). Methods used varied over the period of monitoring, from direct measurement of erosion pins in the intensive phase to use of a total station in 2001. Some of the erosion pins placed in 1980 survived to provide fixed points for subsequent surveys. Results of the intensive monitoring showed that the crest region of the dunes is the most active. The crestlines migrate over a lateral distance of as much as 14 m over a 12-month period, but with little net change over periods of years due to changes in seasonal wind directions. On the dune studied by Livingstone, the crest area changed from a relatively high single crest in the 1980s to a slightly lower double crest form in the 1990s, and then back to single crest form by 2001, regaining much of its original height (Fig. 18). The lower, or plinth, areas of the dune showed little change over the period of study. Livingstone (2003) attributed the changes in dune crest characteristics to changes in the relative magnitude and frequency of strong easterly winter winds, which increased in the late 1980s. The studies also suggested that these large dunes are not migrating because no lateral movement was detected. More recent studies show, however, that the rate of lateral migration of these dunes over periods of hundreds to thousands of years is only 0.13 m/year (Bristow et al., 2007), so the net migration over the period studied by Livingstone would have been ~0.25 m, and therefore difficult to detect.

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Geological monitoring of caves and associated landscapes

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INTRODUCTION

Caves are naturally occurring underground voids. They occur in many types of rocks in many ecosystems. Common types of caves include solutional (karst) caves, lava tubes, sea caves, talus caves, regolith caves (formed by soil piping) and glacier caves (ice-walled caves). Caves range in size from only a few meters long to over 100 km long; the longest known cave, Mammoth Cave in Kentucky, is 580 km long. They also vary considerably in complexity, depth, volume, number of entrances, and many other fundamental parameters.

A concept closely related to solutional caves is karst. **Karst** is a landscape that forms through the dissolution of soluble rock. The most common soluble rock types are limestone and dolomite. Other types of soluble rock that form karst include marble, various evaporates (e.g., gypsum, anhydrite, and halite), and occasionally sandstone or quartzite. Karst landscapes are characterized by internal drainage, losing streams, sinkholes, caves, and springs. Karst is a prevalent landscape; ~20% of the United States is karst. Veni et al. (2001) provides a good introduction to karst. Books such as Moore and Sullivan (1997) and Gillieson (1996) provide somewhat more detailed, but still easily understood discussions of the subject.

Caves are significant, non-renewable, geological resources. They are significant in their own right and also because they house other significant resources including geological resources (mineral deposits, paleontological remains, etc), biological resources (cave adapted and/or dependent microbiology, invertebrates, and vertebrates), and cultural resources (archaeological, historical, religious, and cultural materials, remains, and values). Jones et al. (2003) provides a good introduction to some of the aspects of managing these cave resources. Monitoring of the fundamental vital signs of caves is important in protecting the caves as a whole and the resources contained in them. Hamilton-Smith (2002) discusses the rationale and context for cave monitoring. His discussion includes an introduction to different intellectual models upon which existing monitoring strategies are based. Although its focus is on conservation and restoration, rather than on monitoring, Hildreth-Werker and Werker (2006) provides a strong introduction to many cave resources and types of human impacts that may affect them.

Caves and karst are a very important geological resource in the U.S. National Park system. At least 3900 caves have been identified in 81 national parks. Karst, but no recorded caves, occurs in an additional 39 parks.

Monitoring of geological resources and processes in caves is difficult to separate from two related activities. The first of these other activities is inventory. The second is recurring, long-term scientific research. It can often be difficult to distinguish these three activities. Often there may be overlap among them, and a project that starts as either an inventory or recurring scientific study may become a monitoring project.

Inventory is a crucial prerequisite and companion to monitoring. Inventory is necessary to determine what vital signs need to be monitored, to choose appropriate places to monitor, to determine what monitoring techniques are most appropriate, and to establish the initial conditions from which the monitoring will take place. DuChene (2006) provides a good introduction to cave inventory, including a discussion of both rationale and techniques. Many of the techniques used in monitoring are also used in inventory. For example, the same instruments that are used to measure cave climate, water quality, or visitor impacts are used to make an inventory of the same parameters. Inventory differs from monitoring in that inventory determines only the initial state of a vital sign, cave, or cave resource.

Recurring, long-term scientific research is more difficult to distinguish from monitoring as discussed in this volume. An example of recurring scientific research might be a study of dissolution rates of limestone in a cave passage. Such a study might involve taking measurements of a parameter (such as weight of a limestone plate or the retreat of a wall from a set point) at regular intervals using a set protocol. In this way the activity would be

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the same as monitoring. However, for the purposes of this manual, monitoring should have the potential to influence management action. That is, it should be measuring a parameter that is likely to be affected by threats to vulnerable resources or possible management actions, and which will show a change if management actions are altered. In the example above, it is unlikely that most management actions will affect limestone dissolution rates; instead, it would mainly be of interest for its purely scientific value. For this reason the dissolution study might not be considered monitoring in this manual.

The difference between monitoring, as used in this manual, and recurring scientific research is both tenuous and fluid. As we learn more about human impacts on cave and surface systems, many things that may start as recurring scientific research may be found to provide important information about impacts that had been previously unforeseen. In addition, although some impacts cannot be directly affected by the actions of resource managers on a park (or even regional) scale, monitoring may provide important information with which to evaluate, illustrate, or address broader national or multinational impacts. Global warming provides a good example. Monitoring cave temperatures may provide important information on patterns of warming in different areas. Such monitoring will thus serve an important purpose, even if the cave managers cannot take action that will reverse the warming.

A study that starts as a recurring, long-term scientific study may become a monitoring project, as the understanding of human impacts, potential management actions, and the processes being studied changes. Monitoring projects may also contribute data that can be used for scientific studies that seek to understand cave processes. Indeed, as one implements a monitoring project, it is important to try to set it up in a way that provides as much generally useful data as possible.

The Carlsbad Caverns National Park Cave and Karst Management Plan Environmental Assessment contains a brief, but well-developed cave monitoring plan (Carlsbad Caverns National Park, 2006). It discusses the existing monitoring at the park, the rationale that will be used to decide whether new or additional monitoring should take place, and the procedures to be followed in developing new monitoring projects. It provides excellent guidance on how to develop cave monitoring projects.

An important issue in the development of this chapter is that caves are found at the intersection of the geological, hydrological, biological, and atmospheric disciplines. Many of their resources and processes cannot be readily separated into simple categories. For example, evidence of microbiological roles in some speleogenesis (cave formation) and mineral deposition continues to mount (Barton and Luiszer, 2005; Barton et al., 2001; Northup and Lavoie, 2001). Are these microbiological processes best considered biological, geological, both, neither, or something in between? Cave climate, although probably best considered as an air resources issue, has very profound effects on many aspects of caves and cave resources. In fact, it may be the single most important aspect of many caves to monitor for resource protection. In general, I have attempted to discuss the main vital signs that can provide important information for managing caves as a whole or important geological resources within them. In the case of obviously hydrological vital signs, I have generally discussed them with less detail. Numerous agencies, including the National Park Service (NPS) Water Resources Division, U.S. Geological Survey Water Resources Program, the Environmental Protection Agency Office of Water, and various state agencies, can provide additional guidance on water monitoring, as well as access to hydrologists to assist in developing monitoring programs.

A related issue with cave monitoring is that caves contain a range of "geological settings," some of which overlap with traditional surface geological settings that are discussed elsewhere in this book. Managers may find other chapters assist in developing monitoring programs for caves and cave resources. For example, a cave may have active streams or lakes that could be analyzed and monitored in ways at least similar to surface streams or lakes. Lava tubes are obviously volcanic features; some volcanic monitoring techniques may be applicable to at least the youngest lava tubes, such as those found on the island of Hawai'i. Caves may contain very significant paleontological resources; monitoring of these resources will assist in protecting them, but may also provide more general information about impacts to the individual caves.

VITAL SIGN: CAVE METEOROLOGY

Cave meteorology refers to the microclimate and air composition of the cave. It includes parameters such as air temperature, water vapor content of air (variously measured and expressed as absolute humidity, relative humidity, saturation debt, or dew point), evaporation rates, condensation, air movement (speed, direction, flux, etc.), barometric pressure, carbon dioxide level, radon level, and hazardous gas levels (methane, hydrogen sulfide, carbon monoxide). In addition to these air parameters, cave sediment temperature, water temperature, and rock temperature are commonly monitored with cave meteorology.

Cave meteorological parameters are among the most commonly monitored parameters in cave management. There are three basic reasons for this fact. First, many cave processes are very sensitive to changes in cave meteorological parameters. Microclimate can influence the form and morphology of the mineralogy and the crystal structure of **speleothems** (secondary mineralogical deposits that form in caves, e.g., stalactites and stalagmites) (Hill and Forti, 1997). Decreases in humidity can lead to a decline in cave-adapted animal life. For example, an increase in cave temperature may turn an ideal bat hibernaculum into a cave that is not used by bats. Increases in the concentration of carbon dioxide in cave air can lead to dissolution of cave formations. Paleontological, archaeological and cultural resources in a cave can be damaged by changes in cave microclimate. Second, cave meteorology is relatively sensitive to human activities in caves. The presence of people in a cave can significantly alter the microclimate of some low-energy flow caves, and large-scale tourist activities will alter the microclimate even in high-energy

flow caves. Third, some of the cave meteorological parameters, such as temperature and evaporation, are among the most readily monitored cave parameters (at least at a very basic level).

It is difficult to generalize about the variability of cave meteorological parameters, both because of the difference in caves and because different parameters may show different patterns. In general, the variability of temperature, humidity, evaporation, condensation, and carbon dioxide levels is greater near the entrances to a cave. Deep in the cave these parameters may vary by only very small amounts (tenths of a degree in the case of air temperature, or fractions of a percent in the case of relative humidity). Sediment, water, and rock temperatures tend to be much less variable than air temperatures in the same area. Air flow (wind speed and direction) is much more difficult to generalize. Near entrances, significant airflow may be expected; however, in constricted areas deep in the cave, air flow may also be highly variable. In many cases, cave meteorological readings are best interpreted with surface meteorological readings from the same area.

Monitoring of cave microclimate may be needed for several different reasons. Because cave climate conditions are both broadly sensitive to and dependent on external climate conditions, monitoring cave climate conditions (especially in caves that are rarely visited) can provide information on natural regional climate change. More importantly, from a management perspective, monitoring helps to assess risk to resources due to cave climate changes (natural or artificial). In some caves, the presence of, amounts of, and variations in exotic gases (such as H_2S, CO, CH_4, etc.) are important to understanding the cave processes and to protecting people who may enter such caves. Because of the sensitivity of many cave resources to changes in cave microclimate, monitoring should take place when there are significant resources that could be impacted by changes in cave climate, when management actions might result in a change in climate in a cave, or to provide control data for a nearby cave undergoing a management action.

When developing a cave meteorology monitoring program, it is important to consider both the range of values that can be anticipated for various parameters, and how much change in a variable will be significant in affecting cave processes, or likely to result from human impacts or management actions. This type of information would be obtained through an inventory process where a variety of parameters may be measured using either spot measurements or relatively short runs with data logging instruments. This type of inventory will help establish how the parameters vary in the cave over time. It will also provide important data that allows selection of the most appropriate instruments for measuring various parameters.

Radon concentration in cave air is an important parameter that is monitored in a number of caves (including many NPS show caves). Radon variation data can be used to examine cave airflow patterns (i.e., Pflitsch and Piasecki, 2003). However, most, if not all, radon monitoring is driven by regulatory requirements aimed at safeguarding human health. The NPS Air Resources Division is currently revising radon monitoring procedures for NPS caves (B. Carson, Mammoth Cave National Park, personal commun., 2008). In addition, the National Caves Association (the primary show caves industry group in the United States) has developed industry standards for monitoring and mitigating radon exposures in show caves (Aley et al., 2006).

Methods

Methods of monitoring cave meteorology vary from the extremely cheap and easy to the very expensive and complex. The main variable in cost is frequently the instruments used to measure and record the data. The more expensive instruments often provide greater accuracy and precision, greater storage capacity and greater flexibility in timing of measurements. Cigna (2002) provides good information on a range of monitoring solutions for cave meteorology. The National Park Service's Cumberland Piedmont Inventory and Monitoring Network has developed protocols for monitoring some aspects of cave meteorology, in particular air temperature, humidity, and airflow (J. Jernigan, Mammoth Cave National Park, personal commun., 2008). Copies of these protocols are available from the Cumberland Piedmont I&M Network (http://science.nature.nps.gov/im/units/cupn/). In addition, a group of resource management specialists from the NPS are working to expand those protocols to include additional aspects of cave meteorology. This work is scheduled to be completed in 2010.

When these protocols are finished, they will provide very useful guidance for monitoring these parameters. The protocols being developed focus mainly on mixed use of handheld instrumentation and datalogged sensors, and thus would generally fall in the medium level of cost, technology, and expertise. They also focus on developing an understanding of the spatial and temporal variation in parameters as part of developing a monitoring program.

In general, much basic monitoring can be accomplished by relatively inexpensive people, such as Student Conservation Association interns (SCAs), volunteers, citizen scientists, or students with some training using handheld instruments (such as thermometers, sling psychrometers, anemometers, or gas meters; Fig. 1). The timing between measurements will vary depending on the type of issues being examined. For deep cave measurements in caves not subjected to management actions that might alter cave climate, seasonal measurements may provide adequate data. If caves are subject to management actions that might alter climate (or if they serve as controls) more frequent measurement (monthly or weekly) might be appropriate. Because of variation in instruments, calibration is frequently necessary. Many relatively inexpensive thermometers can be calibrated against either a master thermometer or known temperature points (such as an ice and water mix). Cigna (2002) recommends 0.1 °C accuracy and precision for general purpose cave monitoring. Some specialized monitoring may require more accuracy and precision.

Evaporation and condensation are important meteorological processes that may affect cave resources. Evaporation rates may



Figure 1. Taking spot temperature measurements with handheld instruments is the simplest and cheapest way to monitor many cave meteorological parameters. (National Park Service photo.)

affect mineral growth rates and styles, desiccation potential of cave fauna, and cave pool extents and depths. Evaporation can be measured relatively easily with simple evaporation pans with standardized amounts of water. However, in areas near entrances, it may be important to protect evaporation pans from wildlife.

Condensation is also a very important cave process. De Freitas and Schmeckal (2005) discuss important aspects of condensation in caves. Condensation may cause corrosion of cave walls or formations, may lead to deposition of some types of cave formations, may provide water for cave inhabitants and in some cases can lead to degradation of perishable cave resources (through wetting, allowing fungal growth, or through drip damage). Condensation can be measured in several ways. Evaporation pans can measure condensation. De Freitas and Schmeckal (2005) developed a data logging sensor that is capable of detecting and (if properly calibrated) measuring condensation. Their sensor is fundamentally similar to leaf-wetness sensors that are now commercially available. These sensors measure changes in electrical resistance that occur due to water condensing on a circuit board.

The recommended technique for monitoring cave carbon dioxide levels is non-dispersive infrared spectroscopy (NDIR) (James, 2004). Handheld NDIR CO_2 monitors are available for less than $1,000 (all amounts listed herein are in U.S. dollars). Spot and periodic monitoring of toxic gases in caves (such as H_2S, CH_4, CO, etc.) can be accomplished with stand-alone single or multi-gas detectors. Detectors can be purchased for between $500 and $2,000, depending on capabilities.

Automated data collection with either combined sensors and data loggers (such as HOBO brand data loggers) or specialized sensors attached to data loggers represent a medium level of complexity and expense. The data loggers tend to be somewhat more expensive than handheld instruments, although some temperature data loggers that can be readily used in caves are available for about $100 or less. Acquiring cave meteorological data using data loggers has several advantages over human recording using handheld instruments. In general, it is practical to take data more frequently with a data logger. In addition, measurement errors may be reduced. Data loggers are generally easy to use, maintain, and download. However, the large quantity of data that may result from a large network of data loggers may require staff with specialized data management experience.

The use of data loggers in caves is not as straightforward as it is in many surface applications. The high humidity and frequently condensing environment in caves leads to failure in many electronic devices over time. Finding data loggers that will work in caves for long-term application can be difficult. Only instruments rated for outdoor settings should be considered in any but the driest cave environments. In case of separate probes feeding data to a stand-alone data logger, it may be possible to place the logger in a case with drying agents that protect the logger from cave conditions. If you are considering using data loggers in a cave, contact other cave managers to find out what types of loggers have been used successfully in caves like the ones you are monitoring. In the case of caves with toxic, flammable, or corrosive gases, the long-term detection and logging can be even more difficult, because the instrumentation must survive not only cave conditions, but the additional challenges posed by the exotic gases.

Two cave meteorological parameters can be very difficult to measure precisely and accurately in cave conditions. These parameters are airborne moisture (humidity) and airflow (wind speed and directions). Because of this, these two parameters require more specialized approaches.

Humidity is difficult to measure at very high levels (above 95%). Unfortunately, many caves have relative humidities higher than this level. Thus, specialized, often expensive, instruments are needed to accurately measure cave humidity. Few if any of these specialized instruments are designed to function under the rigorous conditions of a cave. In addition, many of these instruments require significant experience to obtain and interpret the results. One example of a potential technology for measuring humidity very accurately is laser absorption. Laser absorption measures the amount of loss of specific wavelengths as they pass through air. This absorption provides a very accurate measure of the amount of water vapor present in the air (absolute humidity). Unfortunately, this type of instrument is relatively expensive ($5,000–$10,000), and has not been tested in cave environments. Less expensive instruments, like sling psychrometers and inexpensive electronic sensors, will provide general information on

humidity changes, but are unlikely to provide truly accurate and precise monitoring.

Unlike humidity, airflow is not inherently difficult to measure in cave conditions. Practical problems do present more difficulty. Although some caves have very strong winds, many have much more gentle airflow or experience gentle airflow occasionally. In addition, depending on passage geometry and meteorological conditions, airflow may vary significantly in different parts of a passage cross section. In fact, airflow at the top of a passage may be in a different direction than that near the floor of the same passage. It is important to understand airflow variability in a cross section before choosing a place to monitor airflow. Further, the potential for a condensing environment causes measurement problems. Anemometers based on physical movements (like cup or propeller anemometers) that are sensitive enough to measure small airflows are also subject to errors when condensation occurs on the mechanism. For this reason, hotwire and ultrasonic anemometers are more appropriate for cave airflow studies and monitoring. Simple hotwire anemometers provide data on flow velocity, but not direction. However, they can be used in pairs with one anemometer shielded to provide information on airflow direction as well (Cigna, 2004). Ultrasonic anemometers (Fig. 2) are beginning to be used to study and monitor cave airflow (Pflitsch and Piasecki, 2003). They have much promise for improving monitoring, but they have some potential drawbacks. It is possible that ultrasonic anemometers could interfere with or disturb bats. In cases where bats may be an issue, anemometers that use frequencies higher than those used by area bats should be strongly considered.

An inventory of expected values and level of change is especially important when dealing with difficult to measure parameters like relative humidity and airflow. For example, many relatively inexpensive instruments, data loggers, and probes will measure relative humidity; HOBO data loggers are a common type that are used in many monitoring situations. For many applications their thin film capacitance sensors provide usable levels of accuracy (±2.5%) in environments with relative humidities between 10% and 90%. However, in environments with a relative humidity above 90%, their accuracy deteriorates to about ± 4% above 95% RH (Onset Computer Corporation, 2007). Thus, in caves or cave areas with fairly low relative humidities (below 90%), it is practical to use standard, inexpensive data loggers, especially if small changes in relative humidity are not likely to be of great significance. In high relative humidity situations or where changes in humidity of less than 2% are important, more expensive or elaborate methods may be more appropriate. Airflow is similar, in that the needed instruments and resolution may depend on what types and speeds of airflow occur in the cave.



Figure 2. A student at the Blowhole at Kartchner Caverns works to determine the optimal position for a Windsonic ultrasonic anemometer. The grid is a temporary string grid that was used to measure point air velocities. The anemometer is being placed in the area of highest wind velocity. (Photo by R.S. Toomey.)

In choosing the correct instrument, it is also important to understand what level of change in a parameter is significant. If a small change in the parameter will result in significant changes in the cave environment or processes, it will be necessary to use an instrument capable of reliably detecting those small changes. If, on the other hand, the cave processes are not very sensitive to changes in the parameter, less advanced instruments, which are often less expensive, easier to use, and more durable, may be used for the monitoring.

In some cases, very small relative humidity perturbations (less than 1%) may have significant effects on cave processes and cave resources. Often these effects are more pronounced when equilibrium relative humidities are near saturation (100%). Numerous geologically and biologically significant processes in caves vary in form, magnitude, and direction within the relative humidity range of 90% to 100%. These include evaporation rates (Buecher, 1999), mineral stability (Hill and Forti, 1997; Onac and Vereş, 2003), and the loss or gain of biological water (Culver, 1982; Howarth, 1983). If cave relative humidities are in this upper range and these types of cave resources are present, the ability to distinguish humidities within this range may be necessary to adequately understand, anticipate, and possibly mitigate (if necessary) changes in these processes. However, if the caves being monitored are outside these high humidity ranges or do not contain resources sensitive to small humidity changes, then less expensive, easier to use instruments may be sufficiently accurate and precise to detect important changes.

Calibration can be a problem with many sensors over long periods of time in cave environments. To address the problem of calibration and to make sure measurements remain comparable over long periods, less expensive data logging sensors can be used for taking measurements, and more accurate handheld instruments can be used periodically to calibrate the data logging sensors. This can also be cost effective, because fewer expensive, high accuracy instruments are needed.

More expensive and complex cave meteorology monitoring programs will use increasingly complex and specialized sensors

attached to networks of data loggers. These sensors might include very sensitive thermometers, complex psychrometers, ultrasonic anemometers, and gas chromatographs (for analyzing cave atmospheric composition). These systems will require very specialized knowledge to develop, maintain, and analyze the resulting data. Developing this level of cave meteorological monitoring will probably require partnerships with academic institutions or groups that have experience with this type of monitoring.

Buecher (1999) discusses a variety of microclimate characterization and monitoring approaches that were used in predevelopment studies at Kartchner Caverns State Park, Arizona. These studies provide the basis for the ongoing monitoring there. One of the tools used for monitoring at Kartchner Caverns is an Environmental Monitoring Station (Fig. 3). These are permanently located stations at which temperature (air, water, and sediment), relative humidity, pan evaporation, and carbon dioxide are taken at regular intervals (weekly for most stations and monthly for more remote stations) by Arizona State Parks staff. In addition, many of these stations have HOBO temperature data loggers for taking measurements between readings. The weekly readings with calibrated thermometers allow for calibration of the HOBO data. These stations have been in use at Kartchner Caverns since 1989. Toomey and Nolan (2005) discuss the continuing monitoring of microclimate at Kartchner Caverns with respect to cave development, tours, and regional climate patterns; they provide a strong argument for including regional data in understanding the results of monitoring.

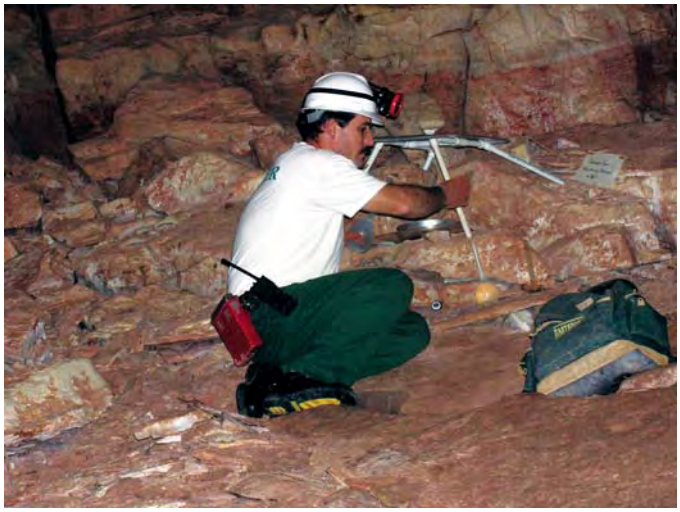


Figure 3. Arizona State Parks ranger checking pan evaporation at an Environmental Monitoring Station at Kartchner Caverns State Park. These stations, which have been in place since 1989, provide a standardized place to conveniently measure temperature, relative humidity, and pan evaporation. The small roofed structure provides the evaporation pan with protection from dripping water. (Photo by R.S. Toomey.)

VITAL SIGN: AIRBORNE SEDIMENTATION

The sedimentation of dust and lint in caves is a significant issue for cave protection, especially in show caves. Natural sedimentation of dust can occur in caves due to natural cave processes such as airflow. However, when caves are visited, the natural level of dust can be supplemented by additional dust (mineral component) and lint (hair, skin cells, and clothing fibers) due to human activity. Monitoring dust and lint in caves that have sizeable visitation or sensitive resources is important because increased deposition can have profound effects on caves. Management actions can increase or reduce deposition. Dust deposition can alter and dull the color of cave formations; dust and lint can also alter the cave life. The deposition of organic materials (like lint) can increase food levels in the cave; the increases in food can allow the cave to be invaded by less cave-adapted forms and displace cave adapted organisms. In addition, decomposition of organic lint on formations can lead to corrosion of the formation surfaces. Jablonsky et al. (1995) and Michie (2001, 2004) provide good summaries of the issues involved with dust and lint in caves.

Methods

Dust and lint can be monitored by examining either the material deposited or the material in the air. In both cases, monitoring both the amount and composition of the dust is most desirable. In almost all cases, comprehensive monitoring of dust will require both specialized training and specialized equipment.

Level 1/2 Methods

General characterization of lint removal activities. If lint clean-up occurs at a cave, it would be desirable to quantify and characterize the lint that is collected in the clean-up. This can vary from simply weighing the lint that is collected to using microscopes and higher tech chemical means to characterize the lint content. The level of training and equipment needed depends on what detail of lint identification is desired. When using these approaches, it is important to standardize for different amounts of collecting effort in different areas or years.

Level 2/3 Methods

Analysis of dust and/or lint collecting plates. Collecting dust and lint to measure deposition rates is generally straightforward. A series of glass plates (or Petri dishes) are placed in the cave to collect falling dust. They can be placed in transects to look at trends in dust deposition or as single plates to look at spot deposition. Plates are left in the cave for set amounts of time. The amount of time that plates should be left varies with deposition rate, the goal of the study (general monitoring or testing a particular management strategy), and sensitivity of the method of quantifying dust deposition. Frequently, multiple plates or dishes are placed together, so that individual plates may be analyzed at different intervals (Fig. 4). The plates are then removed from the cave and the amount and types of dust and lint are determined. Plate collection provides integrated information on dust and lint deposition over a known time period.



Figure 4. A cluster of Petri dishes for integrated time sampling of dust and lint at Kartchner Caverns. This group of dishes is designed to monitor sedimentation along a transect from a tourist trail in the cave. The white fungal or bacterial material growing in the front dish shows one potential problem with this type of monitoring strategy. Where the dish was inadvertently touched by the person deploying the dishes, a bacterial bloom has grown on the skin oils. (Photo by R.S. Toomey.)

Methods to measure the amount and/or types of deposited materials include light transmission through plates (Michie, 2001), microscopic counting and identification (Jablonsky et al., 1995), or removal for chemical or physical analysis (such as weighing or chromatography). The field work to deploy or collect plates can be accomplished by volunteers and only inexpensive equipment is used in the field. However, the analysis of the collected plates requires both specialized equipment and trained scientists. The method is generally a Level 2 or 3 method, depending on the level of identification of sedimentation components and methods used to identify components.

Level 2/3 Methods

Analysis of airborne dust/lint. Measuring airborne dust and lint in caves is general accomplished by one of two methods. In one method, air can be drawn through a filter and the material trapped on the filter can be analyzed. Dry vacuum filters and impingers (Fig. 5) are two different types of these filters. Methods of analysis include microscopic counting and identification and collecting for weighing and chemical analysis. Another method uses optical means (such as lasers) to measure the dispersion of light caused by airborne dust. Some types of laser measurement devices (such as aerodynamic particle sizers) can determine both the number and size distribution of airborne particles (Michie, 2004). As with the plate collection methods, airborne particle characterization requires both medium level technology and specialists to accomplish. Unlike plate collection techniques, airborne sampling provides information on the amount of dust in the air at a specific time, as opposed to time-averaged rates of sedimentation.



Figure 5. An impinger, such as the one seen here in use at Kartchner Caverns, is one method to quantitatively evaluate atmospheric particles, such as dust, lint, or fungal spores. (Photo by R.S. Toomey.)

VITAL SIGN: DIRECT VISITOR IMPACTS

Direct impacts of cavers and tourists are the most important manageable source of loss and damage of cave resources. Direct impacts include such impacts as breakage of cave formations, development and expansion of trails in caves, damage to cave surfaces from traffic, and graffiti or similar damage. Impacts such as these result in direct loss and damage to cave resources (including geological, biological and cultural resources). Monitoring can help managers to understand patterns of impact, devise strategies to limit impact, and determine whether and how management actions change impacts. Related to monitoring of visitor impacts is monitoring visitor traffic in caves. Another direct impact that can occur in caves with fixed lighting is the growth of "lamp flora."

Unlike some other types of cave monitoring, most regularly used visitor impact monitoring methods require only minimal

technology. However, some require specially trained staff to accurately assess impact.

Methods—Visitor Numbers

Level 1 Methods

Visitor counts (tickets, permits, cave registers). Monitoring the number of visitors to caves seems like a simple task, and indeed it can be. In show caves, recording the number of people on the tours can provide this basic information. In wild caves, monitoring the number of visitors can be more difficult. **Cave registers** are in-cave forms on which cave visitors record such information as their names, ages, home cities, affiliations, and party size. Filling these out is voluntary, so the forms do not necessarily provide complete, accurate information. Placing multiple registers in different areas of a cave can provide some data on relative visitation in different areas. Caving permit systems, where cavers are required to get permits to visit caves, provide an additional estimate of cave visitation. Estimates will be more accurate for caves where access is restricted by a gate or other barrier, because gates should limit the number of non-permitted entries. These techniques are all very easy ones to implement with volunteers or inexpensive paid personnel; they also require only inexpensive materials.

Visitor counts (data loggers). Another approach to monitoring visitation in non-tour caves is to use some type of data logger (or automatic counter) to count groups and individuals visiting caves. Several groups have developed techniques that can be used to monitor visitation. Most of these techniques have focused on using the presence of light in normally dark areas of the cave to detect and log visits (Drummond, 1992; Gibson, 1994; Johnson et al., 2002; and Toomey et al., 2001). Some have used data loggers that record when an infrared beam is broken. Other types of trail counters (including pressure pads and air-tube counters) have the potential to be used for monitoring cave visitation, but reports do not suggest that these have been used frequently in caves. Unfortunately, calibration of all of these types of counters has proven difficult. They provide a count of events, rather than of individual visitors. At this point they are better suited to provide information on timing of cave use and general patterns of visitation than accurate visitation numbers. Overall, this approach to monitoring visitation is relatively easy to accomplish with inexpensive personnel and materials (less than $500).

Methods—Direct Impact Assessment

Several techniques can be used to monitor direct visitor impacts, such as cave formation breakage, trail development, and trail compaction. Five techniques discussed here are photomonitoring, formation breakage counts, visitor impact mapping, trail compaction monitoring, and light detection and ranging (**LIDAR**) scanning.

These methods vary due to the wide range of impacts measured. Many of the methods do not require specialized equipment and can be accomplished with specialized volunteer labor. However, most are quite labor intensive, especially if the area of cave that must be assessed is large or complex. For this reason, most methods are classified as level two.

Level 1 Methods

"Lamp flora" mapping. In show caves with fixed lighting, algae, **cyanobacteria** (commonly called blue-green algae), and higher plants may grow on moist **cave surfaces** that are brightly lit. This invasive plant growth, known as "lamp flora" can significantly impact cave geological, biological, and cultural resources. A discussion of techniques to limit or control the growth of lamp flora is well beyond the scope of this discussion. Aley (2004) and Olson (2006) provide a good introduction to the subject. In caves where lamp flora occurs, it is important to monitor both the growth of lamp flora and the actions taken to control it. Monitoring growth of lamp flora is relatively simple. Such monitoring may consist of photomonitoring areas of growth, or manually mapping or recording sites of growth. Manually mapping of algal growth areas can be accomplished for relatively little cost with volunteer or inexpensive paid labor. It does not require any specialized equipment.

Monitoring changes in what organisms make up lamp flora growth is much more involved and expensive. Doing so will require working with experts in algae. In general, this kind of specialized study is beyond the scope of "lamp flora" monitoring studies.

Sediment compaction. When sediment floors of a cave are traversed, the development of trails and associated trail compaction almost invariably occurs. Such compaction can be a significant impact on the cave sediments. It can also impact other cave resources, such as archaeological or paleontological materials contained in the sediment fill. Compacted sediments may also inhibit the movement of some cave animals and may alter or prevent the growth of some types of cave minerals that grow out of the sediments. Sediment compaction can be easily monitored with trained volunteers, students, or employees using fairly inexpensive equipment. A soil compaction tester or penetrometer can be used to map the soil compaction in trails and in adjacent non-trail areas. Monitoring trail compaction can be used to adjust limits on numbers of visitors and may be used to limit access to impacted areas. In some types of sediments, **bioturbation** (churning of sediments by animals) and mineral growth can reverse compaction if travel is halted or reduced. Although monitoring of sediment compaction is listed here as Level 1 monitoring, the complex nature of cave sediment floors can make interpretation of compaction patterns and changes quite complex. Initial study design may require assistance of a soil scientist (J. Roth, 2006, personal commun.).

Level 2 Methods

Photomonitoring. Photomonitoring is a very important technique for a range of condition monitoring in caves and other environments. It is so important that it is covered in a separate

chapter. However, photomonitoring in caves can be a somewhat challenging. Werker and Hildreth-Werker (1996) and Hildreth-Werker (2006) provide many useful suggestions for improving photomonitoring of the cave environment. The amount of specialized equipment needed for cave photomonitoring is limited. Specialized permanent mounting systems have been developed to allow easy repetition of monitoring photos (Werker and Hildreth-Werker, 1996; Hildreth-Werker, 2006) for areas where monitoring will be relatively frequent; these mounts are generally inexpensive. Photomonitoring in caves can be, and often is, accomplished by volunteers. However, these volunteers must be either well trained or experienced in the techniques.

Formation breakage counts. Formation breakage counts are a very simple means to monitor breakage of cave formations. In this technique, an inventory is made of broken formations in a cave (or area of a cave). All broken formations identified in this inventory are inconspicuously marked. In a study in Carlsbad Caverns (D. Pate, 2005, personal commun.), small red ink dots were placed on each broken formation as it was inventoried (Fig. 6). Broken formations are re-inventoried at intervals and broken formations without red dots are counted as new breakage. An alternative that would allow for larger or more conspicuously placed dots would be to use indelible ink that reflects only in the ultraviolet range. Oregon Caves National Monument is experimenting with the use of such inks for marking previously broken formations (Hale, 2007). Repeated formation breakage counts are a very low-tech way to monitor the breakage of formations in both show and wild caves. In addition, the technique does not require highly trained staff. However, in a highly decorated cave, anything more than a very small area can take many hours to monitor. In addition, this technique works better with larger speleothems like stalactites and draperies, than with smaller or more complex speleothems such as coralloids or helectites. Overall, although this technique is inexpensive and can be accomplished with volunteers, it is usually quite labor intensive. For this reason, it has been classified as a Level 2 technique.



Figure 6. In a formation breakage study the previously broken formation can be subtly marked with a small dot of ink. When the area is monitored again, broken formations without a dot of ink were broken between the times of the monitoring. These formations are part of a breakage study along the tourist trail at Carlsbad Caverns. (Photo by R.S. Toomey.)

Visitor impact mapping and inventory. Visitor impact mapping is another technique to monitor human impacts on caves and cave resources. Bodenhamer (1996, 2006) developed this technique as a way to quantify and monitor impacts such as formation breakage and floor surface impacts. In visitor impact mapping, a cave or cave area is examined for visitor impacts (such as compaction and trails, sediment disturbance, mud transferred to clean surfaces, broken floor crusts, and broken formations) and these impacts are mapped onto a detailed map of the cave. The technique, a specialized form of cave mapping, does not require specialized technology. It does, however, require cavers skilled in cave mapping and trained in the technique. It also requires detailed base maps of the cave or cave area; Bodenhamer (2006) suggests that cave mapping with a minimum scale of 1:240 (1 inch equals 20 ft or ~1 cm equals 2.5 m) provides a good base map. Initial visitor impact mapping takes about the same amount of time as setting up a photomonitoring transect; however, repeat mapping to assess impacts is usually completed more quickly (Bodenhamer (2006). Allison (2004) describes the application of this technique in Lechuguilla Cave, Carlsbad Caverns National Park.

Oregon Cave National Monument has taken a related, but different approach to visitor impact mapping (Hale, 2007). Rather than mapping the impacts using the Bodenhamer (2006) method, they inventory impacts using 29 categories of impacts that can be readily identified and classified. The inventory is made using a portable digital assistant using ArcPad. The integration of the inventory into cave geographic information system (GIS) data sets assists in the analysis of impacts.

Impact mapping does not require specialized equipment. However, it does require highly trained volunteers or specialists. In most cases, these specialists or volunteers are skilled cavers who map visitor impacts to assist management agencies. The fact that the process is often quite labor intensive, especially in large or complex cave areas means that this is usually a Level 2 monitoring method.

Level 3 Methods

LIDAR or time-of-flight laser scanning. In very sensitive areas with unique, rare or valuable resources, **LIDAR** (light detection and ranging) or time-of-flight laser scanning can be used to monitor changes in the area. This is a technique that requires very expensive technology and highly specialized personnel. In this technique, a laser scanner is used to map a cave area in great detail. A laser is scanned across the area and the distance to each point in the room is measured to a high degree of precision and accuracy. These distances are used to develop a "point cloud" that maps the room in three dimensions. Repeated scanning at intervals can be used to monitor even small changes

in cave resources. This technique, although undoubtedly powerful, currently has a number of limitations in addition to cost and personnel needs when it is applied to caves. Depending on the setup, precisions near one millimeter are possible; however, even at these resolutions, the types of visitor impacts that can be detected are limited to relatively large impacts such as broken cave formations. The scanning units are relatively large, heavy, and delicate (Fig. 7). In addition, they require either large batteries or electrical connections. While they may be useful in show caves, these methods probably have limited application to backcountry wild caves.

VITAL SIGN: PERMANENT OR SEASONAL ICE

Some caves at high latitudes or high elevations have either permanent or seasonal ice. This ice is important for several reasons. First, it helps control the cave microclimate. Second, it can contain a wealth of paleoclimatic data (material such as pollen trapped in the ice, an isotope record of climate, etc). The extent of ice in caves can itself be used to interpret climate changes (Luetscher, et al., 2005). Yonge (2004) discusses the characteristics of ice in caves and different mechanisms which lead to seasonal and permanent ice.

Natural variation in climate (in particular, local and regional variations in precipitation and temperature) can affect the extent of ice in caves with such ice. In addition, management actions, such as land use changes or entrance modifications, may also affect ice extent (thickness, area, or temporality). Monitoring ice extent may provide information on both long-terms changes in climate and the effects of management actions.

Ice volume in caves may be very sensitive to seasonal conditions. For this reason it is very important for monitoring to take place during the same season or seasons each year. An alternative approach is to measure thickness or extent when it is at its minimum each year; such measurements may represent a better indication of net annual effects (J. Roth, 2006, personal commun.).

Methods

Level 1 Methods

Manual measuring of ice thickness or extent. Ice extent and thickness can generally be monitored using inexpensive means that do not require specialized personnel. The extent of ice can be readily mapped using several techniques. Mapping with respect to set landmarks can be accomplished using a detailed map of the cave area, simple survey instruments, a prepared set of landmarks, or an established grid.

Ice thickness is a common parameter for monitoring changes in ice volume. One easy way to monitor ice depth is to establish a vertical datum or reference point somewhere above the ice. The distance of the ice below the datum is then tracked. As ice volumes increase, the distance between the ice and the datum decreases. An increase in the distance indicates that ice volume is decreasing.

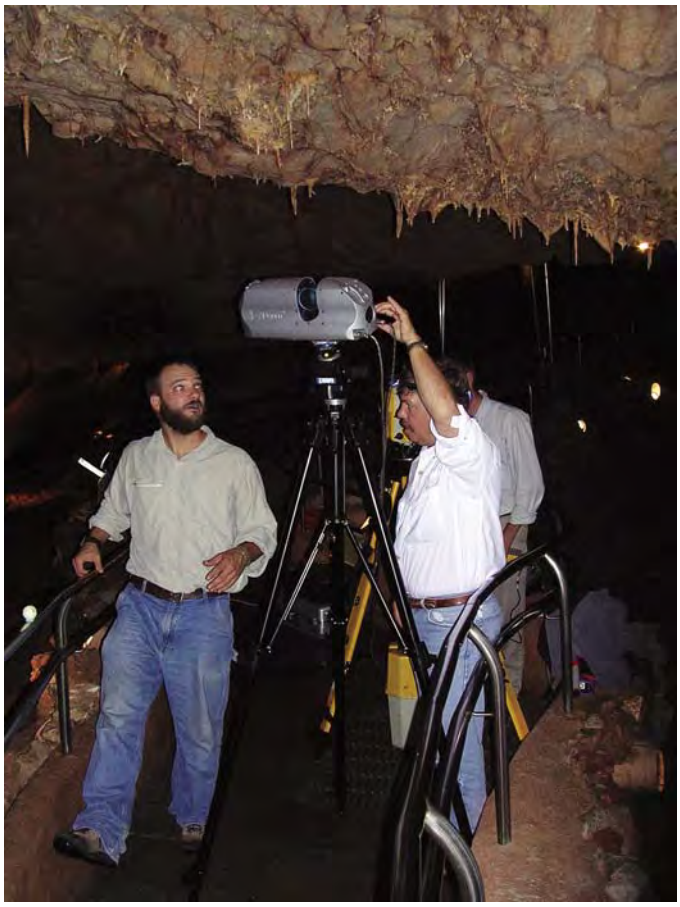


Figure 7. Time-of-flight laser scanning in the Big Room at Kartchner Caverns. (Photo by R.S. Toomey.)

Ice extents and thicknesses have been monitored at Lava Beds National Monument since the 1970s (W. Devereaux, 2005, written commun.). In 2005, ice levels were monitored in nine caves. Monitoring of levels is performed by volunteers who measure the distance from the ice to permanent datums marked with stainless steel screws in each cave. The distance to both water on top of ice and to the ice itself are recorded. In addition, the condition of the ice, the presence of dead animals on the ice, and the condition of the rooms with ice are noted.

Level 2 Methods

Photomonitoring. Repeat photography is another method for monitoring ice extent, although with very clear ice, it may be difficult to discern ice extent in photographs. Historical photographs may be used to estimate past ice volumes and extend the monitoring record (Luetscher, et al., 2005). Werker and Hildreth-Werker (1996) and Hildreth-Werker (2006) provide many useful suggestions for improving photomonitoring of the cave environment.

Level 3 Methods

LIDAR or time-of-flight laser scanning. Repeat laser scanning can track ice extent accurately; however, the technique

requires expensive equipment and highly trained specialists for data acquisition and reduction. A more complete discussion of the limitations of this technique can be found in the Direct Visitor Impacts section above.

VITAL SIGN: CAVE DRIP AND POOL WATER

Dripping and pooled water are important components of many cave environments. Dripping water transports minerals, microbes, and chemicals into the cave. It is responsible for depositing minerals, resulting in the growth of many types of cave formations, most notably stalactites and stalagmites (Hill and Forti, 1997). Pooled water formed by infiltration (through dripping or flowing) is also responsible for the formation of several types of formations, such as shelfstone, rafts, pool fingers, and pool spar (Hill and Forti, 1997). Dripping and pooled water also acts to maintain cave moisture. Drip water can also transport contaminants into caves.

Because of its crucial roles in depositing cave formations and maintaining moisture, monitoring cave drip and pool waters is desirable. Three major parameters that are basic to monitoring drip water are drip locations, drip rate, and drip volume. In addition to these basic parameters, drip water chemistry, microbiology, and temperature can be monitored in more complete programs. For pool waters, the basic parameter for monitoring is often water level. In more complete monitoring programs, pool water chemistry, microbiology, conductivity, and temperature would potentially be monitored.

Changes in the amount or distribution of dripping or pooling water in a cave may be the result of either natural processes (such as drought) or due to modifications caused by human action (changes in land use in the contributing watershed for the cave, changes in cave microclimate caused by management actions, etc.). Monitoring may be used to identify such changes and to plan mitigation, if appropriate. For example, monitoring of pool levels in Carlsbad Caverns (McLean, 1971, 1976) identified airflow through the elevator shaft as a significant impact on the cave and provided information that the park used to mitigate the impact.

Monitoring water quality (chemistry, microbiology, etc.) can provide important information on contaminants that may be brought into the cave and damage cave resources. Studies by Brooke (1996) and van der Heijde et al. (1997) identified areas of Carlsbad Caverns that had been impacted by contaminants brought into the cave from the surface (parking lots, sewage system, buildings, etc.) by infiltrating waters. Caldwell (1991) examined pools in Carlsbad Caverns to determine the impacts of visitors on their chemistry and microbiology.

Methods

As with cave meteorology, there are two basic approaches to monitoring drip and pool water parameters. The simplest approach is to manually monitor parameters with handheld instruments. Using automated sensors tied to data loggers is the higher-end approach.

Level 1 Methods

Manual measuring with handheld instrumentation. Monitoring the location and amount of dripping water in a cave is often accomplished manually. Several different methods can be used, depending on the type of monitoring, available resources, and accessibility of sites. Buecher (1999) and Sanz and Lopez (2000) discuss several manual drip monitoring methods. One approach is to monitor drip rate, drip volume and other parameters such as water chemistry at defined drip-monitoring locations. Drip rate can be estimated using a stopwatch, by either counting the number of drips in a set time or determining the time for a set number of drips. The estimate will improve as the observation time increases. Drip volume can be estimated by using a graduated cylinder to collect dripping water. Again, estimates can be made by determining either the volume in a particular time or the time required to fill to a particular volume. Water collected in such a study can be used to monitor drip water chemistry (Buecher, 1999; Musgrove and Banner, 2004). In cases where the drip rate of individual stalactites is highly variable, samples can be pooled to provide a smoothed rate of flow. This can be accomplished by using a larger bucket that collects drips from multiple stalactites or using a tarp to catch and channel flow from several stalactites. Another approach to monitoring the quantity of dripping water in a cave or cave area is to monitor water accumulation in random areas rather than choosing specific drips. Buecher (1999) did this by placing circular, 23 cm diameter pans in locations and measuring water accumulations over set times.

Specific conductivity (a measure of the electrical conduction of the water due to ions dissolved in it) is probably the most commonly measured chemical parameter in drip water monitoring. It is a preferred parameter both because it is relatively easy to measure using inexpensive handheld instruments and because it provide important information on the potential for the water to deposit or dissolve cave minerals.

Another very commonly measured water chemistry parameter (in dripping, pooling, and flowing water) is hydrogen ion activity (expressed as pH). The pH value of karst water is important in its own right; it is also used to calculate other values that provide important information about karst systems (such as saturation indices). Measuring pH can be problematic under field conditions, especially when small variations in pH can lead to large differences in calculated parameters. Sasowsky and Dalton (2005) provide a good discussion of the problems associated with field measurement of pH and provide recommendations for improving measurements.

Monitoring of pool water levels can be an important component of a monitoring program. Changes in pool level may indicate changes in cave climate. For example, changes in pool level at Carlsbad Caverns were an important indicator of increased evaporation due to the elevators (McLean, 1971, 1976). Monitoring

pool water level can be accomplished manually by either measuring pool depth at a set point or measuring the distance to the pool surface from a set point.

Methods that take spot measurements of drip and pool parameters with handheld instruments can be accomplished quite cheaply. Commonly available instruments generally perform well for most cave situations. Trained volunteers or inexpensive personnel can perform the monitoring.

Level 2 Methods

Automatic measuring with datalogged instrumentation. Automated drip water monitoring is significantly more complex and uncommon (Genty and Deflandre, 1998). There are no standard, off-the-shelf solutions to monitoring drip frequency, drip volume, or drip chemistry. A variety of custom-built instruments have been installed for scientific research, but not for routine monitoring. Some of these instruments use a tipping bucket approach to measure frequency and volume of drips (Beddows et al., 2005). Less frequently, more exotic approaches, such as laser beams, photoelectric, or a vibrating drum principle (Baker and Brunsdon, 2003; Genty and Deflandre, 1998), are used. In general, automated monitoring of cave drips will require a person skilled in designing instruments.

Monitoring of pool water levels can also be automated. The most common means of automating measurement of pool levels is through the use of pressure transducers attached to data loggers. This method will generally require some level of specialized knowledge to set-up.

Pool or drip chemistry and/or microbiology. The monitoring of pool or drip chemistry depends on the parameters being measured. U.S. Geological Survey (variously dated) provides guidance on measuring water quality parameters. Krawczyk (1998) also describes procedures of measuring a variety of chemical parameters including pH, dissolved oxygen, specific conductivity, hardness, calcium, magnesium, sodium, potassium, bicarbonate, chlorides, sulfates, nitrates, phosphates, and silica. As with pool level, some of the water quality parameters can be monitored continuously or periodically with datalogged sensors. The ease and utility of this approach varies with parameters. For example, it is difficult to automate pH sensors for long-term monitoring, because accuracy, measurement drift, and calibration issues are significant in these sensors.

Microbiology can be an important parameter to monitor in infiltration water in either drips or pools. The most common reason for monitoring microbiology in cave drips and pools is to detect deleterious bacteria entering the cave due to contamination from human or animal waste. The presence of elevated coliform, fecal coliform, and *E. coli* are common indicators of potential contamination. These parameters are measured using standard procedures for other freshwater (including waste water and drinking water); Myers and Wilde (2003) provide guidance on standard, accepted procedures for biological indicators of water quality.

Sampling for pool or drip chemistry can generally be accomplished by volunteers or employees using inexpensive equipment and techniques. However, laboratories with specialized instruments are needed to measure many of the parameters. If such a lab is available for running analyses, these methods would generally be considered Level 2 methods. If, however, an onsite lab is going to be developed for this testing, the method would better be considered Level 3, due to the cost of equipment and skilled technicians needed to run analyses.

VITAL SIGN: MICROBIOLOGY

The study of the microbiology of caves is a relatively recent development, and it is evolving rapidly in terms of both methodologies and results. Recent studies have shown that microbes play an important role in a number of cave geological processes including wall corrosion and development of corrosion residues, precipitation of a variety of secondary minerals and speleothems, and sulfuric acid speleogenesis and cave enlargement (Barton and Luiszer, 2005; Barton et al., 2001; Northup and Lavoie, 2001). The microbiology of caves can potentially be significantly altered by a large range of activities such as exploration, actions that lead to contamination of infiltrating water (land use changes, construction, etc.), and tour/caving activities (Hunter et al., 2004; Ikner et al., 2007). The potentially profound role that microbes play in cave processes and their susceptibility to alteration due to human activities make cave microbiology an important vital sign to monitor.

Methods

Level 3 Methods

Develop and implement specialized site-based monitoring. As noted above, cave microbiology is still in the relatively early stages of development as a science. Most of the studies that have been undertaken so far are exploratory in nature. They focus on what microbes are in the system, how different cave microbial ecosystems function, or how microbes are involved in different cave processes. For this reason, there are no standard methods that have been agreed upon for studying cave microbiological systems, let alone methods for standardized monitoring. Some parameters that are likely to be important in monitoring include microbe diversity, activity of various microbial ecosystem components, and the presence of microbial taxa indicating disturbance or perturbation of natural systems. Because of the interaction between surface and cave environments and the role of soil bacteria in the carbon dioxide flux in soils and groundwater, soil microbiology above the cave may also be an important indicator of changes and human impacts. Any microbiological monitoring, beyond simply identifying the presence of certain common bacteria associated with human activity (e.g., total coliform, fecal coliform, and *E. coli*) will require working with scientists using a variety of specialized laboratory techniques.

VITAL SIGN: STABILITY-BREAKDOWN, ROCKFALL AND PARTINGS

The stability of the cave ceiling in terms of number, location, size, and frequency of rockfalls can be an important vital sign to monitor. Breakdown in caves is a natural process that occurs for numerous reasons (E.L. White, 2005). The location, style, and cause of breakdowns vary spatially within the cave and temporally during the development of the cave. Monitoring of breakdown is generally undertaken for two somewhat different reasons. One purpose can be to understand the ongoing breakdown process to determine if some sort of mitigation is needed. A second purpose of monitoring breakdown may be for safety, i.e., determining when to limit people traveling under a particular area.

Monitoring breakdown to understand changes in the process due to changing cave conditions can be undertaken in several ways and at several time frames. However, monitoring for safety should provide some ability to predict the likelihood of additional breakdown. In addition, monitoring to understand the pattern of breakdown can be done on whatever time frame is convenient; that is, monitoring can take place annually, or on even longer time frames. Monitoring for human safety, on the other hand, should be done on time frames that are meaningful for protecting people from possible dangers. The more frequent the interval of monitoring, the better equipped you will be to warn people of potential dangers. The logical extension of this observation is that to have a true warning system for potential rockfall, real-time data gathering and analysis may be necessary.

Changes in rockfall number, location or size may indicate that changes have occurred which promote more rockfalls. For example, changes in entrance configuration that lead to more penetration in freezing temperatures can lead to increased rockfall due to freeze-thaw ice wedging.

Additional approaches to monitoring rockfall and slope stability may be found in the chapter on slope features and processes.

Methods

Level 1 Methods

Breakdown records. One of the simplest means to monitor breakdown is to simply record the date and location of each new piece of breakdown that occurs in a particular section of a cave. This is simple in theory, but it can be complex in practice. It may be difficult to distinguish new breakdown from existing breakdown in a cave passage with a rocky floor. In addition, if the cave is not visited very often, timing is impossible to determine and new rockfall may be hard to identify. This technique is probably most amenable to show caves where daily visitation occurs by people very familiar with the cave (guides); in addition, tour trails provide a clear area that can be monitored. This is an inexpensive method that can be accomplished with volunteer or other trained labor.

Manual crack monitoring. A simple, manual method to monitor movement on **bedding plane** partings and cracks that may lead to breakdown is to monitor the sizes of those cracks using mechanical means. One method is to place small wood or metal wedges into the cracks. If the wedges loosen, it may be an indication that movement is occurring on the cracks. A similar approach is to affix small strings or bands across the cracks. Breakage of the string or band can indicate movement. For this technique, bands or strings must be composed of a material that will not expand or contract significantly under cave conditions. This technique will provide general information, but is not an adequate substitute for more precise methods that might be employed in conditions where significant breakdown hazards are anticipated.

Level 3 Methods

Mining engineering stability techniques. To accurately monitor movement on cracks and bedding planes, technology and expertise is needed. Getting the appropriate assistance from a geological or mining engineer is especially important if the goal of monitoring is to increase safety. The mining industry uses a variety of techniques to monitor the stability of rock ceilings and walls. These include wire extensometers, EDM (electronic distance measurement) prism surveying, microseismic monitoring, surveying displacements, displacement transducers, time domain reflectometry, inclinometers, and LIDAR (Girard and McHugh, 2000; Bhatt and Mark, 2000). At Kartchner Caverns, wire line extensometers tied to a data logger were used to monitor several bedding planes during development at the cave.

VITAL SIGN: MINERAL GROWTH

Secondary mineral formations, or speleothems, are an important geological cave resource. The deposition and loss of these secondary minerals are very important processes. However, in most cases the processes are too slow to be monitored using simple processes. Seasonal mineral growths that may occur due to changes in cave microclimate represent an important group of exceptions to the general rule of the slow growth of cave formations. A variety of these types of seasonal mineral growths occur; most are related to seasonal changes in relative humidity. Seasonal drying leads to the growth of various minerals that are not stable under moist season cave conditions. Some examples include nitrocalcite at Kartchner Caverns and sulfates, such as gypsum, epsomite, and mirabilite in a number of caves including Mammoth Cave, Kentucky (Hill and Forti, 1997).

Color changes and staining of cave formations may be an indicator of human impacts that may be degrading the geological resources or the cave. In some cases local staining can be caused by cave visitors touching a formation. Groundwater contamination with sewage or metals may also result in changes in the color of formations in a particular area.

Methods

Level 1 Methods

Manual seasonal mineral presence mapping/inventory. Monitoring the seasonal growth and loss of cave mineral deposits is usually done manually. The extent of mineral deposits can be mapped in both space and time by trained individuals. The amount of training and equipment that is required to identify and map mineral deposits depends on the particular minerals that occur seasonally. Some seasonal minerals can be easily distinguished in the field, others require specialized mineralogical techniques. Often potential seasonal mineral deposits to be monitored are identified through mineralogical inventories. Following the initial identification of the minerals, visual examination may help to distinguish the mineral for seasonal mapping. Changes in the pattern and timing of mineral growth may indicate changes in regional climate or alterations to microclimate conditions in the cave. Because the deposition and disappearance of these minerals is seasonal, it is important to map the occurrences and extent of these minerals in different seasons.

Level 2 Methods

Photomonitoring and impact mapping/inventory. Color changes and staining of formations can be an important indicator of impacts to cave mineral resources. Monitoring for staining and color changes is probably best accomplished as part of a visitor impact mapping/inventory or photomonitoring program. These approaches are discussed in more detail in the Direct Visitor Impacts section above. To be able to accurately determine color and track changes, it is important to include a color standard in your photomonitoring pictures.

Level 3 Methods

LIDAR or time-of-flight laser scanning. As LIDAR and other laser scanning techniques have improved, it has become possible to measure the growth rates on some of the faster growing speleothems. In the near future it is possible that this technology may become widespread and inexpensive enough that it can be used for monitoring changes in speleothem growth rates. At this point, however, the technology is more appropriate for scientific studies of speleothem growth than it is for actually monitoring growth. This method involves expensive, specialized equipment which requires skilled operators. A more complete discussion of the limitations of this technique can be found in the Direct Visitor Impacts section above.

VITAL SIGN: SURFACE EXPRESSIONS AND PROCESSES

Although caves are an underground feature, they are intimately tied to the surface by conduits that transport water, sediment, and organic matter both in and out. These conduits vary from large entrances and springs to microscopic cracks and porosity. Karst processes closely link the surface to the caves through springs, sinkholes, cracks, etc.

Monitoring of the surface may provide important information about the state of the cave and karst resources. In addition, cave and karst resources can be degraded due to actions on the surface. For these reasons, monitoring of the surface can be an important component of cave and karst monitoring.

This discussion focuses on two major types of surface monitoring in karst. The first type of important surface monitoring in karst is monitoring springs for changes in water quality and quantity. The second is the use of remotely sensed data (photographs, satellite data, and airborne LIDAR) to monitor karst areas for changes (land use, sinkhole formation, etc.).

Springs are an important location for monitoring potential impacts on cave and karst systems. Changes in the quantity and quality of spring water may be symptomatic of changes that are degrading cave resources, such as changes to land use or contaminant leakage.

The topic of monitoring land use changes is largely beyond the scope of this book. However, land use changes may alter or degrade cave and karst resources by affecting water quantity, quality, or distribution. Monitoring land use changes is especially important for managers who have caves whose watersheds extend beyond the area they have control over. In cases such as these, actions of land managers many miles away may result in changes in caves that are being managed to protect resources. For example, in the well-developed karst of Missouri, dye tracing has indicated that water from as far as 61 km (38 miles) away is discharged at Big Spring (Imes and Fredrick, 2001).

Methods

Level 1–3 Methods

Spring water quality and quantity monitoring. Springs are often an important surface expression of karst processes. A detailed discussion of water flow and quality monitoring techniques is beyond the scope of this book. Nevertheless, monitoring water quantity and quality can be very important in monitoring the overall state of karst systems and related caves. As with other general water quality and quantity monitoring (such as in streams and wells), spring monitoring programs should be designed in consultation with hydrologists or hydrogeologists who specialize in karst aquifers. W.B. White (2005) provides insight into spring processes and the ways spring discharge and chemistry can be monitored. The techniques and approaches for monitoring spring flow and water quality vary depending on the needs and available resources. Some techniques can be done inexpensively using volunteers; others require scientists, complex equipment, and specialized laboratory analyses.

Level 3 Methods

Remote sensing of karst landscape changes. Identifying changes in landscape (such as development of new sinkholes in

karst) and monitoring changes in land use that may affect cave and karst resources is often best achieved using periodic remote sensing methods such as airborne and satellite imagery and data gathering. In addition to visible spectrum imagery, several types of sensing using other portions of the electromagnetic spectrum have been used to study karst processes and terrains.

Airborne LIDAR has been used to identify karst features in a few studies. Notably, it has been used to map karst topography in rain forests in Alaska (Baichtel and Langendoen, 2001; Langendoen and Baichtel, 2004). It has also been used in the low-lying karst of central Florida to both identify and map sinkholes (Seale et. al., 2004) and also to predict the location of potentially hazardous subsurface features (Montane and Whitman, 2000). These studies have focused on the use of airborne LIDAR to inventory karst features rather than monitoring them for changes; however, monitoring would be an additional possibility once inventory was completed. Airborne LIDAR is a powerful tool for monitoring changes in karst landscapes. It is also an expensive tool that requires specialized equipment and personnel.

Remotely sensed thermal infrared imagery can also prove useful in identifying and potentially monitoring karst features. Campbell et al. (1996) successfully used airborne thermography to map springs, caves, swallets, and losing stream reaches in northern Alabama (Campbell et al., 1996; Campbell and Keith, 2001) and Tennessee (Campbell and Singer, 2001). The use of thermography to identify or monitor non-spring cave entrances is less developed, but it is an area of active research (Thompson and Marvin, 2006).

Remote sensing will generally require participation of experienced scientists. If the remote sensing is being accomplished specifically for karst monitoring purposes, it will also require mobilization of expensive, specialized equipment (such as tasking airplanes and satellites). In addition, the data processing requirements are substantial. The use of existing, off-the-shelf, remotely sensed, georeferenced data sets will reduce the costs for data acquisition; however, specialized knowledge will likely still be needed to interpret the data.

VITAL SIGN: REGIONAL GROUNDWATER LEVELS AND QUANTITY

Caves, and solutional caves in particular, are often an expression of the regional groundwater flow. Changes in local or regional aquifers may affect cave resources by changing cave microclimate, flooding previously dry areas, drying existing pools or streams, or altering dissolution or deposition of minerals. Both natural processes (such as drought) and human processes (including groundwater pumping, surface flow alteration, and chemical contamination) can alter the water quantity and quality of local and regional aquifers. Processes, such as pumping or drought, which lower water levels in regional aquifers, may impact caves in the area. In addition, these processes may cause other impacts in karst terrain; one notable impact is causing or increasing sinkhole collapse.

Monitoring local or regional karst aquifers associated with a cave may be an important tool for understanding and protecting cave resources of all types. Regional groundwater can be monitored in caves (e.g., pool water and stream water) or on the surface using springs. Methods for monitoring these vital signs are discussed elsewhere in the manual. In addition, wells into karst aquifers may be used to monitor groundwater levels and chemistry. A variety of agencies can assist in developing appropriate water quality monitoring programs.

Methods

Level 1 Methods

Spot monitoring of wells. Wells for monitoring water quality and quantity in karst aquifers may be specifically constructed for the purpose, or may be preexisting. The cost and expertise to develop this kind of monitoring depends greatly on whether existing wells can be used or whether new wells must be drilled for this purpose. Static (unpumped) wells are preferred for monitoring water levels in an aquifer. Having a pump in the well (whether it is used at other times or not) greatly aids water sampling for water quality monitoring.

The water level and quality in these wells can be monitored either periodically (as at Kartchner Caverns, Graf, 1999; Toomey, 2005; Toomey and Nolan, 2005) or continuously (as is done in many aquifers that provide significant drinking water like the Edwards aquifer in Texas). Manually measuring the water level in wells, or more accurately measuring the depth to the top of the water, is easily accomplished by three common methods: tape or cord, electrical sounder, or air line (Powell and Rogers, 2005; Thornhill 1989). In tape (or cord) and electrical sounder methods, a measuring device is lowered into the well until it hits water (as indicated by marking on the tape or completing an electrical circuit). In air line methods, a known length of thin air tubing is placed into the well. The length must be longer than the depth to water. The amount of air pressure needed to purge the line of air provides a measure of the length of tube that contains water. That length is subtracted from the total length of tube installed to indicate depth to water (Powell and Rogers, 2005). The frequency of measuring depends on the dynamics of the aquifer and the nature of potential threats from changing aquifer levels. In relatively non-dynamic aquifers that are subject to mainly natural changes, such as at Kartchner Caverns State Park, Arizona, monthly monitoring may be sufficient to understand trends (Toomey, 2005; Toomey and Nolan, 2005) in groundwater level and their relationship to cave changes (Fig. 8). If, however, groundwater pumping is a significant issue that may affect cave resources, more frequent monitoring may be necessary. These monitoring methods require relatively little training or specialized equipment.

Level 2 Methods

Monitoring of well chemistry. Water quality measurements depend on potential threats to the regional and local aquifer and

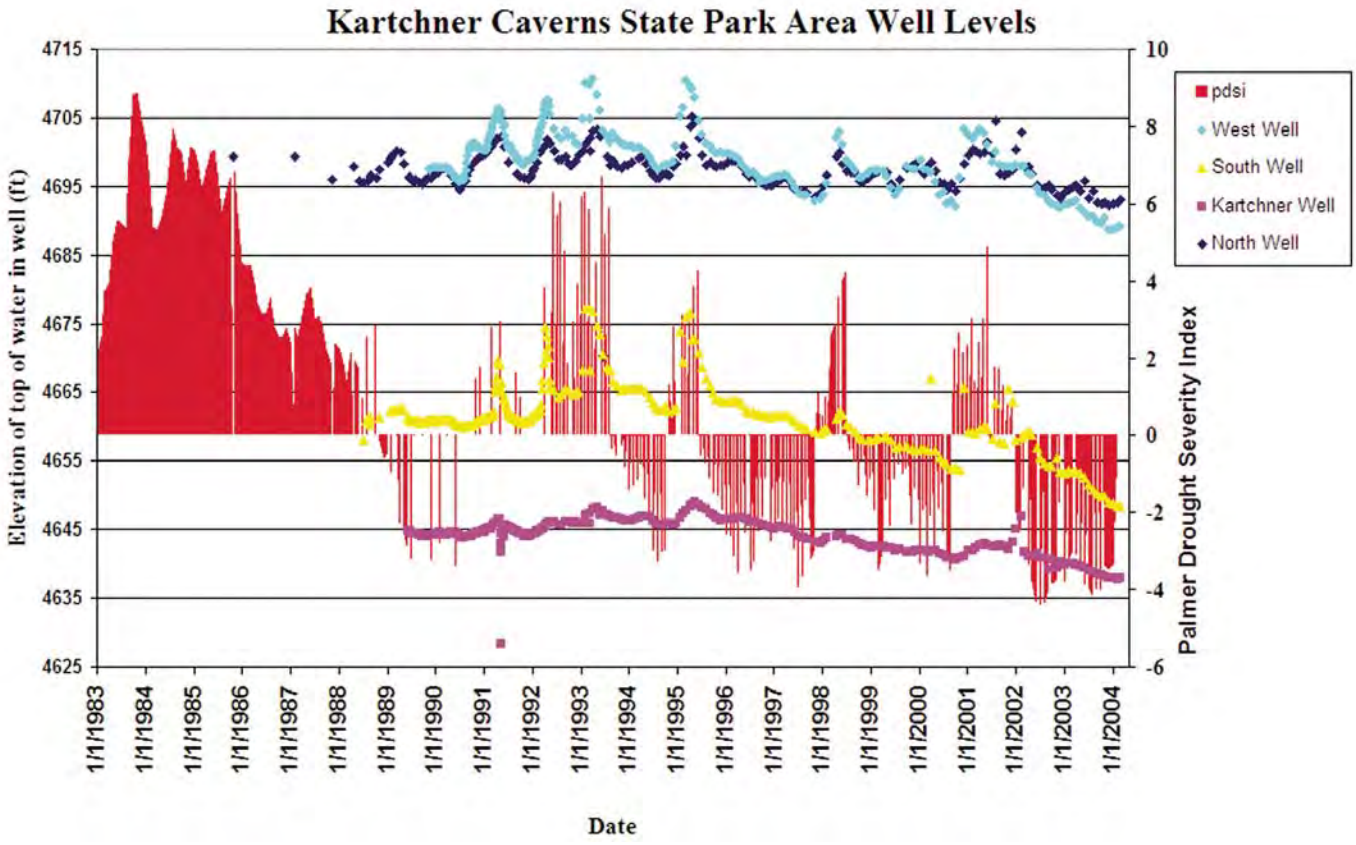


Figure 8. Groundwater levels monitored in four static water wells around Kartchner Caverns show regional lowering of groundwater levels due to drought (as represented by the Palmer Drought Severity Index for southeastern Arizona). These data provide some regional background against which to evaluate cave drying.

caves. Basic parameters for monitoring karst waters include temperature, pH, dissolved oxygen, specific conductivity, hardness, calcium, magnesium, sodium, potassium, bicarbonate, chlorides, sulfates, nitrates, phosphates, and silica (U.S. Geological Survey, variously dated; Krawczyk, 1998). In addition, microbiological parameters, such as coliform bacteria, fecal coliform bacteria, and *E. coli* may be important parameters for detecting contamination from septic systems. Depending on land use in the watershed of interest, it may also be important to monitor for a variety of organic and inorganic pollutants. Collecting samples for groundwater chemistry is fairly straightforward and inexpensive. However, many chemical analyses require specialized laboratory equipment.

Automatic monitoring of groundwater levels in wells. Continuous monitoring of groundwater levels is achieved by attaching a sensor that measures water depth in the well to a data logger, which records the level at set intervals. Two different kinds of sensors are commonly used for measuring water depth in wells. The first kind consists of floats that measure the elevation of the top of the water. The second kind consists of pressure transducers that measure the height of the water column over the transducer. Automatic monitoring of groundwater levels requires specialized sensors and some technical knowledge to install them.

VITAL SIGN: FLUVIAL PROCESSES

In many caves, particularly those in karst landscapes, water flows in underground streams and rivers. Those streams and rivers are important for many reasons. They are often the main agent of ongoing speleogenesis in their caves. They provide important habitats for numerous aquatic species (including numerous endangered ones). The water in karst streams and rivers is often the groundwater used for drinking water.

The properties of these streams and rivers, including water quality, water quantity, sediment characteristics, and distribution of water inputs, are subject to alterations that may degrade cave and karst systems. Water quality can be affected by human activities and land use changes (septic systems, non-point-source pollution, and conversion to or from agriculture). The quantity and distribution of waters can be impacted by such things as impervious cover, channelization, sinkhole modification, and storm water diversion. Changing land use patterns around sinkholes

and other inputs can radically change the sediment load, balance, and characteristics of a cave stream. Changes such as these can, in turn, alter the bed characteristics.

Methods

Monitoring of fluvial processes is covered in a separate chapter in this manual. Many of the approaches described in that chapter can also be applied in cave streams. Among the most important parameters for monitoring cave streams are water quantity, turbidity, and water chemical characteristics. Changes in stream bed, in particular siltation or scouring, may also be quite important; however, these may have more effects on biological systems in caves than on the geological resources themselves. In addition, various agencies, including National Park Service Water Resources Division, U.S. Geological Survey Water Resources Program, and the Environmental Protection Agency Office of Water can provide additional guidance and assistance in monitoring cave stream parameters. In addition, references such as U.S. Geological Survey (variously dated) and Krawczyk (1998) provide details on techniques that can be used.

CONCLUSIONS

Developing a monitoring program for a cave, set of caves, or caves and associated karst landscapes is a complex task involving many disciplines. Although this chapter has focused on vital signs that are either geological in nature or which may significantly influence geological processes and resources, a complete monitoring program would also focus on biological resources (including bats, other vertebrates, invertebrates, and microbiology), cultural resources (archaeological and historic), and paleontological resources. In addition, monitoring programs must follow a systematic inventory, which is necessary to identify the resources to be monitored and the potential impacts to them.

The Carlsbad Caverns National Park Cave and Karst Management Plan Environmental Assessment contains a well-developed cave monitoring plan (Carlsbad Caverns National Park, 2006). It discusses the existing monitoring at the park, the rationale used to decide whether new or additional monitoring should take place, and the procedures to be followed in developing new monitoring projects. It provides an excellent guidance for developing cave monitoring projects.

Since monitoring is presumably tied to vulnerable resources, management actions, and needs, it is important to identify the vital signs that are most subject to human impact under existing and potential conditions. The monitoring of some vital signs is likely to be important under a wide variety of conditions. For example, most cave monitoring plans will probably include at least some monitoring of cave microclimate. The reason for this is that cave microclimate may affect a wide range of geological, biological, and cultural resources in a cave. Other types of monitoring may be limited to caves that undergo particular impacts. For example, monitoring of lamp flora growth or lint deposition would probably be applicable only in show caves. Water quality monitoring is likely to be more important where a significant threat of contamination exists due to land use or human use of the cave.

Budget is also a significant factor when designing a monitoring program. Fortunately, most of the basic means for monitoring geologic resources in caves do not require expensive, specialized equipment, but they often require either trained or specialized personnel (Table 1). Automating some of the measuring, where possible, may reduce the time requirement for personnel. However, the larger volumes of data from this approach may require personnel with more training to adequately analyze the results.

At few, if any, caves has a monitoring plan been implemented that addresses the entire list of vital signs discussed in this chapter, let alone the biological, microbiological, paleontological, and cultural resource monitoring that would constitute a complete monitoring program. However, this list of vital signs should serve as a guide to what might be monitored, depending on resources needing management, potential and actual threats, budget, and availability of experienced assistance.

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TABLE 1. SUMMARY OF CAVE VITAL SIGNS AND MONITORING METHODS

Vital signs and methods	Expertise	Special equipment	Cost*	Personnel	Labor intensity†
Cave Meteorology					
Spot measurements with generally available hand-held instruments	Volunteer	No	$	Individual/ small group	Low/medium
Common data loggers and probes	Volunteer/scientist	Yes	$	Individual	Low/medium
Specialized precision instruments/data loggers	Scientist	Yes	$$	Individual	Medium
Specialized meteorological instrument networks	Scientist	Yes	$$–$$$	Individual	Medium
Airborne Sedimentation					
General characterization of lint removal activities	Volunteer/scientist	No/Yes	$–$$	Individual	Low /High
Analysis of dust/lint accumulation plates (field work)	Volunteer	No	$	Individual	Low
Analysis of dust/lint accumulation plates (analysis)	Scientist	Yes	$$–$$$	Individual	Medium-high
Analysis of airborne dust/lint	Scientist	Yes	$$–$$$	Individual	Medium
Direct Visitor Impacts					
Visitor counts (tickets, permits, registers)	Volunteer	No	$	Individual	Low
Visitor counts (data loggers)	Volunteer	Yes	$	Individual	Low
Photomonitoring	Specialized volunteer/scientist	No	$–$$	Individual/ small group	Medium-high
Formation breakage counts	Volunteer	No	$–$$	Group	Medium-high
Visitor impact mapping/inventory	Specialized volunteer	No	$–$$	Group	Medium-high
Sediment compaction	Scientist	Yes	$	Individual	Medium
Time-of-flight laser or LIDAR scanning	Scientist	Yes	$$$	Group	High
“Lamp flora” mapping	Volunteer	No	$	Individual/ small group	Medium
Permanent or Seasonal Ice					
Manual measurement of thickness or extent	Volunteer	No	$	Individual	Low
Photomonitoring	Specialized volunteer/scientist	No	$–$$	Individual/ small group	Medium-high
Time-of-flight laser or LIDAR scanning	Scientist	Yes	$$$	Group	High
Cave Drip and Pool Water					
Manual monitoring with handheld instrumentation	Volunteer	Yes	$	Individual	Medium-high
Automated monitoring with datalogged instrumentation	Volunteer/scientist	Yes	$–$$	Individual	Low
Microbiology					
Develop and implement specialized site-based monitoring	Scientist	Yes	$$$	Individual	Medium-high
Stability – Breakdown, etc.					
Record breakdowns	Volunteer	No	$	Individual	Low
Manual crack monitoring	Scientist	No	$	Individual	Medium
Mining engineering stability techniques	Scientist	Yes	$$–$$$	Individual	Medium-high
Mineral Growth					
Manual seasonal mineral presence mapping/inventory	Specialized volunteer/scientist	No	$	Individual	Medium
Photomonitoring/impact mapping of staining/color changes	Specialized volunteer/scientist	No	$–$$	Individual/ small group	Medium-high
Time-of-flight laser or LIDAR scanning	Scientist	Yes	$$$	Group	High
Surface Expression and Processes					
Spring water quality and quantity	Specialized volunteer/scientist	Yes	$–$$	Individual/ small group	Medium-high
Remote Sensing (LIDAR, aerial photography, thermography)	Scientist	Yes	$$$	Individual	High
Groundwater Levels and Quality					
Spot monitoring of wells	Specialized volunteer/scientist	No	$	Individual	Medium
Monitoring of well chemistry	Specialized volunteer/scientist	Yes	$–$$	Individual	Medium-high
Automatic monitoring of groundwater levels in wells	Specialized volunteer/scientist	Yes	$–$$	Individual	Medium-high
Fluvial Processes					
See Lord et al. (this volume) for information on monitoring cave streams					

*Cost (US$): $ = <$1,000, $$ = $1,000 to $10,000, $$$ = >$10,000

†Labor intensity: low = <few hours; medium = <full day; high = >full day. Labor intensity will often vary greatly depending on size of cave or cave area being monitored.

LIDAR—light detection and ranging.

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Coastal features and processes

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INTRODUCTION

The coast is one of the most dynamic environments on the planet. It is where wave and tidal energy are expended to carry out erosion and transport; it is the meeting place of the hydrosphere, the lithosphere, and the atmosphere. The coastal zone is subject to constant change: minute by minute as waves break and currents move alongshore; daily with high and low tides; monthly with tidal cycles; yearly with seasonal changes in wave approach and storm energy; and over the longer term with changes of climate and sea level. This constant change can cause major problems for coastal communities and management of geologic resources.

There is much informal or inconsistent terminology used to define or describe the coast. According to Oertel (2005), **coast** and **coastline** should be used when referring to the boundary between land and water at a regional scale; **shore** and **shoreline** are terms reserved for the same boundary but at a local scale. The area commonly referred to as the **coastal zone** is not strictly defined, but rather includes all land and water areas affected by marine processes. This may include areas many miles inland where even the weakest of tidal forces can be felt. In common usage, one tends to think of the beach as the primary or maybe only coastal environment. And the beach may be the most prominent, or most well known, of the coastal environments. The beach can be defined as an accumulation of sediment, moved by waves and currents.

The coastal environment, in a broad sense, is often considered to include anything landward of the shoreface, the water depth at which incoming waves begin to interact with the seafloor (Fig. 1). Such interaction begins when the water depth diminishes to one-half the wavelength on the incoming wave. That water depth marks the beginning of movement of sediment and is the dividing line between the offshore and the beach/dune system. The practical aspect of this demarcation is that it is the greatest depth from which waves are able to push sediment landward through the interaction of wave orbitals with the seafloor. Allen (1970) and Swift (1976) refer to this line as a "littoral energy fence" across which sediment from the landward side must move in order to be removed from the beach/dune system. A more practical limit for the water depth at which waves begin to impact on the sea bottom is one-quarter of a wavelength (Clifton and Dingler, 1984). Limits of terms inner shelf, mid-shelf, and outer shelf as used in this paper are shown. It is obvious that because wavelengths are so variable, usually an average is considered.

At an even larger scale, all earth-surface environments can be considered as either terrestrial (on land), transitional (transitional between land and water), or marine (under water). The transition zone between terrestrial and marine environments includes such environments as tidal flats, estuaries, dunes, and beaches and barrier islands. The focus of this chapter, then, is probably more correctly referred to as the transitional environment. The marine realm is covered in another chapter of this volume (Bush, this volume). Several terrestrial environments likewise are dealt with within their own chapters within this volume. Regardless, part of the beach system also belongs to the nearshore zone so it is impossible to completely disassociate the beach/transitional zone from the nearshore marine system. Standard beach terminology delineating the environmental zones of the nearshore system is shown in Figure 1.

The *Encyclopedia of Coastal Science* (Schwartz, 2005) is a lengthy (over 1200 pages) and expensive book, but it is comprehensive and contains a wealth of information on nearshore processes and sampling/monitoring techniques.

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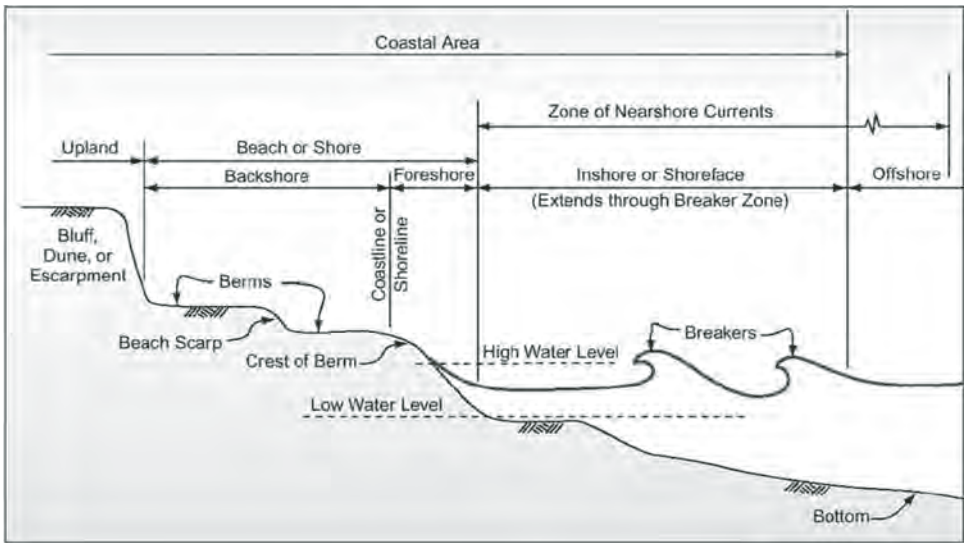


Figure 1. Standard beach terminology. The zone labeled "shoreface" can be considered the seaward extent of the area covered in this chapter. From FEMA (2000).

STRESSORS/POSSIBLE CHANGE TO THE COASTAL SYSTEM

The coastal system includes water, land, and air, and thus changes to the coastal system are a complex dynamic equilibrium of stimulus and response of those three spheres. That is, hydrodynamics of the nearshore marine system, substrate/land type and vegetation cover, plus the aeolian environment. The coast is subject to many different types of stressors including those natural and human induced (Table 1; Morton, 2003). The physical processes driving changes in the coastal system are fairly straightforward. These include waves, currents, and storm surges. The drivers of those forces include winter storms (known as extratropical cyclones), hurricanes (tropical cyclones), and possibly the effect of El Niño events. These forces act to modify sediment supply which ultimately changes the coastal geomorphology. Waves and currents may steepen unconsolidated shores forcing landslides and bluff retreat. Finally, there is a large-scale overprint of global sea-level rise and ground subsidence. Climate can also change over long enough time scales, which will exert control on coastal morphology and vegetation. Not to be understated is the role of human activities in land loss. Modifications of natural systems may include such things as transportation infrastructure, coastal construction, river modification, the extraction of hydrocarbon and groundwater, coastal excavation for beach replenishment, and stresses on wetlands.

One of the most obvious coastal vital signs to monitor is water depth (sea-level) change. Those are addressed in the chapter "Marine features and processes" (Bush, this volume).

The monitoring of water depth is largely addressed by the National Oceanic and Atmospheric Administration (NOAA); as a result, local or regional tide gauge data can be easily obtained at NOAA's Web site (www.noaa.gov). Within the NOAA site, see http://www.ngdc.noaa.gov/mgg/bathymetry/relief.html for bathymetric data and links to other sources.

Waves, currents, and seabottom composition (substrate) are also important aspects of energy flux in the water column. These, too, are addressed in the marine chapter.

This chapter will focus on the shoreline (and shoreline change) and landward. The "Marine features and processes" chapter covers seaward from the shoreline/low-tide line. It is impossible to completely separate one system from the other, but for purposes of organization of this manual, we will do just that.

Thus, the "land-based" coastal features begin with the shoreline—the meeting place of water and land. Change in the position of any particular shoreline in the long term is controlled by sea level. The change in sea level in any given location is a function of what global sea level is doing and what the local/regional land surface is doing. Both can be changing, sometimes in the same direction, sometimes in opposite directions. See Douglas et al. (2001) for an overview of not only the physical driving forces of sea-level rise, but also the societal impacts. More than just the actual shoreline, other nearby features needing monitoring included the beach (shape and slope), dune line, bluff location and height, etc.

Coastal dunes change with changing wind patterns, sediment supply, and human impact. Their presence or absence, vegetation cover, volume and elevation, and even their precise positional changes are important. Nordstrom et al. (1990) gives a good overview of dune processes. Dunes offer protection for more landward environments and for the built environment (Fig. 2). Many types of coastal vegetation can only flourish behind stable dunes.

Vegetation often indicates relative environmental stability, age, and elevation. For example, the maritime forests are areas that are inundated relatively rarely (Fig. 3). Mangrove shorelines, however, are subject to frequent flooding. Pine forests do not survive frequent saltwater intrusions, so their presence suggests stability. Salt marsh vegetation, on the other hand, requires frequent intrusion.

TABLE 1. COMMON PHYSICAL AND ANTHROPOGENIC CAUSES OF COASTAL LAND LOSS

Natural Processes	
Agent	Examples
Erosion	Waves and currents Storms Landslides
Sediment Reduction	Climate change Stream avulsion Source depletion
Submergence	Land subsidence Sea-level rise
Wetland Deterioration	Herbivory Freezes Fires Saltwater intrusion

Human Activities	
Agent	Examples
Transportation	Boat wakes, altered water circulation
Coastal construction	Sediment deprivation (bluff retention) Coastal structures (jetties, groins, seawalls)
River modification	Control and diversion (dams, levees)
Fluid extraction	Water, oil, gas, sulfur
Climate alteration	Global warming and ocean expansion Increased frequency and intensity of storms
Excavation	Dredging (canal, pipelines, drainage) Mineral extraction (sand, shell, heavy minerals)
Wetland destruction	Pollutant discharge Traffic Failed reclamation Burning

Note: From Morton (2003).



Figure 2. Coastal dunes offer significant protection for structures located behind them. Atlantic Beach/Fort Macon, Bogue Banks, North Carolina; Program for the Study of Developed Shorelines photo.



Figure 3. Cape Lookout, North Carolina. The denser, forested areas are more stable than the sandy or grassland areas. Storms are more likely to erode areas of less stability. Program for the Study of Developed Shorelines photo.

In general, the taller and thicker the vegetative growth, the more stable the site and the coastal geomorphic features. Maritime forests grow only at elevations high enough to preclude frequent overwash. In addition, because a mature maritime forest takes at least 100 years to develop, forested areas are generally the most stable. Major clearance of stable vegetation for development or by disease/fire greatly decreases the stability of coastal landforms.

In the tropics, from as far north as the southern Florida coast, mangroves fill an ecological niche that is similar to that of marsh grasses farther north. Mangroves perform the same ecological functions as marsh grass, that is, sediment stabilization, flood control, and habitat. Mangroves also are sensitive to the same negative impacts of development and pollution. If your shoreline property is lined with mangroves, do not remove the vegetation. The intertwining roots buffer erosion, trap and stabilize sediment, and provide critical habitat for juvenile stages of many marine animals.

Salt marshes—ecosystems that also flourish in quiet waters—often line the bay sides of islands, as well as the mainland margins of bays. The true salt marsh is a unique botanical environment because it consists of a single plant, ***Spartina***. Marshes are important breeding grounds for many marine species and offer considerable protection from wave attack as well. Many salt marshes have been filled in for development, a practice that is now illegal. Areas around finger canals often have been built up with material dredged from the marsh to form the canal. Such sites have their own resulting problems. Buried marsh provides poor support for building foundations and does not provide a

quality groundwater reservoir. Thus, such building sites typically have settling problems, an inadequate supply of fresh water, and septic systems that do not function properly. In addition, effluent waste from such sites has closed adjacent marshes to shellfishing. Marshes are very susceptible to flooding from even minor storms. New marsh can be planted on bay shorelines, and such replanting should be considered as an erosion buffer alternative to bulkheads and seawalls.

Another problem is that of non-native vegetation. For example, Australian pines (***Casurina***) flourish in Florida, Hawaii, and Puerto Rico (Fig. 4). These pines have shallow root systems and are easily blown over or knocked over by storms, causing damage or becoming obstructions to evacuation and recovery. These trees do not stabilize dunes or help them to grow, and they furnish large amounts of debris to be cleaned up after beach storms. The pine's toxic needles do not support undergrowth or encourage a diverse biota. Although they are attractive, it may be preferable to remove them and plant native vegetation.

The composition of beach and inshore material reflects the local and regional source of sediment. Thus, a detailed description of the sediment or other material making up the beach, dunes, bluff, or intertidal zone, will tell a great deal about the geologic history and sedimentological processes of the area. State geological surveys normally have much information, including soil surveys, and the U.S. Geological Survey (USGS) geological quadrangle maps are an important source of information as well.

Wetland dynamics, especially during a rising sea level, are a critical part of the coastal system. Monitoring the landward or seaward movement of a wetland margin and the total acreage of a coastal wetland helps to manage and forecast changes that will influence flora and fauna and provides indicators of overall system vitality.



Figure 4. Australian pine (*Casurina*) is toppling along an eroded bluff south of Guayabo, Puerto Rico. The shallow root structures cause these trees to be uprooted and toppled during storms. Photo by Chester Jackson Jr.

Just as barrier islands do, wetlands migrate landward with rising sea level. This occurs by drowning or eroding of the wetland on its ocean/estuary margin and formation of new wetland on its upland margin. Studies in Delaware Bay, for example, have shown that coastal wetlands were more extensive in the past than they are today (Allen, 1977). Numerous studies have examined the process and rate of vertical accretion in coastal wetlands (Reed, 1988; Stumpf, 1983; Richard, 1978; Harrison and Bloom, 1977). Many others have focused on the erosion or drowning of the seaward margin of coastal wetlands (Darienzo and Peterson, 1990; Hackney and Cleary, 1987; Orson et al., 1985; Hardisky and Klemas, 1983; and Rosen, 1978). These studies have shown that, as a general rule, vertical accretion in salt marshes is not keeping up with prevailing local relative sea-level rise. Furthermore, the aerial extent of these salt marshes has decreased over the last several decades. As stated earlier, coastal wetlands are dynamic environments and respond to sea-level rise by expanding on the upland margin. Yet, one can infer from this recent evidence of wetland loss that the rate of wetland transgression is not keeping up with the destruction of wetland on the seaward margin. This being the case, it is likely that further narrowing of our coastal wetlands can be expected under a regime of continuing, if not accelerating, sea-level rise (Fig. 5).

Clearly, if assumptions are correct in that sea level will continue to rise and our coastal wetlands will continue to erode on the outer margin while transgressing on the upland margin, a precise understanding of the nature and magnitude of the new wetland formation is needed. This information is necessary so that managers, governments, and concerned citizens will be able to make informed decisions on the disposition of wetland fringing lands.

SELECTED METHODS FOR MONITORING COASTAL FEATURES AND PROCESSES

Monitoring vital signs of physical aspects of park ecosystems helps give insight not only into the general state of systems but also into changes in the systems or system vitality. The vital sign concept is very similar to the geoindicators approach to monitoring environments. The International Union of Geological Sciences (IUGS) defines geoindicators as "measures of surface or near-surface geological processes and phenomena that vary significantly over periods of less than 100 years and that provide information that is meaningful for environmental assessment" (Berger, 1996), and they are applied to a wide variety of environments (Berger, 1997). Geoindicators have a variety of management applications including environmental auditing and monitoring. Berger (1997) notes that the geoindicators approach identifies a minimum set of parameters that describe short-term environmental dynamics and that are proxies representing all the parameters on which processes depend.

Vital signs of coastal features and processes will be starting at the shoreline and moving landward. Table 2 summarizes



Figure 5. The gravity of the wetland migration situation can be seen in this coastal North Carolina image. As sea level rises, the wetland behind the island in the foreground must be free to aggrade and to migrate landward with the rising sea level. Development on the mainland may preclude natural wetland transgression, leading eventually to wetland loss and habitat degradation. Masonboro Island, North Carolina; Program for the Study of Developed Shorelines photo.

the monitoring techniques discussed below. There is an infinite number of monitoring techniques and equipment available for monitoring the component environments of the coastal system. The following are selected in order to give a range of methods from low cost and low level of expertise needed, to high cost and higher level of expertise needed. Expertise needed may refer to either the expertise needed to use the equipment or to expertise needed to interpret the data, or both.

Vital Sign 1: Shoreline Change

Definition. Change in position of any particular shoreline marker (beach, dune line, bluff, etc.).

Significance. Monitoring changes in the position of the shoreline or other shoreline markers indicates the dynamics between sea-level change, sediment supply, hydrography, and meteorology. The actual shoreline, the dividing line between land and the marine realm, is the most obvious. Perhaps no data is more critical for coastal management than shoreline change history.

Shoreline change data are critical in providing sound scientific basis for coastal management decisions including a baseline for setbacks, establishing long and short-term erosion rates, hazards and risk assessments, and coastal planning. In addition to creating a scientific basis for shoreline monitoring and management, shoreline change calculations will also provide useful data on the impacts of engineering structures on erosion, which is needed to fully understand the consequences that may surround emplacement of a specific type of structure. This information can be used to provide effective recommendations on management issues with minimal impacts to the environment. Therefore, it may be possible to devise shoreline management strategies and property damage mitigation plans that anticipate shoreline erosion due to sea-level rise and coastal storms.

Level 1: Geoindicator-Based Photo Monitoring

Equipment needed. Geoindicator checklists, camera, maps for location.

Methodology. Select sites for monitoring based on input of local knowledge of, for example, areas of erosion or suspected vulnerability to overwash (Fig. 6) or other coastal hazards (Fig. 7). At each site complete a geoindicators checklist using the methodology of Bush et al. (1999) or similar evaluation. Table 3 is an example of a checklist for a barrier island shoreline from an evaluation for a Cumberland Island location. Table 4 is an example of a blank checklist for a mainland shoreline. Photographs up and down the coast, plus inland, are taken and recorded. Detailed photographs of interesting features should be taken as well. As much detailed description of the site and its features should be made. All information, checklists, and photos should then be put in a three-ring binder for archiving. As more visits to the site are made, the materials are added to the binder. Continue for other sites as well.

Timing. Can be done monthly, preferably; seasonally, if possible; and at least yearly. Also, so-called "event capture" meaning just before and then immediately after and continuing for a predicted event such as a major storm.

Complexity. Very simple.

Cost. Almost nothing; just printing photos and the cost of a camera if not in hand already.

Level 2: Repeat Profiles

Equipment needed. Beach profile stakes, recording sheets.

Methodology. The simplest approach is the Emery method (Emery, 1961), also known as the "stake and horizon" method (Fig. 8). Two stakes are used in a profile perpendicular to the beach with sighting the horizon to determine whether the forward stake at higher or lower elevation than the backward stake. It takes two people on the stakes and one to record the measurements. It is decidedly low-tech, but gives very representative and reproducible results. A video available from the University of Maine Public Affairs Office (Kelley et al., 1999) gives an excellent demonstration of the methodology. A Global Positioning System (GPS) unit for precise locations will add accuracy to the studies. A limitation is the height of the people taking the surveys (Fig. 9). A small boat or skiff, if available, can be used to extend the profiles offshore some distance.

A very high-tech method of extending profiles farther offshore is the U.S. Army Corps of Engineers' Coastal Research Amphibious Buggy (CRAB; Fig. 10). Mentioned here only because of its uniqueness, the three-wheeled vehicle is capable of operating in all but the most severe storms. The operations platform of the vehicle is 35 feet above the ground, so it has a fairly extensive working water depth as its position is located precisely by an electronic survey and tracking system.

TABLE 2. COMPARATIVE METHODS OF MONITORING COASTAL VITAL SIGNS

Vital signs and methods	Expertise[#]	Specialized equipment	Cost*	Personnel	Labor intensity[†]
Shoreline Change					
Photo monitoring	SCA/Volunteer	No	$	Individual	Low
Repeat profiles	Scientist	No	$	Group	Moderate
Repeat aerial photography	Expert	Yes	$$	Group	Moderate
Coastal Dune Geomorphology					
Photo monitoring	SCA/Volunteer	No	$	Individual	Low
Repeat ground surveys	Scientist	Yes	$$	Group	Low
LIDAR	Expert	Yes	$$$	Group	Moderate
Coastal Vegetation Cover					
Ground surveys	Scientist + SCA/volunteer	No	$	Group	Moderate
Vegetation classification	Scientist	Yes	$$	Group	Moderate
Aerial photography/satellite images	Expert	Yes	$$$	Group	High
Topography/Elevation					
Repeat photography	Scientist + SCA/volunteer	No	$	Group	Moderate
GPS or traditional survey	Scientist	Yes	$$	Group	Moderate
LIDAR	Expert	Yes	$$$	Group	High
Composition of Beach Material					
Repeat photography	Scientist + SCA/volunteer	No	$	Group	Moderate
Selected sampling	Scientist	Yes	$$	Group	Moderate
Sedimentological description	Expert	Yes	$$$	Group	High
Wetland Position/Acreage					
Simple surveys	SCA/Volunteer	No	$	Group	Low
Repeat aerial photography	Scientist/Expert	Yes	$$	Group	Moderate
Satellite interpretation	Expert	Yes	$$$	Group	High
Coastal Wetland Accretion					
Sediment traps	Scientist	Yes	$$	Group	Moderate
Cryogenic coring	Scientist	Yes	$$$	Group	Moderate
Historical rates	Expert	Yes	$$$	Group	High

Note: GPS—Global positioning System; LIDAR—light detection and ranging.

[#]Expertise: Student Conservation Association (SCA)/volunteer—needs no experience, minimal training and some observation sufficient; scientist—needs modest technical background in field or related field, but need not be expert in field; expert—must be scientist specifically trained in field and in use of specialized equipment.

*Cost (US$): $ = <$1,000; $$ = $1,000 to $10,000; $$$ = >$10,000.

[†]Labor intensity: low = <few hours; medium = <full day; high = >full day.



Figure 6. Overwash fans along the Outer Banks of North Carolina after Hurricane Isabel (2003) give evidence of how quickly shoreline position, along with barrier island topography, can change. Program for the Study of Developed Shorelines photo.



Figure 7. Gaps in dunes, perhaps caused by foot or vehicle traffic, can be sites of penetration of storm waves and storm surge, increasing risk to property behind the dune. Tropical Storm Dennis, 1999; Program for the Study of Developed Shorelines photo.

TABLE 3. GEOINDICATORS ASSESSMENT FOR A SITE ON CUMBERLAND ISLAND, GEORGIA

Geoindicators	High risk		Moderate risk		Low risk	
General Parameters						
Elevation	< 3 m		3–6 m		>6 m	X
Vegetation	Barren; sparse; toppled; non-native species		Well-established shrubs and grasses; none toppled		Forested; mature vegetation; no evidence of erosion into vegetation	X
Shoreline Parameters						
Offshore setting	Wide shelf; shallow open water		Shelf of moderate width; offshore bars		Steep, narrow shelf; limited fetch; natural protection (reefs, bars)	X
Erosion rate	Severely to slowly eroding		Stable	X	Accreting	X
Beach width, slope, and thickness	Narrow and steep; thin with exposed mud, peat, or stumps; poor sand supply		Moderate to narrow width of dry beach; potential for disruption of sand supply		Wide with well-developed berm; good sand supply	X
Bluff configuration (if present)	Bare face; recent or no talus ramp		Vegetated face and well-developed ramp		Low slope angle (large ramp); mature cover of vegetation	X
Dune configuration	No dunes (see overwash)		Low, or discontinuous dunes; bulldozed dunes		High, wide, continuous, unbreached ridges	X
Overwash	Frequent; overwash apron or numerous fans; dune gaps at road termini		Occasional; overwash fans of limited extent		No overwash	X
Engineering structures	Numerous groins; seawalls; offshore breakwaters; beach scraping		Few structures		No structures	X
Inlet Parameters						
Site relative to inlet or river mouth	Very near		Within sight		Very distant	X
Inlet potential	Spit or island narrow; low with open water on landward side; historic inlet; finger canals		Moderate width and elevation if open water on landward side; short finger canals		Spit or island wide; little open water on landward side, or wide protective salt marsh; no finger canals	X
Interior Parameters						
Dune configuration	No dunes or dunes artificially removed, disrupted by road cuts, building sites, walkways; deforestation or vegetation removal		Discontinuous; moderately well vegetated; minor disruption (roadcuts; leveling for building sites)		High, forested dunes; roads go around dune fields; pedestrian walkovers keep foot traffic off of dunes	X
Drainage	Poor		Moderate		Good	X
Soil	Compactable; lacks suitability for septic facilities (impermeable)		Reasonable good bearing strength; variable		Permeable; good bearing strength	X
Other features	Open water (sound, lagoon, estuary) on backside of barrier; marsh, or swamp (mangrove)		Floodplain or low-elevation terrace	X	Upland	
TOTAL INDICATORS:	OF HIGH RISK →→		OF MODERATE RISK →→	2	OF LOW RISK →→	14
RISK/COMMENTS →→	Overall a low-risk setting. High elevation, natural vegetation, wide dunes. Tidal difference between 10:30 a.m. through 1:30 p.m. was 0.82 meters. Assessment for: N 30.74039 W 81.45692; Date: 20 January 2003					

TABLE 4. GEOINDICATORS ASSESSMENT FOR A MAINLAND/ESTUARINE SITE

Assessment for:			Date:			
Geoindicators	High risk		Moderate risk		Low risk	
General Parameters						
Elevation	< 3 m		3–6 m		> 6 m	
Tidal range	Microtidal		Mesotidal		Macrotidal	
Vegetation	Barren; sparse; toppled; non-native species		Well-established shrubs and grasses; none toppled		Forested; mature vegetation; no evidence of erosion into vegetation	
Bluff configuration (if present;	Bare face; recent or no talus ramp		Vegetated face and well-developed ramp		Low slope angle (large ramp); mature cover of vegetation	
Evidence of historical storm impacts	Obvious		Possible		None	
Development Parameters						
Type of structures	Non-engineered (not to code; at grade)		Non-engineered (to code)		Engineered (commercial buildings, high-rises, etc.)	
Density of development	High		Medium		Low	
Engineering structures	Seawalls, bulkheads, docks, piers, major marinas		Few structures		No structures	
River/Tidal Creek Parameters						
Site relative to river or creek mouth	Very near		Within sight		Very distant	
Inland Parameters						
Soil and drainage	Compactable; lacks suitability for septic facilities (impermeable); drains poorly		Reasonable good bearing strength; variable; drains moderately		Permeable; good bearing strength; drains well	
Surroundings	In/near sound, lagoon, estuary, or swamp (mangrove)		Floodplain or low-elevation terrace		Upland	
TOTAL INDICATORS:	OF HIGH RISK→→		OF MODERATE RISK→→		OF LOW RISK→→	
RISK/COMMENTS →→						

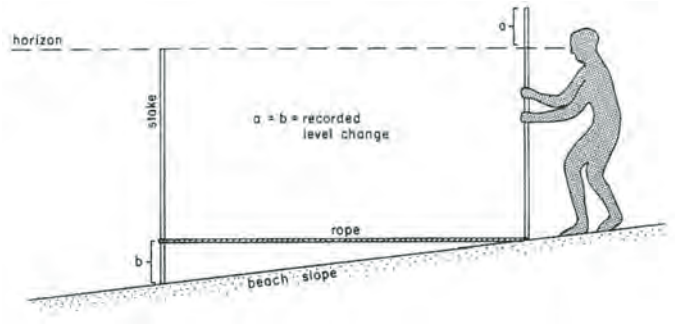


Figure 8. The Emery Method for beach profiling. From Emery (1961).



Figure 9. Using the stake and horizon method of Emery (1961), the distance offshore that the profiles can extend is limited by the height of the field assistants.



Figure 10. The U.S. Army Corps of Engineers Coastal Research Amphibious Buggy (CRAB).

Profile data can be plotted on a simple graph (Fig. 11) and the data from several profiles can summarized in various ways (Fig. 12).

Timing. As with the geoindicator monitoring, profiling should be done as often as possible, at least yearly.

Complexity. Simple after a little training.

Cost. Very low; no specialized equipment is needed, and stakes can be made from scrap lumber.

Level 3: Repeat Aerial Photography

Air photo surveying is one of the best ways to monitor shoreline change. A series of several generations of shoreline position data, digitized off air photos, and analyzed in a geographic information system (GIS), can provide a wealth of data on shoreline behavior.

Equipment needed. A source for air photos. Typically photos can be obtained for a nominal cost from departments of transportation, the National Ocean Service, various state Departments of Natural Resources or equivalent agencies, the U.S. Department of Agriculture, and the U.S. Geological Survey.

Methodology. Shoreline change is doubtless very important, both for scientific understanding of the coastal system and for management. But there are limitations in mapping historical shoreline positions driven by limits of methodology accuracy, on data "quality," and on our lack of understanding of the behavior of the system. Currently, shoreline mapping methods include point measurements (Stafford and Langfelder, 1971), photo enlargements (Dolan et al., 1980), the metric mapping system (Clow and Leatherman, 1984), digital shoreline detection (also known as raster scanning; Shoshany and Degani, 1992), and use of an analytical stereoplotter (American Society of Photogrammetry, 1980). Over the last two decades shoreline mapping has moved into the realm of the Digital Shoreline Mapping System (DSMS). The system provides digitizing routines for maps and aerial photographs and utilizes commonly available hardware/software such as electronic digitizers, UNIX-based computers, and GIS. The system calculates shoreline positions for maps and photographs and produces GIS-compatible output. Once the data are entered digitally and digital maps are produced, then the data can be analyzed digitally within a Digital Shoreline Analysis System (DSAS). DSAS reads the GIS-generated shoreline position data and, using extensive user specification such as choosing a reference baseline location and an alongshore sampling interval and cross-shore sampling tolerance, the system can calculate several measures of change simultaneously such as end-point rate (EPR; Fig. 13), average-of-rates (AOR), linear regression (LR), and jackknife (JK). The system produces reports on calculations for each transect and provides flexible output file format. DSAS systems are being continually upgraded by several researchers.

An example including digitizing and georeferencing historical, non-photographic shoreline data from NOAA tide sheets (T-sheets) for use in the shoreline change analysis of the Georgia coast is given by Langley et al. (2003) and air photos (Bush et al., 2003; Alexander et al., 2001).

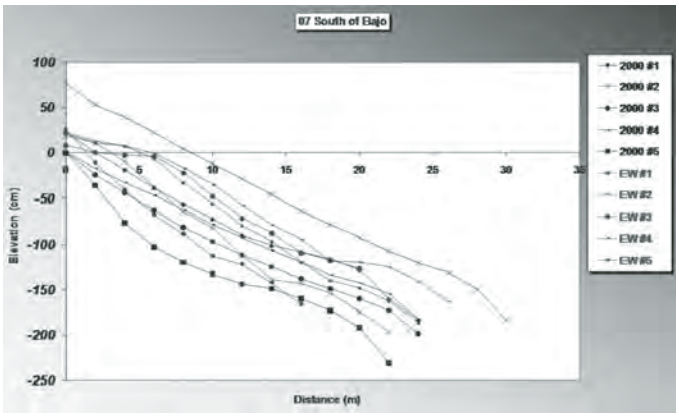


Figure 11. Beach profiles were taken on walled stretches of shoreline with adjacent sandy stretches in Puerto Rico by Wright (1989). Subsequent studies (see Bush et al., 2007) compared more recent profiles to those of Wright.

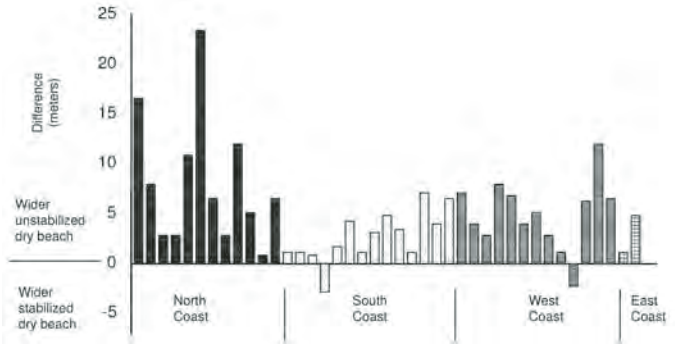


Figure 12. Results of a study of dry beach widths by Wright (1989). The goal of that study was to determine if there is a difference in dry beach width and beach profile steepness in front of seawalls compared to immediately adjacent unwalled beaches. Only beaches with walled plus unwalled segments were measured. On the graph, bars represent average widths of several profiles along individual beaches. Bars reaching above the zero line indicate that the unwalled portion of the beach in question was wider. Bars reaching down from the zero line indicate that the dry beach was wider in front of the walled portion of the beach. Clearly, beaches in front of walls were narrower. It is thus argued that hard stabilization contributes to shoreline erosion and degradation.

A major problem with an historical shoreline change study is determining the map accuracy and rate resolution. There can be horizontal RMS (root mean square) error for shoreline coordinates and error in the original data sources and converting the original sources (air photos or survey sheets) into historical shoreline position data. For example, in calculating the error in simple end-point rate calculations, imagine an error in oldest shoreline position of 9.25 m and an error in most recent shoreline position also of 9.25 m, giving a total error of 18.50 m. The longer the period of study (years between oldest and newest shoreline position data source), the less the error per year. For example, in the above calculation, if the number of years between the two shorelines is 36 years, the average error per year is on the order of 0.51 m/yr, an acceptable error.

But what do the data really tell us? That is, do the data answer important geologic questions such as: do the data reflect the real long-term trend? How many data points do we have? Are there storm influences or seasonal changes? Do decadal or climatic variations play a role? Are there wind-, wave-, or tide-influenced fluctuations? We may never know the pre-photo events affecting the area of study. Moreover, what are we really measuring? That is, which is the best shoreline indicator? Most surveys now use the wet/dry (mean high water or MHW) line. Some, however, use a vegetation line, bluff line or cliff line. Which is most stable? Which is more reproducible?

Historical shoreline change is typically determined using aerial photographs from as many different surveys as possible (Fig. 14). It is especially good to have air photos from each decade if possible. The more generations of air photos covering the most amount of time, the better the data and the fewer the errors. Methodology and discussions on shoreline position errors are discussed in several studies (for example, Anders and Byrnes, 1991; Crowell et al., 1991; Dolan et al., 1980; Douglas and Crowell, 2000; Moore, 2000; Danforth and Thieler, 1992a, 1992b; and Thieler and Danforth, 1994a, 1994b). All shoreline positions have some degree of inaccuracy, and such errors should be reported so that rate-of-change calculations may be interpreted and used judiciously.

Timing. Updates can only be done as often as new generations of air photos become available. It may be years between flights. Local managers should work with state and federal agencies for information on planned air photo flights in order to be made aware of availability.

Complexity. Very complex; highly skilled personnel is needed for data entry and analyses of shoreline position data.

Cost. High, depending on cost of air photos. A GIS computer work station is needed. The computer equipment and even the expertise may be available at nearby universities.

Vital Sign 2: Coastal Dune Geomorphology

Definition. Monitoring the nature of coastal dunes (presence/absence, dune volume/elevation, dune position)

Significance. Coastal dunes provide a measure of protection for the land against forces of the sea including storm waves and surges. A study of the impacts of Hurricane Hugo (1989) in South Carolina revealed that buildings behind large dunes suffered little damage during the storm (Thieler and Young, 1991).

Level 1: Geoindicator-Based Photo Monitoring

See the description for Vital Sign 1, Level 1, above, using the geoindicator approach.

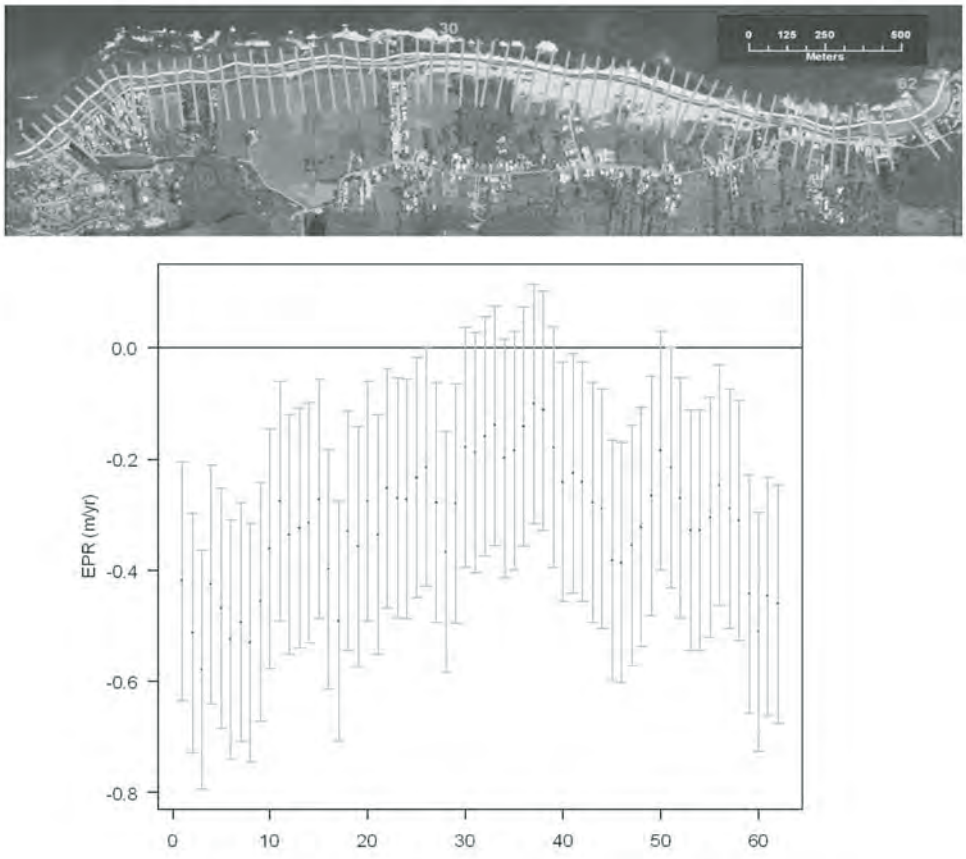


Figure 13. Most of Puerto Rico's shoreline is eroding. Erosion is far more important on unconsolidated shorelines than on rocky stretches. Here is an example of a recent study of the northwestern corner of the island, which is mostly a rocky coast. On the graph at right, the horizontal axis is alongshore virtual transect numbers, the vertical axis is end point rate calculation shoreline change rate and error ranges from air photos. From Bush et al. (2007).

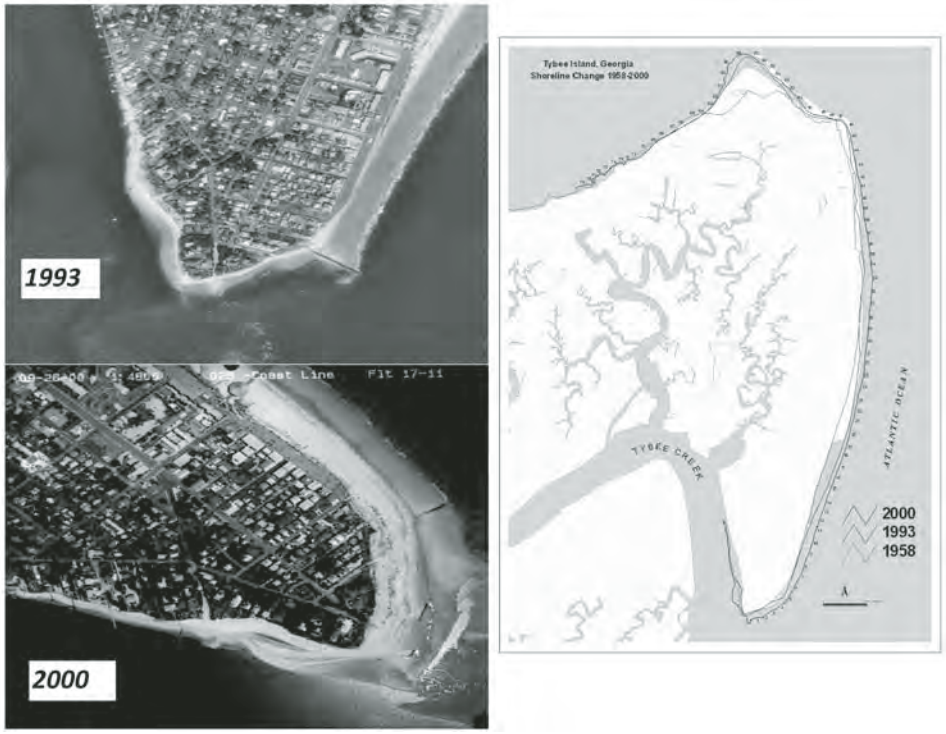


Figure 14. Historical shorelines for Tybee Island, Georgia, from air photos (Alexander et al., 2001).

Level 2: Repeat Ground Surveys

The same approach as presented for Vital Sign 1, Level 2, can be employed by expanding the methodology inland and measuring individual dunes or other features (Fig. 15).

Level 3: LIDAR

Equipment needed. Very specialized, high-technology equipment, typically available only through governmental agencies. There must be partnering with other agencies for application of light detection and ranging (LIDAR) methodology. The USGS maintains a LIDAR Web site (http://lidar.cr.usgs.gov/) called CLICK. It is the USGS Center for LIDAR Information Coordination and Knowledge. See also NOAA's coastal remote sensing Web site at http://www.csc.noaa.gov/crs/rs_apps/sensors/lidar.htm.

Methodology. LIDAR is a remote sensing system used to collect topographic data. Lasers are used from aircraft to measure in great detail variations in the vertical dimension. Precisions on the order of 15 cm are possible. Repeat surveys can be used to detect shoreline changes, including volumetric changes (Fig. 16). See the CLICK site or NOAA's http://www.csc.noaa.gov/products/sccoasts/html/tutlid.htm for further information.

Timing. Owing to the cost of data collection and time and cost involved in data analysis, LIDAR data are likely going to be sparse for many areas. Areas along, for example, the Gulf of Mexico coast, however, have had repeat surveys because of frequent hurricane impacts.

Complexity. Highly complex.

Cost. High.

Vital Sign 3: Coastal Vegetation Cover

Definition. The degree and nature of the vegetation cover in the immediate coastal zone.

Significance. Vegetation cover is a good indication of the relative stability of coastal landforms. In general, the taller and thicker the vegetative growth, the more stable the site and the coastal geomorphic features. Changes in vegetative cover can occur naturally by fire, disease, storm impacts, or by long-term erosion (Fig. 17). However, human destruction of vegetation for development may be the greatest negative impact.

Vegetation cover also is important in evaluating the hydrologic system of the area of study (Fig. 18). Existing, older, land-use maps are outdated and generalized, so often new land-use classification gives an accurate picture of current development trends. Land-use classification goes beyond vegetation cover to include all other types of land cover such as developed areas (roof tops, paved expanses, etc.) waterways, agricultural lands, and so forth.

Level 1: Checklist-Driven Ground Surveys

See the description for Vital Sign 1, Level 1, above, using the geoindicator approach, concentrating on the vegetation. Vegetation classes to include will depend on local environment.



Figure 15. Beach, dune, and marsh environments along Shackleford Outer Banks of North Carolina. Monitoring of the areal extent of the various environments can be done in a variety of ways. Program for the Study of Developed Shorelines photo.

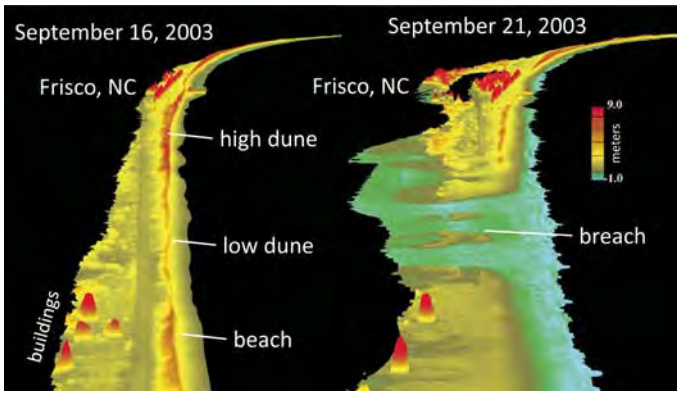


Figure 16. Light detection and ranging (LIDAR) survey before and after Hurricane Isabel (2003) near Hatteras, North Carolina. U.S. Geological Survey image.



Figure 17. Fallen trees are obvious evidence of rapid shoreline retreat. Program for the Study of Developed Shorelines photo.

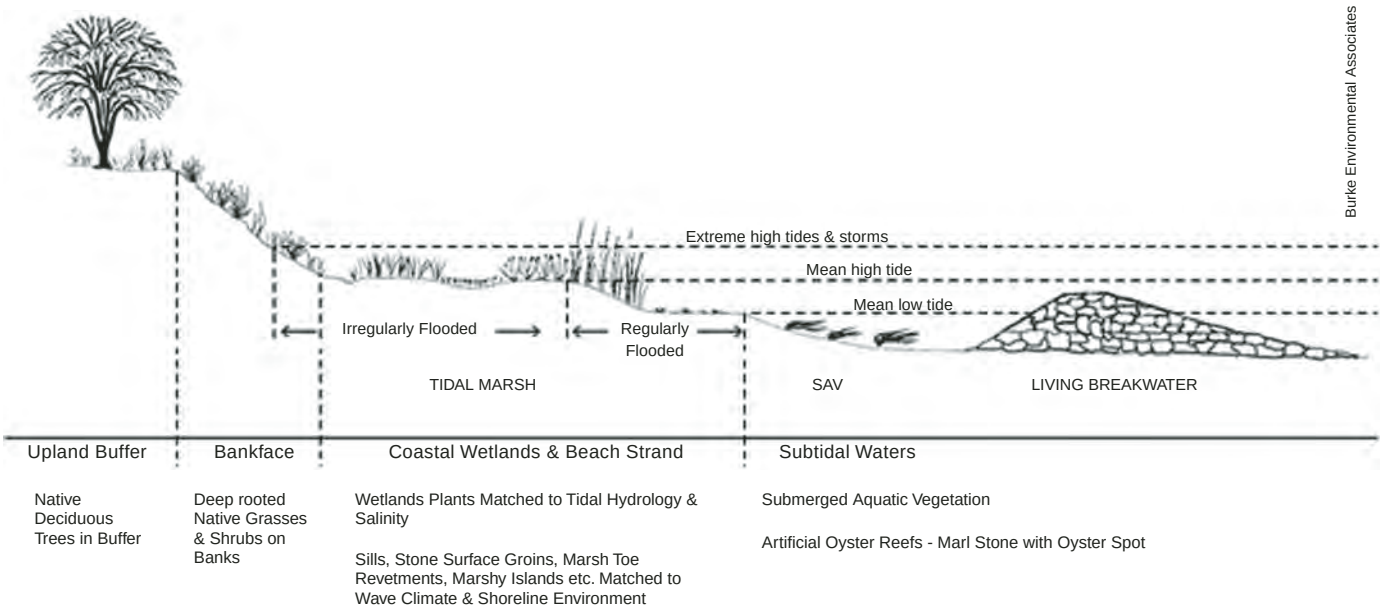


Figure 18. Coastal shoreline continuum and typical "living shorelines" treatments. NOAA diagram (http://habitat.noaa.gov/restorationtechniques/public/images/burke_environmental.gif).

Level 2: Ground Surveys with Vegetation Classification

Equipment needed. A more thorough evaluation than Level 1 only in means of adding much more complete surveys of vegetation cover instead of evaluating selected sites as in the geoindicators approach.

Methodology. Involves driving, walking, using an all-terrain vehicle, etc., over study area to map vegetation cover from site inspection covering the area in as much detail as possible.

Timing. Yearly surveys would be ideal, but are not critical. However, if there are areas observed to be undergoing rapid change because of natural or human impacts, more frequent surveying is warranted.

Complexity. Low complexity, but labor intensive.

Cost. Low to moderate cost. Transportation, photography, and maps are the greatest expense.

Level 3: Repeat Aerial Photography, or Satellite Images

Equipment needed. Air photos as discussed for shoreline change, above, are needed. Color photographs are much more useful for vegetation cover mapping while black and white will suffice for shoreline change detection. Black and white photographs are of some use for vegetation cover, but color is much better.

For both air photo and for satellite imagery evaluation, specialized geospatial analysis computer equipment, software, and expertise are needed.

Methodology. Digitizing air photos, and manipulating air photos and satellites imagery, is done within GIS and remote-sensing computer work stations. Ideally, computer results would be field checked for ground truthing of results. Only an abbreviated methodology is given here because the work is so highly specialized that the person or persons actually performing the investigation will be well versed. In general, though, air photos would require hand digitizing of different vegetation cover types, whereas the satellite imagery can be analyzed digitally based on the various electromagnetic wavelengths reflected by different plants and other land cover types.

Some type of satellite imagery is needed (Fig. 19; base maps, and database of roads, streams, wetlands, etc.). Direct field observations of selected sites to confirm the vegetation cover in that area will increase the validity of imagery analysis done by the computer.

See the Web site of the USGS Land Cover Institute at http://landcover.usgs.gov/ for more information.

Timing. As new satellite imagery or air photos become available.

Complexity. Very complex. Must be done by experts. Partnering with a university or federal agency is probably a must.

Cost. A main cost can be the satellite imagery, assuming the computer equipment and software is already available.

Vital Sign 4: Topography/Elevation

Definition. Cross-shore elevation allowing for a determination of coastal geomorphology and sediment volumes.

Significance. Topographic changes of coastal landforms are a reflection of the dynamics between processes of air, water,

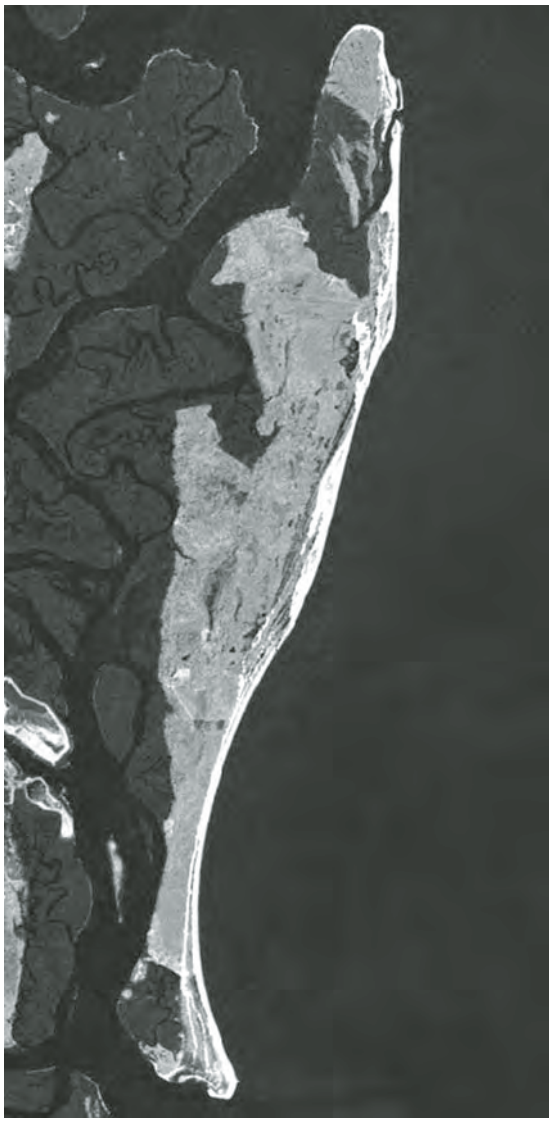


Figure 19. Satellite image of Cumberland Island, Georgia.

and land. A standard geomorphology concept is that, in general, the larger the feature, the more persistent it is. That is, the more slowly it changes. Thus, smaller features such as dunes will change much more quickly and dramatically than larger features such as interior beach ridges. Therefore, the type of monitoring and the frequency of monitoring will depend, in part, on the feature to be monitored.

Level 1: Repeat Photography

The approach is not too different than those given using air photos in previous sections. The only difference is the feature to be monitored: shoreline position in the case of Vital Sign 1 and vegetation type and expanse in the case of Vital Sign 3. In this case, coastal landforms are the target of interest on the air photos. Other than that, all descriptions given above hold true for this case.

Level 2: GPS or Traditional Survey

Equipment needed. A GPS receiver or hand surveying tools.

Methodology. A GPS survey means driving or walking around a feature making several recordings of position using a handheld GPS receiver. The more frequently position data are recorded, the more precisely a feature can be recorded and monitored. The horizontal dimensions are very accurate (within a meter or so) with a good GPS system. Vertical dimensions may not be quite as accurate, but accuracy can be improved by employing higher quality equipment or by tying GPS readings into an elevation benchmark or to a traditional survey. A traditional survey entails hand surveying. This involves many detailed measurements from known locations. It is very accurate, but very time consuming.

Timing. Depends on the dynamics of the feature or features to be monitored.

Complexity. Moderate.

Cost. Moderate, depending on the GPS unit. If surveying by hand, personnel costs will be very high.

Level 3: LIDAR

See discussion of LIDAR, above.

Vital Sign 5: Composition of Beach Material

Definition. Description of the sediment or other material making up the beach, dunes, bluff, or intertidal zone.

Significance. The composition of the material comprising the area of study gives great detail about the geologic history including human impacts in many cases. Obviously, a rock cliff at the coast will behave much differently than a sandy bluff during an individual storm as well as over longer time frames. Dominance of shell material means a marine source for much of the sediment. Pure quartz indicates an area not only away from marine influence but also sediment that has been reworked many times so that other, less-resistant, material has eroded away.

Level 1: Repeat Photography with Field Notes

Equipment needed. A camera, field notebook, and GPS for positioning.

Methodology. Take photographs with detailed descriptions. Take close-ups of unique or interesting structures. Make sure to get close ups and shots of the area for context. Identify areas of potentially more rapid change such as eroding bluff of a river or scarped dunes (Fig. 20), and pay particular attention to these. Keep a detailed notebook with photographs and descriptions.

Timing. Yearly at least.

Complexity. Low complexity.

Cost. Low.

Level 2: Selected Sampling

Equipment needed. Sampling devices, sample storage containers.



Figure 20. A scarp in the beach is evidence of the passing of a recent storm.

Methodology. Sampling on land can be as simple as spooning some sediment into a plastic bag. The *Encyclopedia of Coastal Science* (Schwartz, 2005) is a lengthy (over 1200 pages) and expensive book, but it is comprehensive and contains a wealth of information on nearshore processes and sampling/monitoring techniques. Description of the samples must be done using standard methodologies such as those described by Lewis and McConchie (1994) or Sukhtankar (2008).

Timing. Yearly should suffice.

Complexity. It is not overly complex, but training is needed.

Cost. Moderate.

Level 3: Detailed Sedimentological Description

Equipment needed. In addition to the equipment needed to obtain samples, analysis can be very complex and costly. It would be advantageous to develop a working relationship with a nearby university or USGS laboratory for help in sedimentological descriptions.

Methodology. Analysis of samples is an entirely separate issue from obtaining the samples. Depending on facilities everything from simple textural analyses (grain size and sorting) to composition (identification of grains) to organic carbon content, and even radiometric age dating is possible. The USGS has loads of information on sedimentologic techniques. See, for example, USGS (2000) as an example of techniques for grain size analysis and data handling.

Timing. Yearly at most.

Complexity. Very complex, particularly in the nuances of sedimentary structures and microstratigraphy.

Cost. Can be very high if sophisticated techniques are required.

Vital Sign 6: Coastal Wetland Position and Acreage

Definition. Monitoring the landward or seaward movement of a wetland margin and the total acreage of a coastal wetland.

Significance. Coastal marshes (Figs. 21 and 22) play a critical role in sustaining the health of coastal ecosystems. They are centers of biological productivity important for active fisheries. They may act as a buffer between the marine and freshwater environments, filtering out contaminants from the uplands. They are pathways of migration for numerous species of waterfowl (the availability of wetlands is important in maintaining species diversity). It is clear that preserving and properly managing this nation's coastal wetlands will directly or indirectly benefit us all. It is imperative that any agency charged with managing large portions of coastal wetlands understand the dynamics of these environments. Protecting coastal wetlands in a period of continued, and possibly accelerating, sea-level rise may require flexible management techniques that have yet to be considered.

As sea level rises, barrier islands, fringing marshes, and other coastal environments move landward up the adjacent coastal



Figure 21. Coastal wetlands stretch for miles along many portions of the coastal zone. Program for the Study of Developed Shorelines photo.



Figure 22. This marsh on Jekyll Island, Georgia, is located between a modern and a Pleistocene beach ridge.

plain (upland). To properly monitor this ecosystem, it is necessary to first understand the historical effects of sea-level rise on wetland evolution by studying the transgressing edge of the coastal marshes and the upland environments onto which they are transgressing. Ultimately, a predictive model of future wetland evolution in the time of a rising sea level will result aiding in management.

A necessary first step is simply to monitor the size and location of identified wetlands. The techniques will not differ much from those previously discussed.

Level 1: Simple Surveys

Equipment needed. GPS units and record keeping materials.

Methodology. Identify the boundaries of the wetland in question. Take as many position readings as possible using hand held GPS units. Post data on a map. Each generation of maps could ultimately be digitized for easy comparison with future maps using computer graphics. That is not necessary, however, as hand comparison is worthwhile as well.

Timing. Probably once every several years is enough unless there is some kind of disturbance, human-induced or natural, that bears watching.

Complexity. Not complex; need knowledge of working with GPS units and plotting data on a map.

Cost. Low cost.

Level 2: Repeat Aerial Photography

The approach is not too different than those given using air photos in previous sections. The only difference is the feature to be monitored. In this case, coastal marshes and wetlands are the target of interest on the air photos. Other than that, all descriptions given above hold true for this case. In fact, considering wetland vegetation, this could be considered as part of the vegetation monitoring program.

Level 3: Satellite Interpretation

Same as for vegetation monitoring only concentrating on wetlands.

Vital Sign 7: Coastal Wetland Accretion

Definition. The rate of sediment accumulation in a coastal wetland.

Significance. Sediment accumulation in coastal wetlands is critical for the land surface to keep pace with sea-level rise. Otherwise, the wetlands would become inundated. Inherent in that, is that as the surface of the marsh rises, the organic material trapped within the sediments may account for a large amount of carbon locked out of the atmospheric system. Much effort has been directed at understanding carbon accumulation, cycling, and long-term storage in wetlands. Studies have ranged from site-specific determinations of soil organic matter accumulation (e.g., Craft et al., 1993) to region-wide accumulation (e.g., Botch et al., 1995), and ultimately, global assessments of the total carbon mass stored in wetland soils during the Holocene (Moore and Bellamy, 1974). Much recent interest has focused on changes in wetland carbon reservoirs during historical times—primarily human induced. Armentano and Menges (1986) estimate changes in carbon flux and loss of carbon storage capacity for temperate zone organic soils due to wetland drainage and similar disturbances. They found that the wetlands in some regions of the world (e.g., central Europe) are presently carbon sources rather than sinks due to agricultural drainage, forestry operations, and peat burning.

Level 1: Sediment Traps

Equipment needed. Field sediment traps.

Methodology. This is a highly sophisticated sampling technique, necessarily so because of the sensitivity of the data. Accumulation rates are often very low, so high precision is a must. See Mudroch and MacKnight (1994) for sampling methodology and Leonard et al. (2002) for an example application of sediment trap methodology in estuaries. Large sediment traps might be necessary in some instances as in the nearshore or lake environments. See Honjo and Doherty (1988) for an example.

Timing. Seasonal if possible, and during events.

Complexity. Will need a high level of expertise for deploying sediment traps and retrieving and analyzing the data.

Cost. Moderate for cost of traps and field work.

Level 2: Cryogenic Coring

Equipment needed. Cryogenic coring uses liquid nitrogen to freeze the marsh substrate thus making it possible to retrieve a core sample (Fig. 23). It is especially advantageous in that, once frozen, the soil does not compact, so accumulation rate data obtained is much more precise than conventional coring techniques. See Knaus (1986), Knaus and Cahoon (1990), or Cahoon et al. (1996) for description of the coring device.

Methodology. Cryogenic coring is a highly specialized undertaking. See the USGS Web page http://www.pwrc.usgs.gov/set/readMarkers.html for an example of the technique.

Timing. Yearly at the most.

Complexity. Highly detailed sampling techniques means this is best left to the experts.

Cost. Moderate.

Level 3: Determination of Historical Rates

Equipment needed. To investigate historical rates of wetland accretion means having to bring in the third and fourth dimensions. Highly precise spatial data are needed, and absolute dating methods must be employed. This is necessarily equipment and labor intensive.

Methodology. Each site to be studied will be covered with several vibracore transects extending from the upland across the transition zone into the marsh. Vibracores (after the methods of Lanesky et al., 1979) can be supplemented with one-inch diameter, hand-auger cores. The hand-auger will be used to fill in any gaps in resolution not provided by the vibracores (e.g.,



Figure 23. Cryogenic coring. The bottle has liquid nitrogen used to freeze the marsh substrate thus making it possible to retrieve a core sample. U.S. Geological Survey photo.

detailed mapping of the transgressed upland surface). The vibracore tops will be surveyed in using differential GPS providing the detail necessary to examine the elevation of the transgressed upland surface in the cores. This kind of detail is important for determining accurately the slope of this surface and the rate of transgression of the marsh edge.

Vibracores must be taken to a lab where they can be split, photographed, and sampled at ~10 cm intervals downcore. The boundary between the submerged upland and the base of the salt marsh must be identified and the basal marsh sediments (this is the leading edge of the transgressing marsh) sampled for radiocarbon dating. Depending on available funds, the more radiocarbon dates the better. A hand-auger core should also be recovered at each vibracore location for possible ^{137}Cs and ^{210}Pb sequences to determine if accretion rates vary across the transition zone and from site to site.

The modern surface sediments in each site should be sampled and analyzed using standard sedimentological techniques—grain size analysis by settling tube (Theide et al., 1976) and percent loss on ignition as a proxy for plant organic content (Davies, 1974). These characteristics can then be mapped as a sediment facies map. The modern vegetational assemblages should be mapped in detail using a standard line/interval method listing the species dominance hierarchy at each sediment sample site. These maps will provide the baseline data set for the modern biogeological relationships at each site. Similar procedures should be carried out for the sediments at 10 cm intervals in the vibracores in order to determine if the sedimentology, vegetation, or the relationships between the two have changed during marsh transgression. Analysis of the marsh flora in the cores must be carried out using, for example, the methods of Allen (1977). It is important to determine whether these coastal marshes are transgressing as stable vegetational communities or whether they are changing as they migrate.

The results of such a study can include profiles, topographic contour maps, sediment isopach maps, and sediment facies maps. Ultimately, a series of maps for each study area can be produced predicting areas of new wetland formation and floral succession during the next 50, 100, 250, and 1000 years, assuming minimum, moderate, and maximum sea-level rise scenarios. Predictions will be based on the determined rate of wetland transgression at each transect adjusted for any changes in the bordering upland slope or environment. Notations on the maps will indicate areas where human activity may interfere with or prevent the formation of new wetland. This is the ultimate in long-term management of the system.

Timing. Probably will be done once only.

Complexity. Exceedingly complex.

Cost. Very expensive.

CASE STUDY—CUMBERLAND ISLAND, GEORGIA

The Georgia coast extends ~150 km. Only four barrier islands are accessible by car (Tybee, St. Simons, Sea Island, and Jekyll), and are heavily developed.

A two-part approach to evaluating coastal hazards was developed to aid coastal planning and management decisions for Cumberland Island National Seashore (Barrett et al., 2003). The goal was to provide guidelines for environmental assessment of a shoreline and to serve as an evaluative tool for examining natural hazard risk, to aid in developing management strategies. The first component of the plan is a field-based program of observations and documentation. This involves (1) a simple geoindicators checklist of several hazards-related parameters including descriptions of the general setting, shoreline state, nearshore setting, and onshore setting; (2) beach profiling using a simple stake and horizon method; (3) a set of photographs to document the setting; and (4) recording site locations using a handheld GPS unit.

The second component of the plan is a computer-assisted analysis utilizing remote sensing and GIS technology. This involves (1) land use/land cover from satellite imagery; (2) shoreline change analysis from air photos and NOAA T-sheets; (3) evaluation of historical beach profiles (if and when available); (4) creating and managing a database; and (5) creating and maintaining a Web site for maximum distribution of findings.

Phase One: Field Documentation

Field sites were selected based on field inspection, anecdotal evidence of interesting erosion patterns, or any number of reasons suggesting that the site is deemed worthy of monitoring. For each selected field sites (Fig. 24), field description was made along with completion of a geoindicators checklist (Table 3), beach profiling using the Emery (1961) method discussed earlier (Figs. 8 and 9), and photo documentation. Each site's photographs, geoindicators checklist, beach profile plots, and any other information are organized into a 3-ring binder. Stakeholders were encouraged to visit each site at least once a year, or more frequently in the case of passage of a large storm.

Phase Two: Digital Applications

Land cover change was assessed using satellite imagery (Fig. 19). Shoreline change analysis from T-sheets and aerial photography was done (Fig. 25). See also Jackson (2006), Jackson et al. (2007), and Langley et al. (2003) for methodology. Historical beach profiles were not available, but should be acquired if possible. Shoreline change was calculated using end point rate method. That is, the difference between the oldest and youngest years' shoreline position data available divided by the number of intervening years. Shoreline changes of the estuarine shoreline of Cumberland Island (Jackson et al., 2007) are shown in Figure 26.

Conclusions

Field inspections of several sites on Cumberland Island National Seashore showed that, at least for the sites visited, there are no major coastal hazards present on this undeveloped island. Shoreline change analysis from air photos confirmed this observation. A flow chart was developed to provide an easy to follow guide to initiating and continuing the proposed coastal evaluation technique (Fig. 27). The beauty of this approach is that the field observation component is very inexpensive and can still provide enough information on which to base management decisions. The digital component is not strictly necessary, but can be used to complement the field observations if and when resources are available. A byproduct of such a study is that the amount of data generated must be kept organized and accessible. As such, creating and managing a database and Web site is critical.

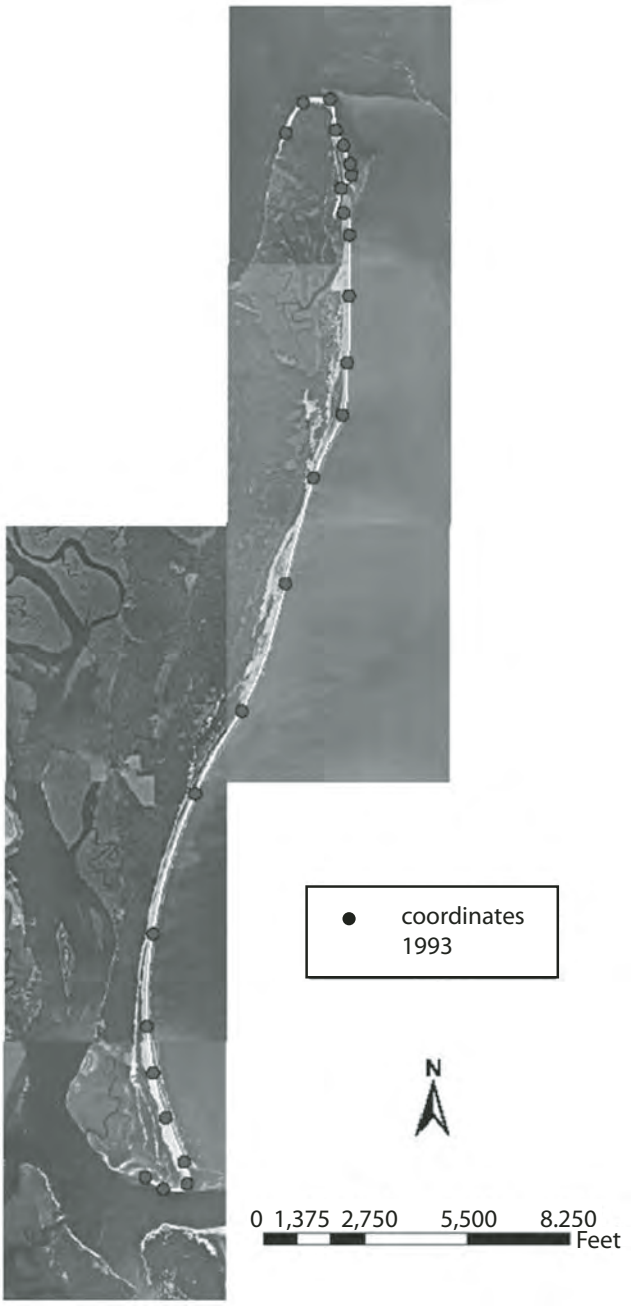


Figure 24. Monitoring sites (dots) along the Cumberland Island, Georgia, shore. Sites were selected based on input of National Park Service personnel, previous studies, and field observations.

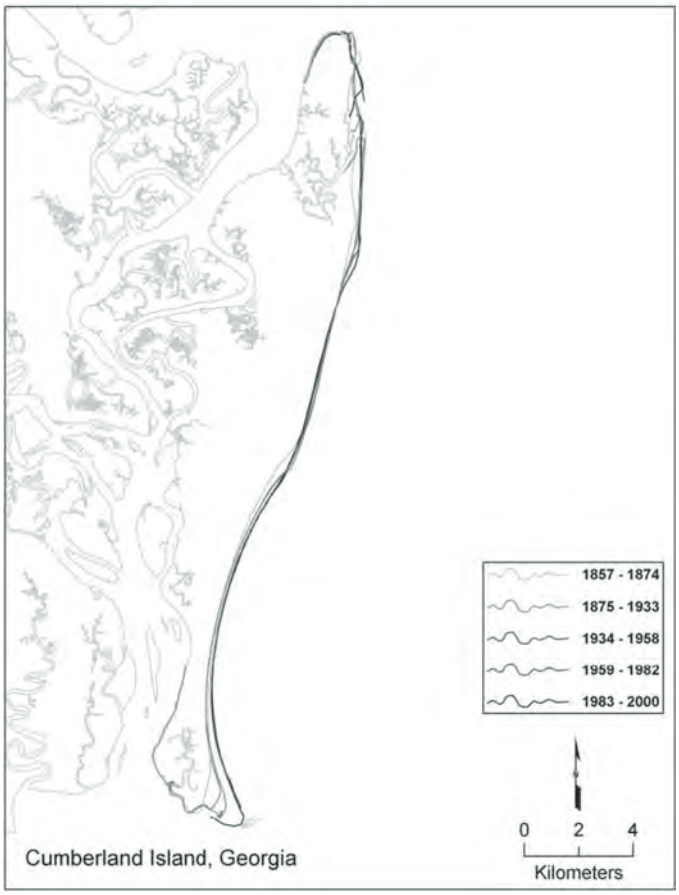


Figure 25. Historical shoreline positions, Cumberland Island, Georgia. From Jackson (2006).

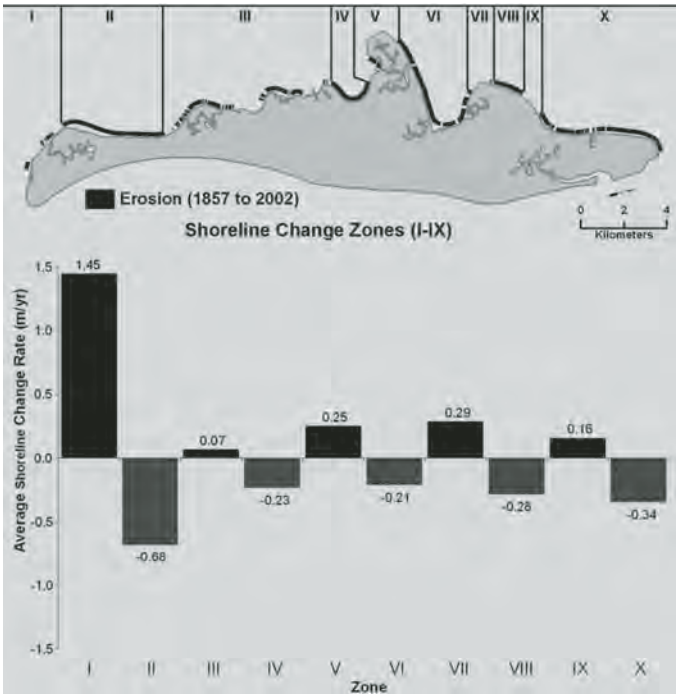


Figure 26. Historical changes in the estuarine shoreline of Cumberland Island, Georgia. From Jackson et al. (2007).

CONCLUSIONS

There are myriad techniques and types of equipment that can be used to monitor the coastal environment. The vital signs and various levels of study described in this chapter barely scratch the surface. There are additional data sets that can be important and, depending on the resources and needs of the area of study, could be important factors for monitoring.

Additional aspects of the coastal zone that may be of interest include the following.

Meteorology and Oceanography:

- Storm frequency
- Wind speed and direction
- Local wave data
- Rate of local relative sea level rise
- Nearshore bathymetry
- Location of nearshore hardgrounds

Other:

- Land use change in coastal watershed
- Location of coastal engineering structures
- Beach replenishment history
- Degree of alteration of coastal wetlands
- Location of former inlets on barrier islands

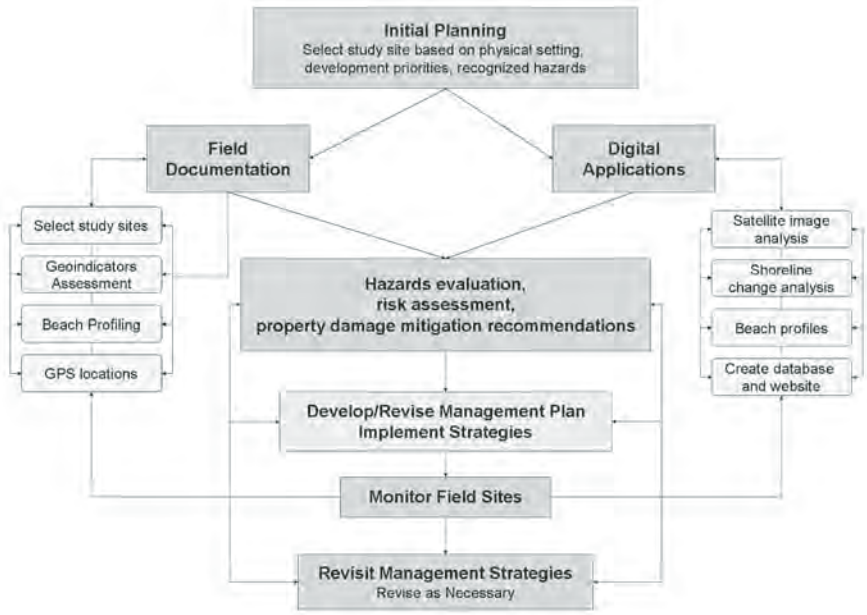


Figure 27. Flow chart of the two-phased approach to coastal monitoring.

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Fluvial geomorphology: Monitoring stream systems in response to a changing environment

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PURPOSE AND SCOPE

The purpose of this chapter is to provide an overview of river and stream dynamics, describe possible stressors that may lead to channel instability, and provide guidelines and methods for monitoring streams and rivers. Because there are great differences in budget, staffing, and management needs and objectives between managed lands, we provide procedures for three levels of monitoring protocols. The three levels progress from low-budget methods where minimal expertise in fluvial geomorphology is required, to higher-level methodologies requiring greater expertise, a larger budget, and more time. We recognize that personnel range from people having no formal training in fluvial geomorphology to people holding graduate degrees in the field. In the past decade, there has been increased emphasis on stream water quality, monitoring, and restoration from government and nongovernment associations. With this, people from a wide variety of backgrounds have become involved in monitoring and sampling of streams. While, indeed, many methods for sampling and monitoring are simple, the design of a study and interpretation of data are not simple—they require a sophisticated understanding of stream systems. Improper study design and interpretation has led to, in many cases, the collection of useless data, or worse, the implementation of land use plans or stream restoration projects that made problems worse. Because of this, we have put considerable emphasis in the overview of fluvial geomorphology to describe how stream processes relate to channel form and the dynamics of these complex, highly interconnected systems. Understanding how a stream works, how it relates to other systems (natural and artificial), and how it relates to the entire watershed defines the core of knowledge necessary for designing a successful monitoring plan and interpreting the data properly.

To the extent possible, in this short treatment of the subject, we aim to provide a description of methodologies that are useful to most readers. Good descriptions of methods for monitoring fluvial systems are increasingly abundant because of the environmental emphasis on stream systems and because of the on-going effort of many agencies, mostly government, to make methods available on their Web sites. More experienced individuals would be well served to read this chapter and then use a more comprehensive, detailed coverage, such as Kondolf and Piégay (2003).

This chapter focuses on monitoring fluvial systems and does not attempt to provide guidelines for channel restoration. A philosophical statement and guidelines for river restoration are given in Doyle et al. (1999) and by the Applied Fluvial Geomorphology Ad Hoc Committee of the Geological Society of America Quaternary Geology and Geomorphology Division (2004). Although short courses in river restoration are available (Rosgen, 1996), there is growing body of compelling literature and direct evidence that suggests that the level of expertise gained from a short course is not sufficient preparation to guide restoration efforts (Kondolf and Micheli, 1995; Miller and Ritter, 1996; Juracek and Fitzpatrick, 2003; Kochel et al., 2005). We strongly recommend that land managers consult experienced people holding graduate degrees in fluvial geomorphology for restoration efforts and complex problems.

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BASICS OF FLUVIAL GEOMORPHOGY

Systems Approach

When evaluating rivers or streams, the natural tendency is to focus on a segment, or "reach" of the channel. Typically, the segment size is determined by the needs and scope of the project. With respect to a national park, the segment might be dictated by the park boundaries. Whereas the reach-specific perspective may appear to be a logical approach, it will invariably prove to be insufficient for most purposes. Any segment of a river must be recognized as being a part of an integrated system, and the characteristics and dynamics of a segment of interest will be significantly affected by circumstances prevailing in the drainage basin upstream of the reach, and may also be affected by processes and events occurring downstream (Schumm, 1977). Therefore, any section of stream should be evaluated within the context of its position in a drainage basin or watershed, regardless of whether the upper basin is within or extends outside of park boundaries. The upstream drainage basin delivers sediment and water to the channel, and significant changes in the hydrology or sediment delivery from the watershed have the potential to change the equilibrium conditions in the channel (Fig. 1). Likewise, instability originating in the downstream segments of a system has the potential to migrate upsystem and destabilize a section of channel far removed from the site of initial disturbance (Schumm, 1977). This instability is commonly reflected by a **knickpoint**, which is a sharp break in slope of the longitudinal profile of a stream. In every case, it is important to view any segment of river within the framework of a fluvial system (Schumm, 1977; Petts and Amoros, 1996).

Drainage Basin Inputs

The **drainage basin** or **watershed** is a zone of production, where precipitation accumulates to be delivered to streams and rivers, and sediment is produced by landscape erosion (Schumm, 1977). When precipitation falls on a landscape, some portion of the water seeps into the ground and makes its way to the drainage network as shallow subsurface throughflow or as slow flowing groundwater. Water that does not infiltrate into the subsurface flows across the surface and moves rapidly to the drainage network as direct runoff. Because flow rates vary with pathways, the hydrology of the stream network is directly related to the relative percentage of water following various flow paths from the landscape to the drainage channels. Flow path depends on a number of drainage basin and climatic characteristics such as the infiltration capacity of the soil and bedrock, topography, vegetation, seasonal effects (frozen ground, snow cover, and foliage), variation in precipitation intensity through time, and land use (Burt, 1992). Each drainage basin will have an annual hydrologic regime that results from the integration of all of these variables.

In a similar way, the particle size and volume of sediment produced in a drainage basin will reflect the interaction of landscape and climatic characteristics such as climate, vegetation, geology, tectonics and topography, geomorphic processes (weathering, glaciation, river flow, etc.), process intensity, and land use. The interaction of hydrologic regime and sediment production processes will produce a regime of sediment delivery to the drainage network that is characteristic of the landscape.

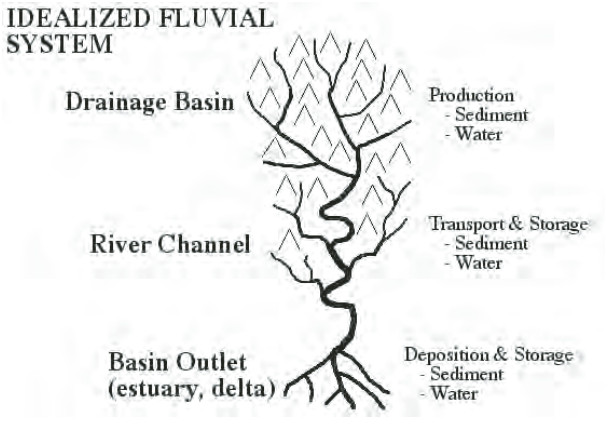


Figure 1. Idealized example of a fluvial system. Water and sediment are collected in the drainage basin (zone 1) and delivered to the drainage network (modified after Schumm, 1977).

River Function

Rivers are dynamic landscape elements whose primary functions are to drain the landscape and transport sediment. **Channel morphology** (the cross-sectional, plan view and longitudinal configuration of a channel) develops a form that is adjusted to the regional topographic gradient, long-term average hydrologic regime, and sediment load of the drainage basin. In turn, invertebrates, fish, **riparian vegetation** (vegetation growing along the banks or on the floodplain), and wildlife adjust to the channel form and hydrologic and sediment transport regimes (Petts and Amoros, 1996). The entire system, physical and biological, develops an equilibrium condition in response to external controlling factors such as tectonics, geology, soils, climate, and land use (Schumm, 1977).

Typical, everyday (non-storm) flow does little to modify channel form, but, the question then arises, what is the channel-forming discharge? Clearly it must be a discharge that generates sufficient shear stress to move the material that comprises the bed and banks of the channel (Andrews and Nankervis, 1995). Although there are important exceptions, much data suggests that **bankfull discharge** (the discharge that fills a channel to capacity; the maximum discharge that a channel can convey without flooding) is the channel-forming discharge, and many channel morphological characteristics scale to bankfull discharge (Schumm, 1977; Leopold, 1994; Rosgen, 1996; Knighton, 1998). For most rivers, this discharge will occur once every two years or so, although tremendous variations exist from region to region and from river to river. For detailed discussions of the frequency of

bankfull discharge and channel-forming discharge, see Williams (1978) and Castro and Jackson (2001).

Extreme rain or snowmelt runoff events are part of the normal dynamic, and although a major flood event may result in changes in the channel that may appear to represent episodes of instability and channel change, often these are temporary disturbances that rivers will recover from in subsequent months or years (Wolman and Gerson, 1978).

Sediment transport also varies annually with discharge and supply from the watershed, and channel morphology and biological communities adjust to the long-term sediment transport of the channel. Sediment load is normally subdivided into three types. Material transported in solution or as dissolved chemical species in water is called **dissolved load** or **solution load**. Sediment transported in the water column suspended by turbulence is referred to as **suspended load**, whereas sediment transported by rolling, sliding, or bouncing along the bed is called **bedload**. In general, suspended load consists of fine-grained material such as clay and silt, and bed load normally consists of coarser material such as sand and gravel. However, the relationship between grain size and transport mode also depends on the flow energy of a given stream. Sand and even gravel-sized material can be transported as suspended load during high-energy transport events. Although there are important exceptions to the rule, suspended load is typically controlled by the production and delivery rates from the watershed, whereas bed load transport is more closely related to flow energy. For more detailed discussions of sediment transport and various methods of classifying sediment in transport see Richards (1982), Knighton (1998), or Bridge (2003).

River Channel Pattern and Morphology

Basic Controls

Channel morphology is influenced by the complex interplay among regional geology, climate, topographic gradient, river history, drainage basin hydrology, and sediment load. Although the interactions among these variables can be complex, most data suggest that drainage basin hydrology and channel discharge primarily determine the size of the channel, whereas the caliber and quantity of the sediment load determine channel pattern and cross-sectional morphology (Church, 1992). When describing or evaluating river channel patterns or channel morphology, it may be important to separate small headwater streams from large streams and rivers and to separate bedrock channels from alluvial channels. Bedrock channels change only over very long time frames, and for most short-term monitoring programs, it is reasonable to assume that changes in channel form in bedrock channels will be negligible. Therefore, the discussion that follows focuses on alluvial channels. Small headwater channels often exhibit unique characteristics; thus, some classification schemes developed for large rivers do not transfer directly to small channels. The classification schemes presented here loosely follow the approach presented by Church (1992).

Small and Intermediate Size Channels, and Incised Channels and Arroyos

Small and intermediate size channels. Small and intermediate size channels have dimensions that are scaled close to the size of bed material. Consequently, individual particles and accumulations of particles into bars or localized sediment deposits can have a significant influence on flow dynamics and channel morphology. Small channels, as defined by Church (1992), have flow depths that are closely scaled to large particles in the channel, such that particle diameter to flow-depth ratios are on the order of 0.1–1.0. In most cases, small channels are floored with cobbles (>64 mm) and boulders (>256 mm), and have steep gradients ranging from 2° to 20° (Church, 1992). Small streams, floored by coarse material and flowing down steep slopes, typically have a step-pool morphology (Grant et al., 1990), where the steps are formed of clusters of cobbles or boulders, large woody debris (Keller and Swanson, 1979), or even bedrock (Wohl and Grodek, 1994); the pools are flatter segments underlain by finer-grained material (Figs. 2 and 3F). Step-pool spacings are scaled to channel width; spacing between successive steps or successive pools typically ranges from 2 to 4 times channel width (Chin, 1989; Grant et al., 1990) and spacing is also inversely proportional to channel gradient (Whitaker, 1987; Grant et al., 1990; Abrahams et al., 1995). Measurements and observations in the field and in flumes, along with theoretical arguments, make it clear that step-pool sequences represent equilibrium in high-gradient, coarse-bed streams (Davies and Sutherland, 1980; Grant et al., 1990; Abrahams et al., 1995). Grant et al. (1990) suggest that particles that comprise the steps are typically mobilized only by low frequency, high magnitude discharge events with recurrence intervals of 50 years or more.

Church (1992) defines intermediate-size channels as those having water surface widths that are much greater than bed material particle diameters, but these channels are small enough that a large portion of their cross-sections may be blocked by **bars** (sediment accumulated to form discrete channel scale entities) or accumulations of large woody debris. Church (1992) suggests that in forested regions, intermediate scale channels would have widths less than ~20–30 m. In sand and gravel bed channels of this scale, the channel morphology is dominated by pool-riffle sequences, where pool-pool or riffle-riffle spacings are typically 5–7 times the channel width (Keller and Melhorn, 1978). Pools are often located adjacent to alternate bars in straight channel segments or adjacent to point bars in sinuous channels (Fig. 2). In forested regions, pools are often associated with accumulations of large woody debris (Keller and Swanson, 1979). Sand and gravel bed channels of this type are often dynamic, and lateral migration of the channel and redevelopment of pool-riffle locations may represent normal equilibrium behavior.

Incised channels and arroyos. **Incised channels** (channels that have downcut significantly below the valley floor giving them steep banks and low width:depth ratios) range from small gullies meters wide and meters deep, to entrenched channels and arroyos of tens of meters. These channels are typically formed in

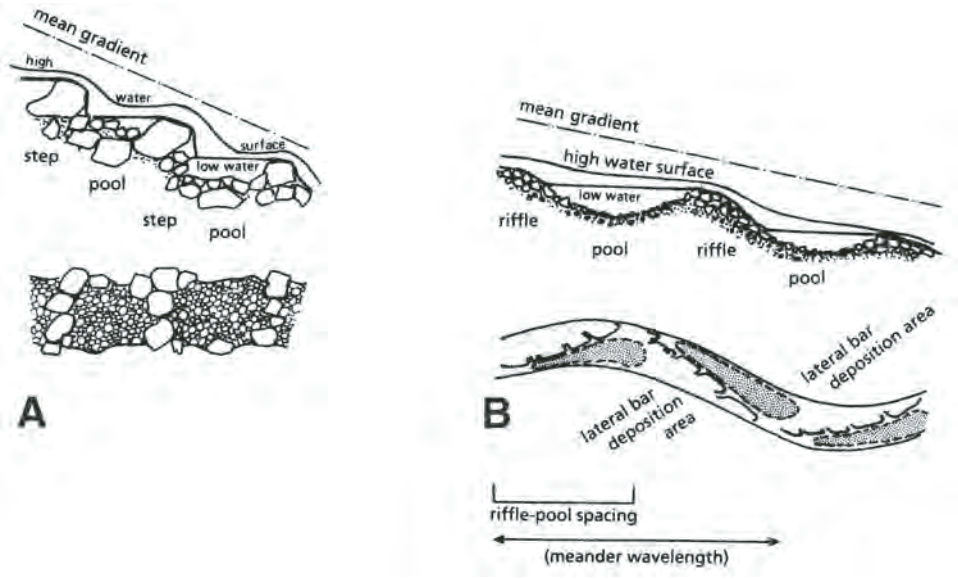


Figure 2. Step-pool and pool-riffle morphologies (from Church, 1992, Channel morphology and typology, *in* Calow, P., and Petts, G.E., eds., The rivers handbook: hydrological and ecological principles: Malden, Blackwell Scientific Publications. Reproduced with permission of Blackwell Publishing Ltd.).

fine-grained material dominated by clay and silt-sized particles, although sand and gravel may be present in significant quantities. Arroyos and incised channels do not fit the dimensionless scaling criterion established by Church (1992), although in absolute dimensions they would be similar to the small and intermediate size channels described above. These channels are most common in areas with relatively low topographic gradients, and range from ephemeral to intermittent-flow channels in arid regions, to intermittent to perennial-flow channels in more humid regions (Schumm et al., 1984; Darby and Simon, 1999).

In humid climates with perennial and intermittent streams, incised channels are typically produced by episodes of rapid incision and channel instability (Schumm et al., 1984). However, incised channels can establish stable morphologies, even in cases where the incised morphology resulted from an episode of channel instability. In fact, Schumm et al. (1984) have described a sequence of processes and related morphologies that unstable incising channels pass through to reach a new equilibrium. Initially, channels will have width-depth ratios ranging from 4 to 7, with a U-shaped cross-section and very little sediment storage in the channel. Where the channel is actively incising, the channel will have very steep, near vertical sidewalls and a width-depth ratio ranging from 3 to 4 as a result of rapid vertical incision. Once the channel ceases to actively incise, it will go through an episode of widening and sediment filling as a result of bank failure and sediment production from actively incising reaches upstream. The channel will continue to widen at a decreasing rate and may form a sinuous pattern with alternate bars within the trench and width:depth ratios of ~6. Finally, the alternate bars and trench sidewalls will be stabilized by vegetation growth as the channel instability gives way to a new semi-equilibrium form. For land managers dealing with incised channels of this type, it is important to determine where a channel of interest is in the evolutionary sequence described by Schumm et al. (1984) in order to make predictions of the trajectory that an unstable channel may follow.

In semi-arid and arid regions, intermittent and ephemeral-flow arroyos are common components of fluvial systems. **Arroyos** are steep-walled, flat-floored channels that may be tens of meters deep and meters to hundreds of meters wide (Fig. 3A). A great deal of uncertainty and even controversy exists regarding whether arroyos are equilibrium channels that naturally cycle between episodes of filling and cutting, or are inherently representative of disequilibrium conditions (Graf, 1983; Hall, 1990; Bull, 1997; Darby and Simon, 1999; Waters and Haynes, 2001). Regardless of whether arroyo incision is the result of natural cycles, climate change, or human influences, these systems require special consideration for monitoring and land management that transcends the short coverage in this volume. We recommend that standard channel monitoring protocols be followed as described below and that land managers immerse themselves in the arroyo literature to develop a deeper understanding of the range of possibilities regarding the morphologies and dynamics of arroyos.

Large Streams and Rivers

Large streams and rivers exhibit a wide range of morphologies, and a variety of classification schemes have been developed to describe channel patterns. Although classification boundaries are somewhat arbitrary because channel patterns grade along a spectrum, natural channels can be effectively categorized for descriptive purposes. We have adopted a scheme presented by Schumm (1981) and modified by Church (1992). This classification has the advantage of describing patterns in terms of controlling variables such as sediment load and stream power (the product of discharge and channel gradient), while incorporating other aspects of channel form and channel dynamics (Figs. 4

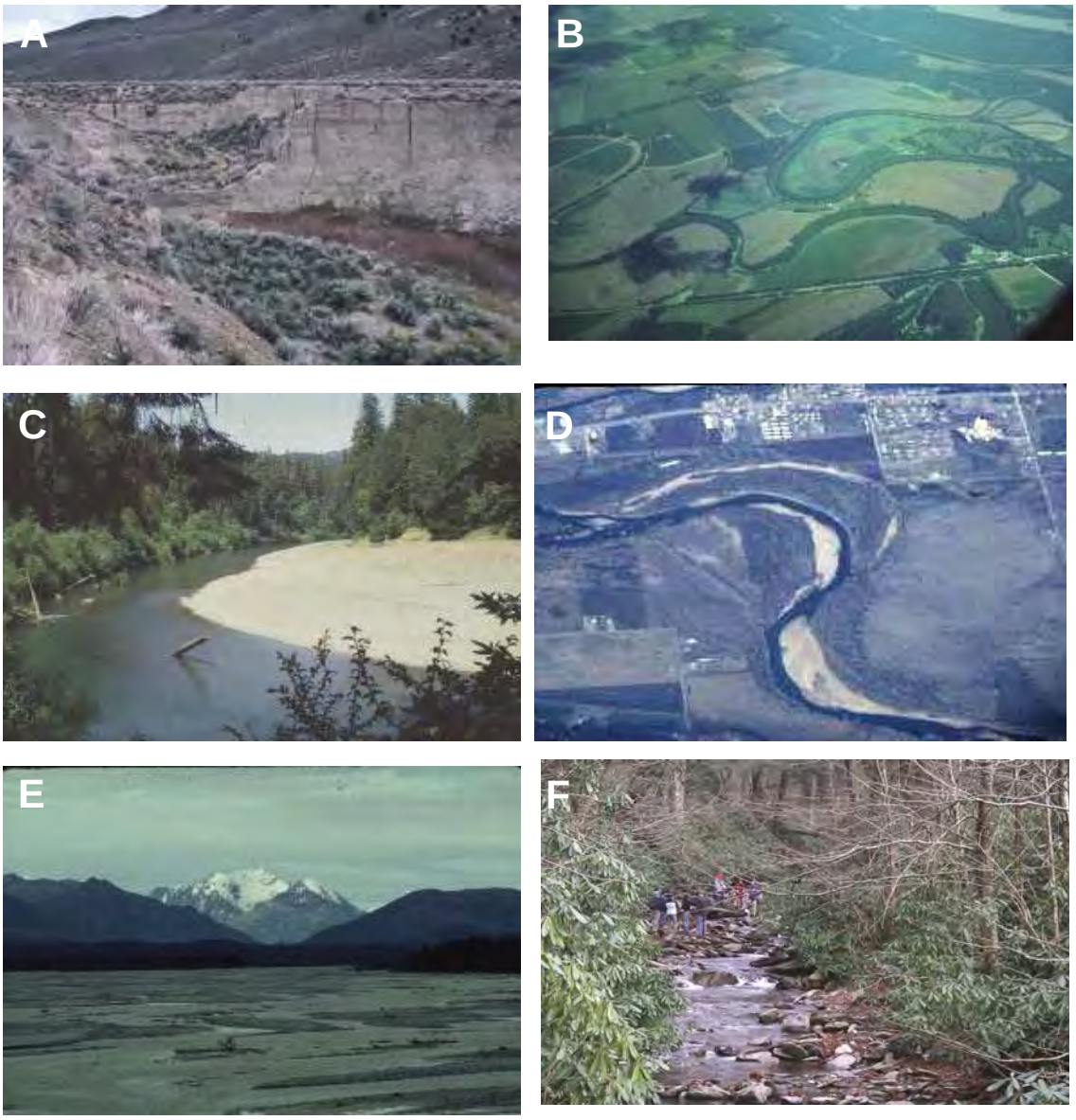


Figure 3. (A) Arroyo. (B) Highly sinuous suspended load-dominated, low-gradient channel. (C) Sinuous, mixed load channel with point bars. (D) Bed load–dominated channel with point bars and mid-channel braid bars. (E) Fully-braided, bed load-dominated channel. (F) Step-pool stream.

and 5). Rosgen (1996) has also developed a channel classification system (Fig. 6). Although we advocate use of the Schumm-Church approach, we present the Rosgen model because it has been used by some government agencies.

In the Schumm model, channels are separated into three sediment load categories: (1) suspended load-dominated, (2) mixed load, and (3) bedload-dominated (Fig. 4). Suspended load-dominated channels range along a spectrum from straight single-channels having low width depth ratios and low stream power (pattern 1, Fig. 4) to highly sinuous single-channels having low width-depth ratios and low stream power (pattern 3a, Figs. 3B and 4; stream type E in the Rosgen scheme, Fig. 6). Highly sinuous, suspended load–dominated channels are stable in form, but the channels migrate laterally and **meander cutoffs** (the process through which a stream cuts through the neck of a meander bend leaving the former channel as an abandoned channel segment) should be expected. Mixed load channels range from straight channels with alternate coarse-grained bars (pattern 2, Fig. 4) to sinuous channels with coarse-grained point bars (pattern 3b, Figures 3C and 4; stream type C in the Rosgen scheme, Fig. 6). Mixed load channels have higher stream power and higher width-depth ratios, and they transport larger quantities of

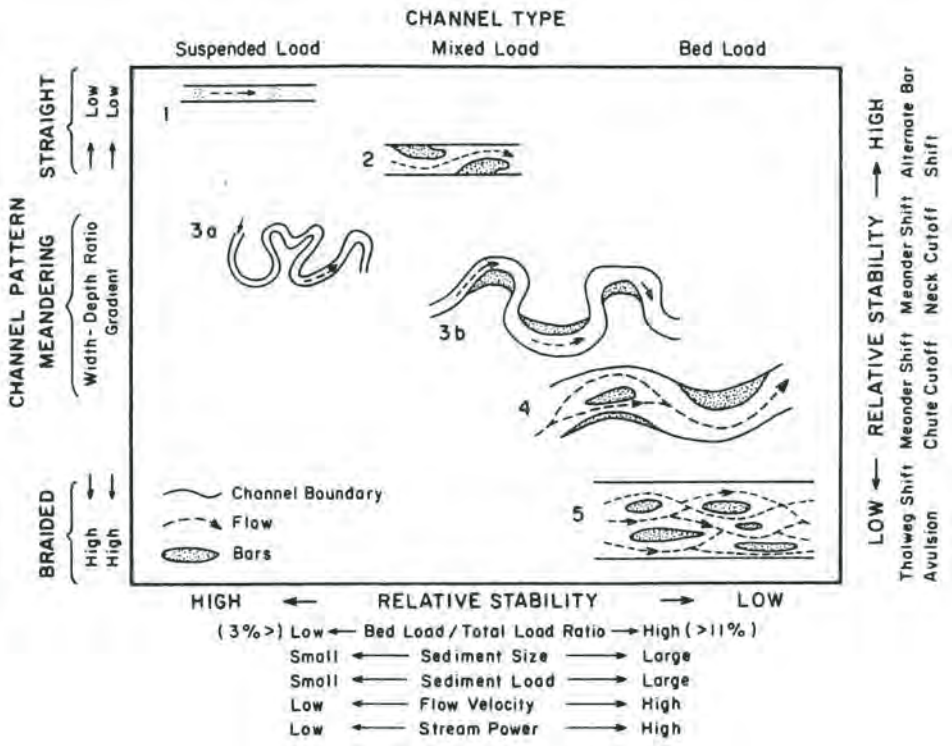


Figure 4. Process-based channel classification scheme (from Schumm, 1981). Used with permission from SEPM (Society for Sedimentary Geology).

coarse-grained sediment than suspended load–dominated channels. Sinuous mixed load channels have higher lateral migration rates than highly sinuous suspended load channels; erosion on the outside of meander bends and deposition on concave bank point bars are normal. These channels are typically characterized by well-defined pool-riffle sequences with spacing 5–7 times the channel width (Keller and Melhorn, 1978). Mixed load channels are also characterized by steeper gradients, high stream power, and higher sediment transport rates than suspended load channels. Bedload-dominated channels range from low **sinuosity** (the ratio of channel length to valley length) channels with point bars and a small number of mid-channel bars (pattern 4, Figures 3D and 4; stream type C or D in the Rosgen scheme, Fig. 6) to fully braided multi-channel rivers with many mid-channel bars (pattern 5, Figures 3E and 4; stream type D in the Rosgen scheme, Fig. 6). Bedload-dominated channels have high stream power, gradients, width-depth ratios, and sediment transport rates (Fig. 4). These channels are highly dynamic with mid-channel bars consumed and re-formed continuously and locally significant bank erosion. (Note the large number of trees deposited across the braid plain in Figure 3E; these trees became "organic load" as a result of bank erosion along the channel.)

Anastomosing channels are a fourth pattern type associated with suspended load dominance and low gradients. Anastomosing channels consist of a branching network of channels that divide and recombine around large segments of the floodplain. The inter-channel floodplain areas are relatively permanent features as compared with the ephemeral nature of braid bars in braided channels (Fig. 5; stream type DA in the Rosgen scheme, Fig. 6). Individual channels in an anastomosing pattern have low width:depth ratios, and channels tend to be much more stable than multi-channel braided channels. Inter-channel areas are typically larger than **bar-scale** (channel bars are smaller than the channels that contain them whereas inter-channel areas in an anastomosing channel are wider than the channels), heavily vegetated, and where present, large woody vegetation offers evidence of channel stability. Figure 5 shows the range of complexity that exists for each of these main channel types, along with indications of the normal dynamics associated with each channel pattern.

It is important to emphasize that each of the channel patterns described above may represent equilibrium morphologies that are adjusted to the prevailing sediment load and hydrology of any drainage basin. Pattern alone does not imply stability or instability. Likewise, any one of these patterns may represent a temporary morphology associated with an episode of channel instability. For example, some literature has suggested that braided channels are overloaded with sediment with the implication that the braided pattern is a non-equilibrium morphology. However, braided patterns could represent equilibrium, aggrading, or degrading conditions (Germanoski and Schumm, 1993). Instability can only be recognized when measurements reveal systematic changes in channel morphology or channel bed elevation.

Indicators of Instability

The identification of unstable channels is an important, though not always easy, part of managing land. Lateral migration and **channel avulsion** (when a channel takes a new path)

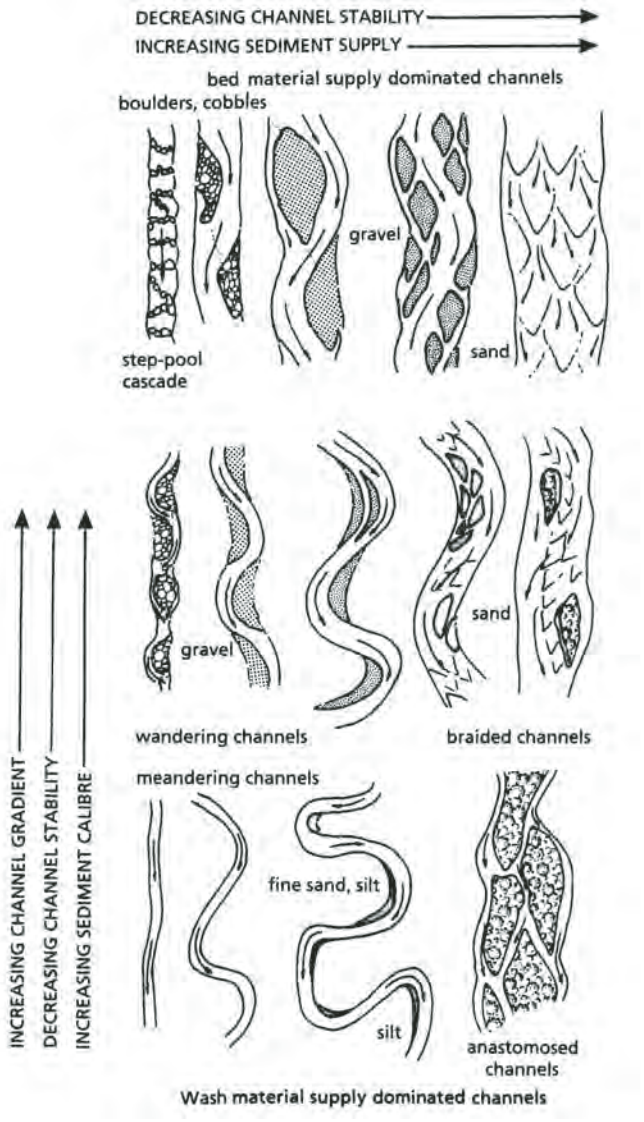


Figure 5. Channel classification showing the range of variability of channel morphologies (by Church [1992] based on concepts of Mollard [1973] and Schumm [1985] Reproduced with permission of Blackwell Publishing Ltd.).

are not necessarily indicators of channel instability. Most natural channels are inherently dynamic; channels migrate laterally, and channel avulsion is a normal process. The degree to which individual channels change position is often characteristic of the particular morphology (Figs. 4 and 5). Instability is manifested by significant changes in channel bed elevation, changes in channel **cross-sectional** morphology (width:depth ratio or cross-sectional area), and/or channel pattern change. In some instances, unstable channels may maintain the same **plan view pattern** (the pattern or geometry of a channel when viewed from above) and the same width:depth ratio, but the channel may experience changes in cross-sectional area. In other instances, unstable channels may downcut or aggrade systematically while maintaining the same cross-sectional form and plan view morphology. Finally, unstable channels may change channel plan view form, channel bed elevation, or channel cross-sectional size in any possible combination. Typically, a channel is considered unstable if any of these changes are systematic.

A balance exists between sediment load and **stream power**, which is proportional to the product of discharge and channel slope. If sediment size or quantity delivered to a channel is reduced, it will tip the balance into a state of channel incision or degradation. Conversely, if sediment size and quantity delivered to a channel is increased, it may result in channel bed aggradation. In either case, degradation or aggradation may also be accompanied by changes in channel morphology. In a similar way, if stream power increases or decreases, a channel may degrade or aggrade and also may experience changes in channel morphology. Predictions of the possible morphological adjustments can be deduced from Figures 4 and 5.

VITAL SIGNS OF FLUVIAL SYSTEMS

Introduction

In this chapter, vital signs are a subset of characteristics of a larger fluvial system that can be monitored to provide information about the overall condition and trends of the system. The vital signs for fluvial systems are introduced here to provide a framework for understanding how fluvial systems respond to natural and anthropogenic stresses (see the next section). These vital signs are fundamental characteristics of fluvial systems; they should be of interest to those making management decisions related to fluvial geomorphology. They are also relevant to other natural resources being monitored in many managed lands (such as biology, water quality, and hydrology). Most importantly, data generated by monitoring these vital signs will permit evaluation of trends to assess and understand the impact of stresses on fluvial systems.

Six vital signs are described to monitor fluvial systems, three of which are directly related to the form of channel: longitudinal profile, planform, and cross-section. These vital signs are consistent with, though not identical in form, to those suggested by the Geoindicators Initiative (Berger, 1996; Osterkamp and Schumm, 1996). The fluvial vital signs are not independent of each other. As stated well by Osterkamp and Schumm (p. 97, 1996), "The processes in one part of the drainage basin cannot be separated from those in another part; thus, measurable change at one site often results in measurable change in others. In this sense, rivers and the valleys they drain are closely linked, and they must be treated as parts of a single, dynamic system."

Vital Signs

1. Watershed Landscape

Definition. Natural and artificial characteristics of the land cover and surface materials throughout the entire watershed.

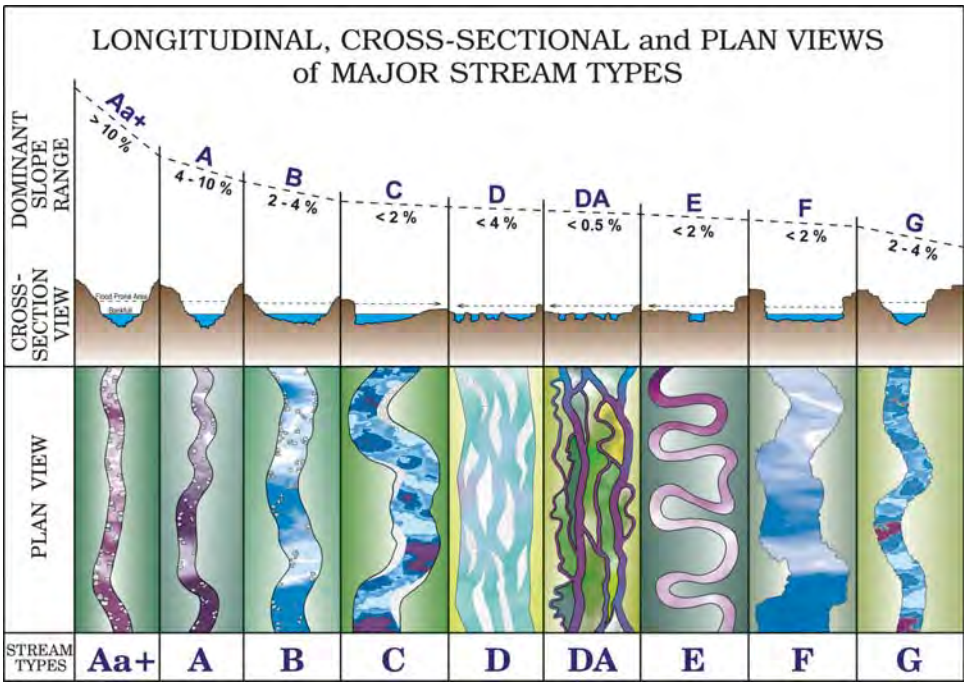


Figure 6. Rosgen (1996) channel classification scheme. Used with permission from *Wildland Hydrology*.

Changes in vegetation, land use, surface geologic materials (soils, sediments, and rocks), slopes, and hydrology may be monitored to assess this vital sign.

Significance. Changes in land cover and materials may be caused by fires, volcanism, climatic change, logging, land use, roads, and other factors. Any change will directly affect the watershed hydrology and may affect any other part of the fluvial system, such as stream form, sediment transport, water quality, flood frequency, and the quality of stream habitat.

2. Hydrology

Definition. Frequency, magnitude, and duration of stream flow rates and their relationship to rainfall, snowmelt, groundwater, and vegetational patterns. Changes in stream hydrology may be monitored directly or through vegetational patterns. Paleohydrology studies may be used to better understand past hydrologic patterns and causal relationships.

Significance. Water drives fluvial systems and connects all parts of a watershed. It is also directly linked to climatic and biologic systems. Hydrologic patterns can react immediately to changes in the watershed; this is unlike other fluvial vital signs, which may take years to decades to respond to changes in forcing mechanisms.

3. Sediment transport

Definition. The rates, modes, sources, and types of materials transported by a stream. Changes in sediment transport may be linked to hydrologic or channel vital signs monitoring programs.

Significance. Sediment transport is very responsive to changes in the watershed, due to changes in both hydrology and physical characteristics. Sediment transport rates are directly related to turbidity and, consequently, are important to water quality.

4. Channel: Cross-section

Definition. The shape, position, and materials of a stream channel cross-section at a specific point. Stream cross-section geometry and characteristics may be monitored at key reaches of scientific or management concern.

Significance. Changes in a channel cross-section can provide readily quantifiable data to determine migration rates, high water marks, and areas of deposition and erosion. As with other channel vital signs, changes in cross-section may be caused by reach or watershed scale changes in hydrology or sediment budgets or natural stream dynamics.

5. Channel: Planform

Definition. The channel type, sinuosity, position, width, and morphology. Changes in channel planform characteristics, including depositional bar forms and materials, may be directly monitored or evaluated by examination of historic aerial photographs and maps.

Significance. Changes in the hydrologic or sediment **budgets** (the long-term average volume of water or sediment delivered to a segment of a channel), at the watershed or **reach scale** (a reach of a channel is a segment of a channel), will likely cause changes in channel form and structure. Any change in channel structure will likely cause changes in the quality of stream habitats.

6. Channel: Longitudinal Profile

Definition. The slope of the stream along its axis, including stream characteristics such as knickpoints, riffles, pools, and

bed materials. Stream longitudinal characteristics and slope can be monitored from scales of a small reach to the entire stream length.

Significance. Changes in the watershed hydrologic or sediment budgets will likely cause changes in stream slope, through aggradation or degradation, and structure. The stream structure (e.g., riffle-pool spacing, bed materials) is directly linked to the quality of stream habitats. In some alluvial streams, knickpoints can migrate rapidly upstream and cause a decrease in the water table and shifts in types of riparian vegetation.

CHANGE IN FLUVIAL SYTEMS

Introduction

The purpose of this section is to discuss the primary stressors that are likely to affect fluvial systems and describe how the vital signs may respond to those stressors. Stressors, as used herein, are forcing mechanisms that can induce change in a fluvial system. These agents of change can be natural or artificial, be driven by forces within a watershed, such as logging, or driven by forces external to the watershed, such as climatic change, and may have a detrimental or beneficial impact on a fluvial system. Simply, stressors cause change in the fluvial systems that may result in instability.

Not all change, however, is due to stressors. Some change is constant in a fluvial system. For example, most naturally meandering streams have channels that migrate laterally. This change is not due to any stressor acting on the system, but merely reflects how the stream operates in a condition of dynamic equilibrium. Understanding the rate of this lateral migration may be of value to management of land even though it is not a response to a stressor. Alternatively, rates of lateral migration may increase significantly in response to a stressor, such as increased storm flow discharges due to altered hydrology or weakening of channel banks due to removal of riparian vegetation.

System Characteristics

Prior to a discussion of stressors and responses in fluvial systems, it is beneficial to review several system characteristics that are fundamental to performing studies of fluvial systems. Foremost, as discussed previously, stream systems are inherently interconnected, not just to fluvial components, but directly to vegetation, soils, water quality, hydrology, and humans. Streams have existed with wide ranges of variability for millions of years prior to any human influence; however, it is now difficult to imagine even one part of the fluvial system that has not been influenced by human actions. A common objective of fluvial studies is to determine the human influence on a stream, but in many cases the response of a stream cannot be singularly ascribed to human causes because of the inherent natural variability of these dynamic systems.

In geologically and climatically stable areas, most stream systems make predictable adjustments to accommodate common, natural variations in water and sediment inputs. Streams are nature's pipes adjusted to the most efficient condition to transport water and sediment within a watershed (Ritter et al., 2002). Anything that changes the magnitude or spatial or temporal patterns of water and sediment inputs will cause the stream to adjust to those new conditions. In some cases, adjustments in the fluvial system may cause a threshold to be crossed and the stream will change to a new condition, for example, from a meandering to braided pattern in response to an increase in sediment load. The magnitude and the spatial and temporal patterns of response will be dictated not only by the changes in inputs, but by the sum of Earth's history in that watershed, from conditions as recent as basin soil moisture conditions two days ago to the geologic framework (sediments, rocks, topography, drainage network) established over millions of years.

The intricacies of possible responses in a fluvial system to stressors are often complex and unpredictable; this characteristic is termed **complexity** or **complex response** (Schumm, 1991). Additional traits of the complexity of fluvial systems important to establishing and understanding cause-effect relationships are **singularity**, **divergence**, and **convergence** (Schumm, 1991). **Singularity** acknowledges that well-established generalizations may not be applicable for site-specific predictions because of unexplained (or unknown) variations at a site. For example, extensive fires in a watershed commonly lead to increases in storm-generated flow and sediment transport from the fire scarred landscape. A specific drainage basin, however, may show little impact from a fire if it does not receive a precipitation event large enough to move sediments prior to the reestablishment of vegetation (Germanoski et al., 2002). The terms convergence and divergence further describe the complexity in establishing cause-effect relationships. **Convergence** is the condition where different processes (causes or stressors) can result in the same response (effect). **Divergence** is the condition where the same stressor (cause) can yield different responses (effects). The example above can demonstrate convergence; an increased rate of lateral migration of a stream (the effect) may be due to decreased strength of channel banks caused by removal of vegetation or increased storm flow discharges. Likewise, two watersheds may respond differently (divergently) to a similar scale fire because one basin received a precipitation event large enough to mobilize sediments prior to the reestablishment of vegetation, while the other did not.

Stressors of Fluvial Systems

There are innumerable individual natural and anthropogenic stressors that can affect fluvial systems. Fortunately, individual stressors can be grouped into a handful of categories based on how and where they affect the processes or properties in fluvial systems (Table 1). At the most basic level, the stressor category **altered hydrology** includes any individual stressor that may affect pathway, rates, frequency, or location of water movement in a watershed. This change in hydrology may be due to specific stressors such as climatic change, forestry practices, or withdrawal

TABLE 1. SCALE, SOURCES, AND EXAMPLES OF STRESSORS THAT MAY AFFECT FLUVIAL PROCESSES AND GEOMORPHOLOGY

Scale	Stressor source area	Stressor category	Specific stressor examples
Basin	Outside watershed	Altered hydrology and altered sediment budget	• climatic change • air pollution
	Inside watershed	Altered hydrology	• urbanization • roads and parking lots • storm drains • vegetation changes • forestry practices • consumptive use of groundwater
		Altered sediment budget	• construction • forestry practices • mining • dirt and gravel roads • trails • agriculture (crops and grazing) • water impoundments • vegetation changes
		Altered topography	• landslides • volcanism • construction
Channel	Inside watershed	Altered hydrology	• water impoundments (dams) • water diversions • consumptive use of surface water
		Altered sediment budget	• dredging • road and trail crossings
		Altered channel	• channelization • dredging • bridges • bank stabilization structures • grazing • removal or change in bank or riparian vegetation • landslides

Note: Adapted from information and organization in Gregory and Walling (1987); Berger (1996); California Coastal Conservancy (2001); and Allan (2004).

of stream water for consumption. Similarly, any specific stressor that may affect the availability and transport of sediment falls in the stressor category of **altered sediment budget**.

While basin-scale stressors are limited to the two general categories above, an additional category of stressor is included for channel-scale stressors—**altered channel**. This category includes individual stressors that directly affect the stream channel, such as dredging, trail crossings, channelization, and trampling of banks by grazing animals. In addition to the scale at which the stressor acts and the stressor category, stressors are also grouped by source area (Table 1). The source of many stresses is within the watershed, but others, such as climatic change, are due to outside changes.

Response of Fluvial Systems to Stressors

The only thing completely predictable in a fluvial system is that change will occur. In response to a change in a stressor, the changes in a fluvial system may be direct or indirect, occur immediately or long after the initial change, may be large scale or small scale, may have an initial response that differs from the final response, and may be adverse or advantageous. In spite of this complexity, there are general styles of response to stressors that are very well documented. In this section, the response of fluvial systems to stressors is characterized. This discussion is not comprehensive, but strives to demonstrate how fluvial systems respond to common stressors. Emphasis is placed on how the vital signs of fluvial systems may respond to stressors or how they may be monitored to better understand the effect of a stressor on a given watershed. With this background, appropriate methods can be selected to monitor fluvial vital signs depending on the needs and conditions the land area being managed.

Altered Hydrology

The hydrology of a stream system can change immediately in response to changes in land cover throughout the watershed. Anything that affects the volume or timing of water entering a stream will affect the flow regime and, subsequently, the channel geomorphology. Alteration of the hydrology of a basin may

arise from situations such as changes in vegetation, which affects evapotranspiration rates; land development, which almost invariably causes a decrease in the infiltration capacity from the natural condition; or construction of storm water drains. Hundreds of studies have documented the hydrologic and geomorphic effects of development within a watershed. Four categories of general effects of development are now well known: alteration of hydrologic patterns, disturbance of stream geomorphology, degradation of water quality, and deterioration of stream habitat (U.S. Environmental Protection Agency, 2002; Cottingham et al., 2003). The specific response will vary depending on the degree of development (from a few roads and buildings to a fully urbanized watershed with storm drains) and the natural characteristics of the basin.

Basin development generally leads to an increase in the frequency and magnitude of storm discharges and a decrease in groundwater recharge and, consequently, baseflow discharge in streams (Figs. 7A,7B, and 7C). The increases in storm flow discharges can be dramatic, increasing several hundred percent over that of undisturbed watersheds (Gregory and Walling, 1987; Cooke and Doorkamp, 1990). The increase in storm flow discharges can lead to over a sixfold increase in channel–cross-sectional area over that of a natural stream (Knighton, 1998). The basin hydrology and streams will also respond in a similar way to clearcutting, due to the combined effects of decreases in evapotranspiration and decreases in soil infiltration capacities caused by logging operations (Fig. 7). Groundwater recharge rates have been shown to decrease by up to 100% due to urbanization (McClintlock et al., 1995). Storm hydrographs (see vital sign 2) in developed basins are flashier than in undisturbed watersheds, meaning they have a shorter lag time, higher peak discharge, and shorter duration (Fig. 7D). The increased temporal variability in stream flow, with higher highs and lower lows, can have an adverse impact on aquatic species. In Southern California, the change in flow regime caused by urbanization led to a competitive advantage of exotic aquatic vegetation over native vegetation (California Coastal Conservancy, 2001).

Changes in sediment transport and channel geomorphology will occur concurrently with changes in hydrology, or soon after. The spatial scale of the change will increase with time, starting at the area of highest impact. With respect to vital signs of fluvial systems, change will most likely progress from changes in sediment transport rates, to bed configuration, to channel cross-section, and to channel planform and longitudinal profile (Knighton, 1998). This lag in reaction time to a stress is related to the energy expenditure necessary to cause the change (Ritter et al., 2002). In summarizing documented effects of watershed development on stream systems, Gregory and Walling (p. 295, 1987) state that "an increase in peak discharges due to the effects of urbanization could, for example, lead to an increase of channel cross-section size, an alteration of channel shape, and increase in the size of meanders and metamorphosis of planform along selected reaches from single thread to multithread as sedimentary bars accumulated."

Altered Sediment Budget

Changes in the availability of sediment or the ability to transport sediment will immediately affect stream sediment transport rates and may affect all three channel vital signs: cross-section, planform, and longitudinal profile. The sediment budget may be altered simply by changes in hydrology—the driving force behind sediment erosion and transport. For example, development of a basin may affect the sediment budget in two general ways: (1) an increase in the amount of soil erosion and sediment input into channels due to an increased percent of overland flow in the basin, and (2) an increase in sediment derived from within the channel due to channel enlargement or extension caused by higher storm flow discharges. Alternatively, the sediment budget may be directly affected by natural or anthropogenic changes in land cover within the watershed that change the resistance or availability of soils and other **surficial material** (unconsolidated material or sediment on the land surface).

On a longer time scale, climatic change exerts control over the sediment budget, and can cause stream systems to go through periods of aggradation (net deposition) or degradation (incision). Like many processes in fluvial systems, however, the relationship is not straightforward. It may seem obvious that a watershed with a higher amount of precipitation will have a higher sediment yield, but this is not necessarily the case; vegetation is also affected by precipitation, and it exerts a strong control on sediment availability. Thus, drainage basins in sub-arid climates tend to have a higher sediment yield because they receive enough precipitation to erode and transport sediments, but the roots and canopy afforded by vegetation are still sparse enough to leave much of the land surface unprotected (Fig. 8). This relationship also indicates that the responses of different drainage basins to climatic change may be divergent, depending on the initial climatic conditions. For example, an increase in effective precipitation can cause an increase, decrease, or no change in sediment yield depending on whether the basin was desert, grassland, or rain forest prior to the climatic change (Fig. 8). Other studies relating climate and sediment yield since that of Langbein and Schumm (1958) show more complexity than in Figure 8, but a link between climate and sediment yield remains clear (Knighton, 1998).

Natural cycles of climatic change, shifts in vegetation patterns, and variations in sediment availability can make it difficult to discern other influences on streams. For example, some early studies suggested that incision of many streams (arroyos) in the southwestern United States in the late 1800s was triggered by overgrazing associated with settlement of the region. However, recent studies now suggest that the synchronous, widespread incision of streams was caused by alterations of the region's hydrologic and sediment budgets driven by climatic change (Ritter et al., 2002). This does not mean that human activity has not affected or will not affect these stream systems, but it does mean that: (1) many changes in fluvial systems are likely affected by both natural and artificial stressors, and (2) deciphering and quantifying the role of individual stressors can be difficult because

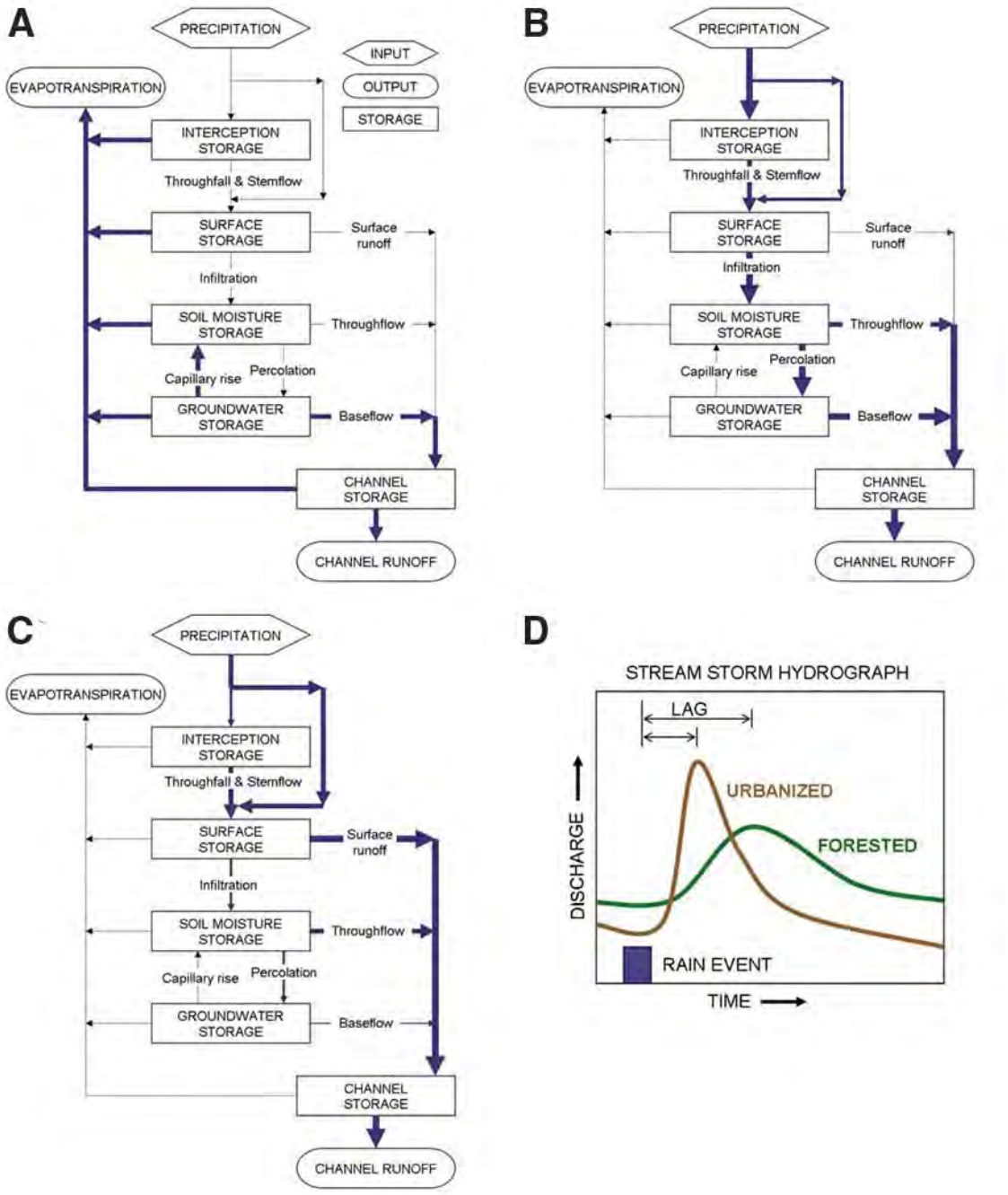


Figure 7. (A–C) Flowcharts of basin flow pathways and processes. Arrow line thickness is proportional to activity of pathway. During baseflow (A), groundwater is the primary source of channel flow. During a storm in a forested watershed (B), little surface runoff is generated because of high infiltration capacities in contrast to a developed basin (C), where surface runoff is readily generated. Consequently, a storm hydrograph (D) for an urbanized basin has a shorter lag time and higher peak discharge than a comparable forested watershed. Basin hydrology chart is adapted from Gregory and Walling (1987).

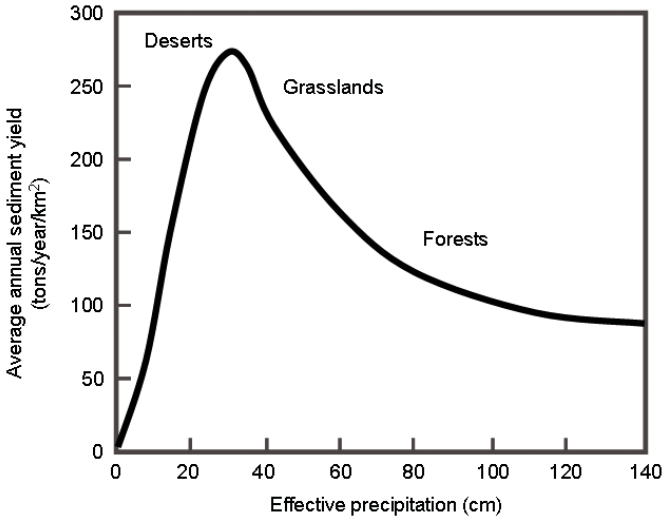


Figure 8. Variations in sediment yield versus effective precipitation. (Langbein and Schumm, 1958, Yield of sediment in relation to mean annual precipitation: American Geophysical Union Transactions, v. 39, no. 6, p. 1077. Copyright 1958 American Geophysical Union. Reproduced/modified by permission of American Geophysical Union.)

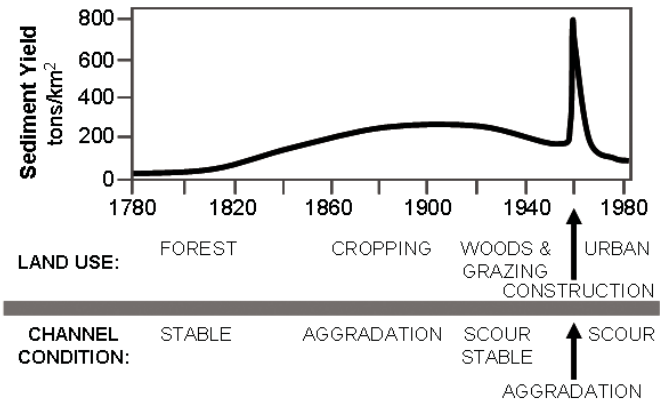


Figure 9. Sediment yield and channel conditions change in response to different land uses in northeastern United States (modified from Wolman, 1967, A cycle of sedimentation and erosion in urban river channels: Geografiska Annaler, v. 49A. Reproduced with permission of Blackwell Publishing Ltd.).

of **overprinting** (when there is a change in process or process intensity in a system that changes the channel or landscape the changes will occur progressively but there may still be vestiges in the channel or landscape of the previous process regime).

Changes in the sediment budget caused by natural stressors, such as climatic change, landslides, or fires, clearly affect the sediment dynamics, but, in many cases, anthropogenic stressors can have an even more pronounced effect. For example, an estimated one-third of the sediment load naturally delivered to coastlines of the United States is trapped upstream of dams (Berger and Iams, 1996). Urbanization and general land development have been repeatedly shown to cause significant increases in soil erosion and sediment transport, especially during periods of active construction. In a classic model of river adjustments to land development in the northeastern United States, Wolman (1967) related land use practices to sediment yield and channel condition (Fig. 9). He attributed a sharp increase in sediment yield and stream aggradation to a period of high construction rates. Numerous studies have corroborated the influence of construction on sediment yield. The sediment record in an impounded lake in the southern Appalachians showed a five- to ten-fold increase in sedimentation rates coincident with active home development in a small watershed (Miller et al., 2005). A change in land cover can also affect the sediment budget and channel form. For example, streams with a forested riparian zone in eastern Pennsylvania are wider and have slower lateral migration rates than nonforested riparian zones because of differences in the erodibility of channel banks (Allmendinger et al., 2005).

Changes in a watershed or stream sediment budget not only will affect sediment transport rates, but can affect water quality (e.g., turbidity), quality of streambed habitats, and channel cross-section (Cooke and Doorkamp, 1990; U.S. Environmental Protection Agency, 2002; Allan, 2004). As mentioned in the *Basics* section, channel pattern is controlled by the amounts and types of sediment load, and thus may change in response to shifts in the sediment budget of a stream. As with alterations of hydrology in a watershed, the system response time to a stressor that causes changes in sediment dynamics will vary, from immediate to 100 or more years, depending on the distance from the site of the stressor and the energy necessary for the reaction.

Altered Channel

Direct alteration of stream channels largely results from anthropogenic activities, but can be caused by natural processes, such as landslides. Alteration of stream channels by humans dates back thousands of years. In Denmark, up to 98% of streams may have been directly altered from their natural condition (Brookes, 1995). This degree of alteration is much lower in the United States, especially in the generally rural areas of federally managed lands. Reasons for direct alterations of channels include flood control, straightening (channelization) to facilitate transportation or land development, and bank stabilization. Today, there is an increasing amount of direct channel alteration to restore and rehabilitate streams. Stream restoration attempts to return a channel to its natural, predisturbance condition. More commonly, streams are rehabilitated with the objective of partially restoring their structure and ecosystem function. The variety of direct channel alterations means that a simple summary of possible stream responses is beyond the scope of this chapter.

Nevertheless, in relation to altered channels and prior to the description of fluvial methods, it is instructive to recall that the natural channel form is a result of the sum of the conditions and processes affecting the stream and the watershed—that is, the climate, vegetation, topography, geology, and hydrology. Artificially altered channels designed without consideration of natural controls are highly unlikely to remain stable. In some cases, artificially straightened channels have regained a meandering

pattern in ~100 years (Brookes, 1995) because of poor designs that do not account for the increased energy caused by the higher stream gradient and the tendency of many streams to meander. It is also worthy to note that many stream restoration projects have failed (Kondolf et al., 2003; Kochel et al., 2005). The high failure rates are likely perpetuated from simplistic approaches to classifying streams to predict stream behavior and select restoration approaches (Miller and Ritter, 1996; Kondolf et al., 2003; Kochel et al., 2005). In many cases, it requires significant expertise in fluvial geomorphology to assess the root causes of channel instability, determine the potential for restoration, and implement a successful restoration plan.

MONITORING FLUVIAL SYSTEMS

Overv iew

The six vital signs presented in this chapter are individual metrics for monitoring components of fluvial systems. All of the vital signs are interrelated, however, though certain ones may be more relevant in a given region than others. A monitoring program that is designed to assess changes in a single parameter may leave out investigation of a seemingly irrelevant component of the fluvial system. This section presents procedures according to three levels of intensity, which should enable land managers to customize a monitoring program by selecting their methods from a menu of options. A useful approach for designing a monitoring program is outlined by Reid and Dunne (1996). Their approach for rapid evaluation of sediment budgets is easily altered for use in a monitoring program for fluvial systems, and an example of such an adaptation is presented in Table 2.

Three levels of methods or investigations for monitoring each of the six vital signs are described below. The general traits of these three levels are described in the introductory chapter of this book. For monitoring fluvial systems, as with other geologic systems, selection of a high-level method (i.e., level 3) does not negate the concurrent use of the less intense, sophisticated methods (i.e., levels 1 and 2). In fact, in some cases, it would be impossible to carry out a level 3 investigation properly—either in design or interpretation—if a lower-level study had not been completed. After a brief description of how to design a study, this section provides a brief description of methods for each vital sign, then discusses how to approach a study to monitor the vital sign. Detailed descriptions of methods are abundant in books and journals (for example, Kondolf and Piégay, 2003), and, increasingly, through scientifically validated Web sites—for example, from the U.S. Geological Survey, the U.S. Environmental Protection Service, the National Park Service, and the U.S. Forest Service. We do not attempt to repeat this information here.

Design of a Study

In order to gather the information necessary to understand and properly manage a fluvial system, the study must be designed effectively. It may seem obvious, but an oft forgotten step in a study design is to identify the question that the monitoring is intended to answer. A poorly formed study question, without specific objectives, is likely to result in the collection of too little or too much data. In general, *study questions* in fluvial systems are rarely defined too narrowly. Alternatively, *study designs* are commonly too narrow because they fail to recognize the interconnectedness of fluvial systems.

A study design should answer the following questions.

1. What is the overall study question or purpose? (Is the question in response to a specific event, past action, proposed action, or problem where a ***targeted monitoring*** program is required? Or, is the purpose to establish a reference to identify or compare spatial or temporal ***trends***?)
2. What are the smaller-scale questions that must be addressed to answer the larger question?
3. What information is needed to answer the questions? (Also, are qualitative or quantitative data necessary? What degree of accuracy is needed?)
4. What resources are available to address the question? (How important is this question compared to others that need to be addressed? How many people will be available? What is their skill level? How much time can the people commit? What equipment is necessary? How much money is needed? When does the study question need to be answered?)
5. What method should be used to gather the data?
6. Where should data be collected?
7. When and how often should the data be collected?
8. How will the data be analyzed and interpreted?
9. Can this study be piggybacked with complementary studies for improved efficiency and understanding? (Water quality? Stream habitat? Hillslope processes? Soils?)
10. Will the results of the study be used as part of an adaptive management program? How?
11. Other? Additional questions pertinent to study design will arise due to the unique circumstances of the land or management—for example, safety, logistics, access.

Some of the practical matters that must be considered in any study design are summarized in Table 3 for all methods, including approximate cost, equipment needs, and skill level required.

METHODS FOR VITAL SIGN 1: WATERSHED LANDSCAPE

Synopsis

Changes in the watershed land cover will alter the hydrology and sediment budgets of fluvial systems and, therefore, the stream processes and form. The preliminary objective in monitoring this vital sign should be to identify regions of different land cover, especially those that are most likely to influence the path or rate of water flow through a watershed. If changes in land cover are

TABLE 2. A GENERAL PROCEDURE FOR MONITORING FLUVIAL SYSTEMS

1.	Define research goals	Simple example: "to monitor changes in the fluvial system"
2.	Acquire background information	Learn about: • Geology—type and condition of bedrock, type and thickness of soils • Climate—average annual rainfall and temperatures • Vegetation—coniferous/deciduous? Native/non-native species? • Land use—what types are present? How long have they been there?
3.	Delineate & subdivide watershed	Use maps and photos to determine: • Total watershed area • Sub-areas associated with: Hillslopes—predominantly gravity-driven sediment transport Floodplain—predominantly water-driven sediment transport Forests and meadows—regions with protection from erosion Urban/agricultural—potential influences on hydrology
4.	Interpret remote sensing data	Identify appropriate study reaches for monitoring: • Changes in land cover • Channel plan form type • Bends in rivers • Changes in topography or bed slope
5.	Conduct field work	Reconnaissance trips to: • Photograph points of interest • Create sketch maps • Collect simple measurements (grain sizes, channel width, etc.) Conduct land surveys to measure: • Longitudinal profile • Channel cross-section • 3-D maps Install gages and instruments to monitor: • Watershed hydrology • Sediment transport
6.	Analyze data	Compare new data with data from previous years to determine change
7.	Assess and modify the program	Adjust the protocol for time and budgetary efficiency

Note: After Reid and Dunne (1996).

observed or planned as part of management, predictions can be made about the potential impact on stream form and processes.

Methods

Level 1: Watershed Events Journal

Before any spatial analysis can occur, it will be necessary to define the boundaries of the watershed on a topographic map or scaled aerial image (Fig. 10). This process involves: (1) locating the mouth of the stream; (2) identifying all the topographic high points that separate that stream's tributaries from its neighbors; and (3) drawing a line that connects these points. A detailed procedure for delineating a watershed by hand is described in detail in Sanders (1998).

Land managers should keep a journal of all the activities that influence land cover, especially if spatial data are not available. The journal entry should include a description of the activity, whether the change is natural (fires, landslides, floods) or artificial (new construction, clear cutting), a description of its location, and the dates of the activity or event.

Level 2: Aerial Photographs

Level 2 investigations should include the calculation of drainage area and the surface area devoted to each different type of land use/cover. These calculations should be kept in a journal for the watershed of interest. This should be repeated any time there is a change in land cover or proposed change in land cover; otherwise this only needs to be done on a decadal scale.

The measurements can be estimated using paper maps and aerial photographs. A great deal of valuable fluvial geomorphic data can be stored for future analysis using carefully taken scaled photographs. Aerial photograph coverage is available for much of the country, and can be used reliably for larger rivers and watersheds to interpret channel planform, sinuosity, and major sediment sources such as landslides and forest fires. Aerial photographs must be taken at known elevations which can easily be

TABLE 3. SUMMARY OF FLUVIAL SYSTEMS VITAL SIGNS AND MONITORING METHODS

Vital signs and methods		Expertise	Special equipment	Cost*	Personnel	Labor intensity†
Level	**Watershed Landscape**					
1	Watershed Events Journal	Volunteer	No	$	Individual	Low
2	Aerial Photographs	Scientist	Yes	$	Individual	Medium
3	Geographic Information Systems	Scientist	Yes	$$	Individual	Medium
Level	**Hydrology**					
1	Hydrologic Events Log	Volunteer	No	$	Individual	Low
2	Hydrologic Monitoring	Volunteer	Yes	$$	Individual	Medium
3	Hydrologic Stations and Data Analysis	Scientist	Yes	$$$	Group	Medium
Level	**Sediment transport**					
1	Sediment Transport Event Logs	Volunteer	No	$	Individual	Medium
2	Stream Sediment Load Sampling	Volunteer	Yes	$$	Group	Medium
3	Automated Stream Load Sampling	Scientist	Yes	$$	Group	High
Level	**Channel: Cross Section**					
1	Repeat Photography and Observations Log	Volunteer	No	$	Individual	Low
2	Cross-section Measurements	Volunteer	No	$	Group	Medium
3	Repeat Surveys at Monumented Sites	Scientist	Yes	$$–$$$	Group	High
Level	**Channel: Plan Form**					
1	Channel Characterization	Volunteer	No	$	Individual	Low
2	Historical Analysis	Scientist	Yes	$$	Individual	Medium
3	Image Analysis and Mapping	Scientist	Yes	$$–$$$	Group	Low
Level	**Channel: Longitudinal Profile**					
1	Profile Characterization	Volunteer	No	$	Individual	Low
2	Profile Mapping	Scientist	Yes	$	Group	Medium
3	Profile Surveys	Scientist	Yes	$$$	Group	High

*Cost (US$): $ = <$1,000; $$ = $1,000 to $10,000; $$$ = >$10,000.
†Labor intensity: low = <few hours; medium = <full day; high = >full day.

converted into a photo scale. The simplest method for estimating areas from a map or aerial photograph with known scale is to: (1) highlight areas of interest, (2) superimpose a grid network, and (3) count the number of grids that fall within the highlighted boundary. Advanced methods to determine the area include using a planimeter or digitizing software.

Level 3: Geographic Information Systems

Geographic Information Systems are the tool used most frequently for spatial analysis, and should be incorporated in to an investigation of any level, if it is feasible to do so. A database should be constructed that contains information about all of the changes in land cover that can influence geomorphic processes that operate within the watershed. This would include information about bedrock geology, soils, slopes, hydrography, and vegetation type and density. This database can be used for identifying sensitive areas to study in greater depth, and to drive various types of visual and numerical models that relate precipitation to surficial processes such as runoff, groundwater flow, and soil erosion.

Study Design and Limitations (see Table 3)

Site Selection

Optimally, a watershed events journal (level 1), should be collected for all of the watersheds in the managed land. If this kind of coverage is not feasible, select watersheds for study in which either changes in land cover have occurred in the past, or are likely to occur in the future. For example, it would be important to collect this kind of data from watersheds that have been targeted for timber harvest or from those that have recently been affected by wildfires or landslides. In the case of watersheds that have already experienced a change in land cover, "before" and "after" data may be unavailable. In these cases, comparisons can still be made by substituting space for time. For example, to estimate the hydrologic impact of a new roadway on the sinuosity of streams downstream, reaches located upstream from the new parking lot can be used as a proxy for the (historical) "pre-disturbance" morphology and compared to reaches located downstream from the disturbance. Alternatively, comparisons could be made to neighboring watersheds with similar slope, substrate, aspect, and drainage area where similar disturbances have not occurred.

Scale Limitations

Land cover in large watersheds will obviously require more effort to measure than in smaller watersheds. The most useful approach to addressing the issue of watershed scale is to begin by quantifying land cover in low-order drainage basins and integrating these measurements to describe the larger watershed. Depending on the type and size of drainage network, data may be



Figure 10. Delineation of the Cullowhee Creek watershed. Stream channels are highlighted in gray, and watershed boundaries are highlighted in white. This image was downloaded using Google Earth.

required for areas ranging from 100s of square meters for gully and rill systems in arid regions to 1000s of square kilometers for large fluvial systems. Obviously larger land areas require larger map and image coverage.

Time Limitations

In most cases it will be adequate to document changes in land cover using a series of "snap shots" taken at decadal intervals. However, in watersheds where catastrophic landscape changes such as landslides or forest fires occur, it may be necessary to reassess the land cover immediately following the disturbance event and then annually as vegetation cover is reestablished and new sedimentary deposits or soils begin to form. A similar approach should be taken when studying the effects of timber harvesting or the construction of new buildings, parking lots, and roads.

Because most spatial analysis involves map, air photo, and/or satellite image interpretation, investigations that are based on these approaches do not typically have many time restraints. However, if a project requires the construction of maps or the acquisition of new photographs, some thought should be given to the timing of these projects. For example, a large-scale series of aerial photographs that are to be used to measure the surface area of roadways should not be scheduled for a time of year when foliage from trees growing along the roadside will obscure the road. Autumn may not be useful either since fallen leaves or snow may obscure the road. Late winter or early spring may be the most optimal time to collect these data to minimize the influence of these factors.

METHODS FOR VITAL SIGN 2: HYDROLOGY

Synopsis

The basic purpose for monitoring watershed hydrology is to document relationships between precipitation, groundwater, and stream flow. As discussed in the introductory section, any change within the watershed, natural or artificial, is likely to have an immediate effect on the hydrology. Hydrologic data can be used to identify flood-prone locations in the watershed, to estimate likelihood of channel forming events, and relate data to sediment transport.

Hydrologic data are commonly presented in a hydrograph, which relates stream discharge to time. Frequently, hydrographs for wells or streams are compared with precipitation intensity to produce **storm hydrographs**. These graphs are used to demonstrate a river response to rainfall events, and provide useful data for understanding the interaction between a stream network and the atmosphere, and the stream channel and its floodplain (Fig. 7D).

Discharge for a stream is traditionally calculated using a simple continuity equation based upon hydraulic geometry:

$$Q = AV$$

Q is the stream discharge (L^3T^{-1})

A is the cross-sectional area of the channel that is occupied by water (L^2)

V is the water velocity (LT^{-1})

This equation can be replaced with a flow regime equation that is based simply on the width of the channel:

$$Q = aW^b$$

Q is the stream discharge (L^3T^{-1})

W is the width of the channel (L)

a and b are unnamed constants

The use of this equation requires calibration for different watersheds since they rely on unspecified values of two constants. The constant **a** contains variables that may vary from one location to the next within a single watershed (Parker, 1979) and can be expected to vary on the watershed and regional scales as well. Because of its importance, discharge is related to many stream characteristics and can be used to understand stream stability (see summary in beginning of this chapter).

Methods

Level 1: Hydrologic Events Log

Thousands of stream and precipitation gauges are established across the United States and likely exist in or nearby most managed land areas—many of these gauges have decades of records. If present, level 1 investigations begin with compiling a record of rain and discharge data. The U.S. Geological Survey stream gauge data are accessible through its Web site; many sites include statistics on average and flood flow discharges. Using these data, a database for hydrology can be assembled to calculate statistics for both storm and flood frequency in the area of interest. They can also be examined for patterns that may be related to climatic change or land use change.

In addition to these data, it is important that simple observations be made with respect to the date, location, extent, and duration of all overbank (flood) events in the areas of interest.

Level 2: Hydrologic Monitoring

More complex studies will require further instrumentation than that collected with level 1. Staff gauges should be installed throughout in the direct area of interest. (A staff gauge is simply a relative water-level indicator established on a permanent feature such as a bridge, tree, or post.) This will permit the collection of quantitative data, which though not as valuable as stream discharge data, can be used to identify patterns of hydrologic response. In addition, precipitation gauges should be installed at multiple locations throughout the watershed; large, complex watersheds will require more gauges than small, simple watersheds. These gauges should be monitored routinely, but especially during and after precipitation events. The frequency of monitoring will depend on the study design and question.

When overbank flows occur, maps should be constructed of the maximum extent of the water surface using flood debris or other such indicators. After enough hydrologic data has been collected along the stream of interest, standard methods can be used for flood frequency analysis (Bedient and Huber, 1988).

Level 3: Hydrologic Stations and Data Analysis

In addition to level 1 and 2 data, a network of more sophisticated gauges should be installed for continuous monitoring of precipitation, river stage, and water table elevation. More detailed studies of floodplain hydrology could include a variety of data collected with specialized tools. For example, tipping-bucket rain gauges can be fitted with data loggers to monitor precipitation intensity during rainfall events. Repeated measurement of water levels in nested piezometers could be used to monitor changes in the elevation of the water table, to demonstrate how hydrology changes with depth, and to demonstrate rates of flow toward or away from the channel. Defining the nature of the interaction of groundwater and stream water is very important to stream ecosystems.

In order to calculate stream discharge from river stage data, it will be necessary to measure water velocity and survey cross-sections where water-level recorders are located. Standard U.S. Geological Survey stream gauging stations record stage in 15-minute intervals. The stream stage data can be related to stream discharge by the establishment of rating curve—an empirical curve that relates discharge to stage by repeated measurements of actual discharges at a variety of flow conditions. Establishment of a rating curve requires the measure of velocity and depth at numerous points in a stream (Fig. 11). Velocity measurements are commonly made with specially designed instruments such as the pygmy or AA meter. These devices are held below the water surface at 6/10 of the river depth, where flowing water causes a propeller to spin. Electromagnetic flow meters and acoustic Doppler velocimeters can also be used to determine velocity (Kondolf and Piégay, 2003).

Study Design and Limitations (see Table 3)

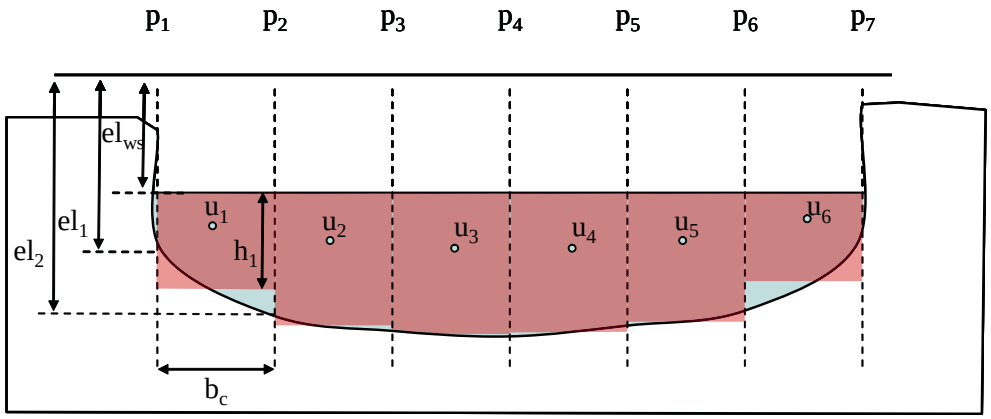
Site Selection

Since precipitation can vary significantly with microclimate, simple geography (rain-shadow effects, etc.) as well as specific geomorphic characteristics such as elevation, slope, and watershed aspects can have a dramatic influence on the volume of precipitation accumulating at any single location. Controlling these variables during the installation of rain gauges can greatly reduce the amount of error associated with the study results. Groundwater wells should be installed along a line perpendicular to topographic contours. Optimally, the wells should be deep enough to sample water below the water table during late summer and fall. A line of groundwater wells should begin on **colluvial slopes** (hillslopes mantled by material transported and deposited primarily by gravity) in the recharge zone of the watershed where soils are thin, and continue across the alluvial floodplain.

Stream hydrology should be monitored in stable reaches of streams that are free from obstructions such as boulders and large woody debris. It is also wise to minimize the effect of bedform roughness by limiting studies to cross-sections with uniform depth, such as in large riffles or chutes. In streams where the channel may be too shallow to measure velocity during low flows, select cross-sections to monitor where the flow is constricted. For example, if a large boulder that significantly decreases the effective width is present along one bank, depth will be slightly higher in that location. Regardless of where stage is measured, it will be necessary to survey the cross-section to make discharge calculations.

Scale Limitations

Investigations of precipitation and groundwater flow in large watersheds require a large number of instrument stations. Floods in higher-order streams are caused by seasonal snowmelt or long duration, low-intensity storms that influence large areas of Earth's surface. This means that a large network of rain gauges is required to acquire useful rainfall data for large watersheds. Since the elevation of the water table is determined by local



h = depth (L)

el = elevation (L)

b = width (L)

p = position on tape (L)

A = area (L^2)

Q = discharge (L^2)

u = velocity (LT^{-1})

$h_1 = (el_1 - el_{ws}) + (el_2 - el_1)/2$

$b_c = p_2 - p_1$

$A_1 = b_c \times h_1$

$Q_1 = A_1 \times u_1$

$Q_t = Q_1 + Q_2 + Q_3 + Q_4 + Q_5 + Q_6 + Q_7$



Figure 11. The equal-area method for estimating flow velocity.

rainfall, similar reasoning can be applied to studies of groundwater flow in large watersheds. During intense precipitation events, the rainfall from a single storm may only fall over a single small watershed, causing short, high-intensity floods. Monitoring rainfall and groundwater flow in a small watershed requires fewer instruments, but since small watersheds are more abundant than large ones, the scale of the study is determined by the number of small watersheds to be monitored.

There are very few low-order watersheds with stream gauges in them, despite the fact that most sediment produced in a watershed comes from these streams. Budget limitations frequently demand the use of a small number of gauges, making it less feasible to monitor stream hydrology in small watersheds. Water-level recorders work just as well in large streams as they do in small ones, but it is more challenging to survey cross-sections in large rivers.

Time Limitations

Short-term studies of hydrology rarely provide realistic records for a watershed since variance over the short term is subject to minor fluctuations in weather events. Longer records are required to determine statistically significant return intervals for precipitation and flood events. Where long-term records are not available, it is frequently possible to establish a relationship between data from a gauge with a short record to data from a nearby gauge with a longer record. Using that relationship and the longer record, historical data for the short-record gauge may be reconstructed. New hydrologic data should be collected on a daily basis throughout the year, but this data collection from gauges or loggers takes very little time.

Cost Limitations

Level 1 investigations require only data that are readily available online. Monitoring at this level can be done at no cost if a computer is available with Internet service. Level 2 investigations require the use of basic tools such as simple rain gauges and staff gauges. This equipment is inexpensive ($10 to $100; all amounts herein are in US$) and easy to acquire or construct using materials found in any hardware store. Level 3 investigations require more sophisticated instruments including tipping-bucket rain gauges ($100 to $1,000), stilling wells with water-level recorders ($1,000 to $10,000), groundwater monitoring wells ($100 to $1,000), and data loggers ($1,000 to $10,000).

METHODS FOR VITAL SIGN 3: SEDIMENT TRANSPORT

Synopsis

Sediment contamination is the largest source of pollution in our country's waterways. Sediment itself may be the problem when it is deposited in some location in too much abundance, or when it resides in the water column, blocking out light from aqueous ecosystems. As discussed previously, changes in land cover will likely change the sediment budget of a stream system, which, in turn, may cause a change in channel form or type.

Sediment transport data are normally presented on a rating curve, which shows how sediment concentration changes over time. Since there is so much temporal variance in the transport of sediment, there is little value in measuring sediment without knowledge of the date, time, and hydrological conditions when the sample was taken. Further, a single measurement or a few sporadic measurements are not particularly useful either, since sampling from a variety of discharges is required to construct credible rating curves. Measurement of sediment sampling, unless automated, is time intensive; because of this, mapping of bedload material can be used to make indirect inferences about sediment transport (see *Vital Sign* methods for *Channel Planform* and *Longitudinal Profile*).

Methods

Level 1: Sediment Transport Event Logs

A log of observations of characteristics of sediment transport can be made during rain or snowmelt events in a manner similar to that described for the hydrology vital sign. The observations needed depend on the type of sediment load (suspended or bed) important to the study problem. Qualitative observations of turbidity can be made by simple comparison of stream water turbidity to standards. Visual observations can be made of sand and gravel movement in smaller streams where the bed remains visible. To be of any value, these observations must be linked to stage or discharge data.

If the channel bed cannot be observed during high flow, then observations of sediment sizes and distribution on the channel bed at areas of interest can be made after the event.

Level 2: Stream Sediment Load Sampling

Any quantitative assessment of sediment transport will require direct sampling and analysis of stream water under a variety of conditions. Because high flows are of the most geomorphic significance, safety is a common concern during sampling.

Bedload samples are commonly collected with specially constructed nets or traps. The sampler is placed on the bed of the stream for a specified time interval, and then removed. The most commonly used instrument used for discrete samples is the Helley-Smith sampler, which is little more than a sturdy net with a metal screen (Fig. 12B). The sediment is emptied into a container and transported to the laboratory where it is sieved and weighed. Suspended sediment samples are collected in a similar way. A depth-integrated sampler consists of a torpedo-shaped metal housing, a wading rod, and a plastic sample bottle. The DH-48/59 depth-integrated sampler is the standard tool for this job (Fig. 12C). The operator starts at the water surface and slowly lowers the sampler to the bed and then back to the top at a constant rate, recording the length of time the bottle has been submerged. The sample bottles are then transported to the laboratory, where the solids are filtered out and weighed.

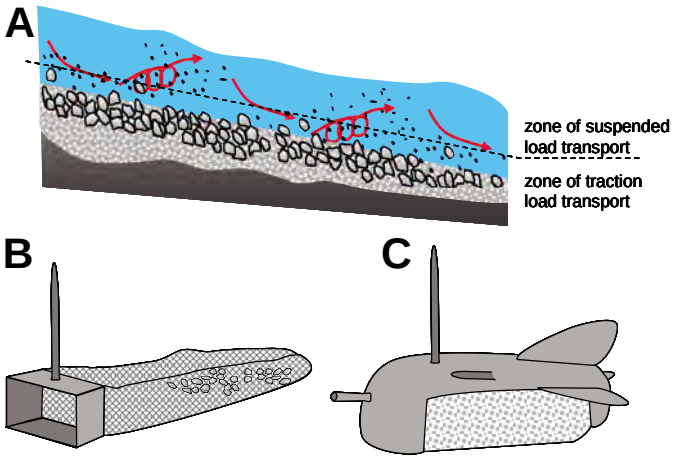


Figure 12. (A) Zones of tractive and suspended load transport on a channel bed. (B) Helley-Smith sampler for measuring bedload sediment. (C) D48 depth-integrated sampler for measuring suspended sediment.

Level 3: Automated Stream Load Sampling and Analysis

Various high-tech tools are available to monitor sediment flux and its influence on stream hydrology on a continuous basis. This information can be used to determine sedimentological responses to rapidly changing hydrologic conditions associated with intense storms, or releases of water from reservoirs upstream. When used with hydrologic data from gauging stations, these instruments provide scientists with extremely accurate sediment rating curves. Multiparameter recording instruments can be placed in strategic locations to collect measurements of turbidity, total suspended solids, and total dissolved solids on a continuous basis. Similar data can be collected for bedload transport through the use of bedload traps, which are placed on the streambed and emptied periodically while hydrologic conditions are being measured. The usefulness of data from bedload traps is somewhat limited since the time resolution of the record is limited by the frequency with which the traps are emptied. There are a few places in the world where conveyor-belt–driven bedload sampling traps are in use, but the expense of these tools makes them impractical for most monitoring projects.

Study Design and Limitations (see Table 3)

Site Selection

Sediment transport investigations should be conducted in sampling areas with relatively homogenous **bathymetry** (topography of the streambed), and without major obstructions such as boulders or large woody debris. Sampling reaches should have low sinuosity and the banks should be free of vegetation that might alter the flow velocity. If bedload sediment is the focus of the study, then the study reach of the stream should be divided into like sections with similar observations made in each section.

Scale Limitations

Sampling sediment in large rivers may require specialized equipment that must be permanently installed on channel banks. Representative locations across the width of the channel are selected, and sediment concentration or volume from discrete samples in several theoretical stream tubes is averaged to determine the total sediment discharge. This approach, while similar to that used for smaller streams, will require much more effort and time in large ones.

Time Limitations

In order to construct a useful sediment rating curve for a stream network, multiple samples must be taken from multiple locations on a daily basis. Since a great deal of laboratory work is required for grain-size analysis of a large number of samples, it may be impractical to do more than measure sediment concentration. Likewise, the usefulness of data from bedload traps will depend on the frequency with which the traps are emptied. Bedload samples are extremely difficult to transport to a laboratory, so daily analysis in the field may be required. Remotely sensed data using acoustic samplers, on the other hand, may only require a few infrequent visits to the field site to download data.

METHODS FOR VITAL SIGN 4: CHANNEL CROSS-SECTIONAL GEOMETRY

Synopsis

Repeated surveys of channel cross-sections can be used to quantify channel enlargement, channel migration, and the volume of sediment deposited or eroded from the bed and banks. Channel cross-sections can be compared with others from different locations at a single time to assess physical characteristics of different reaches, or from different times at a single location to monitor channel change. Changes in cross-sectional area measured at multiple locations can be integrated over the length of a study reach to construct a sediment budget for a channel network as part of a long-term investigation of stream response to changes in watershed land cover or sediment yield.

Methods

Level 1: Repeat Photography and Observations Log

Simple investigations of stream cross-sections begin with descriptions of bank characteristics, commonly with use of a template for characterization and/or classification, at the sites of interest. Characteristics that should be recorded include channel shape, evidence of erosion or deposition, and bank geometry. In addition, scaled photographs should be taken from several vantage points, including views of the cross-section taken from upstream and downstream with the photographer standing in the channel. Locations should be plotted on a map and/or aerial photograph, and located with a global positioning systems (GPS) unit.

Level 2: Cross-section Measurements of Key Features

Measurements of channel width, depth, and key geomorphic features add to the quality of data of level 1. Width should be measured relevant to a geomorphically stable reference point or datum, but should be made at as many different points as are present (Fig. 13). Widths should be measured by stretching the tape perpendicular to the average flow direction. The simplest and most effective depth measurement is the maximum depth along the cross-section between the elevation of the selected datum and the bed of the stream. These data can be augmented by careful repeat photography so that changes in channel cross-section can be quantified.

Level 3: Repeat Surveys at Monumented Sites

Repeated surveys of monumented cross-sections are the most effective approach to studying change in channel dimensions. The end points of a cross-section can be monumented with a ½-inch steel rebar pin driven into the ground at each end of the channel cross-section. Their positions should be mapped with precise distances and bearings to landmarks, such as large trees or boulders, so that they can be found easily during future visits. Channel cross-section data can be collected with survey equipment or with a tape measure and survey rod. Enough data points should be collected to fully define the geometry of the channel and show key geomorphic features (e.g., channel bank, slumps, sediment bars). If detailed aerial photographs are available, channel dimensions (width) can be measured at many places rapidly. These data will be most valuable if historic aerial photographs are available, so that rates of change can be determined.

Study Design and Limitations (see Table 3)

Site Selection

Multiple cross-section sample sites will need to be established, whether the study purpose is for targeted or trend monitoring, because of the high variability in channel cross-sections. At least one cross-section site should be established for each similar reach of the study stream. Study sites for targeted monitoring of channel geometry should be in locations where recent and persistent change is evident, as these are likely of highest management concern. Figure 14 depicts characteristics of a dynamic cross-section stream section with evidence of scour on the cut banks, a general deepening of the channel toward the scoured bank, a pronounced ridge atop the inner bank deposit, and a pronounced depression between the ridge and the valley flat adjacent to the inner bank.

If the goal of a monitoring project is not to document changes in channel form of a single stream, but to document differences between multiple streams, study sites may be located in more stable reaches and compared using the ergodic approach (see section on watershed land cover). Cross-sections in a nearby watershed with similar drainage area, slope, bedrock geology, substrate, and aspect can be compared with respect to average dimensions such as width, depth, the width:depth ratio, entrenchment ratios, and cross-sectional area.

Scale Limitations

The type of equipment required for monitoring cross-section geometry depends to a large extent on the width of the channel. Channels as wide as 20 m may be measured effectively using simple measuring tapes and an auto level. For larger channels, the length of the section may make it difficult to keep the tape straight and level. Some of this sagging may be addressed by switching to a steel tape or tag line. Larger channels may also require the use of more sophisticated survey equipment. Cross-sections in large rivers are measured from boats using sonar devices to record depth soundings.

Time Limitations

As with measurements of the longitudinal profile, the temporal resolution of cross-section measurements depends to a large extent on local hydrology and substrate type. For most alluvial streams, an annual or semi-annual resurvey should be adequate to monitor channel position and geometry. Cross-sections of bedrock streams will likely change minimally on an annual basis. Similarly, if low flow dominates for a number of years, cross-sectional geometry of alluvial streams may not change much at all. Straight reaches of alluvial streams can be remarkably stable over long periods of time, making it unnecessary to repeat surveys frequently. On the other hand, a very flashy stream (characterized

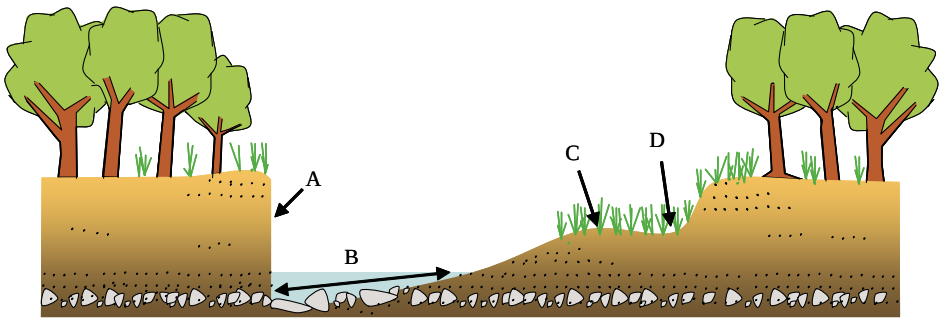


Figure 13. Characteristics of a dynamic cross-section: (A) evidence of scour along the outer bank, (B) bed slopes toward the outer bank, (C) pronounced peak on inner bank deposit, (D) pronounced depression between peak and inner bank floodplain.

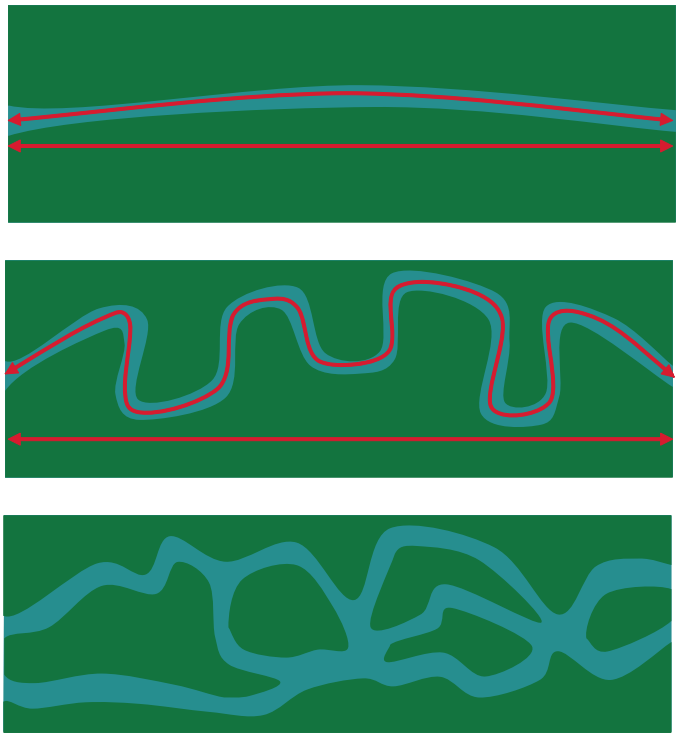


Figure 14. Three broad categories of channel planform. (A) In sinuous/straight reaches sinuosity (the ratio of channel length to valley length) is less than 1.5. (B) In meandering reaches, the same ratio is greater than 1.5. (C). In multiple-thread channels such as braided streams or anastamosing rivers, the sinuosity is more difficult to measure.

by rapid changes between peak and low flows) may scour its banks with great frequency, requiring repeat surveys to be conducted after any high flow event.

Cost Limitations

A single person can compile descriptions and maps of bank morphology using U.S. Geological Survey topographic maps ($10 to $100), a customized classification scheme, and a digital camera ($100 to $1,000). It may require two people to measure channel dimensions with a measuring tape ($10 to $100) or a laser range finder ($100 to $1,000). Surveys of channel cross-sections can be measured using an auto level ($1,000 to $10,000) for narrow channels, or a total station or survey-grade GPS ($10,000 to $100,000) for broader channels.

METHODS FOR VITAL SIGN 5: CHANNEL PLANFORM

Synopsis

Stream channel planform can vary significantly in response to changes in parameters such as stream gradient, discharge, or sediment load. Through careful analysis of channel planform it is possible to identify reaches where erosion, deposition, or transport processes are dominant. Analysis of channel planform provides data needed for determining morphological characteristics such as pool spacing and meander intensity. Channel planform data are usually presented in the form of maps or aerial photographs. Maps or photos representing multiple time steps are compared to determine changes in sinuosity and overall channel form.

Detailed maps can be used for a variety of purposes, but are most commonly needed to document important spatial relationships in the riparian zone, or to illustrate dramatic shifts in channel position, planform, or sinuosity. For example, maps of riparian vegetation types may reveal information about soils and hydrology; maps of sedimentary deposits in the riparian zone could be used to demonstrate the extent of flood water; and maps of puddles and puddle depressions can reveal information about flood hydrology. A series of maps of features such as terraces, avulsion channels, levees, bank tops, channel bars, or water surface limits can be used to document rates of bank erosion, changes in channel curvature, or the transition between a single thread and a braided channel.

The type of map required depends upon the scale of interest and the properties to be mapped. Simple two-dimensional maps can be constructed using a variety of different techniques that require varying levels of expertise. Pace-and-compass can involve a significant amount of error from imprecise bearing measurements and pace-length estimates, even under ideal conditions. Two-dimensional maps are sufficient for demonstrating spatial relationships in the channel and riparian zone, but for more detailed geomorphic maps, a three-dimensional method may be required. For example, three-dimensional maps can be used to measure the volume of sediment in channel bars or the height or depth of important features such as floodplain levees or stream banks.

Methods

Level 1: Channel Characterization

The planform type can be determined using maps of the channel or aerial photography. The channel can be classified in terms of the number of channels, bed topography, presence, type, and abundance of bars, and the sinuosity. When describing channel planform, the field person should classify the channel planform type as either single thread, sinuous or straight, single thread meandering, braided, or anastomosing. Floodplain and channel characteristics can also be documented using scaled photographs of each of these elements. Initial field surveys can be repeated in subsequent years to document any changes in conditions. Field observations of selected sites should include locations of sediment bars, pools, and knickpoints.

Channel sinuosity is easily measured using U.S. Geological Survey topographic maps for long reaches of a river, and large-scale aerial photographs for shorter reaches. Sinuosity is simply a measure of the ratio between the length of the channel and the straight-line distance between the same two points (Fig. 14).

Level 2: Historical Analysis

At this level, more detailed comparisons can be made using historical maps and air photos, with particular attention paid to changes in overall pattern, rates of lateral migration, and sinuosity. Using simple tools such as those mentioned in the level 2 investigation of watershed land cover, the size and number of channel bars can be measured and compared from one year to the next. Also, shifts in channel position can be noted and measured. If aerial photographs are available for different years during the same season, changes in vegetation on the floodplain and on channel bars can be also be noted. Repeated field observations should note changes in bed topography and features, and permit the determination of pool sizes and spacing.

Sketch maps should display the position of the channel(s), the width of the floodplain, the type and dispersion of vegetation, the size and location of different types of sediment deposits, channel obstructions such as large woody debris or bed structure, the location of any standing water, muddy depressions, or avulsion channels. Vegetation maps should include the location of large trees and clusters of shrubs, and the distribution of herbaceous vegetation. Maps of large sedimentary features should denote the shape, size, and strike of the deposits, and the map symbol should designate whether the sediment is predominantly gravel, sand, or mud. Maps can be completed on enlarged aerial photographs or topographic maps, or by pace-and-compass maps.

Level 3: Image Analysis and Mapping

Advanced spatial analysis of the channel planform can be conducted using remotely sensed data acquired from low-altitude reconnaissance flights, or from satellite images. Annual surveys of extended reaches can be conducted to measure channel geometry in detail, to evaluate changes in bank form, and to determine rates of channel migration. Detailed topographic maps of the channel bed will provide more precise measurements of pool and riffle spacing, size, and form. They can record the positions of bank tops, channel bars, vegetation boundaries, sediment deposits, and water surface edges. Dating of vegetation, or dendrochronology, on sediment bars can be used to establish a time frame for origin of key features. Planform maps can also be used to estimate the surface area of channel bars, the water surface, or the riparian zone. Collection of these data would likely be done in tandem with monitoring methods for other vital signs (e.g., longitudinal profile).

Study Design and Limitations (see Table 3)

Site Selection

In order to monitor pertinent changes in channel form, it may be necessary to collect data from any reach in the stream network that isn't confined by bedrock. Initial analysis using maps and photos will help to identify reaches where change is most likely. These reaches should be mapped in greater detail, or with a greater frequency. For most streams, analysis of planform characteristics need only be done at several-year intervals or after key hydrologic or sedimentation events. Bedrock systems will require less frequent monitoring.

Scale Limitations

Low-order streams in forested watersheds are poorly suited for analysis using remote sensing data. They are, however, much easier to survey and map in the field than larger streams. While larger rivers are more difficult to map in the field, they are easier to study using aerial photography and satellite images. The size of the streams being investigated will determine the most appropriate form of remote sensing data. The resolution of satellite images is good enough for investigations if useful data has been acquired for a large river (more than 200 m wide), while aerial photographs are more useful for smaller streams (Gilvear and Bryant, 2003).

Cost Limitations

Air photos are often easy to acquire, but data from a useful coverage over sequential years may be cost prohibitive ($1,000 to $10,000). Digital versions of the same coverage may be available at a lower cost on CD ($10 to $100), but this may require an investment in software ($1,000 to $10,000) that provides the analyst with tools for interpreting the images. Having a large-scale set of aerial photographs taken of a watershed is an option for regions where coverage does not already exist. The cost of acquiring these images is a function of the size of the area to be photographed and the desired scale of the photos ($1,000 and up).

METHODS FOR VITAL SIGN 6: CHANNEL LONGITUDINAL PROFILE

Synopsis

A longitudinal profile is an x-y plot showing bed elevation as a function of downstream distance. Surveys of the longitudinal profile of a stream are used to identify locations where (1) sediment is being produced from bedrock exposed in streambeds, (2) bed sediment is accumulating, and (3) channel incision is occurring. By resurveying these profiles, it becomes possible to estimate volumetric changes in the transfer of bed sediment from one reach to another and the production of new sediment from bedrock erosion. Longitudinal profiles can also be used to monitor changes in pool spacing, the progress of a sediment pulse from a landslide through the watershed, or upstream migration of knickpoints.

The upstream migration of knickpoints in streambeds has been related to rates of denudation (landscape lowering). In tectonically active regions of the country, rates of knickpoint migration may be related to rates of tectonic uplift. Bed aggradation and degradation typically reflects changes in sediment input from upstream. Development or deforestation, for example, may cause changes in hydrology that could result in increased rates of deposition and erosion. Similarly, a channel with an increasing abundance of bedrock exposure in the bed may indicate elevated rates of bed scour or channel incision.

Methods

Level 1: Profile Characterization

The locations of bed features such as knickpoints, bedrock, and major pools and bars can be documented by marking on aerial photographs and/or maps, or using photographs and/or maps, or using a mapping or recreational grade GPS. Large knickpoints in streambeds (such as the waterfalls shown in Fig. 15) are frequently photographed by park visitors, especially when they are located near roadways and popular trails. Scaled photographs can be taken at these locations to graphically demonstrate the height of knickpoints, the spacing of pools, or the character of bed materials. The approximate location of non-bedrock knickpoints is most important because it is generally an indicator of channel instability.



Figure 15. (Top) A knick point along the Cullasaja River near Highlands, North Carolina. This picture shows evidence of erosion caused by headward migration. Historically, tourists used to drive their cars beneath these falls. (Bottom) Another knickpoint just downstream from the first picture in this figure. This is an unscaled photograph of a scene that is frequently photographed by tourists from the region, making it useful for comparison with scaled photographs that could be added to a land management database.

Level 2: Profile Mapping

Simple mapping of selected stream reaches can be done with tools such as hand-levels, tape measures, and range finders to document the bed slope, riffles, pools, steps, bed materials, and knickpoints. When constructing simple sketch maps of a segment of a stream, field technicians should use standardized map symbols to characterize bed sediment material, pool depth, and the direction and type of stream flow (Fig. 16). Additionally, it may be desirable to include information about the riparian zone on these maps including floodplain vegetation, standing water, or landmarks such as large trees, channel bars, or large woody debris.

Level 3: Profile Surveys

More precise measurements for bed features identified in level 2 can be collected using more sophisticated tools. At this level, a mid-channel line is surveyed at regularly spaced intervals

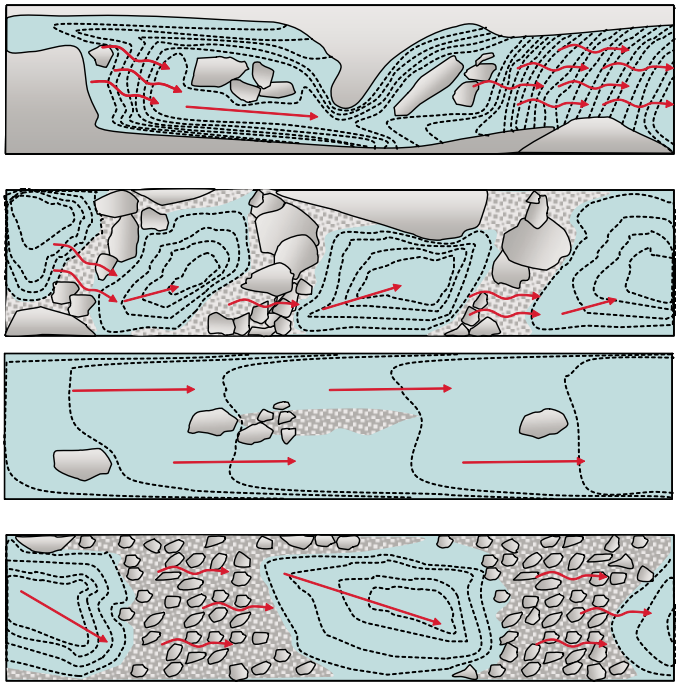


Figure 16. Four major types of channel bed morphology shown in planform. Dashed lines in these maps are benthic contours. (A) In cascading streams, turbulent flow occurs where the gradient is steep, and becomes steeper between knickpoints. (B) In step-pool reaches, flow is turbulent over bed structure elements, and becomes laminar in the pools. (C) In planar-bedded streams, flow near the bed is turbulent due to grain roughness, and may become laminar at higher stages. (D) In riffle-pool streams, flow is turbulent in riffles, and becomes more laminar over pools. Laminar flow conditions are locations where finer sediment is commonly deposited due to weaker cross-channel and vertical currents.

over the entire length of the channel using an auto-level, a stadia rod, and a measuring tape. The appropriate approach for surveying a longitudinal profile depends on the specific goals of the monitoring project. For example, surveying only a few geomorphically significant points along the profile can suitably depict the height of knickpoints, or the pool spacing in a small reach of the stream (Fig. 17) if the goal is simply to determine the average dimensions of these features, while a survey of the entire channel may be required to identify regions of the stream where pools are anomalously shallow or absent (Fig. 18).

More detailed maps of the bed topography can be created for reaches of interest using a total station or survey-grade (sub meter) GPS system. The large number of rod positions that are required to produce meaningful data make this approach difficult to apply to lengthy segments of the stream network; however, the value of the resultant maps for visualizing subtle changes in bed topography make 3-D mapping practical for many investigations. A common approach to detailed bed surveys is to construct a series of cross-sections of the bed at closely spaced intervals. The map in Figure 19 was constructed using such an approach.

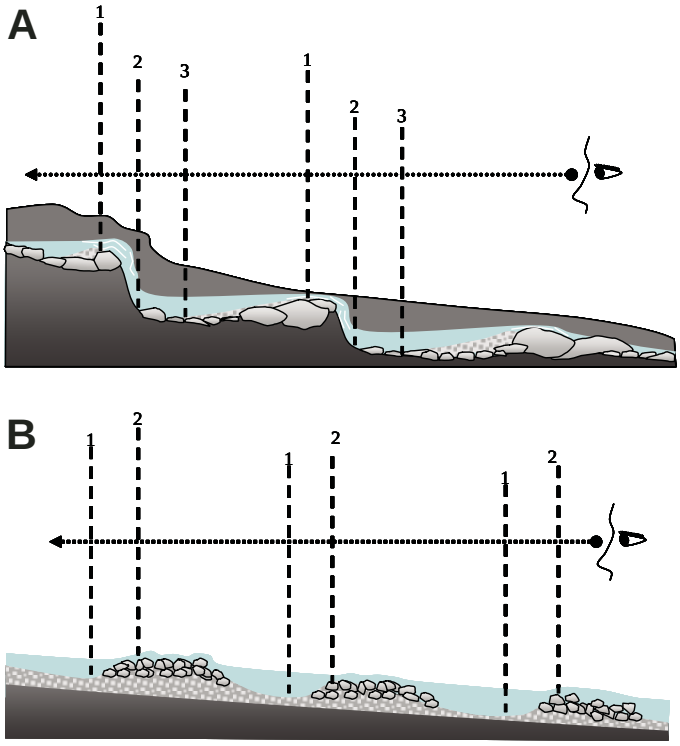


Figure 17. Measuring the longitudinal profile of river channels. (A) In a step-pool channel, knickpoints commonly form the risers of the steps. Geomorphically significant points along the profile include (1) the tops and (2) bottoms of the knick points (significant breaks in slope), and (3) the deepest point in the pool. Stream gradient should be determined using either points 1, 2, or 3 (similar points in the profile. (B) A similar approach can be used in streams with riffle-pool bed morphology. Surveying the upstream ends of riffles (2) should illustrate pool spacing, and including the deepest part of the pools will illustrate the bed relief.

Study Design and Limitations (see Table 3)

Site Selection

If the study goal is for targeted monitoring of an unstable reach, data on the longitudinal profile can be invaluable at monitoring changes because slope directly relates to hydraulic energy—all else being equal, steep slopes have more energy and are the most likely location of change. If the study area is too large to be mapped, then representative reaches should be selected for study. Longitudinal profiles provide measurements that are also necessary for making predictions about sediment transport and hydrology. Future changes in land cover will result in some degree of change in profile, so a baseline survey will be a valuable resource. Longitudinal profiles should be collected in any watershed where dramatic change is anticipated, or where it has occurred in the recent past. For example, these might include watersheds with anomalously high sediment yield, numerous sediment bars, abundance of bedrock exposures, or a large number of knickpoints.

Scale Limitations

High-order streams may be too large to survey using the methods described above. Large rivers may require the use of boats with sonar equipment to retrieve depth soundings. Longitudinal profiles take serious effort, even in smaller rivers. For this reason, it will probably be most effective to construct the profile using widely spaced points at first, and then survey with greater detail in small reaches with knickpoints, or unusual pool sizes or spacing.

Time Limitations

In the case of most undisturbed "natural" streams, changes in longitudinal profile may only be noticed over long periods of

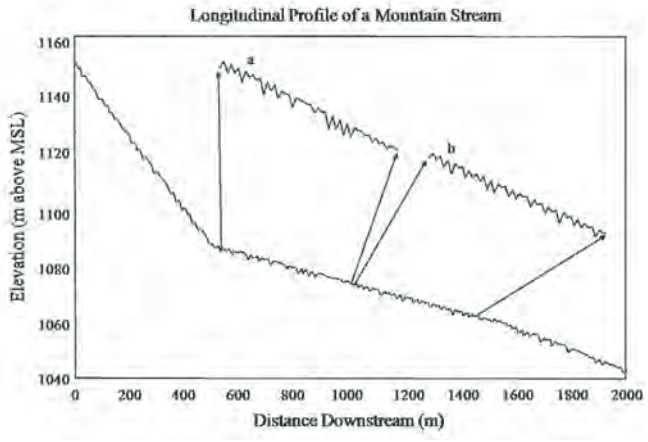


Figure 18. The longitudinal profile of a typical mountain stream can be used to identify regions of bed aggradation and degradation or changes in pool-riffle spacing. The downstream portion of reach "a" has two segments with notably shallower pools in it. This could be the result of excessive deposition in this reach.

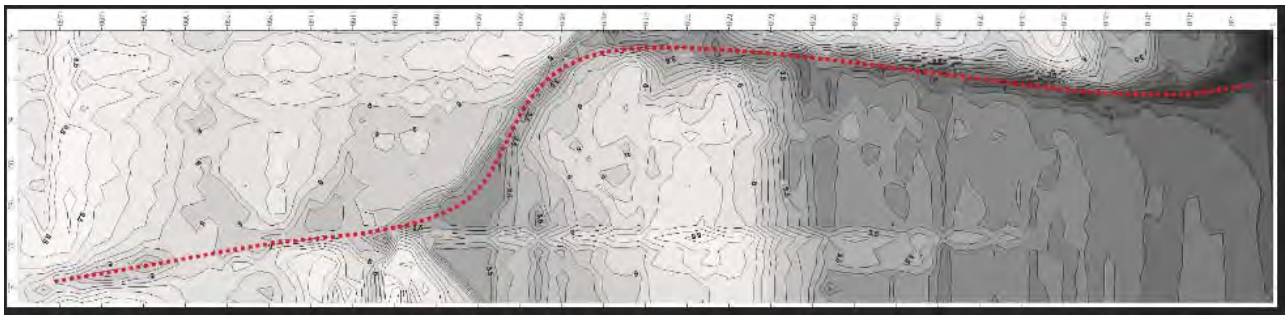


Figure 19. A 3-dimensional map of a small stream constructed using a total-station and 3D mapping software (Surfer, from Golden Software).

time. For these streams, it may only be necessary to repeat these measurements once every ten years. If the stream has indicators of instability or has experienced a disturbance such as a landslide, dramatic change in land cover, or intense precipitation, it may be necessary to repeat measurements on an annual basis, or even more frequently. For example, alluvial knickpoints can migrate rapidly upstream, especially in arid or semi-arid regions where meters of migration can occur in a single event. Alternatively, riffles and pools are able to migrate downstream or expand and contract over time, depending on the intensity of the discharges they are subjected to. A sediment pulse deposited by a landslide may move downstream through translation, dissipation, or a combination of both. The appropriate sampling interval for studying these kinds of processes will vary, and can only be determined through frequent visits to the reaches of interest.

Cost Limitations

Stream-walk mapping of knickpoints and bedrock outcrops can be conducted by a single person using U.S. Geological Survey topographic maps, a Jacob staff, and a laser range finder. The cost associated with this type of investigation is therefore relatively low ($100 to $1,000). More precise maps can be constructed with optical surveying devices such as automatic levels or mapping-grade GPS ($1,000 to $10,000). More advanced survey equipment such as traditional or robotic total-stations ($10,000 to $100,000) require a clear line of sight. Survey-grade GPS ($10,000 to $100,000) do not require a clear line of sight, and are almost as accurate as total stations.

CASE STUDY: A SCIENCE-BASED APPROACH TO UNDERSTANDING, MANAGING, AND RESTORING MONTANE RIPARIAN MEADOWS OF THE GREAT BASIN, NEVADA

Overview

A case study is used here to demonstrate some of the methods and approaches reviewed in this chapter. The project described here has likely involved a larger budget and more personnel than most land managers will have available, but, nonetheless, does exemplify many of the principles, methods, time-scales, system characteristics, definition of study goals, assessment of needs, choosing of methods, and interdisciplinary cooperation that should ideally be used in many studies. The study described here is ongoing, but much of the work has been published in a book, *Great Basin Riparian Ecosystems: Ecology, Management, and Restoration* (Chambers and Miller, 2004).

Riparian corridor and meadow ecosystems in upland watersheds are of local and regional importance in the Great Basin. Covering only 1–3% of the total land area, these ecosystems contain a disproportionately large percentage of the region's biodiversity. Stream incision is threatening these sensitive ecosystems. The downcutting by streams lowers the groundwater table and results in a vegetational shift from wet meadow species to drier communities. Many of these upland watersheds are located in the Humboldt-Toiyabe National Forest. Understanding the structure and function of riparian meadows and the impact of stream incision on these ecosystems has been a concern of the USDA Forest Service. A multidisciplinary research team of scientists from government (U.S. Forest Service and U.S. Environmental Protection Agency) and academia has been working to better understand the geologic and geomorphic settings, surface and subsurface hydrologic regimes, vegetation patterns, and interconnections of biological and physical systems of upland riparian meadow systems in central Nevada. This information is also being used for prioritizing ecosystem degradation and restoration potential to better direct available resources and evaluate the success of restoration alternatives. Brief descriptions of some the study questions, methods, and results are described below.

What is the natural setting that supports wet meadow complexes? What is the long-term and short-term record of stream incision?

Methods. The geologic, geomorphic, and hydrologic setting of upland riparian meadows was evaluated throughout five mountain ranges of central Nevada to learn the conditions necessary to support riparian meadows. These methods included mapping in the field and on aerial photographs and installing and

monitoring groundwater wells. The stratigraphy of modern and ancient stream sediments was studied in conjunction with the geomorphology to establish a long term record. The longitudinal profiles of streams were characterized using level 1 and 2 methods (profile characterization and mapping, repeat photography).

Results. Meadows are present in groundwater discharge zones with high flow rates that are geologically controlled to maintain high groundwater tables. Many of the meadows are present upstream of side-valley alluvial fans (Fig. 20). The interplay of faults, differential sediment inputs from down-valley and side-valley sources, and alluvial fan form and sediments create conditions necessary for riparian meadows (Miller et al., 2004; Jewett et al., 2004). Study of the long-term record (4000–5000 years) showed that incision of streams in the central Great Basin occurs periodically and is largely controlled by climatic change (Miller et al., 2004). Although some land use practices have increased rates of stream incision, these studies showed that the region is now a natural cycle where streams are prone to incision.

Repeat photography of active knickpoints demonstrates rapid changes in the channel and an unstable system (Fig. 21).



Figure 20. Aerial photograph (top) of Kingston Canyon, Nevada showing stark contrast of wet meadow complexes with surrounding vegetation. Oblique view (bottom) of Kingston meadow, circled on top photograph, shows meadow position upstream of the two side-valley alluvial fans. Photograph by Mark Lord.

Why are some drainage basins more sensitive to incision than others?

Methods. Simple (level 1) field mapping techniques were used for many streams in basins supporting riparian meadows. These methods included determination of stream cross-sections, longitudinal profiles, bed materials, and degree of incision (Fig. 22). In addition, the geologic and drainage basin morphometric characteristics of each study site were determined.

Results. Based on the field data, stream systems were categorized into different sensitivity groups—that is, some basins are much more likely to undergo incision if the systems are stressed by natural or anthropogenic causes. The variation in the nature of system response appears to be controlled by geology, drainage basin morphometry, and watershed hydrology (Germanoski and Miller, 2004). This information is valuable to help prioritize management and restoration activities. Sequential aerial photographs show rapid upstream migration of channel systems into a previously unincised wet meadow complex (Fig. 23).

What is the relationship of vegetation, hydrogeology, and geomorphic setting?

Methods. Mapping and classification of vegetation, installation and monitoring of groundwater wells, and stream discharge measurements were used to understand the hydrologic characteristics of sites, groundwater-stream water interactions, and relationships to vegetation.

Results. A strong correlation exists between types of meadow vegetation and the depth of the groundwater table below the ground (Fig. 24) and some stream characteristics (e.g., depth of incision, bed material grain size). Stream incision is immediately followed by a drop in the groundwater table and, with some lag time, a change in vegetation type (Chambers et al., 2004; Jewett et al., 2004). Understanding the relationship of groundwater, stream water, geomorphic setting, and vegetation can be used to: (1) assess the impacts of existing stressors, (2) make predictions about potential impacts from stressors, (3) select best management or restoration options, and (4) estimate the likelihood of success of rehabilitation options.

CONCLUSIONS

Monitoring fluvial systems can be a daunting task because of the scale and interconnectedness of river systems. The form and processes of a stream are a response to most natural and artificial processes and properties within the watershed. They are also subject to external factors—most notably climate. Recognition of the importance of streams continues to grow as the relationship to ecosystems and land use activities increases. There are dozens upon dozens of methods to monitor stream systems. A monitoring program, more than an understanding of the methods, requires an understanding of the basics of fluvial geomorphology, characteristics of systems, the types of stressors that are most likely to drive change in fluvial systems, vital signs most important to monitor to understand or predict change, and a knowledge







Figure 21. Photo series of incised Cottonwood Creek, Toiyabe National Forest, Nevada. Incision of this stream was triggered by downstream flood sediment depostion in 1983 that caused rerouting of the stream reach shown. Subsequently, a knickpoint migrated upstream all the way up through a meadow (1998). The channel has widened since then (2004), but the channel bed elevation appears to be stabilized because of a coarse-grained channel bed. Photographs by Jeanne Chambers.



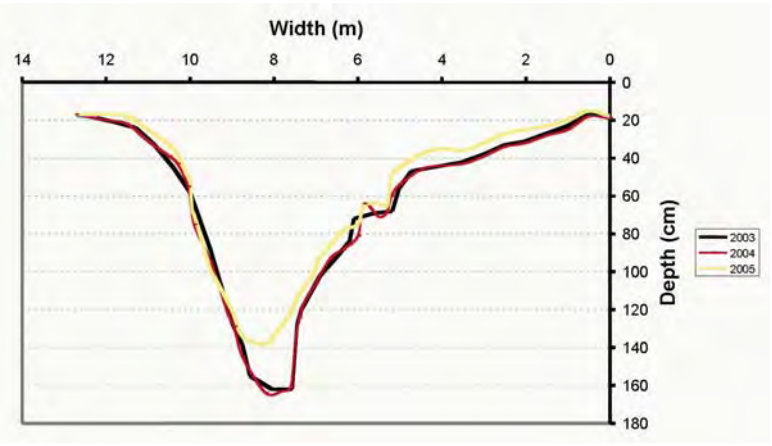


Figure 22. Determination of a channel cross-section (top) can be completed with very simple tools and is effective for characterizing and monitoring streams. Sequential cross-sections (bottom) show of a meadow channel show sediment infilling between 2004 and 2005. Photograph by Mark Lord.

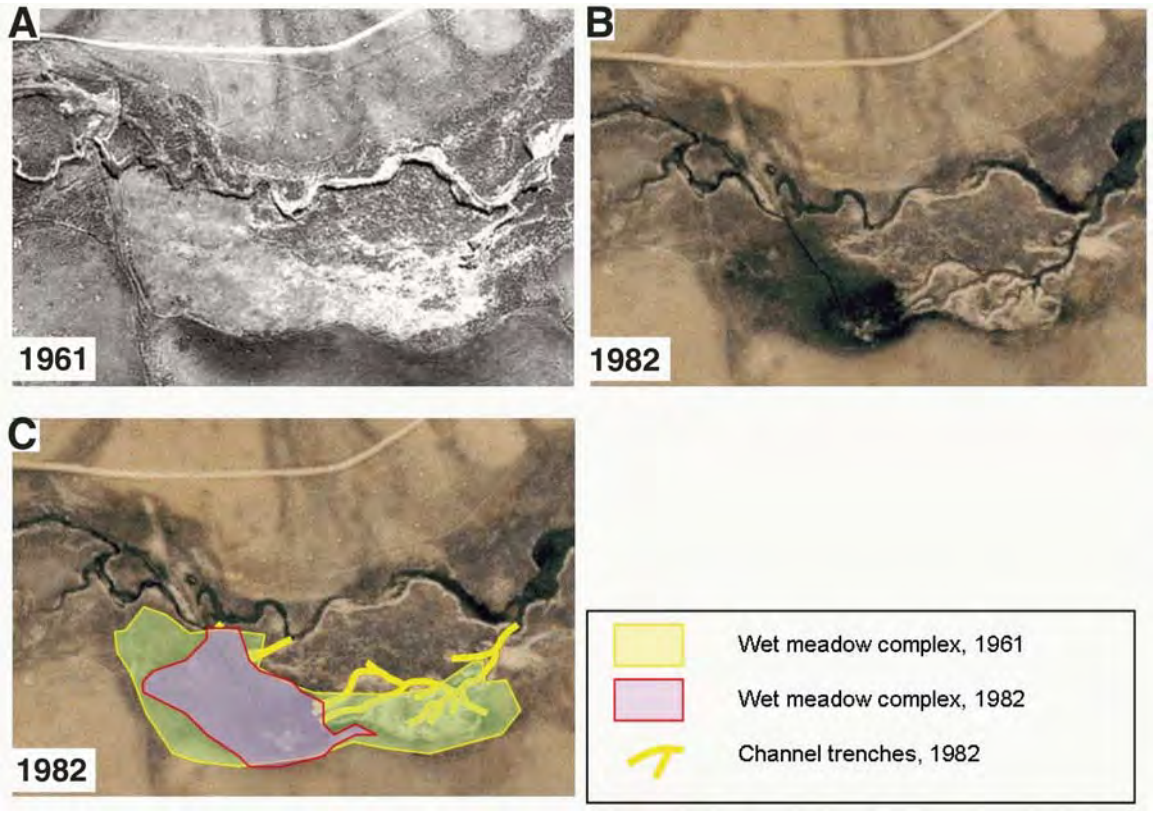


Figure 23. Sequential aerial photographs (Indian Creek Valley, Nevada) used to determine rates of change in area of riparian wet meadow complexes and channel extension; photo width ~0.8 km. Note absence of any channels in main part of meadow in 1961 (A) and meadow complex loss by 1982 (B) due to incision of meadow by headcut migration of channel trenches (C). Example headcut is shown in Figure 24C.

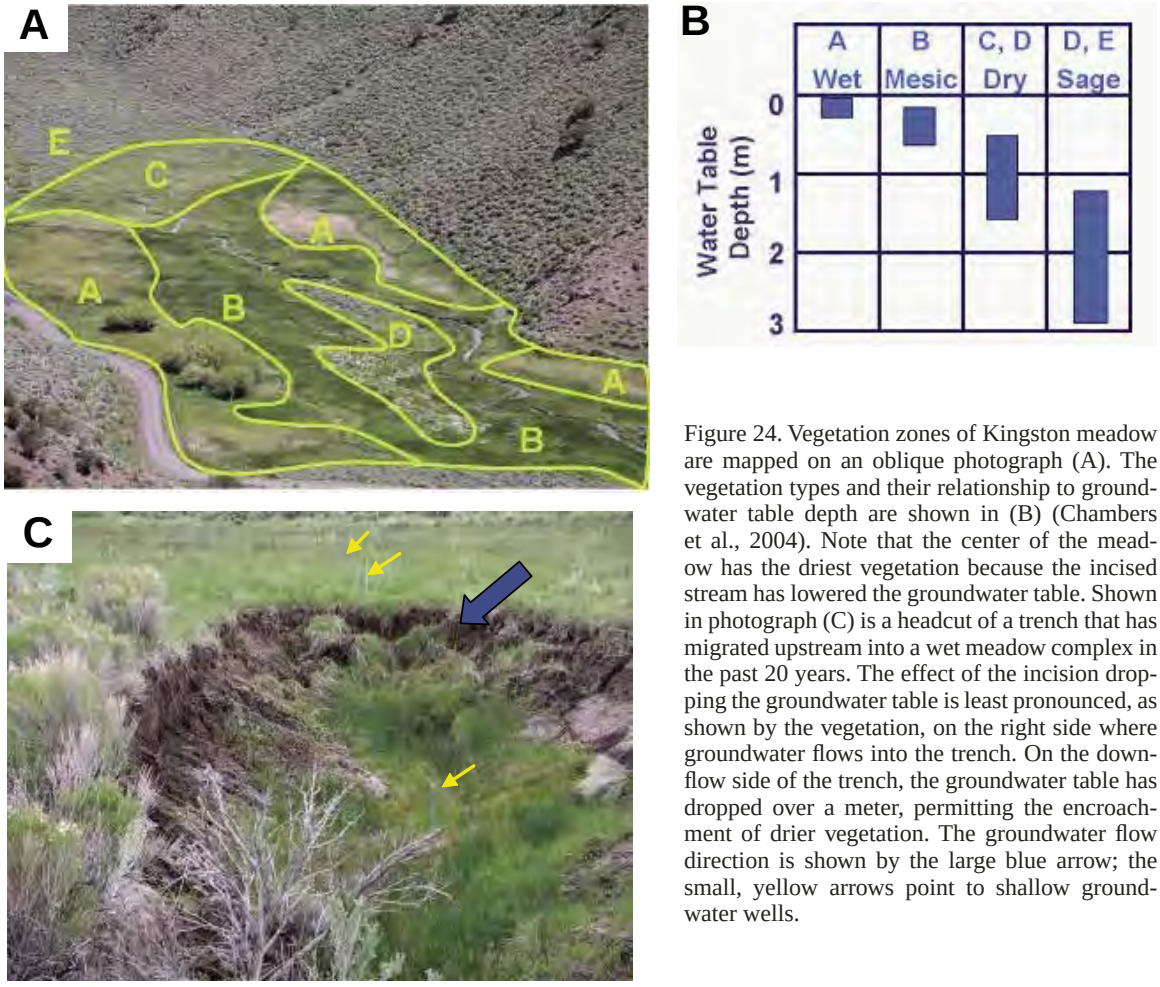


Figure 24. Vegetation zones of Kingston meadow are mapped on an oblique photograph (A). The vegetation types and their relationship to groundwater table depth are shown in (B) (Chambers et al., 2004). Note that the center of the meadow has the driest vegetation because the incised stream has lowered the groundwater table. Shown in photograph (C) is a headcut of a trench that has migrated upstream into a wet meadow complex in the past 20 years. The effect of the incision dropping the groundwater table is least pronounced, as shown by the vegetation, on the right side where groundwater flows into the trench. On the downflow side of the trench, the groundwater table has dropped over a meter, permitting the encroachment of drier vegetation. The groundwater flow direction is shown by the large blue arrow; the small, yellow arrows point to shallow groundwater wells.

of how to develop a good study design. Three levels of methods are presented for the six vital signs of fluvial systems described. Significant experience, time, and money are required for in-depth studies that will likely address several vital signs. Simple, valuable methods, however, can be used to assess all fluvial vital signs even when resources are limited. Initiating a fluvial monitoring program should be done in consultation with an experienced fluvial geomorpholgist. Once a local experience base is built up, a land manager should be able to develop and carry out a wide variety of monitoring studies. If possible, these studies should be done in concert with other monitoring programs, especially those most directly related to stream systems.

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Geothermal systems and monitoring hydrothermal features

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INTRODUCTION

Hot springs, geysers, mud pots, and fumaroles are dynamic surface features that represent interacting subterranean systems of water, heat, and rocks. Identifying the locations of these features and monitoring their heat, water flow, and chemistry can provide land managers with data needed to make informed decisions about management options.

This chapter describes vital signs and contains options for monitoring surface and near-surface geothermal features, such as hot springs, geysers, mud pots, and fumaroles. Its focus is the description of techniques for detecting change in hydrothermal systems through time due to natural or human-related causes.

The goal of this chapter is to describe selected techniques for monitoring important vital signs of geothermal systems. Information in this chapter will not make the reader an expert in all geological aspects of geothermal systems. Some monitoring techniques are simple and can be performed by interested volunteers with no specialized background. Other techniques are complex and are best done by experts, with study results interpreted by seasoned practitioners. The described monitoring options may not meet all statutory and regulatory requirements that land managers may face.

The terms **geothermal** and **hydrothermal** have specific connotations as used in this chapter (Jackson, 1997). **Geothermal** refers to any system that transfers heat from within the Earth to its surface. Hot rocks, without water, are geothermal. **Hydrothermal** is a subset of geothermal, and means that the transfer of heat involves water, either in liquid or vapor state (hence the "hydro"). Hot springs and geysers, for example, are hydrothermal features. It should be noted that the terms geothermal and hydrothermal may be used differently in other publications.

The potential for geothermal systems exists over broad regions of the United States (Fig. 1). Although most of the geothermal systems occur in the western United States, isolated geothermal features are also found in the eastern United States.

The Geology of Geothermal Systems

Three geological components are required for the formation of a hydrothermal feature: (1) water, (2) heat, and (3) permeability through rocks so water can flow in the subsurface and rise to or near the land's surface. Geologists conceptualize these as three interrelated systems. Meteoric water, or water that entered a geothermal system at Earth's surface, such as rainfall, snowmelt, rivers, and lakes, forms most of hydrothermal fluids. Water recharge, or the site where water soaks into the ground, may be distant (up to tens of kilometers) from the discharge site. Some waters reach several kilometers depth. The source of heat is either magma, in the case of volcano-related systems, or heat from the normal temperature increase with depth in the earth. Fractures in rocks (Fig. 2) often create permeability, but in some systems interconnected pores or large cave systems allow fluids to flow. In hydrothermal systems, seismic activity may open fractures or alternatively may close them.

While to a layperson a hot spring may be just that, a solitary spring, to a geologist a hot spring is the surface tip of a subterranean system that may extend for kilometers. A hydrothermal system includes an area where water gets recharged to the subsurface by the infiltration of rainwater or snowmelt. The system includes the underground flow of the waters, perhaps to depths of several kilometers, typically through fractures (Fig. 2) and/or pores in the underground rocks. It is important not to think of geothermal waters as typically flowing through underground caves (except in unusual circumstances). Water circulating near magma or deep enough to be heated by warm rocks forms hydrothermal fluids. Hydrothermal systems also include a zone where the hot waters flow upward to the land surface, driven by pressure or density,

Heasler, H.P., Jaworowski, C., and Foley, D., 2009, Geothermal systems and monitoring hydrothermal features, *in* Young, R., and Norby, L., eds., Geological Monitoring: Boulder, Colorado, Geological Society of America, p. 105–140, doi: 10.1130/2009.monitoring(05). For permission to copy, contact editing@geosociety.org. ©2009 The Geological Society of America. All rights reserved.

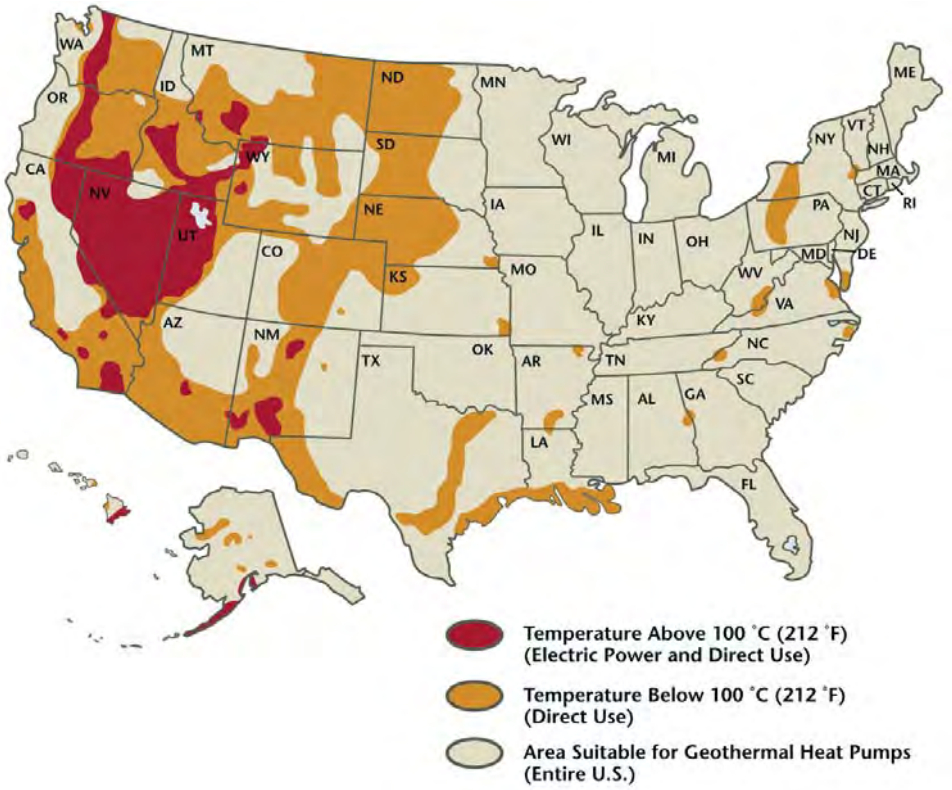


Figure 1. Map showing estimated subsurface temperatures in the United States. Red and orange colors indicate that the western United States is generally warmer than the central or eastern United States. Most hydrothermal systems can be expected to occur in the red and orange areas. However, there are some sites in the central and eastern states where thermal springs occur due to waters rising along deep faults or folded sedimentary rocks. Map from Green and Nix (2006).

giving rise to a spring, geyser, mud pot, or fumarole. Figures 3 and 4 show geologic conceptions of how hydrothermal systems might look underground in areas where the heat source is volcanic and/or magmatic heat (Fig. 3) and where the heat source is non-magmatic heat (Fig. 4). In a magmatic hydrothermal system, the magma heats rocks that then heat deep circulating waters. In a non-magmatic hydrothermal system, thermal waters result from water being heated by higher temperature (through the increase in temperature with depth) rocks and quickly returned to Earth's surface before cooling.

An individual hydrothermal feature is the surface expression of integrated, interacting geologic systems of water, heat, and rocks. An individual hot spring, for example, must be viewed both as the surface expression of the interacting systems, and as one feature in the context of other features around it, with which it may share subterranean connections. For example, Old Faithful geyser exists as an individual feature, but it also exists in the context of the overall Upper Geyser Basin. The Upper Geyser Basin exists in the context of the Upper, Midway, and Lower Geyser Basins. And these geyser basins exist in the overall context of the Yellowstone caldera. Subterranean connections, perhaps at scales that range from local to regional, may also occur in non-volcanic hydrothermal systems. Interconnections commonly exist among multiple hydrothermal features along a fault or flowing from an individual rock unit. The implication for geothermal monitoring is that individual hydrothermal features are part of a hydrothermal basin and also the surface expression of an entire hydrothermal system. Thus, data from one hydrothermal feature may not provide adequate information for decision making in areas that have multiple hydrothermal features.

Individual hydrothermal features require a critical combination of water supply, heat supply, and permeability. Changes in any of these components may lead to changes in the surface expression of the hydrothermal system. Lack of active surface hydrothermal features may not mean, however, that the hydrothermal system ceased to exist. Perhaps the opening of new fractures redirected the flow of hydrothermal water, or perhaps mineralization sealed an existing fracture.

Changes from active to inactive and back again may be typical of hydrothermal systems (Moore, 2007). In Yellowstone, for example, forests have grown during periods of quiescence only to be killed when hydrothermal systems rejuvenate (Marler, 1956). Preliminary dating of a Yellowstone geyser suggests that it may have had periods of activity that were separated by perhaps thousands of years of quiescence (Foley, 2006). Monitoring hydrothermal systems may help determine whether the systems are heating up, cooling down, or remaining the same.

Multiple possible combinations of water sources, heat sources, subsurface rock types, chemical reactions and flowpaths lead to the development of many different kinds of surface hydrothermal features (Table 1). The multiple possible fates of waters, as shown on Figure 3, include such issues as: do the waters boil underground? Does the steam separate or stay with the waters as they rise? Do the waters just cool as they rise, without boiling?



Figure 2. Fractures, identified by the networks of dark linear zones, which indicate the passage of hydrothermal fluids through light-colored volcanic rocks. This photograph shows fractured rocks in Yellowstone. Photo ©2008 by D. Foley.

Do the waters mix with other subsurface waters, either other thermal waters or cooler groundwater? Table 1 summarizes major categories of hydrothermal systems.

The surface expression of a hydrothermal system creates vital signs that can be monitored. Hydrothermal features occur at a location, perhaps in conjunction with other hydrothermal features. They emit heat and discharge hydrothermal water. The water contains chemicals and gases. So, *location*, *area*, *heat*, *water*, and *chemistry* become critical vital signs to monitor. Although these vital signs are observable at the surface, they also provide information about the subsurface hydrothermal system.

Five closely related investigations of hydrothermal systems include: (1) identification, (2) monitoring, (3) research, (4) exploration, and (5) production. **Identification** is simply locating the surface expression of a geothermal feature and perhaps noting its temperature and flow. **Monitoring**, for the purposes of this chapter, is the short-term or long-term observation of the thermal, chemical, or flow characteristics of a surface or near-surface (for example, cave or well) thermal feature or connected group or groups of features. Monitoring also may involve describing how hydrothermal systems change through time and as a result of human activities. **Research** about hydrothermal systems may include more detailed thermal studies, in-depth chemical analyses, geophysical studies of electrical, magnetic, gravity, and seismic characteristics of a site or region, and detailed flow monitoring. Research also may include investigation of the entire hydrothermal system, rather than just surface phenomena. **Exploration** for geothermal resources builds on research and tries to find commercially producible quantities of hydrothermal fluids for either direct heat use (e.g., space heating or industrial processing) or for the generation of electricity. **Production** of a geothermal resource, once the resource is developed by extensive drilling, requires continual studies to assure that adequate quantities of fluids with the necessary temperatures and pressures are present in the system.

In this chapter, the emphasis is on monitoring vital signs of surface or near-surface phenomena in hydrothermal systems to assess natural and human-related changes. It does not include description of techniques that can be used for deep exploration or for monitoring production from a geothermal field. Nor does this chapter include discussion of biological monitoring of hydrothermal systems or monitoring underwater hydrothermal features. While monitoring these may be important in some cases, the sophistication of required equipment and personnel places such work still in the realm of research. Also, enhanced geothermal systems, which are created by drilling two wells into hot but not necessarily permeable rocks, artificially creating or enhancing natural permeability, and circulating water between the wells, are not part of this chapter. Thermal waters produced with petroleum products are also not discussed. In some cases, it may be important for land managers to consider these other thermal systems and consult with professionals.

It is possible that many public lands have hidden geothermal systems. These are also known as “blind” systems, because they have no surface expression. Figure 5 shows a blind hydrothermal system developed through lateral leakage of thermal waters. Until discovered through research and exploration, including well drilling programs, these hydrothermal systems cannot be monitored. Land managers should recognize that current lists of geothermal systems are likely to be increased as exploration for alternative energy continues, especially in the western United States.

The geothermal industry and the U.S. Geological Survey divide hydrothermal systems into two subclasses based on chemically determined maximum subsurface fluid temperatures: (1) high temperature fluids, which are generally defined as those fluids above 90 °C (~195 °F) and may be suitable for the generation of electricity, and (2) low and moderate temperature fluids, which are those that have likely maximum subsurface fluid temperatures below 90 °C (~195 °F). Moderate and low-temperature fluids may be suitable for direct use, such as industrial drying, aquaculture, and space heating. It is worth noting that not all high-temperature systems relate to volcanoes. For example, there is no volcanic activity around the Dixie Valley hydrothermal power plant in Nevada (McKenna and Blackwell, 2004; Kennedy and van Soest, 2006).

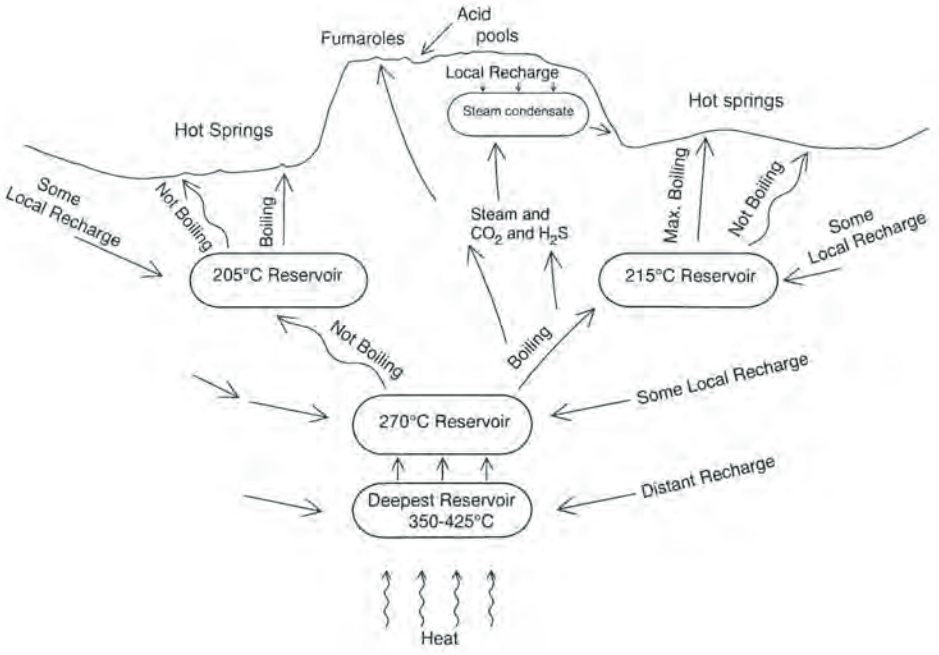


Figure 3. Subsurface geologic flow in a volcano-related hydrothermal system. Deep waters, which have been recharged from distant sources, rise and either conductively cool, boil, and/or mix with more local cold waters, as they make their way to the land surface. At the surface, hot spring, geysers, mud pots, and fumaroles can form. Modified from Fournier et al. (1994).

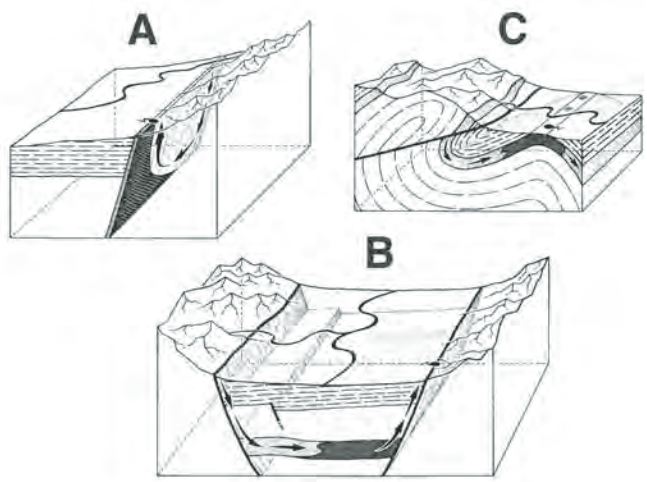


Figure 4. Conceptual diagrams of non-magmatic hydrothermal systems. In drawing A, water is recharged along a fault, flows to depth where it is heated, and rises again along the same fault. Drawing B shows a system where waters flow across a basin between the recharge fault on the left, and the discharge fault on the right. Drawing C shows a system where waters circulate to depth through rock units, and rise along the same units where they are folded upward. From Sorey et al. (1983).

It is also worth noting that the division by temperature between fluids that may be useful for generating electricity and those more suited for direct use is arbitrary. For instance, as this text is written, at least one site in Alaska is using fluids with a temperature ~75 °C (165 °F) to generate electricity (Holdmann, 2007).

Hydrothermal systems exist in a continuum of resource temperatures. At the lowest end, geothermal resources grade into normal-temperature resources. In most non-geothermal areas, the temperature of shallow groundwater will be approximately the same as the mean annual air temperature. With heat pumps, almost all areas of the United States can derive useful heat from normal temperature groundwater. Monitoring normal temperature groundwater is not covered in this chapter.

Why Monitor Hydrothermal Systems?

Hydrothermal systems can change as a result of local or distant events that alter the water source or flow path, the heat source, thermal characteristics along the subsurface flow path, and/or the fractured rock that the waters are flowing through. Some of these changes may be natural, for instance as a result of weather patterns, climate changes, or earthquake activity. Other changes may relate to human activities, such as nearby production of petroleum resources, geothermal energy (Sorey, 2000) or even pumping a water well. Changes in flow may be either rapid, for instance as a result of an earthquake, or slow, as water supply changes with climate. Table 2 lists some reasons to monitor hydrothermal systems.

Before beginning a monitoring program, it is helpful to compile existing data about an area. Contacting federal agencies, such as the U.S. Geological Survey and the U.S. Department of Energy, as well as state agencies, such as geological surveys, departments of energy, and departments of environment or ecology, may reveal a great deal of information that is useful in monitoring programs. For instance, there is a compilation of thermal springs for the entire United States (Berry et al., 1980). This list is now available online,

TABLE 1 MAJOR CATEGORIES OF HYDROTHERMAL FEATURES

Dominant form of rising fluid	Typical surface feature	Photograph of hydrothermal features	Further characteristics
Liquid water	Hot springs		Silica-depositing springs with significant runoff. Silica deposits, known as siliceous sinter, indicate subsurface temperatures above about 210 °C.
			Carbonate-depositing springs with significant runoff. The carbonate deposits form the rock travertine. Carbonate-depositing systems typically indicate lower maximum subsurface temperatures than silica-depositing systems.
	Geysers		Intermittently erupting springs.
Steam	Mud pots Fumaroles		Relatively dry systems, with little runoff. Acidic conditions are typical.

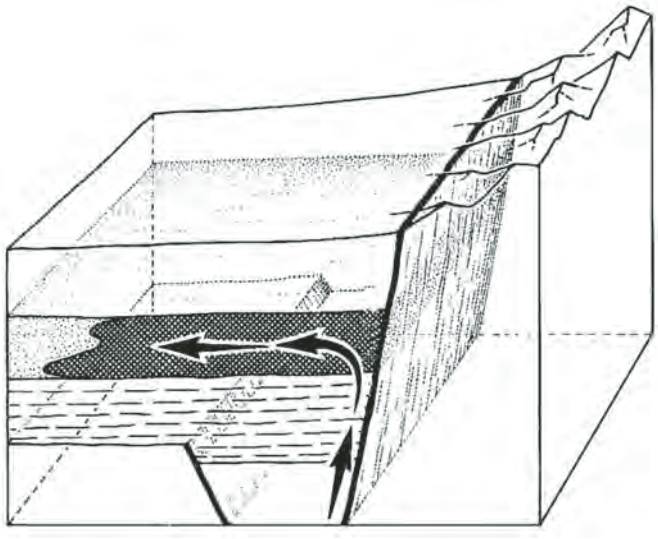


Figure 5. Diagram of a blind hydrothermal system. Note the subsurface lateral flow through permeable geologic units. Blind systems do not need to have active surface manifestations. Modified from Sorey et al. (1983).

in both PDF and searchable formats (see list of URLs at the end of this chapter). Some states, such as Washington, have updated and expanded the list (Schuster and Bloomquist, 1994). Local and regional universities are also likely sources of information, especially where students may have done thesis work on hydrothermal systems. It can also be very instructive to look at an area of interest through online mapping resources, such as GoogleEarth.

Stressors/Possible Change

Geothermal heat is the fundamental driver of hydrothermal systems. But, hydrothermal systems also require water and permeability. Changes in water quantity, changes in heat source, changes in permeability, and human activities interact to alter hydrothermal systems.

Figure 6 summarizes the stressors that can influence hydrothermal systems and identifies vital signs that can change as a result of changes in the stressors.

Many different geologic processes can bring about changes in these stressors. Changes in water quantity, for example, may occur as climate changes or new patterns of precipitation develop. Changes in the heat source can occur as a result of either an input of new magma or cooling of magma. Changes in permeability can occur as minerals precipitate along fractures and fill pore space and as earthquakes open or close fractures. Human activities may noticeably change water quantity through pumping nearby wells or otherwise removing or adding water to hydrothermal systems.

Because hydrothermal systems are linked by interactions of water systems, heat systems, and rock systems, they can provide monitoring data useful to many geologic disciplines. Hydrothermal systems can provide early evidence of moving magma (see Smith et al., this volume), potential hydrothermal explosions (Fournier et al., 1991), or even earthquakes (Silver and Valette-Silver, 1992).

GENERAL SAFETY DISCUSSION

Safety is a primary concern when taking measurements near hydrothermal features. Personnel may incur thermal burns from hot water or die from immersion in scalding thermal water. Thin, overhanging ledges of siliceous **sinter** (a chemical sedimentary rock composed primarily of silica, which is formed by precipitation from thermal waters) partially obscure some hydrothermal features; thin crusts of sinter may completely cover other hydrothermal features (Figs. 7A and 7B). Boggy ground may conceal dangerous hydrothermal features. Field personnel may sustain chemical burns from acidic or caustic thermal waters and soil. Hot, acidic, splashing thermal mud also may inflict injury. Some thermal waters contain toxic substances such as mercury, arsenic, and other elements.

Hydrothermal features and areas may experience rapid, drastic changes. Field teams must be aware of changing conditions at *all* times. Also, field personnel should carefully reevaluate safety each time they visit a thermal feature or thermal area. Because conditions may have changed since the last visit, a formerly safe approach may turn deadly.

Toxic gases may be present in hydrothermal areas. Depending on the heat source for the hydrothermal system, gases that may exist in dangerous concentrations include sulfur dioxide, hydrogen sulfide, and carbon dioxide. Field personnel need to be aware of the potential for the presence of such gasses and implement appropriate safety procedures.

It is important that the field team is aware of safety concerns *before* entering a thermal area. Pre-visit safety awareness may include literature reviews of the chemistry, literature reviews of hydrothermal site conditions, and discussions with experienced personnel. With each visit to a hydrothermal area, the field team should conduct a careful evaluation of any changes in the hydrothermal system that may affect safety.

VITAL SIGNS OF HYDROTHERMAL SYSTEMS

Vital Sign 1: Location of Hydrothermal Features

Locating hydrothermal features is the most basic way to describe and identify hydrothermal features. Names of individual features may change over time, whereas their geographic coordinates are unique. Coordinates may include the familiar latitude and longitude grid system, Universal Transverse Mercator (UTM), or State Plane Coordinate System (SPCS). The Public Land Survey System (PLSS) is another common method used to locate features on a map.

Locating hydrothermal features is a key component of mapping and the first step in monitoring hydrothermal features. When located and mapped, relationships to rivers, infrastructure, other

TABLE 2. REASONS TO MONITOR VITAL SIGNS OF HYDROTHERMAL SYSTEMS

Reasons	Explanation
Human health and safety	• Hot systems can cause thermal burns (and death). • Some systems may cause chemical burns (acid waters, vapors or rocks). • Some systems concentrate toxic chemicals (mercury, arsenic, etc.). • Some systems produce toxic gases (hydrogen sulfide, carbon dioxide). • Some systems may have the potential for hydrothermal explosions.
Baseline data	• Without baseline data, natural variation in heat, water and chemistry cannot be assessed, and potential impacts from human activities, seasonal variation, climate change, etc., cannot be determined. Without baseline data, it is difficult to determine what are normal changes and what are significant changes that might portend broader geologic events. Short-term (daily, weekly, seasonal, annual) variation needs to be distinguished from long-term trends (are systems getting larger or smaller; hotter or cooler?). • Baseline data are also critical for scientific researchers to be able to test hypotheses about hydrothermal systems and their components. • Baseline data may be useful to researchers in other fields (e.g., seismicity, geomicrobiology). • Baseline data may help clarify the interaction of thermal water with local cold groundwater.
Environmental impacts	• Hydrothermal systems may be having an impact on wildlife (Chaffee et al., 2007; Varley and Schullery, 1998)) or on water quantity and/or quality of adjacent streams. • Gases may produce indoor air pollution where there are buildings (Durand, 2006).
Development of local or neighboring resources	• Water (even local cold), geothermal, oil, gas, or mineral production may influence underground water flow path characteristics and therefore ultimately the resulting surface hydrothermal feature; springs may dry up, or change from hot spring to fumaroles as water table drops (Allis, 1983; USGS, 2003; Barrick, 2007). • Monitoring can also help document recovery of hydrothermal features if anthropogenic impacts stop. • Monitoring elevation data can detect subsidence from nearby fluid production.
Planning, development or construction activities	• Geothermal features may be impacted by development or construction, or the thermal features may impact managerial decisions (e.g., road construction in thermal areas).
Research and education activities	• Research and education activities can be a source of data for monitoring efforts (see discussions of vital signs later in this chapter), but if conducted improperly, research and education may have a detrimental impact on geothermal features.
Vandalism	• Vandalism cannot be documented without baseline information about what existed before damage.
Interpretation activities	• Monitoring data can provide data for local interpretation activities.
Volcano monitoring	• Chemical changes may indicate impending hydrothermal explosion (Fournier et al., 1991). • Changes in physical appearance of spring may mean other hazards exist, such as landslides (springs reportedly became cloudy prior to a landslide in a Guatemala thermal area). • Changes may be indicator of magmatic activity (see discussion of fumarole gasses in Smith et al., this volume)

hydrothermal features, and landmarks are apparent. Documenting and monitoring the location of hydrothermal features as well as other attributes allows a database of temperature, chemistry, and photography to be constructed. Digital archives of hydrothermal features assists information sharing, change detection, and integration with other spatial data.

Level One: Basic Mapping and Repeat Photography

Methods. The simplest way to map the location of a hydrothermal feature is to place the feature on a topographic map. Knowledge of basic map reading skills such as topographic contours, landforms, coordinate systems, and map scale allows personnel to plot the location of the thermal feature on a map (refer to Case Study I).

Topographic maps may display several coordinate systems: geographic coordinates (latitude, longitude), UTM coordinates (eastings and northings), and SPCS (x, y). Latitude and longitude are angular distances of measure (spherical coordinates) and difficult to use when plotting a location in the field. In contrast, the UTM coordinate system uses a linear scale of measurement based on dividing the Earth into 60 zones and measuring locations in meters from baselines established for each zone. This linear measurement of distance means that field personnel can use a simple scale, ruler, or grid to easily and consistently plot hydrothermal features on a map or determine coordinates of a new hydrothermal feature.

When reporting the coordinates, field personnel should note the datum of the coordinate system along with its x, y coordinates

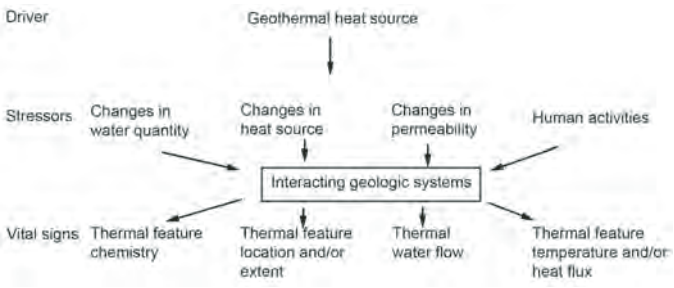


Figure 6. Diagram showing driver, stressors, and vital signs of hydrothermal systems.

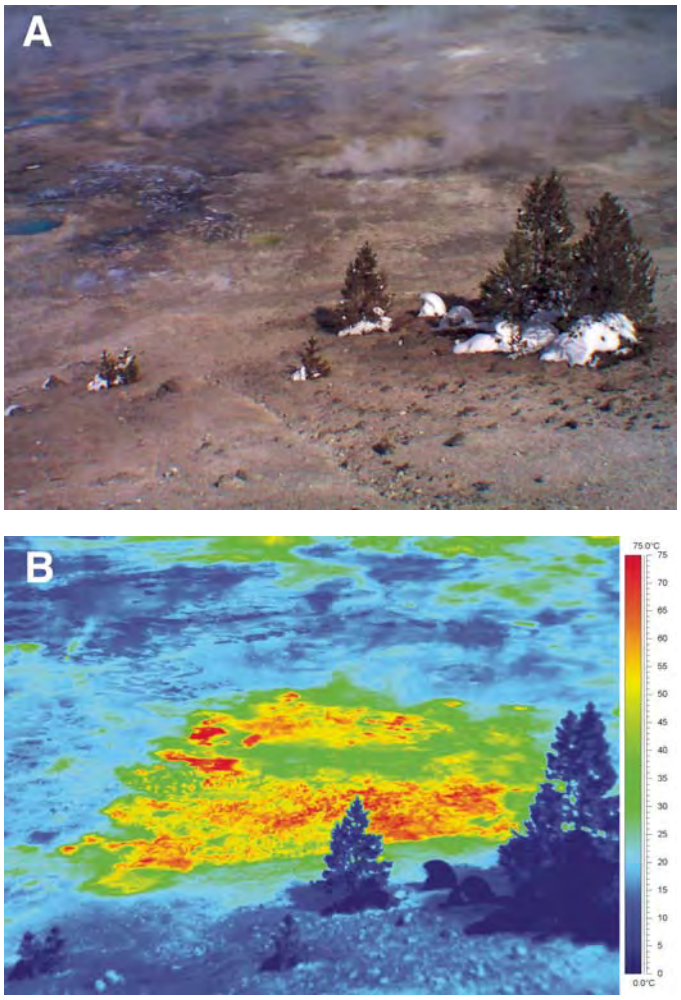


Figure 7. (A) In this daylight photograph, the areas of steaming ground are obviously dangerous. Areas of unsafe, hot ground may be difficult to determine by simply looking at the hydrothermal area. (B) Thermal-infrared photograph of the same area shown in A. The area between the steam vents and the trees is hot (50–75 °C) and extremely dangerous.

(i.e., latitude and longitude or northings and eastings). **Datums** are a set of parameters and control points used to accurately define the three-dimensional shape of the Earth. U.S. Geological Survey topographic maps commonly use the North American Datum (i.e., NAD 27). Incorrect datums or no information about the datum cause position errors (tens of meters) and negate efforts to accurately map a location. Coordinates (x, y, and the datum) can be entered into a spreadsheet along with elevation, date of observation, name(s) of field personnel, and name (if any) of the hydrothermal feature.

Repeat photography may show changes in morphology of the hydrothermal feature, changes in the outflow channel (amount of water, color, shape), or changes in the microbial community at a variety of scales. Changes in vegetation, either new vegetation growing or established vegetation being killed, may be identified. The challenge is to gather enough information to document natural changes and distinguish natural changes from anthropogenic changes.

When locating a hydrothermal feature, it is wise to determine a site for repeat photography. Characteristics of a good site for repeat photography include a clear view of the hydrothermal feature as well as its spatial extent, identifiable landmarks, and accessibility to the site. Information about the photographs can be added to a spreadsheet. In addition to repeat photography, this spreadsheet becomes a central data repository for temperature measurements and chemical measurements of hydrothermal features.

Visualization and analyses of the spreadsheet data is important for understanding hydrothermal systems. It is difficult to see relationships between attributes of hydrothermal features or temporal trends within a spreadsheet or table. When viewed as a graph or map, the same data easily allows spatial relationships and temporal trends to be discerned. A variety of free to low-cost software allows visualization of spreadsheet data and three-dimensional viewing of map information.

Timing and frequency. Absent human impact, dynamic and changing hydrothermal activity ultimately determines the timing and frequency of repeat mapping and photography. For stable, silica-rich hot spring systems, a visit once per year may be sufficient to map hydrothermal features. Monthly visits for mapping and repeat photography may be required in acidic hydrothermal systems near infrastructure or developed areas. In rapidly depositing, carbonate-rich hydrothermal systems, weekly visits and photographs may document dramatic changes in the hydrothermal feature as well as the system's associated vent, pool, and terraces. Hydrothermal areas with the potential for catastrophic changes (hydrothermal explosions or collapse) may require daily visits for repeat photography. New hydrothermal activity or changes in hydrothermal activity requires additional mapping.

Equipment and costs. The easiest map to use for documenting the location of hydrothermal features is a U.S. Geological Survey 7.5 minute topographic map. Topographic maps display elevation, contours, streams, lakes, infrastructure, coordinate systems, and other cartographic information. These 1:24,000-scale topographic maps cover an area of ~10 by 14 km and are

available at no cost on the Internet from the U.S. Geological Survey. Scales designed for consistently reading map coordinates (lat/long or northings and eastings) are available for less than $20 (all amounts herein are in US$). Waterproof notebooks and all-weather pens preserve field data, especially when field personnel are working during wet weather. Although any existing camera allows repeat photography, a digital camera is excellent. Digital images allow links in databases, easy comparisons with other digital photographs, and information sharing. A computer capable of storing electronic images and entering data into a spreadsheet program is necessary.

Limitations. Limitations include the spatial accuracy of the location and the need for data storage and/or archival space. The most significant limitation is the accuracy of locating hydrothermal features on a topographic map. Factors affecting spatial accuracy include the inherent accuracy of the topographic map, identifiable landmarks, changes in topography, vegetation changes, date of the topographic map, and skills of field personnel. Digital photographs require space for data storage and space for backup and/or archive of images.

Interpretation. The estimated precision of a hydrothermal feature's location affects how changes in the location of the hydrothermal feature are evaluated. For example, if the hydrothermal feature is poorly located (within 10 m), then it is difficult to detect small changes. Level-one mapping can easily document changes in hydrothermal feature location or activity if new hydrothermal features appear or existing features cease being active.

Level Two: GPS Survey and Monuments for Repeat Photography

Methods. A handheld, recreational-grade global positioning system (GPS) receiver can improve the accuracy and precision of locating hydrothermal features. With a handheld GPS receiver, field personnel directly gather coordinates in the field. Field personnel need to consider their personal safety when approaching a hydrothermal feature and should note the GPS position with respect to the hydrothermal feature (i.e., coordinates were taken at the northern edge of a 10-m-wide pool). Although GPS receivers and associated data loggers automatically log positions, field personnel also should write the feature's x-y coordinates and associated map datum in a waterproof field notebook. This recommendation is important whether field personnel are taking measurements in easily accessible hydrothermal areas or difficult-to-access hydrothermal areas. The precision of the GPS receiver determines the number of hydrothermal features to be mapped or located within an area. For example, if the GPS receiver is precise to ±4 m, it makes little sense to map hydrothermal features that are 2 m apart.

For repeat photography, a high-quality camera, fixed photographic monuments, and photographic software improve the accuracy of locating hydrothermal features and detecting change within the hydrothermal system. Some digital cameras allow input from a GPS receiver, thereby locating the site of the photograph. The GPS data become part of the data file that accompanies each photograph. A fixed photographic monument can be as simple as a mark on a handrail or the ground. With fixed photographic monuments, field personnel can take photographs from a consistent location. With a fixed location, personnel can view time-sequences of digital photographs and may see change occurring over days, weeks, months, or years. Documentation of change is more exact due to the improved estimate of location and establishment of photographic monuments.

Visualization and analyses of data are important at any level. With moderate funds, data from the GPS receiver can be integrated with low-cost software for comparison of photographs, low-cost geographic information system (GIS) software or any existing GIS programs. Professional versions of visualization software allow users more options for importing GIS data and visualizing the data with existing or newly acquired high-spatial resolution airborne imagery. Some photographic hardware and software even allow the creation of a movie from photographs taken from the same location through time.

Timing and frequency. Similar to level-one efforts, the dynamic and changing hydrothermal activity ultimately determines the timing and frequency of additional mapping and repeat photography. The types of hydrothermal systems (stable silica-rich, hot spring systems, acidic hydrothermal areas, rapidly depositing, carbonate-rich systems, hydrothermal explosions or collapse features) also influence whether visits are annual, monthly, weekly, or daily. With a recreational-grade GPS receiver, improved mapping precision may warrant more frequent visits by field personnel.

Equipment and costs. A recreational-grade, handheld GPS receiver costs hundreds of dollars. Basic digital cameras with associated software also cost hundreds of dollars, whereas specialized photographic software may cost thousands of dollars. Training for field personnel and field personnel time are additional costs.

Limitations. On-the-job training, increased data storage, and misrepresentations of hydrothermal features are limitations of the level-two survey. If field personnel are not already familiar with GPS technology, coordinate systems or low-cost digital mapping, then some on-the-job training is necessary for accurately locating hydrothermal features. Both level-one and level-two surveys of hydrothermal features view hydrothermal features as points on Earth's surface. A point is a very simplistic way to represent a large irregularly shaped hydrothermal pool. Another limitation is the difficulty in determining coordinates for hydrothermal features that are closer to each other than the precision of the GPS receiver. The amount of data storage significantly increases if a large megapixel digital camera is used for repeat photography.

Interpretation. Similar to level one, the estimated precision of a hydrothermal feature's location affects how changes in the location of the hydrothermal feature are evaluated. For example, if the hydrothermal feature is only located to 5 m, it is difficult to detect small changes. However, the increased mapping precision of a level-two survey allows better documentation of changing hydrothermal activity.

Level Three: Mapping or Survey-Grade GPS Receivers and High-Spatial Resolution Airborne or Satellite Imagery

Methods. High-precision mapping or survey-grade GPS receivers accurately locate hydrothermal features. Mapping-grade GPS receivers are precise to within ±20 cm using post-processing differential corrections or real-time beacons. Survey-grade GPS receivers identify locations within ±1 cm or less. A single point may represent an individual hydrothermal feature or a polygon may represent the perimeter and area of a hydrothermal pool. With personal safety in mind, field personnel can use distance-measuring lasers linked with the GPS receiver to create an offset distance and safely walk the perimeter around an extensive hydrothermal feature such as a pool. Additionally, high-precision GPS receivers potentially enable field personnel to map closely spaced hydrothermal features.

High-spatial resolution airborne (less than 1 m pixels) or satellite imagery (1–5 m pixels) allow efficient and safe mapping of hydrothermal features over a large area. Instrument platforms may include a balloon, an unmanned aerial vehicle (UAV), helicopter, a fixed-wing aircraft, or satellite. Airborne sensors may be visible and near-infrared. Digital cameras attached to a balloon can safely and efficiently map hydrothermal features within centimeters of their actual location (Planer-Friedrich et al., 2008). The precise location of hydrothermal features depends upon several factors, including (1) the pixel resolution of the camera or sensors, and (2) the accuracy of rectifying high-spatial resolution imagery to known locations on Earth's surface. Image processing and GIS programs will import high spatial resolution imagery for georectification, display, analysis, and integration with other spatial information.

At level three, visualization, mapping, image processing, GIS and GPS software reach the pinnacle of data integration. Software will correct field GPS coordinates, import real-time corrected coordinates from a field computer, and display the GPS data with existing GIS data or imagery for further analysis and data integration.

Timing and frequency. The cost and complexity of these level-three methods generally limits the mapping and monitoring of hydrothermal features to an annual effort. An optimal time for mapping hydrothermal features is late fall or when hydrothermal flow conditions are least affected by seasonal snowmelt or other events. During spring, seasonal snowmelt may mask hydrothermal waters. During winter, areas with little or no snow can delineate active hydrothermal areas (Watson et al., 2008; White, 1969). Although mapping hydrothermal features during winter is possible, logistically it can be more difficult, especially if field personnel need to be deployed to support new acquisition of high-spatial resolution imagery.

Equipment and costs. Mapping- and survey-grade GPS systems (receivers, antennas, handheld computers, real-time-beacons, etc.) are available from a range of vendors. Mapping-grade GPS systems cost thousands of dollars; survey-grade GPS systems cost tens of thousands. Software for collecting and correcting GPS data also needs to be purchased and installed on mobile mapping units and office computers. There is additional cost for software on portable mapping units and office computers. Field and office computer costs range from thousands to tens of thousands of dollars. Budgets should include: (1) additional software costs if the integration of GPS data with existing or new GIS data is desired; (2) a high-end computer with data storage, data back-ups, and archive capability for the high-volume of data; and (3) a database manager. Additional costs may include maintenance for hardware and software, as well as technical support.

Image acquisition costs vary considerably. Helium balloon equipment can be assembled for thousands of dollars. UAV and sensors are becoming more common and are available from a variety of commercial, government, amateur, and other sources. Under contract or a cooperative agreement, commercial companies, universities, and government agencies can fly hydrothermal areas and deliver oriented, georectified, and GIS-ready image mosaics. High-spatial resolution satellite imagery may cost thousands of dollars. The cost of software for processing, display, and analysis of images can vary from thousands to tens of thousands of dollars. If budgets preclude new image acquisition, then personnel may use existing high-spatial resolution (i.e., historic) aerial photographs (Shean, 2006) for mapping the location of hydrothermal features and detecting changes in hydrothermal activity.

Limitations. Equipment costs, highly skilled personnel, and time for surveys limit the frequency of high-precision GPS surveys of hydrothermal features. Even though the GPS receiver can locate hydrothermal features very precisely, field personnel may not be able to safely access some hydrothermal features. In addition to specialized software, highly trained personnel are necessary to acquire and process high-accuracy GPS locations.

Several limitations affect the use of high-spatial resolution imagery for locating hydrothermal features. These limitations include weather, accurate ground control points, equipment costs, image acquisition costs, image processing costs, and skilled personnel. Stable weather is necessary for handling a helium balloon and for acquiring airborne imagery. Accurate ground control points may be necessary for rectifying high-spatial resolution imagery to known locations on Earth's surface. Highly trained personnel must insure that image acquisition, geometric corrections, and processed imagery meet the needs of the hydrothermal feature survey. Specialized image processing software is needed for the display, accurate rectification of individual airborne images into a mosaic, and analysis of airborne imagery. Generation of a high-spatial resolution aerial mosaic is a time-intensive process for large areas.

Interpretation. Similar to level two, the estimated precision of a hydrothermal feature's location affects how changes in the location of the hydrothermal feature are evaluated. Mapping- and survey-grade GPS receivers locate hydrothermal features within centimeters. Balloon surveys also may result in centimeter precision. The accuracy and precision of locations derived from airborne imagery can vary considerably. Factors affecting

the accuracy and precision include quality of ground control points, spatial resolution of the airborne imagery, and method of georectification.

Vital Sign 2: Spatial Extent of Hydrothermal Areas

The spatial extent of hydrothermal areas is a basic attribute for identifying active thermal areas as well as thermal barrens. An **active hydrothermal area** means that heat is being emitted from the hydrothermal system. Active hydrothermal areas may be contained within a thermal barren, or may exist independently in areas of vegetation. A thermal barren is a non-vegetated area of white, hydrothermally altered ground that may contain a variety of active hydrothermal features (fumaroles, thermal pools, and possibly geysers).

Thermal-infrared imagery best measures and defines *active* hydrothermal systems at Earth's surface. Similar to the discussion under Vital Sign 1, the location and spatial extent of hydrothermal activity may change over time. An accurate baseline map of the spatial extent of hydrothermal activity is crucial to mapping and understanding changes in hydrothermal systems.

Mapping the visible, spatial extent of hydrothermal areas allows the visualization of the hydrothermal areas in relation to rivers, infrastructure, other hydrothermal features, faults, and landforms. Digital archives of baseline maps for active hydrothermal areas assists information sharing, change detection, and integration with other spatial data.

Level One: Basic Mapping and Repeat Photography

Methods. Similar to Vital Sign 1, the simplest way to map the visible, spatial extent of a hydrothermal area is to locate the area on a topographic map. With basic map-reading skills, field personnel can sketch the extent of the hydrothermal area. It is important to clearly describe the criteria used to define the hydrothermal area. Such criteria may include descriptors such as "white ground barren of vegetation" or "areas of hydrothermal alteration." Entry of field data (date, name of field personnel, etc.,) into a spreadsheet begins the process of creating a database with information about the hydrothermal area.

Repeat photography may show changes in the spatial extent and activity within a hydrothermal area. Similar to the discussion under Vital Sign 1, the challenge is to gather enough information to document natural changes and distinguish natural changes from anthropogenic changes. It is wise to determine a consistent site for repeat photography of a hydrothermal area. Characteristics of a good site for repeat photography include a clear view of the hydrothermal area, identifiable landmarks (mountains, hills, terraces, etc.), and accessibility. Trees are subject to thermal kill and therefore may be poor identifiable features for long-term repeat photography (for example, see Fig. 10). Spreadsheets are a good way to archive information about the photographs. In addition to repeat photography, this spreadsheet becomes the central data repository for temperature measurements and chemical measurements within the hydrothermal area.

Visualization and analyses of the spreadsheet data are important to understanding hydrothermal systems. For hydrothermal features or areas, placing information within a spreadsheet is the first step. However, importing spreadsheet information into a mapping program easily allows spatial relationships and temporal trends to be visualized.

Timing and frequency. Within a hydrothermal area, dynamic and changing hydrothermal activity ultimately determines the timing and frequency of mapping efforts and repeat photography. In stable, silica-rich hot spring systems, one visit per year may be sufficient to map the spatial extent of the visible hydrothermal area or thermal barren. Monthly visits for mapping and repeat photography may be required in acidic hydrothermal areas near infrastructure or developed areas. In rapidly depositing, carbonate-rich systems, weekly visits and photographs may document dramatic changes in the spatial extent of the hydrothermal area. The questions to be answered about the hydrothermal system also influence the timing and frequency of monitoring efforts.

Equipment and costs. U.S. Geological Survey 7.5 minute topographic maps are the easiest base map to use for mapping the spatial extent of active hydrothermal areas. If the spatial extent of an active hydrothermal area is not easily mapped with these 1:24,000-scale U.S. Geological Survey topographic maps, then field personnel need to construct their own maps of spatial extent using pace-and-compass mapping techniques (Compton, 1962). Safety of field personnel is the primary concern when mapping the perimeter of an active hydrothermal area with a pace-and-compass technique. If field personnel need to map the perimeter of an active hydrothermal area, they should assess the personal risk of walking the edge between vegetated and non-vegetated areas. When traversing thermal areas, vegetation is not a guarantee of personal safety; wet, boggy, hydrothermal areas are known to be areas of unstable thermal ground.

A digital camera is best for repeat photography. Digital images allow links in databases, easy comparisons with other digital photographs, and information sharing. A computer capable of storing and archiving electronic images as well as entering data into a spreadsheet program is necessary.

Limitations. Limitations of this method include the spatial accuracy of the mapped hydrothermal area and the storage of data. The skill of field personnel in reading and using topographic maps as well as pace-and-compass mapping affects the spatial accuracy of the baseline maps. Another critical factor affecting the spatial accuracy is the interpretation, by field personnel, of the physical characteristics used to define the boundaries of the thermal area. Other factors affecting spatial accuracy include the inherent accuracy of the topographic map, identifiable landmarks, changes in topography, changes in vegetation, and the date of topographic map. Digital photographs require space for data storage and space for backup and/or archive of images.

Interpretation. Similar to Vital Sign 1, the estimated precision of mapping the spatial extent of a hydrothermal area affects how changes are evaluated. If the active hydrothermal area is

poorly mapped (within 10 m) then it will be difficult to detect small changes in spatial extent.

Level Two: Mapping Spatial Extent with a GPS Receiver and Repeat Photography

Methods. A handheld, recreational-grade GPS can improve the accuracy and precision of mapping active hydrothermal areas. With a handheld GPS, field personnel can map x-y coordinates in the field. Although GPS receivers and associated data loggers automatically log positions, it is highly recommended that the field team record x-y coordinates and the datum in a field notebook. The precision of the GPS receiver determines the accuracy and use of the baseline map of a hydrothermal area.

For repeat photography, a high-quality camera, fixed photographic monuments, and photographic software improve the accuracy of mapping. A fixed photographic monument can be as simple as a mark on a hand rail, boardwalk, or the ground. With a fixed location, personnel can construct a time sequence of digital photographs. This time sequence of photographs may show change over days, weeks, months, or years. The understanding of change within a hydrothermal area will be more exact with improved location and the establishment of photographic monuments.

Visualization and analyses of data are important at any level. With moderate funds, personnel can integrate data from the GPS receiver with low-cost visualization software and low-cost GIS software, or any existing GIS programs. Professional versions of visualization software allow users greater flexibility with data visualization and integration. Personnel may integrate GPS data with existing GIS data and any existing high-spatial resolution imagery, such as aerial photographs, digital orthophotographs, or satellite imagery.

Timing and frequency. Similar to level-one efforts, the dynamic and changing hydrothermal activity ultimately determines the timing and frequency of mapping spatial extent and repeat photography. The types of hydrothermal systems (stable, silica-rich hot spring systems, acidic thermal areas, or rapidly depositing, carbonate-rich systems) also influence whether visits are annual, monthly, weekly, or daily. With a recreational-grade GPS receiver, the improvements in precision and accuracy may require more frequent visits by field personnel.

Equipment and costs. A recreational-grade, handheld GPS receiver costs hundreds of dollars. Basic digital cameras with associated software also cost hundreds of dollars. Highly specialized photographic software may cost thousands of dollars. Field personnel time and training add to the cost.

Limitations. On-the-job training, increased data storage, and misrepresentations of hydrothermal areas are limitations of the level-two survey. If field personnel are not already familiar with GPS technology, coordinate systems, or low-cost digital mapping, then some on-the-job training is necessary for accurately mapping hydrothermal areas. Both level-one and level-two surveys of hydrothermal areas depend on field personnel's interpretation of either thermal barrens or active thermal areas. The amount of data storage significantly increases if a large megapixel digital camera is used for repeat photography.

Interpretation. Both level-one and level-two baseline maps of active hydrothermal areas allow field personnel to represent an area of hydrothermal activity. By mapping the visible, spatial extent of hydrothermal areas, field personnel create an accurate representation of individual thermal pools or an entire hydrothermal basin. Thus, a large irregularly shaped pool can be depicted as an area of hydrothermal activity rather than just an individual point on Earth's surface.

Level Three: Mapping Spatial Extent using GPS with High-Spatial Resolution Aerial Photography or Satellite Imagery

Methods. High-precision mapping or survey-grade GPS receivers can accurately and precisely define the spatial extent of active hydrothermal areas. Mapping-grade GPS receivers determine locations within ±20 cm using post-processing differential corrections or real-time beacons. Survey-grade GPS receivers identify locations within ±1 cm or less. Field personnel can map the spatial extent of an individual thermal pool, an entire hydrothermal sub-basin, or an entire hydrothermal area with many sub-basins by walking their perimeters. With personal safety in mind, field personnel can use distance-measuring lasers linked with the GPS receiver to create an offset distance, and safely walk the perimeter of the hydrothermal area. High-precision GPS receivers potentially enable field personnel to document small changes in spatial extent over short-time intervals.

High-spatial resolution airborne or satellite imagery allows efficient and safe mapping of hydrothermal areas. Platforms may include a balloon, an unmanned aerial vehicle (UAV), or a fixed-wing aircraft. Sensors may be meteorologic, visible, or near-infrared. Digital cameras attached to a balloon can safely and efficiently map active hydrothermal areas within centimeters of their actual location (Planer-Friedrich et al., 2008). Precise location depends upon several factors, including the pixel resolution of the camera or sensors and the accuracy of rectifying high-spatial resolution imagery to known locations on Earth's surface. Image processing programs allow for orientation, georectification, display, and analysis of new airborne or satellite imagery. Skilled personnel may compare the newly acquired high-spatial resolution imagery with any preexisting visible imagery (natural color photographs, color-infrared photographs, and black-and-white digital orthophotographs). Both GIS and image processing software allow the integration of visible airborne or satellite imagery with other spatial information (roads, rivers, buildings, GPS locations of new or changing hydrothermal areas, etc.).

Timing and frequency. The cost and complexity of these level-three methods limits mapping and monitoring to an annual, biennial, or multiple-year effort. An optimal time for mapping is when hydrothermal flow conditions are least impacted by seasonal snowmelt or other events. During spring, seasonal snowmelt may cause an overestimation of spatial extent. During winter, areas with little or no snow can delineate thermal areas (Watson et al., 2008; White, 1969). Winter/late spring image

acquisitions may require field personnel to access snowbound areas and deploy equipment to support image calibration/validation efforts or collect field data. Although mapping the spatial extent of hydrothermal areas during winter is possible, logistically it greatly increases the field effort and time for field personnel to collect field data for calibration/validation of imagery or support of airborne flights.

Equipment and costs. Mapping and survey-grade GPS systems (receivers, antennas, handheld computers, real-time-beacons, etc.) are available from a range of vendors. Mapping-grade GPS systems cost thousands of dollars; survey-grade GPS systems cost tens of thousands of dollars. Software for collecting and correcting GPS data also need to be purchased and installed on mobile mapping units and office computers. The cost for software on portable mapping units and office computers is an additional cost. Field and office computer costs range from thousands to tens of thousands of dollars. A level-three budget should include: (1) additional software costs for integrating GPS data with existing or new GIS data; (2) a high-end computer with data storage, data back-ups, and archive capability for the high-volume of data; and (3) the hiring of a database manager. Additional costs may include maintenance for hardware and software, as well as technical support. Image acquisition costs for new high-spatial resolution airborne or satellite imagery is similar to the level three cost for mapping hydrothermal features.

Limitations. Equipment costs, highly skilled personnel, and time for surveys limit the frequency of high-precision maps of active hydrothermal areas. Even though field personnel can create precise and accurate maps of spatial extents, they may not be able to safely access some active thermal areas, such as the edge of a large hydrothermal pool. In addition to specialized software, highly trained personnel are necessary to acquire and process high-accuracy GPS locations.

Several limitations affect the use of high-spatial resolution airborne or satellite imagery. These limitations include weather, ground control points, equipment costs, image acquisition costs, image processing costs, and skilled personnel. Stable weather is necessary for handling a helium balloon and for acquiring airborne imagery. Ground control points may be necessary for accurately rectifying airborne images to known locations on Earth's surface. Highly trained personnel must ensure that image acquisition, geometric corrections, and processed imagery meet the goals of the hydrothermal survey. The precise rectification of individual airborne images into a mosaic for analysis of airborne imagery requires specialized image processing software. A mosaic of visible, high-spatial resolution airborne imagery is a time-intensive process for large areas, especially with multiple visible bands (red, green, blue, and near-infrared).

Interpretation. Similar to the level-two mapping of hydrothermal areas, personnel should assess any changes in the spatial extent of hydrothermal areas with regard to the estimated precision of the image. Mapping- and survey-grade GPS receivers can define the spatial extent of hydrothermal areas within centimeters. Balloon surveys also may result in centimeter precision. The accuracy and precision of mapped hydrothermal areas using airborne imagery may vary due to the quality of ground control points, the spatial resolution of the airborne imagery, and the method of georectification.

Vital Sign 3: Temperature and Heat Flow

Heat is a fundamental physical property of all geothermal systems. Heat is a form of energy that flows from high to low temperatures. Scientific units of measurement are the joule (Newton-meter) or calorie (energy required to raise 1 g of water from 14.4 °C to 15.4 °C). Scientific units of temperature measurement are in degrees Celsius. Temperature does not directly measure the total heat of a hydrothermal feature or area. The amount of heat emitted by a hot object is related to the temperature difference between an object and its surroundings, the mass of the hot object, and its specific heat. Thus, a thermal pool with a large mass and low temperature may emit more heat than a smaller pool with a small mass and high temperature.

Measured changes in temperature of a geothermal system may relate to the heat source of the geothermal system, heat transfer mechanisms within the system, and/or atmospheric conditions. Heat sources for a geothermal system can vary from molten rock to the normal temperature increase with depth below Earth's surface (geothermal gradient). Heat transfer mechanisms include conduction, convection and radiation. Atmospheric conditions such as air temperature, high winds, and recent local precipitation can lower the surface temperature of a hydrothermal area. Ultimately, observed changes in temperature relate to the natural variability of geothermal systems (heat source or heat transfer mechanisms) and/or anthropogenic influences.

Temperature is an easy-to-measure physical parameter that characterizes a hydrothermal system. Low-cost, alcohol-bulb thermometers, digital temperature probes, and small handheld **thermal-infrared (TIR)** sensors all measure single point temperatures of thermal water or ground. The scientific goal of a geothermal monitoring plan defines the required precision and accuracy of the temperature measurement. For example, bulb-thermometers generally are precise to within ±1–2 °C, whereas digital thermometers are precise to within ±0.1–0.01 °C. Immersion of the temperature-sensing portion of the thermometer in the same location is necessary for accurate and precise repeat temperature measurements (Figs. 8A and 8B). Representative temperatures of thermal features are best measured at or near the vents of the thermal features. Safety considerations sometimes necessitate the measurement of temperatures in outflow channels.

Water, rocks, sediments, and vegetation all emit thermal energy differently. This difference is an important parameter to know when estimating temperature with handheld TIR sensors and aircraft-mounted TIR detectors. **Emissivity** is a measure of how well objects radiate or emit thermal energy. Hot objects that emit 100% of their thermal energy at a specified temperature are perfect emitters of radiant thermal energy. Objects that emit less than 100% of their thermal energy are not perfect emitters of

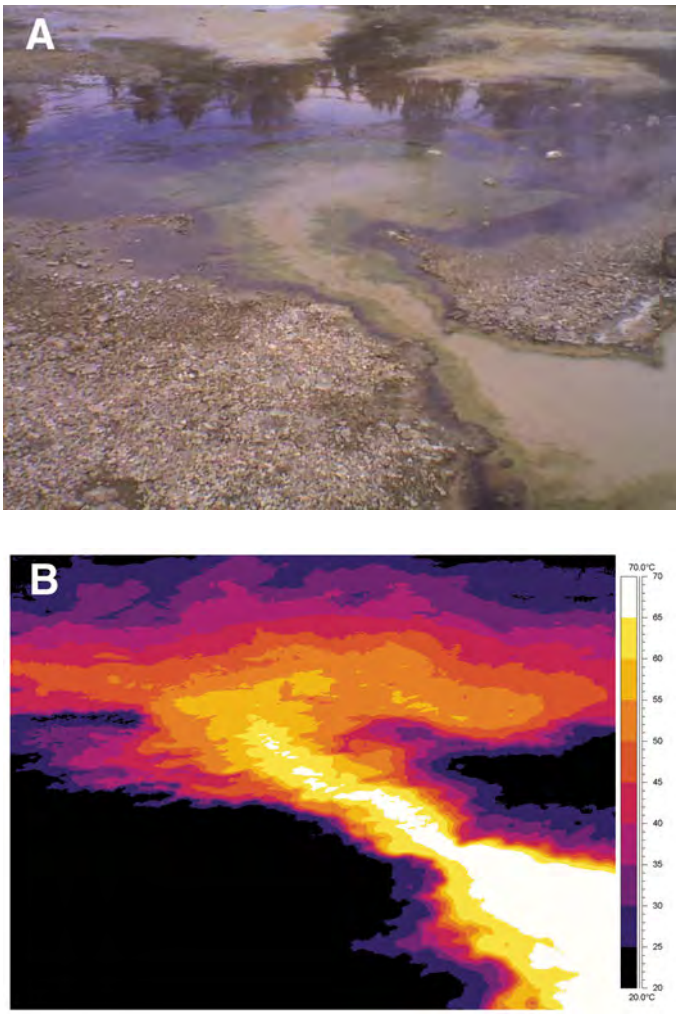


Figure 8. (A) Photograph of the outflow from a thermal pool. At its narrowest portion, the width of the channel is ~30 cm. (B) A forward-looking infrared (FLIR) image of the same thermal outflow shown in A. Note the temperature variation in the pool's outflow channel from 45 °C to 70 °C. When using an immersion temperature probe, field personnel should place the probe at the same location in the outflow channel for repeatability of temperature measurements.

thermal energy. Perfect emitters of thermal energy would have an emissivity of 1.0. All other objects have an emissivity less than 1.0. If a handheld TIR scanner has a set emissivity of 1.0, then the temperature of a hydrothermal pool will be underestimated. For example, a thermal pool measured with a radiant measured temperature of 73 °C, emissivity 1.0, has a temperature closer to 76 °C, using an emissivity of 0.93 for water.

It is important to check the accuracy of temperature probes occasionally. A simple way to calibrate is to insert the probe into a vigorously stirred container of ice and water. The temperature of this mixture (the melting point of water) should be 0.0 °C at one atmosphere. If the measured temperature is significantly different from 0.0 °C, then the temperature probe should be recalibrated according to the manufacturer's instructions. Most manufacturers will perform calibrations on temperature probes for an additional fee.

Level One: Single Point Temperature Measurements

Methods. The purpose of the geothermal monitoring program determines the precision, accuracy, and type of temperature sensors used. The goals of many geothermal monitoring efforts can be met using simple, handheld temperature probes. These simple temperature probes are precise to within a few tenths of a degree Celsius. Personnel should note the type and manufacturer of temperature sensing equipment used and record the type of sensing equipment in a waterproof field notebook, electronic spreadsheet, or database.

Field personnel need to choose the location of the temperature measurement carefully. Although the primary consideration is the safety of personnel, a secondary consideration is how well the chosen site represents the temperature of the hydrothermal feature. For example, a well-mixed outflow channel of a hot spring may provide a representative temperature (Figs. 8A and 8B). This location alongside the well-mixed outflow channel may also be a safe place to stand for repeat temperature measurements. When taking a temperature measurement, it is important to immerse the temperature probe to the same depth so that repeat temperature measurements are comparable. Using this technique, field personnel can also take temperature measurements in the outflow from a pumping well or at shallow depths in wells.

Low-cost, handheld TIR temperature detectors have distinct advantages and disadvantages when compared to bulb and digital thermometers. Because field personnel do not have to immerse a probe into the thermal fluid, handheld TIR detectors are safer to use than immersion probes. The operator simply aims the TIR device at the spot to be measured and reads a temperature from the TIR instrument. Field personnel can measure many temperatures quickly and safely at different locations. However, the TIR sensor is only measuring the surface (skin) temperature of a hydrothermal feature or area of thermal ground. The temperature of the upper few microns may not be representative of the entire feature or area. Any vapor or steam rising from the hydrothermal feature or thermal area will impede the TIR instrument's ability to measure the actual temperature of the hydrothermal feature.

The temperature being measured using TIR devices results from radiant heat transfer. Generally, radiant and immersion temperatures compare well, but sometimes may vary due to an object's physical characteristics (see previous discussion on emissivity). Another disadvantage of handheld TIR sensors is that the temperature of an *area* is measured, not just the temperature of a single point. Field personnel must know the dimensions of the area being measured by the TIR sensor so that temperature measurements are made for the area of interest.

Field personnel should record all data in a waterproof field note book with an all-weather pen, then enter the data into a spreadsheet or database. Recorded data should include: date, time, coordinates of measurement, name of field personnel, type

of temperature equipment, temperature, fluctuations of temperature, and any observations. Location and photographic documentation of the measurement site is important for consistency and comparison with future temperature measurements.

Timing and frequency. Two key factors affecting timing and frequency are study design and accessibility. Once a temperature baseline has been established for a hydrothermal feature, the frequency of temperature measurements can decrease. The study design of a geothermal monitoring plan determines baseline data and maps. For example, a remote backcountry hydrothermal feature unaffected by human activities may only require annual monitoring. However, a similar hydrothermal feature affected by human activities may require monthly or weekly monitoring. Also, simple measuring techniques may not monitor remote hydrothermal features or areas adequately. Monitoring remote hydrothermal features may require temperature loggers. (See discussion in Vital Sign 3, level two, concerning temperature data loggers.)

When starting a monitoring program, temperature measurements should be made frequently to define any daily or seasonal variations. For a high-temperature hydrothermal feature with considerable water flow, the hydrothermal feature's temperature may not vary significantly over time. Thus, one measurement every six months may be sufficient. External factors such as air temperature may affect the measured temperatures of low-temperature and low-flow hydrothermal features greatly. It is a challenge to measure the temperature of these hydrothermal features accurately.

Equipment and costs. Thermometers, digital temperature probes, and handheld TIR sensors may be purchased for tens to hundreds of dollars from a variety of vendors. Alcohol-bulb thermometers are preferable to mercury-bulb thermometers due the environmental consequences of a broken thermometer. Both thermocouple and thermistor digital temperature probes are available. Most vendors sell a variety of probes with different lengths, sheathing, and versatility. Handheld TIR sensors range from $100 and up, depending on factors such as the instrument's precision, ability to set the emissivity, laser-pointing options, and area of ground measured.

Limitations. Even though it is relatively easy for field personnel to take single-point temperatures, these temperatures may not describe the hydrothermal feature or area adequately. For example, personnel may not know the relationship of a thermal spring's outflow to the vent temperature of hydrothermal spring. Also, single-point temperatures do not quantify changes in the total heat of the hydrothermal feature or system. Single-point temperature measurements in wells may be useful, but do not quantify the temperature change with depth in the well (the geothermal gradient).

Logistics, repeatability of measurements and quality-control are additional limitations of using level-one temperature instruments. It may be difficult to revisit remote or dangerous hydrothermal features for repeat-temperature measurements. Also, it may be difficult to repeat measurements of temperatures at the same location due to changes in personnel or inadequate documentation of location. Temperature-measuring instruments require calibration to confirm the accuracy of temperature measurements. Calibration of temperature equipment involves maintenance and requires an investment of personnel and time.

Interpretation. Graphing temperatures as a function of time is the simplest way to interpret temperature data (Fig. 9). These graphs allow analysis of the temporal variations of temperature at a single location. Also, it is possible to compare temperature variations between different hydrothermal features or locations.

Graphing time-temperature relationships allows the comparison of thermal feature temperatures to temporal events. Time-variant parameters include air temperature, precipitation, seismicity, or human-related activities. Graphing temperature with respect to any of these variables helps to show the natural variability within the hydrothermal feature or system.

Visualization and GIS programs allow the production of maps or three-dimensional graphics that assist the spatial analysis of temperatures. The spatial distribution of temperatures allows personnel to define and map hot and cold hydrothermal areas or features. If several maps of temperatures exist, then personnel can clearly identify the changing temperature of hydrothermal features or areas as a function of time.

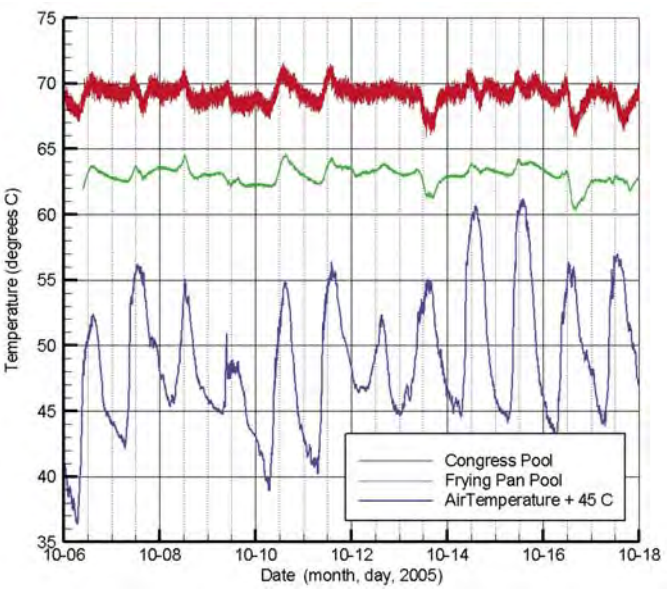


Figure 9. Graph showing the temperature from two thermal pools located 3 km apart in Yellowstone National Park. The purpose of the time-temperature data was to capture temperature in the pools for calibration of an airborne thermal-infrared flight. However, the data is also useful in assessing a potential connection between the pools, as indicated by the similar shape of the time-temperature curves. The air temperature during this time period was not the sole control on the shape of the time-temperature curves for these two hydrothermal features. For example, at noon on 16 October, the air temperature is at maximum whereas the temperatures of the hydrothermal features are at a minimum. Note that the air temperature has been increased by 45 °C for the purpose of graphical clarity.

Level Two: Temperature Data Loggers

Methods. A temperature data logger increases the amount of temperature data gathered at a thermal feature. Temperature data loggers are electronic devices that automatically record temperatures at user-defined temporal intervals. Similar to handheld digital probes, temperature loggers have variable precisions, accuracies, and probe construction.

The placement of temperature data loggers is similar to the placement of handheld temperature probes. A good site for placing a temperature data logger includes (1) safe access, and (2) a representative temperature of hydrothermal feature or area (Fig. 10). When placing a temperature data logger, field personnel must protect the electronic device from low or high pH, high temperatures, water, animals, and vandalism.

It is important to select appropriate temperature precision and sampling intervals for temperature data loggers. The monitoring program's study design determines the required temperature precision and sampling interval (Fig. 9). For example, collecting a temperature every five seconds in a stable hydrothermal feature generates more data than is necessary. Another factor affecting temperature precision and sampling intervals is the data logger's memory. High-precision and frequency of sampling requires more field visits to download temperature data.

Field personnel use a variety of techniques to download temperature data loggers. Some data loggers require a connection to a laptop computer. Other data loggers utilize a small shuttle to download field data. After download, field personnel connect the shuttle to a computer for final download. Radio-telemetered temperature data loggers are available, but require a high level of maintenance.



Figure 10. Field personnel can place temperature loggers safely using a variety of techniques. The round white temperature logger has been placed on the back side of an information sign. The temperature probe extends into the ground to measure 92 °C temperatures in the area of the foot trail. The National Park Service ranger is holding a painting pole with an attached clamp. A temperature sensor attached to this extension pole can safely measure temperatures of nearby hydrothermal features. The trees in the background were killed by thermal activity.

Calibration of temperature data loggers is an important component of the equipment's use. An easy calibration check is the ice-point calibration (see discussion in Vital Sign 3). Most manufacturers of temperature data loggers will conduct calibrations for an additional fee.

For logging temperatures in wells, winch systems allows field personnel to lower data loggers into a well and record temperature as a function of depth. Such temperature-depth data defines the geothermal gradient and water flow characteristics for the well (Ziagos and Blackwell, 1981; Ge, 1998).

Timing and frequency. Temperature data loggers generate a more complete data set for the hydrothermal feature than level-one temperature data. The frequency of automatic measurements depends upon the thermal characteristics needed for measurement. For example, to capture geyser eruptions, intervals of five seconds to one minute may be necessary. For a large hot spring, time intervals of one hour to one day may be sufficient.

Temperature data loggers may remain in the field for up to one year if the battery is viable. The data logger, however, will require multiple visits per year to download data. The logging interval and logger memory determines the number of visits per year.

Equipment and costs. The cost of temperature data loggers varies with the precision of probes, amount of memory, and download method. Temperature data loggers range from one hundred dollars to over a thousand dollars. Most manufacturers supply different probe lengths, probe configurations (surface probes, immersion probes, etc.). Basic winch-type temperature loggers for the measurement of temperatures in wells are available for hundreds to thousands of dollars.

Limitations. Downloading temperature logger data in the field is a major limitation. Issues include: (1) safe access to temperature loggers for manual download; (2) time and effort for downloading multiple networks of temperature loggers; (3) maintenance of the data loggers (battery replacement, probe replacement, and calibration); and (4) personnel time. Setting parameters for logging temperature data, download of temperature data, analysis of temperatures, and conversion of temperature data to different formats requires specialized software.

Interpretation. The interpretation of data from temperature loggers follows similar techniques described under the level-one discussion. Level-two temperature data is more complete than level-one temperature data. Personnel can correlate temperature data with temperature of other hydrothermal features (Fig. 9), air temperature, barometric pressure, seismicity, and anthropogenic activities more precisely than with level-one temperature data.

The interpretation of temperature-depth data is beyond the scope of this chapter. However, many references discuss the importance and interpretation of downhole temperature measurements (Ziagos and Blackwell, 1981; Ge, 1998).

Level Three: Forward-Looking Infrared Detectors, Aerial Photography or Satellite Imagery

Methods. Humans view the world by gathering visible information with their eyes and sensing the warmth of the sun or other heat sources. Our eyes are our visible sensors that see various combinations of reflected blue, green, and red light from objects. Our hands can sense or *feel* the heat emitted by hot, glowing objects such as burning wood.

Both visible light (0.4–0.75 microns) and infrared energy (~1 micron to 1 cm) have spectrums of energies (Table 3). Instruments can detect or sense reflected visible energy (less than 1 micron wavelength) or radiated thermal-infrared energy (3.0–14.0 microns). Reflected infrared energy (~1–2.5 microns) occupies the portion of the electromagnetic spectrum between visible energy that our eye can see and the heat energy, or **thermal-infrared energy** that humans can feel. Plants strongly reflect this near-infrared energy and photographers can take advantage of this effect to create dramatic photographs.

Thermal-infrared detectors measure heat radiated or emitted by an object. Because liquid water, steam, or snow absorbs thermal-infrared energy, thermal-infrared detectors commonly operate in discrete bands. Thermal-infrared detectors sense thermal energy through transparent atmospheric windows, or "water-free" bands of the electromagnetic spectrum. Thermal-infrared energy from 3.0 to 14.0 microns is the portion of the electromagnetic spectrum that these detectors sense. Thus, thermal-infrared detectors can sense the thermal energy radiated or *emitted* by active hydrothermal systems at Earth's surface.

There are different types of thermal-infrared sensors. Each thermal-infrared sensor has its advantages, disadvantages, and mapping applications such as monitoring active volcanoes, mapping volcanic eruptions, monitoring fires, or monitoring hydrothermal areas (Table 4). The size of the thermal pixels or picture elements (spatial resolution), width of the thermal band (spectral resolution), type of sensor, and instrument platform determine the applications. Thermal-infrared detectors can be handheld forward-looking infrared radiometers (**FLIR**) or mounted on an aircraft or satellite. Aircraft may carry broad-band or narrow-band thermal-infrared sensors. Broad-band thermal-infrared sensors generally operate at 8–12 microns or 3–5 microns. Satellites with thermal-infrared sensors include: the advanced spaceborne thermal emission and reflection radiometer (**ASTER**), the moderate resolution imaging spectrometer (**MODIS**), LANDSAT and the advanced very-high resolution radiometer (**AVHRR**). The MODIS/ASTER simulator, or MASTER (Hook et al. 2001) is an airborne thermal-infrared sensor that acquires thermal-infrared energy in 25 discrete bands at moderate spatial resolution.

Some uses of thermal-infrared sensors for monitoring temperature and heat from volcanoes, mapping hydrothermal minerals and estimating radiative heat flux can be found in the literature. Pergola et al. (2004) used the low-spatial resolution but high-repeat AVHRR satellite imagery to detect thermal areas associated with active volcanism. Pieri and Abrams (2004) used ASTER satellite imagery to monitor active volcanoes. Carter et al. (2006) and Vaughan et al. (2005; 2006) integrated ground (FLIR), airborne (MASTER) and satellite (ASTER) sensors for mapping volcanic activity and thermal areas. Kahle (1987) used NASA's experimental thermal-infrared multispectral **s**canner (TIMS) for mapping mineral alteration, as well as calculating surface emittance, temperature, and thermal inertia. Watson et al. (2008) used a LANDSAT satellite image to calculate a park-wide, radiative heat flux for Yellowstone. Using an airborne FLIR camera, Neale et al. (2008) acquired nighttime high-spatial resolution (~1 m) thermal-infrared imagery and generated a calibrated temperature map (Fig. 11) for Yellowstone's Upper Geyser Basin. Thus, ground, airborne, and satellite thermal-infrared sensors can map and monitor the hydrothermal activity within individual basins or over a broad region.

Timing and frequency. The cost and complexity of these level three methods limits the thermal-infrared mapping and monitoring of hydrothermal areas to an annual, biennial, or five-year efforts. An optimal time to acquire thermal-infrared imagery is late fall, or when hydrothermal flow conditions are least affected by seasonal snowmelt or other events. During the fall, image acquisition within one day of a snow fall may result in poor-quality thermal-infrared images. Snow, high relative humidity, and cool air temperatures may produce thermal fog and obscure thermal features. In addition, imagery with snow-covered and snow-free ground increase the difficulty of processing images and creating mosaics of airborne or satellite images. Thus, timing is critical for acquisition of quality nighttime thermal-infrared imagery.

Equipment and costs. The acquisition and image processing cost for thermal-infrared images using aircraft or satellite varies considerably. Daytime thermal-infrared imagery is more common than nighttime imagery. Although daytime imagery is common, skilled personnel must construct mathematical models to remove the non-hydrothermal component (solar input, etc.) from the imagery. Thus, nighttime thermal-infrared imagery is a more direct measure of a hydrothermal system's heat flow or heart flux. Requirements such as temperature precision, high-spatial accuracy, and timing all add significant cost to any monitoring effort.

Thermal-infrared imagery is available from a variety of commercial, government, and other sources. Low-spatial resolution

TABLE 3. WAVELENGTHS OF THE ELECTROMAGNETIC SPECTRUM

0.4 microns or less wavelength	0.4–0.75 microns wavelength	0.75–2.5 microns wavelength	3.0–14.0 microns wavelength	1 centimeter or greater wavelength
Ultraviolet light, X-rays and gamma rays	Visible light (blue, green yellow, orange, red)	Near-IR or short-wave IR or photographic IR	Thermal infrared (heat)	Microwaves, radio, TV, mobile phones

TABLE 4. COMPARISON OF SOME THERMAL INFRARED SENSORS AND PLATFORMS

Name	Thermal-infrared spatial resolution (pixel size)	Thermal-infrared spectral resolution	Instrument platform
ASTER	90 m	5 bands	Satellite
AVHRR	~1 km	2 bands	Satellite
LANDSAT	60 m	1 broad band	Satellite
MODIS	1 km	17 bands	Satellite
FireMapper	variable	3 bands	Experimental/airborne
MASTER	variable	25 bands	Experimental/airborne
TIMS	variable	6 bands	Experimental/airborne
FLIR	variable	1 broad band	Handheld or airborne

Note: ASTER—advanced spaceborne thermal emission and reflection radiometer; AVHRR—advanced very-high resolution radiometer; MODIS—moderate resolution imaging spectrometer; MASTER—MODIS/ASTER simulator; TIMS—thermal-infrared multispectral scanner; FLIR—forward-looking infrared radiometers.

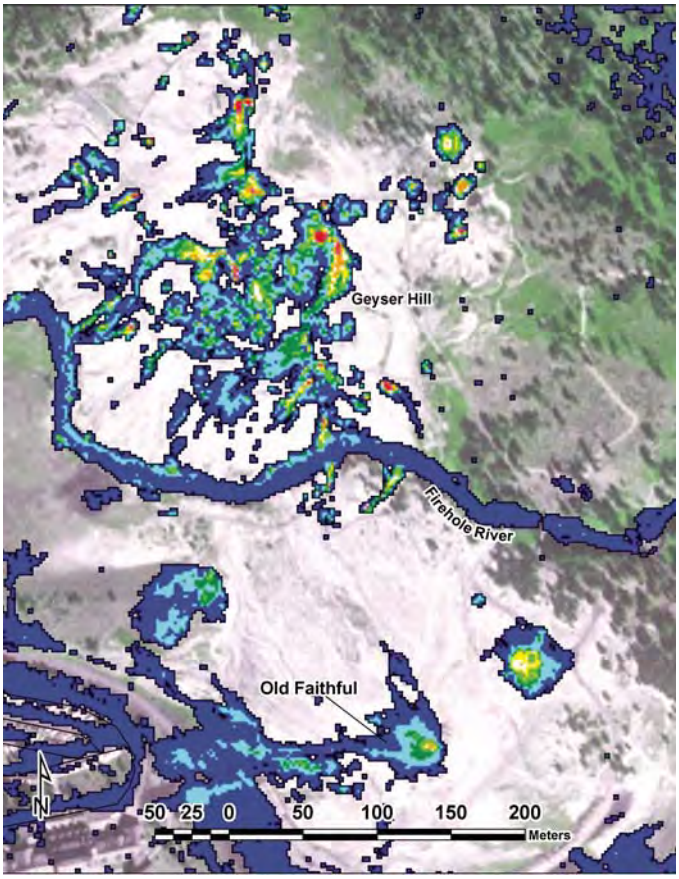


Figure 11. High-spatial resolution temperature map of the Old Faithful area, Yellowstone National Park. This calibrated, nighttime temperature map highlights Old Faithful Geyser and active hydrothermal features on Geyser Hill. This preliminary thermal-infrared (7.5–13 micron), airborne mosaic overlies a color-infrared digital orthophotographic quarter-quadrangle and excludes temperatures less than 5 °C. Darkest blue represents low temperatures between 5 and 10 °C, and red shows high temperatures between 60 and 70 °C. Other intense colors show temperatures between 10 °C and 60 °C. Thermal-infrared imagery courtesy of Christopher Neale and graduate students at Utah State University and Bayani Cardenas at University of Texas.

satellite imagery (thermal-infrared) is available from a variety of vendors. Under contract or collaborative agreements, commercial companies, universities, and government agencies will fly over hydrothermal areas and deliver oriented, georectified and GIS-ready, thermal-infrared mosaics of high-spatial resolution imagery. The cost of software for processing, display, and analysis of images varies. Image processing, data acquisition, flight time, and personnel are the major costs in level three hydrothermal monitoring efforts.

Limitations. Equipment costs, highly skilled personnel, and time for surveys limit the frequency of temperature calibrated, high-precision, nighttime thermal-infrared imagery of active hydrothermal areas. In addition to specialized software, trained personnel are necessary to acquire and process high-accuracy, thermal-infrared imagery.

Several limitations affect the use of nighttime thermal-infrared imagery for mapping the spatial extent of active hydrothermal areas. These limitations include weather, adequate ground control points, equipment costs, image acquisition costs, image processing costs, and skilled personnel. Ground control points or LiDAR images are necessary for rectifying thermal-infrared images to known locations on Earth's surface. In undeveloped areas, it is challenging to accurately georectify daytime, visible imagery. Nighttime, thermal-infrared imagery adds to the complexity. Highly trained personnel also must ensure that image acquisition, geometric corrections, and processed imagery meets the goals of the thermal-infrared survey of active hydrothermal systems. Specialized image processing software is necessary for the display and accurate rectification of individual airborne images into a mosaic and analysis of airborne imagery. A temperature-calibrated, high-spatial resolution, georectified mosaic using thermal-infrared airborne imagery is a very time-intensive and expensive process for large areas.

Interpretation. Nighttime thermal-infrared imagery of hydrothermal areas has many uses. Scientists can construct a baseline map of temperature; efficiently and safely estimate temperatures over large area; calculate the heat flux of hydrothermal sub-basins; and document changes within an entire hydrothermal

system. Earth scientists also may use the thermal-infrared imagery to construct maps of fracture networks affecting hydrothermal systems (see Case Study II). Additionally, thermal inertia maps may show how surficial geology affects a hydrothermal system if nighttime and daytime thermal-infrared imagery is acquired. Because earth materials (volcanic rocks, sedimentary rocks, sediments such as clays or sands, etc.) gain and lose heat at different rates, an interpreted new map of geology may be generated from a thermal image and integrated with existing geologic maps or any visible imagery.

Vital Sign 4: Thermal Water Discharge

A key parameter for monitoring geothermal systems is the amount of thermal water discharged (volume of water per unit time). By measuring and monitoring the thermal water discharged by both hydrothermal features and hydrothermal systems, personnel can document natural variability and anthropogenic disturbances affecting a hydrothermal system. By measuring the thermal water flowing from the hydrothermal system, we can estimate the heat from the hydrothermal system using Equation 1:

$$\Delta Q = cm\Delta T \quad (1)$$

where ΔQ is the change in heat, c is the specific heat of the material, m is the mass, and ΔT is the change in temperature. For example, the amount of heat lost from 1000 g of water (one liter) cooling from 90 °C to 20 °C is 293,020 J or 10,003 calories. (The specific heat of water is 4.186 J/gram °C. From equation one, the change in heat = (4.186 J/gram °C) × (1000 g) × (70 °C) = 293,020 J or 10,003 calories.)

Techniques for measuring the volumetric discharge of hydrothermal waters are identical to the methods used in surficial hydrologic studies. Nolan and Shields (2000); Rantz (1982), Buchanan and Somers (1969), International Organization for Standardization, (1983), and Sauer and Meyer, (1992) provide detailed discussions of surface-water discharge measurement techniques.

Level One: Estimate Volumetric Discharge

Methods. Two simple methods exist for estimating volumetric discharge: (1) measuring cross-sectional area and surface velocity, and (2) measuring volume and time. The first method involves measuring the cross section area of a channel and the velocity of the water flowing through the channel. Equation 2 relates volumetric discharge (Q) to the cross-sectional area (A) and velocity of the stream (V):

$$Q_{\text{volumetric}} = (A_{\text{cross section}})(V_{\text{stream}}) \quad (2)$$

Field personnel usually can measure the cross section area of the channel directly with a tape measure. It is important that a rectangular cross sectional area exists over a sufficient length of stream. The time required for an object to travel a known distance in the stream can be used to calculate the stream's velocity. Speed-sensing devices that use radar may help with velocity estimates. Field personnel should be aware that the surface velocity of the stream may not be equal to the stream velocity at depth.

For the second volumetric technique, field personnel measure water flow with a container of known volume. At low-flows cascading over a barrier, field personnel place a container under a single stream of water, allow the container to fill with water and note the time required to fill the container. Equation 3 relates volumetric discharge (Q) to the volume of water (v) and time (t):

$$Q_{\text{volumetric}} = (v_{\text{water}})(t) \quad (3)$$

Multiplying the container's volume by the time required to fill the container yields volumetric discharge. As with any measurement, field personnel should take multiple readings and average the results for an estimated discharge.

Field personnel working with hot, caustic, acidic, and toxic flowing thermal water should ensure their safety and the safety of their coworkers. Thermal burns from splashing or immersion in water may occur. Chemical burns caused by acidic or caustic waters also may occur. Some thermal waters contain toxic elements such as mercury and arsenic. It is important for the field team to have conducted a literature review of the chemistry and site conditions of the hydrothermal feature before taking flow measurements.

Timing and frequency. At a minimum, field personnel should measure thermal water discharge at high-flow and low-flow conditions. Maximum flow usually occurs at the time of spring runoff. Minimum flows generally occur in late fall or winter. Personnel may use monthly flow estimates to calculate an annual volumetric discharge and associated annual heat flux.

Equipment and costs. Tape measures are readily available and inexpensive. Field personnel may use any container once it is calibrated and marked. A simple volumetric calibration involves filling the container with a known volume of water. The primary cost is personnel time.

Limitations. These level-one volumetric techniques are approximations of volumetric discharge that may be in error by 25% or more. The container technique can be more precise and accurate for low flows. At high flows or when the bucket cannot be easily filled, however, this technique can produce significant errors. Accurate volumetric discharges require expensive and time-consuming techniques such as wading measurements, or the installation of a flume or weir.

Interpretation. Graphs of water flow as a function of time are the simplest way to view hydrologic discharge. These graphs allow personnel to analyze the temporal variations of discharge at a single location. Also, these volumetric graphs allow a comparison of discharge for different hydrothermal features and areas. Graphing other variables allows the comparison of hydrothermal discharge to precipitation, seismicity, or anthropogenic activities.

Level Two: Wading Measurements, Weirs or Flumes

Methods. Wading measurements are a standard way to determine volumetric discharge. This technique divides a stream into a series of small cross sections. Field personnel measure stream velocities in each of the small, cross-sectional areas with an instream velocity meter. Essentially, this technique sums the volumetric discharge from each small cross section, thus yielding a total volumetric discharge for the stream. Nolan and Shields (2000), Rantz (1982), and International Organization for Standardization (1983) fully describe this technique.

Although the technique is conceptually simple, there are many factors that must be considered to make a good discharge measurement. An important consideration for a wading measurement is the location of the cross section. The stream's channel should be straight and as rectangular as possible at the cross section. Taking measurements at bends in the stream channel is difficult and should be avoided. Ideally, the stream bed will be clear of boulders and vegetation, and relatively smooth. When these conditions are met, there is usually laminar (smooth, not turbulent) flow in the channel, which yields more accurate measurements. If repeat measurements are planned at a cross section it is helpful to place markers on the section so the same section can be reoccupied in later measurements. Nolan and Shields (2000) provide an in-depth discussion of wading measurements, cross section selection, and sources of measurement error.

Flumes and weirs are measurement structures that are placed in streams. In these calibrated structures, the height of water flowing directly over the weir or through the flume relates to discharge. While there are many types, each flume and weir has its advantages and disadvantages (Buchanan and Somers, 1969). Key parameters in the design and placement of weirs and flumes include maximum and minimum volumetric discharges, stream gradient, and stream bed characteristics. Field personnel can read the height of water in the flume or weir and look up a volumetric discharge in a rating table. Additionally, a pressure transducer may be placed to automatically measure water heights at specific time intervals. Consultation with skilled personnel trained in weir and flume placement and their installation is highly recommended.

Field personnel should record all data in a waterproof field notebook with an all-weather pen, then enter the data into a spreadsheet or database. Recorded data should include: date, time, location of measurement, datum, name of field personnel, type of volumetric measurement, parameters measured for volumetric discharge, and any observations. Cross-section and velocity data should be archived and saved. Location and photographic documentation of the measurement site is important for consistency and comparison with future discharge measurements.

Timing and frequency. Timing and frequency considerations for level-two measurements are similar to the considerations listed for level-one hydrologic measurements. At minimum, field personnel should measure hydrologic discharge at high-flow and low-flow conditions. Maximum flow usually occurs at the time of spring runoff. Minimum flows generally occur in late fall or winter. Personnel may use monthly flow estimates to calculate a yearly volumetric discharge and associated heat flux.

Equipment and costs. Wading measurement equipment includes wading rods and velocity sensors. This equipment is available from a variety of vendors. Wading rods measure the depth of water for each cross section. Velocity sensors mount directly on the wading rod and measure the water velocity. Some sensors are integrated with digital data loggers and displays, while mechanical sensors require headphones to listen to an audio signal. Wading rods generally cost a few hundred dollars. Velocity sensors and associated displays can range from one thousand to many thousands of dollars.

The cost of weirs and flumes varies greatly. Using a standard design, field personnel may construct weirs from notches cut into sheet metal. In low-flow conditions, personnel can place the weirs and flumes directly into the stream. For high-flow conditions, field personnel and hydrologic experts need to engineer and construct concrete supports. The advice of a hydrologic expert is invaluable in selecting a weir or flume for a specific hydrologic setting.

Limitations. Location, stream characteristics, and total volumetric discharge affect the quality of wading measurements. Imprecise volumetric discharge results from a non-rectangular cross section, high bed roughness or high stream bank roughness. Very low-flow and high-flow conditions are difficult to measure with wading techniques. Precise and accurate wading measurements require highly skilled field personnel. Wading measurements done by experienced personnel have errors of ~3–10%.

Interpretation. Wading, flume, and weir measurements are more precise measurements of discharge than bucket tests or the surface velocity cross-sectional area method. The interpretation of level-two measurements is similar to level-one measurements. Level-two discharge measurements and fluid temperature measurements also allow an estimate of heat transfer by water using Equation 1:

$$\Delta Q = cm\Delta T \tag{1}$$

Graphs of water flow as a function of time are the simplest way to view hydrologic discharge. These graphs allow personnel to analyze the temporal variations of discharge at a single location. With data from a pressure transducer, the frequently collected discharge data allows very precise temporal correlations among different hydrothermal features and hydrothermal areas, as well as with precipitation, seismicity, or anthropogenic activities.

Level Three: Real-Time Gauging Stations

Methods. Stream-flow gauging stations provide a continuous record of discharge. Site selection for a gauging station is similar to selection of a cross section for a wading measurement. Additional requirements are the assessment of stream bank and bed stability for the location of instrumentation and for long-term stability of the site. At a gauging station, the stage or elevation

of the stream surface is measured with a pressure sensor in the river. Stream discharge is computed by correlating the stage of the stream with stream flow measured using wading measurements (Buchanan and Somers, 1969). The resulting correlation (a rating curve) relates river stage to stream discharge. Stream gauges have data loggers to record the stage measurement. In some cases, telemetry allows near real-time preliminary volumetric discharges to be computed. These data can be displayed on base station computers or on the Internet. Users can set the interval for data acquisition and subsequent transmission. Field personnel should conduct wading measurements every one to two months to confirm the validity of the rating curve and discharge calculations (Buchanan and Somers, 1969). The stage datum at a gauging station needs to be periodically remeasured so the conversion of stage to discharge can be recalibrated. This is especially important if active erosion or deposition is taking place at the gauging station site.

Gauging stations can collect and transmit other real-time data such as water temperature, air temperature, specific conductance, and rainfall. The development of new chemical probes holds promise for the real-time measurement of selected ions such as chloride (Fig. 12).

Timing and frequency. Any user-defined interval for the measurement of stage is possible. The U.S. Geological Survey commonly collects stage information every 15 minutes, with data transmission occurring every hour. Data collection of stage may occur more frequently if rapidly varying fluctuations such as geyser eruptions, anthropogenic disturbances, or withdrawal of water need to be monitored. For a stable hydrothermal system, a time interval of one hour between stage measurements may be sufficient.



Figure 12. A U.S. Geological Survey real-time streamflow gauging station that uses a weir (left portion of photograph) and real-time satellite telemetry to transmit stream stage, stream discharge, water temperature, precipitation, and chloride concentration of the stream.

Equipment and costs. The cost of a real-time gauging station depends upon the type of pressure sensor, data, and transmission equipment, and on personnel costs associated with the physical measurements and maintenance of the gauge. Pressure sensors can vary from pressure transducers that cost hundreds of dollars to bubbler systems that cost thousands of dollars. The cost of electronic data transmission equipment depends upon the method of data transmission. Short-distance, local-area-network transmission and reception equipment may be obtained for less than $10,000. Satellite-telemetered equipment is more expensive, in the tens of thousands of dollars.

Data acquisition, quality assurance, and archiving data require specialized equipment and software. Due to the high volume of real-time data, the storage, processing, and archive of the gauge data is a significant cost. Current U.S. Geological Survey costs for installation of a real-time satellite gauging station are about $40,000, with an annual cost of $16,000 to $20,000 for operation and maintenance.

Limitations. Key limitations with real-time gauging stations are the expertise needed to install, maintain, process, and archive data. Knowledge of stream flow, hydrologic measurements, telemetry of data, database management, systems administration, and secure archiving of data are necessary.

Interpretation. Graphing time-discharge relationships allows the comparison of thermal feature discharge to any temporal event. The near-continuous discharge measurements and precise temporal correlations allow the effects of precipitation, seismicity or anthropogenic activities to be correlated very precisely with thermal discharge. The real-time data also allows field personnel and managers to respond in a timely fashion to changes in the hydrothermal flow.

Vital Sign 5: Fluid Chemistry

The locations, temperatures and flow rates of thermal sites (Vital Signs 1 through 4) provide valuable data that should be supplemented with chemical analyses of thermal and local non-thermal waters. Constituents dissolved in hydrothermal waters can include common **anions and cations, trace elements, organic compounds, isotopes, and radio nuclides**. Hydrothermal flow systems are complex (Henley and Ellis, 1983) and often water chemistry analyses are the best way to assess subsurface flow systems.

Kharaka et al. (1991), summarizing their work and the work of Hem (1985) and Ellis and Mahon (1977), note that chemical data, among other uses, can help determine:

- baseline chemistry of hydrothermal systems to determine the natural range of variation of individual features and an overall system;
- subsurface temperatures;
- subsurface mixing of different fluids (for example, deep hydrothermal and local cold water);
- water-rock interaction parameters that might be occurring at depth;

- water flow paths;
- interactions between thermal and non-thermal groundwaters;
- the origin of chemicals in hydrothermal waters;
- hydraulic connections among widely spaced thermal sites;
- possible contributions of magmatic water to hydrothermal systems; and
- the age of hydrothermal systems, through dating waters or hydrothermal deposits.

These are all valid goals for monitoring, as both local and distant stressors can influence the resulting chemistry of a thermal site. Individual land managers will need to assess which of these uses of chemical data are most appropriate for their areas.

Level One: Electrical Conductivity, pH

Methods. Electrical conductivity and pH are two characteristics of geothermal fluids that field personnel can measure easily. **Electrical conductivity** is a measure of the ionized chemicals in water. Generally, high amounts of dissolved minerals and salt concentration in water yield high electrical conductivities. Measurements of electrical conductivity can provide estimates of the hydrothermal fluid's purity and contribute to understanding its flowpath.

A measure of the hydrothermal fluid's acidity or alkalinity is its **pH**; a pH of 7 is neutral, less than 7 is acidic, and above 7 is basic. Changes in the pH may indicate changes in the flow path of the geothermal fluid, changes in the temperature of the geothermal fluid, loss of CO_2, or anthropogenic activities.

To measure conductivity, field personnel immerse a calibrated conductivity probe in water. Prior to making a measurement of electrical conductivity, the field team should calibrate the meter and probe with solutions of known conductivity and according to manufacturer's guidelines. When placed in water, the calibrated probe requires time for the reading to stabilize, or equilibrate, to the fluid being measured. After equilibration, the meter displays the fluid's electrical conductivity.

A pH meter or pH paper can be used for estimating the pH of a geothermal fluid. Personnel dip the pH test-strip in the geothermal fluid, watch for color change, compare color changes in the test strip with a color scale, and read the result. pH determined by the use of paper may not be highly accurate. A pH meter's use is similar to a conductivity meter. Prior to making a measurement of pH, field personnel should calibrate the probe with solutions of known pH and according to manufacturer's guidelines. When placed in water, the calibrated probe requires time for the reading to stabilize, or equilibrate, to the fluid being measured. After equilibration, the meter displays the fluid's pH. It is *critical* that field personnel calibrate the meter and probe according to manufacturer's guidelines.

Field teams should record all data in a waterproof field notebook with waterproof pens. Personnel should then enter the field data into a spreadsheet or digital database. Recorded data should include: date, time, coordinates of measurement, name of field personnel, type of pH and conductivity equipment, pH, fluctuations of pH, temperature of pH measurement, calibration information concerning the pH meter, conductivity, fluctuations of conductivity, temperature of conductivity measurement, calibration information concerning the electrical conductivity meter, and any observations about the fluid being measured. Location and photographic documentation of the measurements sites are important for consistency and comparison with future measurements.

Timing and frequency. Two key factors affecting timing and frequency are study design and accessibility. Once electrical conductivity and pH baselines are established, the frequency of measurements can decrease. Initially, field teams should take electrical and pH measurements frequently to define any daily or seasonal variations. These simple measuring techniques may not monitor remote hydrothermal features adequately or allow the determination of a baseline. Adequate baseline chemical data depends upon the questions asked and answers needed. The questions and expected baseline data are part of the geothermal monitoring study design. For initial reconnaissance, a remote backcountry hydrothermal feature unaffected by human activities may require annual monitoring. However, a hydrothermal feature affected by human activities may require monthly or weekly monitoring of pH and electrical conductivity. As with any monitoring effort, careful compilation and documentation of results from previous studies is critical.

Equipment and costs. Electrical conductivity meters are available from a variety of vendors. The cost is generally a few hundred dollars, with calibration standards costing tens of dollars. Replacement probes are available for about $100.

A variety of vendors sell pH paper. Range of pH paper sensitivity (0–14, 0–6, or 7–14) and type of color change (single indicator or multiple colors) vary between manufacturers. The cost is generally tens of dollars for ~20 pH paper strips.

Numerous vendors sell pH meters. The cost is generally a few hundred dollars, with calibration standards costing tens of dollars. Replacement pH probes are available for about $100. Vendors also sell combination electrical conductivity and pH probes.

Limitations. The maintenance and calibration of field pH and electrical conductivity meters requires effort. Expiration dates of calibration solutions, care of probes and meters, and maintenance and calibration all require time and documentation. Meters can fail in the field.

High-temperature geothermal fluids present challenges for precise measurement of conductivity and pH. Some conductivity and pH meters are not capable of taking accurate readings at higher temperatures (generally greater than 80 °C).

Visual comparisons of color change on pH test strips can be a challenge. Lighting conditions (full sun, part-shade, cloudy day, etc.) and the color perception of an observer affect the visual comparison of color change and the accuracy of the perceived pH.

Similar to taking temperature or hydrologic measurements, field teams must consider personal safety when taking electrical conductivity or pH measurements near hydrothermal features. Personnel may incur thermal burns from splashing or immersion

in thermal water. Also, field personnel may sustain chemical burns from acidic or caustic thermal waters. Some thermal waters contain toxic substances such as mercury, arsenic, and other elements.

Interpretation. Graphs of water chemistry, pH, and electrical conductivity as a function of time are the simplest way to view the data. These graphs allow personnel to analyze the temporal variations of water chemistry, pH, and electrical conductivity at a single location. Also, these graphs allow a comparison of data between different hydrothermal features and areas. Graphing other variables allows the comparison of these data with temperature, precipitation, seismicity, or anthropogenic activities such as pumping wells. In addition, GIS maps of these variables may show important spatial and temporal trends in the data.

Levels Two and Three: Chemical Analyses

Methods. Levels two and three of chemical studies are separated more by the frequency of sampling than by the distinction of what elements or compounds are analyzed. Level-two studies involve fewer samples, and are more directed at monitoring surface and subsurface conditions in the vicinity of hydrothermal features. Level-three studies are larger in scope, more involved, and can extend beyond monitoring local features to providing information on the entire flow path of fluids, from recharge to discharge. Level-two studies are more typical of monitoring programs, while level-three studies provide monitoring data that comes closer to research programs.

To deal with the complexity of chemical programs, it highly advisable to work with specialists in hydrothermal fluid chemistry to assure that sampling protocols are followed exactly, that chain of custody and shipping issues are handled properly, and that a reliable lab is chosen to do the analyses. Experts can also help with interpretation of complex and large data sets.

For monitoring data to be considered reliable, chemical results must be both accurate (representative of what really exists in the field) and precise (measuring what is really in the sample with results that are able to be reproduced). Accuracy can be assured by selecting appropriate sample sites and collecting samples properly. Precision can be assessed by providing labs with duplicate blind samples, and evaluating how close the analytic data are. It may also help to check one lab against another by sending duplicate samples to multiple labs. It is also critical that analyses be performed by U.S. Environmental Protection Agency (EPA)–certified labs. While other labs may provide chemical analyses for lower costs, EPA certification provides an additional level of assurance.

Timing and frequency. The timing and frequency of chemical analyses at levels two and three depends on the questions being asked. Once baselines are established, the frequency of measurements can decrease. In areas where there is little stressor influence on hydrothermal systems, sampling once every few years may be adequate. In areas where there is influence from stressors, sampling may need to occur on annual or monthly cycles. It can be useful, in dynamic areas, to sample weekly to determine the natural range of variation of individual features and an overall system (Fournier et al., 2002)

Equipment and costs. Chemical analyses of hydrothermal fluids have detailed field sampling, sample handling, and sample analysis protocols, which are different depending on the specific elements or compounds being studied. Sampling is much more than going to the field with a bucket and bringing water back to a lab. For example, sampling for multiple chemical species typically requires that some of the fluids be filtered before they are placed in bottle, that some of the fluids not be filtered, that some of the sample be collected in glass bottles, that some of the sample be collected in plastic bottles, that some of the samples be acidified in the field for preservation of chemical species, and that triple-rinsed bottles be prepared well and have the right kinds of lids.

Nicholson (1993) provides an extensive list of considerations for preparation for field work, and Mazor (1991) discusses field sampling requirements for isotopic analyses (even noting that some samples should not be exposed to sunlight). Reference to both Nicholson (1993) and Mazor (1991) will provide broad contexts for considering options and requirements for field sampling programs.

Chemical analyses can range from less than $100 per sample for some elements to more than $500 per sample for isotopes. Therefore, the distinction between levels two and three is determined by the number of individual samples and the number of elements or compounds that need to be analyzed for in each sample. Total costs for studies can range from several hundred dollars for simple studies of a few samples analyzed for major elements only, to many tens of thousands of dollars for detailed, repeat studies including analysis of large suites of samples for many elements, compounds and isotopes.

There also are costs that will be incurred as personnel are appropriately trained to collect samples. If local staff are not trained, then consultants will have to be hired to do the field sampling; this can run from hundreds to more than a thousand dollars a day, depending on the sophistication required for the sampling.

Table 5 indicates some of the more common chemical constituents of hydrothermal fluids that may be analyzed and interpreted as part of a monitoring program.

Limitations. One of the biggest requirements in hydrothermal fluid sampling programs is absolute certainty that the correct samples have been collected from the correct sites in the proper way. What is correct depends on the monitoring questions that are being asked. Sampling to provide data about subsurface temperatures is different from sampling to provide data about what rocks the hydrothermal waters have chemically interacted with at depth. Picking appropriate sites is also important. High-flow springs may provide better chemical characterization of subsurface conditions than low-flow springs (but low-flow springs may be better than no data). Improper sample collection techniques or improper shipping may invalidate chemical results.

Similar to taking temperature or hydrologic measurements, field teams must consider personal safety when taking chemical samples from hydrothermal features. Personnel may incur

TABLE 5. SELECTED PARAMETERS FOR LEVEL TWO AND LEVEL THREE CHEMICAL MONITORING PROGRAMS

Chemical parameter	Potential use of data	Possible Level
pH—field	Acid/alkaline	I, II
pH—lab	Acid/alkaline	II
SiO_2	Geothermometer	II
Na	Geothermometer/Piper	II
K	Geothermometer/Piper	II
Ca	Geothermometer/Piper	II
Mg	Geothermometer/Piper	II
Fe	Evaluate subsurface mineralogy	II
Al	Evaluate subsurface mineralogy	II
Li	Geothermometer	II
Mn	May form surface precipitates	II
HCO_3	Piper; HCO_3/SO_4 ratio may indicate underground flow direction	II
CO_3	Piper	II
SO_4	Piper; may indicate steam concentration	II
Cl	Piper	II
NH_3		II
F	Potential long-term pollutant Host rock characterization	II
As	Potential contaminant	II
Sr	Host rock characterization	II
Ba	Host rock characterization	II
Br	May indicate sea water interaction	II
B	Host rock characterization	II
Rb	Host rock characterization	II
Cs	Host rock characterization	II
Zn	Host rock characterization	II
Rn	Potential contaminant; soil concentrations may indicate fault locations	II
Hg	Potential contaminant; may indicate subsurface boiling and/or fault locations; also in soils	II
Au	Host rock characterization	II
Total dissolved solids		I, II

Isotopes	Potential use of data	Possible Level
$^{3}He/^{4}He$	Identify mantle (magmatic) input	III
^{15}N	Assess water source	III
$^{18}O/^{16}O$	Assess water source	III
^{2}H	Assess water source	III
^{3}H	Dating water	III
^{14}C	Dating water	III
^{13}C	Assess water source	III
^{34}S	Assess water source	III
^{36}Cl	Dating water	III

Note: The chemical constituents listed as geothermometer are useful for calculating potential deep temperatures in hydrothermal systems. The chemical constituents listed as Piper are those used in the plotting of Piper diagrams, as described in the text and shown on Figure 13. Host rock characterization means that the elements, often when compared with other elements in various combinations of ratios (Nicholson, 1993), may provide useful information about the types of rocks that the fluids have interacted with in the subsurface. Elements without specific descriptors are useful as part of integrated studies of waters and subsurface rocks that are usually undertaken as part of level three studies. All analyses undertaken as part of level two monitoring also can be part of level three programs.

thermal burns from splashing or immersion in thermal water. Also, field personnel may sustain chemical burns from acidic or caustic thermal waters. Acids used to stabilize samples can also be hazardous. Some thermal waters contain toxic substances such as mercury, arsenic, and other elements.

Labs may report analytic results using different units for concentrations. All appropriate unit conversions must be made before results are interpreted. Mixing units can lead to major errors in the interpretation of results.

When interpreting chemical results, it is critical to be aware of analytic uncertainties and detection limits. Although a particular analytic result may suggest a potential interpretation, inclusion of the uncertainty associated with the analytical technique clarifies the confidence of the interpretation. Analytic results for

solutes that are close to the lower limit of detection may not be as reliable as results that are well above the limit.

Interpretation. Major and trace element chemistry of hydrothermal fluids can provide data about subsurface conditions and water flow paths. These data are useful in monitoring programs, as they allow insight into deeper geologic processes, and may indicate system changes that are not visible from the surface.

One key question of subsurface conditions is the temperature of hot water at depth. Where direct measurement of deep temperatures, through measurements in wells, is not possible, water temperature at depth is determined through interpretation of water chemistry. The concept of geothermometry is simple: some ratios of elements, gases, or isotopes will become fixed at a high temperature, and the ratio will be maintained as the waters cool. Chemical determination of these ratios, therefore, can be interpreted to give an estimate of the maximum temperature of a particular hydrothermal system. Nicholson (1993) describes many of these ratios and includes appropriate formulas. Some elements that can be used for geothermometry are listed in Table 5.

Piper diagrams are trilinear diagrams that plot water chemistry (Hem, 1985). They can be used to assess the origin and flow paths of waters. Figure 13 is a Piper diagram of data from thermal springs of the Wood River area in central Idaho.

Although gathering field samples can be done by personnel with only a small amount of training in sampling and sample handling protocols, interpretation of chemical monitoring data is best done by experts. Identifying which aspects of the chemistry are a result of the interaction of water and rocks in the subsurface, which aspects are the result of mixing warm and cold waters, which aspects may be the result of subsurface boiling, and which aspects may be changing because of input from stressors, can be complex.

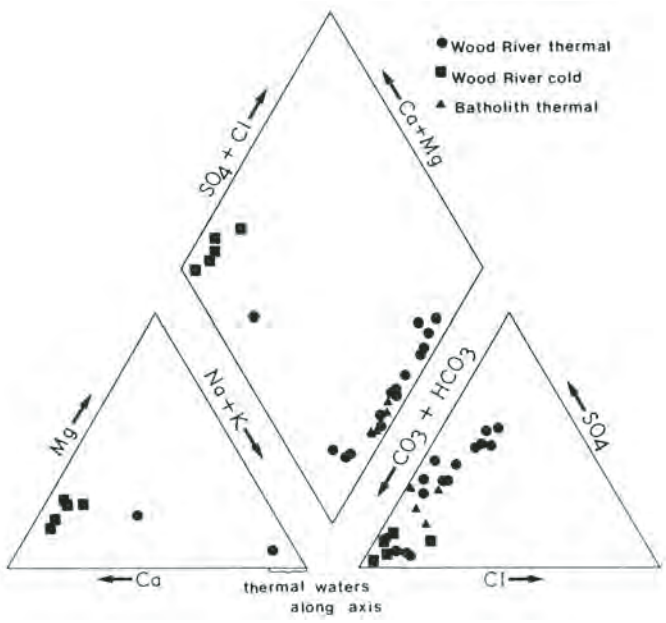


Figure 13. Piper diagram of thermal and non-thermal waters from the Wood River area of central Idaho. Analytic results are plotted in the cation and anion triangles, and then projected into the central parallelgram. Note that thermal waters and non-thermal waters cluster in different parts of the diagram. The lone sample point between the two fields suggests that it is a mixed water, with both thermal and non-thermal inputs (from Foley and Street, 1988).

The discussion above has emphasized monitoring the chemistry of hydrothermal waters. It may also be appropriate, in some cases, to study deposits from hydrothermal systems. Elements in siliceous sinter or calcareous travertine may provide clues to the ages of hydrothermal activity (Kharaka et al., 1991; Foley, 2006).

Advanced Monitoring Techniques that Measure Multiple Vital Signs

Gas emissions from hydrothermal systems and changes in seismic activity, as well as changes in Earth's magnetic, electrical, and gravity fields, can all be monitored as vital signs. Study of these vital signs, however, typically involves professional expertise and sophisticated equipment, making them best suited to level-two or level-three monitoring, or research activities. Geophysical monitoring, for example, often involves expensive equipment, logistic support issues, and, for some techniques, field deployments that can last for months or longer.

Hydrothermal Gases

Although many hydrothermal gases and their isotopes can be studied for research, monitoring programs for H_2S and CO_2 can help identify sites of environmental concern, as well as provide fundamental information about a local system. Both H_2S and CO_2 can be toxic (National Institute for Occupational Safety and Health, 1981), as they are denser than air and can settle in low areas. It may be important to pay attention to place names. In Yellowstone National Park, places named Death Gulch and Poison Spring have been sites of recorded wildlife deaths from gas poisoning.

High concentrations of H_2S are typically found in volcano-related hydrothermal systems where there may be high-temperature systems at depth, or in hydrothermal systems with sulfur deposits or high organic contents in subsurface rocks (Nicholson, 1993). H_2S can also be concentrated in areas with subsurface boiling, such as fumaroles and mud pots. In systems where H_2S is a concern, gas sampling should be done under a variety of weather conditions to establish typical background concentrations. Portable H_2S meters cost more than $500. The data must be carefully interpreted, as a wide range of concentrations may be measured, depending on wind dispersal of gases.

Other than water vapor, CO_2 is typically the most abundant gas emitted from hydrothermal systems. It is found in a wide range of hydrothermal systems, including those associated with volcanoes, those where limestone rocks exist in the subsurface, and those with organic matter in subsurface rocks. In systems where CO_2 is a concern, gas sampling should be done under a

variety of weather conditions to establish typical background concentrations. Portable CO_2 meters to do this sampling cost more than $500. The data must be carefully interpreted, as a wide range of concentrations may be experienced, depending on wind dispersal of gases.

Geophysical Methods

Hydrothermal systems can create anomalous patterns in local geophysical fields. Distinct patterns of electrical, magnetic, or gravity anomalies may indicate zones of increased permeability. Interpretation of these patterns, however, is best done by professionals with expertise in specific subdisciplines of geophysics. For example, someone familiar with electrical fields may not be qualified to interpret patterns in gravity anomalies. Another issue with geophysical methods of investigation is that there may not be unique interpretations of natural patterns. Zones that conduct electricity, for instance, may be created either by moving waters or clay-rich rocks.

Earthquakes are known to affect hydrothermal systems (Marler, 1964). Thus, the monitoring of earthquakes helps define the timing of events that may have significant effect on hydrothermal features. Hydrothermal features can also cause microseismicity (Kieffer, 1984).

Monitoring Overall Systems

Rivers that flow through or drain thermal basins can integrate all discharge from hydrothermal systems. Analyzing river waters for solute concentrations, especially Cl, is a technique that can be used to assess the overall thermal output of systems. The calculation of overall heat flux from a system or region is based on the concentration of Cl and the discharge of rivers draining the hydrothermal systems. This technique has been used in Yellowstone (Hurwitz et al., 2007; Friedman and Norton, 2007), Long Valley (Sorey, 2000) and the Cascade Range (Mariner et al., 1990).

GEOTHERMAL MONITORING STUDY DESIGN

As with any scientific study, the single most critical issue is the *goal* of the study. If personnel do not identify a clear goal for monitoring, then it will not be possible to select appropriate scientific techniques and analyses. A geothermal monitoring program, without a clear sense of purpose, may not meet resource protection needs. Goals of past geothermal monitoring efforts include: (1) determining if the production of water from wells was measurably affecting the flow of a hot spring (Spencer, 1986; Jarvis, 1986); (2) determining if the development of adjacent Known Geothermal Resource Areas might affect an entire hydrothermal area (Sorey, 1991); and (3) evaluating short- to long-term and seasonal variability of hydrothermal features (Cole, 1982; Ingebritsen et al., 2001).

The second critical issue in designing a geothermal monitoring plan is *budget*. As identified in previous sections, the cost difference between level one and three efforts may be considerable. The primary cost of most level-one studies is field personnel. The cost of level-three studies is significant because of the equipment, technical expertise, and time required for analyses of data. Although level-three studies provide the most detailed interpretations of a geothermal system, appropriately designed level-one and level-two studies can provide significant information for resource management and protection (see Case Study I).

A third critical issue in the design of geothermal monitoring plans is to identify, document and follow *scientific protocols* when gathering data. Simple studies can obtain critical data, if personnel follow protocols and document the methods used. If studies are not planned and implemented with care, then data might not be useful, and funds may be wasted.

Questions that must be answered are the key to designing a scientific study. The questions and clearly defined goals of a geothermal monitoring plan direct personnel toward specific scientific techniques and measurement tools. Questions that may help personnel decide what *vital signs* and what *level* of study are necessary include:

- Where are hydrothermal features located?
- How large is the hydrothermal area?
- What are baseline temperatures and flow levels?
- Do features change seasonally? Over a few years? Over a few decades?
- Are hydrothermal features interconnected?
- What nearby factors might influence specific features?
- Are human activities either at the site or on adjacent lands likely to influence the hydrothermal features?

Before starting a monitoring program, it is critical to conduct a literature review and compile information from previous studies. A large amount of data may exist about hydrothermal features and the geology of the study area. There are many sources of information that should be searched. These include scientific peer-reviewed publications, so-called gray literature (federal, state, and local government reports that have not been broadly disseminated), books of both general and local nature, internal agency reports and notes and correspondences that are in agency files, and online data, which for geothermal systems includes information from (but not limited to) the U.S. Geological Survey, the U.S. Department of Energy, the U.S. Environmental Protection Agency, the National Oceanic and Atmospheric Administration, the National Aeronautics and Space Administration, and various state geologic, land management, environmental, energy, and water agencies. County and other local agencies may also have water-related data of interest to studies of hydrothermal systems.

CASE STUDIES

Case Study I: An Inventory of All Thermal Features in Wyoming (Exclusive of Yellowstone National Park)

In the 1970s, the Wyoming Geological Survey (WGS) began a project to inventory all the thermal springs in the State of Wyoming, excluding Yellowstone National Park. During one

year, a WGS geologist inventoried fifty thermal springs in Wyoming (Fig. 14). Information gathered during the survey included location, elevation, ownership, access to the thermal feature, temperature, date of measurement, flow, chemical analyses, a brief description of the spring, and a photograph (Breckenridge and Hinckley, 1978).

With the exception of chemical analyses, the WGS used level-one monitoring techniques. Breckenridge and Hinckley (1978) discuss the techniques used in the following excerpt from page 8 of their report:

> Each spring is located on a U.S. Geological Survey topographic quadrangle by Section, Township and Range. The Section is further divided into quarter-quarter-quarters. … Temperatures were taken with both maximum and constant reading mercury thermometers. Several readings were made to determine each reported maximum spring temperature. All temperatures were taken near the surface, as close to the vents as possible. Rates of flow were visually estimated as channel cross-section area multiplied by a timed surface flow rate.…

This study is an *inventory* and technically not a monitoring plan, because the sites were not revisited systematically and remeasured. However, baseline inventories are very important and a key first step in developing monitoring plans. Once personnel inventory resources, they can then design an appropriate monitoring plan. This level-one and level-two inventory of Wyoming's thermal springs formed the basis for detailed scientific studies of Wyoming's hydrothermal resources (Buelow et al., 1986; Heasler and Hinckley, 1985; Heasler et al., 1983; Heasler, 1982; Hinckley and Heasler, 1984, 1987). Also, this study provided baseline data used to monitor and protect Wyoming's Thermopolis Hot Springs State Park (Hinckley et al., 1982; Jarvis, 1986; Spencer, 1986).

Case Study II: Norris Geyser Basin, Yellowstone National Park

Norris Geyser Basin is the focus of a hydrothermal monitoring plan which incorporates all the *vital signs* described in this chapter. National Park Service personnel implemented the Norris monitoring plan using level-one through level-three strategies. The *goals* of the Norris monitoring program meet the National Park Service's legislative mandates regarding protection of geothermal resources. The primary goal of the Norris Geyser Basin hydrothermal monitoring plan is to define the baseline characteristics of heat flow, water flow, and hydrothermal fluid chemistry. The emphasis is to quantify the physical attributes of the hydrothermal system at daily, monthly, annual, and decadal time scales. A thorough understanding of natural changes is required to detect potential anthropogenic effects. Data from the monitoring plan also improves visitor and employee safety. Because the monitoring plan is the basis of scientific research in the area, it facilitates and focuses academic and U.S. Geological Survey research in Norris Geyser Basin. This focused effort assists the understanding of geologic, hydrologic, and chemical processes occurring within the Norris hydrothermal system.

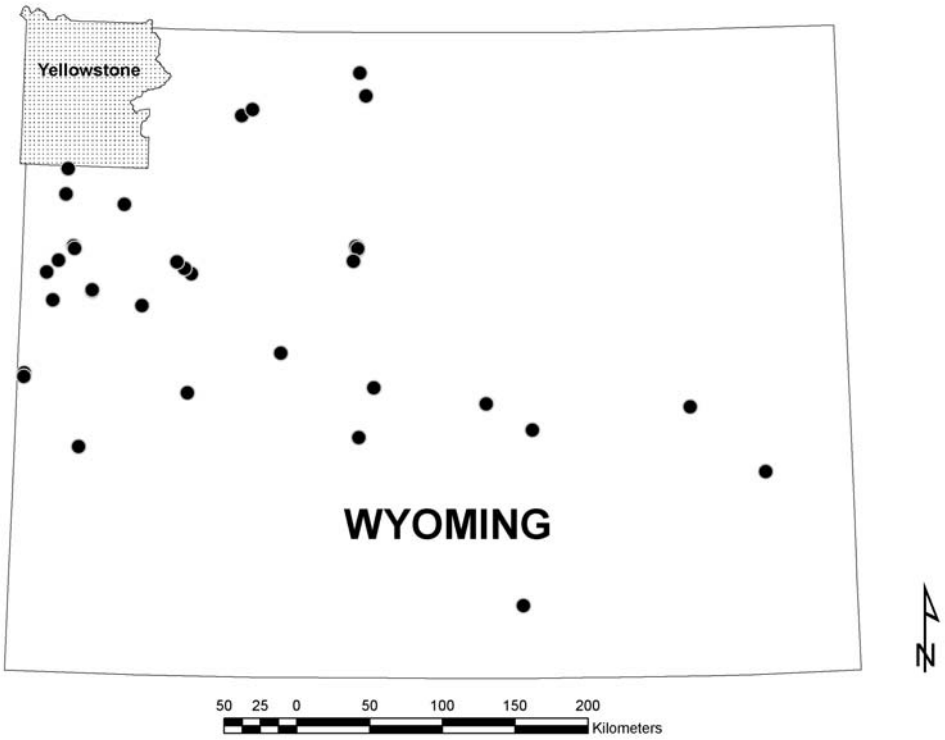


Figure 14. Map showing inventoried thermal springs of Wyoming, exclusive of Yellowstone National Park (adapted from Breckenridge and Hinckley, 1978).

Located in northwestern Yellowstone National Park, Norris Geyser Basin is a dynamic hydrothermal area with numerous hydrothermal features and active geologic processes. Within the 5.5 km^2 area of Norris Geyser Basin, field personnel mapped over 550 individual thermal features (Fig. 15). The water in these features range in pH from 1 to 8 and vary in temperature from 14 °C to 93 °C. Norris Geyser Basin includes a rare acidic geyser (Echinus). Eruptions of Steamboat Geyser at Norris are some of the largest in the world, ejecting boiling, silica-rich water up to 100 m in the air and creating a thunderous roar in its steam phase for days (Fig. 16). Norris Geyser Basin is subject to basin-wide thermal disturbances that change some geysers into fumaroles, cause hydrothermal pools to drain, and change the chemistry of features from neutral to acidic. These disturbances occur over the time scale of days to weeks and generally occur during summer and fall, but also at other times. The 1989 hydrothermal explosion of Porkchop Geyser (Fournier et al., 1991) and the 2003 closure of the Back Basin trail for three months due to high ground temperatures emphasize the dynamic nature of Norris Geyser Basin.

The monitoring plan for Norris Geyser Basin concentrates *all* efforts on the hydrothermal system's heat source and its groundwater flow regime. Understanding the heat source and groundwater flow regime is critical for *protecting* Yellowstone's hydrothermal resources from human activities, such as the

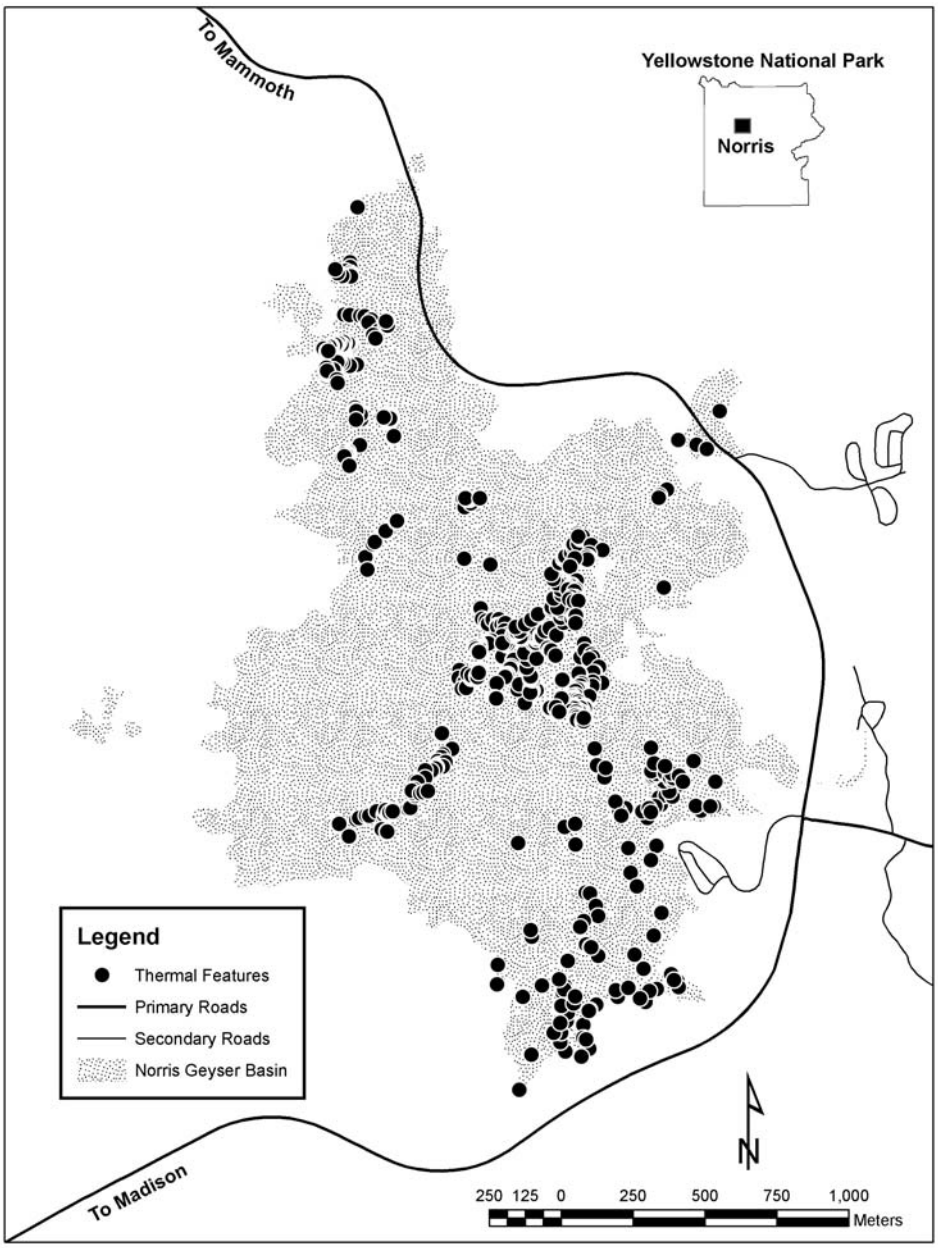


Figure 15. Map showing the location of individual thermal features within Norris Geyser Basin, Yellowstone National Park. See Case Study I, Figure 14 for location of Yellowstone National Park.



Figure 16. The steam phase of Steamboat Geyser, Norris Geyser Basin, during its 22 October 2003 major eruption.

development of energy and water resources. Level-one strategies include basic mapping, repeat photography, taking single-point temperature measurements, measuring electrical conductivity of selected hydrothermal fluids, determining pH of selected hydrothermal fluids, and estimating hydrothermal discharge with the cross-section/velocity method. Level-two strategies include GPS surveys with handheld recreational GPS receivers, deploying temperature data loggers (see Fig. 10), measuring fracture orientations in excavations for wastewater treatment facilities, and estimating hydrothermal discharge with wading measurements. Level-three strategies include the use of mapping-grade GPS receivers to perform surface hydrologic surveys, conducting on-the-ground reconnaissance of changing hydrothermal activity with a forward-looking infrared thermocam (see Figs. 7 and 8), monitoring hydrothermal discharge using a real-time stream gauge, monitoring temperature and water quality, acquiring georectified airborne imagery of hydrothermal areas at night and during the day, generating calibrated temperature maps, and calculating heat flow.

Calibrated temperature maps of Norris Geyser Basin (Fig. 17) provide baseline information about heat flow and changes in heat flow. These temperature maps provide easily interpreted images for managers, interpretive rangers, visitors, and scientists. Visitors and managers can relate a single-point temperature taken with an immersion probe or handheld sensor to a place on the temperature map or to the entire hydrothermal basin. Scientists use the temperature map and convert the temperature information to heat flow or heat flux. Heat flux maps provide a quantitative estimate of heat flow for the entire Norris hydrothermal area annually or over multiple years.

Information derived from a calibrated temperature map enhances the current understanding of the hydrothermal system and its geologic processes. Extracting the area of ground at 20 °C and examining the hydrothermal fluid flow yields a new map, showing major fractures within the underlying bedrock (Fig. 18). Scientific studies can integrate this information with other geochemical, seismic, or hydrologic data.

Highlights of a literature review clearly indicate the amount of scientific studies focused on Norris Geyser Basin. Initial studies (Gooch and Whitefield, 1888; Hague, 1911) provide the earliest geochemistry of thermal water and ideas about the Norris hydrothermal system. Subsequent scientific investigations built upon those initial investigations. Fenner (1936) recovered core and reported on early scientific boreholes, including the Carnegie II hole in Norris Geyser Basin. In addition to measuring the water chemistry of 25 thermal springs, Allen and Day (1935) established weirs near the Gibbon River, estimated discharge, and calculated a convective heat flow for Norris Geyser Basin. White (1957) improved Allen and Day's estimates of convective heat flow. Building upon previous work, Fournier et al. (1976) calculated new estimates of convective heat flow using a chloride-inventory method. Fournier et al. (2002) also performed geochemical inventories of selected thermal springs. White et al. (1975) reported on scientific drilling during the 1960s, including the Y-9 and Y-12 drill holes in Norris Geyser Basin. Geologic mapping by Richmond and Waldrop (1975) and Christiansen (1975) provided base maps for subsequent investigations. White et al. (1988) discussed the basin's geologic setting, chemistry of thermal waters, mineral precipitates, fractures, thermal disturbances, and geologic history. Kharaka et al. (1991) investigated the geochemical and hydrologic connection between the Corwin Springs known geothermal resource area and hydrothermal features along the Norris-Mammoth Corridor. Friedman and Norton (2000) measured chloride in various streams and calculated the chloride-flux for Yellowstone's major streams. Ball et al. (1998a, 1998b, 2001, 2002) conducted regular geochemical surveys of thermal waters including Norris Geyser Basin. This rich history of scientific studies allows today's scientists to use previous observations, drill logs, core from boreholes, estimates of heat flux, chemistry, fracture data, and geologic mapping to compare existing information with new data. Scientists can use all this information to develop new models about the Norris hydrothermal system.

There are numerous scientific studies that compliment all levels of monitoring at Norris Geyser Basin. The Yellowstone Volcano Observatory (YVO) assists by maintaining a permanent GPS station and a permanent broadband seismic station near Norris Geyser Basin, conducting regional surveys to document large-scale ground deformation, analyzing the types and volumes of geothermal gas on the ground as well as using airborne sensors, and analyzing interferometric synthetic aperture radar (InSAR) images for ground deformation. One research effort by the University of Utah involved a temporary deployment of several survey-grade GPS instruments and temporary seismometers in Norris to determine ground deformation within the hydrothermal basin. Another study investigated underground water movement using a very long-period seismometer. Innovative

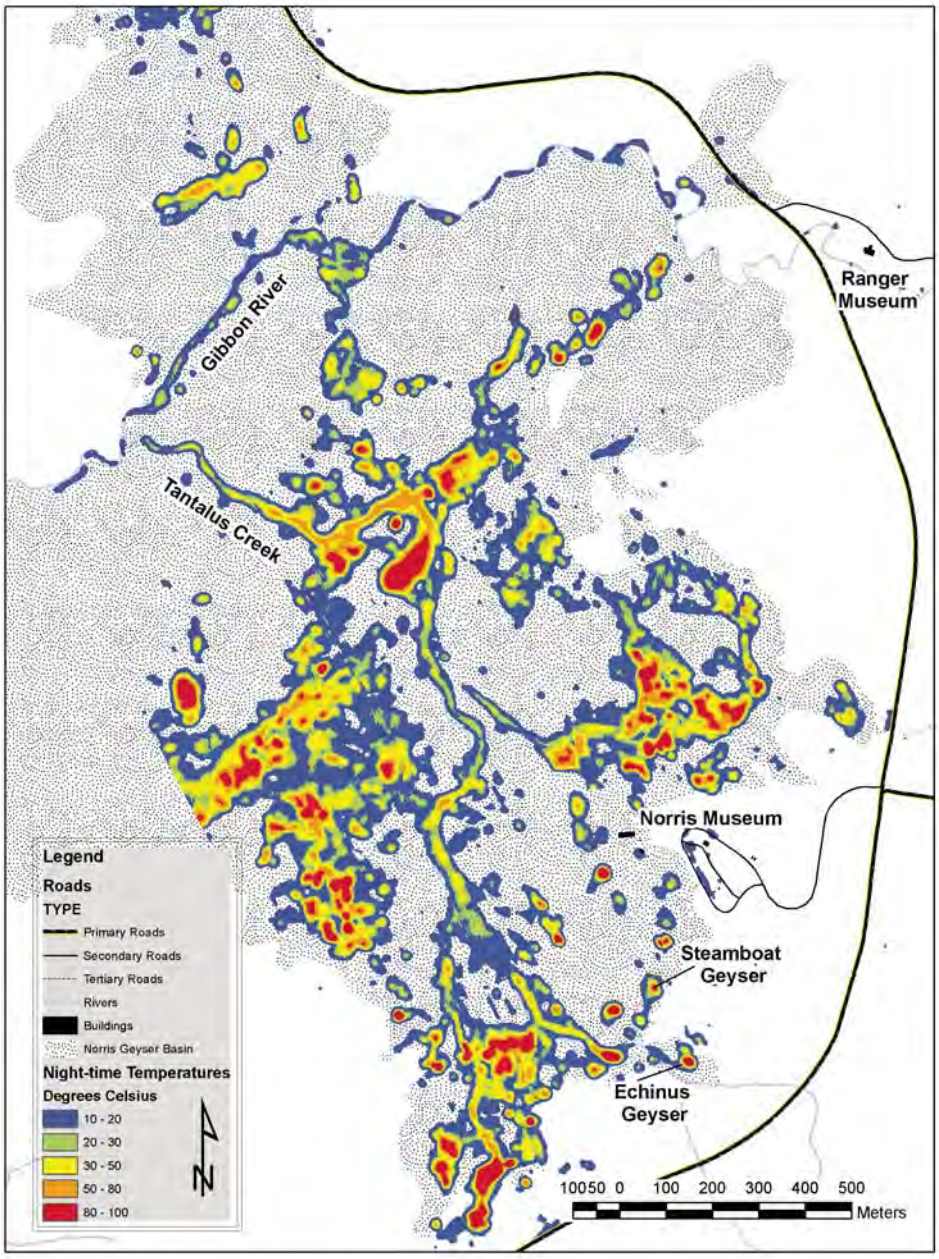


Figure 17. Airborne, nighttime, thermal-infrared image of Norris Geyser Basin for 9 October 2002. Scientists used temperature data loggers to construct the temperature calibration (Hardy, 2005). The calibration line is accurate for temperature between 10 °C and 100 °C. This nighttime, thermal-infrared mosaic clearly shows northwest- and northeast-trending alignments of hydrothermal fluids and features.

university and U.S. Geological Survey airborne surveys generated high-spatial resolution maps of hydrothermal features and their spatial extent using helium balloons and digital cameras. U.S. Geological Survey and university researchers are investigating the near-surface hydrologic system: (1) using an experimental real-time chloride sensor on a stream gauging station; (2) by age-dating hydrothermal waters using environmental tracers, stable isotopes and tritium within as well as surrounding Norris Geyser Basin; and (3) by exploring the groundwater hydrologic system within and around Norris Geyser Basin. A nearby borehole strainmeter maintained by UNAVCO monitors subsurface temperature, determines strain, detects local seismic activity, and enhances the understanding of local groundwater hydrology, chemistry, and flow-paths near a very dynamic hydrothermal area. UNAVCO assists YVO and the National Park Service with acquiring LIDAR (light detection and ranging) imagery over selected hydrothermal areas. A final example of scientific collaboration was the deployment of instruments in 2006 for Norris hydrothermal monitoring, Yellowstone volcano monitoring, and scientific research (Fig. 19).

Scientific researchers use this monitoring data and also provide new information that supplements the Norris hydrothermal monitoring effort. Researchers enhance the fundamental understanding of physical and chemical processes operating within the

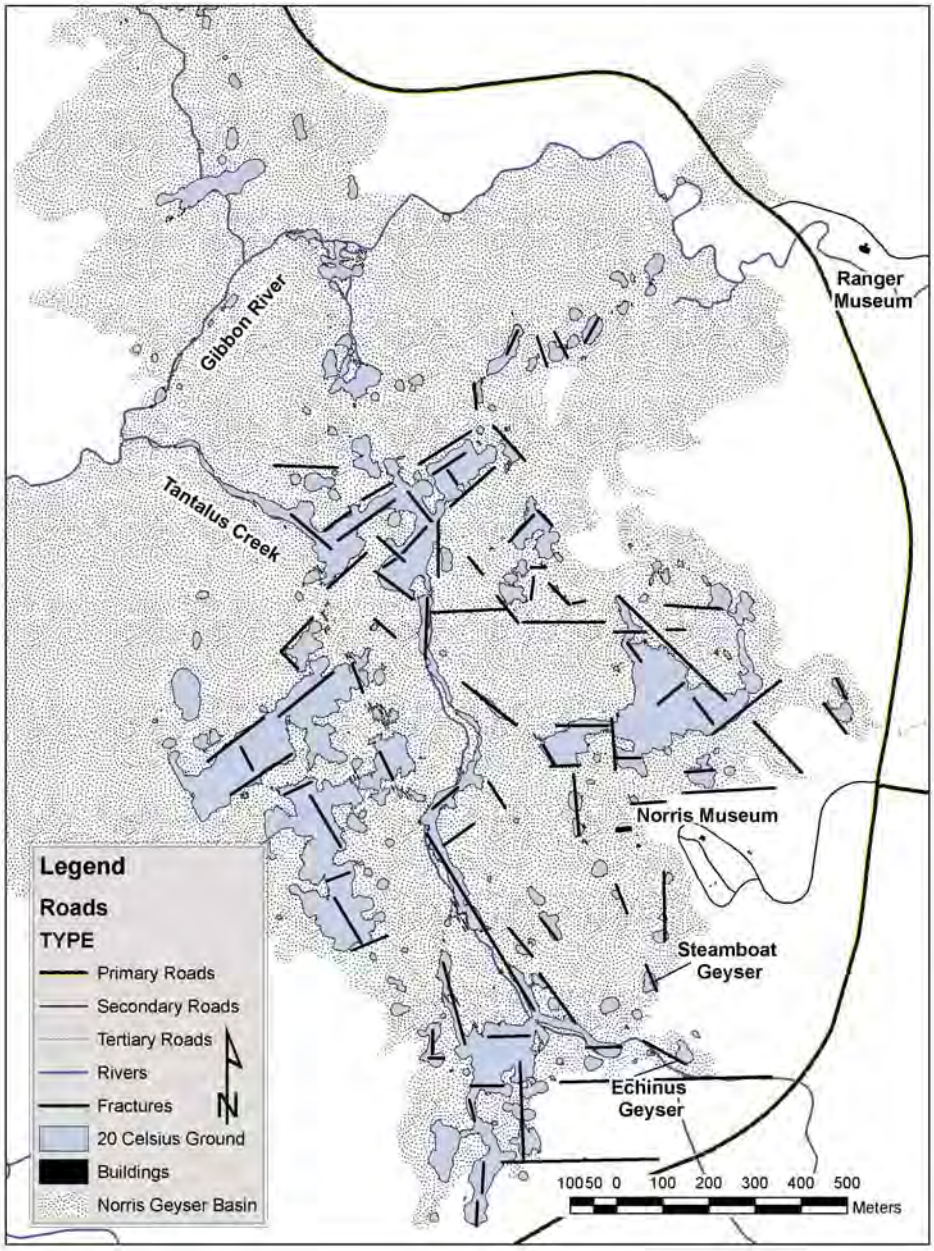


Figure 18. Map showing area of ground at 20 °C at Norris Geyser Basin on 9 October 2002. The calibrated temperature map shown in Figure 17 forms the basis for the area of 20 °C ground and major fractures. This map highlights major fractures that influence the flow of hydrothermal fluids.

Norris hydrothermal system. This new understanding improves the Norris hydrothermal monitoring plan by redirecting monitoring efforts or employing new strategies. Continual reassessment and revision of the Norris monitoring plan ensures that monitoring goals are met.

SUMMARY

There are many reasons to monitor hydrothermal systems and develop a hydrothermal monitoring plan. Clearly identifying the goals of a hydrothermal monitoring plan focuses efforts on monitoring vital signs and employing appropriate techniques. Goals for thermal monitoring may meet legislative mandates, protect geothermal resources, provide for human safety, document anthropogenic disturbances or natural changes, provide baseline information, assess the effects of hydrothermal system on plants and animals, protect natural geologic processes, and support scientific studies.

With limited time and financial resources, personnel must assess their priorities and the important characteristics of a hydrothermal system (Table 6). Changes in water quantity, changes in the heat source, changes in rock permeability, and human activities interact with the geologic system to produce observable changes in a hydrothermal area. These observable changes

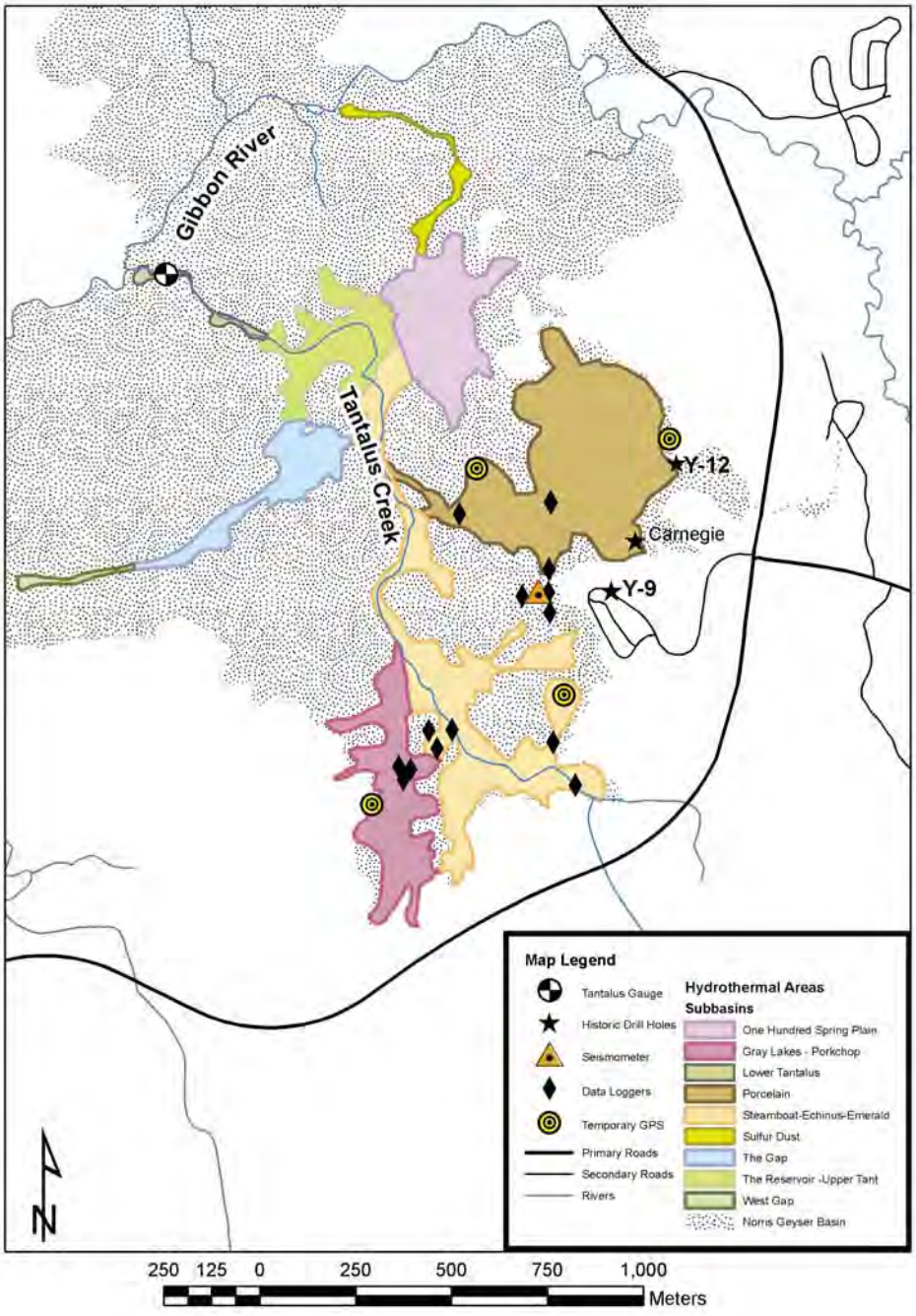


Figure 19. Map showing location of instruments used for hydrothermal monitoring, volcano monitoring and scientific research at Norris Geyser Basin during 2006.

are vital signs. Vital signs of hydrothermal systems include the location of hydrothermal features, spatial extent of hydrothermal areas, temperature and heat flow, thermal water discharge, and fluid chemistry. Personnel can choose from a variety of methods with different levels of expertise, equipment, and cost for measuring each hydrothermal vital sign.

Inventories, baseline data collection, monitoring efforts and scientific studies all provide information for protection of hydrothermal resources (Fig. 20). Ideally, volunteers, resource specialists, and scientists all interact as a team whose various levels of study build upon each other. First, volunteers, resource specialists, or scientists should conduct an inventory of the resource. Inventories may include mapping location, measuring temperature, estimating water discharge, and determining chemistry of individual hydrothermal features or areas. Second, resource specialists or scientists should define baseline conditions, collect spatial and temporal data, and monitor changes in the hydrothermal system. Third, scientific researchers should conduct studies of the hydrothermal system and develop an understanding of the physical processes controlling the hydrothermal system as well

TABLE 6. SUMMARY OF GEOTHERMAL VITAL SIGNS AND MONITORING METHODS

Vital Signs and Methods	Expertise	Special equipment	Cost*	Personnel	Labor intensity†
1. Thermal Feature Location					
Basic mapping and repeat photography	Volunteer	No	$	Individual	Low
GPS survey and repeat photography	Volunteer	Yes	$$	Individual	Medium
Aerial/satellite imagery	Scientist	Yes	$$$	Individual	High
2. Thermal Feature Extent					
Basic mapping and repeat photography	Volunteer	No	$	Individual	Low
GPS survey and repeat photography	Volunteer	Yes	$$	Individual	Medium
Aerial/satellite imagery	Scientist	Yes	$$$	Individual	High
3. Temperature and Heat Flow					
Single point temperature measurements	Volunteer	No	$	Individual	Low
Temperature data loggers	Volunteer	Yes	$$	Individual	High
Forward-looking infrared detectors, aerial/satellite imagery	Scientist	Yes	$$$	Group	High
4. Thermal Water Discharge					
Estimate volumetric discharge	Volunteer	No	$	Individual	Low
Wading measurements, weirs or flumes	Scientist	Yes	$$	Group	High
Real-time gauging stations	Scientist	Yes	$$$	Group	High
5. Fluid Chemistry					
Electrical conductivity and pH	Volunteer	No	$	Individual	Low
Chemical analyses	Scientist	Yes	$$	Group	High
Chemical analyses	Scientist	Yes	$$$	Group	High

*Cost (US$): $ = <$1,000; $$ = $1,000 to $10,000; $$$ = >$10,000.
†Labor intensity: low = <few hours; medium = <one week; high = >one week.

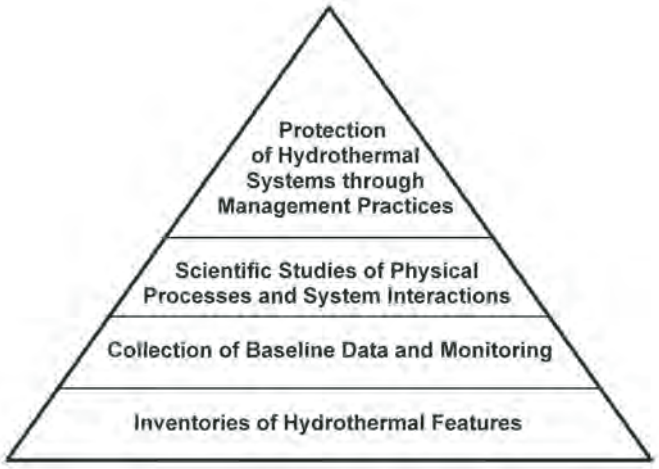


Figure 20. Inventories, monitoring, and scientific studies supply information for the protection of hydrothermal resources.

as system interactions. With these efforts and information, managers can develop strategies, implement management practices and effectively protect hydrothermal systems.

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Wohletz, K., and Heiken, G., 1992, Volcanology and Geothermal Energy: Berkeley, California, University of California Press, 432 p. (*A thorough discussion of different types of volcanoes and their associated geothermal systems. Includes suggestions for field work in volcanic regions, and extensive descriptions of types and locations of hydrothermal systems.*)

GEOTHERMAL WEB SITES OF INTEREST

http://www1.eere.energy.gov/geothermal/ (*U.S. Department of Energy geothermal home page.*)

http://www.osti.gov/geothermal/servlets/purl/6737326-YY5cwq/6737326.pdf (*Thermal springs of United States [(Berry et al., 1980] in PDF.*)

http://www.ngdc.noaa.gov/nndc/servlet/ShowDatasets?dataset=100006&search_look=1&display_look=1 (*Thermal springs of United States [Berry et al., 1980] in searchable format.*)

http://www.unr.edu/geothermal/datalist.html (*GIS layers of data for the Great Basin.*)

http://geothermal.inl.gov/ (*Maps of geothermal resources in western states.*)

http://water.usgs.gov/nrp/proj.bib/mariner.html (*Publications on geothermal—lots of good U.S. Geological Survey references.*)

http://www.uwiseismic.com/Documents/Presentations/SRU%20Geothermal%20Monitoring%20Program_files/frame.htm#slide0001.htm (*University of West Indies; lists chemical constituents being sampled.*)

http://www.ngdc.noaa.gov/seg/geotherm.shtml (*Thermal springs of United States list.*)

http://www.yourownpower.com/Power/ (*Chena power plant description.*)

http://pubs.usgs.gov/twri/twri5-a1/html/pdf.html (*Determination of inorganic substances in water and fluvial sediments.*)

http://pubs.usgs.gov/of/1995/of95-689/ (*Digital maps of low and moderate temperature resources in Pacific Northwest.*)

http://www1.eere.energy.gov/geothermal/glossary.html (*A geothermal glossary.*)

http://www.geothermal.org/powerpoint07_workshop.html (*Geothermal Resources Council 2007 Annual Meeting PowerPoint Presentations Geophysical Techniques in Geothermal Exploration Workshop September 28–29; much valuable data. The Geothermal Resources Council also has much additional data.*)

http://www.unr.edu/geothermal/centerinfo.html (*The Great Basin Center for Geothermal Energy at the University of Nevada–Reno provides geoscientific data on the Great Basin.*)

http://www.smu.edu/geothermal (*Thermal data for the United States.*)

http://geoheat.oit.edu (*Data on low- and moderate-temperature resource uses throughout the United States and beyond.*)

http://www.environmentwaikato.govt.nz/enviroinfo/redi/index.htm (*Geothermal and environmental monitoring data for the Waikato area, New Zealand.*)

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Glacier monitoring techniques

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INTRODUCTION TO GLACIAL RESOURCES

Glaciers are a significant natural resource in Alaska and the Western United States, covering respective areas of ~74,600 and 688 km^2 (Dyurgerov, 2002; Fountain et al., 2007). A large percentage of these glaciers exist within the boundaries of lands managed by the U.S. federal government. For example, glaciers in Wrangell–St. Elias National Park and Preserve and Denali National Park and Preserve in Alaska cover a total area of ~20,000 km^2 (Adema, 2004). In contrast to geologic processes that operate on time scales on the order of thousands or even millions of years, significant glacier change can occur within a human lifetime. The dynamic nature of glaciers strongly influences the hydrologic, geologic, and ecological systems in the environments in which they exist. Additionally, the sensitive and dynamic response to changes in temperature and precipitation make glaciers excellent indicators of regional and global climate change (Riedel and Burrows, 2005). Long-term monitoring of glacier change is important because it provides basic data for understanding and assessing past, current, and possible future conditions of the local, regional, and global environment. A basic understanding of local and regional environmental systems is critical for responsible land management and decision-making.

Glacier Basics

Glaciers are perennial snow or ice masses that move (Paterson, 1994). More specifically, glaciers must have an area where snow accumulates (snowfall, wind drifting, and avalanching) in excess of ablation. **Ablation** includes all processes that decrease the mass of the glacier, such as melting and runoff, evaporation, sublimation, **calving** (the release of a mass of ice from a glacier), and wind erosion (Paterson, 1994). The snow is slowly transformed by compression and recrystallization into solid ice while being transferred by gravity to lower elevations where ablation exceeds mass accumulation (Knight, 1999; Meier, 1964). The area on the glacier where snow accumulation exceeds melting during the summer is the **accumulation zone**. The lower elevation portion of the glacier where ablation exceeds accumulation rates is the **ablation zone**. The boundary between the accumulation and ablation areas, where accumulation equals ablation, is the **equilibrium line**. When accumulation exceeds ablation, the glacier increases in mass and usually advances. When ablation exceeds accumulation, the glacier decreases in mass and thins and/or retreats. A glacier's mass remains stable when accumulation is equal to ablation.

Glacier Controls

The controls on the formation and existence of glaciers include climate and physical conditions (Riedel and Burrows, 2005; Knight, 1999). In most cases, the climatic variables of precipitation and temperature are the dominate influences on glacier formation and survival. Direct precipitation of snow on the glacier typically contributes the largest mass input into a glacier. In some regions of the United States, however, wind drift and avalanching can also play very important roles. Alternatively, ablation on non-calving glaciers is largely attributed to surface melting and sublimation (Knight, 1999). Other climatic influences on glacier development include solar **insolation** (a measure of solar radiation reaching a given surface) and wind (Table 1).

Physical conditions dictate the geographic distribution and spatial extent of most glaciers. Glaciers generally form at high elevations or in polar latitudes where accumulation during the winter exceeds ablation during the summer (Hooke, 2005). The aspect of the glacier is also important as it dictates the amount of solar insolation and wind-blown snow the glacier receives. Accumulation in the form of ice and snow avalanches can contribute a significant amount of mass to the glacier (Fountain et al., 1997; Kaser et al., 2003). Avalanche-nourished glaciers can have accumulation rates as high as four times the winter precipitation rates (Knight, 1999). Glaciers with tidewater, lake, or cliff terminating

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TABLE 1. CONTROLS INFLUENCING GLACIER FORMATION AND HEALTH

Glacier controls	Conditions favoring glacier development	Explanation
Climatic Conditions		
Precipitation	High and winter dominated	Increases accumulation
Temperature	Low annual mean and low summer mean	Reduces ablation
Insolation	Low	Reduces ablation
Wind	Low	Reduces removal of snow from glacier surface
Humidity	High	Increases precipitation and reduces ablation by sublimation
Physical Conditions		
Elevation	Predominately high	Increased precipitation at high elevations results in increased accumulation Lower temperatures at high elevation reduce ablation
Gradient	Low	Low gradient reduces ablation by slowing the transfer of ice from accumulation area to ablation area
Latitude	High	Reduced insolation and air temperature decreases ablation
Continentality	Maritime	Moist air masses increase precipitation and accumulation
Aspect	Poleward and leeward	Shade reduces ablation and leeward aspect increases drifting accumulation
Accumulation character	Large area and prone to avalanches	Increases accumulation
Termination character	Not terminating in water or cliffs	Reduces ablation due to calving or ice avalanches
Landslides/debris-cover	Frequent landsides and highly debris-covered	Thick layers of debris insulate ice reducing ablation
Geothermal heat	Low	Reduces ablation by decreasing basal melting

Note: Table adapted from Knight (1999) with additional information from Hubbard and Glasser (2005); Riedel and Burrows (2005); and Singh and Singh (2001).

margins generally lose a significant amount of mass by calving and ice avalanches (Dyurgerov, 2002). Other physical controls influencing glacier development and health include landslides and geothermal heat. Landslides frequently deposit debris on the surface of glaciers. A layer of debris 1.5–2.0 m thick on the surface of a glacier provides enough insulation that ablation virtually stops (Knight, 1999). Conversely, a very thin layer of low-**albedo** (ratio between light reflectivity and absorption) material can increase ablation. Geothermal heat from the radioactive decay of crustal rocks and heat from the mantle generally results in a few millimeters or centimeters of basal melting per year (Hooke, 2005). Isolated geothermal events such as volcanic eruptions, like those of Mount Redoubt in Alaska or Mount St. Helens in Washington, can result in catastrophic melting events.

Influence of Glaciers on the Environment

Glaciers influence a variety of natural systems in the environment. Monitoring glacier change is important because it links the impact that glaciers impose on the environment with the conditions that influence glacier health. Understanding these relations helps facilitate predictions of how changes in glacier controls may alter the local and global environment. For example, if the climate warms and glaciers melt substantially, then local hydrologic systems will experience reduced capability to buffer against seasonal variability of flow (Fountain and Tangborn, 1985) and global sea levels will rise. The following sections describe the impacts that glaciers have on specific landscape elements.

Glacial Geology

Glaciers are one of nature's most efficient landscape architects, constantly reshaping their environments through the processes of erosion, entrainment, transportation, and deposition (Knight, 1999). Bedrock material ranging in size from clay particles to large boulders are removed by the glacier or meltwater and redistributed in the landscape. Glacial erosion and deposition is responsible for the formation of U-shaped valleys, cirques, **moraines** (mass of glacial debris carried or deposited by a glacier), and a variety of other glacial landforms. Figure 1 illustrates the impact that glaciers can impose on the physical environment. Additionally, glacial sediment is often redistributed by wind or water, forming new soils and affecting the water quality of rivers, lakes, and oceans.

Glacier Hydrology

Glaciers play a significant role in both the local and global hydrologic systems. On a local scale, glaciers act as naturally regulated reservoirs that buffer the local hydrologic regime from seasonal droughts by storing water during cool, wet periods of the winter and releasing it during warm, dry periods of the summer (Post et al., 1971; Fountain et al., 1997). It is estimated that meltwater from glaciers in the North Cascades in Washington annually contributes 800 million cubic meters of water to streamflow (Post et al., 1971). Globally, glaciers serve as "a land-surface water store of fluctuating size, and a slow transport mechanism for throughput of water from the atmosphere, via the land, back to the ocean" (Knight, 1999). Because of these relations, glacier



Figure 1. Glaciers continue to shape the Kichatna Mountains in Denali National Park and Preserve, Alaska. Photo: R.D. Karpilo Jr., 2004.

changes directly influence global sea level, ocean salinity, and sea temperature. Alaska's glaciers are contributing ~0.27 mm of meltwater per year to rising sea level (Arendt et al., 2002).

Glacier Ecology

Glaciers provide habitats for a variety of species of flora and fauna, including ice worms (*Meenchytraeus solifugus*) and springtails (*Collembola*) (Riedel and Burrows, 2005). Glacier meltwater can provide aquatic habitats for endangered species of fish including salmon (*Oncorhynchus*), bull trout (*Salvelinus confluentus*), and western cutthroat trout (*Oncorhynchus clarkii*) (Riedel and Burrows, 2005). Understanding the rates and magnitudes of glacier change is important because the advance and retreat of glaciers changes local habitats, altering the spatial distribution and species composition of the associated biological communities.

Climate

Glaciers and climate have a complex, bidirectional relationship (Knight, 1999). Climatic variables such as temperature and precipitation influence glacier formation and development. Conversely, large glaciers exert control over global climate by affecting albedo and the composition and circulation of the oceans and atmosphere (Knight, 1999). Additionally, glaciers have a microclimate effect on local areas by causing **katabatic winds** (high density air moving downhill) and depressed air temperatures (Riedel and Burrows, 2005).

Glacier Hazards

Glaciers pose several significant hazards to human life and property. Outburst floods, or jökulhlaups, occur when a large amount of meltwater is suddenly released due to the failure of an ice or moraine dam, or rapid melting due to a volcanic eruption (Driedger and Fountain, 1989; Post and Mayo, 1971). Lahars occur when volcanic debris mixes with the glacial meltwater. Calving ice from glaciers in mountainous regions may be released and plunge downslope as an ice avalanche (Knight, 1999). Tidewater glaciers produce icebergs that may threaten passing ships or drilling platforms. Lastly, when glaciers melt they often leave lateral moraine-debris perched on the valley walls. This debris may fall catastrophically to the valley floor as a spontaneous or earthquake-triggered landslide.

GLACIER VITAL SIGNS MONITORING DESCRIPTIONS

Vital Sign 1: Annual Glacier Mass Balance

The annual mass balance of a glacier is a hydrologic budget measuring the difference between the amounts of accumulation and ablation experienced by a glacier during the hydrologic year (Knight, 1999). Depending on the quantity of annual accumulation and ablation; the mass balance value may be positive, negative, or zero. Glacier mass balance is a good measure of the general health of a glacier. A positive mass balance indicates mass accumulation and that the glacier is growing; conversely, a negative balance indicates that the glacier is shrinking. A glacier with a mass balance of zero is in a steady-state and has a constant volume.

Beginning in the 1870s in the Swiss Alps, glacier mass balance monitoring has been used extensively to quantify and assess glacier changes (Mercanton, 1916; Haeberli, 1998). Glacier mass balance monitoring is well accepted by the glaciological community as the most direct measure of glacier health. Mass change is directly linked to changes in glacier volume, climate, and glacial runoff. North Cascades National Park in Washington selected mass balance monitoring as the primary indicator of glacier change in their long-term glacier monitoring plan for the following reasons: "First, it accounts for approximately 90% of the annual change in volume of temperate glaciers. Second, it can readily be measured on the only accessible part of a glacier—its surface" (Riedel and Burrows, 2005).

Climatic changes can be inferred from temporal trends of mass balance dynamics because changes in glacier mass balance are highly correlated to variations in temperature and precipitation (Tangborn, 1980). Trends of positive mass balance over time generally relate to increased precipitation (increased accumulation) or decreased temperature (reduced ablation); and the opposite is typically true for negative mass balance. Monitoring glacier mass balance can provide a seasonal measure of water accumulation, storage, and loss, which is useful for extrapolation to the greater population of glaciers in the region (Riedel and Burrows, 2005).

Level One: Equilibrium Line Altitude and Accumulation-Area Ratio

It is well established that the **equilibrium line altitude (ELA)** (altitude on a glacier where annual accumulation equals annual ablation) at the end of the ablation season is directly related to the annual mass balance of the glacier (Paterson, 1994).

If annual mass balance increases, the ELA will be located at a lower elevation. Conversely, an unusually high ELA indicates a decrease in annual mass balance. Figure 2 shows the position of the ELA on an unnamed cirque glacier in Denali National Park and Preserve in Alaska. If the area above or below the ELA and the total glacier area (see Vital Sign 3) are known, an accumulation-area ratio (AAR) can be calculated. The AAR is determined by dividing the glacier's accumulation area by the total glacier area (Paterson, 1994). Monitoring annual variations in the ELA and AAR of a glacier provides a good estimate of changes in mass balance and variations in climate. There are a variety of acceptable methods for determining ELA, including repeat photography, direct survey with a Global Positioning System (GPS) receiver, and satellite or aerial imagery. Due to the low relative cost, the repeat photography method is presented here.

Methodology. Repeat photography methodology for monitoring the ELA and AAR consists of photo site selection and establishment, photography, ELA plotting, and AAR calculation. The two options for selecting a photo site are to establish a new site or to reoccupy the site of an historic photograph. Reoccupying a previous photo location is preferable if a quality historic photograph of the glacier exists and was taken from an acceptable location. The following criteria should be considered when evaluating a potential photo site: current and future view of the equilibrium line, accessibility, repeatability, and potential hazards. The photo site can be permanently established by installing a fence post, reinforcing bar (rebar) stake, or expansion bolt and washer, or by selecting a suitable natural feature, such as a boulder, as a marker. The position of the site marker is recorded with a GPS receiver and marked on a map. The photo site is photographed and a written description of the location is recorded to assist in relocating the site in the future. The tripod and camera is positioned at the marked location and several images with bracketed exposures are captured. A field notebook is used to record the photo direction, tripod height, lens focal length, camera data, exposure number, date and time, weather conditions, and other observations. For detailed information about photographic monitoring field methods and techniques see Hall (2002), Jorgenson et al. (2006), and National Park Service (2006). The photographs are used to visually estimate and plot the ELA position on a map or to digitize it using geographic information systems (GIS) software. If a digital elevation model (DEM) of the glacier and surrounding area is available, the oblique photographs can be georeferenced to the DEM and the ELA and area of the glacier can be precisely digitized using GIS software. See Corripio (2004) for detailed instructions for georeferencing oblique photographs to DEMs. If the total glacier area is available, the ELA is used to determine the area of the accumulation zone. The AAR is calculated by dividing the accumulation area by the total glacier area.



Figure 2. Equilibrium line on an unnamed glacier in Denali National Park and Preserve. Photo: R.D. Karpilo Jr., 2004.

Timing and frequency. Repeat photography visits should be conducted on days with favorable weather and high visibility and coincide with the late-summer end of the ablation season when the maximum area of snow-free ice is exposed (Fountain et al., 1997). In order to produce a data set useful for identifying mass balance trends, monitoring and mapping of the ELA should occur on an annual basis.

Equipment and costs. Depending on location and accessibility, monitoring the ELA of a glacier with repeat photography can be an effective and economical technique that requires little specialized training and equipment. The monitoring technician should possess a basic understanding of photographic techniques, GPS receiver operation, and map reading skills. Knowledge of GIS is helpful for basic analysis but is not required. Advanced GIS skills are required to georeference the photographs to a DEM and perform the data analysis. The necessary equipment includes a digital camera, tripod, compass, GPS receiver, field notebook, and topographic map. See National Park Service (2006) for a detailed equipment list. Other useful equipment and supplies includes a tape measure, hammer, hand drill, expansion bolts and washers, steel fence posts or concrete rebar stakes, GIS workstation, and a DEM of the glacier and surrounding area (Hall, 2002). The required equipment is widely available and can be purchased from consumer home improvement and photographic supply stores for a few hundred dollars.

Limitations. The primary limitation of this method is that it is an approximation of glacier mass balance. The actual relationship of AAR to mass balance differs from glacier to glacier. Also, it makes the assumption that the snowline is the equilibrium line. While this assumption is fairly accurate for most temperate glaciers, at higher elevations and latitudes the effect of internal refreezing of meltwater at the base of the season snowpack becomes important. In this situation, the refrozen meltwater looks like ice or **firn** (recrystallized and partially compacted snow from

previous seasons) rather than seasonal snow, and the estimated ELA is mistakenly plotted too high on the glacier (Paterson, 1994). This error has never been quantified. Poor topographic map accuracy of the glacier may contribute to errors in plotting the ELA location. This concern is important because most topographic maps are decades old, despite revision dates, and given the general recession of most glaciers they are no longer accurate. Lastly, timing is a limitation because it is important to perform the monitoring near the end of the ablation season, before the first snowfall.

Interpretation. While ELA and AAR do not provide estimates of mass change, unless other site specific information is available, they are good indicators of variations in glacier mass balance and climatic conditions (Meier and Post, 1962; Østrem, 1975). If annual mass balance increases, the ELA will be located at a lower elevation and the AAR will be larger, and vice versa. A "typical" alpine glacier with a mass balance of zero will have an AAR value between 0.5 (Meier and Post, 1962) and 0.7 (Paterson, 1994). If mass balance measurements are available, a relationship between ELA and mass balance can be established, and the mass balance measurements can be terminated. However, the glacier cannot change geometry (area-altitude) significantly; otherwise the relation between the two variables will change.

Level Two: Glaciological Mass Balance

The glaciological method is the most widely used technique for monitoring glacier mass balance (Singh and Singh, 2001). Direct measurement of glacier mass balance components provides the most detailed information about the processes that control mass balance, spatial differences, and changes over time (Fountain et al., 1997). Mass balance for the entire glacier is determined based on a number of repeated point measurements on the glacier surface (Paterson, 1994). The depth of snow or ice that has accumulated or ablated at each point is measured and multiplied by the snow or ice density to determine the mass balance at that point (Kaser et al., 2003). The point values are interpolated and extrapolated across the glacier surface to calculate the mass balance for the entire glacier.

Methodology. Most commonly, point locations of mass balance are measured against poles drilled into the glacier surface. An ideal network consists of ablation poles (or stakes) installed in a pattern covering the entire glacier. In many cases, logistical constraints dictate that the stakes are installed along the centerline of the glacier with occasional transverse profiles more or less perpendicular to the longitudinal profile of the glacier. Stakes should be distributed by equal elevation intervals, not equal horizontal distances (Kaser et al., 2003). The location of each stake must be recorded using a GPS receiver. For small valley glaciers, like those found in North Cascades National Park, 10–15 stakes are usually sufficient (Fountain and Vecchia, 1999; Kaser et al., 2003). Ablation stakes of PVC pipe, wood, aluminum, steel, plastic, and bamboo have all been used successfully for mass balance investigations (Hubbard and Glasser, 2005; Singh and Singh, 2001). An aluminum ablation stake is visible in Figure 3. Stakes



Figure 3. A monitoring technician measures the length of ablation stake exposed on the East Fork Toklat Glacier in Denali National Park and Preserve, Alaska. Photo: R.D. Karpilo Jr., 2003.

are installed on the glacier by drilling holes 2–4 cm in diameter and up to 10 m in depth with a steam drill or hand auger (Heucke, 1999; Østrem and Brugman, 1991; Riedel and Burrows, 2005).

The network of ablation stakes is used in conjunction with snow pits to determine the depth of snow or ice that has melted or accumulated at each measurement location on the glacier (Kaser et al., 2003). Ablation determinations are made by measuring the length of exposed stakes with a tape measure at the beginning and end of the mass balance year. The stakes can be used to measure accumulation if the depth of new snow does not exceed the length of exposed stakes. This is often not possible because in many areas deep snow accumulations bend or break installed stakes; therefore, snow accumulation depths must be determined using snow pits or snow-depth probes (Kaser et al., 2003; Riedel and Burrows, 2005). Figure 4 illustrates the use of snow-depth probes. The density of the snow is determined using a snow density tube and a scale (Kaser et al., 2003).

The mass change at each ablation site is calculated by multiplying the change in length of the exposed stakes at the end of the mass balance season by the density of the snow or ice. The density of snow needs to be determined in the field. See Riedel and Burrows (2005) for detailed field methods for measuring snow density. Glacier ice is assumed to have a density of 900 kg m^{-3} (Paterson, 1994). The mass gained or lost at each stake location is calculated and extrapolated across the entire glacier surface to determined total mass balance. The interpolation/extrapolation of the point data varies according to glacier conditions and the person making the evaluation. See Geografiska Annalar 81A (1999) for several articles presenting a variety of interpolation/extrapolation methods. A GIS method is presented by Riedel and Burrows (2005) and the contour method is explained by Kaser et al. (2003).

Timing and frequency. At a minimum, mass balance field visits should be conducted biannually—one visit at the end of the



Figure 4. A scientist uses a probe to measure the depth of accumulated snow on Silver Glacier in North Cascades National Park, Washington. Photo: North Cascades National Park, 2005.

accumulation season and one at the end of the ablation season (Kaser et al., 2003). This schedule allows direct measurement of the magnitude of seasonal accumulation and ablation (Fountain et al., 1997). Additional visits may be required to inspect and maintain/replace ablation stakes, particularly in regions where ice melt exceeds several meters per summer (Kaser et al., 2003).

Equipment and costs. Monitoring glacier mass balance with the glaciological method is a technique of moderate cost that requires a high level of specialized training and equipment. The monitoring technicians should possess a basic understanding of glaciology and snow science, GPS receiver operation, GIS mapping techniques, and glacier safety. The minimum required equipment includes: a GIS workstation or topographic map, GPS receiver, ablation stakes, a steam drill or ice auger, snow probes, snow density tube, scale, snow shovel, and tape measure. The necessary computer hardware and GIS software can be purchased for approximately $2,000 (all amounts herein are in US$), and a GPS unit will cost a few hundred dollars. The ablation stakes can be constructed for a few dollars per stake with materials purchased from a home improvement store. A steam drill will cost several thousand dollars, while the ice auger option will cost only a few hundred dollars. The remaining equipment can be purchased for a few hundred dollars.

Limitations. The glaciological method is an excellent technique for assessing glacier mass balance; but it does have several inherent limitations. One potential limitation is that this method does not account for ablation due to calving (Fountain et al., 1997). Mass balance calculations on calving glaciers require the monitoring of the terminus position and glacier velocity to determine calving rates. A second limitation is that the glaciological method only measures ablation on the glacier surface. Approximately 90% of ablation occurs on the glacier surface; thus it is assumed that the subsurface change is negligible and can be ignored in the calculations (Mayo, 1992; Riedel and Burrows, 2005). The third limitation is that crevasses or steep terrain may not allow installation of stakes in a desired arrangement. Other complications include field visits under adverse weather conditions, complicated and expensive logistics and labor, and the slow rate of data acquisition (Kaser et al., 2003).

Interpretation. The glaciological method is considered to be the most accurate surface-based method to date and provides highly detailed information on the spatial variation of mass balance magnitudes. Monitoring glacier mass balance provides insights into the hydrologic cycle of the glacier and allows a comprehensive evaluation of glacier dynamics.

Level Three: Geodetic Mass Balance

Geodetic mass balance is determined by calculating an ice mass's volumetric change through time from repeated topographic surveys of surface elevation and extent (Paterson, 1994). This technique offers a remote-sensing alternative or complement to the field-based glaciological method. There are several acceptable methods for determining the geodetic mass balance of a glacier, including the use topographic maps, DEMs based on satellite or aerial imagery, and light detection and ranging (LIDAR) surveys (Kaser et al., 2003). The aerial photography method is presented here.

Methodology. The comparison of vertical aerial photography with geodetic control from two different time periods provides an efficient method of assessing changes in the volume of a glacier. The geodetic mass balance methodology consists of image acquisition, image scanning and georeferencing, DEM production, and glacier change calculation. Images are obtained through vendors or appropriate government agencies specializing in aerial photography. The acquired images must be of sufficient scale to discern glacier margins from the surrounding terrain and should be taken late in the ablation season (Riedel and Burrows, 2005). A useful scale for small glaciers, such as those found in Washington and Oregon, is 1:12,000 scale (Riedel and Burrows, 2005). The purchased images should be photogrammatically corrected, georeferenced, used to produce a DEM with an appropriate grid interval, and delivered in a GIS-compatible digital format. A grid interval of 25 m was used successfully to measure the geodetic mass balance of Gulkana Glacier in Alaska (Cox and March, 2004). Surface elevation change is calculated using GIS software by subtracting coregistered DEMs from different time horizons (Cox and March, 2004). Refer to Granshaw (2002) for a detailed procedure for determining surface elevation changes using a GIS. The net change in glacier mass balance over the time interval between aerial photos is calculated by multiplying the density of glacier ice by the change in volume (Cox and March, 2004).

Timing and frequency. Aerial photography flights should be scheduled to coincide with the late-summer end of the ablation season when the maximum area of snow-free ice is exposed (Fountain et al., 1997). The interval between photographic surveys

can range from a few years to a few decades, depending on monitoring objectives and financial resources (Cox and March, 2004). Mapping should be conducted in years of minimal snow because anomalous late-season snow can obscure the terminus or margins and make it impossible to accurately determine glacier extent (Riedel and Burrows, 2005).

Equipment and costs. Monitoring glacier mass balance changes with aerial photography is an efficient technique that requires specialized training and equipment. Producing aerial photographs requires a large capital investment and expert personnel; therefore images must be purchased from remote-sensing vendors or obtained from the appropriate government agencies. The monitoring technician responsible for the analysis should possess a basic understanding of remote-sensing techniques and be competent in the use of GIS. The necessary materials and equipment includes: large-scale, digital, georeferenced images, derived DEMs, and a GIS workstation. The minimum required computer hardware and GIS software can be purchased for approximately $2,000. The cost of the aerial photographs is highly variable. Depending on the area and scale desired, imagery costs can range from free image data sets available on the Internet to over $100,000 for commissioned, custom products. For example, North Cascades National Park in Washington paid approximately $70,000 in 1998 to obtain 1:12,000 scale, color, stereo air photos of the 2800 km^2 park (Riedel and Burrows, 2005).

Limitations. The geodetic method is an effective technique for remotely assessing glacier volume change, but it does have several inherent limitations. The primary limitation of this method is the high cost of obtaining geodetic-quality aerial imagery (Riedel and Burrows, 2005). The second limitation is the potential error derived from assuming "the density of the material gained or lost is equal to the density of ice" (Cox and March, 2004). This assumption may result in overestimating the mass of snow and firn in the accumulation area. Other complications include errors from areas of limited photographic contrast (including icefields with limited relief), and poor DEM registration, typical of the snow-covered accumulation zones (Arendt et al., 2002; Andreassen, 1999; Østrem and Haakensen, 1999).

Interpretation. It is important to note the difference between this method and the glaciological method because the products can be confused. The geodetic method produces a volume change for the entire glacier, which after some assumptions about density, is converted to mass change. This method provides an important check on the glaciologic method and should be used in conjunction with it. The geodetic method does not provide point-specific mass balance data, such as annual mass balance up a centerline. For example, a glacier in equilibrium will show zero volume change and zero elevation change up the centerline. In contrast, the glaciological method will show increasingly negative mass balance down glacier from the equilibrium line and increasingly positive mass balance up glacier. The sum of the glaciologic mass balance along the centerline would be zero. The difference in results from the geodetic and glaciologic methods is because the geodetic method measures the geometric response to changes in mass input and output, whereas the glaciologic method measures the actual input and output.

The greatest utility of the geodetic mass balance method is in calculating average balances over long periods of time and in validating the glaciological cumulative mass balance (Singh and Singh, 2001; Elsberg et al., 2001). This technique can be used to extend the mass balance record into the past by applying the methodology to historic aerial photography and topographic maps.

Vital Sign 2: Glacier Terminus Position

The glacier terminus position is defined as the physical position of the snout of the glacier (Singh and Singh, 2001). Figure 5 shows the terminus of La Perouse Glacier in Glacier Bay National Park and Preserve, Alaska. In non-calving glaciers, the glacier terminus continually adjusts to variations in mass balance by advancing or retreating; and is useful in validating mass balance measurements (Fountain et al., 1997; Singh and Singh, 2001). Glacial extent is a critical indicator of climate change; therefore, monitoring changes in terminus position provides useful data for understanding the impact of climate change on water resources and ecosystem evolution (Kaser et al., 2003; Fountain et al., 1997; Huybrechts et al., 1989). Additionally, past terminus positions can be reconstructed from historic photographs and terminal or recessional moraines to understand changes in past climate (Kaser et al., 2003; Porter, 1977; Meierding, 1982; Rodbell, 1992).

Level One: Repeat Photography

Repeat photography is a useful tool for documenting changes of glacier terminus position. Based on landmarks in the photograph, the glacier terminus position can be approximated and sketched on a map. Photo pairs or sequences of images provide visual representation of glacier change over time, and the



Figure 5. The terminus of La Perouse Glacier on the outer-coast of Glacier Bay National Park and Preserve, Alaska. Photo: R.D. Karpilo Jr., 2003.

mapped terminus positions can be used to estimate changes in glacier length and area.

Methodology. Repeat photography methodology for monitoring a glacier terminus position consists of photo site selection and establishment, photography, and terminus plotting. The two options for selecting a photo site are to establish a new site or to reoccupy the site of an historic photograph. Figures 6 and 7 present an example of a photo pair utilizing historical photography. Reoccupying a previous photo location is preferable if a quality historic photograph of the glacier exists and was taken from an acceptable location. The following criteria should be considered when evaluating a potential photo site: current and future view of the glacier terminus, accessibility, repeatability, and potential hazards. The photo site can be permanently established by installing a fence post, rebar stake, or expansion bolt and washer, or by selecting a suitable natural feature, such as a boulder, as a marker. The position of the site marker is recorded with a GPS receiver and plotted on a map. The photo site is photographed and a written description of the location is recorded to assist in relocating the site in the future. The tripod and camera is positioned at the marked location and several images with bracketed exposures are captured. A field notebook is used to record the photo direction, tripod height, lens focal length, camera data, date and time, weather conditions, and other observations. For detailed information about photographic monitoring field methods and techniques see Hall (2002), Jorgenson et al. (2006), and National Park Service (2006). The photographs are used to visually estimate and plot the terminus position on a map, or they are digitally captured using GIS software. If a DEM of the glacier and surrounding area is available, the oblique photographs can be georeferenced to the DEM and the terminus position of the glacier can be precisely digitized using GIS software. See Corripio (2004) for detailed instructions for georeferencing oblique photographs to DEMs.



Figure 6. Glacier in the Teklanika River Valley in Denali National Park and Preserve, Alaska in 1919. Photo: S.R. Capps, U.S. Geological Survey, 1919.



Figure 7. Glacier in the Teklanika River Valley in Denali National Park and Preserve, Alaska in 2004. Photo: R.D. Karpilo Jr., 2004.

Timing and frequency. Repeat photography visits should be conducted on days with favorable weather and good visibility and should coincide with the late-summer end of the ablation season when the maximum area of snow-free ice is exposed (Fountain et al., 1997). Under ideal circumstances, terminus monitoring and mapping should occur on an annual basis. If yearly photography is not practical, monitoring should generally occur on a five- to ten-year schedule. It is important to note that the terminus position of calving glaciers can change significantly over a brief period and may require a shorter (one- to five-year) monitoring interval (Post, 1975). Conversely, a longer (five- to ten-year) monitoring interval may be adequate for small cirque glaciers (Fountain et al., 1997). If significant changes are observed during the interim period between monitoring visits, a more frequent monitoring schedule may be appropriate.

Equipment and costs. Monitoring glacier terminus change with repeat photography is an economical technique that requires little specialized training and equipment. The monitoring technician should possess a basic understanding of photographic techniques, GPS operation, and map reading skills. Knowledge of GIS is helpful for basic analysis but is not required. Advanced GIS skills are necessary to georeference the photographs to a DEM and perform the data analysis. The necessary equipment includes a digital camera, tripod, compass, GPS receiver, field notebook, and topographic map. See National Park Service (2006) for a detailed equipment list. Other useful equipment includes a tape measure, hammer, hand drill, expansion bolts and washers, steel fence posts or concrete rebar stakes, GIS workstation, and a DEM of the glacier and surrounding area (Hall, 2002). The required equipment is widely available and can be purchased from consumer home improvement or photographic supply stores for a few hundred dollars.

Limitations. The primary limitation of this method is that unless the photograph is georeferenced to a DEM, it is an approximation of the terminus position based on the interpretation of the monitoring technician, rather than an unbiased and precise measurement.

Interpretation. Interpretations from this monitoring technique require the comparison of a minimum of two mapped

terminus positions. For this reason it is beneficial to reoccupy a site of an existing historical photograph. This approach facilitates future analysis, but also allows an immediate assessment of past changes with only one monitoring visit. Changes in glacier terminus position generally result in changes in glacier area (Fountain et al., 1997). Therefore, it is logical to assume that if the glacier advances, the surface area has also increased; if the glacier retreats, the surface area has decreased. It is possible to crudely estimate volume changes based on changes in the terminus position, but caution must be exercised, as a glacier may advance and increase surface area without changing volume. Similarly, a glacier with insulating debris covering the terminus may thin without a corresponding retreat of the terminus. Using the photo pairs to quantify glacier change is the primary goal of this method, but the anecdotal and educational value of the photo pairs themselves should not be overlooked.

Level Two: Survey Terminus with GPS

Surveying the position of a glacier terminus with GPS is a simple but effective method of monitoring glacier terminus change. Depending on the access and size of the glacier and the mapping precision required, the terminus is mapped either by walking or flying along the snout of the glacier with the GPS receiver recording a track log, or by surveying with a laser range finder and a GPS, using offset mapping techniques. The comparisons of mapped terminus positions over time provide a record of glacier change and can be used to calculate changes in glacier length and area and provide insights into changes in glacier volume.

Methodology. The methodology for monitoring glacier terminus change with GPS mapping consists of data collection, post-processing, and GIS analysis. If the glacier terminus is safe and accessible by foot, data collection consists of mapping the position of the terminus by recording a GPS track log while walking along the glacier terminus. A similar technique can be employed on large glaciers by flying along the terminus in a helicopter while recording a GPS track log. Alternatively, glaciers with inaccessible termini may be surveyed from a safe location by performing offset mapping using a laser range finder in conjunction with a GPS unit. If the GPS receiver supports real-time differential correction, it should be employed during data collection. After the GPS data is collected, it is downloaded to a computer and differentially corrected using data collected simultaneously at a GPS base station. Post-processing the GPS data reduces errors, including the signal degrading effects of the atmosphere, and improves the accuracy of the data. Positional accuracy of differentially corrected data is generally less than 5 m. Data is imported into the GIS for inspection and quality control. Any points that severely deviate from the general trend of the track log and represent obvious errors should be removed from the data set. The GPS points collected in the track log are used to construct a line representing the terminus position of the glacier. The GIS is used to compare the current terminus position with those collected in previous and subsequent years.

Timing and frequency. Terminus mapping visits should be conducted at the late-summer end of the ablation season when the maximum area of snow-free ice is exposed (Fountain et al., 1997). Under ideal circumstances, terminus monitoring and mapping should occur on an annual basis. If yearly field visits are not practical, monitoring should generally occur on a five- to ten-year schedule. It is important to note that the terminus position of calving glaciers can change significantly over a brief period and may require a shorter (one- to five-year) monitoring interval (Post, 1975). Conversely, a longer (five- to ten-year) monitoring interval may be adequate for small cirque glaciers (Fountain et al., 1997). If significant changes are observed during the interim period between mapping visits, a more frequent monitoring schedule may be appropriate.

Equipment and costs. Monitoring glacier terminus changes with GPS mapping is a technique of moderate cost that requires a moderate level of specialized training and equipment. The monitoring technician should possess an understanding of GPS and GIS mapping techniques. The minimum required equipment includes a GIS workstation and consumer-grade GPS receiver. If high-precision results are desired, a survey-grade GPS receiver and base station are necessary. The necessary computer hardware and GIS software can be purchased for approximately $2,000; consumer-grade GPS receivers are widely available and can be purchased from electronic and outdoor equipment stores for a few hundred dollars. A survey-grade GPS system and a laser range finder will cost several thousand dollars.

Limitations. The primary limitation of ground-based GPS mapping is that it is highly labor intensive and inefficient for monitoring a large number of glaciers. Another limitation is that the glacier terminus can be an inaccessible and dangerous place. Hazards include icefalls, calving events, rockfall, and stream crossings. These issues can sometimes be mitigated through the technique of offset mapping with a laser range finder and a GPS unit. Glaciers with debris-covered termini pose a substantial challenge for mapping. It can be difficult to discern debris-covered ice from the surrounding terrain. It may also be difficult to differentiate stagnant ice from active ice. Data collectors should also be aware that poor GPS signal reception is commonly encountered in narrow valleys and other terrain with a limited view of the sky. An additional consideration is that it is important to perform the monitoring near the end of the ablation season.

Interpretation. Interpretations from this monitoring technique require the comparison of a minimum of two mapped terminus positions. The first data collection season will establish a baseline for future comparison. The use of the GIS for data analysis facilitates calculating changes in glacier length and estimating changes in glacier area using the mapped terminus positions. It is possible to estimate volume changes based on changes in glacier surface area; however, as mentioned in the previous section, caution must be exercised, as it is possible for a glacier to change in volume without a corresponding change in terminus. The greatest utility of this method is the ability to identify general trends and estimate rates of glacier change.

Level Three: Aerial Photos or Satellite Images

Vertical aerial photographs and satellite images are a highly efficient tool for documenting changes of glacier terminus positions (Fountain et al., 1997). Remote-sensing techniques allow the monitoring of a large number of glaciers without the effort associated with field-based techniques. Additionally, historic aerial photos or satellites images of glaciers are often available, extending the terminus monitoring record into the past. Historical sequences of images provide a visual representation of glacier change over time, and are useful for communicating glacier change to diverse audiences. Glacier terminus positions can be digitized from georeferenced images using a GIS. The digitized terminus positions are then used to quantify changes in glacier length and area.

Methodology. Vertical aerial photography and satellite imagery with ground control "provides a quantitative base for accurate mapping of surface features" (Granshaw, 2002). The methodology consists of image acquisition, image scanning and georeferencing, and glacier terminus digitizing. Images are obtained through vendors or appropriate government agencies specializing in aerial photography or satellite imagery (examples include Landsat, ASTER, or IKONOS). The acquired images must be of sufficient resolution to discern glacier margins from the surrounding terrain and must be taken late in the ablation season (Riedel and Burrows, 2005). A useful scale for small glaciers, such as those found in North Cascades National Park in Washington, is 1:12,000 scale (Riedel and Burrows, 2005). Larger glaciers like the tidewater glaciers located in Southeast Alaska can be photographed at larger scales. The purchased images should be georeferenced and delivered in a GIS-compatible digital format. Once the images are loaded into the GIS, the spatial position of the glacier terminus is recorded using manual, on-screen digitizing techniques (Riedel and Burrows, 2005).

Timing and frequency. According to Fountain et al. (1997), satellite or aerial photographic surveys should occur "late in the summer so the terminus will be in its most retracted position; the transient snowline nearest its final, seasonal position; and the accumulation-area ratio at its seasonal minimum." The satellite or aerial surveys should generally be conducted on a five- to ten-year schedule. It is important to note that the terminus position of calving glaciers can change significantly over a brief period and may require a shorter (one- to five-year) monitoring interval (Post, 1975). Conversely, a longer (five- to ten-year or longer) monitoring interval may be adequate for small cirque glaciers (Fountain et al., 1997). If significant changes are observed during the interim period between surveys, a more frequent schedule may be appropriate.

Equipment and costs. Monitoring glacier terminus changes with aerial photography or satellite images is an efficient technique that requires highly specialized training and equipment.

The costs associated with this technique are directly related to the size of the area covered and the desired resolution of the imagery. Producing aerial photographs and satellite images requires a large capital investment and expert personnel; therefore, images must be purchased from remote-sensing vendors or produced by appropriate government agencies. The monitoring technician should possess a basic understanding of remote-sensing techniques and be competent in the use of GIS. The necessary materials and equipment includes large-scale, digital, georeferenced images and a GIS workstation. The required computer hardware and GIS software can be purchased for approximately $2,000. The cost of the aerial photographs or satellite images is highly variable. Depending on the area and scale desired, imagery costs can range from free image data sets available on the Internet to over $100,000 for custom products.

Limitations. In many cases, the primary limitation of this method is the high cost of obtaining large-scale satellite or aerial imagery (Williams et al., 1991). Aerial imagery of mountainous environments often contains shadowed areas that may conceal glacial margins, making it difficult to interpret the glacial boundary. Debris-covered glaciers pose a substantial challenge for mapping, as it can be difficult to discern debris-covered ice from the surrounding terrain. Additionally, it is important to differentiate between stagnant ice and the active ice terminus. Another issue is timing; it is important to acquire the satellite or aerial photography late in the ablation season, but before the first snowfall of winter.

Interpretation. Interpretations from this monitoring technique require the comparison of a minimum of two mapped terminus positions. If no historical aerial imagery exists, the first digitized data set will establish a baseline for future comparison, and may be useful for comparisons with historic terminus positions derived from terminal moraines. The use of the GIS for data analysis facilitates the comparison of the mapped terminus positions and aids in the quantification of glacier change by calculating changes in glacier length and estimating changes of glacier area. This method allows the efficient monitoring of future glacier change over large areas and the ability to systematically integrate historic imagery to identify past trends.

Vital Sign 3: Glacier Area

Monitoring changes in glacier area is important because it generally provides a direct measure of glacier advance and retreat and the associated creation or destruction of terrestrial and aquatic habitats (Riedel and Burrows, 2005). Measuring the surface area of a glacier is critical for calculating glacier mass balance, identifying the location of the ELA, and calculating accumulation-area ratios. Monitoring changes in glacier area provides an indicator linking the response of glacier length to changes in mass balance (Kaser et al., 2003). Documenting long-term trends of glacier area change provides a good index for understanding local climatic changes.

Level One: Repeat Photography

Repeat photography is a useful tool for documenting changes in glacier area. The position of the glacier margin can

be approximated based on landmarks in the photograph, and then sketched on a map. Photo pairs or sequences of images provide visual representation of glacier change, and the mapped area can be used to quantify changes and identify trends in glacier length, width, and area.

Methodology. The methodology consists of photo site selection and establishment, photography, and glacier margin plotting. The two options for selecting a photo site are to establish a new site or to reoccupy the site of an historic photograph. Reoccupying a previous photo location is preferable if a quality historic photograph of the glacier exists and was taken from an acceptable location. The following criteria should be considered when evaluating a potential photo station: current and future view of the glacier margins, accessibility, repeatability, and potential hazards. The photo station can be established by installing a fence post, rebar stake, or expansion bolt and washer, or by selecting a suitable natural feature, such as a boulder, as a marker. The position of the site marker is recorded with a GPS receiver and marked on a map. The photo site is photographed and a written description of the location is recorded to assist in relocating the site in the future. The tripod and camera is positioned at the marked location and several images with bracketed exposures are captured. Figure 8 illustrates a typical photo station. A field notebook is used to record the photo direction, tripod height, lens focal length, camera data, exposure number, date and time, weather conditions, and other observations. For detailed information about photographic monitoring field methods and techniques see Hall (2002), Jorgenson et al. (2006), and National Park Service (2006). Large glaciers may require several photo stations for complete coverage. In the office, the photographs are used to plot the estimated glacier margin positions on a map or are digitized using GIS software. If a DEM of the glacier and surrounding area is available, the oblique photographs can be georeferenced to the DEM and the area of the glacier can be precisely digitized using GIS software. See Corripio (2004) for detailed instructions for georeferencing oblique photographs to DEMs.



Figure 8. Repeat photography of the Muldrow Glacier in Denali National Park and Preserve. Photo: G.W. Adema, Denali National Park and Preserve, 2004.

Equipment and costs. Monitoring glacier area changes with repeat photography is an economical technique that requires little specialized training and equipment. The monitoring technician should possess a basic understanding of photographic techniques, GPS operation, and map reading skills. Knowledge of GIS is helpful for basic analysis but not required. Advanced GIS skills are required to georeference the photographs to a DEM and perform the data analysis. The necessary equipment includes a digital camera, tripod, compass, GPS receiver, field notebook, and topographic map. See National Park Service (2006) for a detailed equipment list. Other useful equipment includes a tape measure, hammer, hand drill, expansion bolts and washers, steel fence posts or concrete rebar stakes, GIS workstation, and a DEM of the glacier and surrounding area (Hall, 2002). The required equipment is widely available and can be purchased from consumer home improvement or photographic supply stores for a few hundred dollars.

Timing and frequency. Repeat photography visits should be conducted on days with favorable weather and good visibility and should coincide with the late-summer end of the ablation season when the maximum area of snow-free ice is exposed (Fountain et al., 1997). Under ideal circumstances, glacier surface area monitoring and mapping should occur on an annual basis. If yearly photography is not practical, monitoring should generally occur on a five- to ten-year schedule. It is important to note that the area of calving glaciers can change significantly over a brief period and may require a shorter (one- to five-year) monitoring interval (Post, 1975). Conversely, a longer (five- to ten-year) monitoring interval may be adequate for small cirque glaciers (Fountain et al., 1997). If significant changes are observed during the interim period between monitoring visits, a more frequent monitoring schedule may be appropriate.

Limitations. The primary limitation of this method is that unless the photograph is georeferenced to a DEM, it is only an approximation of the area, based on the interpretation of the monitoring technician rather than an unbiased and precise measurement. Potential sources of errors are the "measurement of areas covered by snow or debris, and improperly located ice divides" (Riedel and Burrows, 2005).

Interpretation. Interpretations from this monitoring technique require the comparison of a minimum of two mapped glacier areas. For this reason it is beneficial to reoccupy sites of existing historical photographs. This approach facilitates future analysis, but also allows an immediate assessment of past changes with only one monitoring visit. It is possible to crudely estimate volume changes based on changes in glacier surface area, but caution must be exercised, as it is possible for a glacier to change in surface area without changing volume. Using the photo pairs to quantify glacier change is the primary goal of this method, but the anecdotal and educational value of the photo pairs themselves should not be overlooked.

Level Two: Survey Area with GPS

Surveying the surface area of a glacier with GPS is a simple but effective method of monitoring glacier change. Depending on the access and size of the glacier and desired mapping precision, the glacier area is mapped either by walking or flying in a helicopter along the margin of the glacier with the GPS receiver recording a track log, or by surveying with a laser range finder and a GPS using offset mapping techniques. The comparisons of mapped glacier areas over time provide a quantitative record of glacier change.

Methodology. The methodology for monitoring glacier area change with GPS mapping consists of data collection, post-processing, and GIS analysis. Data collection involves visiting the glacier and recording a GPS track log while walking the margin of the glacier. The area of large tide-water glaciers or other glaciers that are inaccessible or dangerous can be mapped in a similar fashion by recording a GPS track log while flying along the margin in a helicopter. Alternatively, some glaciers with inaccessible margins can be surveyed from a safe location by performing offset mapping using a laser range finder in conjunction with a GPS unit. If the GPS receiver supports real-time differential-correction it should be employed during data collection. After the GPS data is collected, it is downloaded to a computer and differentially corrected using data collected simultaneously at a GPS base station. Post-processing the GPS data mitigates the signal-degrading effects of the atmosphere and improves the accuracy of the data. Positional accuracy of differentially corrected data is generally less than 5 m. Data should be imported into the GIS for inspection and quality control. Any points that severely deviate from the general trend of the track log and/or represent obvious error should be removed from the data set. The GPS points collected in the track log are used to construct a polygon representing the area of the glacier. The GIS is used to compare the current area with data collected in previous and subsequent years. Using these techniques, changes in glacier length and area can be quantified and monitored.

Timing and frequency. Area mapping visits should be made in late summer near the end of the ablation season when the maximum area of snow-free ice is exposed (Fountain et al., 1997). Under ideal circumstances, area mapping should occur on an annual basis. If yearly mapping is not practical, monitoring should generally occur on a five- to ten-year schedule. It is important to note that the area of calving glaciers can change significantly over a brief period and may require a shorter (one- to five-year) mapping interval (Post, 1975). Conversely, a longer (five- to ten-year) monitoring interval may be adequate for small cirque glaciers (Fountain et al., 1997). If significant changes are observed during the interim period between mapping visits, a more frequent monitoring schedule may be appropriate.

Equipment and costs. Monitoring glacier area changes with GPS mapping is a technique of moderate cost that requires a moderate level of specialized training and equipment. The monitoring technician should possess an understanding of GPS and GIS mapping techniques. The minimum required equipment includes a GIS workstation and consumer-grade GPS receiver. If high-precision results are desired, a survey-grade GPS receiver and base station are necessary. The necessary computer hardware and GIS software can be purchased for approximately $2,000; consumer-grade GPS receivers are widely available and can be purchased from electronic stores for a few hundred dollars. A survey-grade GPS system and a laser range finder will cost several thousand dollars.

Limitations. The primary limitation of ground-based GPS mapping is that it is highly labor intensive and inefficient for monitoring a large number of glaciers or glaciers that are large in area. Another limitation is that glacier margins can be inaccessible and dangerous. Hazards include icefalls, calving events, rockfall, and stream crossings. These issues can sometimes be mitigated through the use of aircraft, but aerial GPS mapping is costly and lacks the precision of a ground-based survey. Glaciers with debris-covered termini, like the Kahiltna Glacier in Figure 9, pose a substantial challenge for mapping. It can be difficult to discern debris-covered ice from the surrounding terrain. It may also be difficult to differentiate stagnant ice from active ice. Data collectors should also be aware that poor GPS signal reception is commonly encountered in narrow valleys and other terrain with a limited view of the sky. An additional issue is timing; it is important to conduct the monitoring near the end of the ablation season but before the first snowfall.

Interpretation. Interpretations from this monitoring technique require the comparison of a minimum of two mapped glacier areas. The first data collection season will establish a baseline for future comparison. The use of the GIS for data analysis facilitates the calculation of changes in glacier length and area. It is possible to crudely estimate volume changes based on changes in glacier surface area, but caution must be exercised, as it is possible for a glacier to increase or decrease surface area without changing volume.



Figure 9. The debris-covered terminus of the Kahiltna Glacier in Denali National Park and Preserve. Photo: R.D. Karpilo Jr., 2004.

Level Three: Aerial Photos or Satellite Images

Vertical aerial photographs and satellite images are a highly efficient tool for documenting changes of glacier area (Fountain et al., 1997). Remote-sensing techniques allow the monitoring of a large number of glaciers without the effort associated with field-based techniques. Historical sequences of images provide a visual representation of glacier change over time and are useful for communicating glacier change to diverse audiences. Glacier areas can be digitized from georeferenced images using a GIS. The first set of digitized areas can be compared to measurements from subsequent years to identify trends and quantify rates of changes in glacier length and area.

Methodology. Vertical aerial photography and satellite imagery with ground control "provides a quantitative base for accurate mapping of surface features" (Granshaw, 2002). The methodology consists of image acquisition, image scanning and georeferencing, and glacier area digitizing. Images are obtained through vendors or appropriate government agencies specializing in aerial photography or satellite imagery. The acquired images should be of sufficient scale to discern glacier margins from the surrounding terrain and must be taken late in the ablation season, before the first snowfall (Riedel and Burrows, 2005). A useful scale for small glaciers, such as those found in Washington, is 1:12,000 scale (Riedel and Burrows, 2005). Larger glaciers like the tidewater glaciers located in Southeast Alaska can be photographed at larger scales. The purchased images should be georeferenced and delivered in a GIS-compatible digital format. Once the images are loaded into the GIS, the spatial position of the glacier area is recorded as a polygon, using manual, on-screen digitizing techniques (Riedel and Burrows, 2005). Figures 10 and 11 show a Landsat TM-7 image of the Kahiltna Glacier and the digitized glacier and perennial snow polygons.

Timing and frequency. According to Fountain et al. (1997) satellite or aerial photographic surveys should occur "late in the summer so the terminus will be in its most retracted position; the transient snowline nearest its final, seasonal position; and the accumulation-area ratio at its seasonal minimum." The satellite or aerial surveys should generally be conducted on a five- to ten-year schedule. It is important to note that the terminus position of calving glaciers can change significantly over a brief period and may require a shorter (one- to five-year) monitoring interval (Post, 1975). Conversely, a longer (five- to ten-year or longer) monitoring interval may be adequate for small cirque glaciers (Fountain et al., 1997). If significant changes are observed during the interim period between surveys, a more frequent schedule may be appropriate.

Equipment and costs. Monitoring glacier area changes with aerial photography or satellite images is an efficient technique that requires highly specialized training and equipment. Producing aerial photographs and satellite images requires a large capital investment and expert personnel; therefore, images must be obtained from remote-sensing vendors or the appropriate government agencies. The monitoring technician should possess a basic understanding of remote-sensing techniques and be competent in the use of GIS. The necessary materials and equipment includes large-scale, digital, georeferenced images and a GIS workstation. The required computer hardware and GIS software can be purchased for approximately $2,000. The cost of the aerial photographs or satellite images is highly variable. Depending on the area and scale desired, imagery costs can range from free images available on the Internet to over $100,000 for custom products.

Limitations. The primary limitation of this method is the high cost of obtaining large-scale satellite or aerial imagery (Williams et al., 1991). Aerial imagery of mountainous environments often contains shadowed areas that may conceal glacial margins, making it difficult to interpret the glacial boundary. Debris-covered glaciers pose a substantial challenge for mapping, as it can be difficult to discern debris-covered ice from the surrounding terrain. Additionally, it is important to define where the stagnant ice ends and the active ice terminus begins. It is important that the satellite or aerial photography survey occur late in the ablation season before the first snowfall of winter.

Interpretation. Interpretations from this monitoring technique require the comparison of a minimum of two mapped glacier areas. If no historical aerial imagery exists, the first digitized data set season will establish a baseline for future comparison. The use of the GIS for data analysis facilitates the comparison of the mapped areas and allows the quantification of glacier change by calculating changes in glacier length and area. The greatest utility of this method is the ability to identify quantifiable trends and rates of glacier change.

Vital Sign 4: Glacier Surface Velocity

Glacier surface velocity is a measure of the rate at which a glacier is moving downhill under the influence of gravity, through the processes of sliding on its bed and internal deformation of the ice (Singh and Singh, 2001). Generalized, singular velocities are often presented for entire glaciers, but it is wrong to imagine the motion of the glacier to be like that of a train, uniformly descending a mountain pass. On the contrary, the nature of glacier movement is temporally and spatially variable.

Glacier movement is analogous to the internal motion of water in a river; in which the friction of the bed and the banks reduces the water velocity relative to the faster, unimpeded water near the surface centerline of the main channel. Glaciers typically behave in a similar fashion; the velocity of a glacier is greatest at the surface along the centerline and least near the valley walls and floor, where flow is inhibited by friction (Singh and Singh, 2001). Changes in gradient along the glacier profile results in variable flow velocities. Steep gradients, such as those found at icefalls, yield the highest flow rates. Typical valley glaciers have surface velocities ranging from 10 to 200 m yr^{-1} for most of their length, while icefalls may have rates as high as 1 or 2 km yr^{-1} (Singh and Singh, 2001). During the quiescent phase, surging glaciers may have a velocity consistent with non-surging glaciers (10–200 m yr^{-1}) until interrupted by short periods of rapid advance. Rates of up to 100 m d^{-1} were observed during

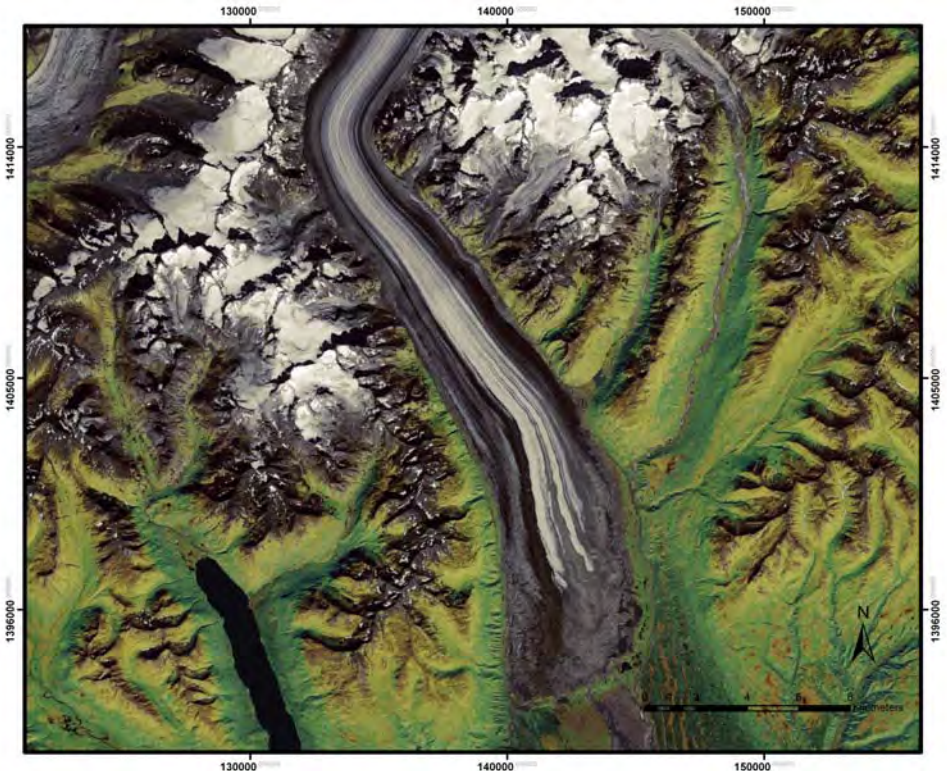


Figure 10. Landsat Thematic Mapper 7 (TM-7) satellite image of the terminus of the Kahiltna Glacier in Denali National Park and Preserve, Alaska. Image: Denali National Park and Preserve, 2000.

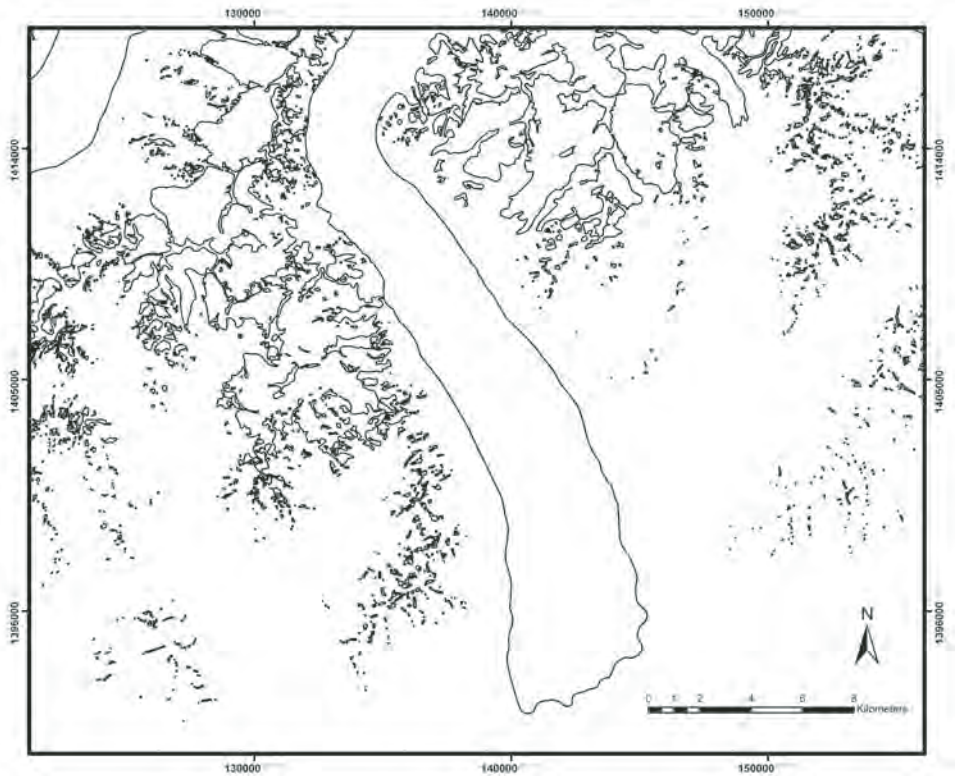


Figure 11. Polygons representing the glacier and perennial snow cover of the Kahiltna Glacier and the surrounding area were digitized from a 2000 Landsat TM-7 satellite image. Image: R.D. Karpilo Jr., 2005.

the 1993 surge of Bering Glacier in Alaska (Molnia, 1993). Glacier movement is seasonal, with the highest flow velocities coinciding with warmer ice temperatures and increased presence of basal meltwater during the summer (Knight, 1999). A few glaciers exhibit summer velocities that are twice as fast as their winter rates (Singh and Singh, 2001).

"The fact that glaciers move is critical to the hydrologic cycle, the functioning of the ocean/atmospheric system, and to all geological and geomorphological phenomena that arise from glaciation" (Knight, 1999). Monitoring glacier movement provides an important link between fluctuations in mass balance and the corresponding changes in glacier geometry (Fountain et al., 1997). The rate of glacier flow determines how quickly mass is redistributed and is an important factor in determining whether the glacier is advancing or retreating (Hooke, 2005).

Increases in the climatic variables of temperature and precipitation can affect glacier velocity. An increase in air temperature increases ice temperature; which correspondingly reduces the ice viscosity and increases glacier velocity. Increasing the air temperature increases the volume of basal meltwater, which reduces basal friction and increases glacier velocity. If precipitation increases, the ice thickness also increases, which can result in increased glacier velocity.



Figure 12. Landslide debris on the surface of the Buckskin Glacier in Denali National Park and Preserve in Alaska. Photo: R.D. Karpilo Jr., 2004.

Level One: Repeat Photography

Repeat photography is a useful tool for determining the general surface velocity of a glacier. Based on landmarks in the photograph, the position of natural targets on the glacier surface can be approximated and plotted on a map. The change in distance of the location of the target in the photo pairs, and the known interval of time between images can be used to calculate the surface velocity of the glacier at the target location.

Methodology. The methodology for using repeat photography for monitoring glacier surface velocity consists of photo station selection and establishment, photography, target plotting, and velocity calculation. It is critical to select a photo station with a view of a recognizable natural feature, such as a large boulder or landslide debris, on the glacier surface. Figure 12 shows large lobes of landslide debris on the surface of the Buckskin Glacier in Denali National Park and Preserve in Alaska. It may be possible to utilize a photo station previously established for monitoring the glacier terminus or area, if an identifiable natural feature is visible from this location. The following criteria should be considered when evaluating a potential photo site: current and future view of the natural feature and fixed reference landmarks, accessibility, repeatability, and potential hazards. The photo site can be permanently established by installing a fence post, rebar stake, or expansion bolt and washer, or by selecting a suitable natural feature such as a boulder as a marker. The position of the site marker is recorded with a GPS receiver and marked on a map. The photo site is photographed and a written description of the location is recorded to assist in relocating the site in the future. The tripod and camera are positioned at the marked location and several images with bracketed exposures are captured. A field notebook is used to record the photo direction, tripod height, lens focal length, camera information, exposure number, date and time, weather conditions, and other observations. For detailed information about photographic monitoring field methods and techniques see Hall (2002), Jorgenson et al. (2006), and National Park Service (2006). The photograph is used to plot the position of the natural target feature on a topographic map or is digitized using GIS software. If a DEM of the glacier and surrounding area is available, the oblique photographs can be georeferenced to the DEM and the location of the target can be precisely digitized using GIS software. See Corripio (2004) for detailed instructions for georeferencing oblique photographs to DEMs. After the prescribed interval, the photo station must be reoccupied and the target re-photographed from the same camera position. Calculating the surface velocity is achieved by dividing the change in distance of the natural target (measured on the map or calculated using the GIS) by the change in time between the photos. The calculated velocity can be presented on a topographic map as a vector representing the magnitude and direction of the measurement (Singh and Singh, 2001).

Timing and frequency. Repeat photography visits must be scheduled when the natural target is snow-free and easily visible. Under ideal circumstances, a camera with an intervalometer can be permanently fixed at the photo station, capturing time-lapse images at a rate of one or two frames per day. In many cases a permanent camera may not be practical; therefore, weekly, monthly, or annual photo station visits may be appropriate.

Equipment and costs. Monitoring glacier velocity with repeat photography is an economical technique that requires little specialized training and equipment. The monitoring technician should possess a basic understanding of photographic techniques, GPS operation, and map reading skills. Knowledge of GIS is helpful for basic analysis but not required. Advanced GIS skills are required to georeference the photographs to a DEM and perform the data analysis. The necessary equipment includes a

digital camera, tripod, compass, GPS receiver, field notebook, and topographic map. See National Park Service (2006) for a detailed equipment list. Other useful equipment and supplies includes a weather-proof camera housing, tape measure, hammer, hand drill, expansion bolts and washers, steel fence posts or concrete rebar stakes, GIS workstation, and a DEM of the glacier and surrounding area (Hall, 2002). The required equipment is widely available and can be purchased from consumer home improvement or photographic supply stores for a few hundred dollars. A basic GIS workstation can be purchased for approximately $2,000.

Limitations. Using repeat photography to monitor glacier surface velocity has many limitations. The primary limitations of this method are that monitoring is restricted to glaciers with easily identifiable, natural targets, and that measurements are limited to a few sample locations on each glacier. Each monitoring location has fixed life span because the natural target will eventually move down the glacier and out of the field of view of the camera station or reach terminus of the glacier and stop moving. Other limitations are that measurements must be made during the snow-free summer season and are restricted to the ablation zone, due to year-round snow coverage of potential natural targets in the accumulation zone. Finally, unless the photograph is georeferenced to a DEM, plotting the position of the natural target on the map is an approximation based on the interpretation of the monitoring technician rather than an unbiased and precise measurement.

Interpretation. The results of this monitoring technique should be judiciously interpreted due to the many limitations previously presented. The paucity of data produced with this method precludes an in-depth analysis of ice dynamics, but may provide a useful indication of the dynamic response of the glacier to changes in mass balance (Kaser et al., 2003).

Level Two: GPS Survey

Surveying the position of artificial targets on the surface of a glacier with GPS is a simple but highly precise method of monitoring glacier surface velocity. This technique requires installing velocity stakes on the glacier surface and repeatedly surveying the position of the stakes using high-precision GPS. The change in distance of the location of the velocity stake and the known interval of time between surveys can be used to calculate the surface velocity of the glacier at the target location.

Methodology. The methodology for monitoring surface velocity with GPS surveying consists of velocity stake installation, data collection, post-processing, and velocity calculation. A convenient alternative to installing new stakes specifically for glacier velocity monitoring is to utilize stakes installed for mass balance monitoring (Kaser et al., 2003). If mass balance stakes are not available, velocity stakes must be installed by drilling a small diameter hole several meters deep with a steam drill or ice auger and inserting the velocity stake. Data collection involves recording a precise location of the velocity stake using a survey-grade GPS receiver. Figure 13 shows a high-precision GPS receiver mounted to a mass balance monitoring stake. To maximize precision, the position of the lowest exposed portion of the stake should be used for the measurement (Kaser et al., 2003). If the GPS receiver supports real-time differential-correction it should be employed during data collection. After the GPS data is collected, it is downloaded to a computer and differentially corrected using data collected simultaneously at a GPS base station. Post-processing the GPS data mitigates the signal degrading effects of the atmosphere and improves the accuracy of the data. Positional accuracy of differentially corrected data collected with a survey-grade GPS receiver is generally within a few centimeters (Vadon and Berthier, 2004). At this point, data should be imported into the GIS for inspection and quality control. After the prescribed interval, the velocity stake must be resurveyed. Calculating the surface velocity requires dividing the change in distance of the velocity stake (calculated using the GIS) by the change in time between surveys. The calculated velocity can be presented on a topographic map as a vector representing the magnitude and direction of the measurement (Singh and Singh, 2001).



Figure 13. A high-precision GPS receiver is mounted to a stake drilled in to the glacier surface. Photo: A. Bucki, Denali National Park and Preserve, 2003.

Timing and frequency. Glacier velocity surveys may be scheduled for any time of the year; however, winter surveys in many locations may be difficult and dangerous to access due to severe weather and avalanche conditions. If high-resolution data are desired, it is possible to program the GPS receiver to continuously record positions and leave it running at the survey location for a predetermined length of time. In many cases continuous position logging may not be practical; therefore weekly, monthly, or annual survey visits may be appropriate.

Equipment and costs. Monitoring glacier velocity with GPS surveying is a technique of moderate cost that requires a moderate level of specialized training and equipment. The monitoring technician should possess an understanding of GPS surveying and GIS mapping techniques. The minimum required equipment includes: velocity stakes made of aluminum, PVC pipe, or wood; a steam drill or ice auger; a GIS workstation; and a survey-grade GPS receiver and base station. The velocity stakes can be

purchased from a home improvement store for a few dollars per stake. A steam drill, like the one pictured in Figure 14, will cost several thousand dollars, while the ice auger will cost a few hundred dollars. The necessary computer hardware and GIS software can be purchased for approximately $2,000; a survey-grade GPS system will cost several thousand dollars.

Limitations. The primary limitation of ground-based GPS surveying is that it is highly labor intensive and limited to the accessible portions of the glacier (Berthier et al., 2005). Surveying enough points to satisfy a complex ice-dynamics investigation is generally time-consuming and expensive. Data collectors should also be aware that poor GPS signal reception is commonly encountered in narrow valleys and other terrain with a limited view of the sky.

Interpretation. Despite the limitations, monitoring glacier surface velocity with GPS by utilizing existing mass balance stakes, or installing velocity stakes, provides a good indication of the glacier's dynamic response to changes in mass balance (Kaser et al., 2003).

Level Three: Aerial Photos or Satellite Images

Tracking the motion of natural targets on a glacier surface using a series of vertical aerial photographs or satellite images is an effective technique for monitoring glacier velocity (Berthier et al., 2005; Hubbard and Glasser, 2005; Fountain et al., 1997; Harrison et al., 1992; Krimmel and Rasmussen, 1986; Meier et al., 1985). Remote-sensing techniques facilitate the monitoring of a large number of glaciers without the effort associated with field-based techniques. The displacement of natural features can be calculated from a series of georeferenced images using a GIS. The change in distance of the location of the target in the photo pairs and the known time interval between images can be used to calculate the surface velocity of the glacier at the target location.



Figure 14. A steam drill for installing mass balance and velocity stakes on the glacier surface. Photo: R.D. Karpilo Jr., 2004.

Methodology. Vertical aerial photography and satellite imagery with ground control "provides a quantitative base for accurate mapping of surface features" (Granshaw, 2002). The methodology consists of image acquisition, image scanning and georeferencing, target displacement measurement, and velocity calculation. Images are obtained through vendors or appropriate government agencies specializing in aerial photography or satellite imagery. The acquired images must be of sufficient scale to identify the target features and must be taken late in the ablation season and before the first snowfall (Riedel and Burrows, 2005). A useful scale for small glaciers, such as those found in North Cascades National Park in Washington, is 1:12,000 scale or smaller (Riedel and Burrows, 2005). Larger glaciers like the tidewater glaciers located in Southeast Alaska can be photographed at a larger scale, as long as surface features are easily identifiable. The purchased images should be georeferenced and delivered in a GIS-compatible digital format. Once the images are loaded into the GIS, the spatial position of surface features, such as large boulders, are plotted using manual, on-screen digitizing techniques (Riedel and Burrows, 2005). After the prescribed interval, a new set of images is obtained and the spatial positions of the target features are digitized. Cross-correlation techniques are used to determine the displacement of the target features during the elapsed time between the respective images (Hooke, 2005). Calculating the surface velocity requires dividing the change in distance of the natural target by the change in time between the images. The calculated velocity can be presented on a topographic map as a vector representing the magnitude and direction of the measurement (Singh and Singh, 2001).

Timing and frequency. The aerial photographs or satellite images must be taken when the natural target is snow-free and easily visible. Aerial imagery of mountainous environments often contains shadowed areas that may conceal portions of the glacier, making it difficult to identify the target; therefore images should be timed to avoid low sun-angles. Depending on the temporal resolution desired; annual to decadal monitoring may be appropriate.

Equipment and costs. Opportunistic monitoring of glacier velocity with aerial photography or satellite images is an effective technique that requires specialized training and equipment. Producing aerial photographs and satellite images requires a large capital investment and expert personnel; therefore, images must be purchased from remote-sensing vendors or government agencies. The monitoring technician should possess a basic understanding of remote-sensing techniques and be competent in the

use of GIS. The necessary materials and equipment includes large-scale, digital, georeferenced images, and a GIS workstation. The required computer hardware and GIS software can be purchased for approximately $2,000. The cost of the aerial photographs or satellite images is highly variable. Depending on the area and scale desired, imagery costs can range from free image data sets available online to over $100,000 for custom products.

Limitations. The primary limitation of this method is the high cost of obtaining large-scale satellite or aerial imagery (Williams et al., 1991). Another potential limitation is that monitoring is restricted to glaciers with easily identifiable, natural targets, so measurements may be limited to a few sample locations on each glacier and may not be repeatable due to the target traveling down the glacier. Measurements are restricted to the ablation zone, because year-round snow covers most potential natural targets in the accumulation zone. Additionally, it is important that the satellite image or aerial photography survey occurs after the spring snowmelt, but before the first snowfall of winter to assure that the targets are visible.

Interpretation. The use of aerial photographs or satellite images is a proven method for monitoring glacier surface velocity. Interpretations from this monitoring technique require the comparison of images from a minimum of two time horizons. Historical images may be utilized to determine past surface velocities. If no historical aerial imagery exists, the first digitized data set will establish a baseline for future comparison. "For a long-term program, where the mass and volume of a glacier are expected to change, a coincident data set of flow information is useful for determining the dynamic response of glaciers to changes in mass input" (Fountain et al., 1997). Understanding how a glacier responds to changes in mass balance provides useful insight into how the glacier may respond to future climate changes.

STUDY DESIGN

Natural resource managers interested in monitoring glaciers must evaluate several study-specific variables before designing and implementing a glacier-monitoring plan. These criteria include: purpose of monitoring, availability of resources, study scale, and resource value. Defining these criteria will ensure that the glacier-monitoring plan will be successful in producing the appropriate data and decision-making information.

Monitoring Purpose

What are the goals of the glacier-monitoring study? The primary goal of most monitoring studies is to produce data and information for a wide range of uses (Haeberli, 1998). Typically, these uses include: providing information and evidence for management decisions and policy, producing data for the scientific community, and educational material for the general public. It is also important to define specific research goals for the study. For example, North Cascades National Park listed the following as the goals of its glacier-monitoring program: "(1) monitor the range of variation and trends in volume of glaciers in the park; (2) relate glacier changes to status of aquatic and terrestrial ecosystems; (3) link glacier observations to research on climate and ecosystem change; and (4) Share information on glaciers with the public and professionals" (Riedel and Burrows, 2005). Clearly defining the monitoring purpose allows the development of specific objectives necessary for achieving study goals.

Availability of Resources

What resources can be devoted to the glacier-monitoring study? Budget, personnel, and expertise are typically the limiting factors in most projects; therefore, is it important to identify these limitations and adapt the monitoring goals to the available resources. Limited resources should not preclude glacier monitoring. The vital signs presented in this chapter list a range of methods to fit most financial and personnel situations. Additionally, cost-sharing agreements with other projects should be considered when obtaining expensive material with multiple uses, such as aerial photography.

Study Scale

What is the extent of the study area and how large are the glaciers? This is an important consideration, because a park such as Wrangell–St. Elias National Park and Preserve in Alaska, with several thousand square kilometers of glaciers, will require a much different monitoring strategy than a park with only a few small glaciers, like Rocky Mountain National Park in Colorado. Parks with few glaciers may be able to intensively monitor all of the glaciers within their boundaries, while parks with a large number of glaciers should use an approach similar to the strategy developed by the U.S. Geological Survey (USGS) and outlined in Fountain et al. (1997). The USGS strategy "employs a nested approach whereby an intensively studied glacier is surrounded by less intensively studied glaciers and those monitored solely by remote sensing" (Fountain et al., 1997).

Resource Value

Why are glaciers important? Glaciers have significant scientific and economic value. Monitoring glacier change is scientifically important because it links the impacts that glaciers impose on a variety of natural systems in the environment with the drivers that influence glacier health. The economic value of glaciers is related to their impact on regional water supplies and status as major tourist attractions.

CASE STUDY

The following case study illustrates the use of repeat photography for monitoring changes in glacier terminus position and area. Reid Glacier in Glacier Bay National Park and Preserve in Alaska was photographed in 2004 as part of a joint U.S.

Geological Survey and National Park Service study assessing glacier change over the past century in several Alaska national parks. Beginning in 2003, the research project repeated over a hundred historic glacier photographs in Glacier Bay National Park and Preserve, Denali National Park and Preserve, and Kenai Fjords National Park.

Methods

The investigation consisted of searching photo archives, locating the historic photo stations, field visits, and data analysis. The majority of images used in this study were found at the U.S. Geological Survey Photo Library Collection in Denver, Colorado, and the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado. The archive searches focused on collecting historic images of glaciers in Alaskan national parks. A large number of images taken by G.K. Gilbert during the Harriman Expedition in 1899 fit the search criteria. The locations of the photo stations were determined by consulting with National Park Service staff, triangulation using natural features, and trial and error. The photo stations were accessed by boat and on foot. The images in Figures 15 and 16 show a repeat photo pair of Reid Glacier in Glacier Bay National Park and Preserve in Alaska, taken by Gilbert in 1899 and by the author in 2004. Despite being located only 100 m above the shore, it took several hours of bushwhacking to locate this photo station. The location of the Reid Glacier photo station was recorded with a GPS receiver to expedite future visits. The 1899 Gilbert image consists of three mosaicked large-format images. To achieve a similar field of view and perspective, four images with a professional digital single-lens reflex camera with a 50 mm lens were required.

Data Analysis

Natural landmarks in the images were used to plot the 1899 and 2004 terminus positions on the topographic map in Figure 17. The terminus positions were digitized using GIS software. Based on the GIS analysis, Reid Glacier has retreated ~3.0 km and lost a total of ~4.5 km^2 of ice during the 105 years between images.

CONCLUSIONS

Glaciers are a dynamic natural resource that are influenced by environmental changes and have the capacity to alter local and global ecosystems. The glacier vital signs and associated monitoring levels presented in this chapter provide techniques for assessing glacier conditions and identifying trends in glacier change. The glacier monitoring methods presented in this chapter are summarized in Table 2. Several methods in this chapter can be used to monitor more than one vital sign. For example, repeat photography can be used to estimate glacier mass balance, terminus position change, area change, and velocity. Additionally, methods such as geodetic mass balance can be used to validate the results of the glaciological method. The techniques presented in this chapter are not intended as an exhaustive list of glacier research methods, but rather are designed to provide a variety of glacier monitoring options for a range of personnel resources and budget constraints. The goal of this chapter is to emphasize that regardless of the resources available, glacier monitoring can be conducted and valuable information can be produced. Monitoring glacier change generates critical data and information for conducting scientific research, making management decisions, and educating the public.



Figure 15. Panoramic view of the terminus of Reid Glacier in Glacier Bay National Park and Preserve in Alaska taken by G.K. Gilbert on the Harriman Expedition in 1899. Note the dark debris-covered ice in the foreground. Photo: G.K. Gilbert, U.S. Geological Survey, 1899.



Figure 16. Repeated image of Reid Glacier in Glacier Bay National Park and Preserve in Alaska taken by the author in 2004. The glacier has retreated several kilometers during the 105 years between images. Photo: R.D. Karpilo Jr., 2004.

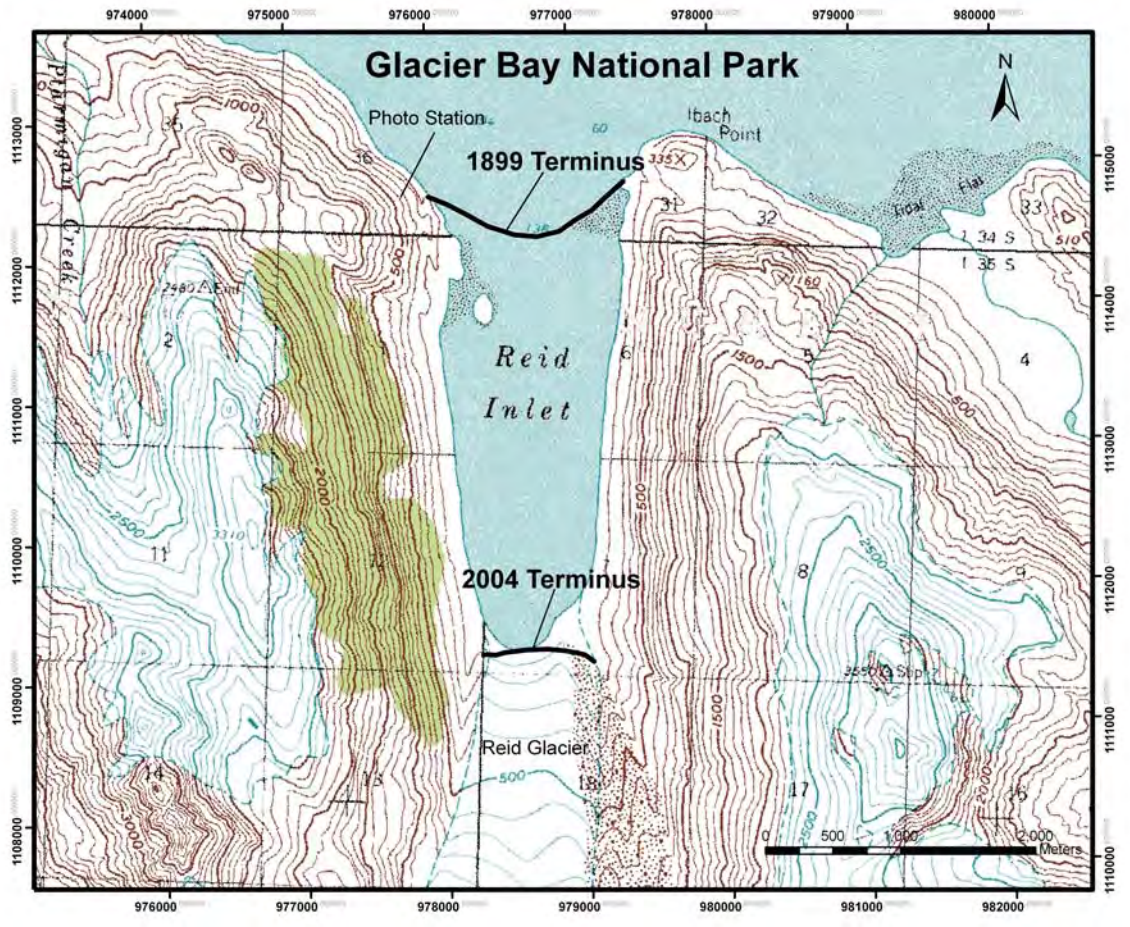


Figure 17. Topographic map of Reid Glacier in Glacier Bay National Park and Preserve in Alaska with 1899 and 2004 terminus positions. Map: R.D. Karpilo Jr., 2005.

TABLE 2. SUMMARY OF GLACIER VITAL SIGNS AND MONITORING METHODS

Vital signs and methods	Expertise	Special equipment	Cost*	Personnel	Labor intensity†
Glacier Mass Balance					
ELA and AAR	Volunteer	No	$	Individual	Low
Glaciological	Scientist	Yes	$$	Group	High
Geodetic	Scientist	Yes	$$$	Individual	Medium
Glacier Terminus Position					
Repeat photography	Volunteer	No	$	Individual	Low
GPS survey	Volunteer	Yes	$$	Group	High
Aerial/satellite image	Scientist	Yes	$$$	Individual	Low
Glacier Area					
Repeat photography	Volunteer	No	$	Individual	Low
GPS survey	Volunteer	Yes	$$	Group	High
Aerial/satellite image	Scientist	Yes	$$$	Individual	Low
Glacier Velocity					
Repeat photography	Volunteer	No	$	Individual	Low
GPS survey	Scientist	Yes	$$	Group	High
Aerial/satellite image	Scientist	Yes	$$$	Individual	Low

Note: ELA—equilibrium line altitude; AAR—accumulation-area ratio; GPS—Global Positioning System.
*Cost (in US$): = <$1,000; $$ = $1,000–$10,000, $$$ = >$10,000.
†Labor intensity: Low = <few hours; medium = <full day; high = >full day.

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Fountain, A.G., Krimmel, R.M., and Trabant, D.C., 1997, A strategy for monitoring glaciers: U.S. Geological Survey Circular 1132, 19 p. *(The authors of this U.S. Geological Survey paper present rationale, techniques, and study design information for monitoring glaciers in Alaska and the continental United States. The monitoring strategy utilizes three hierarchical levels of monitoring intensity; ranging from intensive glaciological mass balance studies to region-wide remote-sensing inventories.)*

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Marine features and processes

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INTRODUCTION

Marine environments include anything seaward of the shoreline, the dividing line between land and water. All environments can be considered as either terrestrial (on land), marine (under water), or transitional (transitional between land and water). The transition zone between terrestrial and marine environments includes such environments as tidal flats, estuaries, dunes, and beaches and barrier islands. Beach features and processes are covered in another chapter of this volume (Bush and Young, this volume). Part of the beach system also belongs to the nearshore zone, so it is impossible to completely disassociate the beach/transitional zone from the nearshore marine system. Standard beach terminology delineating the environmental zones of the nearshore system is shown in Figure 1.

To define the limits of the beach and the limits of the nearshore marine system, begin with the above water part of the beach, the part landward of the shoreline. This is known as the **backshore**, but is also often referred to as the dry beach, the recreational beach, or the subaerial beach. Looking seaward, the shallowest part of the beach is the intertidal zone, the portion between high tide and low tide. This is also known as the **foreshore**. Seaward of the foreshore is the inshore, commonly called the **shoreface**, the deeper water extent of the beach system. The shoreface is the zone where waves approaching land first start to interact with the seafloor. Another way to look at it is that the shoreface is the seaward extent of sediment movement caused by waves. Because the beach is actually defined by the movement of sand, the shoreface, then, is the seaward extent of the beach. The shoreface typically extends seaward to a water depth of 30 feet, though the depth is variable depending on the local wave heights. The seaward extent of the shoreface may be found within a few hundred yards or many miles of the shoreline, depending on the steepness of the seafloor.

For the purposes of this chapter, marine features and processes will be considered seaward from the low tide line—that is, beginning with the shoreface. The marine environments seaward of the foreshore (below the low tide line) can collectively be referred to as the subtidal environment (literally, below the tides). The subtidal environments may be dominated by calcareous sediments (calcium carbonate) if the water is warm and clear enough (Wilson, 1975). If the setting is not tropical, or is dominated by fine sediment input from land, then the environment will be dominated by sediments derived from land sources, or **siliciclastic sediment**.

More than just waves, the nearshore zone is also acted upon by tides, ocean currents, sea level changes, sediment supply, and biologic effects. Oftentimes it is easy to disregard the nearshore, or submarine, landscape and to forget that it is part of the larger dune/beach/nearshore single system. Indeed, the nearshore is intimately tied to the onshore. Sediment moves alongshore as well as onshore and offshore, depending on wave energy and the passage of storms. Nearshore topography exerts a major control on the magnitude of storm surge and coastal flooding that will be caused by the passage of a hurricane or winter storm. Offshore hardgrounds may actually protect portions of the coast from erosion. Nearshore sand bars and their movement can have great effects on natural beach rebuilding following storms. Engineering structures along the shoreline or offshore may exert a major influence on nearshore topography. For example, although jetties may be necessary to provide safe harbor entrances, they protrude so far out into the nearshore sediment transport system that they can essentially block all the sediment from being transported along the coast, causing "sand starvation" on the downdrift side. The resulting shoreline erosion can be spectacular. The impacts may be manifested on the subaerial portion of the system, but major changes are occurring in the submarine portion.

Another way to classify the nearshore system is by dominant bottom types. It may be sandy or rocky (see discussion of substrate later in this chapter). Tropical locales may have reef growth if conditions allow (see discussion of reefs later in this chapter). A good general reference for nearshore processes is the second

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Bush, D.M., 2009, Marine features and processes *in* Young, R., and Norby, L., eds., Geological Monitoring: Boulder, Colorado, Geological Society of America, p. 163–188, doi: 10.1130/2009.monitoring(07). For permission to copy, contact editing@geosociety.org. ©2009 The Geological Society of America. All rights reserved.

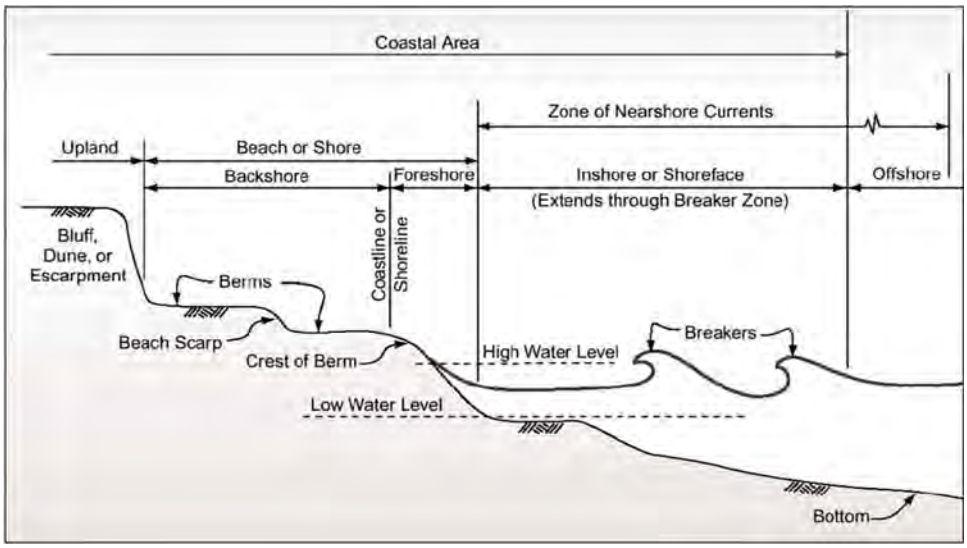


Figure 1. Standard beach terminology. The zone labeled "inshore" is now more commonly called the shoreface. From U.S. Army Engineer Waterways Experiment Station (1984).

edition of *Beach Processes and Sedimentation* (Komar, 1997). The *Encyclopedia of Coastal Science* (Schwartz, 2005) is a lengthy and expensive book, but it is comprehensive and contains a wealth of information on nearshore processes and sampling/monitoring techniques. A series of articles published in the *Journal of Coastal Research* (Gorman et al., 1998; Larson et al., 1997; Morang et al., 1997a, 1997b) give a good overview of the various aspects of nearshore processes and monitoring from an engineering perspective.

Limits of the Nearshore Zone

The marine nearshore zone stretches from the beach seaward to a water depth where average waves begin to interact with the sea bottom. That water depth will vary from place to place depending on the wave climate, but typically is around 30 feet. One can see that the distance from shore to a water depth of 30 feet will vary depending on the slope of the seafloor. In gently sloping environments, such as off Cumberland Island, Georgia, and the Cumberland Island National Seashore, the distance to 30 feet water depth is approximately five miles.

Alternatively, a water depth of 30 feet can be reached relatively quickly in less than one-half mile, off the northern coast of St. Croix, U.S. Virgin Islands, near the Buck Island Reef National Monument.

This chapter addresses issues related to the shallow water systems of continental or insular shelves. Without question, the nearshore marine environment is tied to the onshore portion of the coastal zone. The beach, for example, includes not only the dry, recreational beach, but also the underwater volume of sand that is moved by waves and nearshore currents. The subaerial portion of the coastal zone is covered in another chapter.

It is certainly beyond the scope of any manager to be able to, or to need to, monitor every aspect of the nearshore zone. Some important aspects, though, that can be easily observed and monitored include bathymetry of the nearshore, hydrography (waves and tides and perhaps currents), reefs (if applicable), other offshore barriers (sand bars, for example), substrate, water column turbidity, and water column chemistry and quality.

STRESSORS/POSSIBLE CHANGE TO THE MARINE NEARSHORE SYSTEM

Change in any natural system is the result of stimulus and response. The principal agents of geologic change are wind, water, ice, gravity, and biologic. The nearshore marine system can be subdivided into the water column and the seafloor. Shorelines and shoreline change are addressed in another chapter. The water column can further be broken down into the material suspended in it, material dissolved in it, and energy or motion supported by it (waves and currents).

One of the most important coastal marine vital signs to monitor is water depth and water depth changes. Such changes can give insight into processes acting on long or short time scales. The longest time scales are changes in sea level. See Wilgus et al. (1988), Fletcher and Wehmiller (1992), or the National Oceanic and Atmospheric Administration (NOAA) Web site (www.noaa.gov) for a synopsis of sea level changes. Douglas et al. (2001) considers not only the physical driving forces or sea-level rise, but also the societal impacts. Monitoring this vital sign does not address short-term depth changes resulting from tidal fluctuations or storm surge, but rather tracks long-term bathymetric changes caused by subsidence of the seafloor or global sea-level change. The monitoring of water depth is largely addressed by NOAA; and as a result, local or regional tide gauge data can be easily obtained at NOAA's Web site (www.noaa.gov). Within this site, see the links to bathymetric data and other sources.

Waves and currents are another important aspect of energy flux in the water column. The speed, power, and direction of currents vary constantly. Though a little dated, Bascom (1980) gives

a thorough introduction to the subject. Regional-scale conditions are also monitored by NOAA, and that information is also available online. In many cases, however, detailed local information may be lacking. For example, a manager of a coastal marine environment may wish to monitor the current flow in a sensitive tidal creek, or understand the differential in wave energy between the windward and leeward sides of a reef, or during the passage of a storm.

Offshore barriers, such as reefs and sand shoals, provide critical protection to the sandy shorelines and can act as sensitive indicators of local and global environmental change; therefore, it is critical to measure and monitor the vitality and spatial extents of these important resources. Many reefs around the world are being negatively impacted by rising water temperatures, dust input, and human action, including ecotourism associated with diving and boat anchoring. In addition, protective offshore barriers may be much smaller in scale than reefs and also may be nonbiogenic. For example, sand bars, rock outcrops, and shoals may offer relative protection for portions of the shoreline or submerged resources.

Seabottom composition, known as **substrate**, may consist of one or more of the following materials: mud, sand, gravel, or rock. In addition, portions of the seabottom may be covered by sea grass. The sea grasses provide habitat and protection for juvenile species of fin fish and shellfish, while also acting as a sediment stabilizer. Intertidal marsh grass or mangroves in low latitudes can serve similar purposes.

Summaries of nearshore and shelf hydrodynamics and bottom composition, as well as evolutionary changes through time can be found in a number of texts. Particularly thorough and well organized are Davis (1985), Carter (1988), and Carter and Woodroffe (1994).

Finally, the quality of the water itself is important and can be monitored. Changes in suspended sediment in the water column may be an indicator of seasonal or event-related influx of sediment or degrading conditions caused by increased runoff from land over time. Material dissolved in the water may influence the health and vitality of plants and animals living in the water. This chapter will address suspended sediments only. All dissolved substances (nutrients, solids, and gases) plus any pollutants, toxins, and flora and fauna, are considered part of the biological realm and beyond the scope of this discussion.

SELECTED METHODS FOR MONITORING MARINE FEATURES AND PROCESSES

Monitoring vital signs of physical aspects of park ecosystems helps give insight not only into the general state of systems but also into changes in the systems or system vitality. The vital sign concept is very similar to the **geoindicators** approach to monitoring environments. The International Union of Geological Sciences (IUGS) defines geoindicators as "measures of surface or near-surface geological processes and phenomena that vary significantly over periods of less than 100 years and that provide information that is meaningful for environmental assessment" (Berger, 1996). They are applied to a wide variety of environments (Berger, 1997). Geoindicators have a variety of management applications including environmental auditing and monitoring. Berger (1997) notes that the geoindicators approach identifies a minimum set of parameters that describe short-term environmental dynamics, and that are proxies representing all the parameters on which the processes depend.

Vital signs of marine features and processes will be addressed as follows: (1) the general setting of the environment, of which water depth is the primary indicator; (2) the energy of the environment, waves, and currents; (3) barriers including reefs and other offshore barriers, which block energy; (4) seafloor composition, or substrate; and (5) water column turbidity. As previously mentioned, the biology of the water column is beyond the scope of consideration of this chapter, though an introduction is given. Table 1, at the end of this chapter, summarizes the monitoring techniques discussed below.

There is an infinite number of monitoring techniques and equipment available for monitoring the component environments of the nearshore marine system. The following are selected in order to give a range of methods from low-cost and low level of expertise needed, to high-cost and higher level of expertise needed. Expertise needed may refer to either the expertise needed to use the equipment or the expertise needed to interpret the data, or both.

Vital Sign 1: Bathymetry of the Nearshore

Definition. **Bathymetry** is the study of water depth of any body of water. The study may include simply collecting data on the water depth, or any analysis of such data including changes over time, at any time scale.

Significance. Of particular importance may be water depth changes caused by single events (storms) and subsequent post-event recovery. Also, seasonal changes may be of note, as well as long-term changes. Changes in water depth may be indicators of conditions of sediment movement, such as sand shoals migrating by marine currents. Such movements may be in one direction if unidirectional currents dominate, or they may be bidirectional on a daily (tidal) or seasonal basis. Understanding of water depth changes on that time scale will best be understood with respect to the hydrographic regime of the area in question. Water depth changes may also be due to much longer-term phenomena such as crustal subsidence or uplift, or sea-level rise. Water depth changes on a long temporal scale are beyond the scope of this chapter.

Most nearshore marine areas have existing bathymetric data either from NOAA, the U.S. Geological Survey (USGS), academic studies, or perhaps even their own in-house research. This information may be adequate baseline data, but systematic monitoring is recommended in dynamic settings where sea bottom and water depth changes are expected. It is very likely that available bathymetric surveys will not be very detailed, so if detail is needed over a small area it will be necessary to do your own monitoring.

Long-term changes in water depth caused by sea level change or land subsidence or uplift are beyond the monitoring scope of this report. For such long-term change consult the USGS or NOAA. Regardless, the data from nearby tide gauges should be consulted for overall long-term changes. Long-term bathymetric changes may indicate global sea-level change, or subsidence or uplift of the seafloor. On shorter time scales, bathymetric changes may indicate changes in sediment bedforms on the seafloor or growth or destruction of biogenic structures such as reefs.

Any measurement of water depth is called a **sounding**. For any bathymetric survey, the two important pieces of data to be collected are the water depth itself and the geographic location of the depth measurement. One is useless without the other. Measuring water depth can be as simple as using a pole or rope, but geographic location data may be slightly more difficult to obtain.

Level 1: Manual Surveys

Methods of monitoring bathymetry can be done very simply by testing the water depth with poles for shallowest areas or rope or cable (wire rope) for deeper areas. The simplest techniques are rarely used nowadays, because low-cost fathometers are readily available. But for an inexpensive and hands-on approach, and perhaps for training of students with boat and diving abilities, these can be great learning exercises, and fun as well. As mentioned above, obtaining the exact geographic location of each water depth measurement is critical. In a truly manual, very low-cost survey, locating the data point would likely be done by what is known as **dead reckoning**. This means estimating your position by carefully moving from a known position, using such factors as course and speed. Dead reckoning requires a great deal of experience and should only be used in extenuating circumstances.

Equipment required. The only equipment needed is a long sounding pole or a rope or cable (wire rope) to measure the depths. To record location data, a chart or topographic quadrangle map are good bases to use for beginning from a known starting point. Assuming the observers are in a boat or skiff, they will use a compass for heading and binoculars for keeping focused on known points. Again, this method gives very low-quality precision and accuracy but is a good training exercise. With experience, and considering studies over small areas, it may be possible to accurately locate within 100 m. It can be used especially for reoccupying specific features or study sites where one only needs to get in the vicinity of the feature in order to orient oneself.

Methodology. Map locations can be made by dead reckoning on topographic quadrangles, estimating distances from known points or features onshore or offshore, or from buoys or other permanent markers. This type of effort is not the best for detailed studies, but can certainly be used to monitor individual spots of interest. And again, for students, these can be great exercises for learning to estimate distances and to get a real hands-on feel for the environment.

Timing. Timing should be as necessary, depending on the dynamics of the system. For example, if the feature to be monitored is a reef or other hard or biogenic structure, once a year is sufficient. If the feature is a sand shoal or bar in a strong current area, it should be monitored monthly or quarterly. And if storms are predicted, **event capture** should be considered, where the feature is surveyed immediately before and after the storm and then subsequently at regular intervals to monitor change induced by the storm and recovery.

Level 2: Fathometer Traces

A larger area can be covered with a simple fathometer from a small boat (Gorman et al., 1998). Track lines can be plotted from locations gathered using a handheld or boat-mounted Global Positioning System (GPS). Printouts of bathymetry (Fig. 2) are still utilized, though digital recording is now commonplace.

Equipment required. Fathometers with printout and/or digital recording can be obtained at any marine supply store. A simple handheld GPS unit can be used for spot locations of track lines. If available, a differential GPS gives the best location data, with accuracy to within a meter. For differential GPS, a second, stationary receiver is needed. It continually records its known location, so any drift or error can be corrected using post-processing.

Methodology. If surveying a relatively unknown area, or if making a baseline survey, it is best to run a series of straight north-south and east-west grid lines over the area of interest. After assessment of any directional trends of important features to be monitored (or if such trends are already known), directions of track lines can be adjusted to give the best longitudinal versus transverse coverage. Additionally, if time and resources permit, track lines in even more directions will give the most detailed data. From all the track line data, contour maps of bathymetry can be drawn.

Timing. As above, surveying should be done as needed, with event-capture if possible.

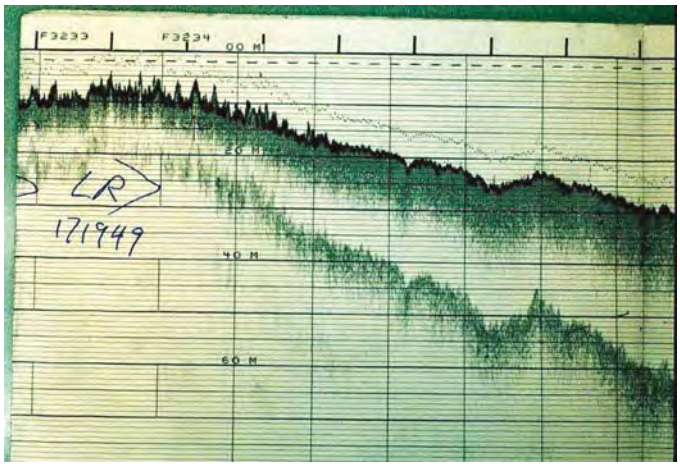


Figure 2. Ragged appearing fathogram trace caused by coral heads on the eastern side of Eleuthera Island, Bahamas. From the National Oceanic and Atmospheric Administration's Historic Coast and Geodetic Survey Collection, taken by personnel of NOAA ship *PIERCE*, 1984.

Complexity. This level of surveying and monitoring can certainly done by students and trainees with some supervision. Gathering the raw data, the fathometer traces, requires supervision to make sure track lines are properly located and that the data are consistent. Plotting and contouring the data requires a good deal of skill and experience.

Cost. The cost of this method is moderate. Perhaps fathometers and GPS units can be borrowed or shared, though they are not terribly expensive. Boats should be available and maintained by any park with marine features.

Level 3: Computerized and Integrated GPS and Fathometer

For the most detailed survey, a computerized and integrated GPS and side-scan sonar plus fathometer, digitally recorded and processed, will give the most accurate and precise data and allow for digital manipulation and three-dimensional display of results. In addition, the sonar will give information about the composition of the substrate (see Vital Sign 5 on substrate, below). The U.S. Geological Survey is a good place to go for information on seafloor mapping. The USGS Web page, http://woodshole.er.usgs.gov/operations/sfmapping/interp.htm, is well illustrated. A shaded relief image of a portion of the seafloor southwest and south of Alcatraz Island reveals several identifiable features (Fig. 3). For large seafloor features, **towed arrays** such as side-scan sonar can cover wide swaths and be digitally integrated with bathymetric data for three-dimensional viewing (Gorman et al., 1998; Larson et al., 1997; Morang et al., 1997a; 1997b). See also Barnhardt et al. (1998) for a discussion of the application of these techniques in areas of complex seafloors.

Equipment required. Complex multibeam arrays, digital recorders, processing computers, and display and printing equipment are needed for this highest level technique. Cooperation with experts at the USGS or NOAA is recommended.

Methodology. Methodology is similar to running fathometer track lines as above, but usually at this level an array of sound sources and receivers is towed behind a ship instead of the signal being sent from the ship or boat. This allows wider coverage of the seafloor. Also, raw data is recorded digitally for later processing. Side-scan sonar data gives a record of the acoustic properties of the seafloor. Such data can be confused with photographs because they are so detailed. Here, instead of recording light reflections for a photograph, it is sound reflections that are being recorded, and thus interpretation is necessary. See Gardner et al. (1996) for discussion of techniques and results from deep-water surveys, and McMullen et al. (2005) or Poppe et al. (2004) for recent shallow water studies. Integration of bathymetric data with the sidescan sonar acoustic data can give realistic images of the seafloor in three dimensions.

A tethered sled array can be used to measure bathymetry and other seafloor attributes in waters with strong currents and high surf. Sea Surveyor, Inc., has developed a heavy sled system with a mast with reflector prisms for surveying location (Fig. 4). The sled is towed out to sea by a boat, and towed back in by a tractor and/or winch. At equidistant stops along the inward tow, a surveyor on land can determine the elevation of the seafloor. Profiles are mapped, and data contoured.

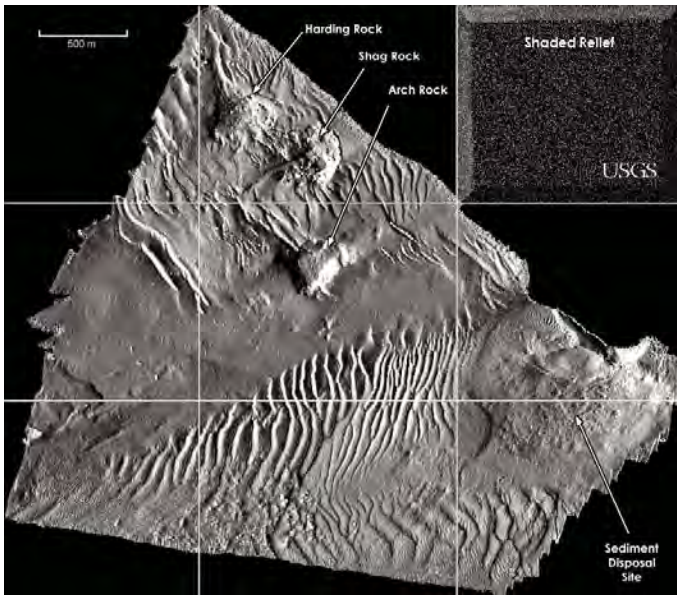


Figure 3. Shaded relief image near Alcatraz Island, California. Several features are identifiable in the image and are labeled. From the U.S. Geological Survey Project: Sediment and Pollutant Transport in Central San Francisco Bay, Multibeam Backscatter and Bathymetry Mosaics (http://terraweb.wr.usgs.gov/TRS/projects/SFBaySonar/Alcatraz_sr/). See also Williams et al. (2000).

Timing. As with the other surveys, timing should be on a regular interval and as needed for event capture.

Complexity. This type of survey is highly complex, and outside assistance will be needed. The USGS has a great deal of experience with these techniques and would be good partners. Discussion of a USGS multi-beam project can be seen online at http://ccma.nos.noaa.gov/products/biogeography/usvi_nps/overview.html.

Cost. The cost of digital surveys is high. The equipment will likely be beyond the limits of most offices. Partnering with an organization that owns the required equipment, such as the USGS or NOAA, will probably be necessary.

Vital Sign 2: Hydrography

Definition. **Hydrography** refers to any type of wave and current climate, including tides, storm waves, average wave heights, rip currents, etc. It is the physical oceanographic setting of a particular study area—the movement of energy through a water column.

Significance. Because currents and waves are the dominant agents of sediment movement in the nearshore, it is important to understand and monitor the hydrography of a body of water for complete understanding. Sediment movement is important to monitor because it may lead to burial of important natural or

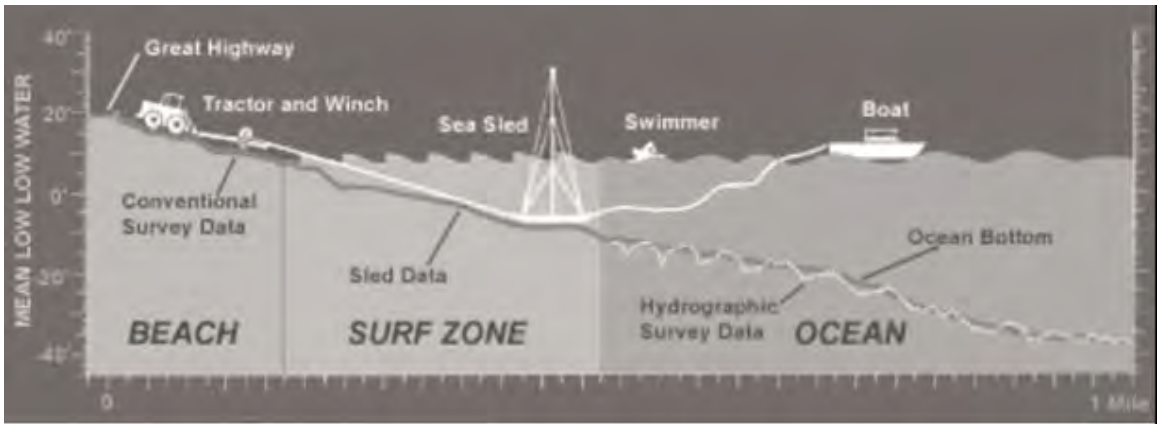


Figure 4. A tethered sled array can be used to measure bathymetry and other seafloor attributes in waters with strong currents and high surf. Photo and description courtesy of Sea Surveyor, Inc.

cultural resources. Additionally, loss of sediment (erosion) from public lands may be a concern.

Oceanic currents transport water, sediment, and storm debris both parallel to and perpendicular to the shoreline. By far the greatest volume of water moved is in an alongshore direction, because waves approaching the shore at an angle set up a current—called the **longshore current**—in the general direction of wave travel (Komar, 1997).

Because storm waves are so large, they begin to break much farther from shore than normal or fairweather waves. The net effect is a widening of the surf zone. The longshore current described above is a surf-zone phenomenon, so merely by enlarging the width of the surf zone, more water is moved parallel to shore. This current can move sediment out of one local area and into another, resulting in a loss of sediment from one portion of the coast. The loss of sediment is not necessarily permanent. Sometimes it a seasonal change in the direction of approach of waves that causes sediment to be alternately moved out of, and back into, a study area.

Storms are also responsible for bottom currents which move at high angles, sometimes perpendicular, to the shoreline. Such currents are known as downwelling pressure gradient currents and are set up because of the local rise in sea level caused by the storm surge. The storm surge sets up a sea surface tilted away from land, generating a gravity-driven flow back out to sea. Rip currents are an example of pressure gradient current on a small scale, which weakens seaward and dissipates at the seaward limit of the surf zone.

Similar in generation, but at a larger scale, are currents created during storms that, even with extreme turbulence created by breaking storm waves, have an overall net flow seaward (Allen, 1982). These seaward-flowing currents are not very strong, and they move a much smaller volume of water than longshore currents, but they can move great quantities of sediment away from the beach and into deeper water (Hayes, 1967). They are efficient at moving sediment because they are accompanied, and even partly created, by large storm waves. Storm wave scour and turbulence resuspend sediment. Once sediment is resuspended, only the slightest current is needed to carry the sediment away. Seaward-flowing currents can actually carry sediment many miles offshore, often so far that the sand is lost from the beach system. This loss is true erosion of the shoreline—a permanent net loss of sediment from the beach and dunes.

In some cases, when storm surge flows back to sea, either by the force of gravity alone or when driven by offshore-blowing winds, an erosive ebb current can be generated. This type of current is different from the ones described above because it occurs while the storm is moving out of the area or diminishing. **Storm-surge ebb** can cause an existing inlet to change shape; it can create a new inlet, such as on Pawleys Island, South Carolina, during Hurricane Hugo (1989); it can scour channels across beaches and the shoreface; and it can cause permanent removal of sand from the beach/dune system to the deeper offshore. After Hurricane Hugo, the shoreface in front of Myrtle Beach, South Carolina, was covered with deep scour tracks, perpendicular to the shoreline. These were formed by the storm-surge ebb. Similar cross-shelf channels and evidence of sediment transport were reported from off the northern coast of Puerto Rico by Schwab et al. (1996).

Tides and tidal currents may also be important, especially in areas of high tidal range or where their currents are funneled through narrow channels. See, for example, the discussion of tidal current funneling in the Vieques Passage off the eastern coast of Puerto Rico and its effect on a large sand deposit (Rodríguez et al., 1994). Data on timing and range of tides is available from NOAA (see "Tides Online" at http://tidesonline.nos.noaa.gov/). A local tide gauge is a must for marine park workers making their own observations.

Local short-term currents can be set into motion by the wind. These currents are strongest at the sea surface and decrease with depth. Currents can be measured with a wide variety of sensing equipment, from mechanical to electronic to acoustic. Current meters typically have a data logger, which must be retrieved and

the data downloaded, or they may be attached to a transmitter to continually transmit data. The latter is more sophisticated and more expensive.

NOAA maintains an Office of Coast Survey within the National Ocean Service. The Coast Survey is the oldest scientific organization in the United States, dating from around 1807. Visit their hydrography home page at http://chartmaker.noaa.gov/hsd/hydrog.htm for everything from nautical charts to information on hydrographic surveys.

Level 1: Observations from Shore/Drogue Study

Timing wave periods, heights, and angle of approach can actually give some very good information on local hydrography. It may seem like an overly simplified method, but if observations are recorded in a log book, with photographic documentation, over time a good set of data can be collected. Observations should be made at the same time each day and from the same location, and before, during (if possible), and after storms. Even weekly or monthly observations will be worthwhile, especially if augmented with event capture records. Nearshore currents can be observed and measured with drift cards or **drogues** (Fig. 5) which are timed and their locations plotted on a map.

Equipment required. For waves, a log book with a standardized format for making repetitive observations of wave heights and periods from shore is required.

Methodology. Wave heights are estimated either against a graduated pole or by pure estimation. For currents, drift markers need to be dropped from a known location at a recorded time. As markers are collected, time and location are recorded on a map. Current direction and speed are then revealed.

Timing. This should be done as needed.

Complexity. This method is very simple.

Cost. There is essentially no cost, other than for maps and drift cards.



Figure 5. Drogue used for current studies. Drogues are released from known locations. Future recover gives overall movement, but not details of movement. Photo courtesy of Sea Surveyor, Inc.

Level 2: Mechanical Current Meters, Short Time Period Observations

A handheld current meter can be obtained very cheaply and used to make spot measurements of currents. By lowering the device to different water depths, a vertical series of measurements can be made to observe current velocity and direction changes with depth. These types of measurements are time consuming and can be somewhat tedious, but for students they are a good way to gain intimate knowledge of the physical system, and they are a great learning tool.

Equipment required. A simple handheld, direct reading current meter and a small boat or Zodiac are required.

Methodology. Using either dead reckoning or GPS for locations, the current meter is lowered to the desired depth or series of depths. Measurements are taken and recorded.

Timing. Use this method as needed.

Complexity. This method is fairly simple, and can be done by unsupervised students with boating experience.

Cost. The cost of this method is low.

Level 3: Monitoring of Waves and Currents by Deployed Meters

Both waves and currents can be measured using an equipment array combining pressure transducers to measure wave height and period, and a current meter to measure current direction.

Equipment required. Some sort of deployed current meter system which will give measurements of not only currents, but pressure (for water levels including wave heights and tides), water temperature, salinity, light transmission, etc. (See Fig. 6).

Methodology. These systems are usually deployed for a set amount of time—typically several months. They are then recovered and the data downloaded; the array is serviced and redeployed.

Timing. These types of systems are recording continually.

Complexity. This method can be highly complex because of the need for deployment and retrieval of equipment, plus downloading and processing data.

Cost. The cost of this method is high.



Figure 6. InterOcean S-4 current meter can be configured to record currents, waves, tides, turbidity and more. Photo used with permission of Sea Surveyor, Inc.

Vital Sign 3: Reefs

Definition. The word **reef** is sometimes used for any submerged feature that provides a barrier to waves. Even shipwrecks and unconsolidated material can be considered reefs by some. Dunham (1970), however, defines a reef as a wave-resistant framework constructed in part by organisms. Reefs can be either classified as **barrier** types that have open marine water behind them (a lagoon), **fringing** types that are built directly out from the coast, or **patch** reefs that are more or less circular and are often behind a barrier reef. A simplified diagram of U.S. Virgin Island reef setting is shown in Figure 7. The Buck Island Reef National Monument just offshore of St. Croix, U.S. Virgin Islands, is a fully marine protected area within the National Park System. More information on the reef park is given in the case study later in this chapter.

Coral reefs are largely restricted to tropical oceans because they need warm water to flourish (Goreau et al., 1979). Coral reefs need sunlight to grow because they have a single-celled algae called zooxanthellae living symbiotically in the cellular lining. Zooxanthellae are necessary for reef building because they allow the corals to grow and reproduce quickly by supplying food to the corals. The corals provide protection for the zooxanthellae. Thus corals are restricted to the shallow water (less than 100 m deep). Reefs also need relatively high wave energy to supply food, nutrients, and oxygen, and to prevent deposition of sediment from covering the reef structure.

Much is known about reef growth, reef vitality, and reef stressors. An important aspect of reefs is the control of sedimentation on reef development (Hubbard, 1986) and subsequent responses (Rogers, 1990). There has been a general decline in Caribbean corals owing to various stressors including water temperature increases, dust, and pollution (Gardner et al., 2003).

Significance. Reefs exert some measure of control on their local environment. Physically, barrier reefs block waves and create a lower energy marine setting behind them. Ecologically, reefs support many types of flora and fauna, and are among the most productive environments on Earth. Reef vitality is a key indicator of health of the environment. Reefs may be stressed by high or low temperatures, turbidity, pollutants, physical damage from ships and anchors, or deleterious impacts by humans.

Coral reefs are excellent indicators of overall health of the local marine ecosystem. Two main stressors on reef vitality are pollution from land and overfishing. The U.S. Coral Reef Task Force (USCRTF) was formed in 1998 to improve government actions to preserve and protect coral reefs (http://www.coralreef.gov). USCRTF recommends assessing reef health, monitoring water quality, reducing pollution sources on land, and improving education (U.S. Coral Reef Task Force, 2000). See especially the report on the USCRTF Web site by Jameson et al. (1998), Development of Biological Criteria for Coral Reef Ecosystem Assessment. The techniques applied by Mehrtens et al. (2001) to monitor reefs in Roatán, Honduras, were very simple, involved students, and produced high quality data. See also USGS (2001) for a report about the impacts of Hurricane Mitch (1998) on the reefs of Honduras, and see U.S. Department of the Interior Web page, *Protecting the Nation's Coral Reefs*, at http://coralreef.gov/.

Because offshore barriers offer protection to sandy shorelines behind them, and because reefs are both a barrier and a resource, it is critical to measure reef extent and vitality. Reefs are included as a separate item because where they exist, they are profoundly valuable natural resources.

Level 1: Direct Observations by Snorkelers or Divers

During the observational dives (Fig. 8), photographs are taken, and immediately after the dive a geoindicators-type assessment of key reef/barrier characteristics is done. This would include a checklist of various indicators of reef vitality.

Equipment required. Cameras, notebooks, and a measuring stick for scale in photographs are needed.

Methodology. At known locations of importance, reoccupation of sites should be done at regular intervals to monitor key aspects of reef health. This may also extend to an event capture where more frequent visits would be made after a major storm to monitor reef damage and subsequent repair and growth.

Timing. This should be done at regular intervals, yearly at least, and event capture if possible. It is especially important to make observations after major storms and floods to determine

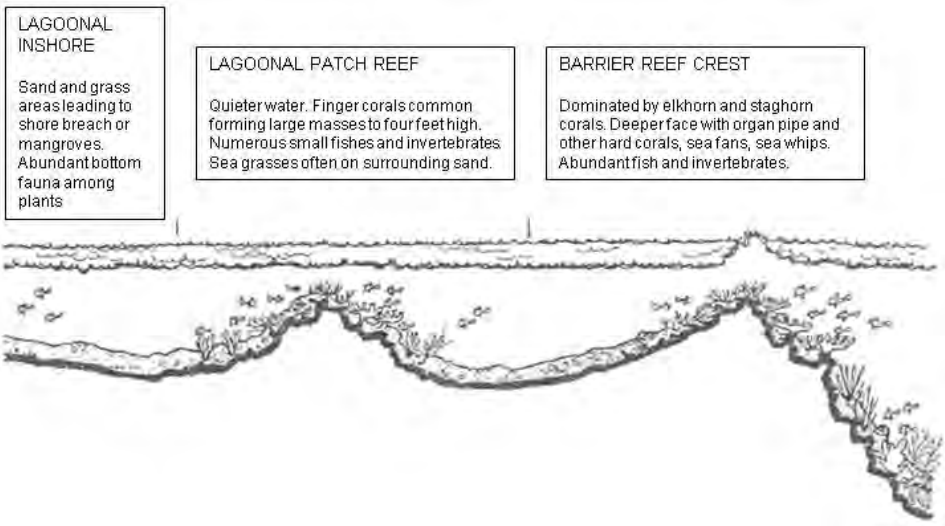


Figure 7. Simplified coral reef settings for the U.S. Virgin Islands. From USVI (1976).



Figure 8. In almost any shallow water setting, snorkeling can be used to make simple observations, collect samples, or deploy and recover sampling equipment. National Oceanic and Atmospheric Administration photo.

impact of the event on the reef. Influx of sediment or pollution from runoff from land should be monitored.

Complexity. This method is fairly simple, but diving/snorkeling and boat handling abilities are required.

Cost. This method is inexpensive, other than for diving equipment and boats.

Level 2: Abiotic Monitoring of Reefs

This is a more detailed, quantitative, and rigorous monitoring program than Level 1. Transects are identified and marked with rods embedded in the sea bottom. A camera array mounted on a 1-m-square bottom frame is placed on or as close to the reef as possible. Photographs can be automatically digitized to measure live versus dead reef coverage (Fig. 9).

Equipment required. Diving equipment, underwater camera, and an array are required. The array can be made from PVC pipe, and need not be expensive.

Methodology. The techniques applied by Mehrtens et al. (2001) are very simple, involved students, and produced high quality data. See also the online USGS Open File Report 2001-113 (USGS, 2001) for a study of the impacts of Hurricane Mitch on the coral reefs of Honduras.

Timing. Timing is usually yearly, and after major storms.

Complexity. The complexity of this method is moderate.

Cost. The cost of this method is moderate.

Level 3: Remote Sensing

Newly developed techniques allow for the study of reefs from satellite imagery in some situations. Instead of having to dive and take many measurements and observations, a readily available satellite image can be obtained (Lubin et al., 2001). Ground truthing must still be done, but this offers exciting possibilities. The USGS Center for Coastal and Watershed Studies in St. Petersburg, Florida, has experience using the Along-Track Reef-Imaging System (ATRIS). ATRIS provides photographic and video transects of the seafloor with GPS location information (Fig. 10). LIDAR (light detection and ranging) aerial surveys can give information not only on elevations, but there is the capability to analyze multi-spectral information to map coral reef geomorphology, topography, and habitats with a resolution of two meters or less. See the USGS Center for Coastal and Watershed Studies remote sensing information page at http://coastal.er.usgs.gov/remote-sensing/.

NASA has developed a worldwide coral reef library for coral reef remote sensing data. It includes satellite images in the Millennium Coral Reefs Landsat Archive, available at http://oceancolor.gsfc.nasa.gov/cgi/landsat.pl.

Equipment required. Aerial-borne LIDAR systems, satellite images, and processing equipment are expensive, but they can often be shared by several investigators. In addition, the USGS AmericaView Program may provide imagery for educational purposes in some cases, including research at the university level (see their Web site at http://www.americaview.org/).

Methodology. The satellite imaging needs to be processed specifically for identifying unique colors in the coral. This can only be done by highly trained remote sensing specialists. A knowledge of the characteristics of the water column at the time the image was taken is also needed. Satellite images can cover large areas, though resolution is sacrificed. If a snapshot of the overall vitality of a large reef expanse is desired, this may be a good way to acquire it.

Timing. Timing should be yearly, or perhaps less often. Timing and frequency will depend on the availability of satellite images without obscuring cloud cover and with sufficient resolution.

Complexity. This method is very complex, owing to the great deal of expertise needed for processing images.

Cost. If imagery is shared or available gratis, the only real costs are for the remote sensing personnel who may be available in collaborative ventures for little or no costs, especially from universities.

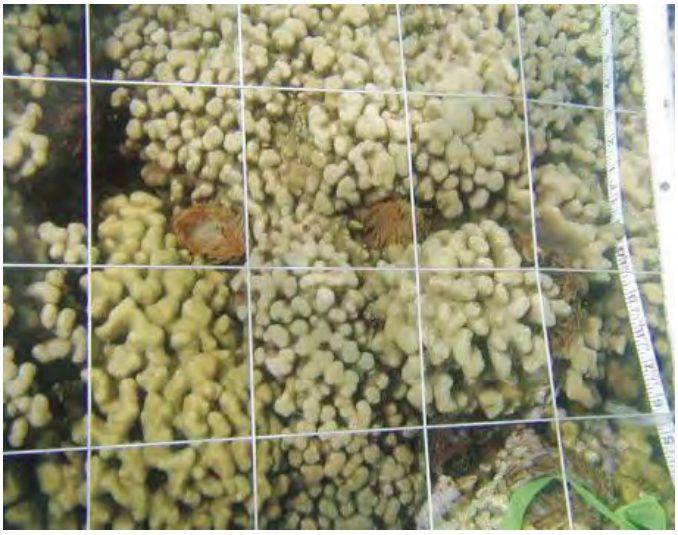


Figure 9. Transect and quadrant methods are used for mapping coral cover. Finger coral (Porites compressa) is the species seen here; feather duster worms are visible among coral fingers. National Oceanic and Atmospheric Administration photo.

Vital Sign 4: Other Offshore Barriers

Definition. Reefs are important barriers to wave energy but are not the only barriers that may be of interest for understanding the physical setting of a study area and for monitoring of changes. Non-reef types include any sediment buildups such as sand shoals, or consolidated material such as submerged or partially submerged rock or erosional remnants of rocks. Obviously, resistant rock barriers will not change over the short term. In some tropical locations, Pleistocene eolianite comprises significant nearshore barriers, both emergent and submergent. Kaye (1959) is the authoritative source for information on the shoreline features of Puerto Rico, and gives a good background on eolianite, which is a dominant coastal rock along the northern coast of Puerto Rico. Eoliante is dominated by calcareous beach sand and calcareous cement. It is not particularly resistant to wave erosion, so monitoring will reveal changes on scales of decades.

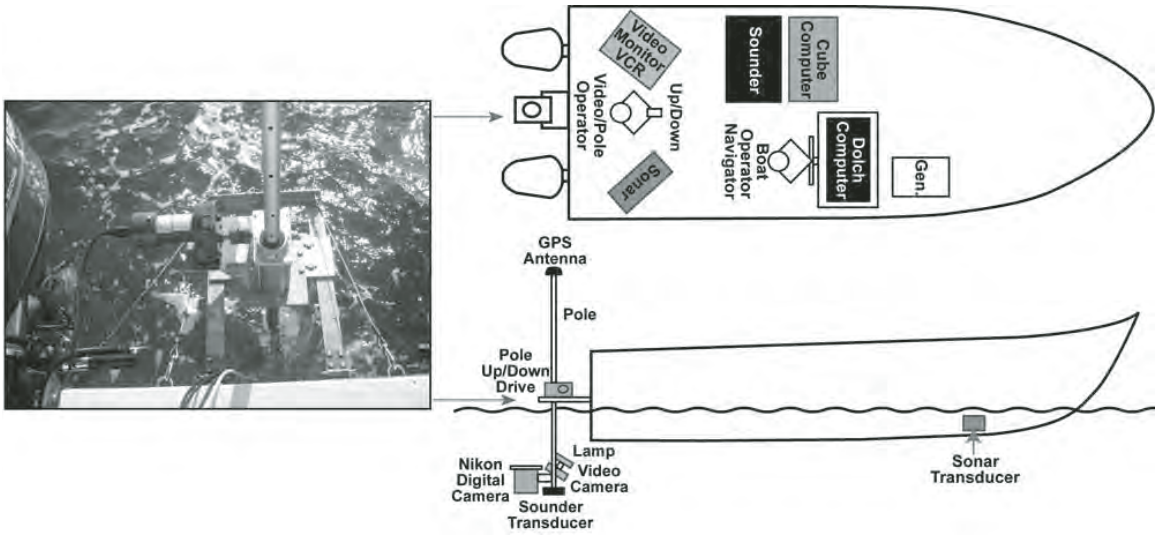


Figure 10. ATRIS survey under way. The vessel-mounted array collects photographs, video, bathymetry, and position data. From U.S. Geological Survey Center for Coastal and Watershed Studies, remote sensing information page, http://coastal.er.usgs.gov/remote-sensing/.

Significance. As with reefs, a barrier will at least partially control the environment, providing lower-energy settings are behind it. Rocky barriers will also serve as an anchoring site for benthic (bottom) organisms and support a hard bottom ecosystem. Unconsolidated barriers will block some wave energy, but remain mobile in response to ocean currents and storm waves.

Protective offshore barriers may be much smaller in scale than reefs and also may be nonbiogenic—sand bars, rock outcrops, and shoals, for example. Some, like rocks, will be essentially stable over long time periods. Large shoals may shift and reorganize during major storms. Offshore bars may change daily.

The shape and size of all such offshore barriers (including reefs, above) is of paramount importance. For those composed of unconsolidated sediment, however, another important attribute to be monitored is the internal (sub-seabottom) composition and stratigraphy. For the overall external shape and size, observation and monitoring techniques discussed above under bathymetry are applied. Sub-seabottom monitoring will be discussed below.

Level 1: Simple Observations by Snorkelers

Again, assuming the overall external size and shape of the feature is monitored using bathymetric techniques, above, and that one is dealing with unconsolidated sediment features, simple sampling by snorkelers or divers is a good way to look at the internal characteristics of the sediment column and to monitor any potential changes (Fig. 8). Most dramatic changes will likely occur during major storms.

Analysis of samples is an entirely separate issue from obtaining the samples. Depending on facilities, everything from simple textural analyses (grain size and sorting) to composition (identification of grains) to organic carbon content, and even radiometric age dating is possible. The USGS has loads of information on sedimentologic techniques. See, for example, USGS (2000) as an example of techniques for grain size analysis and data handling.

Equipment required. Snorkeling or diving equipment, boats, cameras, and sample bags are required. Sediment analysis equipment and supplies as needed, depending on the detail and types of studies desired.

Methodology. A detailed description of sedimentologic laboratory techniques is beyond the scope of this report. Refer to USGS (2000) or standard sedimentology lab manuals such as Lewis and McConchie (1994).

Timing. Timing should probably only be yearly or after a major storm. Bar shape and size might be monitored more frequently, at least quarterly, and definitely before and after a major storm to monitor rebuilding of the beach and bar migration.

Complexity. Laboratory analysis is more complex than obtaining samples. It is suggested that partnering with a university with an existing lab and students needing course projects would be the best way to obtain data.

Cost. Costs are low to moderate, depending on the types and number of samples needed.

Level 2: Sediment Sampling to Determine Detailed Internal Structure and Composition

This goes beyond Level 1 in that it provides high-quality, detailed stratigraphic information. This necessitates some sort of careful direct sample recovery, for example **Van Veen grab samplers** or short push cores. Van Veens take only shallow samples from unconsolidated sediments, maybe six inches to one foot, and the sediment will be mixed up if care is not taken. Push cores are useful up to about one meter in length. Beyond that, a mechanical coring device is needed.

Equipment required. A Van Veen or other grab sampling device (see USGS [2000] for description), or a push core is needed.

Methodology. See USGS (2000) for methodology of grab sampling devices. A **push core** is simply a plastic or PVC tube, one meter or shorter in length, that is physically pushed into the seafloor. A stopper or plastic cap is then applied to create suction, and the tube pulled out of the seafloor. A gravity core can be used from a boat and basically behaves like a dart (Fig. 11). It is tethered to the boat and is dropped overboard. Gravity cores can retrieve cores one to five feet long and are a very cheap and simple method of coring surficial (surface) sediments.

In the laboratory, the plastic core tube is sliced through, taking care not to disturb the sediment. The sediment is then carefully split open with a knife or spatula. The core is photographed and subsampled. Subsamples are then processed, as any sediment samples would be.

Timing. Timing should be yearly or less frequently, unless a large storm has passed.

Complexity. Retrieving samples is not overly complex. Processing and analyzing can be.

Cost. Costs are moderate to high.

Level 3: Sophisticated Assessments with Side Scan Sonar, High Resolution Seismic, Vibracoring or Piston Coring, Plus Bathymetric Mapping

This is a full-scale program to sample and monitor the seafloor and subbottom with highly sophisticated techniques. Everything has been presented previously except for vibracoring. **Vibracoring** is the state of the art technique of obtaining long,



Figure 11. Gravity corer. Photo courtesy of Sea Surveyor, Inc.

undisturbed cores in sandy sediments. **Piston coring** is the state of the art method for muddy (cohesive) sediments. The bathymetric data must be digital and of high precision in order to measure changes with time and calculate sediment volume changes over time.

Equipment required. In addition to that previously discussed for bathymetric and sidescan sonar observations, a vibracore or piston core array is needed. This is expensive equipment and can only be used by highly trained personnel with a support team.

Methodology. There are several types of equipment available for coring of unconsolidated sediment from the seafloor. Vibracoring is probably the most widely used. Vibracoring rigs can be diver operated (Fig. 12), which work very well in limited water depths, usually shallower than 50 feet. For deeper water, a ship-borne vibracorer is necessary, and the Alpine Vibracoring system is the most used (Fig. 13). A mini-vibracoring system designed by Sea Surveyor (Fig. 14) is available for collecting 5′ to 15′ sediment cores from small, shallow-draft vessels. It is easy to transport to remote sites. For very muddy sediments, a piston core works best (Fig. 15). See Lanesky, et al. (1979) and Watson and Krupa (1984) for detailed background information.

Remote sensing techniques can also be used, primarily subbottom profiling. These various seismic techniques are available in many frequencies and powers. The higher the frequency, the greater the resolution, but high resolution sound signals are subject to higher attenuation, so depth of penetration is limited. Lower frequency signals have greater penetration but decreased resolution. High power signals increase penetration but the equipment is more expensive. The tradeoffs must be decided based on the local resources. A high resolution subbottom profiler is shown in Figure 16. From a high-resolution survey and local geologic knowledge an interpretation of the subbottom can be made (see Fig. 17.)



Figure 13. Alpine vibracore rig. Photo courtesy of Sea Surveyor, Inc.



Figure 12. Diver operated vibracore. U.S. Geological Survey photo.



Figure 14. Mini-vibracore system. Photo courtesy of Sea Surveyor, Inc.

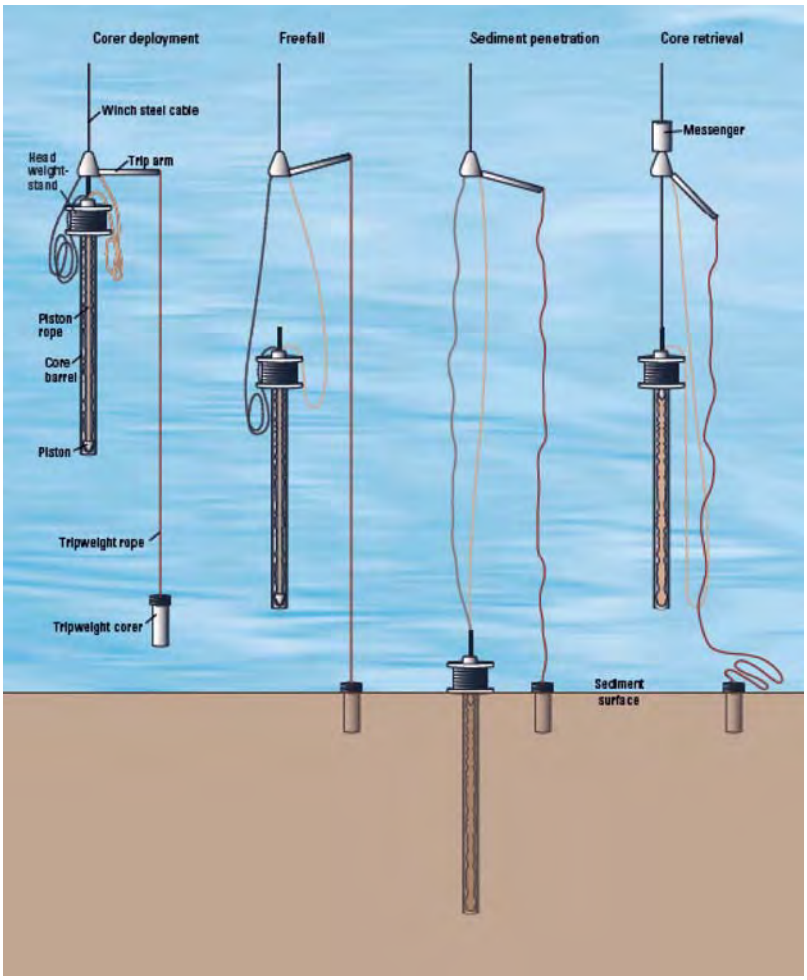


Figure 15. A benthos-gravity piston corer. The core barrel is approximately 3.5 m long and 6.3 cm in diameter. U.S. Geological Survey diagram.

Timing. Timing should be as needed and possibly just before and after major storms.

Complexity. Coring is very complex.

Cost. Coring is very expensive. Partnering is suggested.

Vital Sign 5: Substrate

Definition. **Substrate** is sea bottom composition. It may be mud, sand, gravel, or rock; this is the composition of the material on the seafloor itself, which may also include stratigraphy below the seafloor. Observation and analytical techniques are the same techniques discussed for unconsolidated offshore barriers above.

Significance. The seafloor may be covered by plants or animals adapted to only one substrate type. Changes in substrate, such as mud covering a sandy bottom, or sea grass flourishing on a sandy bottom being killed by pollution, may have a negative impact on marine communities.

In addition, however, a portion of the seabottom in the area of interest may be covered by sea grass. Expanses of grasses such as eel grass or turtle grass are critical habitats for juvenile fin and shell fish. Changes in extent of grasses can be caused by storms, changes in sediment input, or human activity. Monitoring of seagrass beds is high priority and can easily be done with direct observations, air photos, or even from satellite images in many cases, if the expanse of sea grass is large enough. See also the discussion of reef and other barriers above. The remote sensing techniques will be essentially the same.

Instead of soundings from a boat, another simple method of monitoring bathymetric changes plus making observations about the depth of sediment movement can be done using steel rods emplaced on a grid system or on a profile. Detailed observations made before and after a storm, or at some regular intervals (seasonally, for example) can provide adequate information on sediment dynamics at the points of study (Greenwood and Mittler, 1984). This is a very inexpensive method, but does require diving expertise. Its advantage is being able to show the immediate event effects as well as recovery and changes over time.

Many of the techniques previously discussed are also applicable to substrate sampling and monitoring. See USGS (2000) for a list of common sediment sampling devices and references to key work. The Open-File Report is available at http://pubs.usgs.gov/of/2000/of00-358/. Also, the NOAA Coastal Services Center



Figure 16. High frequency profiler gives high resolution data of the shallow subbottom. Photo courtesy of Sea Surveyor, Inc.

Web site has information on benthic habitat mapping at http://www.csc.noaa.gov/benthic/, and sediment sampling at http://www.csc.noaa.gov/benthic/mapping/techniques/sampling.htm.

Level 1: Observations by Snorkelers

These simple, direct observations are the same as discussed previously.

Equipment required. Cameras, boats, and notebooks are needed.

Methodology. The method is the same as above, with simple occupation of known locations, photographic documentation, and note taking.

Timing. Timing should be quarterly or yearly at least, and after major storms.

Complexity. This method is very simple.

Cost. The cost is low.

Level 2: Map Distribution from Available Air Photos

Sea-grass beds and other types of substrate should be readily observable on low-altitude air photos, which should be available from the USGS or NOAA or other sites. For site-specific studies, consider high resolution side scan sonar surveys. Air photo approaches are discussed in the case study on Pleasant Bay, Massachusetts, later in this chapter.

Equipment required. Air photos and tracing paper are needed, and/or digitizing equipment, if available.

Methodology. The simplest method is to trace the expanse of sea-grass beds onto tracing paper. Alternately, if resources are available, air photos can be georeferenced and the expanse of sea-grass beds digitized. This is a superior method as it produces instant results of areas and makes changes easy to quantify and track.

Timing. Timing should be yearly and before and after major storms.

Complexity. This method is not overly complex. The digital approach requires knowledge of geographic information system (GIS) software.

Cost. If geospatial analysis equipment is available, cost is relatively low except for air photos, which may be available at low or no cost from collaborators.

Level 3: Distribution from Studies using Digital Remote Sensing Techniques

Changes of sediment and other substrate can be observed from satellite images in many cases as discussed above. For sea-grass changes, if the expanse of beds to be studied is larger than the resolution of readily available satellite images (30 m), then this is a reliable method to monitor changes. This is especially true if satellite imagery is available for free from collaborators or from the USGS AmericaView Program, or if it already has been obtained for other uses. High-resolution side-scan sonar equipment (Fig. 18) can produce highly accurate charts showing the spatial distribution and density of different species of marine vegetation, as well as water depth, sediment type, and size and shape of reefs (Fig. 19).

Equipment required. Satellite imagery is needed instead of air photos. Side-scan sonar and ancillary equipment, if available, are also required.

Methodology. Processing of satellite images as discussed previously requires a great deal of expertise in order to make sure the sea grasses can be observed in the greatest detail possible.

Timing. Timing should be yearly and/or before and after major storms.

Complexity. Processing of satellite imagery and GIS manipulation of data is highly complex.

Cost. The cost of geospatial analysis and equipment is high.

Vital Sign 6: Water Column Turbidity

Definition. Water column turbidity is solid particles suspended in the water. These particles may be inorganic (fine sediment, ash, dust) or organic (plankton, etc.).

Significance. Increased turbidity, if caused by sediment, may be an indicator of event-related resuspension of sediment, or

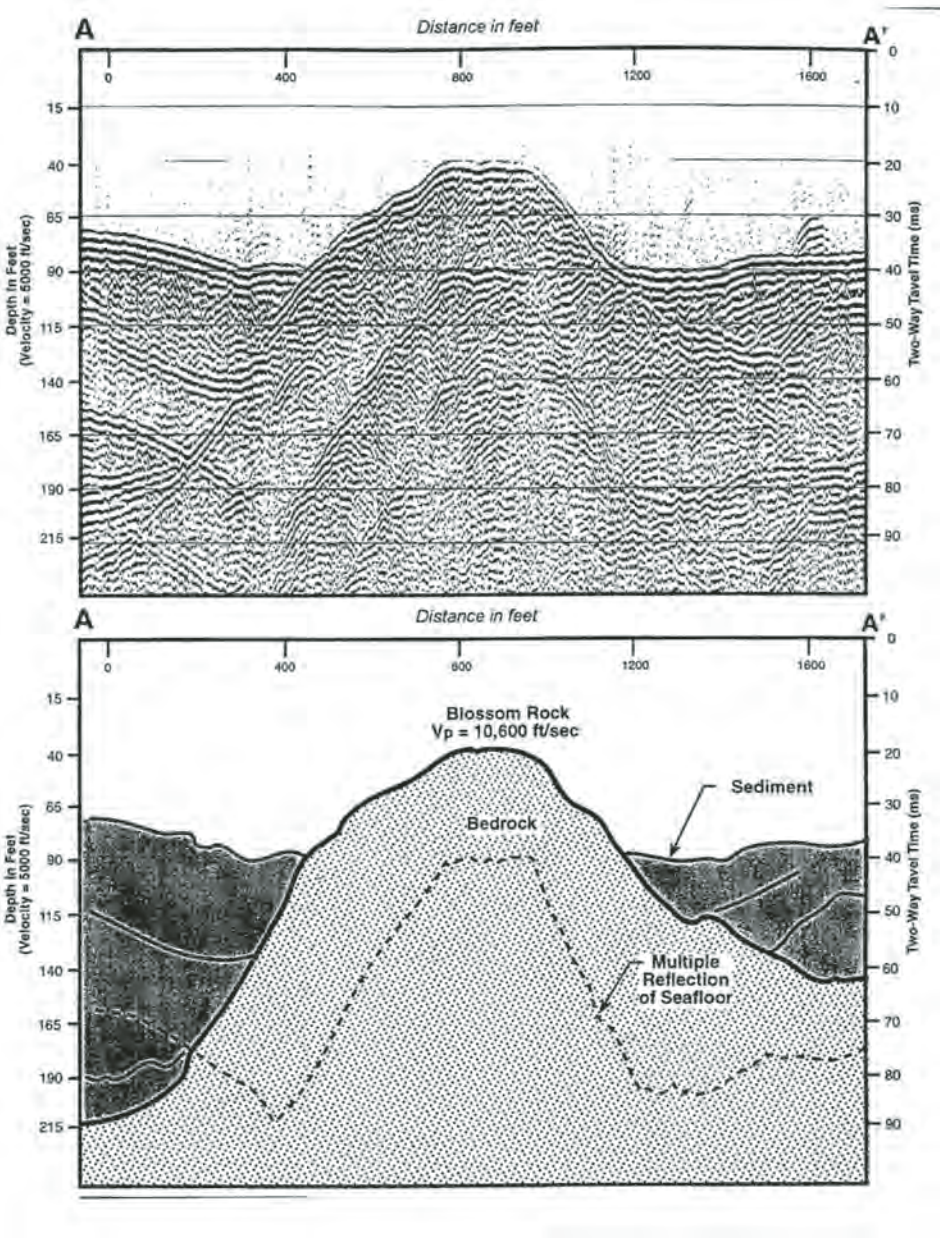


Figure 17. High resolution seismic section and geologic interpretation of Blossom Rock, in San Francisco Bay. The high resolution subbottom profiler shown in Figure S was used in this study. Figure and discussion courtesy of Sea Surveyor, Inc.

influx of sediment, or degrading conditions caused by increased runoff from land over time. If caused by plankton, it may be a sign of algal blooms or even red tides.

It is possible to make observations of water turbidity from satellite data. A USGS study of resuspension of sediment by storms and the subsequent changes of water clarity in Florida Bay is available as part of the South Florida Information Access (SOFIA) project at http://sofia.usgs.gov/projects/sed_turbidity/.

Level 1: Secchi Disks to Measure Water Clarity

This is a very simple approach, wherein the limit of the disk's visibility is recorded in a log book. The U.S. Environmental Protection Agency has a factsheet about **Secchi Disks**. The Secchi Disk was developed by P.A. Secchi in 1865 for a Vatican-financed Mediterranean oceanographic expedition and is still in use. It is a weighted circular disk with alternating black and white painted quadrants. The disk is lowered into the water until it is no longer visible and that depth is read from a graduated rope (Fig. 20). Secchi disks are easy to make and use, and can involve students and community volunteers. See http://www.epa.gov/owow/lakes/month/pdf/dip_factsheet.pdf for more information. The U.S. Environmental Protection Agency has information on the technique and also on a nationwide volunteer program to record Secchi depths. See http://www.epa.gov/volunteer/.

Equipment required. A boat, Secchi disk, and a log book are needed.



Figure 18. High resolution digital side scan sonar used for marine vegetation surveys. Interpretations of substrate and marine vegetation cover are made (see Fig. 19). Figure and discussion courtesy of Sea Surveyor, Inc.

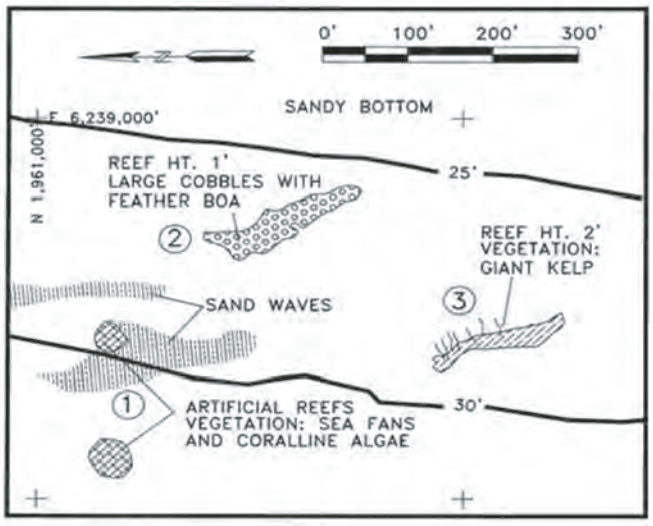


Figure 19. An example of a marine vegetation survey using a high-frequency side-scan sonar and a survey-grade fathometer. Figure and discussion courtesy of Sea Surveyor, Inc.

Methodology. The disk is lowered into the water until it can no longer be observed. This depth is recorded.

Timing. These measurements can be done very frequently, often when other observations are being made, such as current speeds and directions. This should be done at least seasonally to monitor such changes.

Complexity. This method is very simple.

Cost. The cost is very low. The disk can be made instead of purchased.

Level 2: Handheld Turbidity Meters

Handheld turbidity meters can be used in a variety of applications. Some models will also sample salinity and other water quality characteristics.

Equipment required. A meter and snorkeling/diving gear are needed.

Methodology. The method involves simple metering and recording.

Timing. This should be performed as needed.

Complexity. This method is very simple.

Cost. The cost is moderate, as meters can be around $1,000.

Level 3: Permanently Installed and Continuously Recording Turbidity Meters

If turbidity needs to be continuously monitored, some sort of permanently installed, heavy-duty equipment is needed. This will rarely be the case, but if so, an array that also measures water temperatures, currents, pressure, suspended sediment, etc., as mentioned above, would be useful.

Equipment required. A bottom tripod array, or some variation, is needed.

Methodology. The device is deployed, monitored, and serviced as necessary.

Timing. The device will be recording continuously.

Complexity. This method is not overly complex, except for equipment maintenance.

Cost. The cost of this method is high.

Vital Sign 7: Water Column Chemistry and Quality

Definition. Water column chemistry and quality involves the dissolved solids and gases in the water.

Significance. This measurement is significant because the dissolved chemicals may influence the health and vitality of plants and animals living in the water. This is bordering on the edge of being outside the realm of geologic studies. A good comprehensive overview of techniques is given by the U.S. Geological Survey's National Field Manual for the Collection of Water-Quality Data, which can be viewed online at http://water.usgs.gov/owq/FieldManual/. The techniques are the same as for turbidity (see above), except with slightly different equipment for measuring other attributes. Typically, however, the same or similar meters or devices can be used.

Level 1: Water Samples Taken by Hand

Basic qualities are measured with a pH meter, electrode (probe), and thermometer, and are recorded on a data sheet. Samples are taken by snorkelers or divers by hand. Samples could also be coupled with sediment sample retrieval, as described above. As many different types of sampling as possible that can

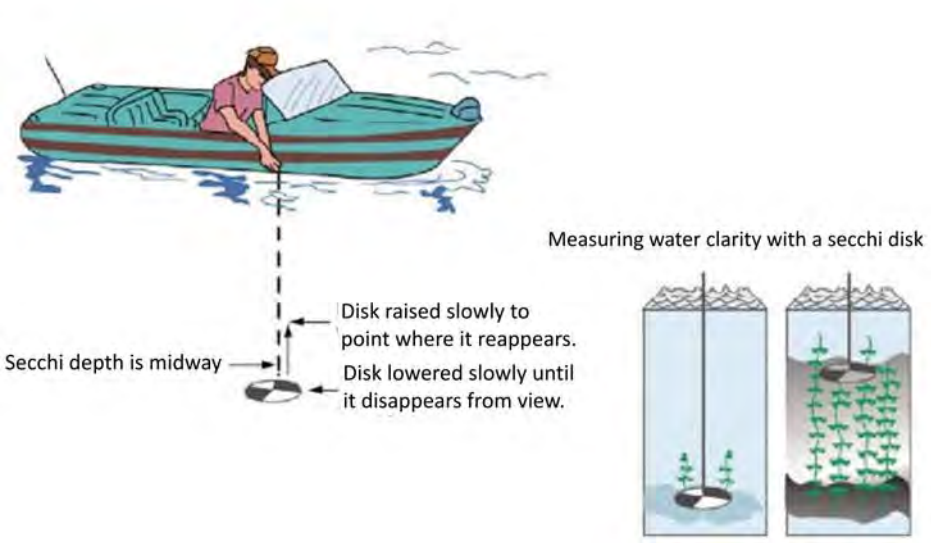


Figure 20. Secchi disk use.

be done simultaneously will give the greatest benefit for the lowest cost and time.

Equipment required. A low-cost multi-parameter meter is needed.

Methodology. Measurements should be taken in situ and recorded on a log sheet or in a workbook.

Timing. Timing should be as needed or as possible.

Complexity. The complexity level is low.

Cost. Initial investment for meter(s) may be moderate to high, but then this method is low cost.

Level 2: Meters with Digital Readouts, Recorded on a Data Sheet

Everything as described immediately above applies, but this method uses a more sophisticated meter, or set of meters.

Equipment required. A low-cost multi-parameter meter and log sheets are needed.

Methodology. Measurements should be taken in situ and recorded on a log sheet or in a workbook.

Timing. Timing should be as needed or as possible.

Complexity. The complexity level is low.

Cost. Initial investment for meter(s) may be moderate to high, but then this method is low cost.

Level 3: Sophisticated Measurements with Automatic Recording Devices, Data Loggers

Automatic recording and downloading of digital data makes long-term monitoring much easier. It is also much easier to share data and use it for research.

Equipment required. High-quality recording equipment with data logging capability.

Methodology. The method is the same as discussed above; only the quality of the equipment is different.

Timing. Timing should be as needed or as possible.

Complexity. This is moderately complex, owing to the need for database creation and data downloading abilities.

Cost. The cost is moderate to high, depending on the type of meters and computer facilities.

CASE STUDIES

Two case studies are presented here: one carbonate and tropical, one siliciclastic and temperate. Buck Island reef is part of the Buck Island Reef National Monument in St. Croix, U.S. Virgin Islands. Pleasant Bay sits just west of Nauset Spit, on the southeastern part of the Cape Cod National Seashore, Massachusetts. The stressors on each setting will be different, as will the sampling and monitoring techniques.

Case Study: Buck Island Reef, U.S. Virgin Islands

Buck Island Reef National Monument, U.S. Virgin Islands, lies Buck Island, is located ~1.5 miles north of St. Croix. The park was established in 1961 and expanded in 2001. It is one of only a few fully marine protected areas in the National Park System. The reef began developing on a preexisting ridge during lower sea level almost 10,000 years ago (Hubbard et al., 2005). The modern reef is dominated by elkhorn coral, *Acropora palmata* (Bythell et al., 1989). Many of the corals are degraded by White Band disease, an affliction that causes loss of tissue creating a line or band of bare white coral skeleton (Gladfelter, 1982). The corals still do grow rapidly, however, and produce large amounts of carbonate sediment which surround the reef (Gladfelter and Gladfelter, 1979).

Buck Island Reef National Monument is a jewel of the National Park System owing to its beauty and accessibility.

Accessibility, however, is a double-edged sword, as human impacts have degraded the reef. A National Park Service Geologic Resource Management Issues Scoping Survey (Hall, 2005) identified four significant geologic issues at the park:

1. Coastal and Marine Features and Processes
   a. Sediment Characteristics
   b. Boating Hazards
   c. Oceanographic Variables
   d. Benthic Habitat Mapping
2. Recreational Impacts
3. Windblown Features and Processes
4. Seismic Activity

The U.S. Geological Survey monitors seismic activity in the Caribbean, including the U.S. Virgin Islands. The remainder of the geologic issues have been evaluated by various researchers over the years (see, for example, Gladfelter et al., 1977, 1978; Gladfelter and Gladfelter, 1979; Hubbard 1986; Bythell et al., 1989; Hubbard, 1992; Hubbard et al., 2005).

Holocene reef development of the Buck Island reef is reported by Hubbard et al. (2005). Study area location, bathymetry, and aerial photograph of the reef are shown in Figure 21. That study reports on several sampling techniques appropriate for monitoring modern reef vitality, especially coring and photography of the reef surface. Coring was done using the SCARID drilling system (Fig. 22). Core locations were done in early work using triangulation by sextant, shore ranges, and direct measurements from features identifiable on topographic maps. Recent locating was done using GPS. Water depth, substrate mapping, and bottom features were identified along regular intervals along two cross-reef transects to identify benthic community boundaries. The character of the substrate (sand, pavement, or mixed) and the major coral types (branching or dominant species or genera) were identified (see Hubbard et al., 2005, their fig. 2). Photo documentation of coral types and reef setting is shown in Figure 23.

Reef Check Foundation

An organization worth looking into is the international nonprofit Reef Check Foundation. Founded in 1996, its goal is to aid conservation of tropical coral reefs and California rocky reefs. Their offices are in Los Angeles, and they have volunteer teams in over 80 countries. Reef Check's goals include focusing on public education on the importance of reef and current marine stressors, training volunteers in scientific monitoring methods, building public and private partnerships, and stimulating action.

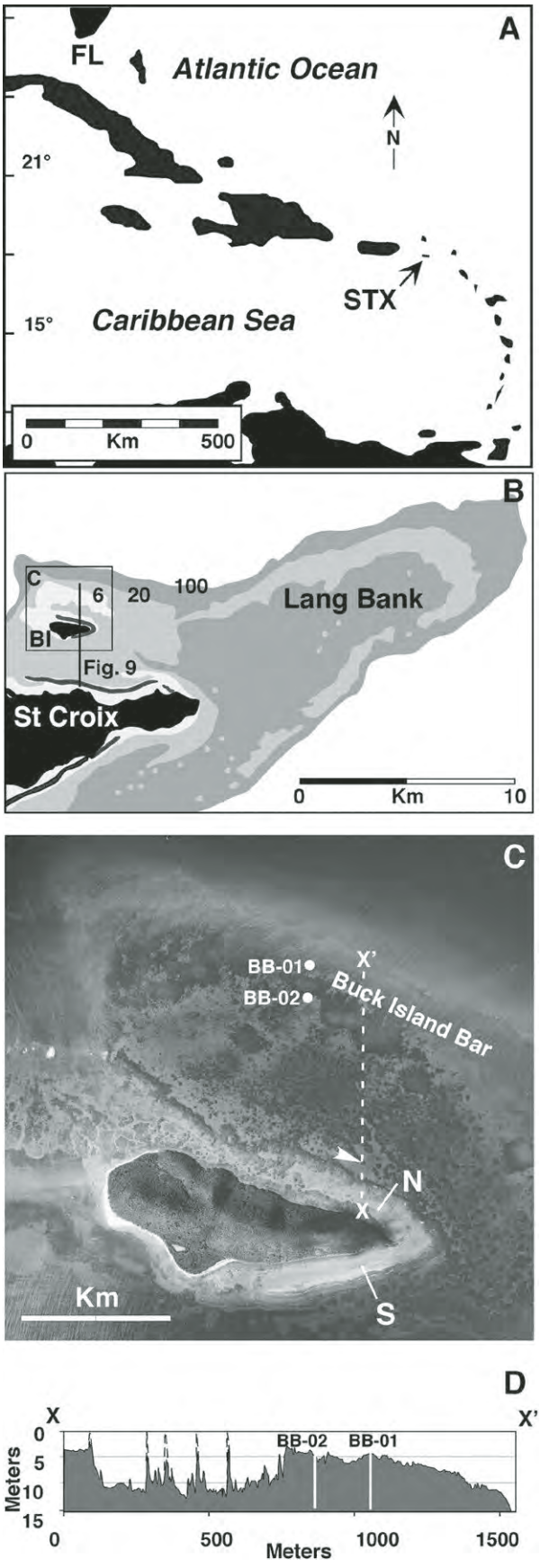


Figure 21. (A) Caribbean map showing the location of St. Croix (STX) in the U.S. Virgin Islands. (B) Map of eastern St. Croix showing Buck Island to the north and Lang Bank to the east. Depths are in meters. The box shows the extent of the National Oceanic and Atmospheric Administration (NOAA) air photo in C. (C) NOAA vertical aerial photograph of Buck Island. (D) Cross-shelf profile showing the steep outer-shelf patch reefs ("haystacks") and Buck Island Bar. From Hubbard et al. (2005); used with permission.

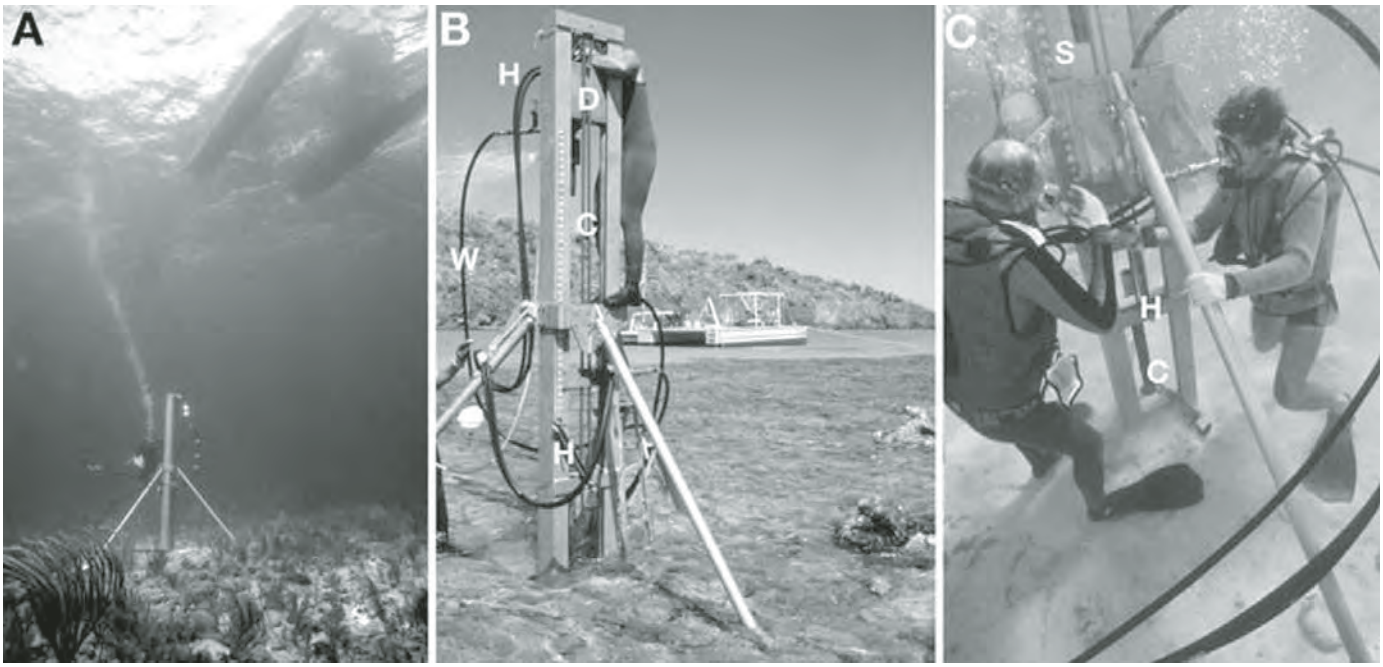


Figure 22. SCARID drilling system used to recover the cores in the Hubbard et al. (2005) study. See that study for details. (A) Drill deployed in deeper water. (B) Drill on the southern Buck Island reef crest. (C) Close-up of the drill in use underwater. From Hubbard et al. (2205), used with permission.

In just a little over a decade, Reef Check has been successful in helping fishermen in St. Lucia increase local fish stocks, guiding the Hong Kong government in monitoring coral reef health, and collaborating with the Global Coral Reef Monitoring Network in scientific publication of its findings. The Reef Check Web site is http://www.reefcheck.org/default.php.

While their monitoring focuses more on biologic impacts, as noted previously reef biology and geology are intertwined. The Reef Check monitoring protocol is available at http://www.reefcheck.org/rcca/monitoring_protocol.php. Also, a global assessment of human effects on coral reefs is available at http://www.reefcheck.org/about_RC_Reef/publications/mpb.pdf. See also Hodgson (1999). The Reef Check California Monitoring Protocol (Shuman, 2007) is available at http://www.reefcheck.org/PDFs/2007_RC_CA_Protocol.pdf. The monitoring protocol for Hawaii (Hodgson and Stepath) is available at http://www.reefcheck.org/about_RC_Reef/publications/monitoring2.pdf.

Case Study: Pleasant Bay, Massachusetts

R. Jude Wilber, president of Capella Consulting Group, a marine environmental science and engineering firm in Falmouth, Massachusetts, devised a sampling program for Pleasant Bay that is precisely the sort that could be of great use to monitoring nearshore environments in many other settings. The Pleasant Bay discussion and documentation is provided courtesy of Dr. Wilber.

Pleasant Bay is a small, tidally influenced estuary in eastern Massachusetts. It is bounded on the east by Nauset Spit, which is part of the Cape Cod National Seashore. Nauset Spit separates Pleasant Bay from the Atlantic Ocean (Fig. 24). It is a siliciclastic temperate system. Nauset Spit builds to the south, controlled by longshore transport of sediment. As the spit builds, the tidal channel connection to Pleasant Bay from the Atlantic Ocean moves southward. Occasionally, storm processes breach the spit, relocating the tidal inlet back toward the north, thus again changing the location of the focus of tidally dominated sediment movement in the bay. In addition to an interesting and varied sedimentological history, the bay also has a diverse fauna. It is dominated by eel grass beds which are nursery grounds for juvenile and adult fin fish and shellfish, as well many other types of organisms. A particularly noteworthy relationship between extent of eel grass beds and bioturbation by horseshoe crabs has been observed and documented. A decrease in the extent of eel grass beds, both by biological bulldozing by horseshoe crabs and demise owing to pollution, reduces the vitality of the estuary and its natural nursery ground effectiveness.

A simple monitoring and documentation approach was used in Pleasant Bay, just landward of the Cape Cod National Seashore in Massachusetts, in a study for the Pleasant Bay Alliance. First, a reconnaissance study was done from aerial photographs, followed by field sampling and surveying. Field observations were compared back to the original photograph survey. Any questions or inconsistencies that arose were checked with another field

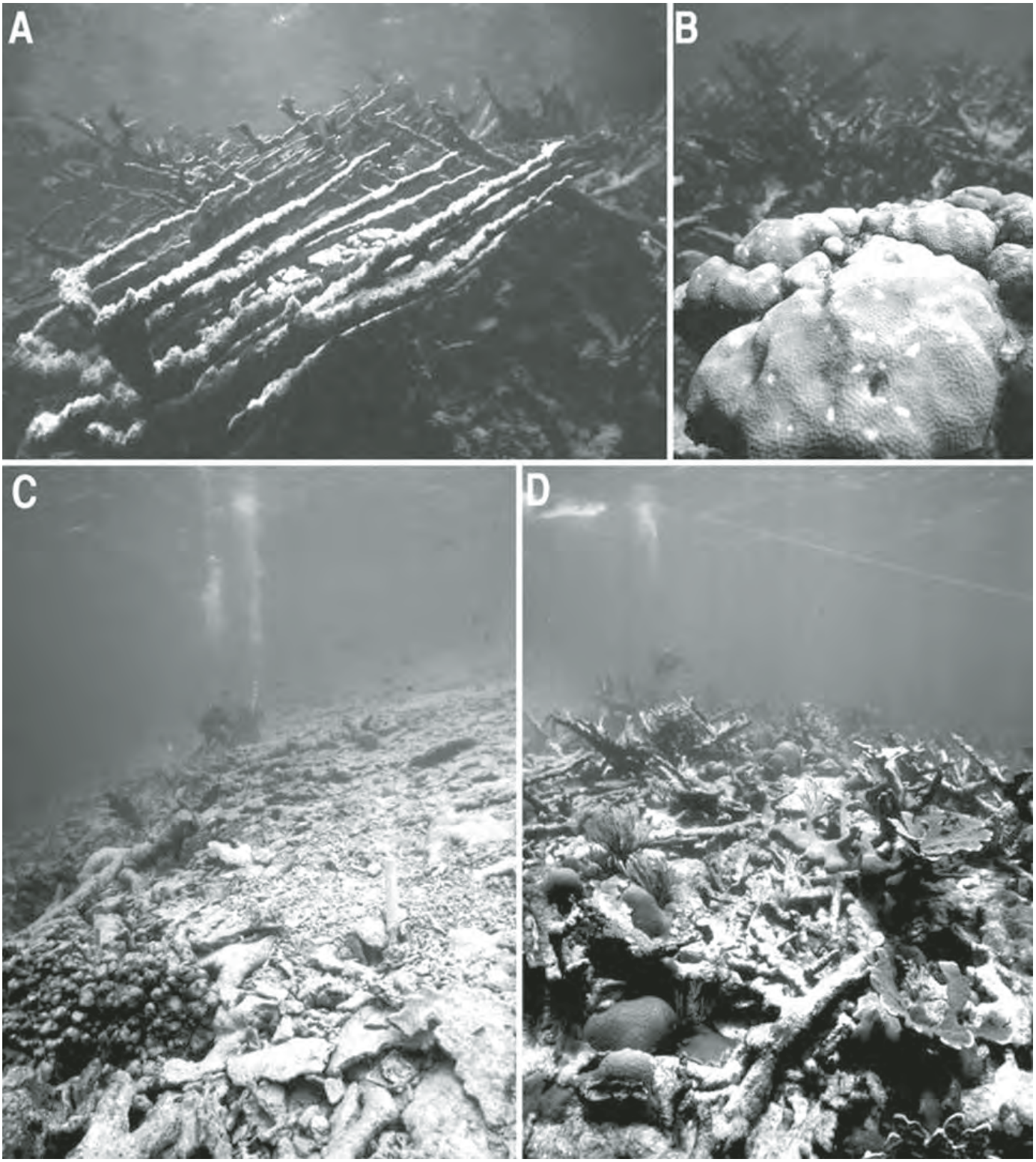


Figure 23. (A) Underwater photograph along the eastern end of the northern forereef in the late 1970s. (B) Photograph from the late 1970s. (C) Southern reef after the passage of Hurricane Hugo in 1989. (D) Buck Island Bar in April 1990. From Hubbard et al. (2005); used with permission.



Figure 24. Southeastern segment of Cape Cod National Seashore. Pleasant Bay is located just to the west of lower Nauset Beach. From National Park Service park map.

survey. The process continued back and forth between photos and field until all questions were answered. This approach works well only when the field area is readily accessible, and the project can be broken down into lab/field segments.

The method approach described above was used to map horseshoe crab density as well as ebb tidal flow patterns and sediment characteristics in Pleasant Bay. A gathering of horseshoe crabs is clearly visible in Figure 25. The elongated black spots are individual horseshoe crabs in action bulldozing their way through the surficial sediment. The photo was taken on an ebb tide and as the water drops, the crabs burrow into the substrate for protection. In this case the upper sediment is buff-colored, indicating an oxic environment. Sediment sampling reveals that a few centimeters below the surface the sediment becomes black in color, indicating anoxic conditions. Thus each dot represents a crab pit, and the "tails" are the stirred-up anoxic sediments being transported by the ebb tide; each is like a little flow vector. (Photo and description courtesy of R. Jude Wilber.) Figure 25 is just a tiny fraction (~1/100th of the original photo in area) of a high-altitude vertical aerial photograph. Just that tiny fraction of this one image provides a lot of information on sediment oxidation state, distribution and behavior of horseshoe crabs, and ebb-tidal flow field.

The air photo survey/field evaluation cycle was used to interpret the biocultivation impact of horseshoe crabs in Pleasant Bay. From the aerials an unusual site lacking any small bedforms was identified. The bay bottom had a distinct brown coloration not found anywhere else. A field investigation revealed hundreds of horseshoe crabs in intertidal setting. The area was sampled through a low tide interval. It was found that the crabs (Fig. 26) burrow into the substrate and bioturbated the sediments, which are anoxic. In so doing, the sediments are oxidized, allowing

a hundred-fold increase in infaunal organisms—mostly polycheates and other worms. Worms are a major food source for crabs. Thus, the burrowing (as protection from dessication) leads to bio-cultivation (farming) of food source. This interesting monitoring story illustrates the need to protect this particular acreage.

Another important component of the floor cover of Pleasant Bay is eelgrass. Marine eelgrass (genus *Zostera*) is common in shallow bays and estuaries in temperate environments. As with most plants in such settings, eelgrass is an important environment for juvenile and adult forms of many shell fish and fin fish. Decrease in eelgrass bed area is a serious problem along the U. S. Atlantic coast and can be attributed to pollution, human activities, and even destruction by biocultivation by organisms sharing the habitat. Such is the case for eelgrass beds in Pleasant Bay where biocultivation by horseshoe crabs is responsible, at least in part, for the demise of the beds.

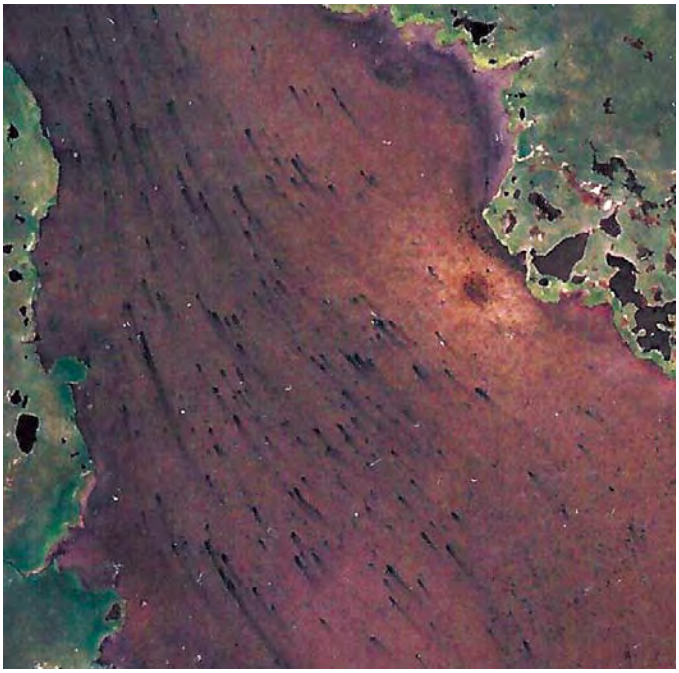


Figure 25. Bioturbation by horseshoe crabs in Pleasant Bay, Massachusetts. Each "dot" is a horseshoe crab pit and the "tails" are stirred-up anoxic sediments being transported by the ebb tide. Photo courtesy of R. Jude Wilber.

As above, an unusual seafloor pattern was first observed in air photos. After field investigation it was determined that eelgrass bed degradation was the result of two mechanisms. The dark patches in Figure 27 are the *Zostera*. The bed had been dissected (linear cuts) due to flood tidal jetting of sediment from bottom to top, and possible ebb-tidal action as well. In addition, there was "ring rot" happening here. The eelgrass was dying back from the inside out, leaving circular holes and, in the extreme, isolated rings of grass. Using a baseline image like this one can proceed to monitoring in the field for timing and processes as this patch wastes away.

A very simple sediment sampling device for grabbing a sample from a small boat can be made by nailing a bucket to a length of 2 × 4 lumber. Dubbed "WiBSAP," the Wilber Benthic Sampling Apparatus, it is hard to beat for the price (Fig. 28). Sediment samples from deeper water (20 feet) anoxic basins within Pleasant Bay were taken using a Van Veen grab sampler. These samples reveal an almost gelatin-like anoxic sediment (Fig. 29). The air photo/field survey cycle here addressed both flora and fauna. It was found that: (1) full-blown anoxia conditions existed from the bottom down; thus, (2) there was no infauna or anything that feeds on such (i.e., crabs); (3) *Mercenaria* clams (quahogs) occasionally were present since they are filter feeders and suck in the phytoplankton detritus; (4) the deep basins were sinks for the macro-flora produced in the eel grass beds and salt marshes; and (5) this was especially true of the eel grass and the deep



Figure 26. Horseshoe crab bulldozing through oxidized surficial sediment in Pleasant Bay, Massachusetts, revealing anoxic sediments below. Photo courtesy of R. Jude Wilber.

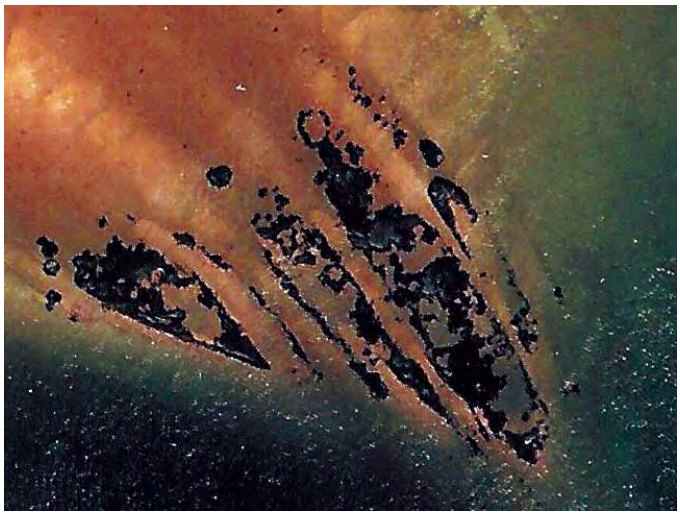


Figure 27. Eel grass (*Zostera maritima*) bed in Pleasant Bay, Massachusetts. Photo courtesy of R. Jude Wilber.

basin where a black organic gel largely from the decomposition of *Zostera* was present. Also, there are large stands of healthy *Zostera* beds with 100% coverage (Fig. 30).

Finally, even sediment dynamics can be monitored with simple photography if water clarity allows. An actively prograding sand shoal with switch from laminar flow to turbulent flow can be seen in Figure 31. In order to sample in swift currents like this, the "WiBSAP" works better than anything else.

CONCLUSIONS

The nearshore marine environment is a dynamic and complex system. Extending from the low tide water level out to the edge of the continental or insular shelves, it encompasses a range of water depths from essentially zero to 120 m or more. The nearshore is acted upon by a wide range of forces, including wind, tides, gravity, waves, and biologic effects including human impact. Water temperature range is as variable as can be observed in any marine system, owing to seasonal and event-related impacts on the shallow water column. The nearshore is a photosynthetic-based ecosystem, so the health and vitality of its fauna is highly sensitive to land-based impacts on water quality, including turbidity and pollutants.

In order to properly manage public lands in a nearshore setting it is prudent to thoroughly monitor several vital signs. Fortunately, high-quality baseline studies and monitoring can be undertaken at modest costs and performed by relatively unskilled and/or student observers. Although highly sophisticated, high-technology monitoring and historical analysis techniques are available as a means of collecting baseline data for nearshore management and policy



Figure 28. Very simple, inexpensive, reliable sediment sampling tool for shallow water in use in Pleasant Bay, Massachusetts. Dubbed "WiBSAP," the Wilber Benthic Sampling Apparatus. Trial and error showed that it worked better than anything else for this type of sampling. Photo courtesy of R. Jude Wilber.



Figure 29. Van Veen grab sampler used to retrieve sediment from small boats in water ~20 feet deep in Pleasant Bay, Massachusetts. Sediment is an almost gelatin-like anoxic mass. Photo courtesy of R. Jude Wilber.



Figure 30. Healthy *Zostera* bed with red sponges. Low-tide photo, courtesy of R. Jude Wilber.



Figure 31. Shallow water sediment dynamics can be monitored with simple photography in the right conditions.

TABLE 1. COMPARATIVE METHODS OF MONITORING MARINE VITAL SIGNS

Vital signs and methods	Expertise*	Specialized equipment	Cost†	Personnel	Labor intensity§
Bathymetry					
Manual survey	SCA/volunteer	No	$	Individual	Low
Fathometer	Scientist	Yes	$	Group	Moderate
Digital array	Expert	Yes	$$	Group	Moderate
Hydrography					
Drogues, observations	SCA/volunteer	Yes	$	Individual	Low
Mechanical meters	Scientist	Yes	$$	Group	Low
Deployed meters	Expert	Yes	$$$	Group	Moderate
Barriers: Reefs					
1. Diver sampling	Scientist	Yes	$$	Group	Moderate
2. Measure by divers	Scientist	Yes	$$	Group	Moderate
3. Remote sensing	Expert	Yes	$$$	Group	High
Barriers: Other					
1. Diver sampling	Scientist	Yes	$$	Group	Moderate
2. Grab sampling	Scientist	Yes	$$	Group	Moderate
3. Remote sensing, coring	Expert	Yes	$$$	Group	Moderate
Substrate					
1.Diver sampling	Scientist	Yes	$$	Group	Moderate
2. Grab sampling	Scientist	Yes	$$	Group	Moderate
3. Remote sensing, coring	Expert	Yes	$$$	Group	High
Water Column					
Secchi disk, samples	SCA/volunteer	Yes	$	Group	Low
Handheld meters	Scientist	Yes	$	Group	Moderate
Deployed meters	Expert	Yes	$$	Group	High

*SCA (Student Conservation Association)/volunteer—needs no experience, minimal training and some observation sufficient; scientist—needs modest technical background in field or related field, but need not be expert in field; expert—must be scientist specifically trained in field and in use of specialized equipment.

†Cost (US$): $ = <$1,000, $$ = $1,000 to $10,000, $$$ = >$10,000.

§Labor intensity: low = <few hours; medium = <full day; high = >full day.

determinations, there are also many scientifically valid, simple tools available, both qualitative and quantitative.

A broad range of costs, expertise, and complexity of methodologies is available for use in monitoring the nearshore, based on the resources of the overseeing agency or department. Table 1 summarizes the monitoring techniques discussed in this chapter. The references cited and the bibliography of suggested reading give many more sources of information.

ACKNOWLEDGMENTS

I would like to thank R. Jude Wilber for supplying his Pleasant Bay information and photos. Thanks also to Sea Surveyor, Inc., Benicia, California, specifically to Steve Sullivan, for generously supplying photos, figures, and descriptions of their various methods and examples of hydrographic surveys, marine geophysical investigations, vibracoring, and other oceanographic sampling techniques. Dennis Hubbard kindly allowed use of his figures and photos of his Buck Island reef studies.

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Monitoring in situ paleontological resources

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INTRODUCTION

Paleontological resources (fossils) are the remains of life preserved in a geologic context. Fossils may consist of the physical remains of a biological organism such as a tooth, bone, shell, leaf, cone, seed, or wood. Evidence of biological activity may sometimes be preserved in rocks, hence tracks, traces, burrows, coprolites (fossil dung and feces), and nests represent other valuable types of paleontological resources.

The fossil record reveals an extremely rich diversity of ancient organisms preserved in the Earth's **strata** (layers of rock). The fossil record of life on Earth spans nearly every period of geologic history from Precambrian bacteria, billions of years old, to more recent Pleistocene or Holocene cave fossils dating back only a few thousand years. Together, fossils from around the world yield significant scientific and educational information regarding the history of life on Earth.

From the moment of death for an organism, a wide array of agents and forces work toward the breakdown and destruction of its physical remains. Raup and Stanley (1978) identify and describe biological, chemical, and mechanical variables associated with the destruction of biological remains. Only a very small percentage of all living organisms become part of the fossil record, and of those, an even smaller percentage have been discovered, collected and studied. The preservation of fossils and the associated biases in the fossil record are directly attributable to the organism's morphologic composition, rate of post-mortem burial, environment of deposition, diagenetic variables, **taphonomic** (after death) factors, and the post-depositional geologic history of the area.

Despite how common or rare a particular species of fossil may be, all paleontological resources are nonrenewable. Whether fossils occur in situ beneath the surface, exposed at the surface, or removed from strata through collection, these resources are finite, a fact which should be reflected in paleontological resource management strategies. Additionally, the distribution of paleontological resources within a given area is generally not uniform. Fossils frequently occur in local concentrations within lithologic units (Shipman, 1981). This non-uniform distribution of fossils presents the fundamental challenge in their in situ management and protection.

The documentation of baseline paleontological resource data is essential in order to develop effective strategies for monitoring the stability and condition of fossil localities. A resource inventory should be designed in order to compile data regarding the scope, significance, and distribution of fossils at each locality. The spatial and surficial distribution of fossiliferous exposures and strata should always be determined and mapped during paleontological resource inventories. A documented paleontological locality is a spatially defined area that may include either in situ fossils or a site from which fossils have been previously collected and curated into a museum repository. Field documentation for each paleontological locality should include a site description, photography, and some level of mapping (Fremd, 1992). It is important to recognize that new localities may be discovered, and previously documented sites may be lost due to natural or human impacts.

Additionally, during the inventory phase, an assessment of the existing or emerging threats (stressors) to the stability of in situ fossils should be undertaken and documented. This is essential baseline information in order to develop and initiate the appropriate design for paleontological resource monitoring. Some examples of important measurable baseline paleontological locality information include: (1) lithology (physical/chemical

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Santucci, V.L., Kenworthy, J.P., and Mims, A.L., 2009, Monitoring in situ paleontological resources *in* Young, R., and Norby, L., Geological Monitoring: Boulder, Colorado, Geological Society of America, p. 189–204, doi: 10.1130/2009.monitoring(08). For permission to copy, contact editing@geosociety.org. ©2009 The Geological Society of America. All rights reserved.

properties) of fossiliferous strata (hardness, solubility, bedding, jointing, etc.); (2) relationship of overlying and underlying strata (rock falls, undercutting, sinkholes); (3) degree of slope of the fossiliferous strata; and (4) type and percentage of vegetation cover.

Some land management agencies have developed strategies to document baseline paleontological resource data. In 2006 the National Park Service Inventory and Monitoring Program funded a multi-year project to undertake baseline paleontological resource inventories for parks throughout the agency. Other valuable sources for paleontological resources data include the U.S. Geological Survey (USGS), state geological surveys, local museums, and universities.

STRESSORS AND THREATS

The scientific and educational values of in situ fossils are directly dependent upon their stability. Various benchmarks can be established to determine or define a stable paleontological resource. Some land managing agencies generate a benchmark referred to as a "desired future condition" to define resource management goals. These goals are often expressed as a qualitative description of the resource condition. Below is a proposed benchmark to define a paleontological resource in good condition.

> Paleontological resources and their associated geologic context are maintained in situ in a stable environment and are in good condition with little or no potential for degradation or impairment by artificially accelerated natural processes or direct human impacts. Similarly, the scientific and educational values are unimpaired and are also preserved in good condition.

A wide range of natural physical, chemical, and biological processes, along with human access and activities, may threaten the stability of in situ paleontological resources. Santucci and Koch (2003) present an overview of these natural and human-related stressors to paleontological resources. The following section identifies some of the natural processes and human factors that influence the stability of in situ paleontological resources. Figure 1 presents a conceptual diagram of these stressors.

Environmental Factors Affecting Stability of In Situ Paleontological Resources

The stability of in situ paleontological resources will always be a function of the natural processes, environmental conditions, and other natural factors at the fossil locality. These natural variables are typically beyond the ability of humans to manage or control, and as natural conditions or processes, should be sustained. For example, natural erosion should not be impeded in order to preserve fossils, except under special circumstances to stabilize a significant locality such as Douglass Quarry at Dinosaur National Monument.

Generally, weathering and erosion are the primary natural processes that affect the stability of in situ fossils. Nearly all of the environmental factors, including climatic, hydrologic, geologic, or biologic conditions or processes, in some manner influence rates of weathering and erosion. It is important to recognize that weathering and erosion serve as agents for both the exposure and reburial of fossils. Therefore, weathering and erosion can expose new fossils while ultimately contributing to the gradual or catastrophic destruction of those already exposed (e.g., Colbert, 1966).

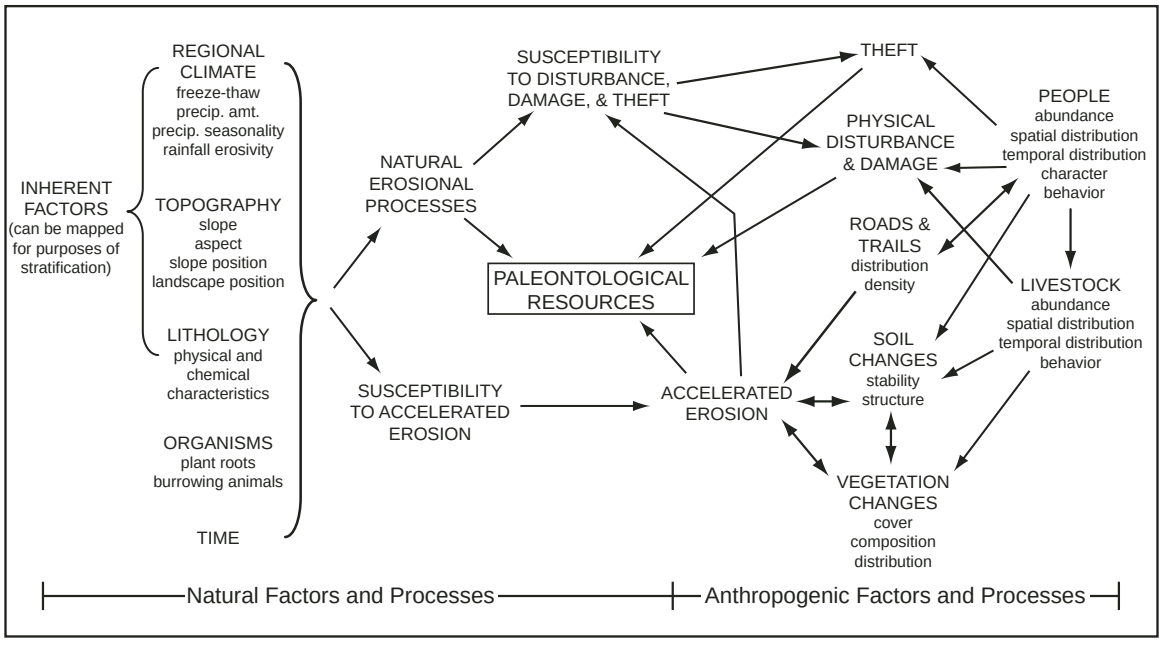


Figure 1. Conceptual diagram illustrating examples of both natural and anthropogenic factors and processes as stressors and threats to paleontological resources. Reproduced from Santucci and Koch (2003). Diagram produced by Sue Miller.

Climatic factors including temperature, precipitation, humidity, and wind can influence rates of weathering and erosion of fossiliferous strata. Both diurnal and annual changes in temperature, particularly when temperatures fluctuate above and below freezing, will cause expansion and contraction of water in rock fractures, contributing to the weathering and erosion of soil, rocks, and fossils. The **freeze-thaw index** is the number of 24-hour periods per year when the temperature fluctuates above and below freezing. Areas with a high freeze-thaw index would theoretically experience higher rates of weathering and erosion than areas with a low freeze-thaw index. The freeze-thaw index can be a useful variable in determining how often fossil sites should be monitored.

Another climatic factor influencing the stability of in situ paleontological resources is precipitation, in the form of rain, snow, hail, sleet, or mist. Rates of erosion are directly proportional to levels and intensity of precipitation. Sites with greater levels of precipitation, or areas with brief (seasonal) periods of intense precipitation, would generally exhibit higher rates of erosion. Therefore, precipitation rates and intensity should also be considered in determining the frequency of monitoring.

Relative humidity or aridity may also influence the stability of in situ paleontological resources. The remains of biological organisms typically experience higher rates of decomposition in areas with high relative humidity. Conversely, rates of decomposition of biological remains may not be as high in arid environments. This relationship is evident in the differential preservation of fossils in arid and humid caves. In arid caves of the southwestern United States, the preservation of soft tissues, hair and dung dating back tens of thousands of years is not uncommon (Santucci et al., 2001b). Similar soft-tissue preservation is generally not found in humid climates.

Winds may also influence the stability of in situ paleontological resources in two ways. Unconsolidated **eolian** (wind-transported) sediments can gradually abrade fossils exposed at the surface. Additionally, winds may contribute to the accumulation of sediments and the formation of dunes. The migration of dunes may result in the burial, exposure, or destruction of fossils at the surface.

Hydrologic factors such as water depth and changes in water depth of oceans, lakes, ponds, rivers, streams, and other hydrologic features, as well as hydrologic processes such as flooding, drought, tides, waves, currents, and stream velocity, can all significantly influence the stability of in situ fossils (Fig. 2). Increases in water depth may impact paleontological resources during periods of flooding along shorelines and riverbanks. Fossiliferous strata may be subjected to higher than normal rates of erosion due to flooding. Decreases in water depth due to drought or other factors may result in the emergence of previously submerged fossils.

A variety of geologic processes and events may catastrophically influence the stability of in situ paleontological resources. Local or regional volcanism, tectonics, seismicity, glacial activity, landslides, and other geologic factors may present significant threats to fossil localities. These may be direct threats, such as lava burying preserved tree molds, or indirect threats that accelerate local rates of weathering and erosion, such as a loss of vegetative cover due to landslides.



Figure 2. Fossil dinosaur track slab exposed along the shoreline of Lake Powell at Glen Canyon National Recreation Area. Fluctuating water levels in the lake periodically inundate or expose such resources along shorelines. National Park Service photo.

A number of biological factors may influence the stability of in situ paleontological resources. Bioturbation of fossiliferous strata can occur at or beneath the surface. Trampling by ungulates (hoofed animals), burrowing by vertebrates and invertebrates, and root development by trees and other plants can all disturb in situ fossils, either directly or by accelerating local rates of weathering and erosion (Fig. 3). Root development from smaller plants can stabilize soil and other surficial deposits, potentially reducing their susceptibility to erosion. Conversely, larger root development can break apart rocks, increasing their susceptibility to erosion. Areas with minimal vegetation cover are generally more susceptible to higher rates of erosion. Numerous factors can affect vegetation cover, and may serve as proxies for potential damage to nearby fossils, including climate/weather, animal grazing/trampling, fire, visitor use, vegetation management activities, and construction.

Human Factors Influencing Stability of In Situ Paleontological Resources

Within publicly administered lands, the disturbance or removal of fossils by humans is often prohibited by laws, regulations, and policies. In certain cases, fossils may be disturbed or removed by individuals or institutions authorized through a permit, subject to an environmental compliance review, or while performing management actions to preserve or stabilize in situ paleontological resources. Nevertheless, human disturbances may threaten the stability of fossils and can be contrary to their



Figure 3. Evidence of ungulate (cattle) trampling and exposed petrified wood (arrow). The trampling not only degrades the petrified wood, but also exposes new specimens. Scale card is 12 cm. National Park Service photo.

management goals. Therefore, any monitoring program or prescription for paleontological resources should consider strategies for identifying, understanding, and evaluating the impacts of human factors on fossils.

Human-related impacts on fossils may be unintentional or intentional and may arise from the activities of visitors, permitees, contractors, or land managers. Unintentional human impacts include activities that contribute to the instability or loss of paleontological resources where either: (1) individuals are unaware that fossils are present in the area; or (2) although aware that fossils are present, the individuals do not understand that their activities may have an adverse impact on the stability of fossils. For example, visitors may be unaware that hiking off designated trails may lead to increased erosion and in turn an accelerated destruction of fossils. Intentional human impacts include activities and behaviors, such as vandalism or fossil poaching (Fig. 4). Such activities disregard resource management goals, policies, regulations, and the scientific and educational values of fossils.

Therefore, any paleontological resource monitoring plan or prescription should include an assessment of human access and



Figure 4. Round holes show where dinosaur tracks have been vandalized and removed from Dinosaur Ridge near Morrison, Colorado. This is a blatant example of intentional human vandalism of in situ paleontological resources. National Park Service photo.

activities and their associated impacts to fossils. Some basic considerations regarding the activities of visitors and land managers in paleontological resource areas should include: (1) the proximity of developed areas and access to fossiliferous strata by the public; (2) visitor use in or near fossil sites, including both the numbers of users and types of activities; (3) plans for construction, development, and any other ground-disturbing activities; and, (4) factors contributing to the theft and vandalism of fossils.

VITAL SIGNS FOR MONITORING IN SITU PALEONTOLOGICAL RESOURCES

Five vital signs are presented here for monitoring of in situ paleontological resources (Table 1). These vital signs exhibit the broadest applicability for the wide diversity of conditions and variables associated with fossil sites. In the future, additional vital signs may be developed for more specific resource conditions. These individual vital signs are not mutually exclusive; rather, there are inherent relationships between vital signs that contribute to an understanding of the stability or instability of in situ fossils.

The vital signs are based on measurable and relevant parameters. Vital signs do not directly measure the “health” of paleontological resources per se, but actually measure variables reflecting their stability in situ. The vital signs discussed in this chapter should help land and resource managers identify thresholds that would trigger the need for some management action or intervention. Monitoring strategies are developed for each vital sign at three levels. Level 1 identifies the simplest and most cost efficient monitoring approach. Level 3 represents a technically sophisticated, but generally most expensive approach. Level 2 is intermediate in cost and complexity. It is important to recognize that the elements of each level are sometimes cumulative through levels 2 and 3.

TABLE 1. SUMMARY OF PALEONTOLOGICAL RESOURCE VITAL SIGNS AND MONITORING METHODS

Vital signs and methods	Expertise	Specialized equipment	Cost*	Personnel	Labor intensity†
Erosion (Geologic Factors)					
Repeat photography	Volunteer	No	$	Individual	Low
Erosion stakes	Volunteer	No	$	Individual	Low
Technology-enhanced	Scientist	Yes	$$$	Group	High
Erosion (Climatic Factors)					
Climatic records	Volunteer	No	$	Individual	Low
Repeat photography	Volunteer	No	$	Individual	Low
Technology-enhanced	Scientist	Yes	$$$	Group	High
Catastrophic Geohazards					
Geologic assessment	Volunteer	No	$	Individual	Low
Digital mapping	Scientist	Yes	$$	Group	Medium
Technology-enhanced	Scientist	Yes	$$$	Group	High
Hydrology/Bathymetry					
Repeat photography	Volunteer	No	$	Individual	Low
Digital mapping	Scientist	Yes	$$	Group	Medium
Technology-enhanced	Scientist	Yes	$$$	Group	High
Human Access/Public Use					
Repeat photography	Volunteer	No	$	Individual	Low
Digital mapping	Scientist	Yes	$$	Group	Medium
Technology-enhanced	Scientist	Yes	$$$	Group	High

*Cost (in US$) = <$1,000; $$ = $1,000 to $10,000; $$$ = >$10,000.
†Labor intensity: low = <few hours; medium = <full day; high = >full day.

The use of high resolution photogrammetry is perhaps the most universally valuable approach for monitoring in situ paleontological resource localities. When possible, the establishment of photo points for long-term photography is the best method for measuring both long- and short-term changes.

Vital Signs 1 and 2 focus directly on monitoring rates of erosion of fossiliferous strata. Erosion is a universal threat to in situ paleontological resources and, unless there is some human intervention (collection or stabilization), it will inevitably cause the destruction of fossils exposed at the surface. The fundamental difference between Vital Signs 1 and 2 relates to internal versus external factors contributing to rates of erosion. Vital Sign 1 focuses on the inherent geologic characteristics and features of the strata in which the fossils occur. These internal factors include lithology, bedding, slope of strata, and geochemistry of the rock unit. Vital Sign 2 focuses on the external factors and forces which influence rates of erosion. Some examples of external factors include precipitation, temperature, and the freeze-thaw index.

Vital Sign 5 relates specifically to monitoring human-related threats to in situ paleontological resources. Both intentional and unintentional human activities can threaten the stability of fossils. Many of the discussions related to visitor use and resource protection are social science issues; the inclusion of this discussion here enables a more comprehensive approach to monitoring the widest range of threats to in situ fossils.

While not all of the other vital signs may be applicable or practical for every fossil site, collectively the vital signs offer some widely adaptable methods for monitoring in situ fossil sites. Land and resource managers can select the preferred vital signs in order to develop monitoring prescriptions tailored to specific locality or management needs. In most cases, the monitoring of one or more vital signs should provide land and resource managers with valuable data for planning and decision-making.

Finally, these vital signs have been designed to be implemented by land and resource managers who do not necessarily have a background in geology or paleontology. For managers interested in obtaining more specific geological or paleontological information or expertise, there are a number of resources, including the National Park Service (NPS) Geologic Resources Division, the Geological Society of America (GSA), the U.S. Geological Survey (USGS), state geological surveys, and local universities, museums, and other institutions.

Vital Sign 1: Rates of Natural Erosion I (Geologic Variables)

Description

Rates of natural erosion for fossiliferous **strata** (rock layers) are influenced by the physical geologic characteristics and properties of the bedrock. Variables such as **lithology** (physical characteristics of a rock), bedding, degree of slope and geochemistry contribute directly to the resistance or susceptibility to weathering and erosion upon fossiliferous strata exposed at the surface.

The stability of in situ fossils present at or near the surface is proportional to the erosion rates of the exposed strata in which they are preserved. High rates of erosion result in more rapid destruction of fossils exposed at the surface, and low rates of erosion often mean slower destruction. Monitoring rates of erosion at fossil sites will enable land and resource managers to better determine how frequently to schedule site assessments or **cyclic prospecting** (periodic field investigation of a fossil locality).

Methods

Level 1: Repeat Photography. Differential rates of erosion for fossiliferous strata and the stability of in situ paleontological resources can be assessed through the use of repeat photography. Each fossil site identified through field inventories should be spatially defined, mapped, and photographed. Photo points must be established for both large-scale and small-scale repeat photography so that consistent points of reference and perspectives are available over time. The schedule or frequency of the repeat photography should be determined based upon site-specific variables and management objectives.

All photographs should be maintained in a secure archival storage facility. Each photograph should be labeled with the site name or number, photo point identifier, date of photograph, and name of photographer. Additional site data, such as stratigraphic, taxonomic, or historical information, should be maintained in an associated file or database.

Repeat photography is a low-cost and low-technology approach to monitoring paleontological sites over time. This photography could be undertaken by a trained volunteer. Photos enable the documentation of observable changes in stability at each site, and the fossils exposed at the surface. This level of information may also enhance resource management and scientific decision making relative to a fossil site, such as the frequency of cyclic prospecting or stabilization of the site.

Level 2: Erosion Monitoring Stakes. Differential rates of erosion for fossiliferous strata and stability of in situ fossils can be assessed through the establishment of erosion monitoring stakes. The stakes are placed into a rock unit perpendicular to the surface. The baseline level is marked directly on the monitoring stake at the point where the stake enters the ground surface. During subsequent site visits, any changes in the ground surface level relative to the monitoring stake should be recorded. Monitoring stakes should be measured at least annually for the first five years after placement (Fig. 5).

Ideally, three erosion monitoring stakes are established at each site. Each stake should have an individual identifier which distinguishes it from the other stakes. Multiple stakes at one locality may show consistency or variation in the local rates of erosion. Additionally, the placement of multiple erosion stakes provides backup monitors in the event that one of the stakes is disturbed.

The most durable and environmentally sensitive material to use for the stakes is galvanized steel. The stakes should be at least one meter in length and approximately 0.75 cm in diameter. Initially, the stake should be driven into the substrate until ~15 cm are exposed above the ground surface. A marker flag may be attached to the top portion of the stake to facilitate relocation in the future (and for public safety). If available, a Global Positioning System (GPS) device can be used to record the location of the stakes.

The establishment of erosion monitoring stakes to measure stability of fossiliferous strata is another low-cost and low-technology approach to monitoring fossil sites. These periodic measurements could be undertaken by a trained volunteer. However, the initial placement of erosion monitoring stakes would benefit from the experience of a professional geologist or paleontologist. The acquisition of data from the erosion monitoring stakes will, over time, enable documentation of measurable changes in stability at each site and the fossils exposed at the surface. This level of information may also enhance resource management and scientific decisions, such as the frequency of cyclic prospecting or stabilization of a site.



Figure 5. Installation, measurement, and documentation of erosion stakes at Fossil Butte National Monument in 2002. Such stakes provide quantitative local erosion rates and can be used in paleontological resource management prescriptions.

Level 3: Technology-Enhanced Erosion Monitoring. Differential rates of erosion for fossiliferous strata and stability of in situ paleontological resources can also be assessed through the use of technology-enhanced monitoring equipment. Digital elevation data (topography) is obtained for each site. Geospatial data for the area is also needed in each locality. Locality and elevation data are then used to produce maps differentiating areas of low, medium, and high slopes. Erosion monitoring stakes are installed in sensitive areas and measured annually. A landslide assessment using aerial photographs and geospatial data can also be initiated. This information can be used to determine which areas would be susceptible to higher rates of erosion and would in turn benefit from more frequent monitoring.

The use of technology-enhanced monitoring to measure the stability of fossiliferous strata is a relatively expensive approach to monitoring paleontological sites. The periodic measurements and evaluation of data require a professional geologist and someone trained in the use of the specific technology employed in the monitoring. The acquisition of this data, over time, will enable documentation of measurable changes in the stability at each site and the fossils exposed at the surface. This level of information may also enhance resource management and scientific decisions, such as the frequency of cyclic prospecting or stabilization of the site.

Discussion

The rates of natural erosion and the stability of associated in situ paleontological resources will be the most important factors in determining the frequency of monitoring for this vital sign. Repeat photography and monitoring of erosion stakes should be scheduled at least annually for the first few years. Once monitoring data becomes available, the land or resource manager will be better able to determine if the timing of site monitoring is appropriate or needs adjustment.

A few additional recommendations are worth considering regarding rates of erosion influenced by the geology of the locality:

- Assess surface morphology for each fossiliferous rock exposure. Rock units which are more resistant to weathering and erosion generally develop into more prominent and vertical cliffs, while units more susceptible to weathering and erosion generally develop into more gentle slopes. Rock units more resistant to weathering and erosion require less frequent monitoring.
- Assess differential erosion, as exhibited in surface morphology, between fossiliferous units and the adjacent overlying and underlying strata. Differential erosion contributes to undercutting, rock falls, landslides, slumps, and other forms of geologic hazards which threaten the stability of in situ fossils.
- Assess differential rates of erosion through the use of aerial and ground photographs in order to identify the areas of greatest instability, and areas to target for more frequent cyclic monitoring.
- Estimate the degree of slope or range of slopes for each fossil site using topographic maps or measure slopes in the field with a Brunton compass. Greater slopes are susceptible to higher rates of erosion. Hence, these areas of greater slope should be monitored on a more frequent schedule. Conversely, areas of low or no slope are less susceptible to erosion. Sites occurring at a low slope require less frequent monitoring.

Vital Sign 2: Rates of Natural Erosion II (Climatic Variables)

Description

Rates of natural erosion for fossil strata are influenced by climatic conditions and variables. Precipitation and temperature contribute directly to the resistance or susceptibility to weathering and erosion upon fossiliferous strata exposed at the surface. High precipitation promotes higher rates of erosion. Another climatic variable influencing rates of erosion is a measurement referred to as the **freeze-thaw index**. The freeze-thaw index, as previously explained, is the number of 24-hour periods per year when the temperature fluctuates above and below 32 °F (0 °C).

The stability of in situ fossils present at or near the surface is proportional to the erosion rates of the exposed strata in which they are preserved. Therefore, high rates of erosion will generally result in more rapid destruction of fossils exposed at the surface. Conversely, low rates of erosion often enable slower destruction of exposed fossils. Monitoring rates of erosion at fossil sites will enable land and resource managers to better determine how frequently to schedule site condition assessments or cyclic prospecting.

Methods

Level 1: Climatic Records. Local climatic data should be compiled and evaluated, including temperature and precipitation records, for at least a five-year period. Fossil sites in areas of high annual precipitation should be assessed more frequently than areas with low annual precipitation. Local temperature records are evaluated in order to calculate the average number of 24-hour periods per year when the temperature fluctuates above and below 32 °F (0 °C). From this average the freeze-thaw index for the park is determined and incorporated into an appropriate schedule for periodic fossil site assessments. Fossil sites in areas with a low freeze-thaw index require less frequent monitoring than those in areas with a high freeze-thaw index.

Once historic climatic data is compiled, temperature and precipitation data should continue to be recorded for areas with fossil sites. During periods of increased precipitation, and/or increases in the freeze-thaw index, more frequent site assessments may be warranted. This method is a low-cost and low-technology approach to monitoring paleontological sites over time.

Level 2: Repeat Photography. Local climatic data should be compiled and evaluated, including temperature and precipitation records, for at least a five-year period, as outlined in level 1. The freeze-thaw index for the fossil site should also be calculated.

During monitoring, differential rates of erosion for fossiliferous strata and the stability of in situ paleontological resources are assessed using repeat photography. Each fossil site identified through field inventories should be spatially defined, mapped, and photographed. Photo points must be established for both large-scale and small-scale repeat photography so that consistent points of reference and perspectives are available. The schedule or frequency of the repeat photography should be determined based upon climatic variables and management objectives.

All photographs should be maintained in a secure archival storage facility. Each photograph should be labeled with the site name or number, photo point identifier, date of photograph, and name of photographer. Additional site data, such as stratigraphic, taxonomic, or historical information, should be maintained in an associated file or database.

Repeat photography is a low-cost and low-technology approach to monitoring paleontological sites over time. This photography could be undertaken by a trained volunteer. Photos enable the documentation of observable changes in stability at each site, and the fossils exposed at the surface. This level of information may also enhance resource management and scientific decision making relative to a fossil site, such as the frequency of cyclic prospecting or stabilization of the site.

Level 3: Technology-Enhanced Erosion Monitoring. Local climatic data should be compiled and evaluated, including temperature and precipitation records, for at least a five-year period, as outlined in level 1. The freeze-thaw index for the fossil site should also be calculated.

Differential rates of erosion for fossiliferous strata and stability of in situ paleontological resources can also be assessed through the use of technology-enhanced monitoring equipment. Digital elevation data (topography) is obtained for each site. Geospatial data for the area is also needed in each locality. Locality and elevation data are then used to produce maps differentiating areas of low, medium, and high slopes. Erosion monitoring stakes are installed in sensitive areas and measured annually. A landslide assessment using aerial photographs and geospatial data can also be initiated. This information, combined with local climatic data, can be used to determine which climatic conditions would result in higher rates of erosion, and thus which sites would in turn benefit from more frequent monitoring.

The use of technology-enhanced monitoring to measure the stability of fossiliferous strata is a relatively expensive approach to monitoring paleontological sites. The periodic measurements and evaluation of data require a professional geologist and someone trained in the use of the specific technology employed in the monitoring. The acquisition of this data will, over time, enable documentation of measurable changes in the stability at each site and the fossils exposed at the surface. This level of information may also enhance resource management and scientific decisions, such as the frequency of cyclic prospecting or stabilization of the site.

Discussion

Climatic variables influencing the rates of natural erosion and stability of associated in situ paleontological resources will be the most important factors in determining the frequency of monitoring activities for Vital Sign 2. In areas with high precipitation the rates of erosion would typically be greater. Therefore, monitoring should be more frequent in areas of high precipitation.

Various systems have been established for classifying climatic zones. The Köppen Climate Classification System is the most widely recognized system for classifying world climate. The Köppen system recognizes five major climate types based on annual and monthly averages of temperature and precipitation. These include:

- **Moist tropical climates:** Climates characterized by year round high temperatures and high levels of precipitation throughout the year.
- **Dry climates:** Climates characterized by a significant daily temperature range and low levels of precipitation. There are two subgroups: arid/desert and semi-arid/steppe.
- **Humid middle latitude climates:** Climates characterized by warm/dry summers and cool/wet winters.
- **Continental climates:** Climates characterized by widely varying seasonal temperatures and moderate to low annual precipitation. This type of climate is typically found in the interior portions of large land masses.
- **Cold climates:** Climates where the majority of the year experiences below-freezing temperatures. This climate is typical of areas where permanent ice and tundra dominate the landscape.

Fluctuations in temperature, in particular at temperatures near freezing, may have a significant influence upon rates of erosion and the stability of in situ paleontological resources. The amount of surface and subsurface water varies from arid to humid climates. Fossiliferous rock units saturated with surface water or groundwater will experience more intense freeze-thaw and frost action than those in arid areas.

The concept of a freeze-thaw index is based upon the perspective that areas subjected to increased frost action and freeze-thaw cycles are likely to exhibit higher rates of erosion. Some geographic areas rarely experience temperatures that drop below the freezing point of water. Southern Florida or the Sonoran Desert are examples of areas where the freeze-thaw index would be very low. In other areas, such as the Rocky Mountains or Great Plains, freeze-thaw cycles may be experienced during more than two-thirds of the year, so the freeze-thaw index is much higher.

In areas with a low freeze-thaw index, the rates of erosion based upon temperature fluctuations are probably low. Therefore, fossil sites in these areas would require less frequent monitoring. Conversely, more frequent monitoring would be needed for areas with a high freeze-thaw index.

Vital Sign 3: "Catastrophic" Geologic Processes or Geohazards

Description

A variety of geologic processes and hazards (also known as **geohazards**) may contribute to the instability of in situ paleontological resources and adversely impact the scientific or educational values of fossils. Geohazards include, but are not limited to, local/regional volcanism, geothermal activity, earthquakes, glacial activity, and mass-wasting events (landslides, slumps, rockfalls, etc). This vital sign would only apply to paleontological resources located in areas at risk for geohazards.

Methods

Level 1: Geohazard Assessment. Potentially catastrophic geohazards which could affect in situ paleontological resources should be identified. Initially, this should be accomplished by researching local geologic resources and processes, review relevant geologic maps and scientific literature, and consulting with professional geologists.

A geohazard assessment is a relatively low-cost and low-technology approach to monitoring paleontological localities. The assessment should be undertaken by a professional geologist. Monitoring of local geohazards which may potentially threaten fossil sites may enhance resource management and scientific decision making.

Level 2: Digital Mapping. Once a geohazard which threatens in situ fossil sites has been identified, more sophisticated

monitoring may be warranted. At this level, site monitoring would benefit from the development of digital maps (GIS) integrating spatial fossil distribution with geohazards. The monitoring design would be directly tied to the type of geologic hazard identified.

Digital mapping requires moderate levels of funding for support in addition to a professional geologist who specializes in geohazards.

Level 3: Technology-Enhanced Geohazard Monitoring. Specialized equipment (e.g., seismometers, cameras, GPS stations, ground motion sensors, high-resolution photogrammetric monitor, etc.) are installed to actively and/or cyclically monitor fossil sites, provide quantitative data on Earth processes, or to provide early warning of imminent impacts. A predictive model and maps through GIS are then developed to identify paleontological areas which would be impacted by the identified hazards, at various degrees of severity (e.g., different earthquake magnitudes, extent of mass wasting events, extent of glacial advance or retreat, etc.).

Because this vital sign requires higher costs and professional support to monitor, this level of monitoring would only be justified for in situ paleontological resources of substantial significance. The level of technical support would be determined by the type of geohazard.

Discussion

This vital sign is limited to very specific circumstances where a geologic hazard is identified as a potential threat to in situ paleontological resources. Depending on the type of geohazard, the alternative may be the salvage of any surficial fossils which might otherwise be destroyed if the geohazard event occurs.

Land and resource managers must also consider the public safety aspects of local geologic hazards. Any planning should evaluate whether site monitoring would place individuals in an unsafe environment.

Vital Sign 4: Hydrology and Bathymetry

Description

Fossiliferous strata and paleontological resources may occur in areas submerged by or adjacent to either marine or fresh-water resources. These hydrologic resources include oceans, lakes, ponds, reservoirs, hot springs, rivers, and streams. Water levels of these features, and any associated hydrologic processes, may change over time due to fluctuations in precipitation, temperature, winds, tidal patterns, and catastrophic events. Tsunamis, hurricanes, rapid melting of ice due to volcanism, landslides, and other factors may result in tidal surges, abrupt changes in wave patterns and intensity, flooding, and other significant hydrologic events.

The stability of in situ fossils located in areas submerged by or adjacent to hydrologic resources is influenced by changes in water levels and forces associated with the movement of water. Therefore, fossils which occur along marine coastlines, lakeshores, riverbanks, and similar areas are threatened by hydrologic processes and events. Human activities may also influence water levels and forces, especially the construction of dams. Changes in water levels may result in the emergence or submergence of fossils. Hydrologic processes contribute to changes in the rates of sedimentation and erosion, therefore leading to the exposure of fossils and influencing their stability at the surface. Monitoring changes in water level, bathymetry, or other hydrologic variables at fossil sites will enable land and resource managers to better determine how frequently to schedule site condition assessments or cyclic prospecting.

Methods

Level 1: Repeat Photography. The stability of in situ paleontological resources in areas submerged by or adjacent to marine and fresh-water resources can be assessed using repeat photography. Each fossil site identified through field inventories should be spatially defined, mapped, and photographed. Photo points must be established for both large-scale and small-scale repeat photography so that consistent points of reference and perspectives are available.

Whenever possible, records of high and low water levels should be maintained for water resources which are associated with in situ fossil sites. The schedule or frequency of the repeat photography should be determined based upon site specific variables including short and long term changes in water levels and hydrologic processes. Any observable impacts to the fossils should be documented and photographed during periods of above- or below-normal water levels.

All photographs should be maintained in a secure archival storage facility. Each photograph should be labeled with the site name or number, photo point identifier, date of photograph, and name of photographer. Additional site data, such as stratigraphic, taxonomic, or historical information, should be maintained in an associated file or database.

Repeat photography is a low-cost and low-technology approach to monitoring paleontological sites over time. This photography could be undertaken by a trained volunteer. Photos enable the documentation of observable changes in stability at each site, and the fossils exposed at the surface. This level of information may also enhance resource management and scientific decisions, such as the frequency of cyclic prospecting or stabilization of the site.

Level 2: Digital Mapping. Fossiliferous strata and stability of in situ paleontological resources are monitored through the development of a digital map (GIS) integrating spatial fossil and shoreline data. High and low water events are recorded and areas where fossils are submerged or emerged are documented. Emergent areas should be assessed and documented during low water periods for exposure of previously submerged paleontological resources. Areas should also be assessed after high water periods for accelerated erosion, landslides, or sediment burial. This data can be used to determine which fossil sites are more susceptible to the impacts of changes in water levels and hydrologic processes.

This level of monitoring requires moderate levels of funding and support, and a trained technician who specializes in geographic information systems.

Level 3: Technology-Enhanced Monitoring. Fossiliferous strata and stability of in situ paleontological resources are monitored with technology-enhanced monitoring equipment. Hydrologic monitors (tidal gauges or flow meters) are established to record changes in water depth and velocity. A predictive model and maps through GIS are then developed to identify paleontological areas which would become submerged or emerged at different water levels. Data from the hydrologic monitoring equipment and the predictive model are used to establish management prescriptions for paleontological sites adjacent to bodies of water. Monitoring data can be used to determine which sites are more susceptible to the impacts of changes in water levels and hydrologic processes.

This method is a relatively high-cost approach to monitoring paleontological localities. The periodic measurements and evaluation of data require a professional geologist and someone trained in the use of the specific technology employed in the monitoring. The data from the technology-enhanced monitoring equipment will enable documentation of measurable changes in stability at each site, and fossils exposed at the surface or submerged beneath water. This level of information may also enhance resource management and scientific decisions, such as the frequency of cyclic prospecting or stabilization of the site.

Discussion

This vital sign is specifically designed for paleontological resources directly associated with water resources. The types of monitoring equipment employed will depend upon whether the objective is to measure changes in water levels or changes in the energy or velocity of moving water. Sometimes watercraft may be needed to conduct site monitoring. Land and resource managers must also consider the public safety aspects of any work in or near water. All planning should evaluate whether site monitoring would place individuals in an unsafe environment. Appropriate water safety training and equipment should be utilized.

Water levels in dam-controlled reservoirs can vary daily, sometimes on a set schedule. The Army Corps of Engineers, U.S. Bureau of Reclamation, and other offices record daily water level for major reservoirs in the United States. This information is generally available online.

Vital Sign 5: Human Impacts

Description

The stability of in situ paleontological resources may be directly associated with human related variables. Public access to fossil sites may increase the potential for either intentional or unintentional impacts. Further, the types of activities and behaviors engaged in by humans may pose significant threats to fossils. Human activities can have both large-scale and small-scale effects on continental erosion and sedimentation (Wilkinson and McElroy, 2007).

The types of human activities permitted on public lands are a function of the laws, regulations, and mission of the respective land managing agency. Certain federal or state land managing agencies may support human activities such as agriculture, forestry, oil and gas development, surface/subsurface mining, and the use of off-road all-terrain vehicles (ATVs). These types of human activities can have direct and significant impacts on the stability of in situ fossils.

In addition to human activities that may be legally permitted, unauthorized activities may also threaten and contribute to the loss of fossils. Theft and vandalism of paleontological resources has been documented at greater frequency on public lands. The unauthorized collecting of fossils ranges from casual souvenir gathering to intensive, systematic collection. An escalating commercial market for fossils may be responsible for the increasing number of incidents of fossil theft documented on public lands.

Given the potential for human impact, monitoring public use would enhance land and resource manager's ability to make informed decisions related to management of fossil sites. Monitoring public use may help determine the scheduling of site condition assessments or cyclic prospecting.

Methods

Level 1: Repeat Photography. The stability of in situ fossils present in developed visitor use areas (e.g., trails, buildings, roads, parking areas, etc.) or areas where future development or construction is planned is monitored using repeat photography. The types of visitor behaviors and activities are documented. Evidence of adverse impacts to paleontological resources through each type of visitor behavior or activity (increased erosion, damage to fossils, theft, vandalism), should also be observed and documented. Each site should be spatially defined, mapped, and photographed. Photo points must be established for both large-scale and small-scale repeat photography so that consistent points of reference and perspectives are available.

Whenever possible, changes in public access and activities should be measured and monitored relative to potential impacts to associated in situ fossils. The schedule or frequency of the repeat photography should be determined based upon site-specific variables, including short- and long-term changes in public use patterns. Any observable impacts on paleontological resources should be documented and photographed in areas where human activities increase or change.

All photographs should be maintained in a secure archival storage facility. Each photograph should be labeled with the site name or number, photo point identifier, date of photograph, and name of photographer. Additional site data, such as stratigraphic, taxonomic, or historical information, should be maintained in an associated file or database.

Repeat photography is a low-cost and low-technology approach to monitoring paleontological sites over time. This photography could be undertaken by a trained volunteer. Photos enable the documentation of observable changes in stability at each site and the fossils exposed at the surface. This level of information may also enhance resource management and

scientific decisions, such as the frequency of cyclic prospecting or stabilization of the site.

Level 2: Digital Mapping. Fossiliferous strata and the stability of in situ fossils should be monitored through the development of digital maps (GIS) which integrate public use data. Areas with the highest public use should be identified, and monitoring prescriptions developed accordingly. Further, digital maps (GIS) should be developed which integrate spatial fossil site data and visitor activity areas. Evidence of adverse impacts from each type of visitor behavior or activity should be observed, documented, and recorded as metadata. Areas where visitor behaviors and activities directly impact in situ paleontological resources should be determined and monitored appropriately.

Impacts of existing or future land use on paleontological resources should be assessed, and recommendations to mitigate possible threats provided. Monitoring data can be used to determine which sites are more susceptible to changes in public use patterns or human activity. This level of monitoring requires moderate levels of funding and a trained technician who specializes in geographic information systems.

Level 3: Technology-Enhanced Monitoring of Public Use. At this level, photographic or video surveillance equipment is installed, with increased frequency at sites experiencing high levels of visitor use. Impacts of future public use patterns on paleontological resources can be assessed and alternatives presented which enhance the protection of susceptible fossils.

A predictive model and maps can be developed through GIS to identify paleontological areas which would be most heavily impacted by increases or changes in public use. Data from the public use monitoring equipment and the predictive model can be used to establish management prescriptions for paleontological sites most impacted by human activities. Monitoring data can be used to determine which fossil sites are most susceptible to the impacts of changes in public use.

Technology-enhanced monitoring is a relatively high-cost approach to monitoring fossil sites. The measurements and evaluation of data require a professional geologist and someone trained in the use of the specific technology employed in the monitoring. The data from the technology-enhanced monitoring equipment will, over time, enable documentation of measurable changes in the stability at each site. This information may also enhance resource management and scientific decision making about a fossil site, such as the frequency of cyclic prospecting or stabilization.

Discussion

The management of public use and activities undertaken by humans is often accomplished at the regulatory level for respective land managing agencies. Some agencies operate under more resource preservation mandates, while other agencies support a broader range of multiple-use activities. Balancing resource stewardship and public use is often the subject of healthy philosophical and legal debate.

Federal and state land managing agencies have evolved over recent decades to consider and recognize the importance of the stewardship of nonrenewable paleontological resources. Federal agencies engaged in ground-disturbing activities which may impact in situ fossils are required to undergo an environmental review process under the guidance of the National Environmental Policy Act (NEPA, 1969) and Section 106 of the National Historic Preservation Act (NHPA, 1966).

Land managing agencies involved in some type of developmental planning must initiate environmental compliance review of the proposed project. A few examples of projects requiring environmental compliance review include: construction of new roads or trails; oil and gas development (Santucci, 2000; Santucci, et al., 2001a); surface/subsurface mining; timber harvesting; and agricultural development. During the compliance review, comments are solicited from professional scientists, engineers, historians, and other stakeholders, as well as the public at large, so that all interests may be considered.

Land managing agencies also evaluate the effects of public recreational use on resources. The use of ATVs, snowmobiles, and other recreational vehicles may significantly impact cultural and natural resources, including in situ fossils. Land managing agencies consider legislation, regulations, and public interests in the development of policies that relate to recreational use on public lands.

In areas designated as "wilderness," public use limits are generally established by law and careful planning by land and resource managers. Wilderness areas prohibit the development of roads and structures, restrict the use of motorized vehicles, and often manage the numbers of visitors through a permit system. Therefore, in situ paleontological resources within wilderness areas typically do not face the same level of human-related threats as those on other public lands.

Depending on the levels of public access and the types of human activities in paleontological resource areas, the impacts to in situ fossils may range from negligible to significant. The types of monitoring equipment employed for measuring any human impact will be dependent on site-specific variables and conditions.

It is also important to consider the loss of fossils through theft and vandalism. Santucci (2002, 2006) provides an assessment of illegal activities which have resulted in either the loss or destruction of in situ fossils on public lands. Surface exposures of petrified wood, dinosaur trackways, and other paleontological resources are often managed in situ to support scientific and public educational goals. Informal monitoring has consistently shown evidence of unauthorized collection of these fossils.

At Petrified Forest National Park, Arizona, the illegal collection of souvenir petrified wood by the public has been recognized for over one hundred years. Photographs of the petrified wood deposits taken during the 1930s can be compared to similar photographs today (Fig. 6). This repeat photography shows areas of the park which have been essentially depleted of petrified wood.

In some areas, such as Petrified Forest National Park, where intensive illegal collecting of in situ fossils has been documented over long periods of time, social science studies have been



Figure 6. This photo pair from Petrified Forest National Park illustrates the use of long-term repeat photodocumentation to document the primarily human stressors and threats to the park's primary resource. Photo on the left is from 1932, photo on the right is from 2002. National Park Service photos courtesy T. Scott Williams.

undertaken to assess this behavior. In these social science studies, researchers evaluate visitor attitudes and perceptions and their relationship to behaviors which may affect the stability of in situ fossils (Williams et al., 1993; Hockett and Roggenbuck, 2002, 2003). Land and resource managers may utilize data from these social science studies to establish targeted monitoring prescriptions for areas where visitor behavior and activity adversely impact paleontological resources.

STUDY DESIGN

Paleontological resource monitoring is distinctly different from other types of geological resource monitoring. As nonrenewable resources which preserve the remains of life in a geologic context, there are scientific, intellectual, and legal reasons for monitoring fossils. As discussed above, there are both natural and human related variables which threaten the stability of in situ fossils.

Once the destructive agents act upon in situ fossils, observable and sometimes measurable outcomes occur. The changes in fossilized remains may be gradual or abrupt, resulting in breakage, fragmentation, crumbling, shatter, scatter, dislodge, transport, disintegration, and even complete loss. These changes diminish the scientific and educational values of paleontological resources. Further, the concept of "limits of acceptable change" is not applicable to the management of nonrenewable resources such as fossils.

The five vital signs proposed for monitoring in situ fossils are designed to focus on those variables which most directly influence the stability (or health) of fossils within a geologic context (Table 1). Monitoring paleontological resources through the use of one or more of the vital signs will enable land and resource managers to identify those stressors, threats, and variables which have the greatest impacts upon the stability of in situ fossils. This data will enhance management's ability to target the most appropriate mitigation strategies and to establish the frequency of periodic condition assessments based upon site-specific variables.

The use of high resolution photography, photogrammetry, or other methods of photodocumentation is perhaps the most universally valuable approach for monitoring in situ fossil sites. Some parks have historic photos nearly 100 years old which depict recognizable fossils which still exist in situ. For example, photographs taken in the late 1800s and early 1900s depict some of the standing petrified stumps along Specimen Ridge in Yellowstone National Park. These prominent features were even featured in postcards produced between 1900 and 1910. Some of the standing stumps featured in the early photos are still present today in the park (Fig. 7). Past and present photographic monitoring of these standing stumps over the past 100 years provides a wonderful record to measure observable short-term and long-term changes to these in situ resources.

During the process of determining which vital signs might be appropriate for monitoring, land and resource managers should review any and all existing paleontological resource inventory data available. The inventory data should provide baseline information which may contribute to successfully determining the existing variables, conditions, and locations where vital signs monitoring may be most valuable. The selection of vital signs should consider such variables as erosion rates, climatic conditions, proximity to active geohazards, changes in water levels or hydrologic patters, or types of human activities which could adversely impact in situ fossils. This evaluation process can be referred to as the development of a "management prescription for vital signs monitoring of in situ paleontological resources." When developing monitoring prescriptions and strategies, they

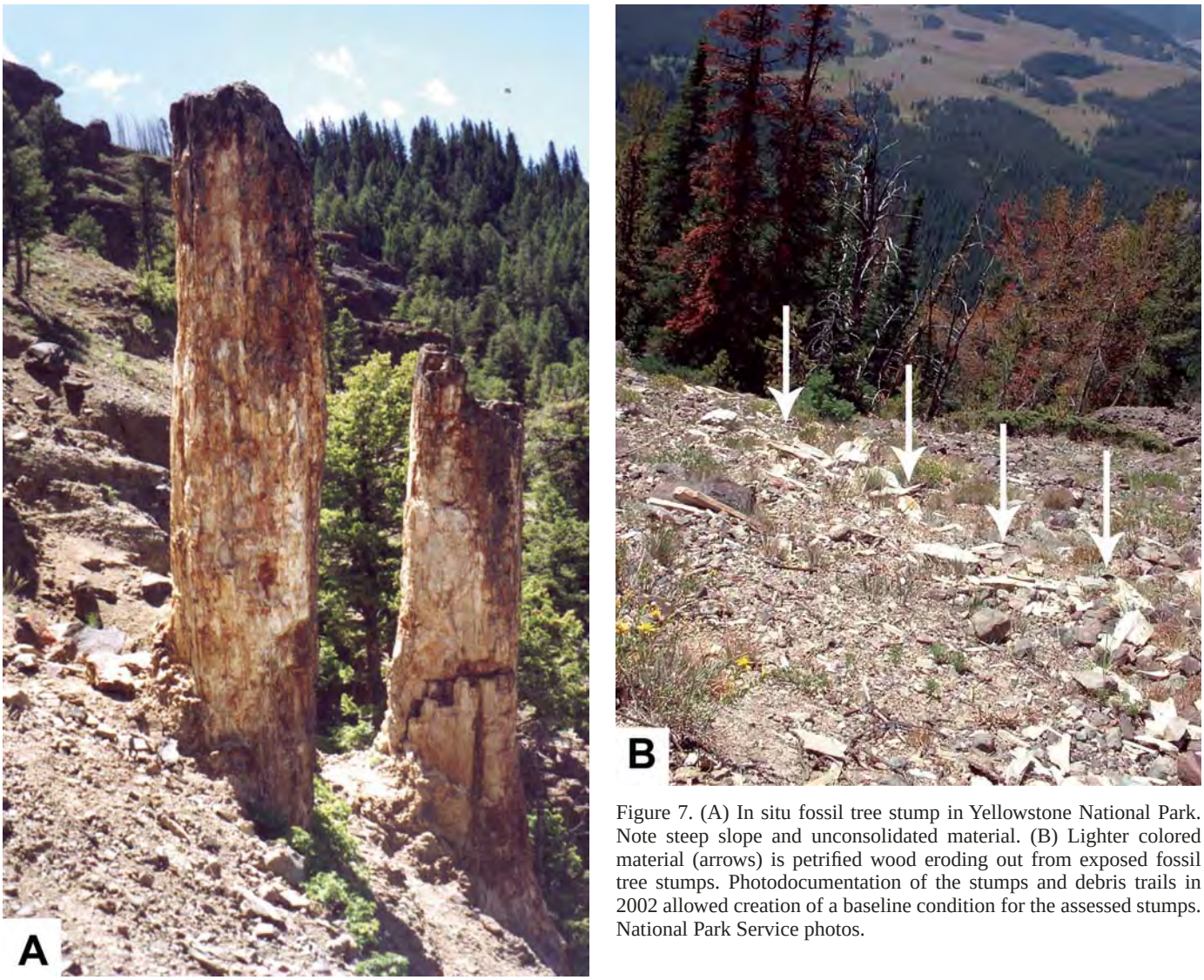


Figure 7. (A) In situ fossil tree stump in Yellowstone National Park. Note steep slope and unconsolidated material. (B) Lighter colored material (arrows) is petrified wood eroding out from exposed fossil tree stumps. Photodocumentation of the stumps and debris trails in 2002 allowed creation of a baseline condition for the assessed stumps. National Park Service photos.

should be consistent with natural resource management policies, such as those outlined for the National Park Service as resource management guidelines, director orders, and management policies (National Park Service, 2001, 2004, 2006).

During the selection and prioritization of sites to include in vital signs monitoring, sites which are the most sensitive or experience the greatest threats would likely be assigned a higher priority. The number of sites to begin monitoring should initially be limited to one or two of highest priority. This will enable staff to learn and become efficient with the methods, and assess funding and equipment needs. Land and resource managers can develop their monitoring skills during the first few years, and then refine them.

Finally, it is worth mentioning that vital signs monitoring is designed to provide land and resource managers with data relative to variables which threaten in situ fossils. Therefore, data may on occasion indicate resource threats at levels higher or lower than anticipated. In these cases, some management intervention or action may be warranted. These determinations are beyond the scope and intent of this chapter.

CASE HISTORIES

The science of paleontology has focused very little attention on the monitoring of in situ fossil sites, as evidenced by the general lack of scientific literature focusing on this issue. Similarly, monitoring strategies and management prescriptions for the long-term assessment of fossil sites are rarely employed by land and resources managers. Despite the paucity of rigorous efforts in long-term monitoring of in situ paleontological resources, a few case studies present lessons learned which contribute to this discussion: Fremd, (1992); Kunzman, et al. (1993); Fremd (1995); Nyborg and Santucci (1999); Koch, et al. (2002); DeBlieux, et al. (2003); Santucci and Koch (2003); and Vissagi, et al. (2005).

Yellowstone National Park: Rates of Erosion—Photo Monitoring

The petrified forests of Yellowstone National Park are frequently located on very steep slopes in poorly consolidated volcaniclastic deposits (Fig. 7A). These conditions create a highly erosive environment, evidenced by the down-slope "trail" of fossil wood fragments associated with many of the in situ stumps (Fig. 7B). The park has historical references and photographs regarding the condition of a few individual stumps. To assess rates of erosion and impacts, the stumps in historical records and photographs were located, captured by GPS, and photographed during field work in 2002. Additional stumps were also identified and inventoried. This photo record created a baseline condition for comparison with subsequent site visits and photographs, allowing resource managers to see changes over time and undertake appropriate management prescriptions.

Fossil Butte National Monument: Rates of Erosion—Monitoring Stakes

The highly erosive Wasatch Formation exposures within Fossil Butte National Monument contain a wide variety of fragmented terrestrial fossils. Because the rates of erosion and subsequent exposure and loss of fossil material are not well understood, the park initiated a multifaceted approach to study erosion rates. The park established a monitoring program incorporating many different vital signs, including the freeze-thaw index and the installation, photography, and GPS positions of erosion monitoring stakes (Fig. 5). Fossil Butte also adopted a procedure in which all fossil material exposed at the surface was located by GPS and collected. These sites are revisited as time and personnel permit. All new material continues to be located by GPS and collected. By comparing initial fossil densities to subsequent collections, a proper collecting cycle can be adopted. The abundance of new material in some areas suggests that a 2–3-year cycle is required, while the paucity of material at most sites suggests that their reexamination is only needed once every 5 to 10 years.

Hagerman Fossil Beds National Monument: Geohazards—Landslides

Landslides in the fossil-rich, but very unstable, Glenns Ferry Formation are a significant threat to paleontological resources within Hagerman Fossil Beds National Monument. More than a dozen landslides have occurred within the park over the past 25 years, some of which have led to the destruction of paleontological sites and in situ fossil material. Leakage from extensive irrigation in the area has fed perched artificial aquifers, believed by hydrologists to be triggers of slope failure. Park staff and an international team of hydrologists, geologists, and landslide specialists continue to intensively study and monitor the ongoing landslide and groundwater activity. Because of the slope instability, the need for increased documentation and monitoring of known paleontological sites is warranted. The park's current paleontological monitoring plan addresses these issues along with the safety of personnel working in such unstable sediments.

Curecanti National Recreation Area: Hydrology and Bathymetry

An assessment of in situ paleontological resources at Curecanti National Recreation Area began in the summer of 2005. Wave action, temperature fluctuations (freeze-thaw index) and human access were identified as significant threats to paleontological resources at the reservoir. In response, the park began to collect as much identifiable surface material as possible and to implement a cyclic monitoring program to determine the rates at which new fossil material is being exposed. As of October 2005, material from at least one threatened site has been collected and identified. In 2006, in response to a technical assistance request to the National Park Service Geologic Resources Division, the park initiated photo monitoring at a number of sites to better document the exposure of new fossil remains, or the impacts on previously exposed material. At one beach site, a series of nine reference stakes were installed at regular intervals above the reservoir's high water cutbank. These GPS-referenced stakes were numbered and photo-documented (Fig. 8). Park staff then measured the distance and bearing from the nearest stake to five significant fossils or landmarks at the site (Fig. 9). The location of the reference stakes also provides a datum for documentation of new specimens. When the stakes were installed, the distance between the stake and the cutbank was also measured. Changes in this distance over time may serve as an indicator of local erosion rates. This cost-effective approach is easily duplicated in similar fossil sites and is highly adaptable to local conditions.

Petrified Forest National Park: Human Impacts—Photo Monitoring

The scientifically significant and easily accessible petrified wood deposits at Petrified Forest National Park are considered among the most endangered by resource theft. Unauthorized souvenir collecting of petrified wood is undertaken by many park visitors. The park utilizes a number of different management strategies to combat this loss of petrified wood, including photographic monitoring. A pilot project initiated in the early 1990s established monitoring plots in areas of varying public accessibility. The plots were photographed and the amount of fossil wood was determined within each plot. Subsequent monitoring of the plots documented significant levels of petrified wood loss, which was calculated to be consistently greater in areas more accessible to the public. Historical photographs showing some of the more famous petrified wood sites in the park extend back to the 1930s, providing the opportunity to measure and monitor long-term loss of petrified wood (Fig. 6).

The discussions associated with the loss of petrified wood at Petrified Forest National Park often include a reference to the

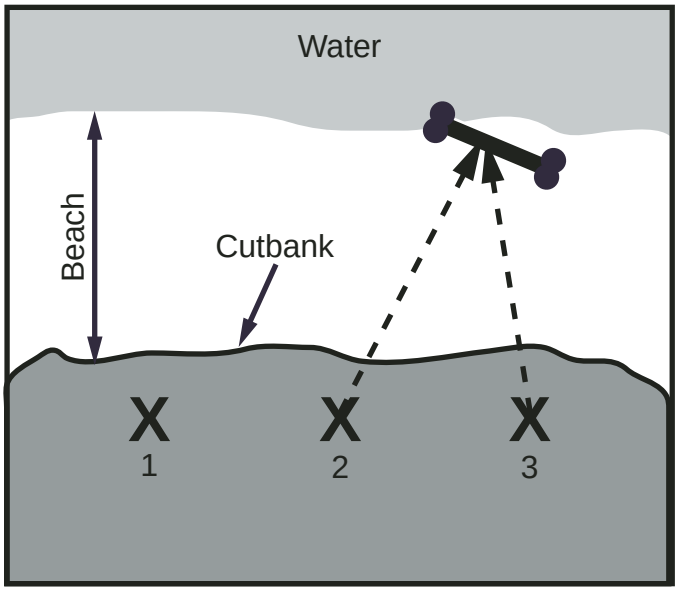


Figure 8. Schematic map illustrating the use of permanent numbered reference stakes (1–3) located above erosional cutbank of a water body. These stakes provide a GIS-based datum for photodocumentation and location of slabs containing paleontological resources below the cutbank. Headings and distance (dashed arrows) from reference stakes to fossils provide location control and are repeated periodically. Distance from each stake to cutbank is also measured and monitored to assess local erosion rates.



Figure 9. Measurement and installation of reference stakes (immediately behind left foot) at Curecanti National Recreation Area in 2006. Note measuring tape. These reference stakes, located above the eroded cutbank, provide a datum for photodocumentation and location of paleontological resources periodically inundated by the Blue Mesa Reservoir. National Park Service photo.

story of Fossil Cycad National Monument. Despite the fact that this important fossil site was established as a national monument in 1922, the lack of resource monitoring at the site and years of unauthorized collecting led to a nearly complete loss of the fossil cycads (Santucci and Hughes, 1998). The mismanagement and loss of these resources at Fossil Cycad National Monument led Congress to officially abolish the monument in 1957.

CONCLUSIONS

The management of in situ fossils presents many interesting and complex challenges to land and resource managers. The variables associated with the stewardship of nonrenewable paleontological resources, as briefly outlined above, do not generally allow for simple textbook solutions. The vital signs presented here are intended as recommendations to be adopted in part or whole based upon the paleontological site variables, conditions, and the resource management goals. At minimum, this information may generate new thoughts and discussions that could ultimately enhance our ability to manage and protect in situ fossils.

It is essential to recognize that resource management practices should not be designed to impede natural processes. Monitoring strategies should be based upon natural processes and their potential impacts on the stability of in situ paleontological resources. Understanding the natural processes acting upon a fossil site or area will enable the development of more precise, locally focused monitoring prescriptions.

Therefore, monitoring schedules should incorporate the rates at which natural processes and/or human-related activities potentially impact each paleontological site. In turn, site assessments (cyclic monitoring) will be conducted at regular intervals, defined within management prescriptions, to minimize the loss of scientifically significant specimens or information due to natural processes or human factors.

Most of the history of life on Earth has yet to be discovered. Our ability to assess and monitor these nonrenewable and scientifically valuable resources will result in a better understanding of the story of life on our planet.

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Permafrost conditions and processes

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INTRODUCTION

Permafrost and the Rationale for Monitoring

Historical Perspective

Permafrost is ground (soil or rock and included ice and organic material) that remains at or below 0 °C for at least two consecutive years. Permafrost terrain consists of an "active layer" at the surface that freezes and thaws each year, underlain by perennially frozen ground. The top of permafrost is at the base of this active layer. The base of permafrost occurs where the ground temperature rises above 0 °C at depth (Osterkamp and Burn, 2002). In some cases, temperature measurements over a period of two years are required to determine the presence or absence of permafrost. Temperature measurements are also required to determine the status of the permafrost. Permafrost that is warm and/or warming is in danger of thawing.

Approximately 25% of the exposed land area of Earth and ~80% of Alaska are underlain by permafrost. Mountain permafrost occurs at high elevations in western North America and on Mount Washington in New Hampshire. Permafrost has also been found near the summit of Mauna Kea in Hawaii.

Permafrost is a product of cold climates. The first permafrost on earth must have existed prior to or formed coincidentally with the first glaciation, ~2.3 billion years ago. Permafrost occurrences, distribution, and thicknesses must have increased during periods of cold climates and decreased during warm intervals. Permafrost may have disappeared in the Arctic ~50 million years ago. The current permafrost in Alaska appears to have been initiated during the climatic cooling that began ~2.5 million years ago. During the past million years, there is evidence of repeated glaciations at ~100,000-year intervals, and permafrost thicknesses varied significantly in response to them (Osterkamp and Gosink, 1991). The last glacial period ended ~12–14 thousand years ago. About 8–10 thousand years ago, the climate may have been slightly warmer than present. During the last millennium, there was a warm period in the medieval era, followed by a "little ice age." Permafrost is currently responding to the global warming since then.

Global air temperatures have increased since the mid-1800s (Hansen and Lebedev, 1987). Increases in air temperatures have resulted in an increase in permafrost temperatures. However, other climatic factors, especially timing, duration and accumulation history of the annual snow cover and site wetness impact permafrost temperatures. These factors modify the effects of changes in air temperatures (Zhang et al., 1996).

The climatic changes of the past century coupled with recent observations of warming and thawing permafrost have caused concern about the future of permafrost (PCCGR, 1983; McBeath, 1984). Thawing permafrost in natural settings has been observed in Alaska (Osterkamp, 1994, 1995; Osterkamp et al., 1998, 2000; Jorgenson et al., 2001a). Warming of the permafrost has continued into the twenty-first century in Alaska, Europe, Svalbard, Canada, Russia, China, and Mongolia (Phillips et al., 2003). There are increasing reports of thawing permafrost and **thermokarst terrain** (an irregular topography resulting from thawing permafrost containing excess ground ice) in Alaska (Osterkamp et al., 2000; Jorgenson et al., 2001a; Jorgenson and Osterkamp, 2005). Thin permafrost is thawing from the bottom up at some sites (Osterkamp, 2003a; 2005). Ice wedges are thawing in the Alaskan Arctic where temperatures were thought to be too cold for this to happen (Jorgenson et al., 2006).

Global circulation models predict that air temperatures will increase up to 5 °C in the next half century (Maxwell, 1992). Since **continuous permafrost** (a region where permafrost occurs

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everywhere beneath exposed land surfaces) is typically colder than –6 °C, no widespread thawing is expected, although some areas may experience localized thawing, slope instability and ice wedge thawing. **Discontinuous permafrost** (a region where some areas are free of permafrost) and **mountain permafrost** (permafrost existing at high altitudes) at low latitudes are much warmer, so any climatic warming will cause thawing. A warming of just a few degrees would cause most of it to begin thawing. Thawing proceeds from the top downward and, eventually, from the bottom upward. Thawing rates are slow, initially on the order of 0.1 m per year near the surface, and theoretically less than 0.02 m per year at the base (Osterkamp, 1983). Thus, times ranging from decades to millennia are required to thaw discontinuous permafrost.

All of the national parks and preserves on mainland Alaska are at least partially underlain by permafrost. Those south of the Yukon River and on the south side of the Seward Peninsula are underlain by warm, discontinuous permafrost, typically within a few degrees of thawing. Recent sparse measurements indicate that much of it is within a degree of thawing (Osterkamp, 1983; 1994; 2005; 2007). These measurements also show that it has warmed significantly during the last quarter century (Osterkamp and Romanovsky, 1999; Osterkamp, 2003a; Osterkamp, 2005; 2007). Thawing permafrost, landslides, and thermokarst terrain have been observed in and around these parks (Osterkamp et al., 2000; Jorgenson et al., 2001a; Jorgenson et al., 2006). An estimated 100,000 km^2 of mountain permafrost occurs in the contiguous states at elevations as low as 2200 m (Péwé, 1983). Many of the parks in the western United States have mountainous areas with higher elevations. While there is little information available, mountain permafrost in the contiguous states is also thought to be very warm (within a degree or two of thawing). Because ice helps bond slope deposits, landslides and thaw slumps are expected to occur when these areas thaw (Huscroft et al. 2004). In addition, permafrost impedes subsurface drainage, creating wet to moist conditions that provide good habitat for many alpine plant species. Thawing of the permafrost would increase drainage and dry the soil, thus impacting the vegetation.

The combination of the above observations and conditions and the predicted climatic warming of the twenty-first century are cause for concern about the future condition of permafrost in national parks and preserves in Alaska and in the mountains of the contiguous states. Thus, it is important to determine what changes have already occurred, to determine the current status of the permafrost, and to monitor changes that may occur in the future.

Cause for Concern

Why should there be concern for thawing permafrost? Current climatic scenarios predict up to 5 °C of additional warming of the air temperatures in Alaska and the Bering Sea regions over the next century (Weller et al., 1995). At the low end of the predicted warming (2–3 °C), most of the discontinuous permafrost in Alaska would thaw, creating many attendant problems (Osterkamp, 1983; PCCGR, 1983; Nelson et al., 1994; Osterkamp et al., 1998). Thawing of ice-rich permafrost and creation of thermokarst terrain has been identified as one of the primary problems facing northern ecosystems as a result of climatic warming (Osterkamp et al., 2000; Jorgenson et al., 2001a). While smaller changes are predicted for the contiguous states, any warming there would cause some of the mountain permafrost to thaw.

Boreal forests typically cover discontinuous permafrost in interior Alaska below elevations of 700–1000 m. Sparse data around these parks indicates that permafrost there is usually within 1–2 °C of thawing. The edges of isolated permafrost bodies are already at the thawing point. If the observed warming of the permafrost underlying boreal forest ecosystems in Alaska continues, then additional permafrost will thaw. Where the permafrost is ice-rich (roughly 50% ice), thawing changes the ice to water, creating a mud slurry that cannot support the weight of overlying soil or vegetation, thereby degrading the physical foundation of terrestrial ecosystems. The observed effects are that the ground subsides, and landslides and thermokarst terrain develop, consisting of channels, pits, troughs, potholes, ponds, lakes, and "drunken forests" (trees leaning in random directions). In addition to these broad-scale climatic effects, thermokarst terrain can also be produced locally by disturbances associated with fires, floods, and human and animal disturbances.

Thermokarst drastically modifies and remolds the ground surface and alters surface and groundwater hydrology. This process can modify or totally change ecosystems, human activities, infrastructure, and the fluxes of energy, moisture, and gases across the ground surface-air interface. Plant species composition and distribution, plant community productivity, soil chemistry, biological activity, and nutrient supply for plant use can be substantially altered by this geological phenomenon. Drainage conditions determine whether standing water will be present. The affected trees usually die, and vegetation changes significantly (Fig. 1). These changes in the flora have a direct impact on fauna. In lowlands or relatively flat areas, a shift from boreal forests to shrub swamps and wet meadows often occurs with concurrent changes in bird and animal populations (Osterkamp et al., 2000; Jorgenson et al., 2001a, 2006). The new ecosystems often favor aquatic birds and mammals.

Thus, the result of thawing ice-rich permafrost in a boreal forest ecosystem is not just a slight shift in the nature of the ecosystem, but rather partial or total destruction of the ecosystem and replacement with a new ecosystem.

Time scales to create thermokarst terrain are around a decade, but can range from several years to centuries. Time scales for recovery of the ecosystems appear to range from centuries to millennia although, in many cases, recovery may be impossible because of permanent changes in relief, drainage, and other factors.

Need for Monitoring

Although little can be done about the terrestrial and ecological changes associated with natural thermokarst, knowledge about the patterns and processes of thermokarst development



Figure 1. Thermokarst terrain in the Slana River valley northeast of Wrangel–St. Elias National Park and Preserve, Alaska, showing the destruction of this boreal forest ecosystem that previously supported terrestrial birds and mammals (including caribou). It is being converted to wetlands with grasses and shrubs favoring moose and aquatic birds and mammals. Note the trees that are tilted and dying in the upper left background of the photo. The permafrost terrain is "inflated" (heaved upwards) nearly 3 m during permafrost formation due to ice growth. The ground surface then settles or compacts a similar amount during thawing of the ice-rich permafrost. (Photo by T. E. Osterkamp.)

is essential for anticipating the potential impacts and for developing rational responses to them. Detailed observations and measurements of the thermal regimes and physical conditions of the permafrost are needed.

Permafrost conditions in the parks and preserves of Alaska and the mountains of the contiguous states depend on a number of factors. Thus, monitoring sites need to be developed in each park to span the range of conditions found there. Accordingly, this chapter makes recommendations for standard methods for observations and measurements that can be applied across a network of parks to determine what changes have already occurred, document current conditions, and monitor future changes.

STRESSORS AND MONITORING SITE REQUIREMENTS

Factors Influencing Permafrost

Factors that influence permafrost are those that cause its surface and internal temperatures to vary as a result of changes in the energy balance at its surface (including sides and bottom). These factors can include: climate (air temperature, precipitation as rain or snow, wind); physical terrain (topography, slope, aspect); hydrology (surface drainage and site wetness, proximity of nearby water bodies, presence of underground water, flooding); vegetation (shading, insolation, snow interception); geology (soil and rock, geothermal heat flow, tectonic setting); and disturbances (human, animal, fire). These factors operate at different time (days to millennia) and spatial (local to regional) scales. Our primary concern is with changes in permafrost conditions ranging from annual to multi-decadal periods. Consequently, this chapter is concerned with monitoring factors that vary significantly over these time scales. Annual changes in permafrost temperatures are caused primarily by changes in air temperatures, snow cover, site wetness, and disturbances. In terms of spatial scale, monitoring should address detailed changes at the site level, along with remote sensing to quantify changes at landscape and regional scales.

Mapping Permafrost for Site Selection

As an initial step toward establishing a network for monitoring permafrost conditions, it is necessary to understand the permafrost distribution within a given area or park. Information on permafrost distribution at the landscape level (1:100,000 scale) could include: (1) compilation of information from detailed field soil surveys and mapping; (2) photo-interpretation of Landsat images by an expert knowledgeable in interpreting periglacial and thermokarst features; or (3) spatially explicit thermal modeling of ground temperatures. This information can be used for the design of a monitoring network, park planning, and assessment of regional ecosystems.

Detailed field soil and ecological inventories have been completed for three parks in Alaska, and the differing mapping products for these parks provide useful examples of how existing soils information could be used to delineate permafrost. In Denali National Park and Preserve, an ecological landscape unit map was created by the National Resource Conservation Service (Clark and Duffy, 2003) that incorporates attributes for surficial geology, soil thermal regime and permafrost abundance (Fig. 2). This map could be used to identify fine-grained lowland deposits with permafrost that would be at high risk for thermokarst, or coarse-grained, stable upland areas where thermokarst potential is low. Similarly, the ecotype map for the Bering Land Bridge National Preserve (BELA) and Cape Krusenstern National Monument (Jorgenson et al., 2004), and the ecological unit map for the Kobuk portion of the Gates of the Arctic National Park and Preserve (Swanson, 2000, 2001a) have units with closely associated soil taxon and permafrost characteristics. In BELA, Lowland Sedge Fen Meadows and Upland Moist Dwarf Birch–Tussock Shrub ecotypes usually are associated with ice-rich permafrost, while the Alpine Alkaline Dry Barrens and Riverine Barrens usually have ice-poor permafrost.

While landscape-level soil mapping for Denali included a specific attribute for permafrost abundance, standard soil maps also are useful because of the incorporation of permafrost soils in the soil taxonomy (NRCS, 2003). When using soil maps, there are certain terms to look for. The **Gelisol order** is specific to permafrost soils that have permafrost within one meter of the soil surface, or permafrost within two meters of the soil surface if the top meter shows evidence of cryoturbation. Some groups (e.g., **Hemic Glacistels**) are specific to extremely ice-rich soils. In

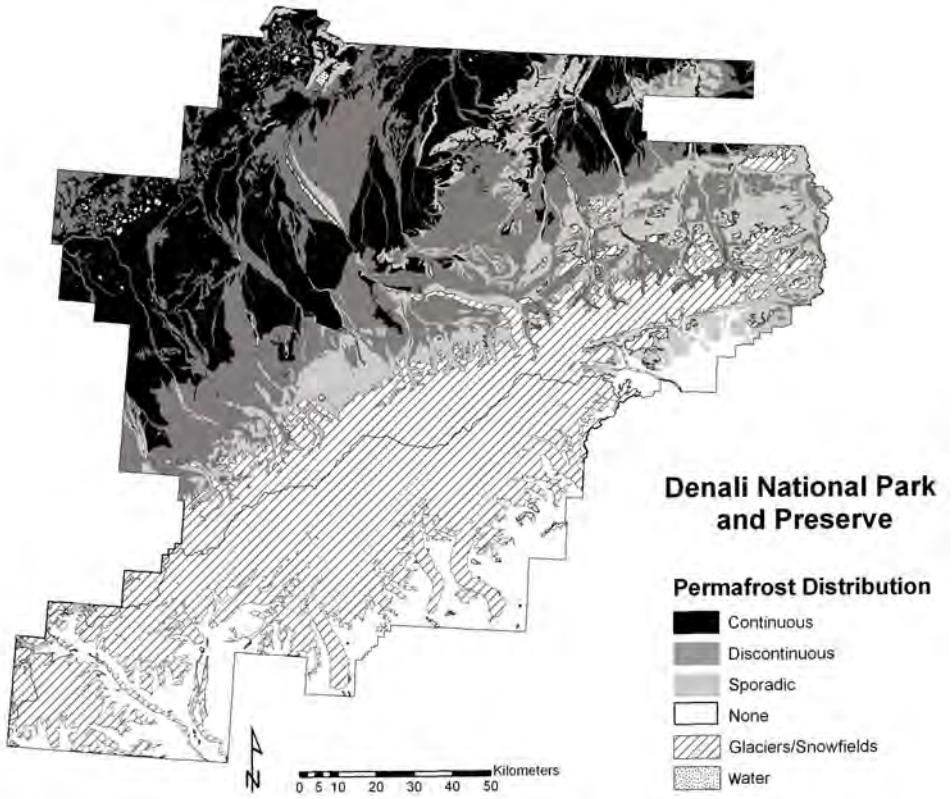


Figure 2. Map of permafrost distribution in Denali National Park and Preserve based on the soil survey of the park (adapted from Clark and Duffy 2003).

addition, the **Gelepts** suborder within the **Inceptisols** differentiates soils that have permafrost below 2 m. These tend to occur in ice-poor rocky soils in alpine areas.

If permafrost information is not available from field surveys, a reconnaissance-level map of permafrost can be developed from interpretation of satellite images or small-scale aerial photography. Methods are well developed for relating permafrost characteristics to landforms and surficial deposits (Stoeckler, 1949; Frost et al., 1973; Brown and Péwé, 1973; Crampton and Rutter, 1973; Ferrians and Hobson, 1973; Zoltai and Pettapiece, 1973; Thie, 1974; Péwé, 1975; Kreig and Reger, 1982; Brown et al., 1997; Camill, 1999; Jorgenson et al., 1999). A more probabilistic approach has recently been used to develop vegetation-soil-permafrost associations for areas in central Alaska (Jorgenson et al., 1999, 2001b). This mapping approach is most reliable in lowland areas with fine-grained soils where periglacial and thermokarst features tend to be well developed. In contrast, the reliability of photo-interpretation is poor for rocky upland and subalpine areas where information on the thermal status is sparse. Recent subsection-level mapping of ecological units for national parks can also serve as the basis for generalized permafrost maps, using the characteristics provided in the map unit descriptions (Swanson, 2001b; Jorgenson, 2001; Clark and Duffy, 2003).

Modeling is another approach that can be used to predict permafrost distribution. The modeling can employ simple index models based primarily on air temperatures (Nelson, 1986; Anisimov and Nelson, 1996) or more data-intensive models that also incorporate topography, soils, vegetation, and snow (Jorgenson and Kreig, 1988; Wright et al., 2000; Jorgenson et al., 2003). The modeling is particularly helpful for hilly or mountainous terrain. Accurate modeling, however, is dependent on site-specific parameterization of these thermal characteristics. In addition, groundwater is an important factor affecting the distribution of permafrost in the discontinuous permafrost zone, but this is absent from current modeling approaches.

Desirable Site Conditions

Preliminary selection of monitoring sites can be done using existing information such as soil surveys, topographic and surficial geology maps, satellite images, and aerial photographs. However, at least two field trips to proposed major sites (those where multiple observation and measurement methods will be employed) should be made during summer and near the time of maximum snow thickness to determine site conditions and select the precise location of the site. The site conditions discussed below are specific to permafrost observatories (including boreholes) designed to study the effects of climate change on permafrost and thermokarst terrain. Some of the conditions are chosen to make data acquisition and analyses easier for the investigator, such as accessibility and terrain. Sites for thermokarst studies must be selected where thermokarst exists. However, requirements can vary depending on whether the site is for thermal monitoring in

deep boreholes, where uniform characteristics are desired, or for thermal and physical monitoring along long transects, where a range of ecological conditions is preferred.

Existence of permafrost. Obviously, permafrost should exist at the site. This can be hard to determine where there are substantial areas with no permafrost or where rocky soils make probing or drilling difficult. In some cases, probing and/or temperature measurements may be necessary to confirm whether or not permafrost exists at a site.

Access. Good access is preferable for intensive monitoring sites, due to the high costs of helicopter or airplane access. This usually dictates placing sites near existing road or trail systems, or in areas that can be reached during winter with over-the-snow transport systems.

Availability of long-term climate data. It is desirable to have major sites near a long-term weather station. The availability of climatological data supplements the site measurements and, after a few years, the measurements can be used to conduct site-specific calibrations of models. Past climatological data can then be used to drive the calibrated models to calculate realistic values for active layer and permafrost conditions for the period of record (Osterkamp and Romanovsky, 1999). The calibrated models can also be used to project permafrost conditions into the future using climate scenarios produced by global climate models.

Terrain. For ease of interpretation and to maximize the usefulness of the data, it is desirable to place sites for deep borehole monitoring in relatively flat, undisturbed terrain (as determined from aerial photographs and topographic maps). The surrounding area should be relatively flat to a distance of at least three times the depth of the hole. However, if the only purpose of the site is to determine change, then sites on slopes and ridges and in hilly terrain can be utilized. For measurements of shallow ground temperatures and physical characteristics, terrain with a range of ecological characteristics is preferable.

Snow cover. The most desirable borehole sites are those where snow cover is relatively uniform and where drifting is not a major consideration. Along transects, snow cover can be expected to vary.

Hydrology. Borehole monitoring sites should be placed far from the influence of water bodies, springs, potential groundwater flow, floods, icings, and areas of unusual ground wetness caused by surface drainage. Seeps can be identified during summer, and icings will be obvious during spring. For physical monitoring along transects, groundwater and surface water can be expected to vary as thermokarst develops.

Geology. Geothermal heat flow and the soil or rock in the vicinity of a deep borehole site should be relatively uniform. This rules out areas with sharp topographical changes and makes those near active volcanoes or mud volcanoes suspect. Variation of soil and surficial deposits along transects is preferable. Locating transects on bedrock is not appropriate.

Vegetation. Areas that have uniform conditions on the surface and in the sub-surface are the most desirable for borehole monitoring. Thus, boundaries between ecosystems, forest edges, and any sharp changes in vegetation should be avoided. Burned areas should also be avoided, except in thermokarst studies. Variations in ecological characteristics along a transect are preferred.

Security. It is necessary that the study sites be secure from human intrusion and disturbance over long time periods (preferably a century or more). This helps to ensure that the sites will remain pristine so that observed changes can be attributed to natural events.

Impacts on Ecosystems

Permafrost in Alaska and mountain permafrost in the contiguous states forms the physical foundation on which terrestrial ecosystems and infrastructure rest. Where the permafrost is ice-rich, the potential problems associated with thawing are illustrated in Figures 1, 4, 5, and 8. Mountain permafrost exists in alpine ecosystems, and the primary problems there are associated with slope instability caused by thawing permafrost (thaw slumps, landslides, rockfalls), thaw settlement (thermokarst), loss of the impermeable layer that impedes drainage in moist to wet ecosystems, and damage to infrastructure. Thus, there are both economic and ecological reasons to monitor permafrost, including mountain permafrost.

VITAL SIGNS MONITORING DESCRIPTIONS

The vital signs (thermal and physical states of permafrost) and study methods discussed below were selected to answer critical questions about the influence of thawing permafrost on ecosystems under a climate-warming scenario. Progression is from simple to more complex methods of study. Only a few methods are described, but several may be available in the literature. Complex and expensive geophysical (Brown, 1985) or remote sensing methods are avoided because they are not practical for widespread, routine monitoring. It is highly recommended that an expert in permafrost studies be made part of any monitoring team from the beginning to provide advice, training, help with the experimental design, and help with the many facets of site selection.

Thermal State

Permafrost is defined by its temperature, which determines its physical condition. The phase equilibrium temperature (0 °C) is critical because warmer ground cannot contain permafrost. The mean surface temperature is of primary interest, since this is the surface boundary condition that influences future thermal states. If the surface temperature warms and stays warm for a long time, the warming will penetrate slowly downward until it reaches the base of the permafrost, whereupon thawing will begin there. Permafrost with mean surface temperature colder than –3 °C is not in immediate danger of thawing. However, under warming climatic conditions, permafrost within a degree or two of thawing may soon begin to do so. Monitoring the full temperature profile of a deep borehole and the corresponding surface temperature

history can tell us if the permafrost is warming or cooling, if it is in danger of thawing, if it is thawing, and the rate of thawing at its surface and base (Osterkamp, 2008).

Level 1. Determination of Frozen or Thawed State

A first step in studying permafrost is to determine its presence or absence and its distribution in the park. Initially, soil survey maps, reconnaissance permafrost maps, or spatial modeling should be used to identify areas where permafrost is likely. Field work to confirm the presence of permafrost is done by physically probing the ground with a handheld probe to determine the presence and depth to an underlying frozen layer (permafrost surface). The presence of permafrost is inferred when the probe strikes a hard surface. This can be uncertain in areas with gravel, rock, or hard subsurface layers, or where the permafrost table is deep; thus, a temperature measurement may be required. The presence of permafrost can also be confirmed, where it is shallow, by digging a pit and visually confirming the presence of ice in the soil in late summer. Generally, it is desirable to make temperature measurements at a few selected points to positively establish the presence of permafrost. When coupled with a temperature measurement made at the top of the hard surface, probing in late summer gives the depth to the permafrost surface (**active layer thickness**). The depth to the top of permafrost in saturated soils is typically less than one meter, although it may reach several meters in coarse dry soils or rock.

Probing is usually done once a year, in late summer or early fall, near the end of the thaw season and just before the time that decreasing ground surface temperatures reach 0 °C. Only one person is necessary, although two are desirable since removing probes from the soil can be strenuous. A tile probe is used, which many researchers fabricate out of metal rod. The tip of the rod should be slightly larger than the shaft to facilitate insertion and removal. In practice, the probe is pushed into the soil using the weight of the observer. Downward motion ceases when the tip reaches the permafrost surface. It may be useful to raise the probe a few centimeters and thrust the tip downward again. Hitting frozen soil makes a dull thud, while rock makes a distinct clinking sound. The depth is then recorded to the nearest centimeter and the probe removed. The error in the measurement is usually a few centimeters, partly because of compressible vegetation at the surface and also because of the potential presence of a somewhat "soft" (partially frozen) layer near the permafrost surface that contains unfrozen water and ice. For areas where the permafrost has already thawed, extensions can be added to the tile probe to reach depths of 3 m or more. This is more difficult and requires two people to push and retract the probe. Alternatively, a probe powered by a mechanical driver can be used (Esch, 1982). In cases where permafrost is not found, the observer should record the maximum depth of probing.

A hollow probe may be used to remove uncertainty about the presence or absence of permafrost. Once the maximum depth of penetration has been reached, a temperature sensor (usually a thermistor on the end of a wire attached to a commercial readout) can be lowered inside the rod to the tip. The temperature is then recorded to the nearest 0.1 °C. Alternatively, the probe could be removed and a commercial soil temperature probe inserted to the bottom of the hole. This temperature should be close to 0 °C, unless salts are present that lower the phase equilibrium temperature at the permafrost surface. If desired, a transect can be made by probing at intervals along a tape measure laid on the ground. The recorded data (date, time, location, vegetation, soil type, depth of permafrost, and temperature if measured) need little interpretation. A simple graph of location versus depth to permafrost provides a visual image of the permafrost surface.

The equipment required consists of a probe, tape measure, a method of determining position (e.g., a long tape), and a method for measuring temperature. If the same site is to be probed annually, then a method for returning there needs to be established, such as stakes driven into the ground, or a borehole pipe as a bench mark. Geographical coordinates should be measured for all reference markers with a Global Positioning System (GPS).

The level of expertise required is that of a trained Student Conservation Association member (SCA) or volunteer. On-site training by a scientist (half a day, one time only) is needed. A soil probe and a temperature measuring device would be required. Costs would be low (less than $1,000; all amounts herein in US$) unless a mechanically powered probe was needed and had to be fabricated. A 100 m line, or ~50 points, could be probed in about half a day. Data reduction, graphics, and archiving requires a scientist for about half a day.

Level 2. Permafrost Surface Temperature

The surface temperature history of permafrost is the upper boundary condition that plays a major role in determining its internal temperatures. Surface temperatures can be measured using relatively simple and inexpensive dataloggers about the size of a match box or cigar. These loggers, which have an accuracy of 0.5 °C or better, are placed near the permafrost surface and programmed to measure temperatures every 2–4 hours. While some dataloggers can be left in place for several years without replacing batteries or retrieving data, the usual procedure is to return once a year in summer to retrieve the data and replace batteries.

The access hole for the dataloggers has to be big enough for the casing in which the logger is to be placed, and should penetrate ~0.3–0.4 m into the permafrost. In fine-grained soils, the hole can be drilled by hand with a soil auger. However, if soils are coarse or the permafrost surface is deep, this can be difficult, and a gasoline powered soil auger should be used. In some cases, this method cannot be used because of difficulties with soil and rock conditions or because the permafrost surface is too deep. An alternative method involves driving a hollow probe to the permafrost surface, leaving it permanently in place, and inserting a temperature sensor attached to a datalogger (Osterkamp and Harrison, 1982).

Care should be taken to keep the site pristine. This can be done by drilling through a thin piece of plywood (or a very stiff tarp) large enough to stand on, so that the cuttings are deposited onto the plywood. This way, the vegetative mat around the hole is not severely compressed, soiled or torn.

A casing consisting of thin-walled metal tubing or plastic pipe is then installed in the hole (Fig. 3) with the top extending a few tenths of a meter above the ground surface. Cuttings from the hole are used to backfill around the casing. Backfilling should be done slowly and carefully to prevent any air gaps around the casing. Tamping with a small rod is helpful. It is important to provide a flange or cap at the bottom of the casing (Fig. 3) to seal it and to prevent it from being heaved out of the ground during freezing of the active layer.

After it has been prepared according to manufacturer's directions, the logger is suspended inside the casing ~0.2–0.3 m below the surface of the permafrost on the end of a wooden rod or wire. The purpose of the rod is to prevent air convection in the casing. If a wire is used, pipe insulation that fills the casing should be placed between the logger and top of the casing. A removable waterproof cap should be placed on top of the casing. Water leaking into the casing will freeze the logger into the casing. When the annual data are retrieved, it is processed according to manufacturer's instructions and usually displayed graphically.

An alternative is to use a multi-channel datalogger to measure both the ground (5 cm depth) and permafrost surface (typically 1 m depth) temperatures. The permafrost surface temperature sensor can be installed by driving a metal rod into the permafrost, removing it, and then inserting the sensor in the hole. The datalogger, which should be waterproof, can be placed under the vegetative mat to shield it from temperature extremes.

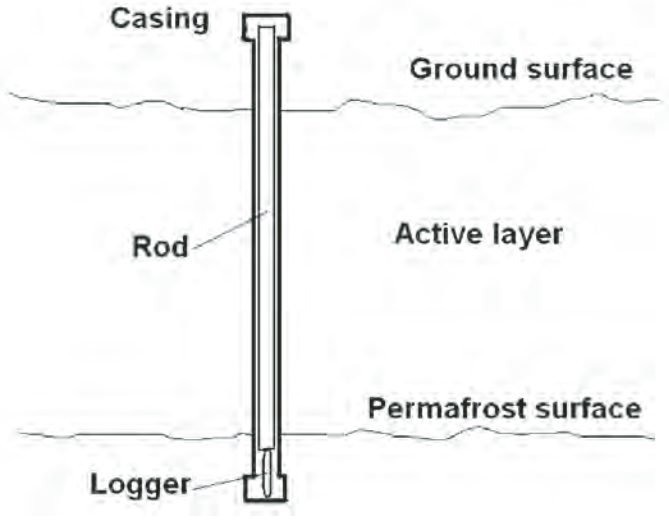


Figure 3. Schematic showing some of the details of the casing and logger installation for measurements of the surface temperature of permafrost.

The installation of one datalogger at one site can be done by one trained SCA/volunteer in about half a day. Training, consisting of a supervised installation by a scientist (one day, one time only) at one or two sites is needed. A scientist would be needed for preparation of the datalogger, (less than half a day). A soil auger, plywood, casing with caps for both ends, datalogger and readout device, and rod or wire (with insulation) are also needed. The costs for equipment are less than $1,000 per site. Data reduction, graphics, and archiving for the annual data from one site requires a scientist for half a day.

Level 3. Permafrost Temperature Profiles

Vertical temperature profiles measured through the full thickness of the permafrost and into the underlying unfrozen material can be used to determine the annual mean temperature at the permafrost surface; annual amplitude with depth; thermal properties; heat flow (in the permafrost and into the permafrost from below); phase equilibrium temperature at the base of the permafrost; and thawing or freezing rates at the base of the permafrost. A borehole is required for access to the permafrost. Criteria for site selection are discussed in the previous section.

While it is desirable to completely penetrate the permafrost with the borehole, useful information can be obtained from shallow boreholes (10–20 m in depth). Boreholes should be drilled during spring, when the active layer is frozen and the snow cover is deepest, to minimize disturbance to the vegetation and ground surface. If the drill rig is large, it should be track mounted. This drilling is normally contracted out to professional drillers. However, for shallow holes where the drilling is not difficult, it is often possible for investigators to drill the holes themselves using small portable equipment (Osterkamp and Harrison, 1982). Air drilling and augering are common because they minimize disturbance to the thermal regime around the hole. Plywood or tarpaulins should be placed on the ground in areas of high use around the drill rig, with the hole drilled through the plywood. Sharp turns with the drill rig while approaching or leaving the site should be restricted to avoid tearing the vegetative mat.

Ideally, sampling should be done in each formation encountered during drilling, as determined from the drill cuttings. However, repeated sampling can quickly drive up drilling costs. Drill cuttings for the relatively shallow holes drilled in parks for permafrost investigations are sufficient to identify soil and rock types. When the drilling is completed, a galvanized iron water pipe (typically ¾ inches inside diameter) is placed in the hole, which is backfilled with cuttings from the hole. The backfilling must be done slowly and carefully to prevent bridging and air spaces around the pipe. Sand added to the cuttings helps alleviate these problems.

Two methods for measuring temperatures are commonly used. In the first, a single sensor on the end of a cable is lowered into the borehole while temperatures are measured automatically or manually (Osterkamp, 1985). This method is technically sophisticated and capable of accuracy better than 0.001 °C (Clow et al., 1996). In the second method, a commercially calibrated

multi-sensor cable is installed in the borehole. The cable may have an attached datalogger or the sensors can be measured manually with a portable commercial read-out device. While the accuracy is typically much lower, this method is still satisfactory for monitoring change. With a multi-sensor cable, depths are fixed and determined by the spacing of the sensors in the cable. Installation of the cable is done according to manufacturer's instructions. Care should be taken to reference the sensor depths to the top of the pipe. Non-freezing fluid (e.g., silicone) should be poured into the pipe to prevent any convection in the pipe, particularly if the cable diameter is much smaller than the pipe diameter. If a datalogger is used, it is necessary to download the data to a storage device according to the manufacturer's instructions. The data are then returned to the office and transferred to a computer. With a manual read-out, the data are handwritten in the field and entered into a computer later. Examples of the data are shown later in this chapter.

The services of an expert are needed for site selection, drilling, cable installation, and detailed interpretation of the data. The annual data can be obtained by a trained SCA/volunteer or technician in one annual trip to the site (half a day). Data reduction, graphics and archiving for the annual data from one site requires a scientist for one day.

The information developed from permafrost borehole temperatures can be made more useful by adding measurements of air temperatures, ground and permafrost surface temperatures, and snow-cover thicknesses at the site (Osterkamp, 2003b). These supplementary measurements allow prediction of past and future permafrost temperatures using calibrated models.

Physical Conditions

Permafrost provides mechanical support for soil and vegetation development and controls hydrologic movement and, therefore, is fundamental to controlling ecosystem processes in cold environments. The characteristics of primary importance are microtopography, which affects surface-water movement, and the frozen/unfrozen status of the permafrost, which affects permeability and drainage. Changes in the water table or free drainage of the soil, due to microtopographic position or subsurface drainage, affects soil oxygen, decomposition, and nutrient cycling. These physical characteristics of permafrost can be assessed at three levels. First, a qualitative assessment of the presence or absence of various forms of thermokarst provides significant information about ground ice and the potential for large-scale conversion of permafrost-dominated ecosystems into other ecosystems. At the second level, involving simple quantitative measurements, the most important parameters for monitoring are ground surface topography, thaw depths (frozen/unfrozen status), and water surface elevations. At the third level of effort, detailed descriptions and measurements of soil and ice stratigraphy from core samples or bank exposures help to evaluate rates of change and to develop predictions of how terrain and ecosystems are likely to evolve. Finally, remote sensing can be used to develop precise estimates of the extent and rate of permafrost degradation.

Level 1. Thermokarst Features

Observations of the presence or absence of thermokarst features can provide evidence of the nature and rate of change associated with permafrost degradation. These observations are particularly useful in lowland areas with ice-rich, fine-grained soils that are susceptible to thaw settlement, but are of little use in upland areas with coarse-grained, thaw stable soils. In high alpine areas, landslides and rock falls may indicate degrading permafrost. For most permafrost-affected areas, even basic information about the presence of thermokarst features is lacking. Interpretation of the presence and type of thermokarst can be greatly improved by the classification of geomorphic features.

Two sampling designs for observing thermokarst and geomorphic features are appropriate, depending on whether the observations can be incorporated into other studies. The most cost-effective approach is to make the observations part of the sampling protocol for vegetation monitoring. Thus, vegetation changes can be linked to permafrost and geomorphic observations. Alternately, a separate effort can be made to make observations stratified by another environmental variable, preferably using ecosubsection or soil-landscape maps. For areas with road systems, the observations can be made along the road. For more remote areas, the observations can be made by fixed-winged aircraft or helicopter flying a low-level (100 m) flight route designed to sample one-third to one-half of the subsections within each park. The sampling should take one day for each park and should be done once every five years.

The classification of thermokarst features should be done according to the system described by Jorgenson and Osterkamp (2005). Photographs of the various classes are provided in Figure 4, and more detailed descriptions are given in the paper. A photograph should be taken at each location described for consistency review.

The classification of geomorphic features entails components at three scales: **landforms** (geomorphic units), **macrotopography** (slope shape and hillslope profile), and **microtopography** (periglacial features). The observer can use a national system if there is a need for standard terminology for all parks (NSSC, 2002). More concise and relevant systems have been developed for Alaska that are more appropriate for permafrost areas. This classification of landforms (also referred to as geomorphic units, terrain units or engineering geology) should follow the classification of Kreig and Reger (1982), which has been further refined for use in other areas of Alaska (Jorgenson et al., 1999, 2001b, 2004). Macrotopographic classification should follow that of the NSSC (2002). Microtopography should follow that of Washburn (1973), which has been updated by Jorgenson et al. (1999, 2004). A tabular listing of the more common classes is provided in Table 1.

Classification of thermokarst features requires a physical scientist or ecologist with one day of specialized training. The work can be a precursor to assess whether more intensive transect monitoring is required when thermokarst becomes evident. This



Figure 4. Photographs representing the most common modes of permafrost degradation in Alaska. Clockwise from upper left, these include: (1) thermokarst lake on the Muddy River Flats, northwest Denali National Park; (2) glacial thermokarst lake on a vegetated, ice-cored moraine; (3) collapse-scar bog infilling with Sphagnum mosses on the Tanana Flats near Fairbanks; (4) high-centered polygons with water-filled troughs formed from degrading ice wedges near Fairbanks; (5) thermokarst gully formed by downslope movement and channelization by water; (6) thermokarst mounds from minor uneven thaw settlement; (7) thermokarst pit filled with water on the Tanana Flats; and (8) the "moat" on the edge of a collapse-scar fen on the Tanana Flats (photographs by T. Jorgenson).

TABLE 1. A TERRAIN CLASSIFICATION FOR ASSESSING GEOMORPHIC CHANGES ASSOCIATED WITH THERMOKARST

Code	Geomorphic Unit	Code	Macrotopography	Code	Microtopography
Bx	**Bedrock—undifferentiated**	**C**	**Crest**	**N**	**Nonpatterned**
Bxr	Bedrock, residual soil	**FH**	**Plateau (high flats)**	**P**	**Polygons (ice aggradation)**
Bxw	Bedrock, weathered	**S**	**Slope, undifferentiated**	Pr	Polygon rim
C	**Colluvial deposit**	Sh	Shoulder	Pc	Polygon center
Ca	Avalanche deposit	Sb	Bluffs/banks, unconsolidated	Pt	Polygon trough
Cf	Slush flow deposit	Sbs	Steep bluff—south facing	Pd	Disjunct polygon rims
Cg	Rock glacier	Sbr	Riverbanks	Pl	Low-centered
Cl	Landslide deposit	Sc	Cliff (rocky)	Plll	Low-centered, low-relief, low-density
Cm	Mudflow deposit	**Su**	Upper slope	Pllh	Low-centered, low-relief, high-density
Cs	Solifluction deposit	Suc	Upper slope, concave	Plhl	Low-centered, high-relief, low-density
Ct	Talus	Such	Nivation hollows	Plhh	Low-centered, high-relief, high-density
Ch	Hillside colluvium	Suv	Upper slope, convex	Pm	Mixed high and low polygons
Cu	Slump deposit	Sup	Upper slope plane	Ph	High-centered polygons
E	**Eolian deposit**	**Sl**	Lower slope	Phl	High-centered polygons, low-relief
El	Loess	Slc	Lower slope, concave	Phh	High-centered polygons, high-relief
Es	Eolian sand deposit	Slch	Nivation hollows	**T**	**Thermokarst**
F	**Fluvial deposit**	Slv	Lower slope, convex	Tp	Pits (small features)
Fa	Aufeis	Slp	Lower slope plane	Tm	Mixed pits and polygons
Fbo	Braided overbank deposit	**T**	**Toe slope**	Tc	Collapse scar (large, rounded features)
Fbr	Braided channel deposit	**U**	**Undulating**	Tw	Moats (linear, water filled)
Fdo	Delta overbank deposit	**B**	**Basins or depressions**	Tk	Kettle (glacial)
Fdr	Delta channel	Bk	Basin, kettle	Tb	Beads (as beaded stream)
Ff	Alluvial fan	Bt	Basin, thermokarst	Tt	Troughs (degraded ice-wedges)
Fg	Glacial/nonglacial, undifferentiated granula deposit	Bd	Basin, drained	**F**	**Frost features**
Fh	Headwater stream floodplain	**D**	**Drainage-way**	Fh	Hummocks (mineral cored)
Fmo	Meander overbank deposit	**F**	**Flat or fluvial related**	Fr	Reticulate
Fmr	Meander channel deposit	Fn	Nonpatterned	Ff	Frost scars and boils
Fs	Retransported deposit	Fpp	Permafrost plateau	Fc	Circles (non-sorted, sorted)
Ft	Alluvial terrace	Fpa	Palsa	Fs	Stripes (non-sorted, sorted)
G	**Glacial deposit**	Fm	Flats margins	Fn	Nets (non-sorted, sorted)
Gm	Moraine	Fw	Water tracks or feather pattern	Ft	Steps (non-sorted, sorted)
Gmo	Older moraine	Fc	Channel, swale or gut	**M**	**Mounds (ice and peat related)**
Gmy	Younger moraine	Fi	Interfluv or flat bank	Mu	Undifferentiated mounds (distinct)
Gt	Till sheet	Fl	Levee	Mi	Ice-cored mounds
Ggm	Ice-cored glacial moraine	Fb	Bar	Mpm	Peat mounds
GF	**Glaciofluvial deposit**	Fs	Crevasse splay	Ms	String (strang)
Gfe	Esker deposit	Ft	Terrace	Mg	Gelifluction lobes (saturated flow)
Gfk	Kame deposit	Ff	Flood basin	Mir	Ice-shoved ridge
Gfo	Glaciofluvial outwash	**W**	Waterbodies	Mid	Ice-rafted debris
Gg	Glacier	**E**	Eolian patterns	Mrs	Soil-covered rocks
Ggs	Snowfield	Ek	Streaked dune	Mrb	Rocks, blockfields
GL	**Glaciolacustrine deposit**	Ed	Dome-shaped	Mrm	Rocky mounds/outcrops
H	**Human modified**	Ec	Crescent	Ml	Tree mounds (downed logs and root balls)
He	Excavation	Ep	Eolian parabolic dunes	Mw	Mounds caused by wildlife
Hf	Fill and embankments	El	Eolian linear dunes	Mh	Mounds caused by humans
Ht	Mine tailings	Er	Reversing	**D**	**Drainage or erosion related**
L	**Lacustrine deposit**	Et	Star	Dt	Water tracks (non-incised drainages)
Le	Emergent lake bottom	Eb	Blowout	Df	Feather pattern (in fens)
Lt	Thaw Basins and thaw Lakes	**H**	**Human modified**	Dr	Ripples
M	**Marine deposit**			Dd	Flow dunes
Mb	Beach deposit			Ds	Scour channels–ridges
Mg	Glaciomarine deposit			Dc	Riverbed cobbles or boulders
Mp	Alluvial-marine deposit			**E**	**Eolian related**
Mt	Tidal flat			Es	Small dune
O	**Organic deposit**			Eb	Scour depression
Ob	Organic bogs			**W**	Water
Of	Organic fen			**X**	Complexes
Os	Organic swamp				

type of reconnaissance level sampling should be done every five years. The materials needed in the field are a classification protocol, field notebook or forms, shovel, 3 m tape, camera, and GPS. Classification of landforms, however, can be more complicated and requires more experience or specialized training. Classification of macro and microtopography can be done reliably with illustrated guides.

Level 2. Surface Characteristics and Thaw Settlement

Photo trend plots for surface characteristics. More detailed information on topographic, soil, and hydrologic characteristics associated with thermokarst can be obtained at semiquantitative photo-trend plots (Fig. 5). This level of monitoring provides information on the nature, rates, and consequences of change, but sampling is usually insufficient to quantify the extent of change throughout a park. Nevertheless, photographs provide an excellent means of communicating the consequences of permafrost degradation to a broad audience. Photo-trend plots along a transect should have three stakes placed at 0, 10, and 20 m. The photograph should be taken with a moderate-resolution camera (~4 MP) at the 0-m stake, with the picture centered on the 10- and 20-m stakes. The top of the picture should include only a little bit of sky above the horizon; thus, most of the photograph is of the ground. The stakes should be painted with 20 cm graduations for scale. The photos should be labeled with park code, site, year, and photographer's initials (e.g., DENA00012004mtj). Information collected at the time of the photo should include: Plot ID, date, time, observer, GPS coordinates (NAD83), thermokarst mode, geomorphic unit, macrotopography, microtopography, dominant plant species, thaw depth at each stake, and notes of pertinent observations.

A permafrost expert is needed for several days to help establish a network of photo-trend plots in areas of degrading permafrost. Once located, a technician can set up, photograph, and document a site in less than half a day. Data compilation and archiving also takes less than half a day per site.

Topographic surveys for thaw settlement. Survey transects are recommended for obtaining precise, quantitative data on the extent and magnitude of thaw settlement associated with degradation of ice-rich permafrost (Fig. 6). The survey transects also provide data on thaw depths and water level changes associated with permafrost degradation, and tie the measurements into surface elevations. Survey transects should be 200 m long and oriented perpendicular to the topographic gradient or across thermokarst features. The transects should be staked (2″ × 2″ × 2′ wooden stake if visibility is important, or a 30 cm piece of ¾″ painted rebar protruding 10 cm out of the ground) at 50 m intervals to facilitate precise relocation of sampling points along a tape measure. Ground surface elevations should be surveyed to the nearest centimenter at 1 m intervals along the tape measure, using an auto-level or laser level set at the 100 m stake. Ideally, a temporary bench mark (TBM) should be established by coring or hammering a ¾″ × 4′ rebar into the permafrost and the TBM referenced to true elevations through DGPS or level surveying techniques. Even without a TBM, the relative elevations taken over differing periods can be adequately matched to reveal differential settling. During leveling, the water-surface elevation of every water body should also be recorded. After leveling, a metal-tile probe (e.g., AMS extendable tile probes) with 4′ extendable sections should be used to determine thaw depths every 2 m along the transect. In segments where thaw depth is more than 2 m, thaw depth measurements down to 3 m should be taken every 5 m to confirm the absence of permafrost. In rocky soils, probing will not be feasible. Groundwater wells (1.5″ × 1 m, slotted ABS or PVC pipe) should be installed at 5–10 high and low points along the transect. The pipe should extend down to the bottom of the active layer if permafrost is present, and down to 1 m if permafrost is absent within the top 1 m. Depth to the water table (+ for above ground surface, – for below ground surface) should be measured to the nearest centimeter at each well. Finally, photos should be taken of the transect at each 50 m stake.

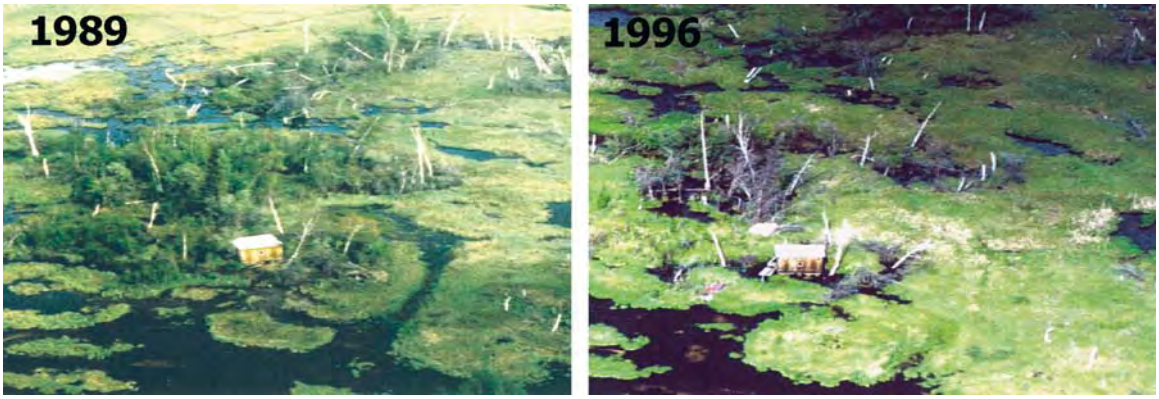


Figure 5. Photo-trend monitoring of the collapse of a birch forest on permafrost as it degrades into a collapse-scar fen (photographs by Chuck Racine).

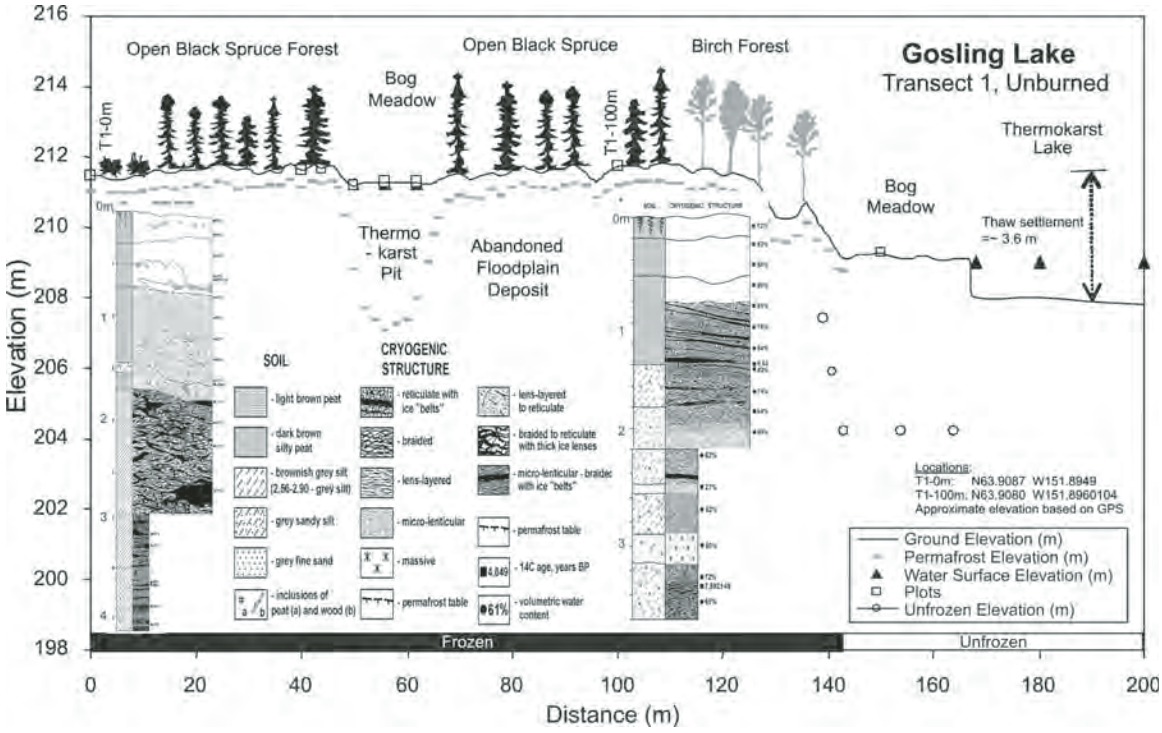


Figure 6. A survey transect of an area near Gosling lake, Denali National Park, Alaska. Relative elevations of the ground and water surfaces, position of the top of the permafrost, and the location of taliks (thawed areas in permafrost) are shown. Soil illustrations by M. Kanevskiy.

Data collection for the transect surveys can be done by technicians with half a day of training and with inexpensive equipment. The equipment needed includes an auto-level, rod, tripod, 100 m tape, 3 m tape, stakes, metal tile probe with extensions, and ABS pipe for shallow wells. Each transect takes half a day for two people to completely survey. The surveying should be done in late summer every two to three years. Data compilation, graphing, and analysis requires a scientist for one day per site.

Level 3. Soils and Ground Ice Stratigraphy and Remote Sensing

Stratigraphy. Two types of studies should be undertaken to better quantify the dynamics and distribution of ground ice and permafrost. First, detailed descriptions and sampling of soil and ice characteristics are useful for evaluating thermokarst potential before thermokarst occurs and the response of soils after thermokarst. Second, remote sensing techniques are useful to quantify the nature and extent of permafrost degradation within a park.

Soil and ice stratigraphy should be described at 4–7 locations representing differing terrain conditions (depending on the number of terrain types) along each survey transect. The stratigraphy of the near-surface soil (i.e., the active layer) should be described from soil pits or cores to assess the depth of thaw, surface organic thickness, and mineral characteristics. Below the active layer, 2–3-m-long frozen cores can be obtained using a 7.5-cm-diameter SIPRE corer with a portable power head. If bank exposures are present nearby, the profiles can be obtained after unfrozen material is removed with a shovel to expose undisturbed frozen sediments. The face of the exposure should be cleaned with a 6″ inshave draw knife, trowel, knife, or other suitable tool. After obtaining the cores or cleaning off the exposure, the soil material should be allowed to thaw for 5–20 minutes to allow the ice features to become more distinct; then, overall and detailed photographs should be taken. A tape measure or other scale should be included in the photos, as well as a site label, boldly written on a yellow "stickynote." Descriptions for each profile should include the fine and coarse textures of each horizon, peat type, coarse-fragment percentage, boundary conditions, organic-matter depth, thaw depth, and visible ice volume and morphology. Soil texture should be classified according to the Soil Conservation Service system (SSDS, 1993). Ice morphology can be classified using the information provided in Table 2 and Figure 7 (adapted from Murton and French, 1994; Shur and Jorgenson, 1998).

Soil samples should be taken at 20 cm depth intervals for determination of volumetric and gravimetric water content, dry density, pH and electrical conductivity. For core samples, the soil volume of each sample should be determined in the field by measuring the length and circumference of each core, with each measurement replicated at different places on the core. For exposures, a portable electric drill, 18–24 V, equipped with a

TABLE 2. SYSTEM FOR CLASSIFYING GROUND ICE STRUCTURES

Primary (Continuity)	Secondary (Shape or Bedding)	Tertiary (Size or Clarity)
Pore (P) (structureless*)	Nonvisible (n)	Ice thickness
Organic-matrix (O)	Uniform (u)	Very fine (<0.5 mm) (v)
Crustal (C)	Irregular (i)	Fine (0.5– <1 mm) (f)
Vein (V)(vertical)	Wavy (w)	Medium (1–3 mm) (m)
Bedded (B, layered, belts)		Coarse (3–5 mm) (c)
Lenticular (L)	Horizontal or planar (h)	Large (5–10 mm)(l)
	Wavy (w)	Very large (10–30 mm (g)
	Curved (c)	Extremely large (30–100 mm) (e)
	Crossbedded or inclined (x)	
Reticulate (R)(net-veined)	Trapezoidal (prismatic) (t)	
	Blocky (lattice, blocky) (b)	
	Curved or crescent (c)	
	Platy (p)	
Ataxitic (A) (suspended)	Round (r)	Thickness of Soil Inclusions
(50–95% ice)	Blocky (b)	Same sizes above
	Platy (p)	
Massive (solid)	Non-stratified, massive (n)	Clarity
(>10 cm thick, >95% ice)	Horizontally stratified, sheet (h)	Clear (c)
	Vertically stratified, wedge (w)	Clear soil inclusions (s)
	Vertically stratified, other (v)	Opaque, clean, white, (w)
	Irregularly stratified (i)	Opaque, soil inclusions (i)
	Fractured (f)	Opaque, rock inclusions (r)
	Discontinuous or porous (d)	Organic-rich, brown (o)
	Columnar (l)	Detritus-rich, plant remains (d)

*Commonly used synonyms.

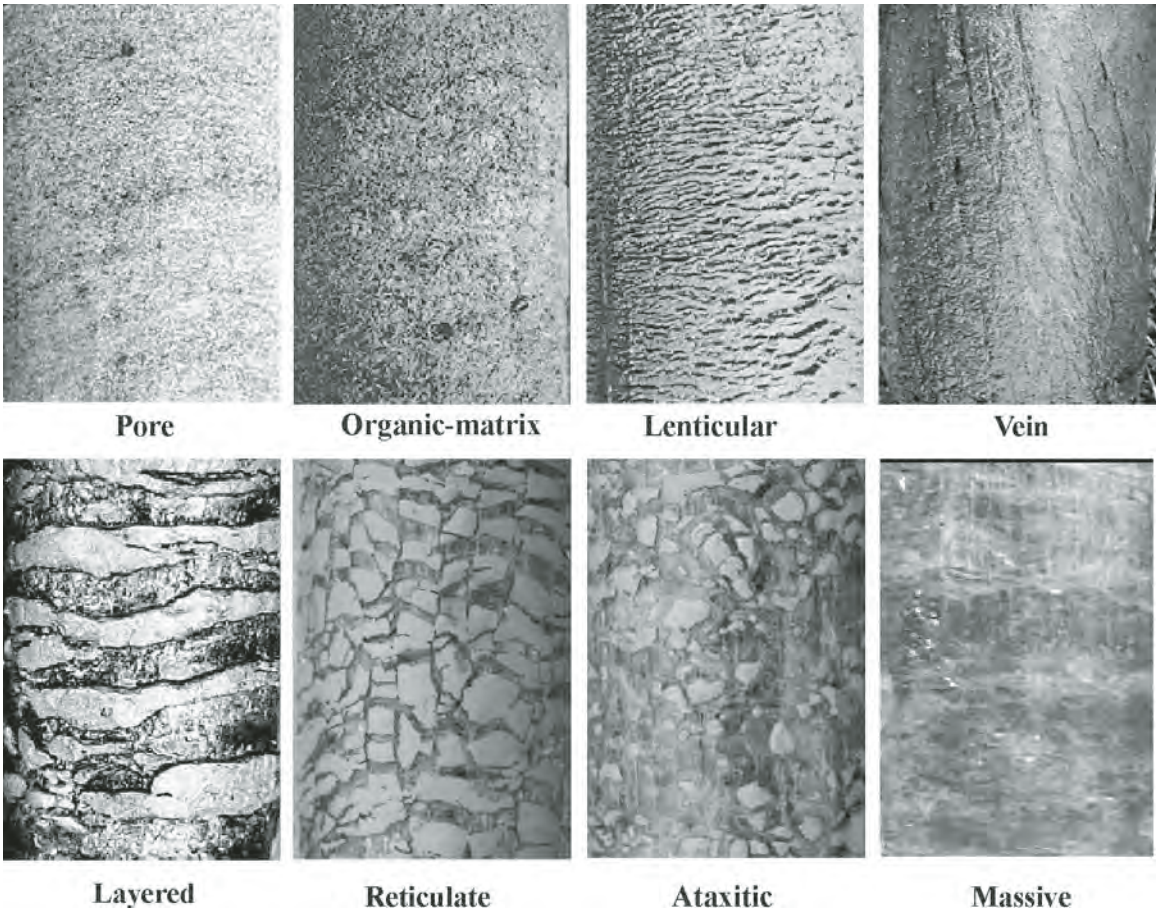


Figure 7. Representative photographs of the major forms of ground ice. The ice structures are closely related to the soil texture, temperature regime, and stage of ecological development (photographs by T. Jorgenson).

2″ diameter hole saw can be used to obtain samples from the exposure wall. The samples should be placed in a quart-sized, re-closable, plastic freezer bag and labeled with site identification and depth. The samples should be weighed for wet weights soon thereafter or frozen for later analysis. After thawing, soil pH and electrical conductivity (EC) should be measured in the bag if the soil is sufficiently wet, or a saturated paste can be made by adding distilled water to the sample. The samples should then be dried at 60 °C to constant weight, then weighed for dry weight. The field volumetric and lab weight measurements should be used to compute volumetric moisture and dry density. Additional desirable analyses are: (1) total carbon and nitrogen (TNC Leco analyzer) for assessing soil response to degradation, and (2) radiocarbon dating of organic samples obtained from the base of the organic horizons in the core or exposure.

The soil stratigraphy and ground ice descriptions should be done by a permafrost scientist. While a physical or soil scientist can be trained fairly quickly in sampling and description, interpretation of the data requires substantial experience. Data acquisition requires a scientist and one or two technicians for one day per site. Data compilation and analysis requires a scientist, one day per site. Fortunately, the soil sampling needs to be done only once when establishing baseline conditions and is not a routine monitoring requirement.

Remote sensing. The abundance and distribution of thermokarst is best determined through remote sensing. The acquisition and analysis of **LIDAR** (light detection and ranging), high-resolution satellite imagery (<5 m resolution), and high-resolution aerial photography are all effective for mapping thermokarst but vary in cost and resolution (Karle and Jorgenson 2004). Moderate resolution imagery (15–80 m), such as Landsat, is not recommended for site-scale monitoring because thermokarst is often a small-scale phenomenon.

LIDAR can be used to collect detailed topography of an area and to provide high-resolution imagery for quantifying thaw settlement. LIDAR is best for detecting change over time by subtracting surface elevation over time. However, the cost is high, and analysis is intensive.

High-resolution satellite imagery (e.g., Quickbird, Ikonos) can be obtained for selected areas or entire parks. The images can be manually photo-interpreted to delineate thermokarst features, or a point-sampling system can be used to determine the presence or absence of permafrost features at systematically distributed grid points. The satellite imagery has the advantage over LIDAR in that vegetation patterns on the images are important for identifying thermokarst features, and the images can be used for other purposes, such as vegetation monitoring.

High-resolution aerial photography can be obtained with specialized, high-quality aerial cameras mounted in specialized aircraft or with a small fixed-wing aircraft equipped with a camera mount and a high-resolution (>6 MP) digital camera. Aerial photographs can be obtained at systematically distributed grid points or in dedicated blocks of terrain. The advantages of the aerial photographs and grid sampling approach are that costs are modest ($3,000 to $10,000) for small, fixed-winged aircraft, resolution is high (pixel <1 m), thermokarst features can be reliably identified, and the probability of capturing the entire photo-set in one season is much higher.

Thermokarst features obtained from small fixed-wing aircraft are illustrated in Figure 8. Sampling of thermokarst features on the photography can be done at two scales. First, the presence or absence of thermokarst features can be photo-interpreted at the center point of each photo (or at multiple points if desired) and frequency of thermokarst features can be tallied to quantify the extent of thermokarst and the modes of permafrost degradation. Second, the presence or absence (or percent cover) of each type of thermokarst mode can be estimated for the entire photograph, or within a set radius around the center point. These data are useful to assess the amount of terrain that could be susceptible to thermokarst. Together, the point sampling provides a precise estimate of thermokarst extent, while the assessment of thermokarst within the larger area of each photograph provides an indication of how much terrain may be susceptible to thermokarst.

Remote sensing of thermokarst abundance and distribution can be done with personnel that have had one day of training. Acquisition of aerial photography requires an experienced fixed-wing pilot, a small plane with a belly mount for the camera, a high resolution digital camera, and a GPS. The photographs should be taken at predetermined locations along transects, with the coordinates uploaded into the GPS. The camera operator should take the pictures as the aircraft reaches the assigned locations. Ideally, the camera should be linked to the GPS to imbed the actual coordinates into the digital file information. Interpretation of the airphotos should be done by an expert, but an entry level scientist can also be trained to interpret airphotos using an airphoto key with illustrated examples. Management of photos and data acquired from a series of photos requires several days. Photo-interpretation of thermokarst features at a sampling point takes less than one hour per photo.

STUDY DESIGN

There are a number of questions that should be addressed in developing a monitoring program for permafrost. While permafrost is common to most of the parks in Alaska, it exists only at high altitude in the contiguous states. Little is known about this high-altitude or mountain permafrost, although some inferences can be made (Péwé, 1983). This temperate latitude mountain permafrost is most likely found where annual mean air temperatures are ~0 °C or negative, snow cover thicknesses are relatively thin, and solar radiation input is low. This suggests high, windswept, north-facing slopes and ridges. An example is Niwot Ridge at an elevation of 3500 m in the Rocky Mountains west of Boulder, Colorado. This permafrost may be expected to be sporadic in distribution, warm (within a degree or two of thawing), and highly susceptible to climatic warming. The questions that a resource manager needs to address are discussed below.

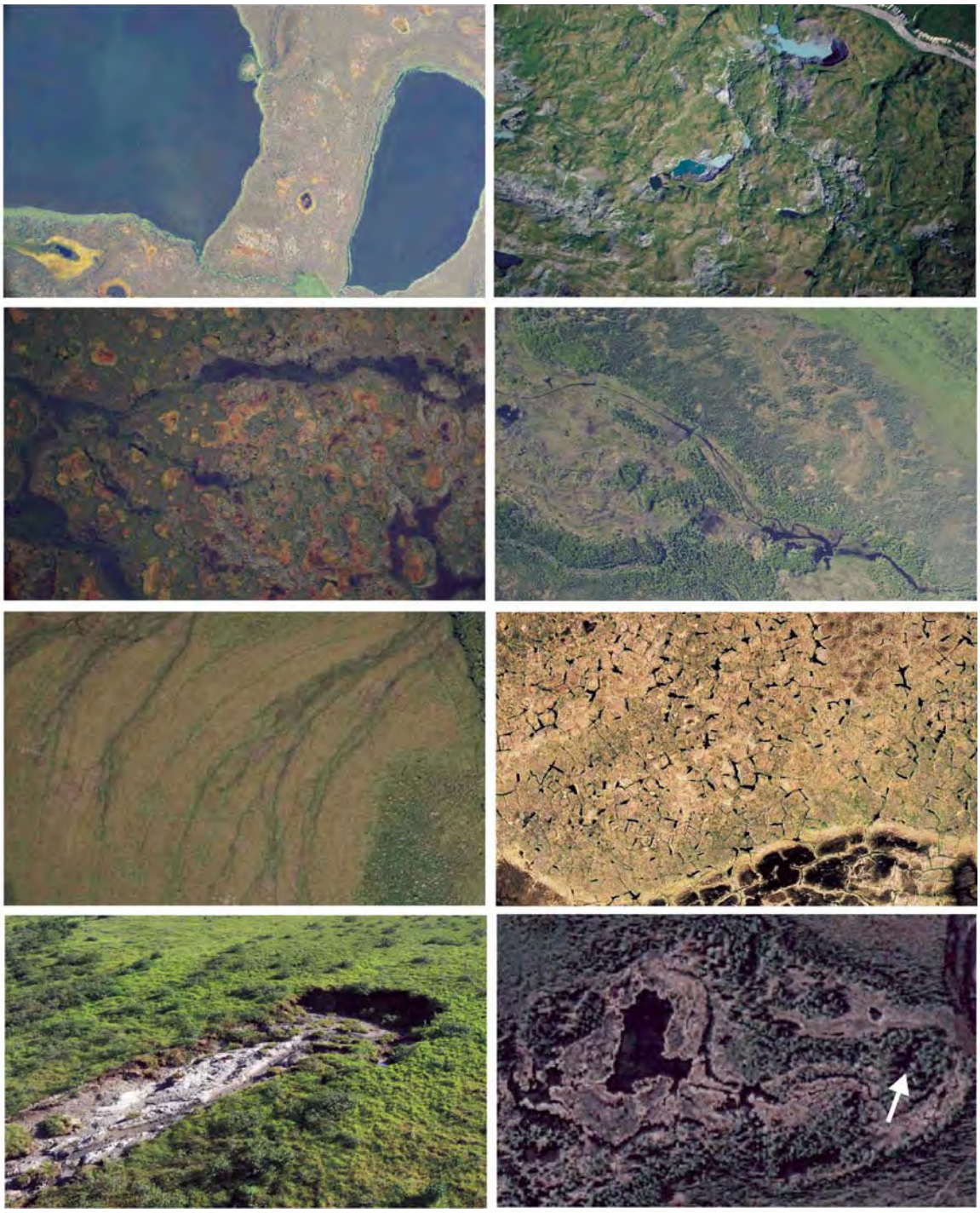


Figure 8. Aerial photographs illustrating the most common types of thermokarst terrain in Alaska. Clockwise from upper left, these include: (1) thermokarst lake on the Innoko Flats; (2) glacial thermokarst lake on the Muldrow glacier moraine; (3) collapse-scar fen on the Tanana Flats; (4) polygonal thermokarst mounds and water filled troughs on the Arctic Coastal Plain; (5) thermokarst pits within birch forest patches surrounded by larger collapse-scar fens near Fairbanks; (6) thaw slump near the Noatak River; (7) thermokarst gullies near Healy; and (8) collapse-scar bogs on the Innoko Flats. These distinct features can readily be identified and mapped or point-sampled from high-resolution airphotos or satellite imagery. (Vertical airhotos 1, 2, 3, 7, and 8 by T. George; 4 by Aeromap; and oblique airphotos 5 and 6 by T. Jorgenson.)

Questions and Priorities

1. Is permafrost present, and is there any evidence (thermokarst terrain, landslides, rock falls) that it has thawed in the past?

The probing method (discussed in this chapter) when coupled with an occasional temperature measurement or an excavated pit provides the necessary information to determine whether permafrost is present. Field work for probing helps discover if there is any thermokarst terrain (including landslides, rock falls) that would indicate that ice-rich permafrost has thawed in the recent past. This information also provides a qualitative indication of the potential for change associated with climatic warming.

2. What is the current thermal state of the permafrost, and what is the current extent of the thawing?

Permafrost surface temperature measurements (discussed in this chapter) provide a partial answer to this question. However, much more detail is provided by borehole temperature measurements even if the hole is shallow (10–20 m). This information, when coupled with the current extent of thermokarst, provides a quantitative assessment of the changes associated with climatic warming since the late 1800s.

3. What is the projected future thermal state of the permafrost, and what are the rates and characteristics of change associated with thermokarst terrain?

Relatively shallow borehole temperature measurements can be used to calibrate thermal models. The calibrated thermal models can then be used to predict the response of the permafrost to climate scenarios such as those generated by global climate models. If there are a number of sites where temperature measurements are being made, and where information on soil ice contents and the rates and characteristics of change in thermokarst terrain are known, then it is possible to determine when and where potential thawing in park ecosystems may occur.

For management of park resources, an important goal of a permafrost monitoring program should be to develop a predictive capability for determining the effects and impacts of climate change on the permafrost. With the information generated by answers to the above questions, thermal models of ground temperature distribution within each type of ecosystem can be developed for the park. The thermal and thermokarst measurements would be used to calibrate the model for each type of ecosystem. The model can then be used to map the spatial distribution of permafrost and its temperatures throughout the park ecosystems and thereby identify those areas of warm permafrost that are most vulnerable to change. Advanced knowledge of areas susceptible to thermokarst can be used to develop management strategies to avoid resource use conflicts.

A comprehensive yet practical sampling design for monitoring permafrost within a park should include: (1) compilation of existing soils and permafrost survey information when available, or a reconnaissance-level survey and satellite image interpretation to assess permafrost occurrence when detailed information is not available; (2) two boreholes at easily accessible lowland and mountain sites; (3) 5–10 survey transects distributed within riverine, lowland, and mountain ecosubsections (physiographic landscapes); and (4) photo-interpretation of the presence and type of thermokarst at 200–300 points on a large-scale grid, using high-resolution satellite imagery or inexpensive aerial photography obtained with a small aircraft. The reconnaissance surveys would use satellite image interpretation, subsection or soil landscape maps, and limited ground-truthing by probing to identify permafrost areas. Within the permafrost area, boreholes should be placed in both a lowland and a mountain environment to capture the elevational temperature gradient and should be monitored yearly. Survey transects should be established to monitor surface and groundwater elevations, thaw depths, and temperatures at the ground and permafrost surfaces. Temperatures at 5 and 100 cm depths in the ground in two to four ecosystem types along the transect should be measured with inexpensive dataloggers. The transects should be monitored every two to three years. Finally, remote sensing of the extent and type of thermokarst by point sampling of high-resolution imagery should be done every 10 years.

CASE STUDIES

Permafrost is highly variable, both spatially and temporally, so no one site can represent a wide range of permafrost characteristics. We will present examples of results obtained using the methods described above and using data from different sites to provide a more complete illustration of the range of permafrost conditions.

Surface Temperatures

Temperature monitoring at a site near Denali National Park shows that permafrost is present at this site since all temperatures are at or below 0 °C (Fig. 9). There was a period extending through the fall and half-way through winter where temperatures remained at 0 °C. This was the time when the active layer was freezing from the top down. Temperatures at the freezing surface in the active layer and at the top of the permafrost were at 0 °C, so that the intervening unfrozen layer was constrained at 0 °C. This caused the permafrost to “disconnect” from the atmosphere (i.e., the atmosphere could not influence permafrost temperatures). Freezing proceeded from the ground surface downwards and the heat of fusion at the freezing interface in the active layer was conducted upwards through the active layer. Freezing also occurred at the permafrost surface, producing a frozen layer that thickened upwards with the heat of fusion conducted downwards into the permafrost. With complete freezing of the unfrozen layer on 2 February 1997, the permafrost was again connected to the atmosphere and cooled rapidly.

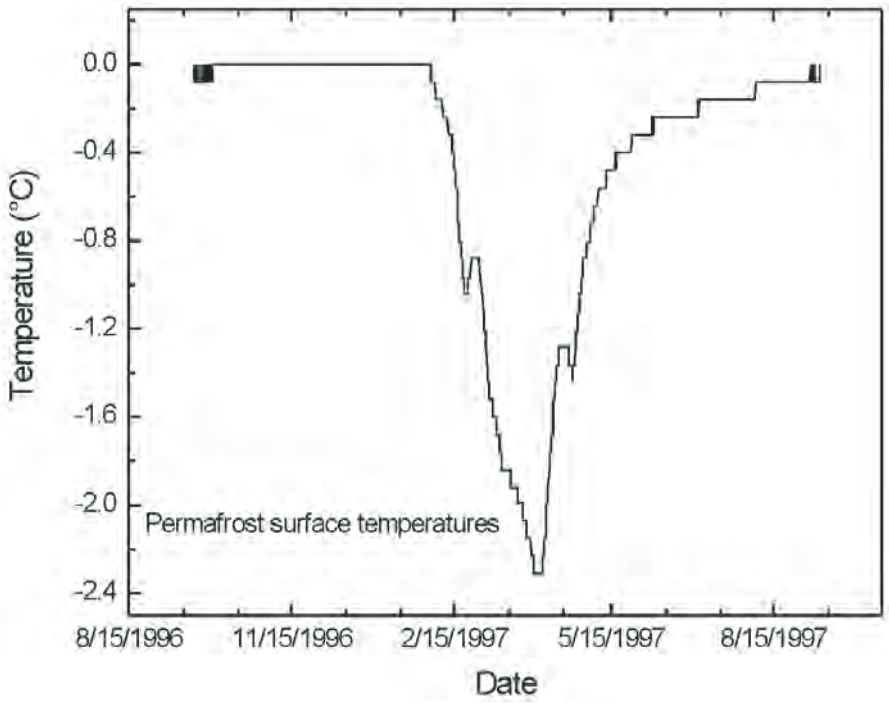


Figure 9. Permafrost surface temperatures measured every 5 hours for one year at a site near Denali National Park, Alaska.

Permafrost surface temperatures continued cooling until the beginning of April when warming began in response to warming air temperatures. Temperatures warmed rapidly during spring and then continued warming slowly through summer until they reached 0 °C about mid-September. At this time, the active layer reached its maximum thickness, air temperatures were cooling and the process was ready to repeat.

The annual mean temperature calculated from the data is –0.4 °C, which is very close to thawing. When a multi-year data set is available, trends in the permafrost surface temperature can be determined. If air and ground surface temperatures and snow cover thicknesses are measured, then a more complete interpretation of permafrost conditions, trends, and reasons for change can be conducted.

Temperature Profiles

While detailed interpretation of the data requires an expert, some information can be obtained by anyone with scientific training. Figure 10 shows a temperature profile from a site in Interior Alaska. Permafrost here is warm, with a mean surface temperature near –1 °C, estimated by projecting the 10–20 m temperatures in a straight line upward to the permafrost surface. Permafrost depth is ~39.4 m, and there is a slight break in the slope of the profile that may indicate a freezing point depression of about –0.16 °C at the base of ice-bearing permafrost. The strong change in slope at 29 m is caused by a change in lithology from sand to clay, as verified from drilling records. The gradual change below 40 m is caused by a change from sand with gravel grading into claystone. Active-layer depth next to the pipe is over a meter. Curvature in the top 22 m in fine-grained soils indicates that a recent surface warming has occurred. Heat flow could be calculated from the linear portion of the profile below 30 m, but this profile is not an equilibrium one and the heat flow would not be representative.

If a time series of temperature profiles are available, these can be used to show how permafrost temperatures are changing (Fig. 10). This hole was drilled in 1983 and permafrost temperatures have warmed consistently since 1985, with the rate of warming increasing significantly after 1995.

Survey Transects for Surface Characteristics and Thaw Settlement

A monitoring transect established near Gosling Lake in northwest Denali National Park (Fig. 6) shows that it has ice-rich, abandoned floodplain deposits that are undergoing widespread thermokarst, resulting in extensive development of thermokarst lakes and bogs. The initial surveys of ground and water surface elevations have established the baseline conditions for thawing along the edge of the thermokarst lake and for the beginning stages of a bog. A floating shore bog surrounds the margin of the lake, and the surface stays slightly above the level of the lake water. Water in the bog, however, is confined by the permafrost and remains isolated from groundwater conditions. Active-layer depths above the permafrost mostly vary between 40 and 60 cm

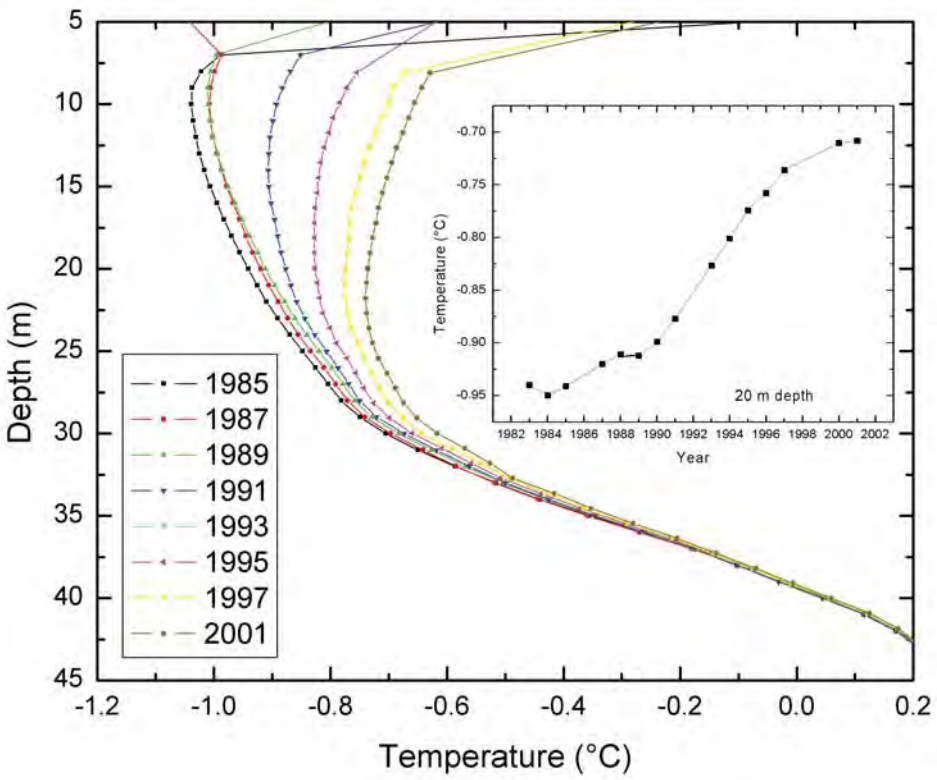


Figure 10. Temperatures in permafrost for odd years only for a site near Wrangell–St. Elias National Park and Preserve, Alaska. Data above 6 m have been deleted for clarity. The inset is the time series for temperatures at the 20 m depth showing the warming that has occurred.

along stable portions of the transect, but probing in the bog indicates that permafrost has thawed up to 4 m below the surface, and a **talik** (perennially thawed zone) has developed above the permafrost. As a result of thawing, the ground surface is now 0.5 m below the original ground surface elevation, although a floating mat of Sphagnum mosses covers the bog and masks the original ground surface. Permafrost is absent at the margin of the thermokarst lake. Probing revealed the presence of a thaw bulb underneath the adjacent shoreline. Also of interest is the shallow depression 40 m back from the lake edge, formed as a result of the thin-surface permafrost layer above the thaw bulb that has cracked and settled above the thawing subsurface material. A repeat survey of the transect in 5–10 years will provide data for quantifying the rate of subsurface thawing and lateral expansion of the thaw lake and bog.

In the zone of discontinuous permafrost, where permafrost temperatures are near thawing, measurements of the active layer are particularly useful for monitoring the stability and degradation of permafrost. Because permafrost is near thawing, the active layer may not refreeze to the permafrost surface every year. This isolates the permafrost throughout the freezing season, causing it to warm continuously during this period. In contrast, in the zone of continuous permafrost, where mean annual permafrost temperatures usually are lower than –6 °C, active layer monitoring is a less useful indicator of permafrost stability because the active-layer thickness depends primarily on summer thaw conditions, and the active layer refreezes every winter. Consequently, the active layer can vary considerably among summers, but it is difficult to detect a trend.

Soils and Ground Ice Stratigraphy

Information on the stratigraphy of soils and ground ice can greatly aid in the interpretation of the dynamics of permafrost degradation. On the Tanana Flats, where the surface topography, groundwater, and thaw depths have been monitored since 1994 (Jorgenson et al. 2001a), subsurface conditions were sampled through coring and deep probing (Fig. 11). The stratigraphy included thick organic horizons at the surface, a moderately thick silt layer, cross-bedded fine sands, and finally gravel at about the 4 m depth. The bottom of the organic layer had a calibrated radiocarbon age of 7.7–8.8 ka B.P. (thousands of years before present). This indicates that the area was initially covered by glacial outwash from the Alaska Range during deglaciation in the early Holocene. The area was then blanketed by eolian silt and eventually covered by organic material around 3.0–5.2 ka BP. This stratigraphy is important because the gravel provides a porous material for movement of water to a downward freezing front during permafrost aggradation, and the silt texture is highly susceptible to formation of segregated ice and frost heaving.

Close examination of the fibrous organic layers revealed that herbaceous peat, composed of buckbean (*Menyanthes trifoliata*)

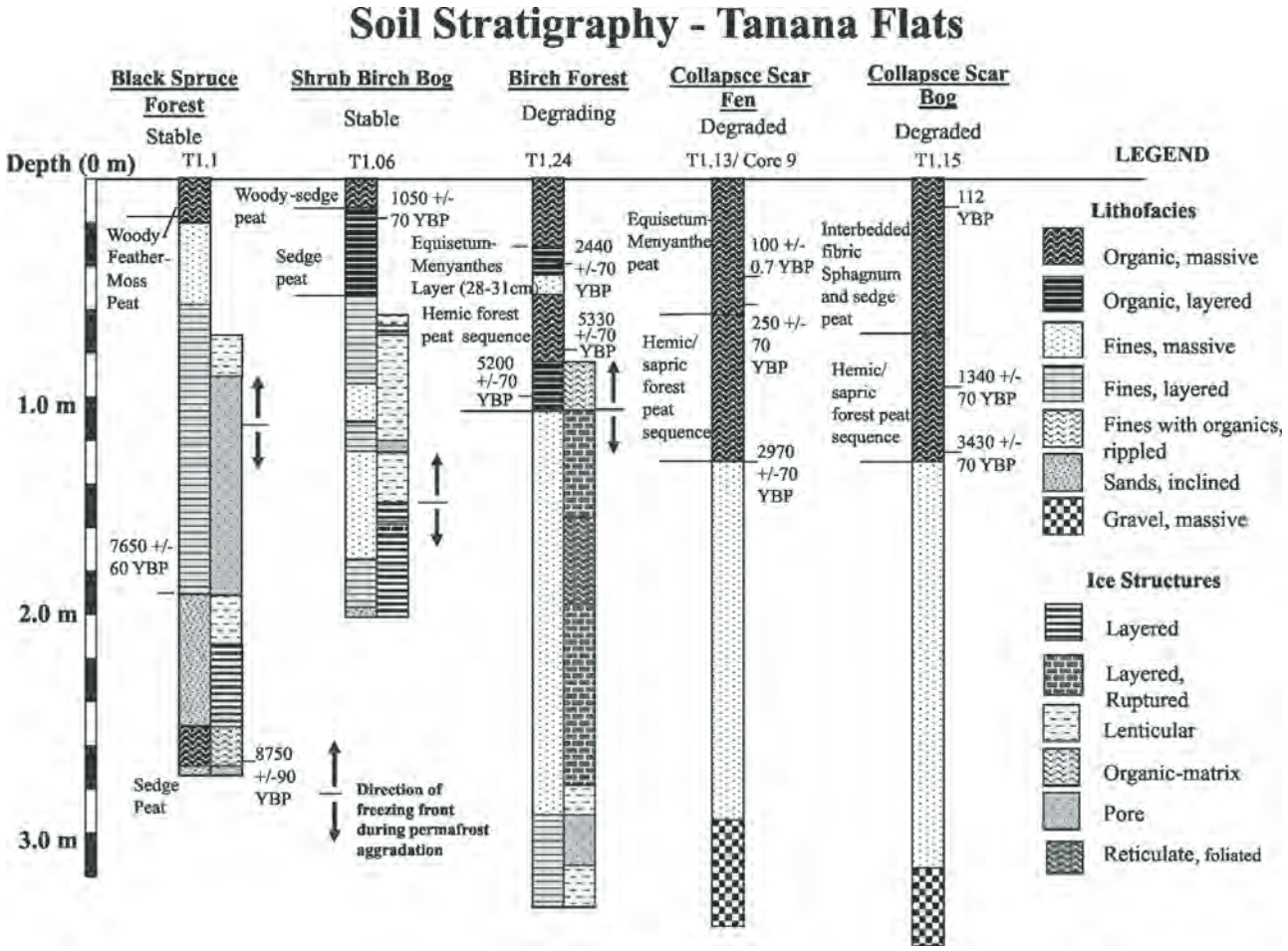


Figure 11. Soil stratigraphy from shallow cores taken from the Tanana Flats, central Alaska illustrating differences in lithofacies and ice structures among various ecosystem types. Pore and lenticular ice is associated with alluvial layered very fine sand and crossbedded sand, and layered and ruptured layered ice is associated with a massive eolian silt deposit.

and marsh horsetail (*Equisetum fluviatile*), underlay the woody forest peat associated with the current birch forest. Radiocarbon dating of the herbaceous peat provided modern dates less than 300 years old. Macrofossil remains of plants that currently are associated only with unfrozen conditions indicate that the terrain has gone from unfrozen conditions within the past 100–300 years, developed permafrost, and is currently becoming thawed once again. Moderately thick ice layers in the silts are consistent with downward freezing permafrost under low temperature gradients with groundwater available to form thick ice layers at the freezing front. The occurrence of fractures and horizontal displacement of the ice and silt layers indicate that the permafrost was deformed during heaving of the developing permafrost. Furthermore, the interpretation of the permafrost stratigraphy and history was aided by the sampling and description of the soils that have formed since the permafrost has degraded. Examination of the fen peat in newly degraded areas provided evidence of the peat structure, plant composition, and decomposition status of the fen peat necessary to identify the fen peat in the soils underneath the degrading birch forest.

Remote Sensing

Time-series analyses of high-resolution, historical aerial photography were used to assess long-term rates of permafrost degradation on the Tanana Flats in central Alaska (Jorgenson et al., 2001a) and on the coastal plain in northern Alaska (Jorgenson et al., 2006). Both polygon mapping and point-sampling methods were used to quantify the rate of permafrost degradation. The more intensive boundary delineation provides information on the change in areal extent of permafrost, rates of lateral change along the permafrost boundaries, and visual features for interpreting degradation patterns and ecological relationships. The point-sampling method provides a rapid means for quantifying the changes in permafrost extent and allows analyses of successional relationships by comparing changes in ecosystem types at each point (Fig. 12).

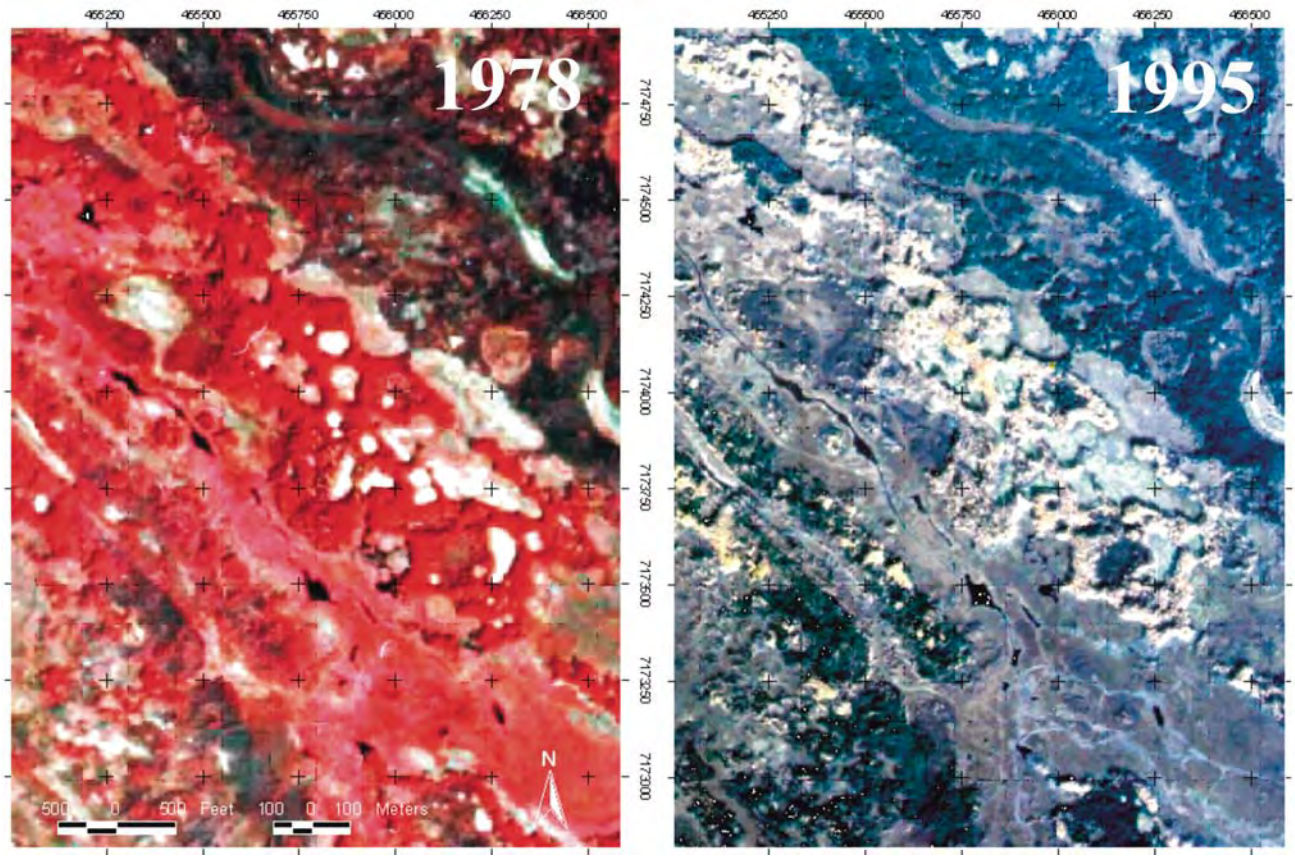


Figure 12. Vertical aerial photographs that were used to quantify the change in thermokarst abundance between 1978 and 1995. The presence or absence of collapse-scar bogs (round, whitish features) and collapse-scar fens (pinkish or brownish, linear features lacking trees) were noted at each cross-hair.

For this area of the Tanana Flats, the percent of the area where permafrost has totally degraded has increased from 39% in 1949 to 47% in 1995. The point-sampling approach has also been used in a statewide effort to quantify the extent of thermokarst features across the discontinuous and continuous zones of northern Alaska (Jorgenson et al., 2005, 2008).

CONCLUSIONS

Global air temperatures have warmed since the late 1800s, and this warming has been pronounced during the last quarter century. There has been a concurrent warming of permafrost. Much of the discontinuous permafrost in Alaska is within a degree or two of thawing, as is the temperate-latitude mountain permafrost of the contiguous states. Global climate models predict continued warming of several degrees during the next century. If this occurs, then much of the discontinuous and mountain permafrost is expected to thaw. Widespread thawing of permafrost is already occurring in some areas. Where the permafrost is ice-rich, thawing produces thermokarst terrain consisting of channels, pits, troughs, potholes, ponds, lakes, "drunken forests" (trees leaning in random directions), landslides, and rock falls. Thawing of ice-rich permafrost with the creation of thermokarst terrain is one of the primary problems facing northern and alpine ecosystems as a result of climatic warming.

Thermokarst drastically modifies ecosystems, human activities, infrastructure, and the fluxes of energy, moisture, and gases across the ground surface-air interface. Vascular and nonvascular plant composition and distribution, plant community productivity, soil chemistry, biological activity, and nutrient supply for plant use can be substantially altered by this geological phenomenon. Drainage conditions determine whether standing water will be present or not. The affected trees usually die, and vegetation changes significantly. These changes in the flora have a direct impact on the fauna. In lowlands or relatively flat areas, a shift from boreal forests to lakes, shrubby wetlands or grasslands often occurs with concurrent changes in bird and animal populations. The new ecosystems usually favor aquatic birds and mammals. Thus, the result of thawing ice-rich permafrost is not just a slight shift in the nature of the ecosystem but rather partial or total destruction of the ecosystem, and its replacement by a new ecosystem.

TABLE 3. CONSIDERATIONS FOR MONITORING PERMAFROST VITAL SIGNS (PER SITE)

Method	Specialized equipment/cost (US$)	Site selection	Personnel training*	Data acquisition	Data handling[†]
Thermal State					
Probing (100 m line or 50 pts)	Yes, <$1,000	Expert, ¼ day	½ day	SCA/volunteer, ½ day	Scientist, ½ day
Manual surface temperatures	Yes, <$1,000	Expert, ½ day	½ day	SCA/volunteer, ½ day	Scientist, ½ day
Surface temperature recorders[§]	Yes, <$1,000	Expert, ½ day	1 day	SCA/volunteer, ½ day	Scientist, ½ day
Borehole temperatures	Yes, >$10,000[#]	Expert, 3 days**	1 day	Technician, ½ day	Scientist, 1 day
Physical Conditions					
Thermokarst features	Yes, <$1,000	Scientist, ½ day	1 day	SCA/volunteer, ½ day	Technician, ¼ day
Photo-trend plots	No, <$1,000	Expert, 3 days	¼ day	Technician, ¼ day	Technician, ¼ day
Topographic surveys	Yes, $1,000–$10,000	Scientist, 1 day	½ day	Two technicians, ½ day	Technician 1 day
Soil and ice stratigraphy	Yes, $1,000–$10,000	Expert, 1 day	2 days	Scientist and two technicians, 1 day	Scientist, 1 day
Remote sensing	Yes, $1,000–$10,000	Expert, 1 day	1 day	Scientist, 1 day	Scientist, 5 days

*Student Conservation Association (SCA)/volunteers or a technician trained on the job by a scientist or expert (one time only).
[†]Data handling includes data reduction, graphics, and archiving.
[§]Training by expert or scientist; ½ day/site needed to prepare datalogger.
[#]Access hole is the primary cost. Cost can be reduced to $1,000–$10,000 if a suitable access hole is available.
**Expert also needed to supervise drilling (if done), calibrate cables, and prepare for measurements (4 days).

TABLE 4. SUMMARY OF PERMAFROST VITAL SIGNS AND MONITORING METHODS

Vital signs and methods	Expertise	Special equipment	Cost*	Personnel	Labor intensity[†]
Thermal State					
Probing	Technician/volunteer	Yes	$	Individual	Medium
Surface temperatures	Technician/volunteer	Yes	$	Individual	Medium
Borehole temperatures	Expert	Yes	$$$[§]	Group	High
Physical Conditions					
Thermokarst features	Technician/volunteer	Yes	$	Individual	Low
Photo-trend plots	Technician/volunteer	No	$	Individual	Low
Topographic surveys	Technician/volunteer	Yes	$$	Group	Medium
Soil and ice stratigraphy	Scientist	Yes	$$	Group	High
Remote sensing	Scientist	Yes	$$	Individual	High

*Cost (in US$) = <$1,000; $$ = $1,000–$10,000; $$$ = >$10,000.
[§]Cost reduced to $$ if a suitable access hole is available.
[†]Labor intensity: low = <a few hours; medium = <a full day; high = >a full day.

Permafrost is a common feature of the landscape of most Alaskan parks and preserves. Mountain permafrost (an estimated 100,000 km^2) occurs in the contiguous states at elevations as low as 2200 m. Many of the parks in western states have mountainous areas with much higher elevations.

The combination of the above observations and conditions and the predicted climate warming of the twenty-first century are cause for concern about the future condition of permafrost in national parks and preserves in Alaska and in the mountains of the contiguous western states. Given the sensitivity of ecosystems to permafrost degradation, a well-designed program is needed to monitor the thermal and physical state of permafrost within national parks. The monitoring should assess past changes, determine the current status, and monitor future changes. The thermal aspect of this monitoring effort can be done at three levels of effort, depending on personnel and funding: (1) probing to assess the presence and distribution of permafrost with inexpensive equipment;(2) measuring permafrost surface temperatures with inexpensive data recorders; and (3) measuring vertical temperature profiles in boreholes. For physical monitoring, the three levels of effort should include: (1) reconnaissance-level observations or photo-trend plots to track occurrence of permafrost degradation; (2) detailed measurements of the relative elevations of the ground surface, permafrost table, and water levels across representative transects; and (3) remote sensing of the nature and extent of the various modes of permafrost degradation. Information (manpower, equipment, costs, etc.) for accomplishing these tasks are summarized in Tables 3 and 4.

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Seismic monitoring

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INTRODUCTION TO SEISMIC MONITORING

Relevance and Rationale for Monitoring

Although earthquakes happen frequently in many parts of the world, any occurrence of a moderate to large event is sudden and unexpected. Thus, the earthquake process can be interesting and even frightening to people. Most earthquakes are associated with natural, dynamic processes that shape Earth's landscape. The vast majority of earthquakes are caused by sudden slip along faults, resulting in seismic waves that shake the ground, often with sufficient force to damage structures or trigger other events, such as landslides. When significant earthquakes occur anywhere in the world, such as the December 2004 tsunami-generating event in Indonesia that killed more than 200,000 people, or the October 2005 earthquake in Pakistan that killed more than 70,000 people, emergency response and relief efforts come from around the globe, and there is renewed interest in understanding the causes and in mitigating the devastating effects of earthquakes.

Earthquakes can be significant hazards, as evidenced by occasional damaging and deadly events. Individuals, governments, and organizations can respond to the hazard by understanding the probability and the likely effects of significant events; preparing emergency response plans; enhancing public knowledge about what to do in case of an earthquake; and taking specific steps (such as reinforcing critical or weak structures) to reduce the risk of earthquakes.

Earthquakes and Seismic Monitoring

Earthquakes are often defined as ground vibrations related to a release of elastic energy, or as the sudden slip of a section of a fault plane, releasing stored elastic energy; the latter is the most common source of significant ground vibrations. The release of **elastic energy** associated with earthquakes generates seismic waves that propagate through the Earth and along the Earth's surface across large distances. Most earthquakes are the result of plate tectonic processes. The Earth's plates are moving at speeds of centimeters per year, which produces deformation at plate boundaries. Due to friction on fault surfaces, faults that make up the plate boundaries generally do not slip continuously. As the plates move, rocks are progressively deformed (strained) along the plate boundaries (often over many years or decades), thus storing elastic energy. When the resulting stress on a segment of a fault plane increases beyond a critical threshold, the fault segment slips, creating an earthquake from the release of stored elastic energy. This process is called **elastic rebound** and was discovered after the 1906 San Francisco earthquake by H.F. Reid (1910) a half century before the development of plate tectonic theory.

The vast majority of earthquakes occur along plate boundaries (Fig. 1) as explained above; this process is best explained by the theory of **plate tectonics** (Kearey and Vine, 1996). Some earthquakes occur in plate boundary or intraplate regions associated with other dynamic geologic processes such as volcanic and hydrothermal activity, reactivation of ancient faults, or **crustal loading** (e.g., topographic loads on the crust such as mountain ranges, water loading due to filling of a reservoir). Some earthquakes are caused by human activity related to filling of reservoirs, detonation of explosions, or injection of fluids into the ground. The dynamic geologic processes that result in earthquakes also create topographic relief and interesting and beautiful landscapes. Many national parks are located in geologically interesting areas that include earthquakes or previous plate tectonic activity.

Many visitors to our national parks are interested in how the features within the park came to be. Thus, the geologic and seismic attractions of the park present an opportunity for public involvement, education, and outreach. Geologic and earthquake displays, brochures, and other information can be used to effectively communicate interesting and important facts and concepts to park visitors. A computer monitor displaying local or relevant earthquake activity and one or more educational seismographs increase interest and enhance the effectiveness of the education

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Braile, L.W., 2009, Seismic monitoring, *in* Young, R., and Norby, L., Geological Monitoring: Boulder, Colorado, Geological Society of America, p. 229–244, doi: 10.1130/2009.monitoring(10). For permission to copy, contact editing@geosociety.org. ©2009 The Geological Society of America. All rights reserved.

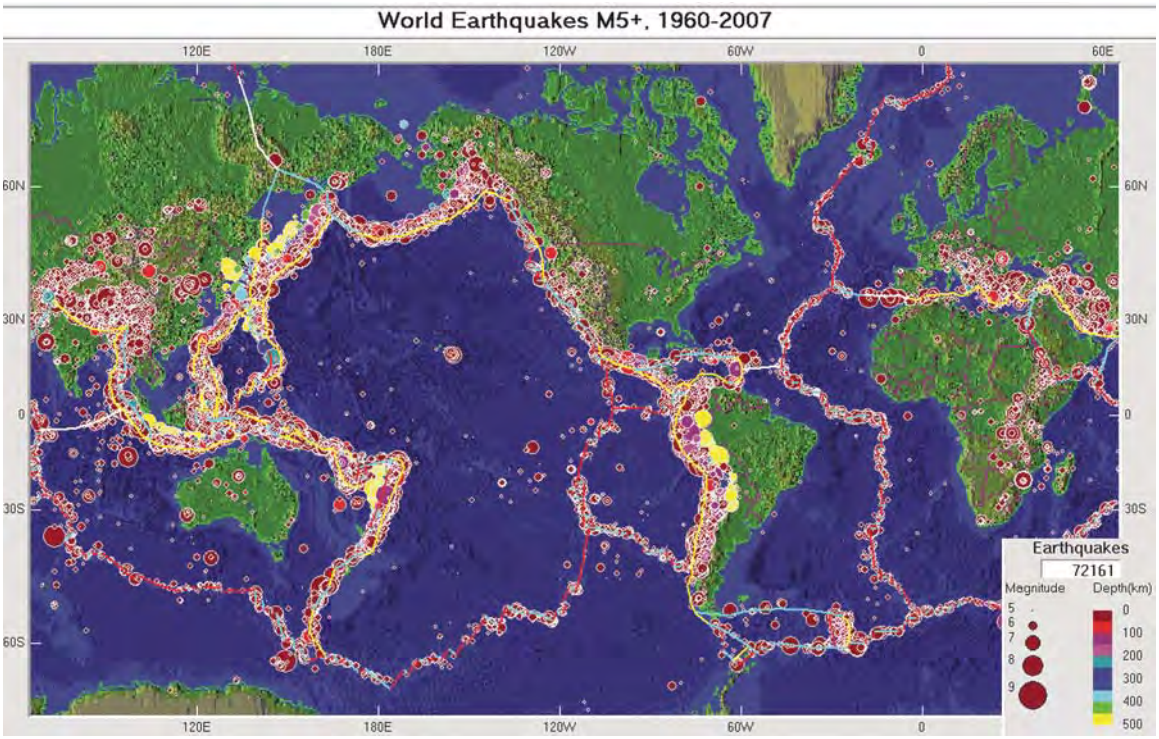


Figure 1. Worldwide earthquakes (M5+, 1960–2007) and plate boundaries (red [divergent boundaries], blue [transform boundaries], and yellow [convergent boundaries] lines; map generated using Alan Jones' Seismic/Eruption program, http://bingweb.binghamton.edu/~ajones/).

and outreach effort. If there is sufficient interest or need because of significant hazard, a more extensive seismic monitoring effort involving a local network of research-quality seismographs may be justified.

Moderate to large earthquakes that are relatively close to an observer may be sensed by the shaking of the ground caused by seismic waves generated by the earthquake. However, even small or distant events can be monitored using sensitive **seismographs** (instruments that record seismic wave motion) which record ground motion and are time synchronized so that the resulting seismograms can be analyzed systematically. By using seismograms from a few or many monitoring stations, one can determine the origin time and location of the event and estimate its **magnitude (M)**—a measure of energy released by an earthquake.

Today, nearly all moderate and larger earthquakes are recorded by seismographs, and most of the recorded events are located using the times of arrivals of seismic waves at seismograph stations. Much of the routine monitoring using global, regional (Figs. 2 and 3), and local seismograph networks has been automated so that event locations and magnitude determinations are often available and distributed online within minutes of an earthquake. Up-to-the-minute online displays of global and regional earthquake activity can be viewed with the IRIS (Incorporated Research Institutions for Seismology) Seismic Monitor at http://www.iris.edu/seismon/ or at the U.S. Geological Survey (USGS) earthquake site, http://earthquake.usgs.gov. Links to U.S. regional and local seismograph networks and near-real-time displays of seismicity and seismograms can also be found at the USGS earthquake site. Instructions for accessing earthquake information online can be found at: http://web.ics.purdue.edu/~braile/edumod/eqdata/eqdata.htm. The USGS/ANSS (Advanced National Seismic System) Web site (http://earthquake.usgs.gov/research/monitoring/anss/products/) contains links to maps and lists of recent earthquakes, shake map displays of ground motion from selected events, hazard maps, and real-time seismogram displays.

Thousands of earthquakes are recorded and located by seismograph stations every year. Many thousands of additional events occur each year but are too small to be recorded, or to be recorded by a sufficient number of stations to be located. The average number of earthquakes per year worldwide is listed by magnitude in Table 1. A frequency-magnitude plot of these data is also shown in Figure 4. The frequency-magnitude plot, also called a **Gutenberg-Richter diagram** after two famous seismologists, represents a fundamental relationship in seismology in which there are about ten times fewer earthquakes within any given area and in any given time period for each increase of one magnitude unit. This relationship is found to be valid for regional and local seismic source zones as well. A frequency-magnitude plot can be used to estimate recurrence intervals. For example,

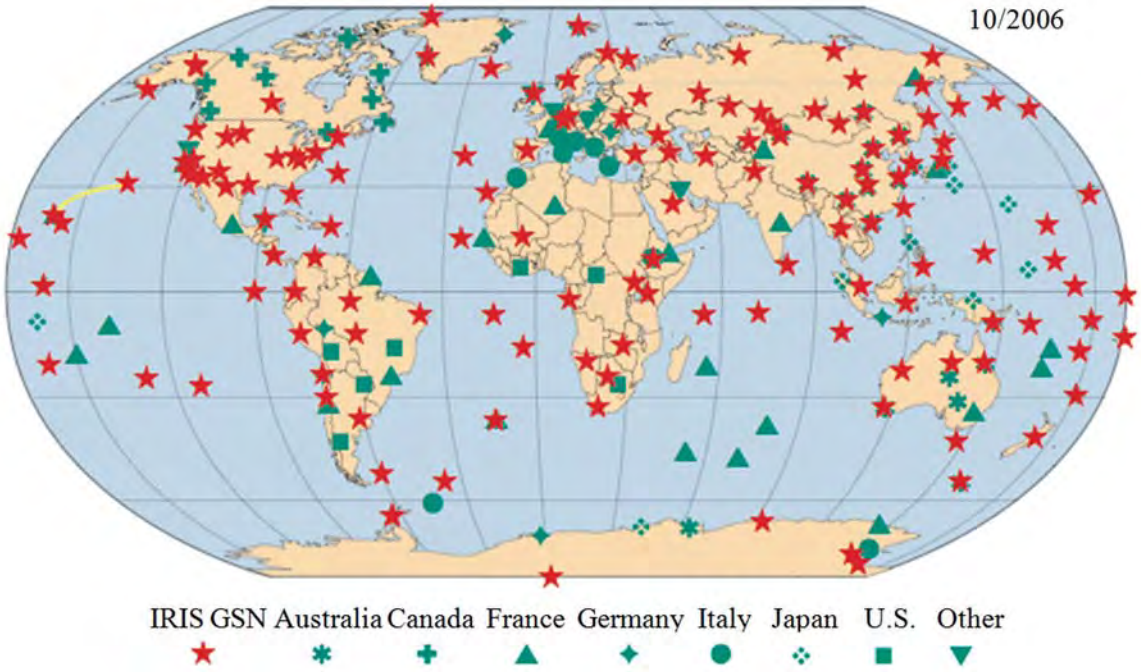


Figure 2. Seismograph stations of the Global Seismograph Network (GSN) and the Federation of Digital Broadband Seismic Networks (FDSN). Map from IRIS, http://www.iris.edu.

from the frequency-magnitude plot shown in Figure 4, we can estimate that there should be ~150 magnitude 6 or greater earthquakes in the world every year, or about one M6+ event every two to three days. A quick look at a list of recent earthquake activity, such as the USGS last 30 days catalog, accessible at http://earthquake.usgs.gov, verifies this estimate. The recurrence interval provides a very useful earthquake forecasting method that can be used for any seismic source area for which sufficient earthquake data are available to allow calculation of a reliable frequency-magnitude plot.

CAUSES OF EARTHQUAKES AND TIME VARIATIONS IN EARTHQUAKE ACTIVITY

As stated previously, the vast majority of earthquakes are caused by plate motions, and ~95% of all earthquakes occur in plate boundary areas. A relatively small number of earthquakes occur in intraplate regions, on reactivated ancient faults, and in areas of crustal loading not directly associated with plate boundaries. Although most earthquakes are related to plate boundaries, some plate boundaries are very wide and diffuse. An example is the complex plate boundary region in western North America in which convergent, divergent, and transform plate boundaries exist in the coastal area and just off the coast. These currently active plate tectonic processes affect the entire western United States. This tectonic activity is evidenced by the widespread seismicity of the western United States (Fig. 5). The seismicity map in Figure 5 also illustrates one of the online tools (the IRIS Event Search) that can perform a catalog search and create a map of earthquake activity for any area in the world.

The time distribution of earthquakes is largely random, though recurrence intervals do provide a probability estimate of the average time between events of a specified magnitude. Because plate motions are continuous, earthquake activity over time is expected to be similar to past activity.

In any given seismic source area, earthquake activity often consists of relatively well-defined "sequences," such as mainshock/aftershocks; foreshock/mainshock/aftershocks; pairs or triplets of significant events; swarms; or long-term, random time distributions that can result in two or more closely spaced significant events, with long periods between such events. Despite some successes and considerable interest and efforts in earthquake prediction, there currently is no consistently reliable method for predicting earthquakes, so significant events occur suddenly and without warning. However, areas of potentially significant earthquake activity are well known, and statistical analysis of past events, including the frequency-magnitude relation, provides valuable estimates of future activity and earthquake hazards.

VITAL SIGNS AND METHODS FOR SEISMIC MONITORING

Seismic monitoring utilizes sensitive seismographs to record the ground motion from seismic waves created by earthquakes or

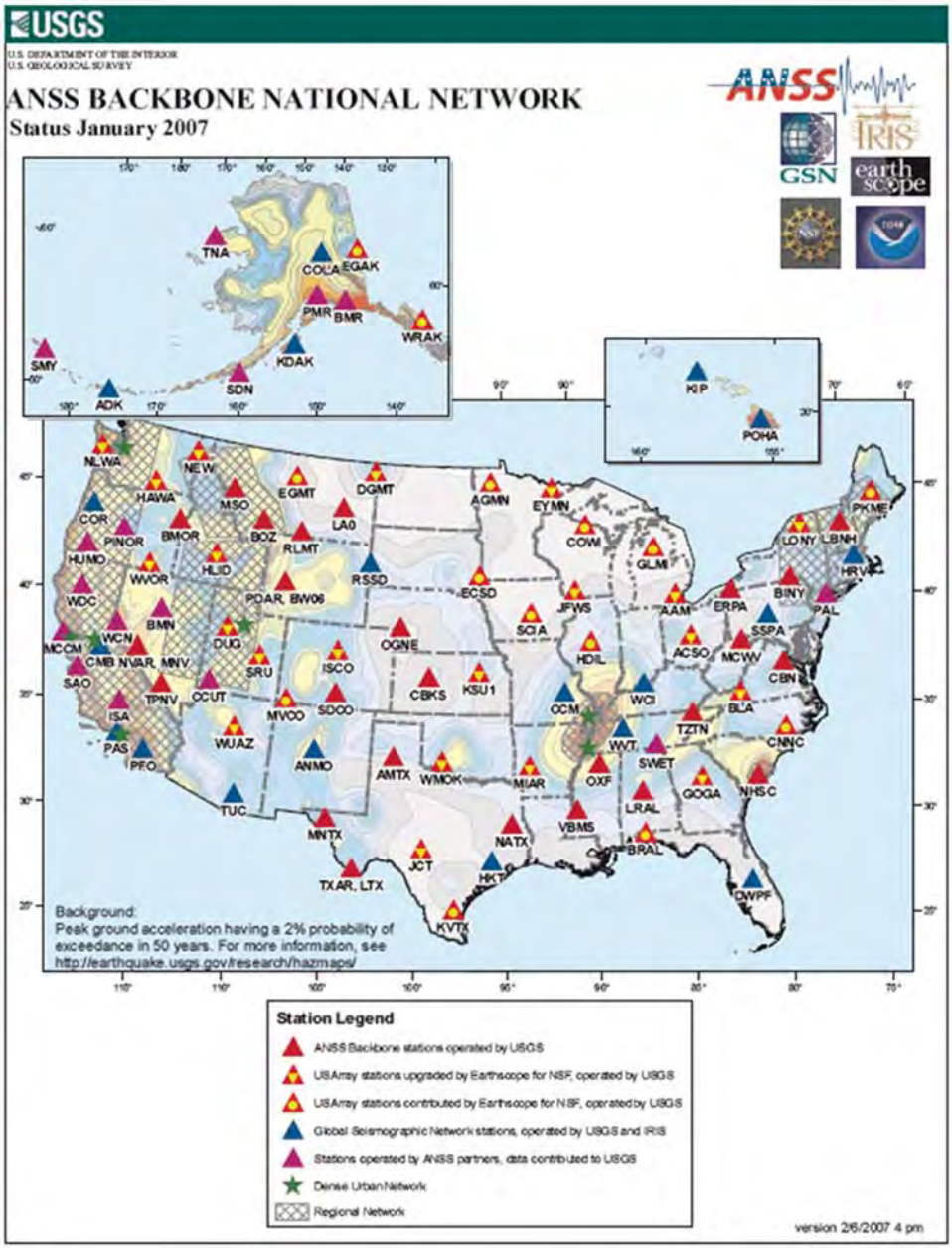


Figure 3. Seismograph stations of the U.S. Advanced National Seismograph System (ANSS). Map from the U.S. Geological Survey, http://earthquake.usgs.gov/research/monitoring/anss/.

other sources. Seismograms from seismic monitoring stations can be used to determine the location, origin time, and magnitude (as well as other characteristics) of earthquakes. The detection ability of a seismograph or network of seismographs is dependent upon the type of instruments, the availability of accurate timing, the number and locations of stations relative to the earthquake location, the size of the earthquake, and the ambient ground vibration noise level.

An excellent description of seismic monitoring is contained in the U.S. Geological Survey Circular 1188 (1999), available at http://pubs.usgs.gov/circ/1999/c1188/circular.pdf. Circular 1188 describes the basic concepts of seismic monitoring (section 2), outlines plans for a modern national seismograph network, the Advanced National Seismic System (ANSS), and describes the major benefits and uses of seismic monitoring. These benefits and uses include: earthquake emergency management, warnings of volcanic eruptions, warnings of earthquake-generated tsunamis, seismic hazard assessment, earthquake engineering, seismology research, public information, and education. Seismic monitoring is also described in *Earthquake Monitoring: Then and Now*, available at http://earthquake.usgs.gov/learning/eqmonitoring/eq-mon-6.php, and in Ansell and Taber (1996), Stein and Wysession (2003), and Bolt (2004). Further information on seismology, earthquakes and earthquake hazards can be found in Abbott (2006), Bolt (1993, 2004), Bolt et al. (1977), Bryant (1992), Hough (2002), Keller and Blodgett (2006), Kovach

TABLE 1. GLOBAL FREQUENCY OF EARTHQUAKES BY MAGNITUDE

Descriptor	Magnitude	Average annually
Great	8 and higher	1*
Major	7–7.9	17†
Strong	6–6.9	134†
Moderate	5–5.9	1319†
Light	4–4.9	13,000 (est.)
Minor	3–3.9	130,000 (est.)
Very minor	2–2.9	1,300,000 (est.)

Note: From U.S. Geological Survey (http://neic.usgs.gov/neis/eqlists/eqstats.html).
*Based on observations since 1900.
†Based on observations since 1990.

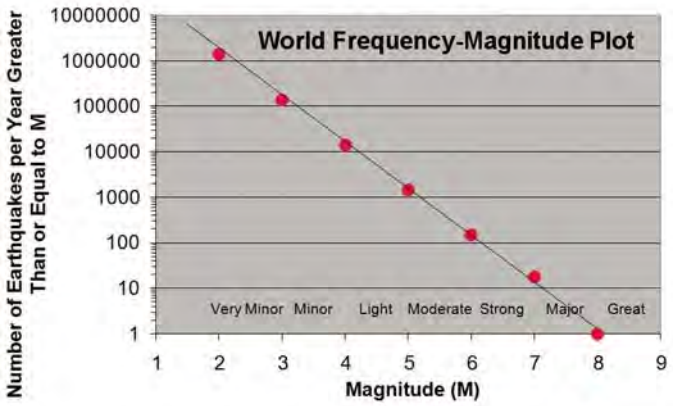


Figure 4. World frequency-magnitude plot (data from Table 1, U.S. Geological Survey).

(1995), Shearer (1999), Stein and Wysession (2003), and Yeats et al. (1997).

Two vital signs related to seismic monitoring are **earthquake activity** and **deformation and active tectonics.** Earthquake activity can be monitored using seismographs; historical data can be used to identify fault zones and other likely sources of future events, and to assess earthquake hazards. Deformation and active tectonics is related to earthquake activity and generally involves mapping and surveying fault scarps or other geomorphic features, and measuring long-term ground deformation using very accurate but traditional survey techniques or GPS (Global Positioning System) monitoring. Selected methods for seismic monitoring of these vital signs are listed in Table 2. This section briefly describes each of these methods, shows some examples of their use, and provides some references for further information or examples of each.

Earthquake Activity

Monitoring Earthquake Activity

Earthquakes are recorded by seismographs. Because many seismograph stations operate around the world and automatically send their data to central locations for routine analysis, a large amount of information about earthquake activity is rapidly available online. The IRIS Seismic Monitor (http://www.iris.edu/seismon/) and the USGS earthquake site (http://earthquake.usgs.gov) are convenient sources of current earthquake lists and maps for global and regional areas. These sites also link to others with near-real-time seismograms. For more local areas, data from regional networks (accessible from http://earthquake.usgs.gov and http://earthquake.usgs.gov/regional/) are also available. Earthquake information from these locations can be easily compiled into local earthquake catalogs, maps for statistical and spatial analysis, or other purposes. Regional and local maps can be created online from the USGS earthquake catalog using the IRIS Event Search and USGS Catalog Search tools. Earthquake information for local to global areas can also be viewed and analyzed using the Seismic/Eruption software (http://bingweb.binghamton.edu/~ajones/) that includes an extensive earthquake catalog. Specialized earthquake data sets can also be imported into the Seismic/Eruption software, as illustrated in Figure 6.

For relatively little cost and effort, one can now install and operate a seismograph at any location to record small (or large) local and regional events, as well as large earthquakes from anywhere in the world. The real-time seismograph display can be linked to additional earthquake information such as a list of significant earthquakes in the area, earthquake history, seismicity maps, and other information online. The seismograph display also provides an excellent opportunity for an education and outreach program in earthquakes, seismology, tectonics and related earth science. An inexpensive and easy-to-operate seismograph for this purpose is the AS-1 seismograph (http://web.ics.purdue.edu/~braile/indexlinks/as1.htm), which is usually described as an educational seismograph, but can very effectively record earthquakes. Another excellent option is the PEPP-V seismograph (http://www.indiana.edu/~pepp/). Other commercial seismographs can also be utilized for a local seismograph station. A guide to installing a seismograph can be found at http://pubs.usgs.gov/of/2002/ofr-02-0144/ofr-02-0144.pdf. A local college or university or geological survey office may be available to provide assistance with seismograph installation or data distribution.

If three or more seismographs are installed in a local area, or a more extensive seismic network established, earthquake locations for local events can be determined from these local stations. These hypocenter determinations are potentially more accurate (depending on the characteristics of the local network and the proximity to stations in established networks) and it may be possible to detect more and smaller events that can be used to better delineate seismic source zones. Earthquake seismograms can also be used to determine principal stress directions and infer the type of faulting (normal, reverse or thrust, strike-slip). For a description of techniques for determining earthquake mechanisms (sometimes referred to as fault plane solutions), see Stein and Wysession, (2003, chapter 4). Earthquake mechanism studies have been very important in tectonic interpretations.

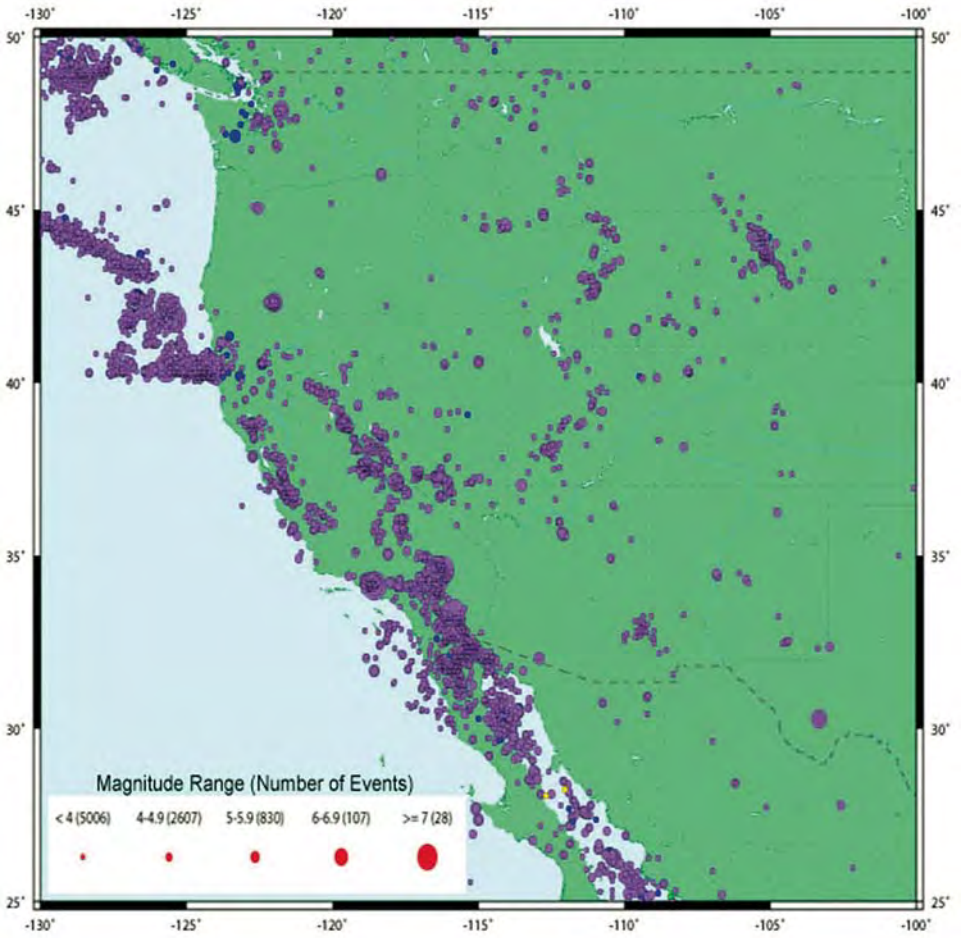


Figure 5. Map created using the IRIS Event Search tool. Earthquakes of M4+ from 1990 to 2000 were obtained from the earthquake catalog for the region shown. The epicenters were then displayed on a map using the online tool.

Local seismograph networks that include a large number of stations often utilize telemetry for rapid and efficient data transmission and collection of data for analysis at a central location. Of course, installing and operating such a network involves the significant costs of purchasing and installing the instruments, as well as maintenance and operation, which requires substantial trained staff. An example of a regional network is the Alaska seismograph network (Fig. 7). Using stations from this network as well as other global and regional stations, extensive earthquake activity and seismicity maps for Alaska (Fig. 8) are available for analysis. A poster showing major faults and associated significant earthquakes in Alaska can be viewed at http://www.aeic.alaska.edu/html_docs/images/earthquakes_in_alaska.jpg.

Analysis and Statistics of Earthquake Activity

Earthquake data for a local area from a local seismograph network, or online data from regional or global networks can be analyzed at very low cost and effort. Analysis can determine frequency of occurrences, including a frequency-magnitude diagram, an earthquake catalog, and a list of notable earthquakes.

If a local seismograph or network is available, one can also maintain a catalog of recorded events and an archive of seismograms. With a little extra effort, seismicity maps of the local area can be prepared (see method 1, above) and compared with fault maps and other geological and geophysical maps for tectonic interpretation. An online tool for accessing Quaternary fault maps for many areas of the United States is available at http://earthquake.usgs.gov/regional/qfaults/. The earthquake activity and tectonic interpretations for local areas can be compared with predicted plate motions from global plate motion models at http://sps.unavco.org/crustal_motion/dxdt/nnrcalc/.

Analysis of Historical and Prehistoric Earthquake Activity

Historical earthquake activity is an interesting characteristic of many areas that can be used to assess future earthquake probabilities and hazards, and to relate to local geological features. In some cases, prehistoric earthquake records may be accessible, which can extend the record of earthquake activity.

For most areas, it is relatively easy to compile a record of historical earthquake activity online. Earthquake catalog searches (described above) can be used to obtain hypocenter, origin time, and magnitude information for any local area. These data are reasonably complete and accurate back to 1973, and generally good even back to 1960. There are also global data files of significant

TABLE 2. SELECTED METHODS FOR SEISMIC MONITORING

Methods	Level*
Monitoring earthquake activity (earthquake origin times, locations, magnitudes, maintain local earthquake catalog)	
a. Internet access to data from global, national, or regional seismograph networks	1
b. Operate local seismograph station (educational seismograph, research-quality seismograph)	1,2
c. Operate seismograph network (3 or more stations, educational or research-quality seismographs; earthquake detection and location including the possibility of recording microearthquakes that may not be recorded by other networks, more accurate determination of hypocenters, and analysis of earthquake mechanisms)	2–3
Analysis and statistics of earthquake activity (determine local frequency of occurrence, maintain earthquake catalog and seismograph archive, prepare seismicity maps, identifying earthquake sequences, comparison of seismicity maps with other information)	
a. Determine local area frequency of occurrence (table and frequency-magnitude graph), compile catalog of events, notable events (significant magnitude, felt, damage or effects, swarm or sequence)	1
b. Maintain seismogram archive, prepare local and regional seismicity maps and compare with fault maps, geologic maps, volcanic or hydrothermal features, other geophysical data (such as gravity and magnetic maps that may indicate faults or other significant structures), analyze cause of earthquakes in relation to existing local and regional geology and tectonic models and plate motions	2
Analysis of historical and prehistoric earthquake activity (analysis of catalogs, maps, accounts, evidence of earthquake effects)	
a. Prepare and analyze catalogs, maps, and accounts of historical earthquake activity; develop earthquake history (earliest account and records, largest magnitude, list of significant events, etc.)	1
b. Investigate prehistoric earthquake activity, Native American accounts	2
c. Investigate prehistoric earthquake activity, paleoseismology investigations (trenching, seismic imaging of faults, analysis of faulted landforms, mapping fault exposures), evidence of fault effects (fault scarps, liquefaction, earthquake-induced landslides, ground failure, creep, vertical movements, tilt, etc.)	2–3
Earthquake risk estimation	
a. Evaluation of seismic source zones and risk maps from published sources and Internet, preparation of local risk map	1
b. Microzonation (local seismic sources, site effects that could produce amplification of seismic waves, maps of sediment thickness and properties), prediction of possible ground motion (acceleration, intensity of shaking, and effects)	2
Geodetic monitoring, ground deformation (precise measurements of position of selected locations, made at two or more times, used to calculate deformation of the ground related to ongoing tectonic, geological, or other processes)	
a. Plate motions predicted from geodetic models available on Internet	1
b. Calculation of deformation rates from earthquake effects (surface rupture, ground failure, creep)	2
c. Geodetic surveying (permanent or campaign Global Positioning System (GPS) measurements, leveling surveys, strain meter, tilt meter, satellite radar interferometry)	3
Geomorphic and geologic indications of active tectonics (geologic mapping of landforms, topography, and other features may indicate recent tectonic control suggesting active tectonic processes)	
a. Topographic features (scarps, mountain fronts, sag ponds, coastal landforms, etc.), locations of natural springs and hydrothermal features, analysis of river drainage patterns, evidence of vertical movements, tilting of lake levels	2–3

*Levels: 1—relatively simple and low cost methods; 2—methods that require moderate effort, some specialized training and experience, and modest cost; 3—methods that require significant effort, expertise, and cost.

events for the past 2000 or more years. The older earthquake information is much less complete, relies on non-instrumental estimates of magnitude (using felt reports, where available), and usually includes only larger events. Several historically significant publications on U.S. earthquakes and earthquake histories of each state can also be found on the USGS earthquake site. Several, older significant events (such as the 1811–1812 New Madrid earthquakes, the 1906 San Francisco earthquake, the 1959 Hebgen Lake earthquake, and the 1964 Alaska earthquake) have one or more publications in journals that focus on the specific event and previous earthquake history. Maps of historical earthquake data can be produced using the online tools in the USGS catalog search and using the Seismic/Eruption software (or other available mapping programs, such as geographic information system [GIS] software or Google Earth); the data is imported into the program with the desired area and time window. Instructions for using the Seismic/Eruption program for such purposes are available in the program help files and online at http://web.ics.purdue.edu/~braile/edumod/svintro/svintro.htm.

In some areas, additional earthquake information may be available from Native American accounts. Such accounts may have already been compiled and published, but some could require original research efforts. Of course, these accounts are incomplete, as they only include felt events and events close to where people lived at that time. Although researching possible Native American accounts of prehistoric earthquake activity would likely be a time-consuming project, it may be of interest to some people as it combines cultural, historical, and scientific studies.

Prehistoric earthquake information can often be obtained from specific geological studies of earthquake effects. These include studies of fault scarps, trenching fault exposures to reveal

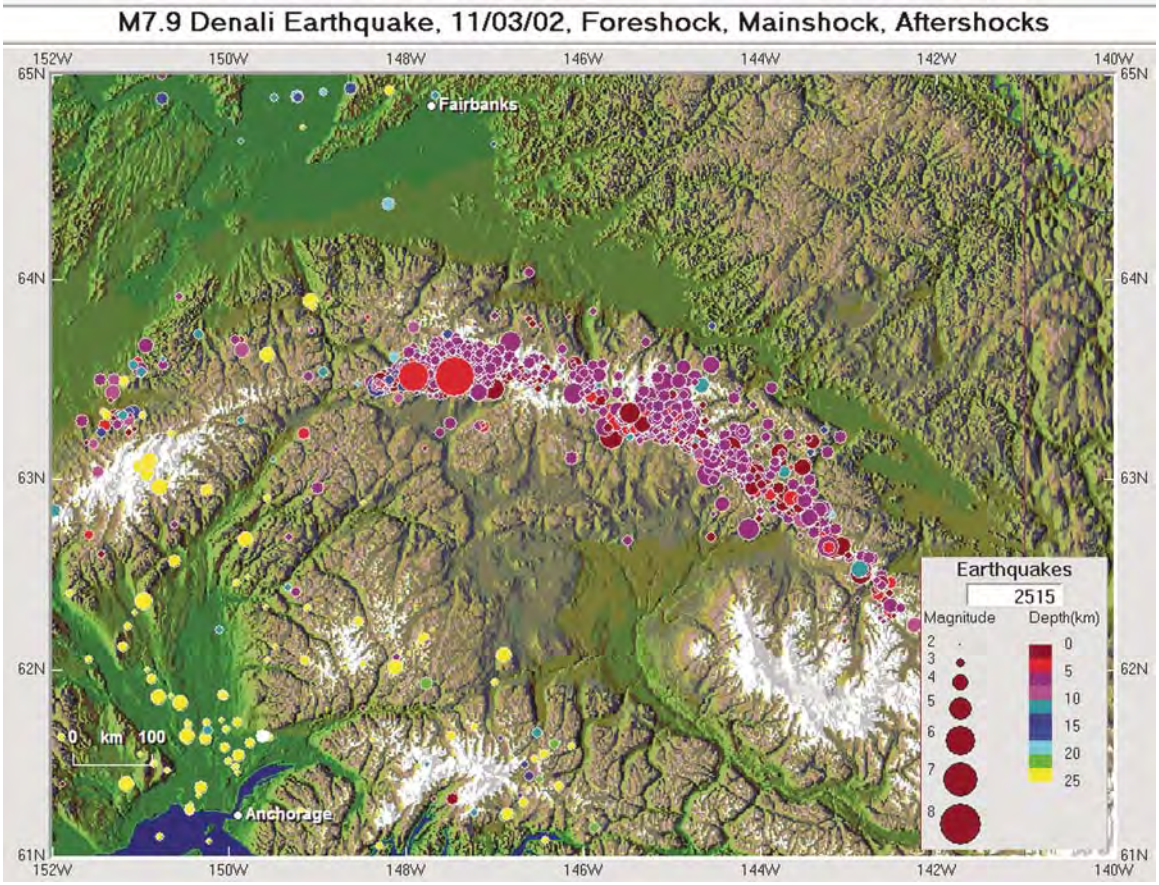


Figure 6. Earthquakes associated with the 3 November 2002 M7.9 Denali event displayed with the Seismic/Eruption software. The earthquake information (hypocenters, origin times and magnitudes) for events of M2.5+ from 1 October 2002 to 30 October 2003 were obtained by catalog search from the U.S. Geological Survey earthquake Web site. The data were then imported into the Seismic/Eruption program and displayed on the software's topographic relief map for the Denali earthquake view. The M7.9 mainshock epicenter (large dot) and the 23 October 2002 M6.7 foreshock epicenter (smaller dot to the west of the mainshock epicenter) have been highlighted in this view. Most of the other epicenters visible on the map are aftershocks that occurred along the area of the Denali fault that ruptured during the mainshock event.

ancient fault offsets that can sometimes be dated, using leveling or other survey techniques to identify deformed surfaces or landforms that may have been produced by earthquake movements, and using geophysical studies of a fault zone to determine its rupture history. These studies are often called **paleoseismology** and usually require extensive and very detailed field studies by experienced personnel. However, paleoseismology offers the potential to identify the most significant events in the recent past and therefore significantly improve the earthquake record, particularly the frequency of occurrence of the largest events in a local area. Further information on paleoseismology and the methods mentioned here are in Yeats et al. (1997) and Keller and Pinter (2002).

Earthquake Risk Estimation

Earthquake risk is usually evaluated using the historical seismicity record that provides information on the probability of occurrence (such as the frequency-magnitude relation for the area) of earthquakes of various magnitudes, and sometimes, an estimate of the maximum magnitude earthquake that is likely to occur. Estimates of maximum magnitude can also utilize the prehistoric record and an evaluation of the faults in the area, especially the length and depth extent of relatively continuous faults. When detailed information about near-surface geology is available, the risk estimation may also include estimations of ground motion and of anticipated effects on buildings, roads, and other structures.

Detailed earthquake hazard maps have been prepared for the United States and most of the world. The USGS has a very useful site (http://earthquake.usgs.gov/research/hazmaps/) that has links to these maps and other information about earthquake hazards. This site also contains an earthquake hazard mapping tool. A latitude and longitude range (within the United States) can be entered, and the tool will prepare a hazard map for that area. The

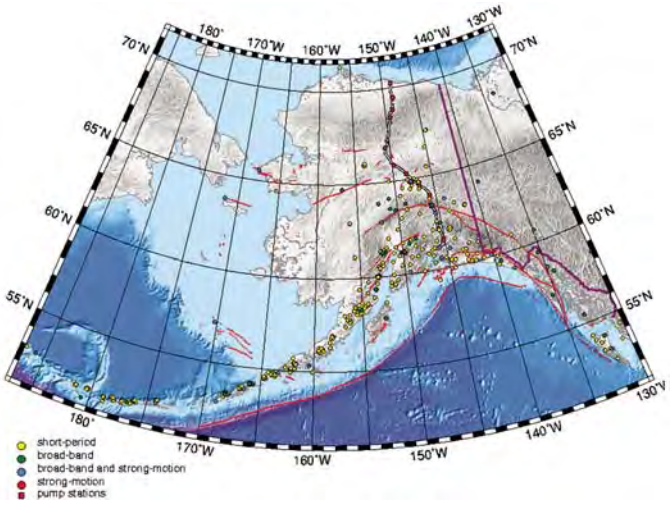


Figure 7. Seismograph stations in Alaska (http://www.aeic.alaska.edu/Seis/maps/map_of_stations.html).

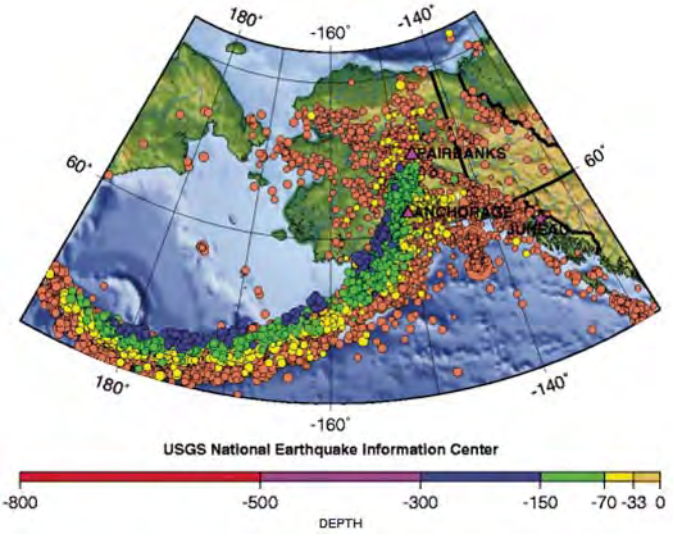


Figure 8. Seismicity of Alaska, 1990–2001, from the U.S. Geological Survey (http://earthquake.usgs.gov/regional/states.php?old=alaska/alaska_seismicity.html).

hazard maps are usually displayed as contour diagrams with the Peak Ground Acceleration (**PGA**) and the probability of its being exceeded in a specified time period (usually 50 years). With this tool, it is very easy to produce an earthquake risk map of any area in the United States.

If a more detailed and complete analysis of earthquake risk is desired for a specific area, it is possible to perform a hazard assessment involving analysis of local and regional seismicity (locations of seismic source zones, probabilities of occurrence of various magnitude events, estimation of the maximum likely magnitude, and detailed mapping of near-surface materials). However, a detailed risk assessment involves considerable effort and should be performed by experienced persons. Some local areas of the United States have already been specifically studied for earthquake risk; detailed maps for these areas are available at the USGS Web site listed above.

Deformation and Active Tectonics

Geodetic Monitoring, Ground Deformation

Geodetic monitoring is often performed to determine plate motions and current (active tectonic) ground deformation for a given area. There are a number of methods available for this purpose, including precise leveling and surveying, strain and tilt meter recording, detailed geologic mapping of active tectonic features, GPS (Global Positioning System) monitoring, and satellite techniques such as satellite laser ranging and satellite radar interferometry. Recently, GPS and satellite techniques have become very popular due to improved technology and computer processing capabilities. Effective application of these methods generally requires multiple observations over fairly long periods of time. A useful summary of these techniques and examples of applications can be found in Keller and Pinter (2002).

Information about potential ground deformation related to plate motions is available online at http://sps.unavco.org/crustal_motion/dxdt/nnrcalc/. This tool allows one to determine a crustal motion (velocity) estimate for any location; velocity is calculated from derived global or regional plate velocity models. Maps of global and regional GPS results can also be generated at the Jules Verne Voyager site at http://jules.unavco.org/Voyager/Earth.

Detailed mapping of fault offsets and other earthquake effects can be used to determine average deformation rates if accurate dating of events can be determined. However, such features may not be present, or it may not be possible to date the movements. Detailed mapping for determination of ground deformation involves significant effort and experienced persons. Additional information on these techniques and examples of their application can be found in Yeats et al. (1997) and Keller and Pinter (2002).

Geodetic surveying using one or more of the methods listed above can be performed for detailed monitoring of ground deformation that is often related to active tectonics and earthquake and volcanic activity. Because the methods used require many precise measurements, repeated observations over many years, sophisticated instrumentation and computer processing, these studies are relatively expensive and are usually performed by experts as part of an extensive, long-term research program. An example of results of satellite radar interferometry for the Yellowstone area is shown in Figure 9.

Geomorphic and Geologic Indications of Active Tectonics

Many geologic processes and landforms are affected by earthquakes and fault activity. Active faults often are visible as fault scarps, topographic breaks, and alignment of springs, lakes or sag ponds, and hydrothermal features. Faults also cause topography, such as in fault-bounded valleys, and produce uplift,

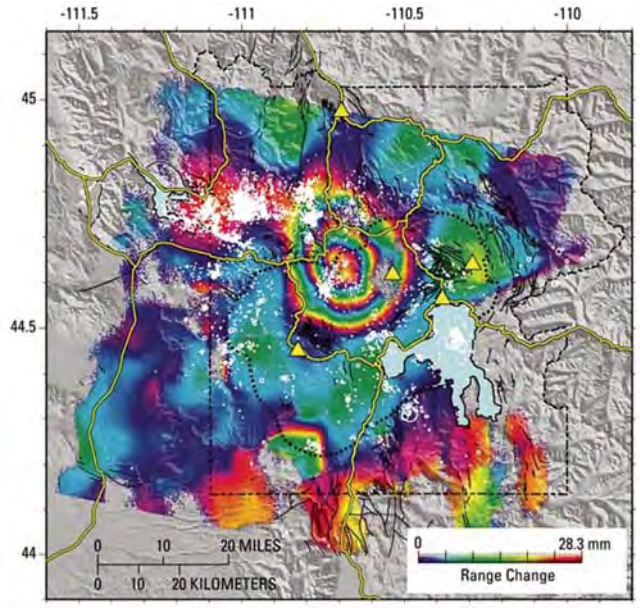


Figure 9. InSAR image of the Yellowstone area from the U.S. Geological Survey fact sheet 100-03 (2004) "Tracking Changes in Yellowstone's Restless Volcanic System" (available at: http://pubs.usgs.gov/fs/fs100-03/). Caption from the fact sheet: "A new satellite-based technique known as Interferometric Synthetic Aperture Radar (InSAR) allows direct and precise measurement of the vertical changes in ground level. This InSAR image of the area around the Yellowstone Caldera (dotted line) shows vertical changes during the 4-year period 1996–2000. The ringed pattern centered northwest of Yellowstone Lake is a prominent area of dome-shaped uplift. Each complete cycle of colors in the color bands represents a little more than one inch (28.3 mm) of vertical change. Yellow triangles are continuous GPS stations; white dots are locations of earthquakes in the period 1996–2000."

subsidence and tilt, and control drainage patterns. Most of these features can be effectively identified and interpreted by detailed geological mapping. If the features are prominent, mapping and associated studies can be relatively straightforward. More subtle or complex effects require extensive study and a multidisciplinary approach, often involving geological interpretation, precise topographic surveying and leveling, collection and interpretation of geophysical data, and age dating. A useful summary of geomorphic and geological methods for study of fault zones, active tectonics, and related earthquake features is provided by Keller and Pinter (2002).

Summary and Recommendations for Seismic Monitoring

Seismic monitoring in and around national parks is used for earthquake, tectonic, and geological research, earthquake hazard assessment, and public education. With only a small effort, one can investigate the earthquake history and hazards of a national park and surrounding areas. In both active and inactive areas, an educational seismograph can be used to monitor local, regional, and global earthquake activity. An operating seismograph is always an attraction for park visitors. More extensive seismic monitoring and analysis of earthquake effects, tectonic activity and earthquake risk requires significant effort, costs and expertise, and may require installation of a seismograph network and other instrumentation.

A few national parks (Yellowstone, Grand Teton, Mount Rainier, Mount St. Helens, and Hawaii Volcano) have seismograph networks or are part of regional seismograph monitoring networks. Parks in California, Nevada, Utah, Washington, Oregon, Alaska, and Puerto Rico are monitored by state and regional seismograph networks. A listing of regional seismograph operators and cooperators is available at http://earthquake.usgs.gov/research/topics.php?areaID=12, with additional information about seismic monitoring and the earthquake activity in these regions. Seismographs operating in national parks in low seismicity areas are generally installed for educational purposes and can generate public interest from recording regional or global earthquake activity. Finally, a list of seismic monitoring methods not discussed in this chapter is given in Table 3.

STUDY DESIGN

In considering a plan for seismic monitoring of a national park (or other local area), the specific or unique features of the park, the level of the local earthquake and tectonic activity, and the goals should be evaluated. For example, some areas are very seismically active (or are adjacent to seismically active areas) and have prominent features (such as fault-related topography, volcanic activity, or springs and hydrothermal activity) related to earthquakes and active tectonics. In these areas, one should also consider the earthquake hazard and emergency management response objectives of seismic monitoring. Scientific research designed to better understand the earthquake activity and geological evolution of the area may also be important. Assistance in seismic monitoring design and objectives may be obtained from the USGS and academic researchers already in cooperation with a specific park. Additional geology and tectonic information on national parks can be found in Harris et al. (2004) and Lillie (2005).

Some areas may not display significant local earthquake activity but may still be selected for seismic monitoring because of visitor interest and educational objectives. As mentioned previously, seismic monitoring and a visible seismograph display can be very effective in generating visitor interest in park features and in the geology of the area, and can be used as a key element of an education program. In both seismically active and relatively inactive areas, at least one educational seismograph for earthquake monitoring and display is a very cost-effective approach to beginning (or augmenting) a seismic monitoring program.

Plans for a local seismic monitoring program must also include consideration of the cost of the program, and the resources and personnel available to be devoted to the effort. Several cost-effective methods for seismic monitoring studies that do not require substantial personnel or experts to conduct the studies are listed in Table 2 and described above. Of course, more extensive

TABLE 3. OTHER SEISMIC MONITORING METHODS NOT DISCUSSED IN DETAIL

Methods	Level*
Tsunami hazard (applies to low elevation, coastal areas, tsunami warning system in place in many area of the United States that are at risk)	
a. Connect to tsunami warning system	1
b. Investigation and mapping of tsunami deposits to determine frequency of past tsunamis that have affected the area	2
Earthquakes caused by human activity (applies to areas where specific human activities are present, such as crustal loading [mostly reservoir filling], deep well injection or removal of fluids, mining that reduces the confining pressure of rocks adjacent to the mined areas, rock bursts, large explosions)	
a. Monitoring and analysis methods are similar to those described in Table 2.	1–3
Forecasting earthquakes (analysis of earthquake statistics, recurrence intervals, earthquake cluster and swarm activity, and aftershock sequences to forecast future events)	
a. Monitoring and analysis methods are similar to those described in Table 2.	1–3

*Levels: 1—relatively simple and low cost methods; 2—methods that require moderate effort, some specialized training and experience, and modest cost; 3—methods that require significant effort, expertise, and cost.

and sophisticated seismic monitoring studies will require greater resources and usually will need to be performed by experienced persons or experts in the particular method selected.

The EarthScope program presents a unique opportunity for parks and other resources and organizations to be involved in earthquake and earth science education and research. Currently, EarthScope has deployed a large array of seismographs over a region in the western United States. The array will be progressively shifted to the east to provide coverage of the entire contiguous United States. The deployment is aimed at investigating the structure and evolution of the continent. The current status of the instrumentation deployment can be viewed at: http://www.earthscope.org/current_status/. In addition, an extensive array of GPS instruments is also being deployed, primarily in the western United States, to study the tectonics and deformation associated with the plate boundaries of that area. Temporary, portable arrays are also being utilized in research projects focused on specific geological features or areas. Data and results from these programs are available and can be used in association with local seismic monitoring and other geological and geophysical studies to enhance our knowledge of these areas and better educate the public. In some cases, it has been possible to deploy EarthScope instruments in national parks and to design specific experiments related to the earth science features in parks. Additional opportunities will exist as additional instruments are deployed and the seismograph array progresses across the United States. Further information on the EarthScope can be found at the EarthScope program Web site (http://www.earthscope.org/) and in Meltzer et al. (1999) and Meltzer (2003).

CASE STUDIES OF SEISMIC MONITORING

As an example of seismic monitoring in a national park, this section describes a study and monitoring program focused on the Joshua Tree National Park area; this study mostly uses data available online. Because Joshua Tree National Park is near a very seismically active area of southern California, earthquakes within or near the park present a significant seismic hazard. Strong ground shaking within the park could damage structures or trigger landslides or rock fall. To view the earthquake activity in and near the park, we used a catalog search and the Seismic/Eruption software to produce a map of seismicity from 1990 to 2004 (Fig. 10). Most of the epicenters are outside of the park, associated with the San Andreas and related faults to the west; nevertheless, large earthquakes on these faults can cause significant shaking within the park (Fig. 11).

Many of the earthquakes shown on the seismicity map (Fig. 10) are aftershocks associated with the M7.4 Landers and M6.4 Big Bear earthquakes that occurred on 28 June 1992. The north-trending zone of epicenters just to the west and north of the Joshua Tree National Park boundary is the area of the Landers aftershocks. The cluster of epicenters near the northwest corner of the maps is the Big Bear epicenters.

A simple and useful statistical analysis of earthquake activity near Joshua Tree National Park can be completed by preparing a frequency-magnitude plot using the earthquake data shown in Figure 10. To obtain the data for the frequency-magnitude plot, one can sort the earthquake catalog by magnitude for the geographical area and time period selected, and then count the events within each magnitude range. The sorting and counting can easily be accomplished in a spreadsheet program such as Excel. Alternatively, if the data are imported into the Seismic/Eruption program, the counter within the software can be used to sequentially count the number of events above a specified magnitude cutoff.

The results of the frequency-magnitude analysis for the Joshua Tree National Park and surrounding area are shown in Figure 12. A straight line has been fitted to the central data points illustrating that the frequency-magnitude relation for this area is approximately linear, similar to that shown for the worldwide earthquakes in Figure 4. The observed number of earthquakes for magnitudes of 2 and above is low because not all small earthquakes are well recorded (or their magnitudes determined) by the available seismographs in the area. Also, the data point for M+ = 7 does not fall on the line, probably because the time period selected (15 years) was not long enough to accurately determine the rate of earthquake activity for large, relatively rare events. For example, an M7+ event occurred within the selected time

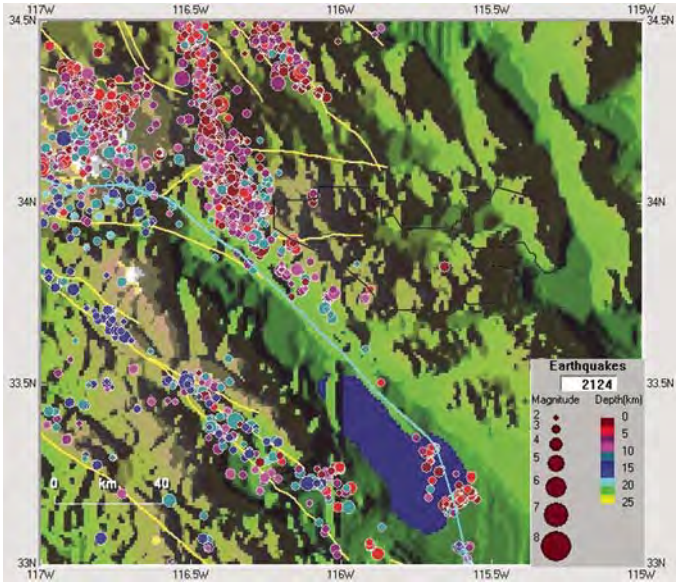


Figure 10. Earthquake epicenters in the Joshua Tree National Park area (park boundaries shown by thin black outline near center of map). Light lines are mapped faults. The earthquake information (hypocenters, origin times and magnitudes) for events of M2.0+ from 1 January 1990 to 31 December 2004 were obtained by catalog search from the U.S. Geological Survey earthquake Web site. The data were then imported into the Seismic/Eruption program and displayed on the software's topographic relief map (topo30) using the "make your own map" tool.

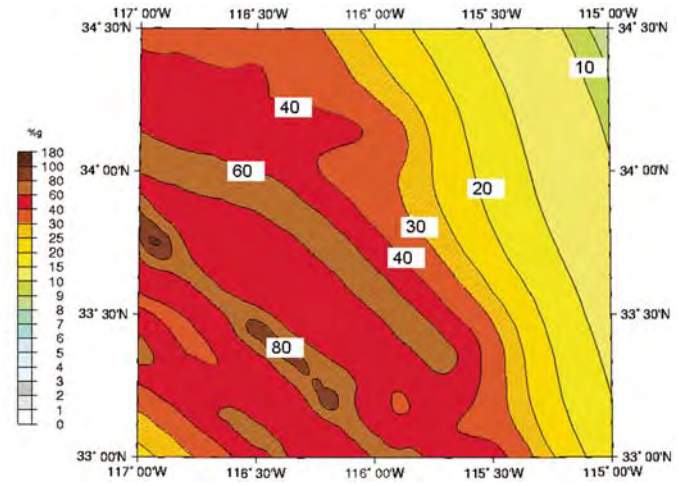


Figure 11. Earthquake risk map for the Joshua Tree National Park area (area shown is the same as in the seismicity map in Fig. 10). The contours show estimated peak acceleration (%g) with a 10% probability of being exceeded in 50 years. Map generated with the U.S. Geological Survey custom map tool on the earthquake hazard map site http://earthquake.usgs.gov/hazmaps/interactive/.

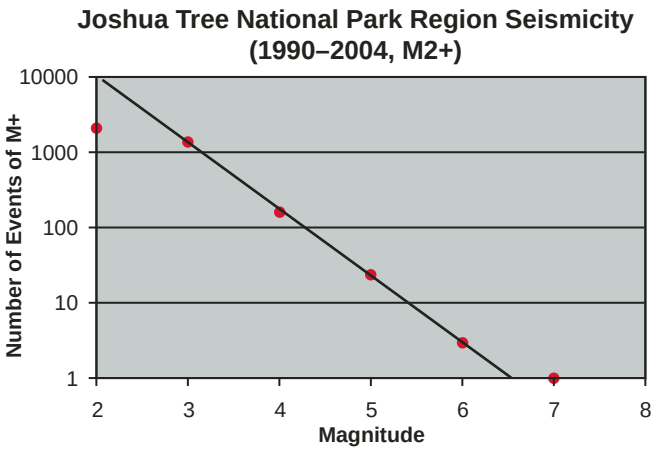


Figure 12. Frequency-magnitude plot for the earthquake data shown in Figure 10. To obtain an estimate of the number of events per year for any specified magnitude, divide the value on the y-axis by 15 years.

period, but if we had chosen a 30-year time period, it is likely that all of the other data points (numbers of events) would be approximately twice as large (and the M7+ data point might still be equal to 1).

The frequency-magnitude relation can be used to estimate the recurrence interval for a given magnitude earthquake. For example, for a magnitude 6 or above event, the number in 15 years is 3, and this data point falls on the linear portion of the frequency-magnitude relation. This suggests that the resulting recurrence interval should be reasonably reliable. Because there were three M6+ earthquakes in 15 years (in the area shown in Fig. 10), the frequency of occurrence for M6+ earthquakes for the selected area averages about one event every five years.

Additional statistical analysis, compilation of a fairly complete catalog and list of notable events, analysis of historical and prehistoric earthquake records, and an earthquake history could be easily developed for Joshua Tree National Park and the surrounding area. Further, earthquake recording (and selected additional studies listed in Table 2) within the park using available seismograph data from the ANSS or California state network (several seismograph stations operate in or very near the park; see http://www.data.scec.org/stationinfo.html for a station map), or from an educational seismograph station installed in Joshua Tree National Park, could be initiated to enhance seismic monitoring in the area.

Seismic monitoring, earthquake activity, and related tectonic and volcanic activity in the Yellowstone National Park area have been extensively studied by University of Utah and USGS scientists and others, and provides another example. A seismograph station map for the Yellowstone National Park area is shown in Figure 13. Earthquakes in the area have been recorded by a Yellowstone National Park seismograph network since the 1970s. Today, many of the stations are digitally recorded and transmit their data in near real time to a central recording site. Near-real-time data

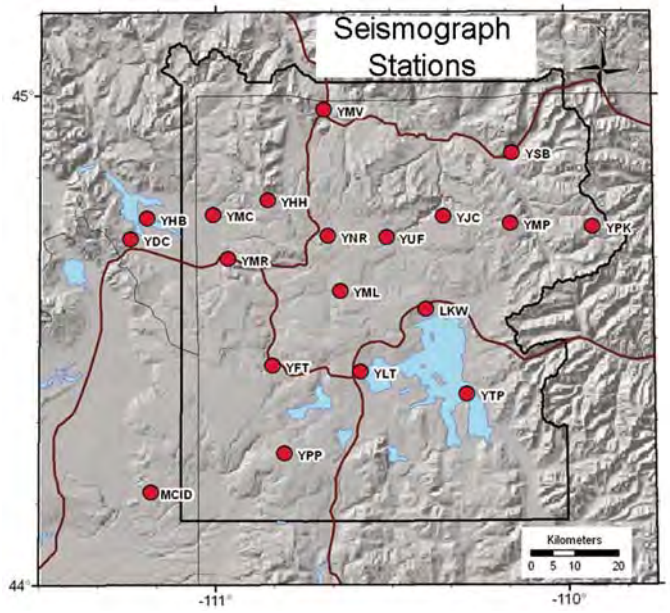


Figure 13. Seismograph stations in the Yellowstone National Park area (2006). From http://www.seis.utah.edu/helicorder/yell_webi.htm.

(seismogram/helicorder display) for many of these stations can be viewed at http://www.seis.utah.edu/helicorder/index.html.

Earthquake epicenters for 1973–1996 for the Yellowstone National Park area are shown in Figure 14. The epicenters are generally clustered within and near the Yellowstone **caldera** (a large bowl-shaped depression or crater formed by collapse into a voided magma reservoir during a volcanic eruption). To the north and west of the caldera, the epicenters display an approximately west-east trend near the epicenter of the 1959 M7.3 Hebgen Lake earthquake. Within the caldera region, the epicenters are generally aligned in a north-northwest direction parallel with the general trend of most of the mapped Quaternary faults (Fig. 14). The nearly continuous seismic monitoring by the local seismograph network operated by the University of Utah, in cooperation with Yellowstone National Park and the USGS, has been particularly important in obtaining accurate locations of epicenters (and depth of focus) of the frequent microearthquakes that occur in the area. The detection ability of the local network, as compared to that from global and regional stations, provides the ability to detect microearthquakes and accurately locate hypocenters. The hypocentral patterns correlate with the mapped faults (Fig. 15) and a shallowing of earthquake depths under the Yellowstone caldera that is probably caused by high temperatures in the crust beneath the caldera (Fig. 16). The detailed earthquake monitoring of the local network has also allowed analysis of earthquake swarms that are characteristic of volcanic systems; further, the monitoring has helped determine earthquake mechanisms that yield important information on the directions of principal stresses and the type of active faulting in the area (Waite and Smith, 2002).

A frequency-magnitude plot for M2+ earthquakes from 1975 to 2004 for the Yellowstone area is shown in Figure 17. The

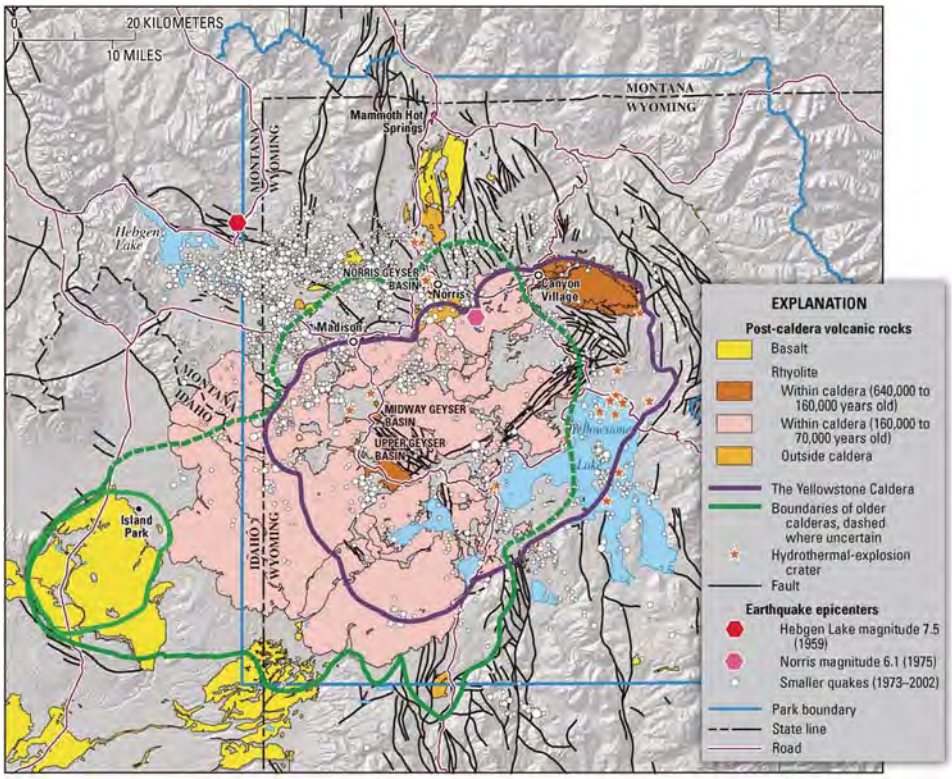


Figure 14. Earthquake epicenters (dots; size of dot is proportional to magnitude), volcanic vents, normal faults, caldera boundaries and volcanic rocks of the Yellowstone National Park area; light line is caldera boundary (from http://pubs.usgs.gov/fs/2005/3024/).

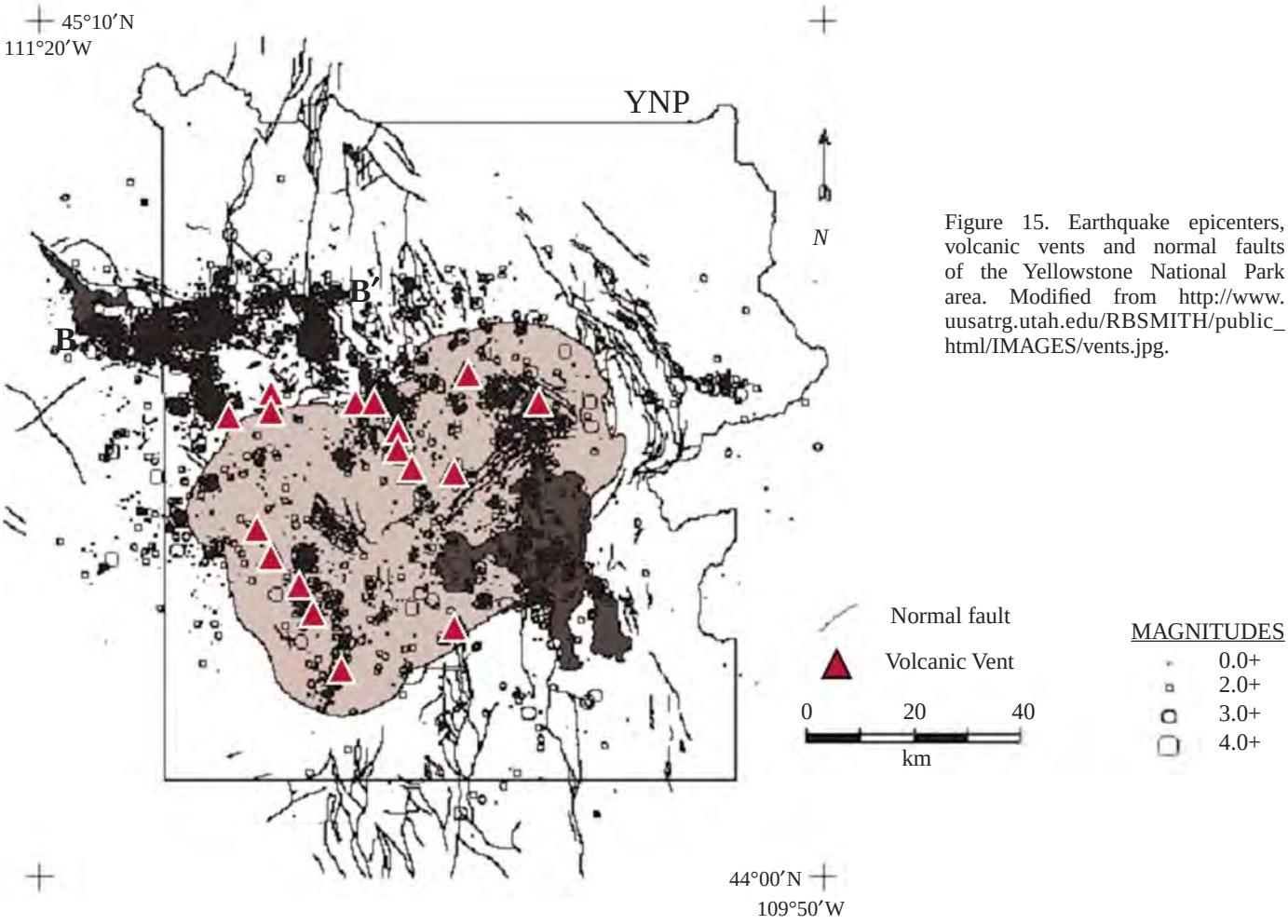


Figure 15. Earthquake epicenters, volcanic vents and normal faults of the Yellowstone National Park area. Modified from http://www.uusatrg.utah.edu/RBSMITH/public_html/IMAGES/vents.jpg.

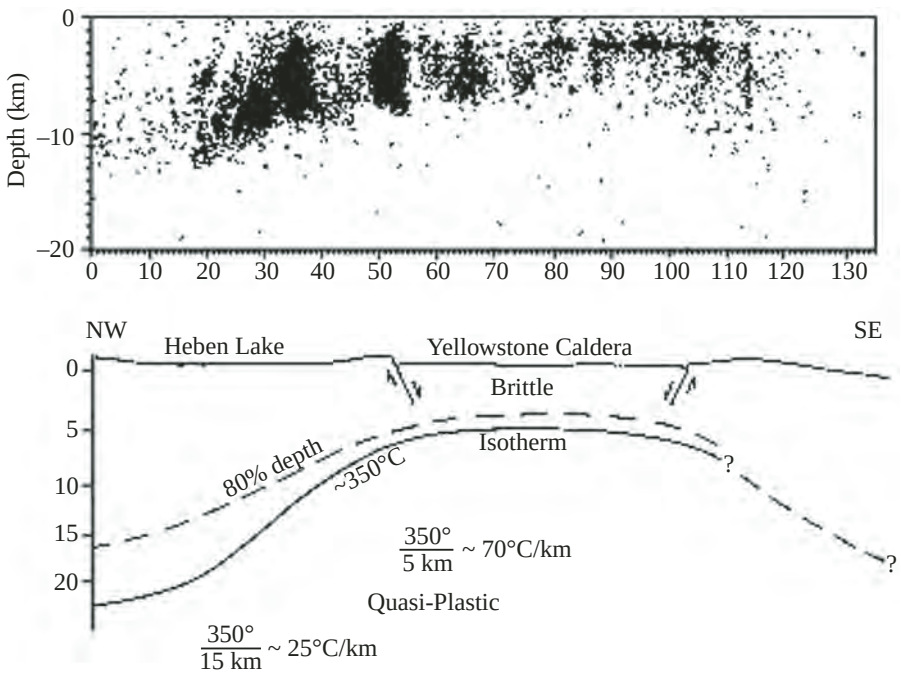


Figure 16. Northwest to Southeast cross section (upper diagram) view of earthquake depths through the Yellowstone caldera. The lower cross section diagram is a schematic illustration of interpreted decrease in the thickness of the brittle crustal layer due to high temperatures beneath the caldera. From: http://www.uusatrg.utah.edu/RBSMITH/public_html/IMAGES/19-36ysxs.jpg.

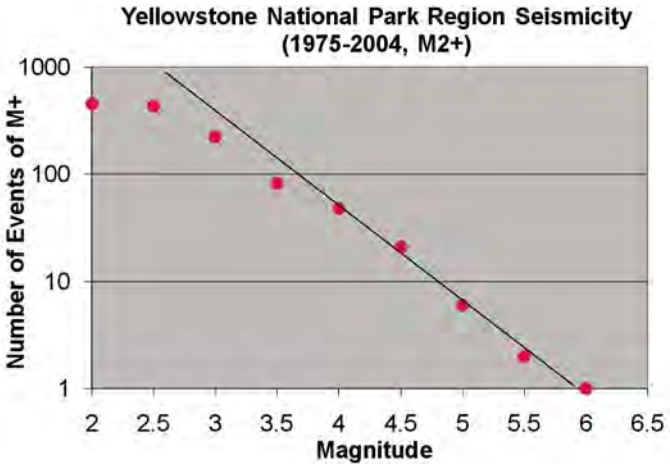


Figure 17. Frequency-magnitude plot for the Yellowstone National Park region (latitude 44°N to 45.1°N, longitude –111.3° to –109.8°). To obtain an estimate of the number of events per year for any specified magnitude, divide the value on the y-axis by 30 years.

data used to prepare this figure were obtained by a catalog search on the USGS earthquake Web site. The results are similar to those in the previously discussed Joshua Tree National Park area. The frequency-magnitude relation for the Yellowstone National Park area (Fig. 17) displays an approximately linear trend for magnitudes of ~3 or greater, suggesting that the earthquake catalog used was not complete for smaller magnitudes. Recurrence intervals can be inferred from the frequency-magnitude plot. For example, there were six M5+ events in the 30 years of earthquake activity considered here, indicating that there should be an average of about one M5+ earthquake in the Yellowstone National Park area about every five years.

Several geodetic and crustal deformation studies have been performed in the Yellowstone National Park area, including the GPS study by Meertens and Smith (1991) and survey and leveling surveys. The previously mentioned satellite radar interferometry study (Fig. 9) also shows that the Yellowstone area is a very active region and is associated with significant vertical movements.

For additional information on the earthquakes, volcanic and tectonic activity of the Yellowstone area, see Smith and Arabasz (1991), Smith and Braile (1994), Smith and Siegel (2000), and the USGS fact sheet 2005-3024 (2005) "Steam Explosions, Earthquakes, Volcanic Eruptions: What's in Yellowstone's Future?" available at http://pubs.usgs.gov/fs/2005/3024/.

TABLE 4. SUMMARY OF SEISMIC MONITORING METHODS

Methods	Expertise	Special equipment	Cost*	Personnel	Labor intensity†
Monitoring Earthquakes					
a. Internet access to data	Volunteer	No	$	Individual	Medium
b. Local seismograph station	Volunteer	Yes	$	Individual	High
c. Operate seismograph network	Expert	Yes	$$$	Group	High
Analysis and statistics of earthquake activity					
a. Frequency of occurrence	Scientist	No	$	Individual	Medium
b. Seismogram archive, seismicity maps	Scientist	Yes	$$	Individual	High
Analysis of historical and prehistoric earthquake activity					
a. Catalog, maps, and accounts of historical earthquake activity	Scientist	No	$	Individual	Medium
b. Investigate prehistoric earthquake activity, Native American accounts	Scientist	No	$	Individual	Medium
c. Investigate prehistoric earthquake activity, paleoseismology, evidence of earthquake effects	Expert	Yes	$$$	Individual	High
Earthquake risk estimation					
a. Seismic source zones, risk maps from published sources and Internet	Scientist	No	$	Individual	Medium
b. Microzonation, prediction of possible ground motion	Expert	No	$$$	Individual	High
Geodetic monitoring, ground deformation					
a. Plate motions predicted from geodetic models available on Internet	Scientist	No	$	Individual	Medium
b. Deformation rates from earthquake effects	Expert	Yes	$$$	Group	High
c. Geodetic surveying	Expert	Yes	$$$	Group	High
Geomorphic and geologic indications of active tectonics					
a. Topographic features, springs and hydrothermal features, river drainage, vertical movements, tilt	Expert	Yes	$$$	Group	High

*Cost (US$): $ = <$1,000; $$ = $1,000–$10,000; $$$ = >$10,000.
†Labor intensity: low = <few hours; medium = full day; high = >full day.

CONCLUSIONS

Seismic monitoring can provide extremely useful and interesting data about the dynamic Earth. Local and regional earthquake activity can be analyzed using data available online from regional, national, and global networks. Local seismic monitoring can also be augmented by installation of local seismographs. These data can be used for many purposes, including determining the frequency of occurrence of earthquake activity, evaluating earthquake risk, interpreting the geological and tectonic activity of the area, and providing an effective vehicle for public information and education.

A comparison of the seismic monitoring methods discussed here is given in Table 4. In this Table, the relative expertise, technology and instrumentation, cost, and personnel requirements for implementing the various monitoring methods are listed.

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Monitoring slope movements

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INTRODUCTION

Slope movements, including types of landslides and extremely slow soil creep (Varnes, 1978), occur throughout the United States and within many national parks. The collection of vital signs of regional landslide information, referred to as monitoring, is not only scientifically useful, but is beneficial for assessment of landslide hazards and risk, which is in turn important for regional operations and planning.

Different types of **slope movement**, such as fall, topple, slide, spread, and flow, can occur in a variety of materials and degrees of slopes. Specific types of **landslides** (Fig. 1), such as rockfall, earth slump, and debris flow, can occur depending upon the types of geologic materials and movement (Cruden and Varnes, 1996). A landslide can be caused by one or more of several factors, of which geological, morphological, physical, and human factors are the most common. The term **landslide trigger** refers specifically to an external stimulus, such as intense rainfall, rapid snowmelt, earthquake, volcanic eruption, or stream or coastal erosion. These stimuli initiate an immediate or near-immediate landslide movement by rapidly increasing shear stresses or pore-water pressures, by ground acceleration due to seismic activity, by removing lateral support, by reducing the strength of slope materials, or by initiating debris-flow activity. Most landslides with recognized triggers are caused by precipitation: rainfall, snow meltwater, or combinations of both. In rock masses, rain and meltwater penetrate joints and produce hydrostatic pressures. In soils, the increase of pore-water pressures reduces shear resistance (Schuster and Wieczorek, 2002).

This chapter will describe several different methods of monitoring slope movements to evaluate landslide hazards and risks.

EVALUATION OF LANDSLIDE HAZARDS

Landslide prediction is rarely possible. Detailed instrumental monitoring of landslides is often not possible because of the lack of scientific expertise or insufficient budgets for instrumentation and subsurface investigation. In addition, instrumental monitoring is often not practical unless a rather small area is involved with intensive examination for a specific purpose. Impacts of monitoring need to be balanced with wilderness purposes. Two general types of information are needed as a background for selecting potential hazard areas and possible return intervals for landslide events. First, inventories of previously known landslides using newspaper accounts, geologic and regional maps, and historic photographs are critical. Second, current landslide observations that are recorded and mapped should then be compared with inventories of prehistoric and historic events.

Indicators of heightened potential for slope movement can be assessed by evaluating the following conditions within a region: seismic activity, intensity and duration of precipitation, climatic conditions affecting freeze-thaw, wind velocity, fire severity and frequency, annual groundwater level variations, stream and river erosion, and park construction and maintenance activities.

For some active landslides, it may not be possible to recognize a triggering event, because some triggers may come from unseen subsurface or indistinguishable events. General causes of slope movement, such as deeply incised tree roots which can gradually decrease the strength of materials, may become apparent after an event, even though it may not be possible to determine what actually triggered the slope failure.

Although basic levels of landslide information could be collected by many people, the gathering of more detailed scientific

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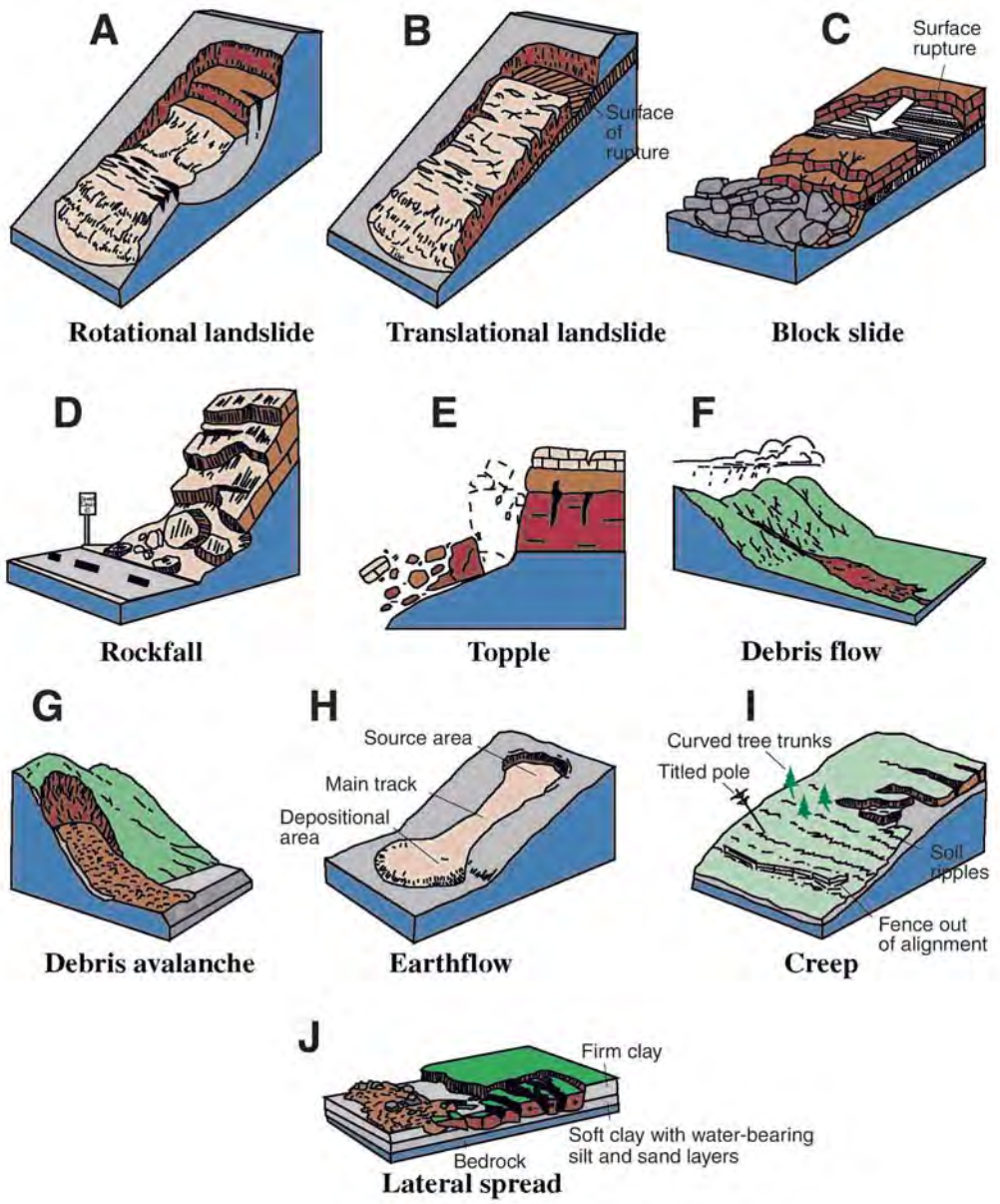


Figure 1. Examples of different types of landslide movement (modified from Cruden and Varnes, 1996).

information by landslide monitoring can benefit from cooperation with the USGS, state geological surveys, or university geology or engineering departments. The National Park Service (NPS) and other public land organizations can establish a landslide observer(s) as collateral duties with base funded positions. Emergency response funding has sometimes been used for initial, short-term landslide observations and safety determinations following a hazardous failure. This may include aerial reconnaissance combined with NPS Search and Rescue operations. Designated NPS observers can establish liaison relationships with relevant scientists; general NPS observations and monitoring procedures should be checked, corroborated, or critiqued by scientists.

SELECTED METHODS FOR MONITORING SLOPE MOVEMENT

Five basic elements or vital signs of monitoring slope movement can be prepared for general regions. These vital signs include: (1) determination of types of landslides; (2) monitoring of landslide triggers and causes; (3) determination of geologic materials involved in landslides; (4) measurement and assessment of landslide movement; and (5) regional assessment of landslide hazards and risks. Each of the following descriptions of these five vital signs contain three relative methods, each of which is progressively more detailed, complex and expensive.

Within each three methods there are systematic discussions of methodology, timing and frequency, equipment and costs, limitations, and interpretation (see also Table 1).

Vital Sign 1: Determination of Types of Landslides

One of the first important vital signs for examination of landslides is determining which of the specific forms of landslide have occurred. Landslides need to be evaluated based on physical observation and comparison of the materials with the different types of slope movement. Distinctive types of landslides, such as rockfall, debris topple, earth block slide, earth lateral spread, debris flow, and complex slump-earth flow (Varnes, 1978; Cruden and Varnes, 1996) often involve various geologic materials; they initiate and continue their movement in different physical methods, and are often started by a variety of events.

Level 1: Identification of Landslides

The type of landslide can be determined by field observation of the physical landslide features, the type of material of the initial movement, and the dominant type(s) of movement. The classification of landslides and materials are characterized by Varnes (1978) and Cruden and Varnes (1996). The types of movement include falls, topples, slides, lateral spreads, flows, and combinations of these types of movement, which are referred to as complex. Initially, landslide materials can be simply classified as bedrock, debris, or earth, although more detailed identification of geologic materials is useful, as described below. **Debris** is classified as containing more than 20% gravel and coarse sizes, whereas **earth** is classified as having greater than 80% sand and finer soil (Hungr, 2005). The initial source of a landslide is not always close to the landslide deposits. For example, identifying a debris flow may often involve locating the widely spread deposits of wet coarse soils on relatively flat **alluvial fans** and subsequently finding the source of the landslide significantly upslope in steeper terrain.

Methodology. Identifying landslides consists of direct field examination (Figs. 2 and 3) and/or inspection of photographs (Fig. 4). Field examination of some landslides is not always possible because of extremely steep terrain. Therefore, it can be useful for detailed inspection of some parts of landslides. Documenting the current stability of a landslide by photography is useful for comparison with any additional slope movement. Vertical aerial photographs of landslides taken with identifiable field reference points can also be used to measure the landslide dimensions, as discussed later in this chapter.

Timing and frequency. Landslides are best observed immediately after the initiation of slope movement. Observing the continuing movement of landslides can aid in the characterization of the type of event. If observation is delayed for days or months, a landslide could reinitiate movement, and the initial character cannot be assessed. For older landslides, vegetative growth and erosion of the landslide features can disguise the original nature of the landslide, so again, it is advantageous to examine landslides soon after they occur.

Equipment and costs. Direct field examination of landslides is often the most useful and the least costly method of identification. Photography is not generally expensive, and if done digitally, files can be easily saved and distributed. Photography of a landslide from a helicopter or airplane can be moderately costly, but can provide detailed information, especially along steep cliffs. Aerial stereo photography and satellite imagery of landslides is more expensive but can provide very detailed documentation. Aerial stereo photographs or satellite imagery, although more costly (possibly several thousand dollars) can be useful for monitoring large regions.

TABLE 1. SUMMARY OF COMPARATIVE LANDSLIDE VITAL SIGNS AND MONITORING METHODS

Vital signs	Methods	Expertise	Technical needs	Relative costs*	Personnel	Labor intensity†
Types of landslides	1. Identification	Volunteer	No	A	Individual	Medium
	2. Measurement	Volunteer	Yes	B	Group	Medium
	3. Imagery	Scientist	Yes	C	Individual	High
Landslide triggers and causes	1. Online data	Volunteer	No	A	Individual	Medium
	2. Climatic and seismic instruments	Volunteer	No	B	Individual	High
	3. Landslide instruments	Scientist	Yes	C	Group	High
Geologic materials in landslides	1. Examination	Volunteer	No	A	Individual	Medium
	2. Surface sampling	Scientist	Yes	B	Group	High
	3. Subsurface sampling and testing	Scientist	Yes	C	Group	High
Measurement of landslide movement	1. Tapes and GPS	Volunteer	Yes	A	Individual	High
	2. Extensometers	Scientist	Yes	B	Group	High
	3. Aerial photos, LiDAR and InSAR	Scientist	Yes	C	Group	High
Assessing landslide hazards and risks	1. Inventory and susceptibility	Scientist	No	A	Individual	High
	2. Volume, velocity, and travel distance	Scientist	Yes	B	Individual	High
	3. Modeling	Scientist	Yes	C	Individual	High

Note: GPS—Global Positioning System; LiDAR—light detection and ranging; InSAR—interferometric synthetic aperture radar.
*Relative costs (in US$): A—up to $1,000; B—>$1,000–$10,000; C—>$10,000.
†Labor intensity: low = <few hours; medium= <full day; high =>full day.



Figure 2. Physical measuring of the length of a rockslide in the mountains of Shenandoah National Park, Virginia.



Figure 3. Measuring thickness of a recent debris-flow deposit along a stream channel in northern coastal Venezuela (Larsen and Wieczorek, 2006).

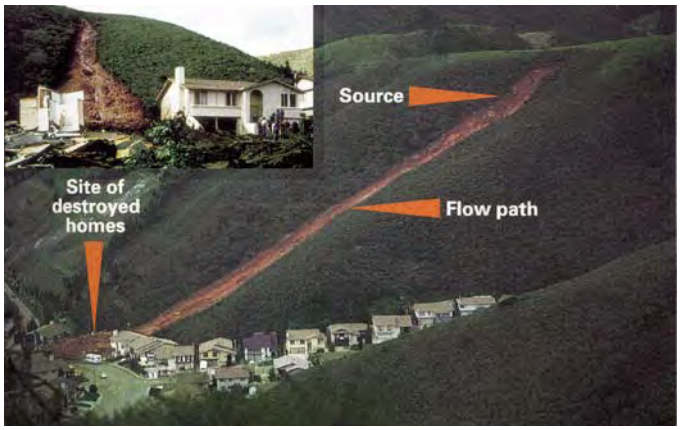


Figure 4. Debris flow triggered by heavy rainfall in a brush covered, concave hillside in Pacifica, San Mateo County, California, where three children were killed and two houses destroyed at ~11:10 p.m. PST, 4 January 1982 (Wieczorek et al., 1988).

Limitations. Identification of type can be more difficult when examining historical landslides because revegetation, erosion, and additional sediment deposit can modify the appearance of the landslide. Aerial and satellite photographs may not be sufficiently adequate for examining relatively small landslides, depending upon the scale of the photographs.

Interpretation. Identifying and determining the type of individual landslide can depend upon the method of slope movement classification (Cruden and Varnes, 1996) and upon how recently it moved. Large, high-velocity landslides, especially rockslides that develop into debris avalanches, are remarkable geological phenomena. A catastrophic landslide at Elm, Switzerland, in 1881 prompted Heim (1882, 1932) to conduct the first scientific study of slope movement events. His research set a pattern of combined interpretation of eyewitness accounts with geomorphological and geological studies of landslide deposits.

Level 2: Physical Measurement of Landslides

Determining the size of a landslide is important for several reasons. Measuring the lateral parts, such as length, width, and gradient is necessary for accurate mapping on a topographic map. In addition, it is important to determine the depth of the moving material because an evaluation of the total volume can help to assess the distance of continuing or future reactivation of the landslide. The size of a landslide can be reasonably estimated by a variety of methods, including making physical measurements with tapes, estimating size relative to nearby buildings or trees, and by figuring an average weight/unit of the failed material. It is also beneficial to sketch the landslide boundaries on a topographic map. Depth of the landslide can be the most difficult to determine, especially if the depth of a deep-sliding mass is not well exposed. For example, deep-seated rotational earth slumps may continue to move slowly for several months per year, but a distinct thickness of the mass may be difficult to identify without subsurface drilling, which can be both difficult and costly.

Methodology. Walking across a landslide and noting the edge of the landslide boundary is necessary for measuring the size of the feature. Stretching a tape across the two boundaries of the landslide is an easy way to measure the length or width. However, depending upon the size and the degree of slope of the landslide, this may be difficult. If necessary, range-finding binoculars can aid in measuring the distance between landslide boundaries. A drilling device can sometimes be used to determine the depth of a landslide. Strong, hard, solid soil or rock materials are often very difficult to hand drill. Access with a drill rig, commonly used with a truck, is helpful, but limited to landslides that can be driven over. Seismic reflection methods which test the subsurface depths of different density can be used to identify the landslide depth, but this can be difficult depending upon the geologic and hydrologic lithology. Drilling can also remove material that can be examined for signs of the failure surface.

Timing and frequency. After a landslide occurs, it is useful to measure the size within a few days. If the landslide keeps moving, repeating the measurement can determine if its size is changing, which could increase the hazards and risks. As long as a landslide remains dormant, repeating measurements is unnecessary. Once a landslide reactivates, it is important to determine whether the size of the feature has increased or decreased. Using a drill rig for determining depth of sliding surface is the most efficient technique, but this can be difficult if the ground surface is too steep, irregularly shaped, or too soft.

Equipment and costs. For surface measurements, tapes are relatively inexpensive. Binoculars cost about $200, and a detailed Global Positioning System (GPS) measurement system may run up to $500. (All amounts herein are in US$.) Accurately determining the depth of a landslide can be both difficult and expensive. Depending upon the type of drilling, the amount of time and cost varies. Some landslides can be drilled with holes wide enough for a geologist to be lowered down into for examination. Cameras can be used in smaller diameter drill holes to collect imagery that can identify failure surfaces. Using a drill rig costs approximately $1,000 per day.

Limitations. Although the surface of landslides can be measured along the ground or evaluated from photographs, the depth of some types of landslides, such as rockfalls, cannot be easily determined, unless the initial mass volume has completely dislocated and has been removed from where the landslide initiated.

Level 3: Application of Landslide Imagery

Mapping and photography can be used to detail specific types of landslides, particularly large landslides that cover much steep terrain. For example, detailed examination of mapping from photos can determine how far recent debris flows have traveled (Fig. 4).

A GPS device can determine the size and displacement of a landslide by setting the boundary points on the GPS and determining the distance between them (Reid and LaHusen, 2004). Small landslide features may not be measured as accurately as larger features using GPS techniques. Aerial imagery, such as **LiDAR** (light detection and ranging), can be used to map landslides (Fig. 5) and evaluate their mechanics and material properties (McKean et al., 2004).

Methodology. Use of aerial photography for examination and mapping of landslides depends upon the scale of the landslides and of the photography. If an individual landslide is being examined, then several detailed aerial photos (scale 1:1000) can be very helpful. If an event has triggered multiple landslides within a region, then it is convenient to obtain imagery that can still show detailed landslide features, so scales of 1:10,000 are preferable. Additionally, different types of photography can be useful. Stereo photography is very important so that the topography can be viewed in three dimensions, making the mapping of landslide more accurate. Color photography is beneficial for mapping; false-color infrared photography can emphasize the contrast between landslides and non-landslide topography (Figs. 6 and 7). For detailed examination of a specific landslide on aerial photos, it can be useful to document specific points on the photograph using GPS instruments in the field.

Timing and frequency. If a region normally experiences many landslides throughout the year, then it would be preferable to obtain imagery several times per year, but not necessarily after the movement of each individual landslide. In contrast, if individual landslides occur infrequently, then it would be very beneficial to obtain imagery soon after each landslide event. If no landslides occurred within a year, then a regular timing of imagery would also be beneficial in order to document the status of the region.

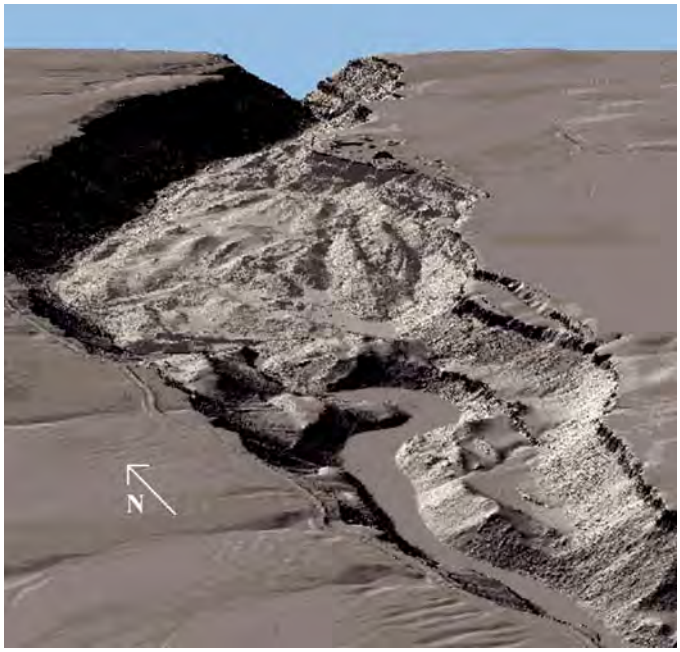


Figure 5. LiDAR perspective view of two landslides along Salmon Falls Creek in southern Idaho. The recent 1999 Salmon Falls landslide (~0.22 km^2) is on the lower right, and the larger (~0.85 km^2) 1937 landslide is to the north (upper left) (Glenn et al., 2006).

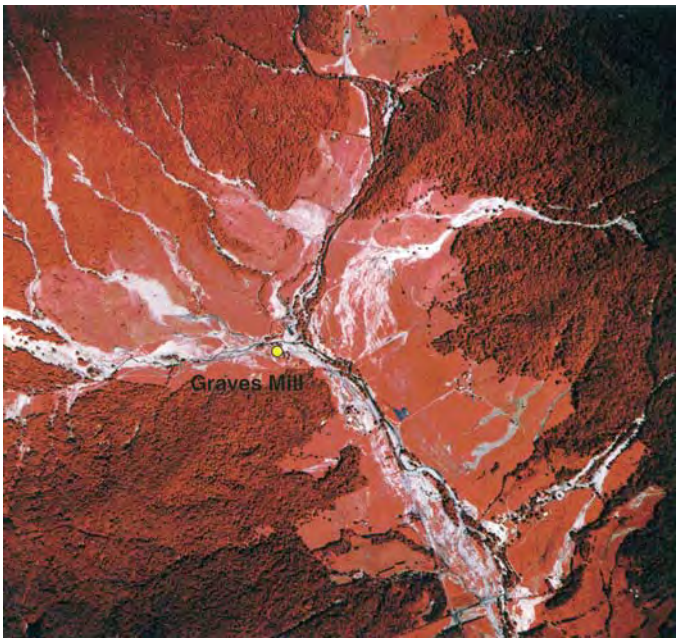


Figure 6. False-color infrared photography showing recent debris flows and flood effects in bright tones (white) with areas of unaffected forest (dark red) and grassland (pink) in Graves Mill, Madison County, Virginia (Wieczorek et al., 2000).

Equipment and costs. The cost of obtaining stereo aerial photography depends principally upon the size of the area and scale of the photos. For individual landslides, the cost could be less expensive than covering larger areas, though the cost for the flight could be similar. For example, the cost of stereo color photos of the 1996 Happy Isles rockfall in Yosemite National Park ranged from $2,500 to $3,000. Obtaining LiDAR imagery can be a more expensive operation. In the Ventura region of southern California, for an area of more than 100 km^2, the cost of LiDAR with 1 m spacing ranged between $200 and $330 per km^2. For a smaller region, the cost per square kilometer could be considerably higher.

Limitations. For aerial photographs or LiDAR imagery, the weather must be relatively clear; otherwise the results will not be accurate. Therefore, if a landslide occurs during fog or an intense storm, it would be necessary for the weather to change before the imagery could be accurately collected.

Additional Information

Determination of the type(s) of landslides is of critical importance for evaluating hazards and risks. The types of material from the landslide source and the deposits should both be carefully examined to determine the types of initial and subsequent movement. For example, some failures, such as rockfall or rockslide, can initiate from a large block of rock, but after a significant distance the rock block mass disintegrates into much smaller pieces. Some landslides initiate as one type of failure, but transform into another during prolonged movement. An initial shallow earth slide can turn into a debris flow over a period of rapid, fluidized, erosive movement. A rockfall can be transformed into a debris slide depending upon soil or **talus** saturation underneath, or beyond the initial release and impact. Typically, these features may be referred to as complex landslides, but it is still worth noting the initial type of landslide movement, as well as subsequent modified types of slope movement. In addition, an evaluation of the relative size of the landslide is important, including not only the size of the initial surface failure, but also the depth of failure of the sliding surface involving either soil, debris, or rock.

Vital Sign 2: Monitoring Landslide Triggers

The triggering of landslides involves meteorological and seismological events affecting subsurface geologic materials (Wieczorek, 1996; Schuster and Wieczorek, 2002). Identifying the trigger or cause of a landslide is important, but can be difficult in some cases. If a landslide is observed starting to move during a storm or an earthquake, then the triggering event can possibly be easily identified. For example, John Muir, awakened by the 26 March 1872 Owens Valley earthquake in Yosemite Valley, immediately observed the Eagle Rock avalanche (Fig. 8) (Wieczorek et al., 1992).

Level 1: Collection of Online Meteorological Data

Collecting meteorological information for a documented landslide is possible by using online contact with weather stations. For example, in California and Nevada, rainfall and snowfall can be easily obtained on an hourly, daily, or longer-term basis from http://cdec.water.ca.gov/snow_rain.html. Earthquake measuring devices, termed **seismographs**, are not frequently located within national parks; consequently, the local ground motion from a distant earthquake cannot be easily determined, especially where steep topography is widely present.

Methodology. Documenting the weather near the time of the initiation of landslide movement can involve several steps. First, the nearest meteorological station to the landslide must be determined. The differences in distance, elevation, temperature, and wind and storm direction between the station and the landslide site can affect the accuracy of determining the actual precipitation affecting a landslide. For example, rainfall measured in Yosemite Valley during the winter is not necessarily equivalent to the amount on nearby mountains. Snow on a hillside has a different effect on the possible triggering of landslides than rainfall infiltrating into the ground. The climatic differences in some areas also depend upon the direction of sunlight. For example, in Yosemite Valley, the amount of snow on the cliffs is very different between north- and south-facing slopes. If several precipitation stations are located near a landslide, then an evaluation of the average measured precipitation factors is best.

Timing and frequency. Measurement of rainfall attributed to triggering debris flows should be determined within at least 24

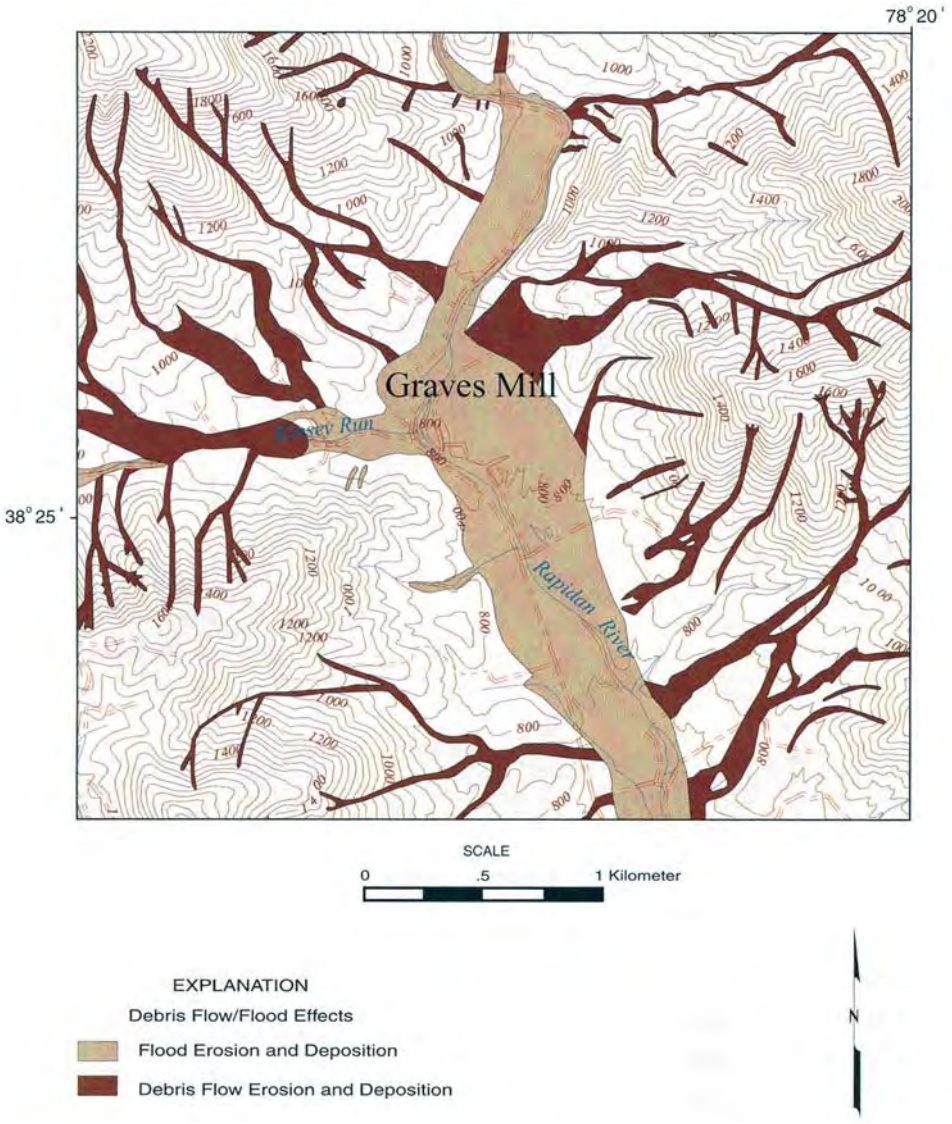


Figure 7. Mapped landslides and flooding within the same region of Graves Mill, Madison County, Virginia. Photos of similar landslide and flooding events are visible from same region in Figure 6 (Wieczorek et al., 2000).

hours; intense rainfall should be measured every hour. Rainfall thresholds for the triggering of debris flows have been evaluated for some specific regions, including near Shenandoah National Park, Virginia (Wieczorek et al., 2000).

Equipment and costs. Obtaining online data from existing meteorological stations is relatively inexpensive.

Limitations. The physical distance from meteorological stations to landslide sites is critical. Generally, if the recorded data is within several kilometers of the landslide, then it should be quite applicable if there is no major topographic difference between the station and the landslide.

Interpretation. There is probably a shortage of sufficient meteorological stations, as well as seismological instruments within most large national parks. Consequently, it is often more useful to install instruments at nearby sites for accurate meteorological measurements, as described below.

Level 2: Installation of Meteorological and Seismological Instruments

A collection of climatic and seismic data can help provide useful information related to the triggering of landslides and evaluation of landslide hazards. The amount of precipitation within certain periods can be collected as basic data for each initiated landslide, and then analyzed for the development of basic rainfall threshold values. For example, rainfall thresholds have been developed within specific regions, including the San Francisco Bay region, Puerto Rico, Virginia, and Hawaii, on the basis of detailed post-event studies where landslides were identified (Wieczorek et al., 2000). Generally, the rate (inches/hour) and duration (hours) of rainfall are both important for the recognition of triggering landslides. Extremely high rainfall was recorded on 27 June 1995 at specific locations and subsequently contoured into a region affected by numerous debris flows and floods in



Figure 8. Triggered by the 1872 Owens Valley earthquake, the Eagle Rock avalanche (right side of photo) initiated from upper region of Union Point and landed near Old Yosemite Village (photo by W.H. Jackson, 1886).

Madison County, Virginia (Fig. 9). Precipitation data can be collected from many different areas, including National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS) stations, though automated, real-time local stations may provide the best data near local landslides. The U.S. Geological Survey (USGS) provides seismological monitoring of earthquakes throughout the United States.

Snowmelt due to increased temperature and/or rainfall can be a climatic landslide triggering event by increasing water infiltration into soil and rock. Horton (1938) found that the process of snowmelt provides a more continuous supply of water over longer periods than infiltration from rain. Mathewson et al. (1990) found that snowmelt may also recharge shallow fractured bedrock and raise pore-water pressure beneath shallow soils, thus triggering debris flows. The rate of snowmelt depends on air temperature, which in turn relates to the timing of debris flows. Instrumentation for this type of monitoring was used to develop a threshold for debris-flow activity near Aspen, Colorado (Chleborad et al., 1997). Installation of instruments for detailed local monitoring of landslide triggering factors, such as rainfall, snowmelt, temperature, and seismicity within the region where landslides occur can provide the detailed information necessary for the development of these thresholds.

Methodology. Meteorological instruments must be installed where vegetation or structures do not interfere with the accurate recording of data. For example, rain gauges near trees may not record accurately due to leaf cover. Likewise, putting temperature gauges near buildings can affect temperature data. Cleared areas are preferable for installation of meteorological instruments. For seismological data, a data logger with a tri-axial accelerometer, telemetry hardware, batteries, and a subsurface protective structure is necessary. Selecting a proper location is also important. Seismic equipment needs to be installed in stable ground. Even though the initiation of landslides can be related to the seismological shaking, both climate and seismic instruments need to be separated from areas that are likely to be impacted by landslide deposits. Regular maintenance is necessary for continued monitoring. For areas that are difficult to reach during some parts of the year, it is extremely important to have automatically transmitted data that can be systematically collected and analyzed. Measuring earthquake-induced ground shaking is likewise important for recognizing what magnitude, distance, and frequency of earthquake events are likely to occur in a specific region and whether landslides are likely to be initiated.

Timing and frequency. The recording of weather information and seismological ground motion should be continuous, although climatic data only needs to be recorded roughly hourly. Seismological monitoring should be recording every few seconds; the most critical information is the largest seismic shaking magnitude within minutes of the initiation of landslide movement.

Equipment and costs. Meteorological equipment and seismological monitoring should have data continuously transmitted by telemetry or Internet. Rain gauges, snow monitor devices, and temperature thermometers are the minimal equipment required. Seismic monitoring equipment, including data logger with tri-axial accelerometer, telemetry hardware and huts, masts, batteries, and concrete for installation of a strong motion reference site could be moderately expensive.

Limitations. The proximity of the meteorological and seismological devices to the location where landslides initiate can be a limitation if the elevation and the type of geologic materials are significantly different. Within extreme elevation variations, weather monitoring can be very difficult because of the many instruments that would be needed to accurately represent the climatic factors from dramatically different elevations. Additionally, even slightly different regional latitudes can produce different rainfall and temperature records.

Interpretation. In analyzing the effects of weather on landslide movement, it is important to examine the antecedent rainfall and temperature for previous days, weeks, or months, and to assess the recent intensity of rainfall. Different rainfall thresholds for the triggering of landslides have been determined in many different regions throughout the world (Wieczorek and Glade, 2005). In steep mountainous regions during winter periods, it is necessary to evaluate the variation in temperature and the amount of rain and

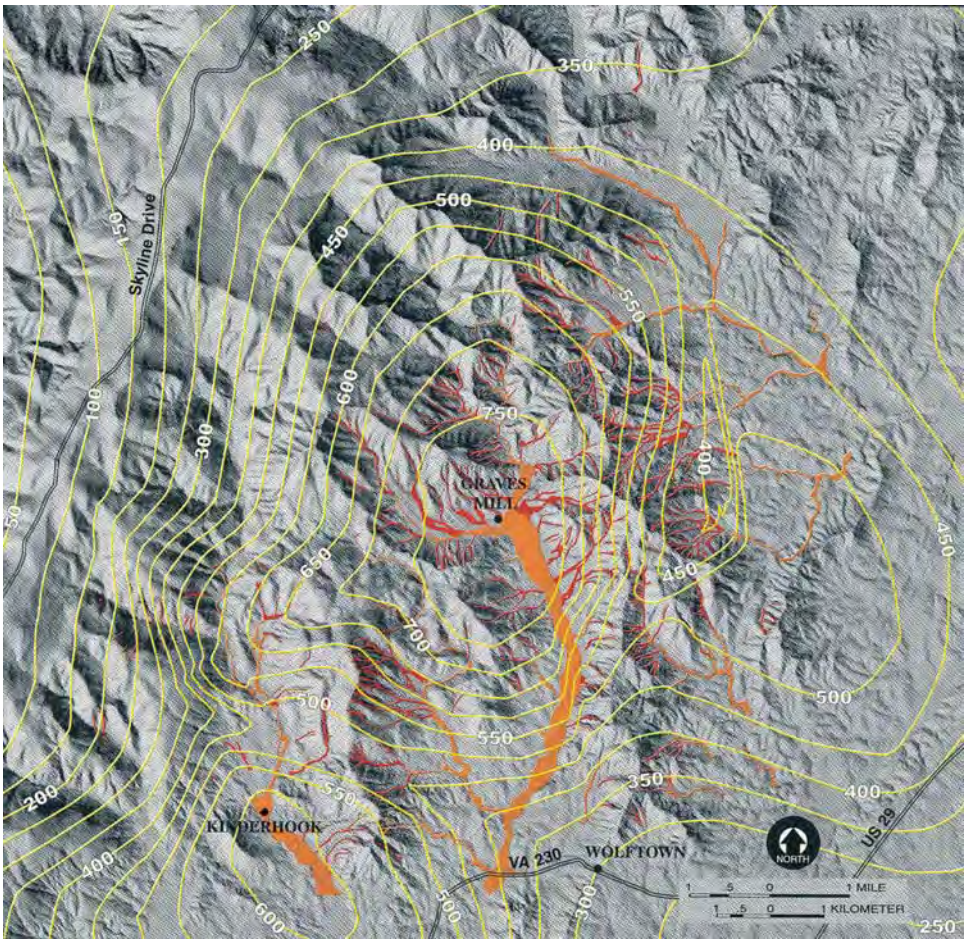


Figure 9. Digital shaded relief of the Madison County, Virginia region showing rainfall contours (mm) from 27 June 1995 storm (yellow), areas of debris flow (red) and areas of flooding (orange) (Wieczorek et al., 2000).

snow. Although distance from the epicenter of an earthquake to the location of a seismological device is critical, the topographic setting as well as the geologic type of subsurface material will also be important to evaluate the seismic velocity data.

Level 3: Installation of Instruments within Landslides

Specific instruments installed within landslides can provide useful information regarding possible landslide movement and the potential for increased hazards. The rate of landslide movement can show whether the velocity is suddenly increasing and posing increased hazards.

Installation of instruments for detecting the depth of water, e.g., **piezometers**, can be used for detailed long-term monitoring of groundwater-level fluctuation and landslide movement. However, the purchase, installation, and monitoring of piezometers can be relatively expensive and demanding for personnel within national parks.

***Methodology*.** Various types of devices can be installed to monitor landslide movement. One of the simplest methods is to install stakes on the surface that can be periodically measured to detect movement. Additionally, movement of trees or other surface features may be worth monitoring. Of course, this provides landslide movement data only as frequently as the site can be measured. More sophisticated instruments of surface movement, such as extensometers, which can record continuous movement, are much more useful.

Instrumentation for monitoring movement throughout the depth of a landslide can be obtained from **inclinometers**. A hollow metal tube can be installed within a drilled hole, which can then be periodically measured to determine the variation of the original inclination of the tube. Ideally, the subsurface location of a landslide rupture can be detected with the inclinometer. Measurement of inclinometer systems can be connected to data loggers so that movement can be regularly monitored and recorded on software.

Piezometers are instruments that are installed within the ground to measure the pressure of groundwater levels at specific depths. Pneumatic piezometers are the most effective measurement technique. Because multiple layers of different types of soils and rocks affect the variation of water levels, an open drilled hole is not sufficient to detect the actual pore-water pressure within complicated geologic materials. A piezometer installed within a drill hole isolated above and below by impermeable sediment gives pore-water pressure at a specific depth. A wire tube can be used for measuring the raised height of water or a more sophisticated device can evaluate the amount of water pressure. The

depth of water from piezometers can be physically measured periodically, or if connected with monitoring equipment, can record variation in groundwater level.

Extensometers can be directly installed from a stable region with wires onto points of the landslide in order to directly measure landslide displacement. The displacement can be continuously measured and recorded within regular periods of time. The measured movement from extensometers includes a combination of both horizontal and vertical displacement.

Timing and frequency. Many landslides remain steady or dormant for a long time until activated by severe storms or earthquakes. They can either move for relatively short periods, or they may continue moving for days or months. Therefore, it is important to be able to detect and measure landslide movement at least daily. Depending upon the severity of landslide movement, the instrumentation for monitoring can be affected and consequently should be regularly assessed once movement has initiated.

Equipment and costs. Depending upon the depth of drilling and the installation of subsurface instrumentation, the operation of piezometers and inclinometers can be relatively expensive. Very small, 3-inch-wide piezometers can be installed for about $30 per foot of depth, whereas installation of larger piezometers may range from $200 to $1,000 per foot. Consequently, depending upon the depth of the installation in the landslide, and how many sites need to be sampled, the cost could be very high.

Limitations. If subsurface instrumentation measurements have to be taken physically, the quality of data can be limited, compared to more costly continuous monitoring methods. However, if landslide hazard warnings are an important reason for monitoring, then continuous monitoring methods are important and alarms can be activated based on evaluation of the relative recordings. Some landslides, such as earth slumps, start moving relatively slowly and can continue moving for days or much longer. If monitoring detects a rate of slow continuous movement of landslides, then hazard warnings can be issued more easily than for rapidly moving landslides, like rockfalls, which can collapse within minutes.

Interpretation. Monitoring of regions capable of landslide movement does require knowledgeable evaluation of the received database on previous knowledge of movement of different types of landslides. For example, the rise of groundwater level is common during periods of heavy rainfall. However, it is necessary to evaluate what level of high groundwater level is necessary for initiating landslide movement.

Additional Information

Landslides, particularly debris flows, often are triggered during or soon after intense rain storms. However, some landslides, especially deep-seated landslides, can be initiated by the slow deep infiltration of rainfall into the ground and subsequent buildup of ground water levels within thick soil. Typically earth slumps or block slides can move slowly enough that they may not be noticed initially unless disturbing trees, roads or buildings. Without some knowledge by measurement of groundwater levels within soil or rock joints, it is not easy to identify landslide triggering events, such as levels of ground saturation, after storms. General causes of weakening slopes, such as tree roots slowly splitting rock joints apart or gradual weathering of rocks, cannot easily be directly observed, but could be a main cause of slope weakening and eventual failure.

Vital Sign 3: Determination of Geologic Landslide Materials

Examining the types of materials involved in landslides is critical for determining the type of landslides and potential hazards. The strengths of different types of soil, debris, and rock are highly variable and affect the development of instability. Examining the degree of weathering, thickness of soil, and orientation of rock joints and fractures also provides necessary information (Fig. 10).

Level 1: Examination of Geologic Materials

Geologic materials involved in landslides can be easily evaluated by a combination of physical examination and studying geologic maps. Depending upon the scale of the landslide, the type of bedrock can usually be directly assessed, if the geologic mapping is accurate, with a small-scale map (equal or less than 1:24,000). However, in some cases, landslides occur within soil that has been developed from weathered bedrock or has been physically relocated by movement from its bedrock source. Therefore, in some cases, physical examination of the material involved is necessary.

Methodology. Landslides can occur in virtually all types of geologic materials. Distinguishing different types of bedrock as



Figure 10. Examining geologic material, numerous joint sets, and local instability along eastern side of upper LeConte Gully west of Glacier Point above Yosemite Valley, Yosemite National Park, California.

well as types of soil is necessary for assessing landslides. Geologists should be capable of identifying and determining the specific types of sedimentary, igneous or metamorphic rocks in landslides from field and laboratory work.

Field examination of the geologic types of landslide materials is relatively direct when the materials are clearly exposed on the ground surface. If landslides are significantly deeper, e.g., from ten to one hundred feet, then it is possible that different types of subsurface bedrock can be involved in the landslide if different layers of bedding are present beneath the ground surface. Consequently, drilling and sampling may be necessary in some cases for determining the different types of geologic materials within the full depth of the landslide.

Examining surficial geologic materials within landslides is typically possible by observation. A rock hammer can expose fresh surfaces of rock and assist in sampling and examining materials at relatively shallow depths.

Timing and frequency. This method should be used as needed.

Equipment and costs. Rock hammers are relatively inexpensive. Drilling and sampling can be inexpensive if the materials are soft and can be hand drilled at shallow depths. Using small, medium, or large drill rig vehicles would be progressively more costly and probably could amount to several hundred dollars per hour, depending on the depth, width and strength of drilling.

Limitations. Within national parks, splitting of rocks with rock hammers is not usually permitted. Likewise, drilling holes to examine subsurface soils and bedrock in national parks would usually require special permission.

Interpretation. The evaluation of different types of bedrock and soils should first be compared with the available geologic maps within the region. However, more detailed evaluation can also be interpreted by delivering soil or rock samples to geologic consultants. Identification of the type of bedrock or soil, strength of the material, and density would also be beneficial in evaluating the different types of materials.

Level 2: Simple Surface Sampling of Landslide Materials

Collecting and examining samples of surface materials involved in landslides can be very informative for determining the type of landslide processes. For relatively shallow landslides, determining the type of material, relative density, and percentage of water content is often possible. Occasionally, samples of dateable material, such as pieces of buried vegetation, can be collected for radiocarbon analysis, and can provide information on the dating of different previous landslide events near the same location (Fig. 11).

Methodology. Surface sampling is an important method of examining landslides. Simple equipment such as rock hammers and shovels can be used to separate and collect material samples at relatively shallow depths. Rectangular samples provide an approximate direct method by using the measured weight and size to determine the specific soil/rock density. Subsequently, drying out material samples can provide the dry unit weight and determine the percentage of water content. Within landslides consisting of jointed or fragmented rock, it is worth noting if water is present within joints, and if possible, measuring the depth of the water within the joint. However, it is better to measure the direction of strike and dip of joint surfaces within bedrock that can affect the instability of rock slopes.



Figure 11. Detailed examination of prehistoric debris-flow deposits in Madison County, Virginia. Radiocarbon dating from this location indicates that debris flow activity since 25,000 yr B.P. has recurred, on average, at least every 2500 years (Eaton et al., 2003).

Timing and frequency. Examining landslide materials is most important either soon after they have begun or immediately after they have completed major movement. Noting when a landslide is starting to move can provide critical information on the specific type of movement and can also be important for issuing landslide hazard warnings. Examining surface samples of landslides can be done for dormant landslides, but need only be regularly repeated if landslides reactivate.

Equipment and costs. The equipment for sampling shallow landslides is commonly available (rock hammers, shovels, and geologic compass) and not expensive; however, the total cost depends upon how many sites need to be sampled.

Limitations. Depth is the primary limitation on conducting easy landslide examinations. Whereas shallow landslides, e.g., debris-flow deposits, can often be directly examined even at the bottom of deposition, deeper landslides, such as earth slumps, cannot usually be fully examined without deeper mechanical drilling. Additionally, rockslides and rockfalls may be difficult to access and examine closely because of extremely steep slopes.

Interpretation. Determining the type of materials and other important landslide criteria, such as joint orientation for rock slopes, requires general geologic training and experience. Reviewing the general types of landslides, documented by Cruden and Varnes (1996), is the most direct method of learning about landslide processes.

Level 3: Subsurface Sampling and Laboratory Testing of Landslide Materials

Field sampling and laboratory testing of the strength of soil or rock materials can determine relative slope stability. Recognizing and determining the type of soils, such as clay, silt or sand, or types of rocks, such as shale, schist, or granite, provide a relative indication of material strength. Clayey soils have a low frictional strength, but a relatively high cohesive strength, whereas silt and sand have relatively high friction angle strength and low cohesive strength. The frictional and cohesive strength control the relative shape and steepness of soils. These strength criteria are important for evaluating the stability of the soil mass. Within rock masses, measuring and evaluating the joint properties is an important factor for assessing slope stability (Harp and Noble, 1993). The direction and steepness of different joint sets in comparison with the slope surface direction and steepness is necessary to determine what type of slope failure is likely. Intersection of different joint sets can generate a more complex form of sliding referred to as **wedge failures** (Markland, 1972; Hoek and Bray, 1974). Extremely steep joints can also result in toppling of sheets of rock. The opening size, smoothness, and filling of joints are also pertinent to the evaluation of stability. Geotechnical laboratory testing of collected samples provides a more comprehensive assessment of soil and rock strength than simple observation and recognition of material types. Although collecting samples from landslides, especially those from deep sites, may be difficult, the laboratory testing is standardized.

Methodology. Subsurface exploration on landslide sites can be conducted in several different ways depending on the length of time required and the types of information being collected. There are both direct and indirect methods that can be used for subsurface exploration. Direct methods utilize test borings and excavation of test pits which allow the examination of materials, usually with the removal of samples (McGuffey et al., 1996). Of course, one of the most important items is determining how deep the failure surface of the landslide is beneath the ground. Subsurface drilling can be conducted for sampling and examination of deep materials, and also for installation of instruments for subsequent monitoring. For shallow landslides, it may be possible to conduct hand operated drilling and sampling if the subsurface material is not too hard. Indirect methods, such as using geophysical surveys, can provide an evaluation of subsurface geologic materials.

Timing and frequency. Examining and sampling landslide features and materials is most informative as soon as possible after landslide movement has occurred and before surface features are modified by weather or human interaction. For example, determining the scarps, flanks, and subsurface ruptures can be most easily detected soon after deformation.

Equipment and costs. Reconnaissance methods and surface geophysical explorations provide indirect data but are relatively less expensive than drilling. Access for reconnaissance and geophysical exploration is much less difficult than for drilling and subsurface sampling, typically because of steeper and physically disrupted surfaces on landslide terrain. Consequently, the costs for drilling and subsurface sampling are much more expensive than reconnaissance and geophysical explorations, because typically drilling and sampling requires several drilling personnel and significant drill rig equipment. For drilling and sampling at several sites within a large landslide, the costs are likely to involve at least $10,000.

Limitations. The physical steepness and irregularity of ground surface on landslides affects accessibility. For example, steep rockfalls can only be accessed by rock climbers, though small samples and measurements using geophysical methods could be taken if the site is sufficiently stable. Some less steep landslides can still be inaccessible to large equipment, especially drilling machines, because the ground movement could have made the transportation impossible.

Interpretation. Interpreting the results of subsurface investigations of landslides does benefit from experienced geological engineers (and engineering geologists). In addition, some of the basic duties, such as applying a drill rig, require extensive experience.

Additional Information

Observing fresh cracks in soil or rock after a landslide has initiated even small movement can indicate potential future instability. For example, shortly after rockfalls on 7 and 13 February 1986 on a cliff above the Nevada Fall trail of the Merced River in Yosemite National Park, a 3–5-m-long, fine fresh crack was detected ~20 m upslope of the overhanging rock. This crack, with only ~0.5 cm of extensional opening, roughly paralleled a deep, weathered joint, but did not connect to any other cracks near the overhang. During a subsequent storm on 8 March which dumped 10 cm of rain, a rockfall of 1500 to1600 tons occurred at this site, covering ~150 m of the John Muir Trail (Wieczorek et al., 1989).

Vital Sign 4: Measurement and Assessment of Landslide Movement

Installation of instruments for monitoring landslide initiation and prolonged movement can provide important information on the relative hazard posed by landslides. A number of instruments can be used to document landslide movement, including GPS monument points, **InSAR** (interferometric synthetic aperture radar), extensometers, and inclinometers.

Level 1: Application of Measurements from Field Monitoring Tapes and GPS

One of the simplest methods of documenting landslide movement is to install surface field monitoring tapes that can be sequentially measured for landslide movement. However, these surface posts can be damaged by animals or people. The frequency of measurements depends on the frequency and rate of landslide movement. Obviously, dormant landslides do not need to be measured as often; however, once a dormant landslide has initiated movement, it is important to make repeated measurements depending upon the velocity and type of landslide.

Methodology. Wooden or metal posts in the ground can be directly installed into a landslide. In addition, some stable reference points beyond the boundary of the moving landslide are needed. The posts should be deep enough into the solid material so that other factors, such as wind and rain, will not displace them. Points that can be detected on aerial photos can be used to observe previous landslide movement (depending on the amount of movement and the scale or accuracy of the photos); otherwise, accurately measuring displacement is not generally possible.

Repeated visits to existing posts using a GPS instrument to establish precise locations can be used for evaluating rate of landslide movement. Accurate GPS measurements can assess both horizontal and vertical displacement. Six sets of 19 GPS observations made between July 1998 and July 1999 showed that the Slumgullion landslide (Figs. 12, 13, and 14), in southern Colorado (Parise et al., 2004), moved throughout the year, but that daily velocities were highly variable on a seasonal basis from <0.001 m per day to 0.024 m per day (Coe et al., 2000a, 2000b).

Timing and frequency. The timing and frequency of measuring landslide movement is most critical when landslides are actively moving. Timing depends upon the rate of movement. If landslides are consistently, actively moving for more than a day, and if application of measurement is safe, then the monitoring should be repeated regularly, preferably daily or weekly, using hand measurements.

Equipment and costs. Equipment and installation of posts (and measuring GPS points) is relatively inexpensive, if the visits to the landslide site are made regularly. Stereo aerial photography also requires the establishment of GPS stationary points and analysis of the topographic locations, but this is usually a moderate expense.

Limitations. Actively monitoring landslide movement can be limited on rapidly moving landslides that are not safe to approach. However, other techniques, such as measuring the velocity of moving pieces on top of a debris flow are possible. Based on the cross-channel flow surface angle, radius of curvature of the channel bend, and channel slope, the approximate mean velocity of debris flow can be calculated (Costa, 1984).

Interpretation. Frequent measurement improves the ability to determine the nature of the movement. The rate of landslide movement can be interpreted differently, depending on how often the measurements are conducted. For example, if an earth flow moved 10 m in a month and subsequently stopped moving, and was measured before and after the movement within the one month, then the rate of movement (10 m/30 days) would be classified as "moderate." However, if the same amount of movement was only measured once that year, then the rate of movement



Figure 12. Aerial view of the Slumgullion landslide, Colorado. The inactive landslide extends from the lake uphill to the active toe. Active toe is the prominent light colored bulge uphill from where Colorado State Highway 149 crosses the landslide. The entire Slumgullion landslide is 6.8 km long, covers an area of 4.74 km^2, and has an estimated volume of ~170 × 10^6 m^3 (Parise et al., 2004).



Figure 13. Slumgullion landslide station with radar corner reflector and GPS monitoring antenna, providing ground truth for InSAR measurements (Parise et al., 2004).

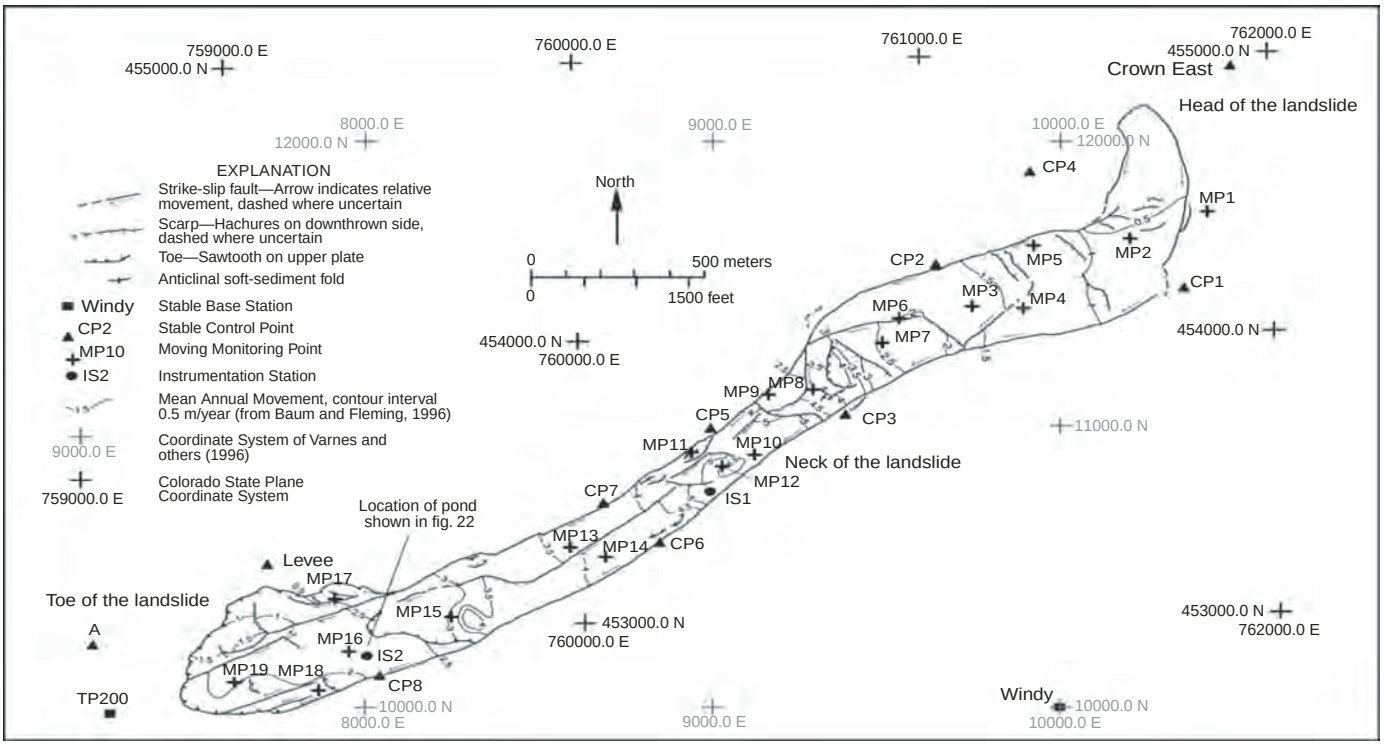


Figure 14. Active part of the Slumgullion landslide with structural elements, contours of mean annual movement, GPS base stations, control points, and monitoring points (Parise et al., 2004).

(10 m/365 days) would be classified as "slow" according to landslide velocity classification by Varnes (1978).

Level 2: Installation of Extensometers for Continuous Monitoring

Instruments installed for continuous measuring of landslide movement are more efficient than periodic measurements. If the rate of movement is known to increase regularly, then instability and potential future movement could be assessed for the purposes of issuing landslide hazard warnings. Data can be retrieved by regularly visiting the site or by transmitting it to another location. However, significant disruption, such as splitting of the ground, could destabilize the operation of the extensometer. For very rapidly moving landslides, such as rockfalls, the initial displacement might happen only seconds or minutes before the accelerated landslide failure. Nevertheless, such measurements could provide useful data for warning systems.

Methodology. Installation of extensometers is similar to establishing movement posts except for the wire connection between the landslide and the stable location adjacent to the landslide. For slow-moving landslides, it may be difficult to determine the location for installing a stable base for the extensometer. Additionally, if the ground is generally creeping outside of the landslide, then the measurement of landslide movement will not be accurate. If a transmitting device is installed for conveying the continuous movement, then the landslide movement can be remotely assessed. Otherwise, the landslide site will need to be regularly visited to download the displacement information from the extensometer (Fig. 15).

Real-time monitoring of landslides is used in selected areas by the U.S. Geological Survey (USGS) to reduce risk from active landslides. Continuous monitoring can detect early indications of rapid, catastrophic movement and provide a better understanding of landslide processes, enabling more effective designs for landslide hazards mitigation. In cooperation with the Eldorado National Forest, California, the USGS acted quickly to install monitoring equipment that would measure landslide conditions and provide the results in real time. The system was installed on the nearby active Cleveland Corral landslide, which has the potential of blocking Highway 50 and possibly damming the American River if the entire slide moved rapidly. With its downslope edge ~150 feet above Highway 50, this landslide moved during the wet winter of 1996 and continued to move slowly downslope during the winter of 1997. In order to detect these kinds of possible precursor movement, continuous real-time monitoring was needed (Reid and LaHusen, 1998).

The USGS also has a cooperative project with the California Department of Transportation (Caltrans) to monitor five active landslide sites (including the Mill Creek landslide) along the Highway 50 corridor. Real-time data from the overall monitoring system, which involves 11 stations and 58 surface and subsurface instruments, are relayed through USGS computers



Figure 15. Measuring landslide movement using a surface extensometer. The extensometer crosses several scarps (breaks that expose the reddish soils) at the head of the landslide (Reid and LaHusen, 1998).

to Caltrans engineers and geologists. These data may provide Caltrans with early notification of landslide activity and may also aid Caltrans engineers in the design of remedial measures to slow or halt active landslides (Reid and LaHusen, 1998). The daily data from one of these landslides are available to the public at http://landslides.usgs.gov/monitoring/hwy50/.

The USGS also installed a real-time monitoring system at the nearby active Cleveland Corral Landslide. A real-time monitoring system provides near-continuous measurements on the hydrologic conditions and ground movement of the landslide. Sensors for the system are installed on the landslide, and the data are transmitted via radio telemetry to USGS computers. Data collected at such a continuous rate and in real-time will greatly increase the understanding of dynamic landslide activity and behavior in the Highway 50 corridor. The amount of downslope movement is recorded by extensometers anchored to the ground surface at the edge of the landslide. Ground vibrations associated with slide movement are monitored by geophones buried within the landslide. Data are sampled from these sensors every second and transmitted to the USGS every 10 minutes. However, data are transmitted immediately in the event of strong ground vibrations associated with massive landslide movement (Reid and LaHusen, 1998).

***Timing and frequency*.** Data are recorded continuously.

***Equipment and costs*.** The installation of the extensometers and equipment for continuous transmitting of the landslide movement data are costly and require regular expert examination for necessary maintenance.

***Limitations*.** The recognition of significant landslide hazards makes the application of extensometers and transmitted data important. Landslides posing hazards to buildings and roads illustrate the need for this type of instrumentation and monitoring. If stable reference points cannot be found, however, then extensometers will not provide accurate landslide movement data.

***Interpretation*.** The monitored rates of landslide movement and variable fluctuation of rates are important relative to the type of landslide. Monitoring the initial movement of reactivated landslides is important, especially if the rate of movement rapidly accelerates posing potential hazards.

Level 3: Aerial Photos, LiDAR and InSAR Techniques

Previous landslides and distances of displacement can be roughly ascertained by examining sequences of photographs—historic, aerial, park operation, commercial, and even visitor photographs—that can be calibrated based on recognizable reference points, and/or using GPS measurements. Identifying reference points on photographs and on topographic maps can serve for evaluating landslide displacement using digital elevation models (DEM). Although the precise date of landslide movement cannot be determined from undated landslides in historical photographs, the careful examination of groups of historical photos can show general periods of landslide movement. The more frequently the photos are taken, the more precise the estimated dates of identified landslide movement.

With high precision new image technology such as **LiDAR** (light detection and ranging), annual images can serve very directly for identifying locations of landslide movement where they might otherwise not have been identified. LiDAR topographic data can be used for: (1) high-quality topographic base information for mapping activities; (2) input for computer algorithms designed to detect land-surface attributes indicative of landslide processes (e.g., McKean and Roering, 2004; McKean et al., 2004); and (3) high-resolution digital elevation models for computing slope stability and potential debris-flow inundation areas. LiDAR can also be used to identify the morphologic signature of shallow landslides that mobilize into debris flows, deep-seated landslide complexes, and the underlying lithologic control on topography. LiDAR can provide detailed topographic data necessary for precise slope stability analyses and subsequent generalization of exportable models. Depending upon the degree of slope, either vertical aerial or horizontal LiDAR coverage may be preferable.

InSAR stands for interferometric synthetic aperture radar, a remote sensing technique using radar satellite images. Those radar satellites (ERS1, ERS2, JERS, IRS, or Radarsat) constantly shoot radar waves toward the earth and record them after they bounce back off Earth's surface. When the radar satellite revisits the exact same portion of the Earth, the phase image should be identical. If not, then something has been going on. By combining those two images, we can measure how much and where the ground has moved.

***Methodology*.** Photographs and GPS measurements can be useful for some types of slow moving types of landslides, such as earth flows and earth slumps. Rapidly moving landslides, such as rockfalls and debris flows, may not be possible to measure physically because of safety concerns. Here, successive photos can be beneficial, especially if the site cannot be easily accessed. An evaluation of regional landslide susceptibility was performed

in Seattle, Washington, using several mapping methods including LiDAR (Schulz, 2005).

Timing and frequency. If the agencies that provide photos or LiDAR coverage are available when requested, clear weather generally determines the timing and frequency of taking imagery. Note that for dormant landslides, aerial photos are generally only worthwhile to determine yearly movement.

Equipment and costs. Obtaining airphotos, LiDAR, or InSAR coverage can be relatively expensive, depending upon the relative size and scale of the requested imagery. For example, in 2005 for landslide examination of the Ventura County in southern California, the USGS obtained research-grade, 1 m LiDAR spacing of ~210 km^2 for approximately $56,000. Generally, smaller LiDAR coverage is more costly per square kilometer. For the same general region, stereo color aerial photographs at the scale of 1:12,000 cost about $6,000. Ground-based horizontal LiDAR is also possible at even finer scales, but cannot cover large regions. Still, it can be very useful for taking imagery of individual landslides.

Limitations. LiDAR is available at 1 m spacing, which can provide evaluation of recognized landslide movement on a relative scale of meters. If regions are thickly vegetated, LiDAR can generally still provide accurate recognition of the ground surface. If the ground surface is recognizable, then ground surface topographic maps can be accurately developed.

Interpretation. Aerial vertical LiDAR imagery does indicate topographic variation, but does not show variation like color photography. Consequently, the same landslide imagery features are not necessarily recognizable in both color aerial photos and LiDAR. For example, some types of landslides, such as debris flows, show more distinctive color differences in infrared photography than adjacent land with no landslides (Wieczorek et al., 2000).

Additional Information

The different mechanisms of initial landslide movement require different monitoring. For example, rockfalls may develop only minimal instantaneous movement before sudden catastro-phic collapse, whereas earth slumps may continue to move slowly at a similar speed for days, weeks, or even months. A relatively simple method of measuring prominent landslide movement can be obtained by using GPS monument points that can be periodically revisited. A slightly more detailed method is using extenso-meters which can continuously register surface slope movement. A potential problem with extensometer instrumentation is possible disruption of the cable by animals or falling vegetation. A more comprehensive measurement technique utilizes installing a pipe sunk into the ground through the sliding plane of the landslide, so that a lowered instrument can periodically measure the pipe's deflection. This device, known as an inclinometer, requires access for drilling which is not always possible because of the steep, irregular landslide slopes. The new technique of InSAR, which utilizes repeated satellite imagery to determine displacement of established reflective ground points, is a sophisticated method which can be used for determining detailed landslide movement remotely on a regular time basis.

Vital Sign 5: Regional Assessment of Landslide Hazards and Risks

Preparation of landslide inventories and mapping of regional landslide events based on historically documented and recently observed landslides can be a prime tool for assessing landslide hazards and risks (Figs. 16 and 17).

Level 2: Mapping of Landslide Inventory and Susceptibility

Compilation of landslide inventory maps is an initial step in the evaluation of regional landslide hazards. Although a landslide inventory map does not necessarily indicate the frequency of landslide activity, the specific types of landslide, or velocity or size, it does show where landslides have occurred in the past, and consequently where landslides might occur in the future under similar conditions.

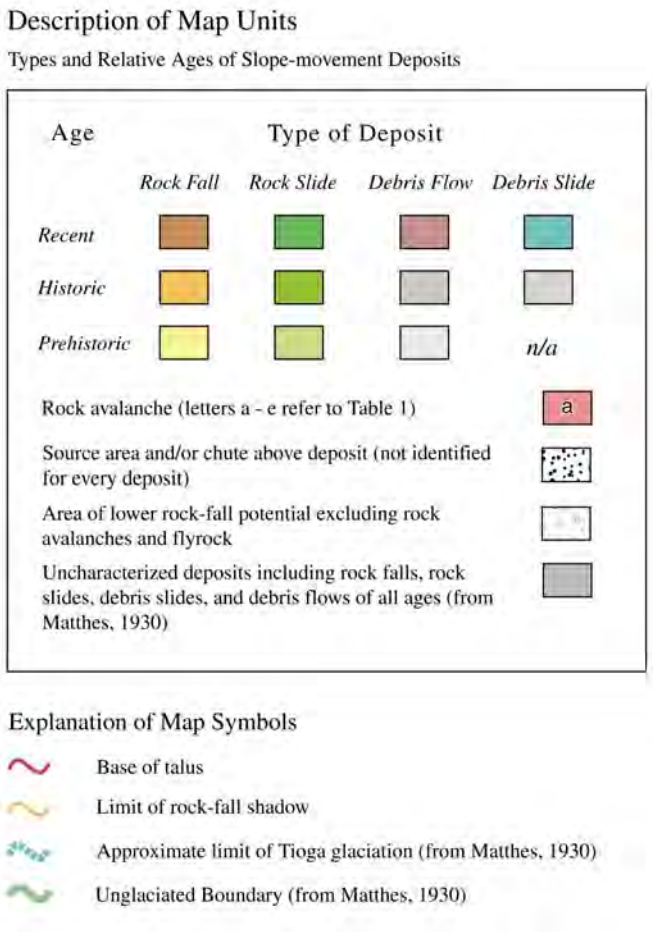


Figure 16. Explanation of Yosemite Valley landslide inventory map (Fig. 17). "Table 1" refers to the table on the map.

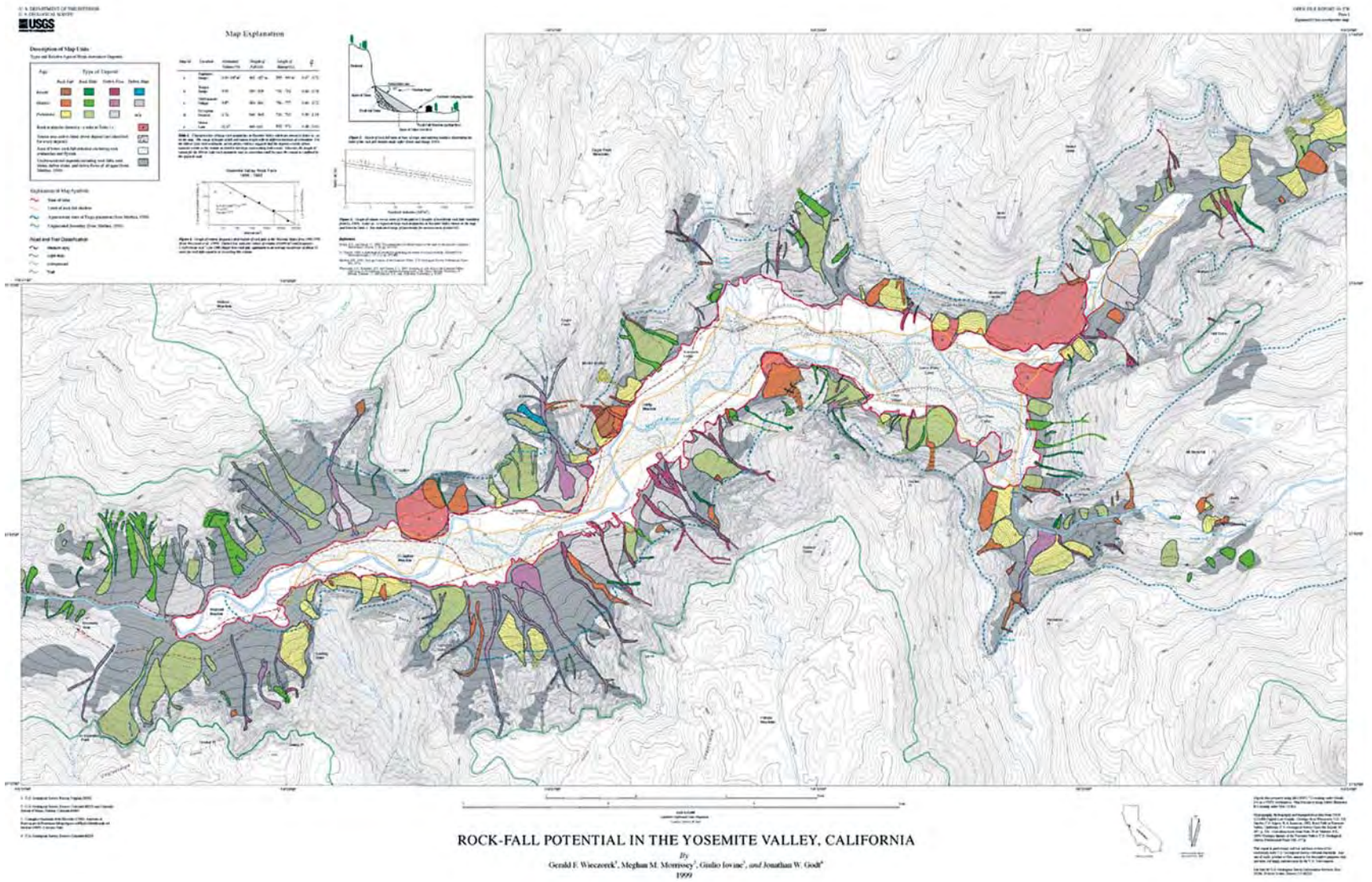


Figure 17. Rockfall potential map of Yosemite Valley, California (Wieczorek et al., 1999). See Fig. 16 for an enlargement of the explanation of information. A file of this map is available at http://pubs.usgs.gov/of/1999/ofr-99-0578/plate1.html.

One of the first comprehensive regional investigations of landslides resulting in a hazard assessment including inventory maps was made along the Columbia River in Washington State (Jones et al., 1961). Geologic investigations of more than 300 landslides along 320 km of the Columbia River valley were conducted intermittently from 1942 to 1948 and continuously from 1948 to 1955, in order to assess the potential instability of land near dams that were being constructed. Inventory maps identified different landslide-age categories such as "recent" and "prehistoric" or "younger" and "older" landslides (Pomeroy, 1977). These maps, ranging in scale from 1:4,800 to 1:62,500, were largely produced from photo interpretation and field investigations. Consequently, the scale of available aerial photography and the scale of the maps determined the size of individual landslides that were depicted. The smaller scale geologic maps were more general in representing areas with landslide deposits. In some cases, surficial geologic maps were prepared which identified landslide deposits, as well as other types, such as glacial deposits (Madole, 1982).

A more direct assessment of landslide hazard is provided by landslide susceptibility maps. Although landslide susceptibility maps, as in San Mateo County, California (1:62,500) (Brabb et al., 1972), Oakland, California (1:50,000) (Pike et al., 2001), and in Butler County, Pennsylvania (1:50,000) (Pomeroy, 1977), do not directly assess the frequency or probability of landslides, the representation of areas subject to landslide hazards is useful for local and regional governments. For improved landslide hazard assessment, details regarding the type of slope movement as well as the recent movement are important on landslide inventory maps. A classification system for the type(s) of individual landslides first developed by Heim (1932) was subsequently refined (Varnes, 1978; Hutchinson, 1968; Cruden and Varnes, 1996).

Methodology. Landslide inventory maps can be developed by using aerial photography and field investigations to identify the locations, relative ages, and types of landslides. Knowing the ages of photos is particularly useful for determining when different landslides have occurred, and possibly determining what rainfall events may have triggered them (Wieczorek, 1984). Landslide susceptibility maps are products of evaluation of the potential of landslides as a function of the type of geologic materials, the degree of slope, and the presence of existing landslides or intact geologic material. Susceptibility maps identify locations where landslides are more likely to occur, but do not predict when they will occur (Jäger and Wieczorek, 1994).

The development of landslide inventory maps, susceptibility maps, and regional probabilistic evaluations of landslides are not effective in reducing hazards unless the information is used by local or regional government organizations in the interests of public safety. To ascertain the rockfall and other landslide hazards in Yosemite National Park, the USGS and the U.S. National Park Service have compiled an inventory and map of historical landslides (Wieczorek et al., 1992). An attempt to assess rockfall hazard based on the "shadow angle" was completed by Wieczorek et al. (1999) and incorporated into the Yosemite Valley Plan prepared by the National Park Service (2000). Measurements of the talus slopes of rockfall deposits and larger individual rocks that occasionally travel beyond the end of the talus can be used for an evaluation of the rockfall hazard (Hungr and Evans, 1988; Evans and Hungr, 1993).

Timing and frequency. The identification of landslides and preparation of a landslide inventory can naturally change with time as more landslide events occur, especially after major storm events. However, a landslide susceptibility map evaluating where landslides can occur may not change dramatically through time and therefore can be a longer-term tool for hazard identification. In order to evaluate landslide hazards and risk, a significant amount of previous investigation and analysis of prehistoric and historic landslide events in a region is necessary. Consequently, a minimum of several months of continuous investigation would be necessary. The presence of previously documented landslides and the availability of regional aerial photographs showing historic frequency of landslide events are necessary, and if available, can expedite the evaluation of landslide hazard and risk.

Equipment and costs. The cost of preparing landslide inventory and susceptibility maps depends upon the size of the region and the number of landslides that need to be examined and analyzed. The more frequent and larger scale of available aerial photos makes accuracy and identification more precise for preparation of the landslide inventory. More frequent evaluation of active moving landslides also provides better information for evaluating the landslide susceptibility of the terrain.

Limitations. Although landslides may regularly occur in some regions due to seasonal rainfall, storms, earthquakes, or even volcanic activity, if these events are extremely large or strong, then the magnitude of the generated landslides can be unusually numerous and large, and consequently have major impacts that cannot generally be anticipated, even if inventory and susceptibility maps are prepared. For example, a storm on 14–16 December 1999 caused catastrophic landslides and flooding along a 40 km coastal strip north of Caracas, in the northern coastal state of Vargas, Venezuela (Fig. 18). The debris flows and floods, which destroyed or damaged more than 8,000 individual residences and 700 apartment buildings, consequently killed 15,000 people. Roads, telephone, electricity, water and sewage systems were severely disrupted. The debris flows and floods inundated coastal communities on alluvial fans at the mouths of a coastal mountain drainage network and destroyed property estimated at more than $2 billion. Beginning in early December of 1999, the interaction of a cold front with moist southwesterly flow from the Pacific Ocean toward the Caribbean Sea resulted in an unusually wet period over coastal northern Venezuela. Moderately heavy amounts of rainfall during the first week of December were followed by extremely heavy rainfall beginning on 14 December and lasting through 16 December. The total 3-day rainfall along the coast for a 52 hour span on 14–16 December totaled 911 mm. These amounts and intensities were highly exceptional; the daily totals (380.7 and 410.4 mm) for 15 and 16 December at Maiquetia exceeded the 1000 year



Figure 18. Aerial view of debris-flow deposits up to 5 m in thickness and totaling ~1.8 million m^3 on the fan of the Río San Julián at Caraballeda, Venezuela. Avulsion at the apex caused flow through the center of the fan to the lower right of photograph. (Photograph by Lawson Smith, U.S. Army Corps of Engineers.)

probability for this location (Wieczorek et al., 2001, 2002; Larsen and Wieczorek, 2006).

Interpretation. Preparing landslide inventories can be fairly standard procedures, although recognizing prehistoric landslides requires experience. Evaluating landslide susceptibility is not a uniform methodology, but nevertheless is an important procedure to identify potential landslide areas. For example, evaluating landslide susceptibility can be significantly different for landslides generated by severe rainstorms than by earthquakes. For example, in San Mateo County, California, an earthquake landslide susceptibility map (Wieczorek et al., 1985) is significantly different from a rainfall induced landslide susceptibility map (Brabb et al., 1972). Other methods of earthquake landslide susceptibility analyses have also been developed (Miles and Keefer, 2000; Wasowski et al., 2000).

Level 2: Evaluation of Landslide Volume, Velocity and Travel Distance

Assessing the combined volume, velocity, and distance of different types of landslide is an important factor for evaluating landslide hazard and risk. Rapidly moving landslides that travel long distances, typically debris flows, debris avalanches, rockfalls, and rock avalanches, can occasionally reach unexpected areas and cause major damage. Physical measurements and analysis of individual landslides are important.

Methodology, timing, and frequency. The most beneficial time for gathering accurate information on landslide volumes, velocity and travel distance is immediately or soon after landslides have occurred. For example, soon after a severe storm in June 1995 triggered as many as ~1000 debris flows in Madison County, Virginia, critical information on debris-flow volume, velocity, and travel distance was collected (Wieczorek et al., 2000). Additionally, the documented times of landslide movement was useful for analysis of how local rainfall could trigger landslides (Morrissey et al., 2001).

Equipment and costs. Physical measurement of landslide volume, velocity, and distance of movement may be obtained using a variety of equipment, and costs depend on the size and depth of the landslide. Drilling of landslides can be expensive, and measuring the scale of the landslide surface area using tapes or GPS equipment is more direct. The depth can then be estimated to calculate the range of possible landslide volume, as for the large landslide above Tidal Inlet, Alaska (Wieczorek et al., 2003). Determining the velocity of landslides is frequently not possible during movement unless instruments have already been installed. If pre- and post-event photographs can be used to evaluate the movement of the landslide, then aerial photos can be useful and inexpensive.

Limitations. It can be physically difficult to observe and accurately measure the velocity of moving landslides, particularly during severe storms, earthquakes, or volcanic events. If instrumentation has already been installed, then measurement of movement is possible (Reid and LaHusen, 1998). Determining the volume of a landslide is sometimes easily possible, if the mass is exposed on the ground surface, as is typical for a rockfall or debris flow. However, the volume of moving landslides that remain entirely or partially beneath the ground surface is not easy to determine without drilling, and can frequently only be estimated.

Interpretation. The risk of potential landslides needs to be interpreted based on the combination of volume, velocity, and travel distance relative to the structures, roads, or other features that are capable of being damaged. The other necessary interpretation is how specific features, such as particular buildings, are likely to be damaged by certain types of landslides with rapid velocities and/or large volumes. Relatively shallow debris flows may travel around structures, if they have been strongly constructed. On the other hand, rapidly moving massive rockfalls, and sometimes individual falling rocks, can severely impact and destroy even well-built structures.

For example, a recent rockfall hazard and risk assessment conducted in Uinta National Forest, Utah (Coe et al., 2005) measured rockfall frequency and rock-mass quality. Rockfalls occurred most frequently from steeply dipping bedrock, and least frequently from shallow-dipping bedrock. Rock-mass-quality measurements, information on historical rockfalls, and engineering-geologic mapping indicated that rockfall susceptibility correlated with the degree of tectonic deformation (folding) of cliff forming, limestone bedrock. Tightly folded, steeply dipping bedrock was very susceptible to rockfall initiation, whereas broadly folded, gently dipping bedrock was moderately susceptible to rockfall initiation. Based on the freshness of talus, degree of soil development, maturity of vegetation, and historical scars of trees and asphalt pavement, rockfall travel paths down from cliffs were identified as the primary paths or secondary paths. Primary paths down primary paths occur with a high frequency of rockfalls. Secondary paths occur with a moderate frequency.

Level 3: Application of Landslide Modeling Techniques

Landslide modeling techniques have developed over the past 100 years. One of the first major landslide investigations followed a large, rapidly moving catastrophic landslide that occurred in Switzerland (Heim, 1882, 1932).

Methodology. A rockfall hazard and risk assessment involving velocity and travel distance was completed in Yosemite Valley, California (Fig. 19) (Guzzetti et al., 2003) using the **STONE** computer program (Guzzetti et al., 2002). STONE is a physically based, rockfall simulation computer program that computes three-dimensional rockfall trajectories starting from a digital elevation model (DEM), the location of potential rockfall release points, and maps of the dynamic rolling friction coefficient, and of the coefficients of normal and tangential energy restitution. For each DEM cell, the software calculates the rockfall velocity and the maximum flying height of the rock. The availability of historical rockfalls mapped in detail allowed the program results to be calibrated to the model parameters.

Timing and frequency. Because the application of landslide modeling techniques requires detailed physical data for specific sites, the necessary information must be accurately collected before the modeling is attempted. Consequently, the techniques cannot be randomly applied without extensive prior field work and technical analysis.

Equipment and costs. The application of the existing modeling techniques is not expensive, but the collection of the necessary field data, including aerial photography and LiDAR imagery, can be relatively expensive. Of course, since only a few types of landslides have available models that can provide the necessary information for assessing hazards and risks, it would be more expensive to develop new hazard assessment methods.

Limitations. The input data required by STONE are similar to the information required by other rockfall simulation programs (e.g., Descouedres and Zimmermann, 1987; Fornaro et al., 1990; Pfeiffer et al., 1991; Spang and Sonser, 1995; Jones et al., 2000).

The location of the detachment areas of rockfalls, the number of boulders launched from each detachment area, the starting velocity and the detachment angle of the rockfall, the velocity threshold below which the boulder comes to rest, and the coefficients of dynamic rolling friction angle and of normal and tangential energy restitution are used to simulate the loss of energy where the block is rolling and at the impact points. STONE differs from other rockfall simulation computer programs because topography is provided by a DEM, and not as pre-defined slope profiles. Values for the coefficients used for modeling the loss of energy at impact points and for rolling are provided in a spatially distributed geographical form. As a result, the outputs produced by STONE are also spatially distributed. STONE is unable to consider the volume and mass of the falling boulder, the shape of the block (e.g., cube, slab, cylinder, disk, irregular), or the tendency of rockfalls to split during successive impacts.

Interpretation. The evaluation and detailed mapping of areas within national parks most frequently experiencing historical and recent landslides can be used directly as an indication of hazards. However, because different types of landslides can occur within a national park, it will most likely be important

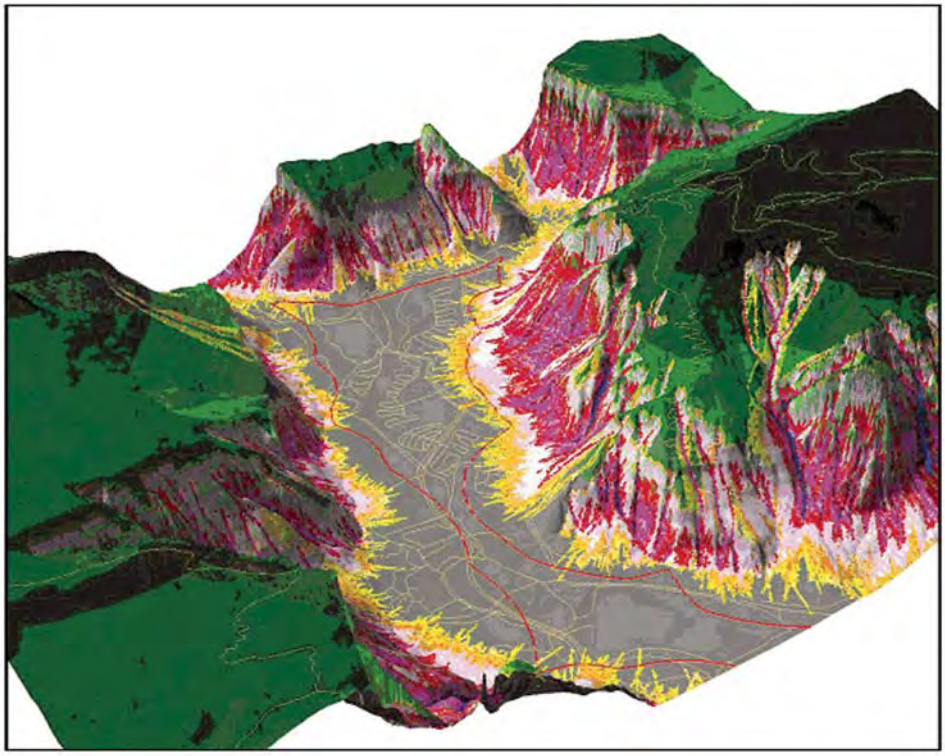


Figure 19. Three-dimensional view of the rockfall hazard using STONE in the eastern section of the Yosemite Valley, California. Colors (from blue, purple, red, pink, to yellow) show a decreasing number of potential rockfalls. The red line is the potential shadow angle rockfall line. Light tan lines are roads and trails (Guzzetti et al., 2003).

to analyze landslide susceptibility depending upon the different types of landslides experienced within a specific park. Numerical models can be used for evaluating possible distance of different types of landslides depending upon volume, types of materials, and degree of slope. For example, various debris-flow modeling techniques have been developed such as the one dimensional DAN (Dynamic Analysis) model (Hungr, 1995) and the two-dimensional FLO-2D model (O'Brien et al., 1993) which predict and compare the runout distance and the velocity of debris flows. For showing potential impacts of landslides from steep cliffs and existing release points, the STONE model can be effective (Guzzetti et al., 2003)(Fig. 19).

Additional Information

The frequency of different sizes (volumes) of landslides and their associated travel distance can be statistically evaluated for hazards and risks. Some published books, such as Landslide Hazard and Risk (Glade et al., 2005), include chapters discussing conceptual models, evaluation, management, and solutions for landslide risks. General references of this type are included in the Further Reading section at the end of this chapter.

STUDY DESIGN

The potential hazard and risk of slope movements should be evident because of historic damage to structures, equipment and roads, as well as injuries and fatalities. The frequency and seriousness of the hazards and risks does influence the relative number and professional qualification necessary for assessment. Size and resources are not specifically relative to the damage and risk of slope movements. The specific costs required for assessment of the hazard and risk of slope movements cannot be easily evaluated in advance. The following section provides specific examples of recent major studies.

CASE STUDIES

Landslides have been scientifically examined in many locations within the last several decades. In 1982, intense rainfall lasting for ~32 hours in the San Francisco Bay region of California triggered more than 18,000 mainly shallow landslides in soil and weathered rock (Ellen and Wieczorek, 1988). Documentation of triggering times for many of these landslides permitted identification of landslide-triggering rainfall thresholds for the San Francisco Bay region (Cannon and Ellen, 1985). A real-time landslide warning system was established and operated by the USGS and the National Weather Service between 1986 and 1995 (Wilson and Wieczorek, 1995; Wilson, 2005). Using a real-time rainfall monitoring system and National Weather Service satellite-based quantitative rainfall forecasts, regional landslide warnings were issued during storms in 1986, 1991, 1992, 1993, and 1995. As a verification of the rainfall thresholds of Cannon and Ellen (1985), the times of landslide hazards in the storms of February 1986 were found to correspond with documented times of shallow landslides (Keefer et al., 1987). The strong El Niño rainfall season of 1997–1998 caused more than $150 million in landslide damage in the ten-county San Francisco Bay region (Godt, 1999; Brabb et al., 2002). Maps were prepared showing the locations of damaging landslides within the ten counties (Godt, 1999). Rainfall thresholds for triggering debris flows have been identified in a number of other regions in the United States, including Puerto Rico (Jibson, 1989; Larsen and Simon, 1993), Hawaii (Wilson et al., 1992), the Blue Ridge of central Virginia (Wieczorek et al., 2000), and Seattle, Washington (Chleborad, 2000, 2003).

A debris slide called the Sentinel landslide occurred in the spring of 1995 in Zion National Park, Utah, and dammed the North Fork of the Virgin River. The subsequent breaching of the dam caused flooding that eroded 180 m along the Valley Floor Highway and damaged underground facilities buried beneath the road. The damage left the Zion Lodge inaccessible, isolating 450 people for several days (Anderson et al., 2000). This slope movement represented the reactivation of a dormant landslide that had experienced similar reactivation and movement in 1923 and 1941 (Grater, 1945). This reactivation was caused by toe erosion from the river along the base of the old slide mass and by rainfall saturation of shale and mudstone within the disrupted landslide mass (Wieczorek and Schuster, 1999).

During the last week of June, 1995, an intense, wet, tropical storm struck the Blue Ridge of Madison County, central Virginia, including parts of Shenandoah National Park, triggering as many as 1,000 debris flows on steep slopes within deeply weathered granite bedrock. The largest debris flow, with a volume of ~57,000 m^3, descended ~400 m vertically and traveled ~3 km horizontally before entering the Kinsey Run stream (Fig. 20). While traveling downhill, this large debris flow cleared a path of vegetation from 30 to 100 m wide and deposited sediment more than 1 m thick, along with large boulders on the lower part of a less steep fan over a maximum width of ~200 m. Estimated velocities of debris flows ranged from ~8 m per second, according to eyewitness accounts, to as great as 24 m per second (Wieczorek et al., 2000) from calculations of mean velocity based on curves of the debris flow channel path (Johnson, 1984). Because many large debris flows initiated in the Shenandoah National Park and subsequently flowed downstream beyond the park boundaries into private property, there was the possibility of the NPS being assessed for damages. The debris flows in this region were photographed and subsequently examined and mapped for evaluation of future potential landslide hazards (Fig. 20) (Morgan et al., 1999).

In July of 1958, a magnitude 7.9 earthquake triggered a rapidly moving large rockslide into Lituya Bay in Glacier Bay National Park, Alaska (Miller, 1960). The impact of the rockslide into the bay initiated a tsunami that ran upward 524 m across the shore on the opposite hillside (Fig. 21) and sent a 30-m-high wave beyond Lituya Bay, sinking two of three fishing boats and killing two people (Miller, 1960).

Another slowly moving large landslide, most likely a rotational rock slump, has been recognized above Tidal Inlet in

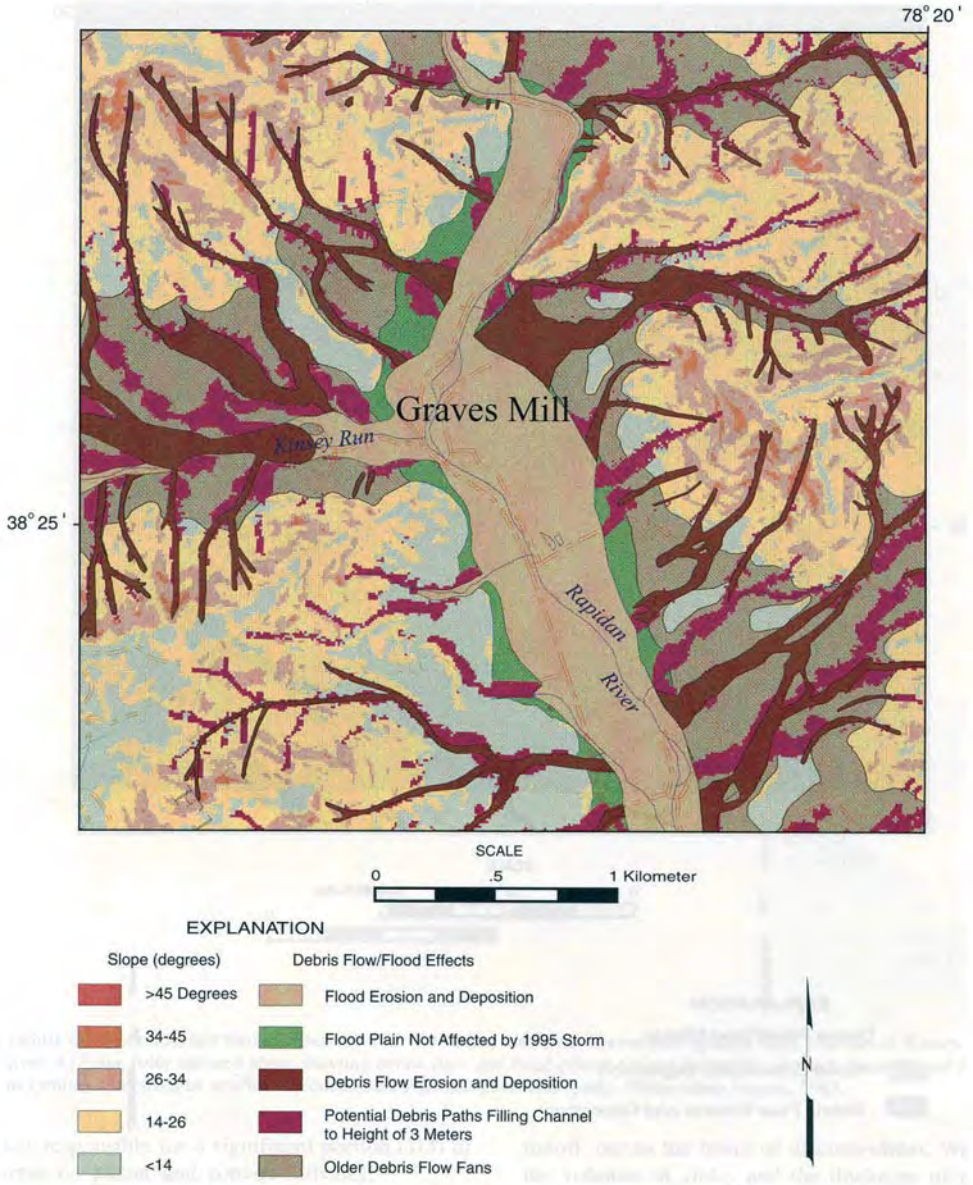


Figure 20. Detailed map showing hazard assessment for debris flows and floods based on inventory of debris flows and floods from June 1995 in Madison County, Virginia (from Morgan et al., 1999).

Glacier Bay National Park. This slump could trigger a large tsunami (Wieczorek et al., 2003; Geist et al., 2003). GPS monitoring of the landslide movement established through a joint effort of the NPS, USGS, and University of Alaska, found southerly horizontal displacement of 7.9 cm (±1.5 cm) between July 2002 and August 2004 (Motyka et al., 2004). Although this movement is extremely slow, the continuing instability creates a potentially hazardous condition with the onset of severe earthquakes, intense rain storms, or rapid heavy snowmelt (Fig. 22).

These landslides show the variety and power of unpredictable natural events. In each case, the history and inventory of slope movement contributed to evaluating future potential hazard and risk. A working relationship between on-the-ground NPS field personnel and USGS and university scientists contributed to monitoring and evaluation. Examples of documented historic landslides in Yosemite National Park, California, will be discussed subsequently as case history examples of monitoring slope movements.

Studies of Yosemite National Park Slope Movement

Following the 1980 Mammoth Lake, California, earthquakes, which triggered nine rockfalls and rockslides and seriously injured two people, the U.S. Geological Survey, in con-

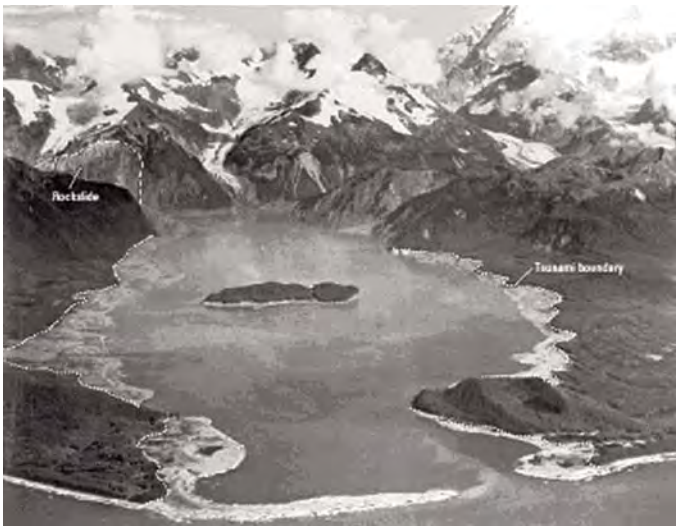


Figure 21. A rockslide (upper left) triggered by a M 7.9 earthquake sent a large tsunami (boundary outlined) through Lituya Bay, Glacier Bay National Park, Alaska, to the Pacific Ocean.



Figure 22. Large detached landslide mass perched above the northern shore of Tidal Inlet, Glacier Bay National Park, Alaska. Potential rapid landslide movement into the inlet could result in tsunami hazard.

junction with the National Park Service, began compiling an inventory of landslides in Yosemite National Park. Recent landslides, previous historic landslides and prehistoric landslides were physically examined as much as possible. As many as 540 reported historic slope failures between 1857 and 2004 have now been documented in Yosemite National Park, which resulted in a total of 14 deaths and at least 62 injuries. Many more slope failures undoubtedly occurred that were not reported. A continuing inventory of the common types of landslides in Yosemite has been compiled, documenting information on the date, size, location, triggering event, damage, and description of individual landslides (Wieczorek et al., 1992; Wieczorek and Snyder 2004). New landslide failures are compared with old events in the inventory for location, cause and trigger, frequency, size, and impacts.

Rockfalls in Yosemite National Park were included in the language and legends of the Native Americans. For example, a site of frequent rockfalls below Middle Brother was called *We-ack*, meaning "fallen rocks," by Native Americans. Many early visitors to Yosemite including Josiah Whitney, state geologist of California; James Hutchings, hotel owner in Yosemite; John Muir, noted naturalist; and Joseph LeConte, professor of geology at the University of California in Berkeley, observed and described landslides. A more systematic recording of both small and large landslide events began after 1916 with the monthly Yosemite NPS Superintendent's Reports. Trail crew and road builders periodically had to evaluate landslide hazards because repairs were necessary to maintain damaged trails and roads. Some trails and roads were permanently abandoned, because of the hazards posed or experienced by landslides. For example, the Old Big Oak Flat Road built in 1874 was closed in 1945 following a large landslide, and the Ledge Trail below Glacier Point was closed ca. 1960 because of frequent rockfalls that injured hikers.

The 26 March 1872, Owens Valley earthquake (M_s = 7.6–8.0) triggered abundant rockfalls and rockslides throughout the southern Sierra Nevada. Several landslides were observed within Yosemite Valley, 180 km northwest of the 1872 earthquake epicenter in Owens Valley. A rockfall behind the Hutchings Hotel in the Old Yosemite Village (Fig. 8) was described by John Muir (1912):

> At half past two o'clock of a moonlit morning in March, I was awakened by a tremendous earthquake…and I ran out of my cabin, both glad and frightened, shouting, "A noble earthquake! A noble earthquake!" feeling sure I was going to learn something. The shocks were so violent and varied, and succeeded one another so closely, that I had to balance myself carefully in walking as if on the deck of a ship among waves, and it seemed impossible that the high cliffs of the Valley could escape being shattered. In particular, I feared that the sheer-fronted Sentinel Rock, towering above my cabin, would be shaken down, and I took shelter back of a large yellow pine, hoping that it might protect me from at least the smaller outbounding boulders…
>
> It was a calm moonlight night, and no sound was heard for the first minute or so, save low, muffled, underground, bubbling rumblings, and the whispering and rustling of the agitated trees, as if Nature were holding her breath. Then suddenly, out of the strange silence and strange motion there came a tremendous roar. The Eagle Rock on the south wall, about half a mile up the Valley, gave way and I saw it falling in thousands of the great boulders I had long been studying, pouring to the Valley floor in a free curve luminous from friction, making a terribly sublime spectacle—an arc of glowing, passionate fire, fifteen hundred feet span…
>
> The first severe shocks were soon over, and eager to examine the newborn talus I ran up the Valley in the moonlight and climbed upon it before the huge blocks, after their fiery flight, had come to complete

rest. They were slowly settling into their places, chafing, grating against one another, groaning, and whispering; but no motion was visible except in a stream of small fragments pattering down the face of the cliff. A cloud of dust particles, lighted by the moon, floated out across the whole breadth of the Valley, forming a ceiling that lasted until after sunrise, and the air was filled with the odor of crushed Douglas spruces from a grove that had been moved down and mashed like weeds.

At 12:16 p.m. on 16 November 1980, a thin, tall 1500 m^3 flake of rock broke loose and fell from a steep rock wall above the trail to Upper Yosemite Fall. The ensuing rockfall destroyed ~800 m along the trail, killed three hikers, and injured another 19 people. The minimum temperature during the three preceding days had fluctuated above and below freezing, and it had rained several days before. The rock pendant above the trail had been heard cracking the previous day, but the noise was mistaken for gunfire. Half an hour before the rock broke, more apparent "shots" were heard by hikers. Subsequent inspection of the release point on the rock wall revealed patterns of roots previously behind the flake indicating that water had access through the jointed rock mass and that ice could have wedged behind the flake. The freeze-thaw process is the most likely triggering event because the rockfall occurred after several days of rain and fluctuating temperatures. Observers realized after the failure that the mistaken "gun shots" were actually warnings of a developing pattern, prompting close attention to cracks and rock noise in later events.

Although the number of historical landslides triggered by earthquakes in Yosemite has been relatively small, earthquakes have accounted for the greatest cumulative volume. At least ten earthquakes have been strongly felt in Yosemite between 1872 and 2004, six of which have triggered rockfalls or rockslides. Using USGS seismic data, the potential for landslides in Yosemite from earthquakes of certain magnitude and with epicenters at particular distances from Yosemite can be roughly determined. The historical record of seismically induced landslides from earthquakes in Yosemite fits within previously observed worldwide upper bounds of earthquake magnitude and distance for triggering similar types of landslides (Keefer, 1984; 1993; 2002).

From the cliffs of Middle Brother, a closely observed large rockfall occurred without an obvious triggering event. On 10 March 1987, National Park Service officials noticed small rockfalls and audible popping noises from Middle Brother. As small rockfalls increased, the NPS closed nearby roads and trails. Later that day, two huge rockfalls from the face of Middle Brother spread rapidly across the talus cone, covered Northside Drive, and sent a few boulders across the Merced River. The combined rockfall volume, estimated at 1.85 million tons, is the largest recorded rockfall event in Yosemite National Park. Because smaller rockfalls continued for several months at this site, Northside Drive was not reopened until the small rockfalls generally ceased in early July 1987. Reopening of the road was based on the pattern of rockfall noise monitored 24 hours a day over several months to determine relative cliff stability (Wieczorek et al., 1995).

The landslide monitoring data collected within Yosemite National Park has provided several types of useful information related to the climatic conditions that can trigger landslides. The collection of rainfall data measured by the National Weather Service within Yosemite for the documented landslide events has roughly characterized thresholds of total storm rainfall that relate to the number of expected landslide events dependent upon the magnitude of the rainstorm. For example, the storm of 17–27 December 1955 which totaled nearly 600 mm (23.5″), including 176 mm (6.92″) on the greatest single day of rainfall, triggered a combination of ten major rockslides, debris slides, and debris flows. By comparison, the 30 December–3 January 1997 storm, with a total of 263 mm (10.38″) and 97 mm (3.83″) on the greatest single day of rainfall, caused flooding throughout Yosemite Valley, but triggered very few slope failures. More difficult is determination of how snowmelt or the freeze-thaw cycles have triggered landslides (Wieczorek and Jäger, 1996).

Since 1980, there have been on average ~10 reported slope failures per year in Yosemite National Park. Nevertheless, it is not possible to predict exactly the time, place, or size of landslides. Only general hazard warning steps can be taken until an emergency occurs or an imminent hazard can be clearly defined. The National Park Service (2000) developed a Yosemite Valley Plan restricting future development in rockfall areas shown on USGS landslide inventory maps (Fig. 16). The collected landslide inventory information has been utilized to evaluate the hazards that are posed within Yosemite. The distance that landslides have traveled and deposited piles of talus have been mapped and characterized as a hazard boundary. However, the existing landslide deposits are not the only indication of hazardous regions because larger collapses on previously unfailed cliffs can certainly occur in the future. In addition, the prospective distance that individual rocks have traveled beyond the talus have been identified as the "rockfall shadow" and were used to recognize potential travel of large individual rocks beyond the talus edge (Wieczorek et al., 1999).

CONCLUSIONS

A basic inventory of past slope movements can show which areas, facilities and operations are more susceptible to landslide impacts than others. An inventory permits comparison and evaluation of relative potential under different circumstances. Combined with mapping talus or landslide-altered slopes, an inventory can show where higher and lower rates of potential rockfall might be. Though slope movement remains largely unpredictable, these conclusions can still relate directly to potential hazardous regions. Despite the complex scientific methods occasionally described within this text, many of the important issues of monitoring landslide movement can be conducted by basic monitoring procedures. Agency cooperation with scientists from universities, state surveys, or the USGS in conducting and reviewing landslide monitoring would produce more complete and effective assessment of landslide hazards and risks.

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INTRODUCTION TO VOLCANO RESOURCES

Volcanoes are not randomly distributed over the Earth's surface. Most are concentrated on the edges of continents, along island chains, or beneath the sea where they form long mountain ranges. More than half of the world's active volcanoes above sea level encircle the Pacific Ocean (see Fig. 1). The concept of **plate tectonics** explains the locations of volcanoes and their relationship to other large-scale geologic features. The Earth's surface is made up of a patchwork of about a dozen large plates and a number of smaller ones that move relative to one another at <1 cm to ~10 cm/yr (about the speed at which fingernails grow). These rigid plates, with average thickness of ~80 km, are separating, sliding past each other, or colliding on top of the Earth's hot, viscous interior. Volcanoes tend to form where plates collide or spread apart (Fig. 2) but can also grow in the middle of a plate, like the Hawaiian volcanoes (Fig. 3).

Of the more than 1,500 volcanoes worldwide believed to have been active in the past 10,000 years, 169 are in the United States and its territories (Ewert et al., 2005) (see Fig. 4). As of spring 2007, two of these volcanoes, Kīlauea and Mount St. Helens, are erupting, while several others, including Mauna Loa, Fourpeaked, Korovin, Veniaminof, and Anatahan, exhibit one or more signs of restlessness, such as anomalous earthquakes, deformation of the volcano's surface, or changes in volume and composition of volcanic gas emissions, that could foretell the onset of another eruption.

Volcanoes, by virtue of their geology and typography, display evocative landscapes and are home to diverse ecosystems, many of which are delicate and unique. Volcanic eruptions can obliterate landscapes and threaten lives, ecosystems and property. For example, the 1980 eruption of Mount St. Helens, although relatively modest on the scale of potential volcanic events in the United States, released energy equivalent to a 24-megaton explosion, devastating forests and obliterating wildlife, including almost 7,000 large game animals, over 600 km^2, killing 57 people, and inflicting more than $1 billion in damages to local economy, agriculture, businesses, and structures. Thus, the very processes that produce the esthetic and ecological resources that we associate with volcanoes are also capable of destroying those resources in minutes.

Most volcanoes are capable of eruptions that pose significant threats to natural landscapes, lives, ecosystems, and property, but fortunately, eruptions are typically preceded by weeks to months of increasing restlessness, allowing eruptions to be forecast if volcanoes are properly instrumented and data are interpreted by teams of experts in the fields of geology, seismology, geodesy, and geochemistry of volcanoes.

In the United States, the Robert T. Stafford Disaster Relief and Emergency Assistance Act mandates that the U.S. Geological Survey (USGS) issue timely warnings of potential geologic disasters to the affected populace and civil authorities. Through this act's mandate, the USGS has the primary responsibility to monitor volcanic activity in the United States. The USGS maintains

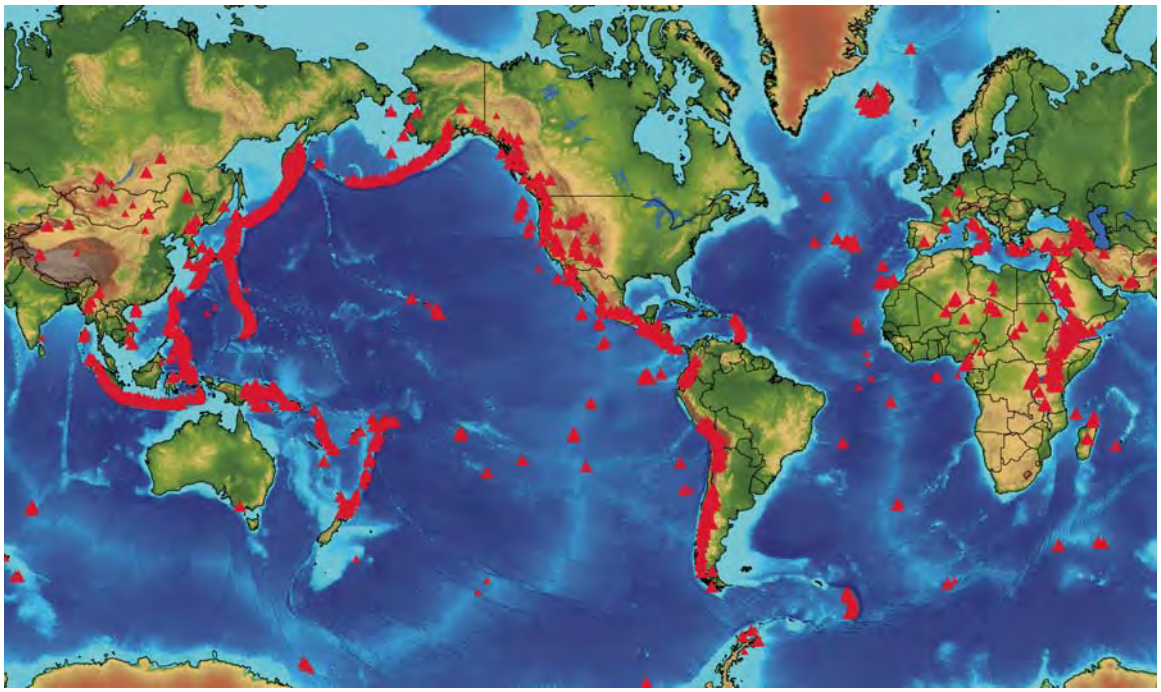
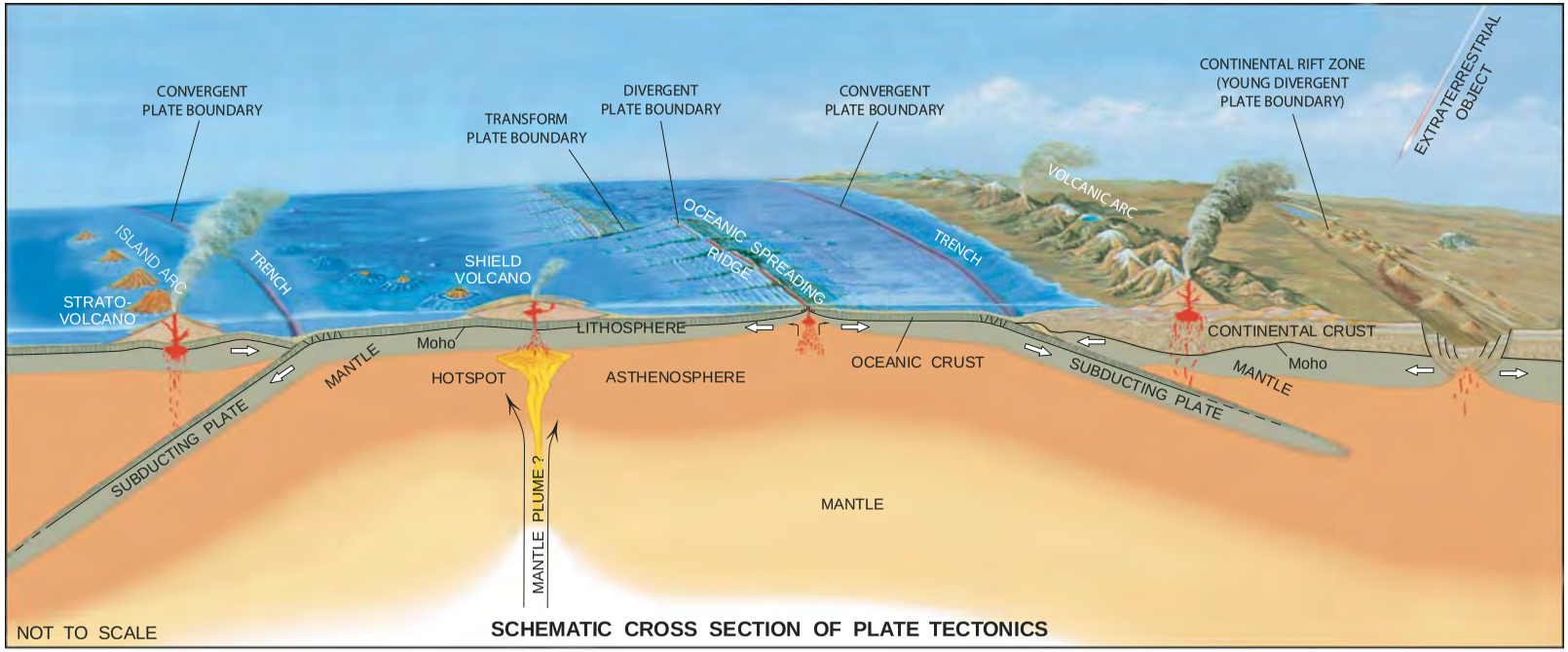


Figure 1. Map of the world showing locations of volcanoes, many surrounding the Pacific Rim and along boundaries of other tectonic plates. Image courtesy of the Smithsonian Institution's Global Volcanism Program (http://www.volcano.si.edu/world/find_regions.cfm). For a more detailed map of volcanoes, earthquakes, impact craters and tectonic plates, see Simkin et al. (2006). Image prepared by Paul Kimberly, Smithsonian Institution Global Volcanism Program.



José F. Vigil and Robert I. Tilling

Figure 2. Schematic cross-section of plate tectonics from Simkin et al. (2006) showing different types of plate boundaries. Image prepared by José F. Vigil and Robert I. Tilling.

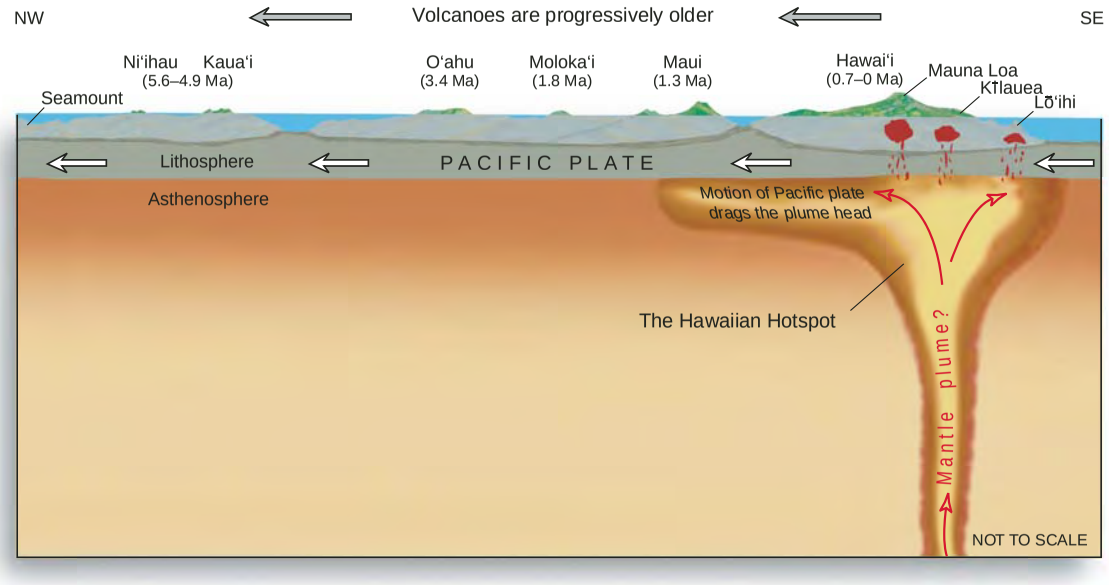


Figure 3. Schematic cutaway view along the Hawaiian Island chain from Simkin et al. (2006) showing the inferred mantle plume that has sustained the Hawaiian hotspot on the overriding Pacific Plate. The geologic ages of the oldest volcano on each island are progressively older to the northwest, consistent with the hotspot model for the origin of the Hawaiian Ridge–Emperor Seamount chain. Prepared by Joel E. Robinson.

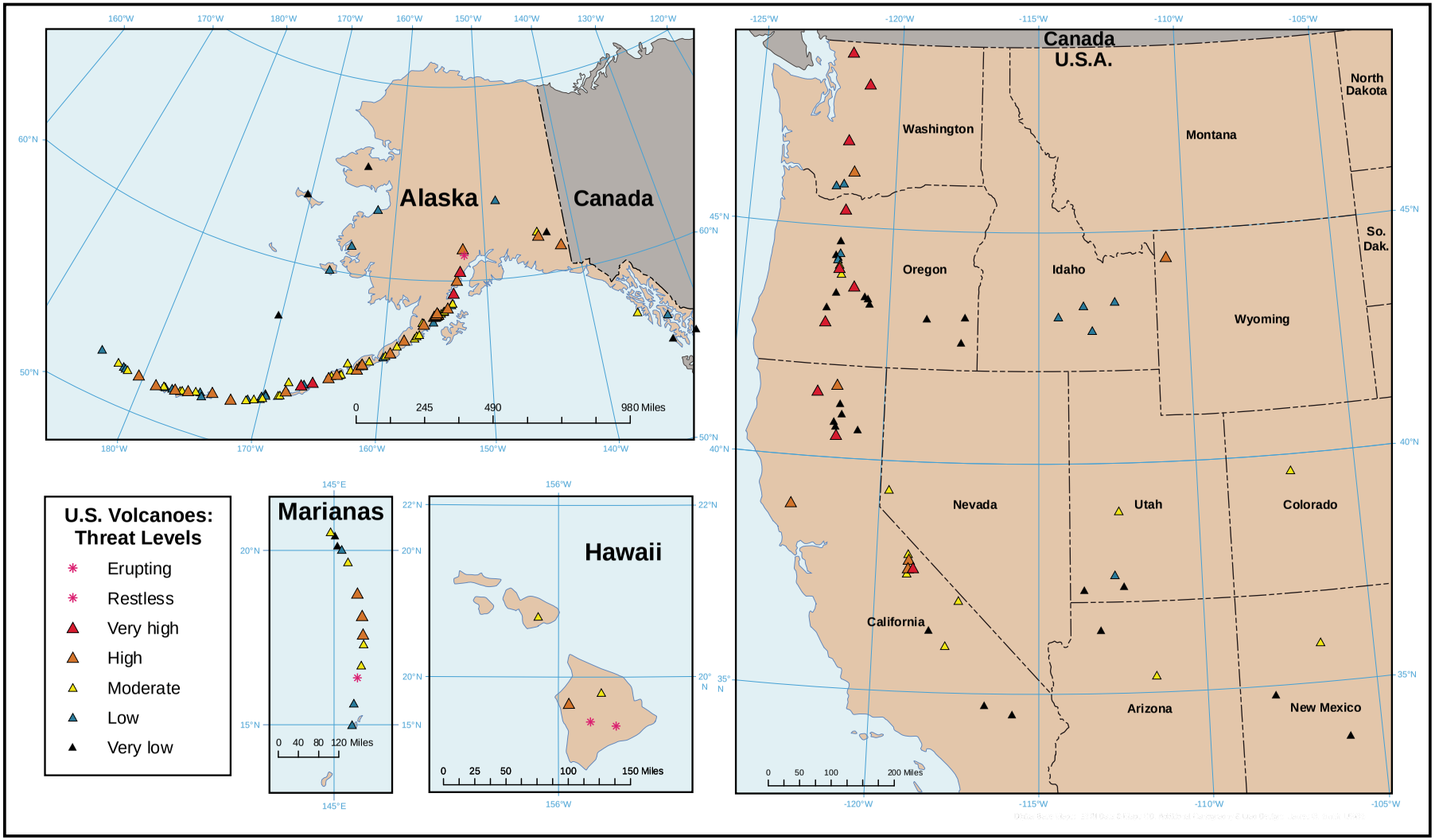


Figure 4. Map showing locations of volcanoes in the United States, classified by threat level as determined by the U.S. Geological Survey National Volcano Early Warning System.

monitoring networks consisting of large numbers and wide varieties of monitoring instruments in order to collect the data needed to forecast volcanic behavior and issue warnings and information to reduce the loss of life, property, and economic impact of hazards related to volcanoes. While the data obtained from these monitoring networks contribute to basic research and advance scientific understanding of volcanoes, the primary justification for instrument deployment is public safety and disaster reduction.

In this chapter, we will discuss the principal vital signs associated with volcanic eruptions, explain the methods for monitoring them, and give a case study. The vital signs described include earthquake activity, ground deformation, gas emission, gas plumes, hydrologic activity, and slope instability. Monitoring methods range from well-established ones to the latest innovations that should become routine in the next few years.

Eruption Style and Frequency

Individual volcanoes erupt different combinations of lava flows, pyroclastic flows, and **tephras** (ash and coarser fragmental ejecta). At some volcanoes, landslides, debris flows, and floods are as hazardous, or more hazardous, than the volcanic eruptions themselves. **Debris flows** are mixtures of mud, rocks, boulders, and water that travel at speeds of tens to as much as 100 km/h. Highly mobile debris flows originating on a volcano are also called **lahars**. Evaluating likely eruptive and hazardous events (event style, size, and frequency) at individual volcanoes is accomplished by constructing geologic maps and conducting hazard assessments.

Factors that influence eruption styles are: the diverse temperatures and chemical compositions of magmas that feed a volcano; the rates at which magma reaches the surface; and local factors, such as the presence of faults or fractures that can serve as easy pathways for magma to reach the surface, or that allow volcanic gases to escape from magma non-explosively. These controlling factors are generally unknown or not sufficiently understood ahead of time to aid in developing detailed hazard assessments or eruption forecasts. Instead, geologic mapping and associated investigations are used to examine, document, and quantify a volcano's past activity. In these investigations, key characteristics are identified that distinguish particular deposits from one another, and overlapping relations between deposits reveal the sequences of events. Tracing individual deposits across the landscape allows geologists to determine the sizes of past events and thus estimate the regions likely to be affected by similar events in the future. Geologists collect samples suitable for age dating by various laboratory techniques. Together, the information on the types of events (eruptions, landslides, debris flows), their magnitudes, and their frequencies are combined to give a history for a volcano. Unexpected features are usually encountered while determining this volcanic history, and detailed studies of these features advance the understanding of general volcanic processes, enabling better-designed monitoring strategies and more accurate forecasts of future behavior.

Volcanic events are **probabilistic**, that is, the time between eruptions, flank collapses, debris flows, or floods can be shorter or longer than the average, and the time intervals can be described by probability distributions (Nathenson, 2001). The simplest approach is to divide the number of known events by the total time encompassed to arrive at an average recurrence interval, but this approach has significant drawbacks. Some volcanoes are known to undergo episodic behavior, where multiple events occur closely spaced in time, and then no events occur for a time interval much longer than the average. Clustering of events is probably typical of all volcanoes to some degree, and underlies the intuition that it is more dangerous to approach a volcano that erupted recently, than it is to approach a volcano which has not erupted for a long time. Furthermore, the likelihood of an event is coupled in some way with the magnitude of the event, with smaller eruptions, debris flows, landslides, or floods taking place more frequently than larger ones. Global data illustrate that long periods of quiet commonly precede the more explosive and dangerous eruptions. For example, of the 16 largest explosive eruptions of the nineteenth and twentieth centuries, 12 were from volcanoes with no previously known historical eruptions (Simkin and Siebert, 1994). Geologic mapping and related field investigations, coupled with age dating, provide the information necessary for probability estimates that link event style, magnitude, and frequency.

Volcano Hazards

Risks from a volcano's hazards commonly extend well beyond a volcano's summit. For example, valley bottoms as far as 80 km beyond Mount Rainier's summit are at risk of inundation by mudflows generated far up on its flanks inside Mount Rainier National Park. More than 150,000 people live in these inundation hazard areas and major transportation lifelines cross them (Driedger and Scott, 2002). Lava flows from the presently restless Mauna Loa volcano in Hawai‘i can reach the highly developed Kona Coast in as little as two hours. The potential harm these hazards can cause, in terms of loss of life and disruption to society and the economy on which it depends, are serious considerations for downslope communities.

Airborne ash clouds are a serious hazard to aircraft. Jet aircraft engines have failed after flying through drifting clouds of even thinly dispersed ash half a continent away from the volcanoes that created them. Large clouds of fine particles of volcanic ash are transported by winds for hundreds to thousands of km beyond their volcanic source (Fig. 5). Volcanic ash particles are angular, abrasive fragments of rocks, minerals, and volcanic glass the size of sand and silt; they have the hardness of a pocketknife blade (Kenedi et al., 2000; Neal et al., 1997). These particles abrade the turbine blades and leading surfaces of aircraft, cause failure of electronics, and melt and coalesce in engines, causing catastrophic and complete loss of power.

Volcanic ash is extremely abrasive. Prolonged breathing of ash causes nasal, throat, and eye irritation and infection in

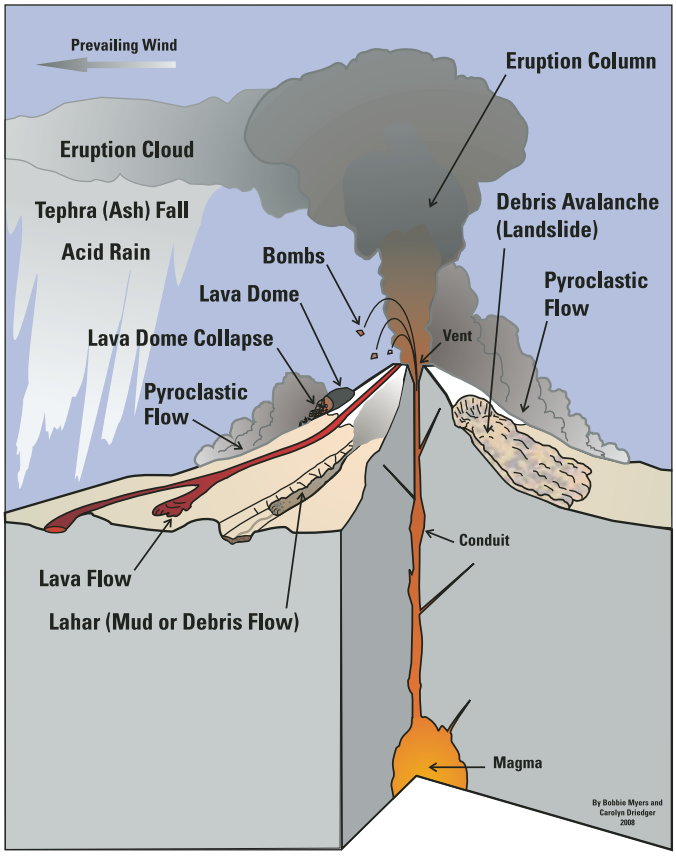


Figure 5. Image of types of volcano hazards. From Myers and Brantley (1995).

both humans and animals. Shortness of breath, sore throats, and bronchitis can occur (from http://volcanoes.usgs.gov/ash/ citing Blong, 1984). Layers of ash just a few millimeters thick will retard growth of plants and if ingested can sicken or kill animals, especially cattle and other domestic and wild ruminants. Thicker ash falls can smother people, plants, and animals. Ash falls can also ruin internal-combustion engines, cause roofs to collapse and communication networks to fail, and break electric power lines. Stones large enough to seriously injure or kill people, plants, and animals can be ejected as far as a few kilometers from an explosive volcano. Winds or even passing vehicles can stir ash back up into the air (Kenedi et al., 2000).

Periods of volcanic unrest, even those that do not lead to eruptions, will likely trigger emergency responses that can lead to area closures and community evacuations. Restless volcanoes challenge public officials because unrest creates uncertainty about how long restlessness will last, when it will end, its severity, who will be affected by it, and even if an eruption will occur at all. All these uncertainties cause major psychological and economic impact in areas around a volcano. Uncertainty brings with it an intense demand for accurate and authoritative information. Civil authorities need information to insure public safety, business owners use information to make business decisions, and news media seek all the information they can get all the time. Satisfying all these demands for accurate and up-to-the-minute information is not easy.

Volcano Threat Levels and Volcano Monitoring

Volcanic threat is a combination of destructive natural phenomena that a volcano is capable of producing (**volcano hazard**) and the people, property, and infrastructure at risk from these phenomena (**exposure**). Matching a volcano's required monitoring level to its threat level provides the most safety for the most people and infrastructure at risk, and it most efficiently distributes funds and scientists' time. Matching required monitoring to threat level became possible in 2005 when the USGS quantified volcano hazard, risk exposure, and threat levels for all 169 geologically active volcanoes in the United States and its territories (Ewert et al., 2005).

Based on its numerical threat score, each volcano was placed in one of five threat categories: very high, high, moderate, low, and very low. Fifty-five of the nation's volcanoes are defined as very high or high threat: this is nearly one-third of all potentially active U.S. volcanoes. Because many volcanoes are either unstudied or incompletely studied, threat scores will likely rise as future studies discover previously unknown past eruptive activity or unrest, and as population and infrastructure at risk increase.

In order to provide adequate warning, volcanoes with high or very high threat levels require intense real-time round-the-clock detailed monitoring. Signals from their monitoring instruments must be transmitted in real-time to a regional volcanic observatory so that volcanologists can quickly diagnose the meanings of the subtlest changes. As a rule of thumb, volcanoes in these two threat categories will require at least 12–20 permanent seismic stations within 20 km of the main volcanic vent, including several stations very close to the vent; routine deformation surveys and continuously recording permanent Global Positioning System (GPS) stations; frequent airborne and ground station measurements of volcanic gases; and instruments along river valleys, sensitive to the unique sounds of passing mudflows, which trigger alarms to warn people downstream. Moderate-threat volcanoes will require real-time monitoring to detect weak pre-eruptive signals as they occur. Typical coverage will require six seismic stations within 20 km of a volcano, including three to four high on its flank, at least six continuously recording, permanent GPS stations in the vicinity, infrequent gas measurements as appropriate for each volcano, and mudflow detectors along river valleys (Ewert et al., 2005).

Of course, if unrest were to start or escalate, or if monitoring data suggested that a given volcano might be moving toward an eruption, monitoring would have to be augmented as quickly as possible for accurate current data to be obtained. In response to increased concern, a wider variety of volcanic phenomena would have to be monitored. New types of instruments would have to

be installed, existing networks of instruments would have to be augmented by reconfiguring existing instruments and adding new ones, and data transmission networks would have to be fortified—all to enable volcanologists to interpret volcanic unrest and forecast likely consequences around the clock.

Low-threat and very low-threat volcanoes, on the other hand, require a lower level of monitoring. For these volcanoes, as for all volcanoes, baseline seismic, deformation, gas, and hydrologic baseline data need to be established, after which low-threat volcanoes require only enough monitoring to detect anomalous activity in near-real time. Very low-threat volcanoes would require even less monitoring.

Because resources were insufficient to instrument and monitor all potentially active volcanoes at an adequate level until quite recently, volcano monitoring by the USGS was done reactively; that is, adequate monitoring was not put in place until some form of unrest was observed at the Earth's surface. Therefore, precursory signals went undetected, and the interval between the first observed signs of unrest and a volcanic crisis was often short. Thus, civil authorities, citizens, businesses, and scientists were forced into playing a dangerous game of "catch up" with volcanoes. Authorities worked overtime to put civil-defense measures in place before unrest escalated to dangerous levels, while volcanologists scrambled to augment instrumentation and install upgraded communication networks, often at great expense and danger to themselves.

Quantitative determination of the specific threat level for each U.S. volcano would allow the USGS to apportion resources so that the most threatening volcanoes could be monitored round-the-clock well before they show any signs of unrest. This proactive approach to monitoring, were it to be implemented, would make it possible for volcanologists to send at-risk communities reliable information from the onset of restlessness, thus giving them the maximum amount of time to activate response and mitigation plans. Proactive monitoring by the USGS gives volcanologists the maximum amount of time to augment monitoring should that be necessary. Even though not every restless volcano erupts, proactive monitoring is still necessary to minimize either overreacting, which costs money, or underreacting, which can cost lives. However, the major obstacle to implementing proactive monitoring in the United States and throughout the world is finding the resources to pay for the necessary equipment and scientists.

Proactive monitoring offers many practical advantages over reactive monitoring. Monitoring:

- Minimizes risk of surprise eruptions.
- Increases time to implement civil defense measures before unrest escalates and a volcanic crisis worsens.
- Enables safe installation of instruments and communication networks at preplanned sites in an orderly fashion. Most very high-threat and high-threat volcanoes in the United States are towering snow- and glacier-clad peaks that are inaccessible except during a short summer season, whereas onset of volcanic restlessness can occur in any season. Summertime installation and equipment maintenance maximizes the probability that preferred sites are snow free, ensures maximum safety for volcanologists and support personnel, and gives adequate time to test instruments and communication networks.
- Increases safety to the more than 80,000 airline passengers per day who fly the busy air routes along the Cascade and Aleutian volcanic arcs. When fully implemented, proactive monitoring of these arc volcanoes will enable volcanologists to notify the Federal Aviation Administration (FAA) within five minutes after a major explosive eruption, allowing planes to change course quickly to avoid ash clouds.
- Improves accuracy and timeliness of future warnings. During the past 25 years, understanding of basic volcanic processes has improved tremendously, based in part on data gained from long-term volcano monitoring. Monitoring data help volcanologists formulate and test models of how volcanoes work. Better models, in turn, improve how volcanoes are monitored, identify the most effective monitoring methods, and suggest new monitoring techniques.
- Adds scientific credibility to land managers' designations of safe areas that can remain open to visitors—in some cases even while a volcano continues to erupt. After 18 years of relative quiescence, Mount St. Helens reawakened in late 2004 when swarms of small earthquakes were detected by the USGS, alerting volcanologists to the presence of magma beneath the volcano. The U.S. Forest Service closed all access to the mountain. Over the next year or so, a series of lava domes episodically extruded within the volcano crater, accompanied by explosions and rockfalls (Schilling et al., 2006). However, by mid-2006, USGS monitoring indicated slowing dome growth, falling rates of volcanic gas emission, and an end to explosive blasts whose effects extend beyond the crater. Although the present dome continued to grow at the rate of about a dump-truck load per minute, which rendered the crater off limits for a time, USGS volcanologists were able to provide guidance to U.S. Forest Service officials, allowing them to reopen trails to the summit in mid-2006. A Web-enabled system for obtaining climbing permits helps ensure visitor safety and allows quick notification should volcanic activity change (U.S. Forest Service, [2007–]).

Restless and Erupting Volcanoes Create Management Challenges

Restless and erupting volcanoes create short- and long-term problems for land managers and civil authorities. Deciding how best to protect human safety while maintaining access and continuing daily life, even while restlessness continues, causes the most short-term challenges. Deciding where to rebuild damaged and destroyed facilities and how to manage destroyed and

damaged natural resources creates longer-term challenges. A few real examples of problems and responses to volcanic unrest illustrate the challenges land managers and civil authorities potentially face. (For more examples and greater detail, see the day-by-day account of events and responses preceding the cataclysmic eruption of Mount St. Helens volcano on 18 May 1980 in Klimasauskas, 2001.)

Restless and erupting volcanoes:

- *Attract spectators who are naively unaware of volcanoes' dangers, but who are nonetheless eager to see the activity for themselves up close.* On 1 April 1980, six weeks before a restless Mount St. Helens erupted cataclysmically, two counties near the volcano asked their state's National Guard for assistance. The counties had maintained six roadblocks around the clock for just four days before they realized they were unable to keep people from entering officially designated danger zones. An FAA spokesman estimated that as many as 100 planes were in the controlled flight zone around the volcano on the same day. Many planes intentionally maintained radio silence presumably to escape detection (Klimasauskas, 2001). A study of wilderness hikers in Hawai'i Volcanoes National Park who ignored prominent National Park Service (NPS) warning signs and attempted to reach active lava flows found that 77% suffered from dehydration, more than half returned with scrapes and abrasions, and 6% suffered from broken bones. "Many hikers were inexperienced tourists willing to disregard warning signs and enter high-risk areas" (Heggie and Heggie, 2004). Several hikers have even died (Johnson et al., 2000). Takahashi et al. (2003, photos 44, 45, and 55) show the spectacular meeting of molten lava with the ocean that draws park visitors to ignore warnings.
- *Require designating areas of restricted access and complete exclusion which in turn requires posting signs, disseminating restrictions to the public, and increasing law enforcement staff to ensure the public are kept out of harm's way.* Boundaries of closed areas have to be adjusted as volcanic unrest waxes and wanes, sometimes for reasons other than public safety. On 8 April 1980, at Mount St. Helens, "Officials moved the roadblock on State Route 503 from Jack's Store back to the Swift Canal east of Cougar after local merchants threatened to sue them over loss of business" (Klimasauskas, 2001). This action moved the restricted area's boundary closer to the volcano. On 10 April 1980, the reported cost of maintaining roadblocks in the vicinity of Mount St. Helens was $9,000 per day. To save money, the U.S. Forest Service closed its press center and grounded its two observation planes. On 15 April 1980, one county shut down some of its roadblocks citing "expense, public harassment, and the stable pattern of explosions at the volcano" (Klimasauskas, 2001). Mount St. Helens' cataclysmic eruption occurred 34 days later. These kinds of problems can be mitigated. For example, close collaboration between the USGS scientists who monitor Hawaiian volcanoes and Hawai'i Volcanoes National Park staff enables the NPS to post regularly updated information on safe and unsafe areas on the park's Web site (http://www.nps.gov/havo/closed_areas.htm).
- *Affect plants, animals (even insects), and humans. In extreme cases, volcanic ash increases morbidity and mortality of plants and animals in the short term.* Lava, ash, and other eruptive materials are sterile when first deposited. Only after weathering do they become the rich, productive volcanic soils typically associated with volcanoes. In the short term, volcanic ash has a deleterious effect on plants and animals. For example, pine trees growing on recently deposited volcanic ash grow more slowly and are shorter than the same species growing on nearby unaffected soils (Ishii et al., 2003). Ash also can clog streams and raise their acidity to levels lethal to fish and aquatic plants. On 2 April 1980, "Operators of a fish hatchery some 5 miles from Mount St. Helens reported a decrease in pH from 6.8 to 5.8 caused by stream leaching of upstream volcanic ash. At a pH of 5.0 the fish would die, so hatchery managers decided to release the salmon when the pH fell to 5.5" (Klimasauskas, 2001). Ruminants are vulnerable to chemical poisoning when they graze in areas where volcanic ash has fallen and to starvation in areas covered by extensive ash deposits (Blong, 1984). Even insects are affected by ash falls; numbers of some species are significantly reduced while others, freed of insect predators, become pests (Fuentes, 1975). See also Brosnan (2000) for a volcano's effect on plant life.
- *Create stress on land management and law enforcement agencies and their staffs to answer public requests for information.* Requested information is not necessarily relevant to the emergency situation, and contacts by irate citizens are common. On 31 March 1980, local newspapers reported that calls to the U.S. Forest Service offices about restless Mount St. Helens included calls from "frustrated citizens who could not access their cabins within closed areas while members of the press had been allowed in…" to "gamblers requesting the number of explosions in the previous 24 hours, to those blaming the volcano's restlessness on the desecration of Indian graves in the area" (Klimasauskas, 2001).
- *Require decisions under pressure on when to relocate or close facilities and businesses, move valuable portable equipment, and relocate people working and living in newly restricted areas.* Relocations and closures, or just the uncertain possibility of them, can result in significant changes in how businesses and government agencies function. These changes commonly affect local economic activity, which generates pressure to avoid economic loss by delaying decisions or rescinding decisions already made.

Conclusions

A variety of precursory signals are generated by the many processes that occur as molten rock (magma) forces its way up through miles of the Earth's crust before eruption at the surface. Many of these signals are extremely subtle and complex, and consequently require expensive arrays of sensitive instruments to detect and scientists with years of experience to interpret. The sections in the rest of this chapter outline the different major techniques used by the USGS to detect, quantify, and interpret each type of signal. In one way or another, each technique tracks types, magnitudes, and locations of earthquakes; uplift and subsidence of the ground surface; or changes in heat, water, and gasses emitted by volcanoes. Because the techniques measure different processes that occur during magma ascent, effective monitoring requires applying many techniques simultaneously to assess near-real-time developments at a volcano.

Just as doctors monitor patients' potential future health risks by studying their medical histories and interpreting results of lab tests over time, so, too, do volcanologists learn about the possibility and size of future volcanic activity by studying a volcano's historic activity and measuring and evaluating the signals it generates over many years. Doctors and volcanologists both know that routine monitoring over time is the best way to detect potential future problems early, when they are most easily dealt with. While patients can go to laboratories for tests, volcanologists can only assess the state of volcanoes in the field by placing monitoring instruments on and near them. Ideally, complete networks of monitoring instruments are put in place while potentially active volcanoes are still quiet. By missing the earliest signals of restlessness, volcanologists risk losing critical early data needed to establish "baseline" trends and accurately estimate the size of a possible eruption. For example, when Mount St. Helens reawakened in 2004, additional monitoring instruments could not be installed rapidly enough to catch the volcano's initial signals. This prevented confident determination of the volume of magma intruded beneath the volcano (Ewert et al., 2005), which in turn added significant error to estimates of the size of potential eruptions.

For updates on activity of U.S. volcanoes in the past seven days, see http://volcanoes.usgs.gov/vhpfeed.php.

STRESSORS/POSSIBLE CHANGE

Volcano monitoring methods are designed to detect and measure signals caused by magma movement beneath a volcano. Rising magma typically will (1) trigger swarms of earthquakes and other types of seismic events; (2) cause deformation (swelling or subsidence) of a volcano's summit or flanks; and (3) lead to release of volcanic gases from the ground and vents. By monitoring changes in the state of a volcano, scientists are sometimes able to anticipate an eruption days to weeks in advance and to detect remotely the occurrence of certain related events like explosive eruptions and lahars (Guffanti et al., 2001). (See Table 1 for a summary of volcano vital signs and monitoring methods.)

VITAL SIGN MONITORING DESCRIPTIONS

Vital Sign 1. Earthquake Activity

Introduction

Movement of magma and associated fluids within volcanoes often occurs with concurrent, measurable earthquake activity (**seismicity**). At restless volcanoes, evolving seismic activity commonly, but not always, precedes eruptions. The most common seismic disturbances are earthquakes in response to stress changes caused by magma movement beneath a volcano.

When magma rapidly intrudes into surrounding rock, the rock breaks abruptly, causing an earthquake whose signal is similar to that of an earthquake along a tectonic fault (Fig. 6A). This type of earthquake is called a **volcano-tectonic (VT)** earthquake. VT earthquake signatures are characterized by clear and often impulsive, or abrupt, wave onsets and contain energy across a broad range of seismic frequencies.

A second type of earthquake associated with volcanic areas is the direct result of magma or other fluids flowing through conduits in volcanic or active hydrothermal areas (Fig. 6B). Pressure variations in flowing magma or hydrothermal fluids force the cracks through which these fluids move to vibrate. Compared to VT earthquakes, these earthquakes appear with a dominant and lower frequency of oscillation and are called **long-period (LP)** earthquakes (e.g., Lahr et al., 1994; Harlow et al., 1996).

In addition to volcanic earthquakes, continuous or sustained ground oscillation is often observed at restless volcanoes. This is referred to as **volcanic tremor** and is closely linked to LP earthquakes. Tremor can be thought of as sustained crack vibration driven by the moving magma (Fig. 6B and parts of 6C).

Explosions at a volcano's vent or at shallow depths beneath the vent create the fourth type of common volcanic earthquakes. Naturally enough, these are called **explosion earthquakes**. Figure 6D shows a recording of a small explosive event at Mount Pinatubo that lasted for only a few minutes. However, sequences of explosion earthquakes can go on for hours as they did at the cataclysmic eruption of Mount St. Helens in 1980. Explosion earthquakes are generally accompanied by forceful ejection of steam, volcanic gases, ash, and fragments of lava in various proportions.

For additional information on seismic monitoring methods, see Braile (this volume).

Level 3, Method 1: Seismic Monitoring

Volcanic eruptions are almost always preceded by increasing seismicity, and the most reliable indicators of impending eruption are shallow earthquakes and tremor (e.g., Chouet, 1996). Typically, volcanic unrest begins deep beneath a volcano and progresses to shallower depths as time to eruption approaches.

TABLE 1. SUMMARY OF VOLCANO VITAL SIGNS AND MONITORING METHODS

Vital signs and methods	Expertise	Special equipment	Cost*	Personnel	Labor intensity†
Earthquake activity					
Seismic activity	Scientist	Yes	$$$	Group	High
Ground deformation					
Electronic distance measuring (EDM)	Scientist	Yes	$$$	Group	High
Triangulation	Scientist	Yes	$$$	Group	High
Leveling	Scientist	Yes	$$$	Group	High
Tilt	Scientist	Yes	$$$	Group	High
Global Positioning System (GPS)	Scientist	Yes	$$$	Group	High
Aerial photography/light detection and ranging (LIDAR)	Scientist	Yes	$$$	Group	High
Interferometric synthetic aperture radar (InSAR)	Scientist	Yes	$$$	Group	High
Emission at ground level					
Direct fumarole sampling of gases and isotopes	Scientist	Yes	$$$	Group	High
On-site instrumental measurements (open-path Fourier transform infrared spectrometer, differential optical absorption spectrometer, gas chromatograph)	Scientist	Yes	$$$	Group	High
Soil efflux measurements	Scientist	Yes	$$$	Group	High
Emission of gas plume and ash clouds					
Correlation spectrometer (COSPEC) and Mini-UV spectrometer (Flyspec)	Scientist	Yes	$$$	Group	High
LI-COR (infrared spectrometer)	Scientist	Yes	$$$	Group	High
Doppler radar	Scientist	Yes	$–$$$	Group	High
Hydrologic activity					
Hydrologic activity	Scientist	Yes	$$$	Group	Medium-high
Slope instability					
(see Hillslope chapter for determining types of landslides and triggers and causes of landslides)					
Lahar hazard delineation (LAHARZ + GIS)	Scientist	Yes	$$	Group	High
Real-time monitoring of lahars—acoustic flow monitor (AFM)	Scientist	Yes	$$$	Group	High
Techniques that can be used to monitor various vital signs					
Remote sensing via satellite	Scientist	Yes	$$$	Group	High
Unmanned aerial vehicles (UAV)	Scientist	Yes	$$$	Group	High
Interferometric synthetic aperture radar (InSAR)	Scientist	Yes	$$$	Group	High
Infrasound	Scientist	Yes	$$$	Group	High

*Cost (in US$): $ = <$1,000; $$ = $1,000–$10,000; $$$ = >$10,000.
†Labor intensity: medium = <full day; high = >full day.

The object of seismic monitoring at volcanoes is to record and monitor the earthquakes and tremor that accompany volcanic unrest. Seismographic networks record the signals radiated from volcanic seismic sources, then specialists analyze and interpret these signals and their patterns.

Seismologists use seismic data from a network of seismometers to locate an earthquake's **hypocenter** (the point directly beneath the Earth's surface where the rupture on a fault begins) and its **epicenter** (the point on the Earth's surface directly above the hypocenter). Seismicity can be detected at greater distances and from deeper sources than other signs of volcanic unrest. Therefore, seismic monitoring typically provides the earliest signals of volcanic unrest. Evolving patterns of hypocenters and epicenters help scientists to infer whether magma is moving either vertically or laterally. Cataloging events as either VT or LP helps distinguish between tectonic faulting and moving magma earthquake origins.

Seismographic Networks

Effective volcano monitoring networks extend from the volcanic center or active vent outward to distances of 20 km. To determine especially shallow source depths precisely, several seismic monitoring stations in the network must lie within a few kilometers of the vent. To locate epicenters and hypocenters precisely, stations should be distributed evenly around a volcano at varying distances from the vent. Best practice requires 10–20 seismographic stations around each potentially hazardous volcano in the United States.

Each monitoring station in a network is equipped with a seismometer, electronics to amplify and convert the signals for

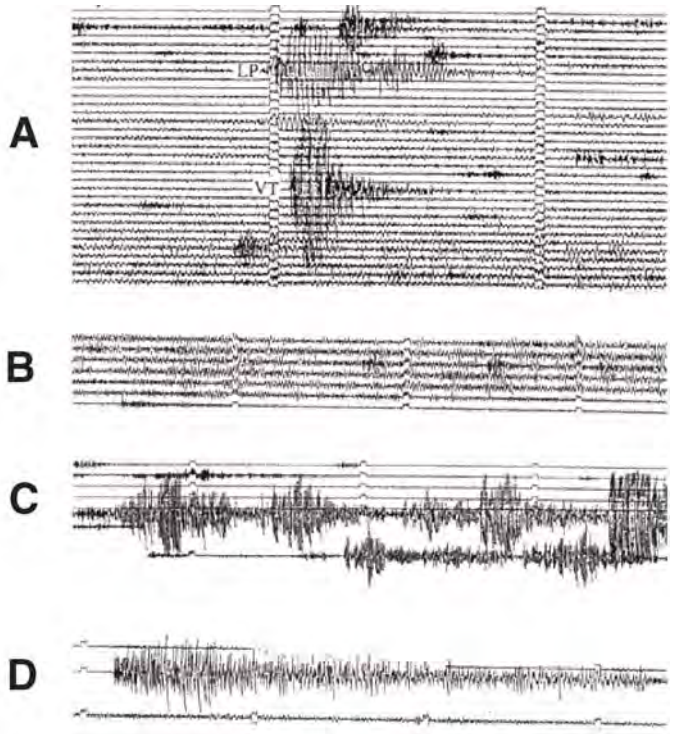


Figure 6. Examples of seismic event signatures observed at Mount Pinatubo in the Philippines, as interpreted and reproduced from Figure 3 of Harlow et al. (1996). (A) Long-period earthquake (LP) and volcano-tectonic earthquake (VT). (B) Tremor consisting of closely spaced LP earthquakes. (C) Tremor consisting of closely spaced deep LP earthquakes. (D) Explosive eruption signal. Time sequence on each seismographic recording is from upper left to lower right; evenly spaced tick marks along each trace mark one-minute intervals.

transmission, telemetry components, and batteries and solar panels to power the station. The seismometer is buried 1–2 m beneath the ground's surface. The station's electronics and power components are installed in small, above-ground housings. The transmission antenna and the solar panel, if not installed atop the station housing, are installed on a short mast. Stations are designed to minimize the impact of the station installation and operation in remote or wilderness areas.

The seismometer registers ground motions, and converts the motions to electrical signals. The converted signals are telemetered in either analog or digital form to a nearby volcano observatory. In general, analog stations cost less to buy and install, use less power, and transmit their signals over longer distances than digital stations. Digital stations provide higher quality data and therefore more accurate recordings of seismic shaking. Once installed, they are simpler to maintain than analog stations. Many seismographic networks use combinations of analog and digital stations. An analog station costs $7,000 to $10,000, while a digital station costs $15,000 to $20,000 (all amounts herein are in US$). In the future, it is likely that the performance advantages of digital stations will become more important than the cost differences. Therefore, the proportion of digital seismic stations in volcano monitoring networks will likely increase.

Seismic Data Processing

Data telemetered from field stations to a volcano observatory are collected onto customized computer systems that make possible real-time and near-real-time analysis of seismic data streams and near-real-time posting of seismic analysis products. Important analysis products include locations of epicenters and hypocenters, earthquake magnitudes and continuous seismic amplitude and spectral displays. Real-time data analysis and display greatly facilitates short-term eruption forecasting and evolving hazard assessment. Observatory staff members interactively review the analysis products to verify the output and enter additional information that more completely describes the events. A computer system with these capabilities consists of a number of workstation computers and costs several tens of thousands of dollars. The computers also store and archive the data. Software packages for seismic data acquisition and analysis are commercially available. Alternatively, similar software packages have been developed, are maintained, and made available by the U.S. Geological Survey.

Discussion

While increased seismicity commonly precedes volcanic eruptions, the time from the earliest earthquakes to an eruption varies widely. Increasing numbers of volcano-tectonic earthquakes may occur months or even years before an eruption. However, not every increasingly restless volcano erupts; seismic activity may wax and wane without an eruption for long periods of time.

Volcanic processes are complex and variable, and therefore produce multiple types, patterns, and numbers of earthquakes (e.g., Chouet, 2003). Missing a volcano's crucial early seismic signals impedes scientists' ability to accurately forecast events. Protection of people and property requires installation of seismic monitoring networks at potentially dangerous volcanoes to measure baseline seismicity and monitor for suggestive increases in seismicity, well before unrest begins or obvious signs of significant unrest are noticed at the Earth's surface.

Baseline seismic monitoring of seismic signals from earthquakes near a volcano as well as from the other side of the globe as they travel through a volcano enables scientists to catch the beginnings of unrest and to determine locations of faults and possible accumulations of magma. Volcano scientists use this knowledge to improve their assessment of a volcano's eruption probability, volume of erupted magma, and location of hazardous areas.

Vital Sign 2. Ground Deformation

Introduction

As magma moves beneath a volcano, it creates space for itself by displacing the Earth's surface. Quantifying the characteristics

of this deformation over space and time can give important information about the depth, volume change, and geometry of magma reservoirs below the ground. For example, when magma accumulates beneath a volcano, perhaps as a prelude to an eruption, the overlying surface will inflate like a balloon. Similarly, after magma has been erupted, or when magma drains to deeper levels or moves laterally below ground to other locations, the surface deflates in response to this removal of the volume. A more detailed explanation is available at http://hvo.wr.usgs.gov/howwork/subsidence/inflate_deflate.html. Displacements of the Earth's surface can be measured by a variety of methods, including both terrestrial and space-based technologies. Each method has advantages and disadvantages; therefore, deformation monitoring should not rely on a single technique, but should instead incorporate as many methods as possible. Concurrently utilizing several different methods offers the best chance of recognizing surface displacements at a volcano and providing information on the probability and timing of an eruption.

Trailing-Edge Technologies

Though several classic volcano deformation monitoring methods have been replaced by newer methods due to technological advancements, these older monitoring methods may still be useful at some volcanoes. These classic methods include electronic distance measurement (EDM) and triangulation. Both methods require precisely located ground points as references for the measurements. Called **benchmarks**, these points are common, especially at the tops of hills and mountain peaks. Benchmarks are usually brass or aluminum disks (Fig. 7A) with centering marks (often a cross or dimple), but can also be less obvious pins (Fig. 7B) or shapes chiseled into rock. It is important that these marks are not disturbed, because they are used for repeat surveys over time. If the marks are destroyed or moved, they cannot be reoccupied and volcano deformation monitoring capabilities are diminished.

Level 3, Method 1: Electronic Distance Measuring (EDM)

EDM measures the distance between two points by placing a laser over a benchmark at one point, pointing it at a reflector array over a benchmark at a second point (perhaps as far away as tens of kilometers), measuring the travel time of a laser pulse between the two benchmarks, and then converting the time to distance. Measured distances are accurate to within a few centimeters. EDM requires at least two people, one at the laser and one at the reflector site. Because variations in atmospheric conditions are the primary source of error in EDM, temperature and atmospheric pressure measurements at both endpoints and along the track of the laser via aircraft are recommended. Repeat measurements between a pair of sites show how the distance changes over time. The Web site http://volcanoes.usgs.gov/activity/methods/deformation/index.php provides a more detailed explanation under the EDM tab.

Networks of EDM line-length measurements were state-of-the-art for determining volcano deformation in the 1960s–1980s.

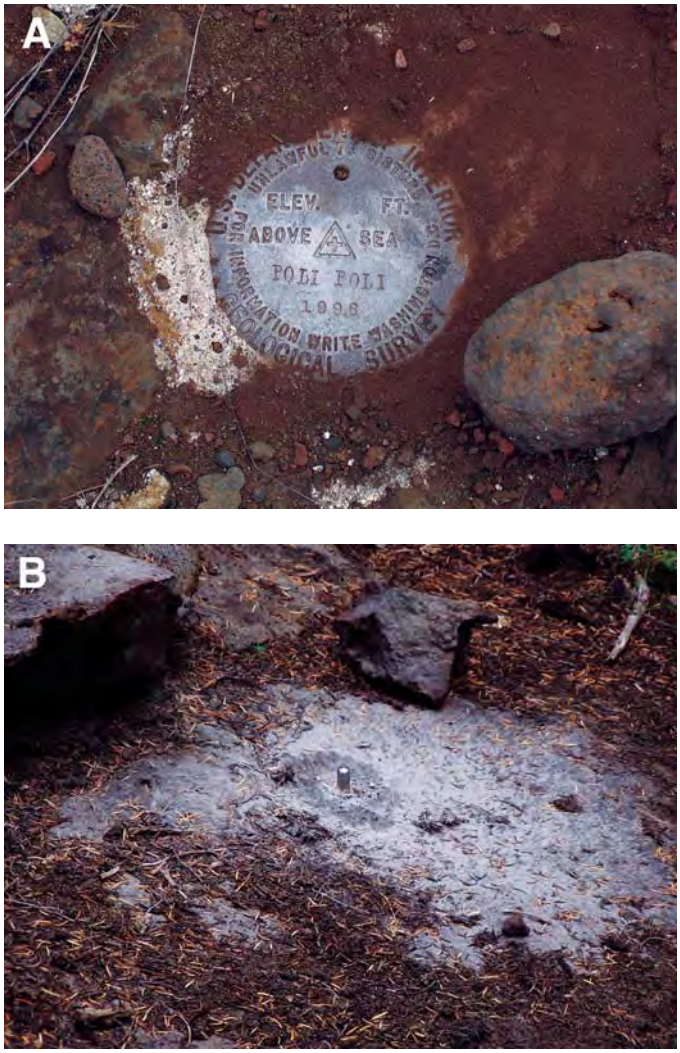


Figure 7. Benchmarks are cemented into the ground and provide known points that can be surveyed year after year. (A) Typical brass disk benchmark, ~10 cm in diameter. The cross at the center of the triangle is the center point of the mark, and is used as the reference point for deformation studies. (B) Occasionally, less conspicuous pins, only ~2 cm in diameter and with center punch at the top, are used as benchmarks. These are harder to see and less likely to be stolen.

Because EDM is now outdated, EDM equipment is difficult to purchase. Instruments can cost $20,000 to $30,000, depending on the model. Reflectors are over $100 each.

Level 3, Method 2: Triangulation

Triangulation uses precise surveying instruments to measure the horizontal angles of a triangle whose vertices are benchmarks that may be tens of kilometers distant from one another. Changes in the angles over time are used to determine horizontal deformation of the Earth's surface. Vertical angle measurements, for example, from the base of a hill or mountain to its top, may also be taken to determine changes in elevation over time. Triangulation

requires a significant investment of time for relatively little data (repeated measurements from each of the vertices in the triangle are required). The instrument used to collect angle measurements is a theodolite, which can cost as much as $20,000.

Though EDM and triangulation were once important deformation monitoring methods, the Global Positioning System (GPS) has largely replaced them. GPS provides better data than most of the classic deformation monitoring methods while requiring less time and personnel (though more specialized training and advanced computing routines are required). Still, many volcano monitoring networks in the United States were originally established using EDM. By comparing past EDM surveys with recent measurements using GPS, it is possible to determine line-length or angle changes since the time of the previous measurement, which can be quite useful for determining long-term deformation of a given volcano. This practice also continues the time series of deformation data, allowing for easier recognition of anomalous signals. For example, an EDM network was established at Lassen Peak in Lassen Volcanic National Park in 1981. InSAR results analyzed in 2004 suggested that the volcano is subsiding ~1.5 cm per year. To obtain independent ground measurements, the EDM network was reoccupied with GPS that same year. Results confirmed the subsidence and suggested that the deformation has been occurring since at least the 1980s.

Both EDM and triangulation measurements require clear lines of sight between the instrument station and target locations. Thus, EDM and triangulation benchmarks tend to be on the tops of hills or mountains, which are often difficult and costly to access. In these cases, it is wise to abandon these sites and establish new GPS stations at more accessible locations. This will reduce the need for helicopter access, decreasing both the expense and intrusiveness of deformation monitoring.

Level 3, Method 3: Leveling

Another classic surveying technique is **leveling**, a method which measures vertical elevations of benchmarks. Unlike EDM and triangulation, however, leveling is still regularly used today. Repeated leveling surveys along a series of benchmarks can determine elevation changes over time to sub-millimeter accuracy. No other method, with the possible exception of continuous GPS, is as sensitive to vertical deformation.

Leveling is accomplished using a pair of precisely graduated rods made of invar (a metal with a low coefficient of thermal expansion), usually 2–3 m tall, and a leveling "gun" (a sight designed to take readings from the rods). The gun is positioned between the two rods and precisely balanced, and the graduations on each rod are read by looking through the gun sight (Fig. 8). Differencing the rod readings determines the difference in elevation between the two rods. After the reading is completed and recorded, one rod leapfrogs the other, the gun is repositioned, and the measurement is repeated. By continuing these measurements along a transect between benchmarks, it is possible to determine the relative elevations of a network of benchmarks. Over time, repeated leveling surveys show how benchmark elevations change, perhaps as a result of magmatic activity beneath the surface.



Figure 8. Leveling crew working in Hawai'i Volcanoes National Park.

Leveling surveys require four to six people: one person to operate the leveling gun, two people to hold the rods, and one to three people to support the survey by finding benchmarks, collecting temperature readings, recording measurements, and directing traffic (most leveling lines are located along roads). An experienced leveling crew can typically survey 5–7 km per day, depending on topography and desired accuracy. Leveling equipment may require reading and recording by the gun operator and an assistant, or may be digitally recorded. In the latter case, the leveling rods have barcodes on them instead of numerical graduations. The gun reads the barcode and determines the elevation difference between rod locations, recording the measurement on a memory card.

A leveling gun costs about $3,000; leveling rods are about $1,000 each for either a digital (barcode) or an optical (graduated) model. Ancillary equipment, including temperature probes, tripods, and traffic signs could cost as much as $1,000. Because the rod scale must be as accurate as possible, recalibration is recommended every 2–4 years (depending on the desired accuracy and frequency of use). Calibration of the rods can only be done by a university laboratory in Quebec and costs about $1,000.

Leveling is still used at numerous volcanoes worldwide. For example, in Hawai'i Volcanoes National Park, annual leveling surveys are an important and informative monitoring method because their great accuracy has shown changes in the magnitude and direction of vertical deformation of Kīlauea volcano. Since the start of the Pu'u 'Ō'ō eruption in 1983 through 2003, the summit of the volcano subsided by as much as 1.5 m. However, the displacement pattern changed to uplift in late 2003, perhaps indicating increasing magma supply to the volcano that may be a precursor to future changes in eruptive activity. In fact, uplift continued through 2007, when new eruptive vents broke

out on the east rift zone, leading to a major change in the eruptive style of Kīlauea Volcano. Leveling surveys have also helped characterize volcanic unrest at Yellowstone National Park, where similar changes from uplift to subsidence, thought to be related to the subsurface circulation of hydrothermal fluids, have been observed over short (1–2 year) time spans.

The most useful applications of leveling are on relatively flat volcanoes that are well covered by roads. Because of the large commitment of time and personnel required by the method, leveling over extreme topography or rough terrain, which requires an inordinate amount of time, generally does not justify the cost. For this reason, leveling is an excellent tool for monitoring volcanoes like Yellowstone caldera, but not optimal for use at **stratovolcanoes** (steep, conical volcanoes built by the eruption of viscous lava flows, tephra, and pyroclastic flows) such as Mount Rainier.

Level 3, Method 4: Tilt

Ground **tilt** has been used to monitor volcano deformation for almost 100 years. Thomas A. Jaggar, founder of the Hawaiian Volcano Observatory, first used tilt to monitor volcanic activity at Kīlauea, Hawai'i, in 1912. Since that time, instrumentation and techniques for measuring tilt have evolved through several iterations. The most cost-effective and modern method uses tiltmeters that are installed in shallow boreholes.

A borehole tiltmeter is analogous to a carpenter's level. The instrument is a cylinder, 0.6–1 m in length (Fig. 9) and filled with an electrolytic fluid that contains a bubble. Electrodes sense the movement of the bubble as the instrument tilts. By placing the tiltmeter in a sand-filled borehole in bedrock, ~2 m deep (which effectively couples the instrument to the Earth), the tilt of the ground surface can be measured. Using a network of tiltmeters, sources of inflation or deflation at active volcanoes can be identified. More information and examples are available at http://volcanoes.usgs.gov/activity/methods/deformation/index.php at the tilt tab.



Figure 9. Borehole tiltmeter installation in Hawai'i Volcanoes National Park. The instrument is being lowered by its cable into a cased hole. The solar panels, telemetry mast, and electronics box have been installed at the right.

Tilt data can be stored at the instrument site in a data logger and periodically downloaded, but it is far more practical to telemeter the data, ideally in real time, to a volcano observatory. The processing and interpretation of tilt data is trivial, since voltages output by the instrument translate directly to magnitude and direction of ground tilt via a simple calibration factor. The simplicity of the data and processing makes tiltmeters attractive as monitoring instruments, but note that tiltmeters do not record displacements, only tilt. Also, the instruments are quite sensitive to environmental changes, including temperature fluctuations between day and night, atmospheric pressure changes, and rainfall. Thus, tiltmeter sites should be equipped with rain gages, thermometers, and barometers so that raw tilt data can be interpreted with respect to environmental factors.

A tiltmeter costs about $8,000, but much additional equipment is needed to operate a telemetered tiltmeter station. A data logger and radios (which can telemeter both the tilt and environmental data) for the site and a receiving station cost an additional $6,000, and a portable drill (hundreds to a few thousand dollars) is needed to make the borehole. Batteries and solar panels, at a cost of $1,000, are necessary to keep the instrument operational, and environmental sensors (thermometer, barometer, and rain gage) can cost a few hundred dollars.

The best example of tilt as a volcano monitoring method is provided by the Hawaiian Volcano Observatory. In Hawai'i Volcanoes National Park, almost 20 borehole tiltmeters monitor Kīlauea and Mauna Loa volcanoes. Each instrument takes a reading once a minute, which is immediately telemetered to the Hawaiian Volcano Observatory. These near-real time tilt measurements routinely provide short-term warnings of changes in volcanic activity, like the new magmatic intrusions in 1997 and 1999, and the 2008 episodic deflation/inflation episodes at Kīlauea's summit that lasted hours to two days. No other technique that is currently in use can detect such activity as it occurs.

Level 3, Method 5: Global Positioning System (GPS)

In the late 1980s, the Global Positioning System (GPS) became a viable method for measuring deformation of the Earth's surface, gradually replacing EDM and triangulation. The primary advantage of GPS over all other deformation monitoring methods is the ability to simultaneously measure horizontal and vertical displacements within accuracies of a few millimeters.

GPS is utilized in one of two modes: continuous and survey. Continuous GPS uses a permanently installed GPS receiver and antenna (Fig. 10A) at one location to track the motion of that station over time. The advantage of continuous GPS is that changes in the magnitude and direction of displacement are well resolved. However, the station cannot be moved; thus, any variations in spatial deformation patterns cannot be identified. In survey mode, a GPS antenna on a tripod (Fig. 10B) is set over a benchmark for

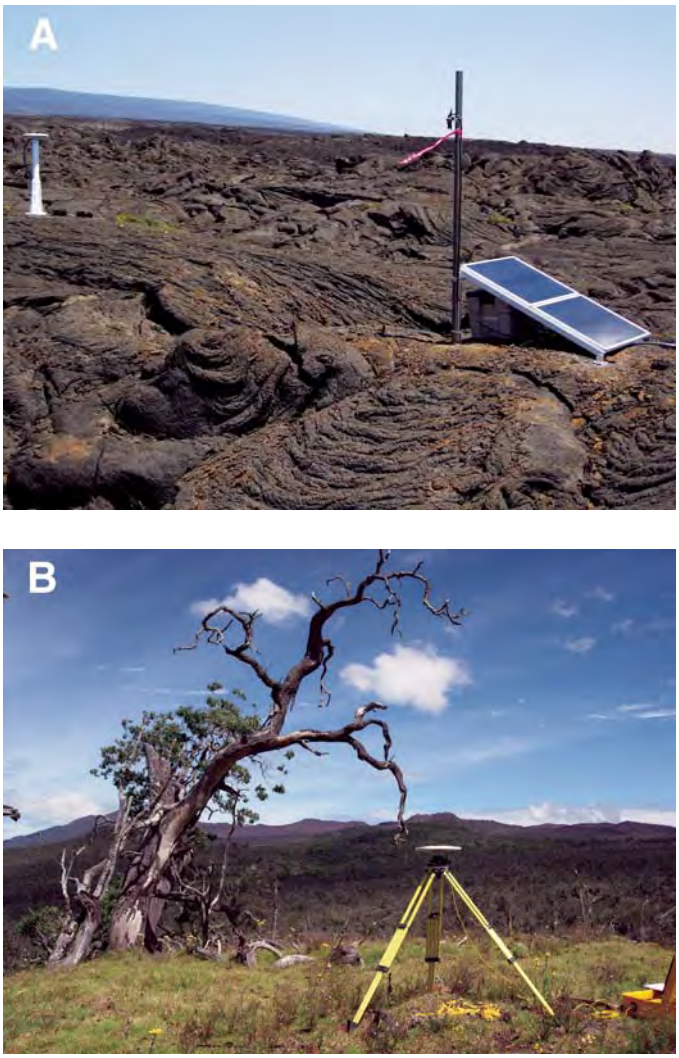


Figure 10. Methods of Global Positioning System (GPS) monitoring. (A) This continuous GPS installation in Hawai'i Volcanoes National Park consists of an antenna (white disk on the pedestal at the left), solar panels, electronics box (beneath the solar panels), and telemetry mast. (B) A survey GPS site, with a GPS antenna and tripod set up over a benchmark. The box at the lower right contains the GPS receiver and battery.

a short time period (e.g., two days) while the station's position is continuously recorded. The GPS installation is then moved to other sites as needed. Repeat occupation of the same benchmarks provides information about how the surveyed points in a region have moved, but time resolution will be poor.

Both methods of GPS monitoring require a clear view of the sky. Obstructions such as buildings and vegetation obscure the satellite signals and result in poor measurement quality. In addition, short-term GPS measurements tend to be contaminated by multipath (satellite signals that do not travel direct lines between the satellite and the receiving antenna). It is important to collect as much data as possible to average out such effects. Survey sites should record data for at least six to eight hours per day. This is not an issue for continuous installations, which record data 24 hours a day.

GPS positions are calculated using processing software that is generally provided free of charge by research institutions such as the National Aeronautics and Space Administration (NASA) and the Massachusetts Institute of Technology. The software is highly specialized and requires substantial experience and training to use correctly. A GPS receiver and antenna cost about $4,000. Continuous GPS sites require batteries, solar panels, and radio telemetry, at a cost of about $3,000 per site. For equipment that is operated in survey mode, only tripods and batteries are necessary (about $500), in addition to the receiver and antenna.

GPS is the ultimate tool for measuring three-dimensional displacements; therefore, it is no surprise that GPS is presently the dominant method for deformation monitoring at volcanoes. In Hawai'i Volcanoes National Park, over 50 continuous GPS stations are supplemented by over 100 sites that are occupied for a few days each during annual or event-driven GPS campaigns. This combination of methods provides the best possible temporal and spatial resolution of deformation patterns associated with active volcanism. GPS surveys of ~40 sites, in the vicinity of Mauna Loa supplemented by three continuous stations, first detected inflation of Mauna Loa volcano, Hawai'i, in 2002. In response to this activity, the continuous GPS network was expanded by ~20 more sites in the following three years. The new continuous stations provide better resolution of surface displacements over time, which will result in more reliable forecasts of future activity of Mauna Loa.

Level 3, Method 6: Aerial Photography/Light Detection and Ranging (LIDAR)

Light detection and ranging (**LIDAR**) surveys and aerial photography are used at restless volcanoes to quantify areas experiencing large surface deformation. Both techniques are also used at erupting volcanoes to quantify the volume of extruded material such as lava flows, volcanic domes, etc. LIDAR surveys and aerial photography are used to construct digital elevation models (**DEMs**) of the ground surface. Volcanologists use DEMs from successive surveys to calculate volume change between surveys. For example, during the 2004–2008 eruption of Mount St. Helens, a time series of DEMs provided the only reliable measure of lava volume as well as its extrusion rate. Tracking volume and extrusion rate helps volcanologists forecast how long an eruption might last and the total volume of lava that might be produced.

Aerial photography is the most basic and cheapest method used to construct DEMs; this is a mature technology in use for decades. A pair of slightly overlapping vertical photos is taken from an aircraft. A stereoscope or specialized computer software is then used to create a topographic map of the ground surface, from which a DEM is generated. During the run-up to the 18 May 1980 eruption of Mount St. Helens, DEMs corroborated the rapidly increasing rate of inflation on the volcano's north flank, leading to the recognition that the north side of the volcano was unstable before the collapse occurred on 18 May 1980.

LIDAR is similar to radar, but uses much higher frequencies of light (usually ultraviolet, visible, or infrared) to survey the elevation of the ground surface. Light, emitted by a laser mounted on an airplane, is reflected from the ground surface, and the travel time is measured by an optical telescope mounted in the same airplane. The light's travel time is converted to distance (analogous to EDM), from which a DEM accurate to within a few centimeters is constructed. LIDAR surveys require precise location of the aircraft, so a reference GPS station on the ground must be available within the survey area. Highly specialized software and extensive operator training are required to process LIDAR results, therefore most LIDAR surveys are completed by private companies.

Generally, the lower cost of aerial photography makes it the method of choice for monitoring volcanoes. A flight to collect aerial photography may cost $1,000 to $5,000, whereas LIDAR flights cost tens of thousands of dollars. LIDAR data also requires several weeks to process, whereas, depending on the desired level of accuracy, aerial photography can be converted into a DEM within days. However, the greater accuracy of LIDAR makes it ideal for locating subtle low-relief features on the ground's surface, such as faults with minor surface offset. In the first weeks following the onset of renewed eruptive activity at Mount St. Helens in late 2004, both LIDAR and aerial photography were used to construct DEMs, which provided important data on the growth of the lava dome in the volcano's crater. However, the great cost of LIDAR caused DEM studies to be done entirely by aerial photography within two months of the start of the eruption.

Level 3, Method 7: InSAR

The use of interferometric synthetic aperture radar (**InSAR**) is described in detail in the Emerging Volcano Monitoring Techniques section below. Although InSAR is rapidly evolving, limiting factors include satellite availability, distortions from atmospheric effects, and the need for relatively long intervals between measurements so that deformation is evident above detection limits. However, InSAR is effective for measuring large-scale, long-term deformation over large areas where other methods would be prohibitively expensive, and it is a good technique for prospecting for deformation where it has not previously been identified, and as a long-term precursor for potential volcanic activity, as illustrated at South Sister volcano (see Emerging Volcano Monitoring Techniques section). With a few exceptions, InSAR is not yet an operational tool for most volcanoes that are showing significant unrest, threatening to erupt, or actually erupting because repeat InSAR images of a given volcano can only be captured at roughly monthly intervals when the satellite is overhead, preventing monitoring of short-term changes.

Remote sensing via satellite, described in the emerging techniques section of this chapter, can also be used to monitor surface deformation. Unmanned aerial vehicles (UAVs), also described in the emerging techniques section, are appropriate in areas that are difficult or dangerous to access to monitor changes in active lava domes, lava flows, and vents, such as the growth and collapse of a new lava dome.

Summary

Combinations of monitoring methods allow comprehensive monitoring of spatial and temporal evolution of a volcano's deformation; only a combination of methods can compensate for the weaknesses of any single method. Clearly, various methods and instruments used to monitor deformation at active volcanoes have advantages and disadvantages. For this reason, effective monitoring strategies employ a mix of continuous and survey methods. For example, in Hawai'i Volcanoes National Park, the U.S. Geological Survey's Hawaiian Volcano Observatory uses 20 borehole tiltmeters, more than 50 continuous GPS receivers, more than 100 survey GPS sites, and InSAR data from several different satellites to monitor deformation at Kīlauea and Mauna Loa volcanoes. The same combination of methods is used at Mount St. Helens, where aerial photography is also employed to create DEMs and track the volume and rate of erupted lava over time.

Vital Sign 3. Gas Emission at Ground Level

Introduction

Volcanic gas is naturally released from both active and many inactive volcanoes. Water vapor is typically the most abundant volcanic gas, followed by carbon dioxide (CO_2) and sulfur dioxide (SO_2). Other common volcanic gases are hydrogen sulfide (H_2S), hydrogen chloride (HCl), hydrogen fluoride (HF), carbon monoxide (CO), and hydrogen (H_2), along with many other trace gases and isotopes as well as volatile metals. Concentrations of these gases can vary considerably from one volcano to the next. The majority of potentially active volcanic areas are characterized by one or more low-temperature fumaroles and a fairly well developed hydrothermal system. Large volcanic systems, such as Yellowstone, have numerous vents and fumaroles discharging volcanic gases to the air over a wide geographic area. Some active volcanic systems, such as Kīlauea in Hawai'i, have a variety of gas vents and fumaroles that can range in temperature up to several hundred degrees.

Volcanic gases can be harmful to humans, animals, plants, and property. Usually, the hazards, which can range from minor to life threatening, are restricted to the areas immediately surrounding volcanic vents and fumaroles. However, heavier-than-air gases such as CO_2 can collect in topographic depressions on the flanks of volcanoes and pose a hazard to human health and safety. Acid gases, such as SO_2, when present in abundance, can combine with water in the atmosphere to produce localized acid rain downwind from volcanic vents.

Molten rock, or magma, beneath volcanoes contains abundant gases that are the driving force of eruptions. Volcanoes become restless when magma begins to move from depth toward the Earth's surface. As magma moves into shallower areas under the volcano, it encounters lower pressure conditions that allow more gases to escape into fractures and cracks. Some of these gases are eventually discharged at the surface through hot fumaroles, active vents, or porous ground surfaces where they, if measured, can provide valuable information about the ongoing processes

below. Rising magma also heats up the rock mass beneath the volcano and eventually causes water in shallow hydrothermal systems beneath the volcano to boil, releasing additional gases. Land management personnel can contribute significantly to identifying the early signs of volcanic unrest by noting and reporting the appearance of new fumaroles, the sudden appearance of a "rotten egg" smell, an increase in fumarole temperatures or the appearance of new hot ground, unexplained animal deaths, and the onset of anomalous vegetation and tree mortality.

A variety of ground-based methods for measuring volcanic gases includes: direct sampling of gases from fumaroles followed by laboratory analysis, measuring one or more gases at a fumarole with portable instruments, establishing long-term gas monitoring stations at volcanic vents, and conducting soil-gas efflux surveys. Each method is discussed below. All are well-suited for long-term evaluation of volcanic conditions. A strategy involving on-site instrument measurements coupled with laboratory analysis of fumarole gas samples can be particularly effective for geochemical volcano surveillance.

Level 3, Method 1: Direct Fumarole Sampling of Gases and Isotopes

Direct gas sampling is ideally suited for long-term surveillance of volcanic systems because it produces a detailed chemical analysis of specific fumaroles and vents. Volcanic gas samples are typically collected by inserting a chemically inert and durable tube into a hot fumarole. After allowing the tube to heat until condensation in the tube reaches equilibrium with the escaping gases, either a specially-designed evacuated-sample bottle or a flow-through sample bottle is attached to the collection tubing. After the sample is taken, it is sent to an analytical laboratory for analysis by ion and gas chromatography and traditional wet-chemical methods. More information can be found at: http://volcanoes.usgs.gov/activity/methods/gas/sample.php. Field gas sample kits cost less than $1,000, while laboratory analytical instruments for performing this type of gas analysis cost about $30,000 each.

Typically, the full suite of major volcanic gases in the sample can be determined, including water, CO_2, SO_2, H_2S, HCl, HF, CO, and H_2, other gases such as nitrogen (N_2), oxygen (O_2), helium (He), and neon (Ne), if present, plus other trace gases. Fumarole temperature plays a large role in determining the quality and utility of direct samples. The higher the temperature, the better the sample will reflect the conditions of the magma supplying the gas.

Direct gas sampling of fumaroles is not well suited for monitoring rapidly changing conditions because laboratory analyses often take days or weeks to complete. However, detailed gas composition analyses often provide critical information for evaluating volcanic hazards and constructing models that provide insight into the condition of the magma at the depth from which the gases originated.

Isotopes uniquely distinguish sources of volcanic gas. Although sample collection vessels can be slightly different, the procedure and cost is generally similar for collecting gas samples from fumaroles for isotope analysis. Isotopes of light elements, such as hydrogen, carbon, nitrogen, and oxygen, as well as those of noble gases, such as helium, can provide insight into the origin of the volcanic gas and the degree of dilution by atmospheric gases. In particular, higher ratios of the helium isotopes ($^3He/^4He$) imply gases derived from deeper sources. Isotopes are analyzed with mass spectrometers, sophisticated laboratory instruments that can cost up to $300,000.

Level 3, Method 2: On-Site Instrumental Measurements

A portable instrument, such as a gas chromatograph (an analytical instrument that separates mixtures of gas or liquid into measurable components) or a spectrometer (an optical instrument designed for measuring gases at specific wavelengths of light) can measure one or more gases directly from the vent or fumarole. A sample tube is coupled directly into the gas source and the gas is directed into the instrument's sample port, eliminating the need to collect a sample and transport it to a laboratory. Portable instruments can be configured to make measurements over several hours and have the advantage of producing results right away, but they often only measure a few of the volcanic gases of interest. The cost of field portable chromatographs and spectrometers ranges from $5,000 to $25,000.

An important new technique for measuring volcanic gases is open-path Fourier transform infrared spectroscopy (OP-FTS). A Fourier transform infrared spectrometer (FTIR), a special type of infrared spectrometer with a moving mirror assembly and an optical telescope, is mounted on a tripod and aimed across a plume of gas emerging from a fumarole or volcanic vent. A large lamp may be positioned on the opposite side of the gas plume to provide an infrared energy source for the instrument. In other instances, hot rocks or even the sun can be used as the light source. FTIR can rapidly analyze for several gases simultaneously and has the advantage, like the instruments described above, of producing results right away. The cost of a field FTIR system is approximately $100,000.

Some gas emission events are relatively brief and would be missed by occasional sampling of fumaroles or short-term deployment of on-site instrumentation. Thus, continuous gas monitoring stations are often deployed to identify short-lived degassing events as well as long-term changes. These typically consist of one or more chemical or optical gas sensors that measure gas concentrations at or near a fumarole. Similar to seismic or GPS monitoring stations, gas monitoring stations consist of a station housing and batteries to power the sensors and data collection equipment, and cost $3,000 to $10,000 each. Their data are typically telemetered by radio or satellite to an off-site facility, or they can be recorded on-site by a data logger.

During volcanic unrest when rising magma begins to heat the volcano's subsurface, measuring SO_2 is particularly important, as increasing amounts of SO_2 gas are often diagnostic of accelerating unrest. Thus, establishing an array of telemetered Flyspec monitoring stations for continuous gas measurements should

always be considered once volcanic unrest is identified. Flyspec, sometimes called mini-DOAS (differential optical absorption spectrometer) is a small ultraviolet spectrometer that measures SO_2 in the air. When used as part of a fixed gas monitoring station, the Flyspec can be configured to scan across the air mass downwind of a volcanic vent or fumarole field. Coupled with wind data from a meteorological station, the Flyspec can produce a reliable measure of the SO_2 emission rate or flux. Flyspec data can be telemetered by radio or satellite links. Telemetered Flyspec monitoring stations cost between $10,000 and $15,000 each, depending on the type of telemetry and whether repeater links are required.

Level 3, Method 3: Soil Efflux Measurements

Soil efflux measurement surveys are usually made in areas where volcanic gases, typically CO_2, rise from depth through faults and fractures and discharge into the soil layer just beneath the ground surface. Since CO_2 is heavier than air, it can collect in low spots or in confined spaces or flow downslope as a density current, presenting a significant hazard to all those who enter such areas. In 1990, a U.S. Forest Service ranger in the Inyo National Forest entered a snow-covered cabin in such an area and experienced near-asphyxia. Subsequent investigations revealed potentially lethal concentrations of CO_2 in the vicinity requiring closure of a nearby campground. Fatal encounters with volcanic CO_2 include gas that flowed down a steep slope and across a road, killing about 150 people who were fleeing an eruption at Dieng (Indonesia) in 1979, and sudden releases of CO_2-rich gas from Cameroon's Lakes Monoun and Nyos that killed about 40 and 1,700 people, respectively, in 1984 and 1986.

Zones of soil gas discharge can be either hot or cold and are often characterized by vegetation and tree mortality. Because the gases can escape from the ground over a broad area, a small soil accumulation chamber coupled with an infrared spectrometer and portable computer is typically used to collect and measure the gas at dozens to hundreds of separate sites. These measurements are used to construct a map of the soil CO_2 anomaly to determine a total gas flux. For more details, see http://volcanoes.usgs.gov/activity/methods/gas/soil.php. The cost of field soil efflux instrumentation ranges from $5,000 to $20,000. Field surveys are typically conducted by a team of scientists over several days and repeated once to several times per year over several years to evaluate the dynamics of gas discharge from depth.

Soil efflux measurements are also useful to search for faults or other zones where volcanic gas is leaking to the surface. It may sometimes be appropriate to install automated soil efflux monitoring stations in zones of soil gas discharge to monitor short-term (hourly) variations in degassing. Automated monitoring stations cost about $20,000 each.

Remote sensing via satellite, described in the emerging techniques section of this chapter, can also be used to monitor thermal emissions, and volcanic ash and gas clouds.

Vital Sign 4. Emission of Gas Plumes and Ash Clouds

Introduction

Gas and ash emissions are monitored by three techniques described in this section, and also by satellite remote sensing, as described in the section below (Monitoring Techniques used for Numerous Vital Signs). Methods 1 and 2 are used to monitor sulfur dioxide and carbon dioxide, respectively, in volcanic plumes. Both gases are important indicators of magmatic activity. Method 3 describes how volcanic ash clouds can be monitored and tracked, generally in combination with satellite remote sensing. Because of the importance of preventing aircraft from entering volcanic clouds, a coordinated international multiagency process has been developed to track ash clouds in real time and communicate key information to aviation interests.

The rate at which a volcano releases gases into the atmosphere is related to the volume of magma within its magma-reservoir system. By measuring changes in the emission rate, usually in metric tons per day (10^3 kg/d), of key gases such as sulfur dioxide (SO_2) and carbon dioxide (CO_2), it is possible to infer changes that may be occurring in a volcano's magma reservoir and whether magma might be moving toward the surface. Although it is sometimes possible to measure SO_2 discharge from the ground, it is most precisely and safely measured from an airborne platform. Accurate CO_2 emission-rate measurements require an airborne platform. See http://volcanoes.usgs.gov/About/What/Monitor/Gas/plumes.html for more information and illustrations on the methods described in this vital sign.

A typical gas plume, whether exhaled from a small source such as a fumarole or forcefully discharged from a large source such as an erupting volcanic vent, rises to the height where its density reaches equilibrium with the atmosphere. The top part of the cloud may be sheared off and carried away by the wind. The gas emission rate can be determined by measuring the amount of a specific gas in the downwind plume and the wind speed.

Sulfur dioxide emission from inactive volcanoes normally ranges from below instrument detection limits to a few hundred metric tons per day. Because SO_2 can react with water and be lost as a gas phase, it is sometimes not present at quiescent volcanoes until unrest begins. In either case, it is important to measure SO_2 and CO_2 during inactive periods to establish baselines for comparison with future measurements if unrest occurs.

Level 3, Method 1: Correlation Spectrometer (COSPEC) and Mini-UV Spectrometer (Flyspec) Measurements

The importance of looking for SO_2 in volcanic plumes cannot be overestimated. When SO_2 appears in the plume during volcanic unrest, it is the definitive indicator for a shallow magma source, demonstrating sufficient heating of the volcanic edifice to establish dry passageways from depth to the surface in which SO_2 is no longer being removed by reactions with groundwater or a hydrothermal system. Very high and sustained SO_2 emission rates imply that magma has intruded to a high

level beneath the volcano and indicate the distinct possibility of an eruption.

The COSPEC (or correlation spectrometer) has been used for more than three decades for measuring SO_2 emission rates from various volcanoes throughout the world. Originally designed for measuring industrial pollutants, the COSPEC measures the amount of ultraviolet light absorbed by SO_2 molecules within a volcanic plume using scattered sunlight as its light source. The instrument is calibrated by comparing all measurements to one or more known SO_2 standards mounted in the instrument. The COSPEC is an optical instrument with an upward-looking telescope, so it is typically mounted in an aircraft with the telescope protruding out a window. Typically, 3–6 traverses are flown underneath the plume at right angles to its direction of travel, to determine the average SO_2 concentration along a vertical cross section of the plume. Wind speed is determined during flight by GPS. From these measurements, a very accurate emission rate can be computed. A COSPEC costs about $80,000 for the instrument and a few hundred dollars for a custom-made mounting plate that is unique to each type of aircraft.

The Flyspec, sometimes called a mini-DOAS (differential optical absorption spectrometer), also measures SO_2 in the ultraviolet light range. However, the Flyspec instrument is considerably smaller and lighter than the COSPEC and can be operated through the USB port of a standard laptop computer. It can be installed in either a helicopter or fixed-wing aircraft and flown underneath the plume using the same measurement strategy as the COSPEC. Depending upon configuration and whether it is a commercial model or not, a Flyspec will cost $5,000 to $12,000.

Flight costs for a typical airborne gas measurement are usually $1,000 to 3,000, but single flights at volcanic systems with widely distributed gas sources, such as Yellowstone, will cost $5,000 or more. Intervals between baseline gas measurement flights at an inactive volcano might be one to three years. At volcanoes experiencing unrest, the flights might be done every one to three months, and when unrest is intense might be needed as often as daily to weekly.

Level 3, Method 2: LI-COR

Carbon dioxide is one of the most important gas species for forecasting eruptive activity because it can provide the earliest geochemical indication of the onset of restlessness within a volcanic system. Because of its low solubility, CO_2 is released from magma very early during its ascent to the surface. Thus a transition of CO_2 from baseline amounts to markedly higher levels indicates that magma is likely involved and on the move from depth. A further increase of CO_2 to even higher emission rates signals that magma is intruding to a high level beneath the volcano. There is no reliable alternative to aircraft for measuring accurate CO_2 emission rates. Aircraft access to restless volcanoes is absolutely essential to adequately and safely monitor gas emissions.

The LI-COR is a small infrared spectrometer that has recently become the standard for determining CO_2 emission rates in volcanic plumes. The LI-COR samples air and volcanic gases through a tube connected to the outside sampling port of a helicopter or twin-engine fixed-wing aircraft; it can analyze CO_2 in the sample air stream at one measurement per second. Unlike the COSPEC and Flyspec which are flown underneath the plume, the LI-COR must be flown through the plume in traverses at different elevations perpendicular to the direction of drift, until an entire vertical cross-section of the plume is analyzed. From these data and a wind speed determined by GPS, an emission rate of CO_2 can be determined.

Because the LI-COR will typically be flown with a COSPEC or Flyspec, the aircraft flight costs and the frequency of measurements will be the same as described above for COSPEC and Flyspec.

Level 3, Method 3: Doppler Radar

Doppler radar monitors the appearance of volcanic clouds and tracks their movements, in contrast to the methods described above, which monitor different chemical components within a volcanic cloud. Thus, Doppler radar is used to help decide when hazardous areas should be closed to people on the ground or to aircraft.

Eruption detection is an easy task when a volcano erupts in good weather, during daylight hours, and/or within plain sight of observers, but it is difficult for eruptions at night, in bad weather, and/or in remote areas. For explosive eruptions, such as might occur at Lassen Peak, Crater Lake, Mount Rainier, and Alaskan volcanoes, these handicaps can be overcome with Doppler radar systems designed to monitor weather. Weather radar detects airborne ash in the same fashion that it detects rain or snow, though it cannot distinguish between ash and weather clouds.

Doppler radar systems produce maps that show anything, including rain, snow, and volcanic ash, that moves and reflects the radar beam. Images are produced at regular intervals and saved as computer files that can be viewed as a time-lapse sequence when other monitoring data indicate possible volcanic activity. For example, unusual seismicity at a volcano indicates that something has happened—perhaps an eruption. If the radar image sequence indicates that a cloud suddenly appeared over the volcano simultaneously with the seismicity, then the cloud was almost certainly produced by an explosive eruption. Thus eruptions can be detected day and night, in both fair and foul weather.

The cost of acquiring radar data ranges from very low to extremely high. The National Weather Service (NWS) provides Doppler radar data for most of the United States at no cost on the internet. However, coverage is limited or nonexistent in some remote areas. NWS radars produce images at intervals of 4, 5, 6, or 10 minutes, depending on weather conditions. Approximately another minute elapses before images become available. Commercial vendors that process and resell NWS radar data will further increase the time between acquisition and delivery

to end-users. If images are obtained from NWS radars, telecommunication problems are apt to be an impediment, whether the images are obtained from the internet, directly from NWS data servers, or from a commercial vendor. Furthermore, users have no control over the NWS data stream, and must make do with what data suppliers offer. Consequently, users must work with image intervals that are substantially longer than is desirable, increasing the time required for eruption detection.

If a volcano is not covered by NWS radars, a standalone radar system would need to be acquired and operated. A large dish antenna is placed on a pedestal with an unobstructed view of (at least) the volcano's summit—typically a few tens to 50 km from the volcano. The antenna is typically mounted on top of a building or tower so that nearby objects do not block the radar beam. Cables from the antenna are connected to an electronic "black box" inside the building that controls the antenna and acquires the raw data. A personal computer processes the raw data and displays it on a monitor in various graphic formats that trained operators can easily interpret.

Radar equipment tends to be expensive. The least expensive (and least capable) systems cost about $50,000. More capable systems cost five to ten times as much. Private radar systems require maintenance and repair, and require staff to operate and maintain them. However, radar systems can operate with little attention for extended periods of time.

Remote sensing via satellite, described in the emerging techniques section of this chapter, can also be used to monitor volcanic ash and gas clouds.

Vital Sign 5. Hydrologic Activity

Introduction

Most volcanoes are tall physiographic features with considerable accumulated snow and appreciable groundwater resources. Surface waters can intercept and absorb both the heat and chemical constituents released from the magma. By monitoring the discharge of water, its composition, and its temperature, workers can detect changes to the volcanic system that accompany renewed magmatic activity. The monitoring can include gauging stations on rivers and streams, downhole monitoring of groundwater wells or simple temperature probes (thermistors) placed in streams or lakes. Sometimes observed changes can precede the geophysical signals that are the dominant signs of an awakening volcano.

Level 3, Method 1: Stream and Well Instrumentation

A stream requires some method to measure its depth and volume of flow. Typically, a small concrete structure that is hydraulically connected to the stream is built. This setup permits reproducible measurements that are unaffected by storms. Real-time data transmission requires a telemetry system, generally a satellite transmitter and a source of power (solar cells, batteries or electrical utility lines if available). Additional instrumentation may include a weather station or water-quality instrumentation to measure rainfall, conductivity, or turbidity.

A stream gage measures a river's stage, or its depth relative to some measured datum. Discharge (the volume of water moving past a given point per unit of time) is also commonly monitored. By carefully measuring a river's cross section and water velocity, one can calculate a rating curve that relates the stage to units of flow, typically in cubic feet (ft^3) per second. Ratings curves are remeasured several times per year by water-resources experts. Additional sensors can be placed near the gauging station to measure air and water temperature, water chemistry, or precipitation, and these parameters can be compared with the discharge through the gauging station. Instruments such as thermistors, pressure sensors, and chemical sensors can be placed down wells, providing information about conditions in an aquifer or groundwater system. The data can be collected on a data logger that is routinely downloaded or telemetered to scientists through radio or satellite systems. Information from either wells or rivers can be viewed as time series relative to other monitoring parameters such as seismicity, deformation or satellite observations to see if changes in flow or water chemistry correlate with changes in other measured phenomena. Information from stream gages is also regularly used for flood warnings, wildlife management (especially fisheries) and for water resource management.

Typically, hydrologic monitoring is undertaken with a stream gage, which can cost $30,000 to 40,000 to construct, plus annual operating expenses of approximately $15,000. The price includes full real-time data transmission (usually by satellite) and periodic tests to provide rating curves for each gage, which can change with time. Downhole monitoring systems for wells cost less to maintain because they do not require updated rating curves. Initial costs are around $5,000 for instrumentation to measure temperature and water depths on an existing well. Drilling several new wells costs hundreds of thousands to millions of dollars and is only rarely undertaken at volcanoes for monitoring purposes alone. Simple thermometers with dedicated data loggers can be placed in the ground or in streams for as little as a few hundred dollars. They are only rarely telemetered, and instead collect data continuously for a number of weeks to months prior to data retrieval.

Water data are reviewed routinely in conjunction with other monitoring data. Data are collected every 15 minutes on typical stream gages. Other parameters may be collected more frequently. Alarm systems can be built so that anomalous chemical concentrations, flow rates or pressure changes are immediately forwarded to monitoring personnel.

Stream gages can become unreliable after large storms because storms may change the shape of the river channel and make the rating curve inaccurate. A new rating curve must be determined by field crews. Storms, snow and other environmental conditions can occasionally interfere with data transmission, so that the monitoring record can be periodically interrupted. Downhole sensors can be degraded by high-temperature and high-pressure conditions and may fail and need replacement periodically. Thermistors for soil and surface water monitoring may

be vandalized by humans or animals and can degrade with time due to harsh conditions.

Large changes in temperature, chemistry or flow that are apparently unrelated to climatic parameters may be due to changes in the volcanic system. Further studies and evaluation are then undertaken.

Stream gages are common throughout the developed world, but less so in the rest of the world. However, not all stream gages are useful for monitoring volcanoes unless they are placed with that objective in mind. One gauging station used expressly for volcano monitoring is located at the Norris Geyser Basin in Yellowstone National Park (http://waterdata.usgs.gov/mt/nwis/uv?site_no=06036940). Real-time data from the Chance water well, monitored by the Long Valley Observatory are located at http://lvo.wr.usgs.gov/cw3_main.htm.

Vital Sign 6. Slope Instability

Introduction

Volcanoes are subject to various types of slope instability, some linked to eruptive processes, others to the steep terrain and unstable slopes that characterize many volcanic edifices. This section addresses **debris flows**, which are rapidly flowing mixtures of rock fragments, mud, and water that originate on steep slopes. Known as lahars when they originate on volcanoes, they are among the most destructive and persistent of volcanic hazards. Lahars threaten lives and property not only on volcanoes but far downstream in valleys that drain volcanoes, where they arrive suddenly and inundate entire valley bottoms. Debris flows can destroy vegetation and structures in their path, including bridges and buildings. Their deposits can cover roads, recreation areas and railways, and fill or divert stream channels, thereby reducing their flood-carrying capacity and navigability.

Lahars may occur as primary or secondary lahars. **Primary lahars** begin during volcanic eruptions, as a result of hot eruptive materials that melt snow and ice or breach lakes or other impounded waters. **Secondary lahars** can develop at any time after eruptions, as the result of heavy rains or glacial outburst floods that mobilize ash, erodible soils or glacial till. Outburst floods have been recorded from four glaciers in Mount Rainier National Park during periods of unusually hot or rainy weather in summer or early autumn, and have inundated downstream roads and recreation areas (Walder and Driedger, 1994a). Unlike some other volcano hazards that are not necessarily constrained by topography, such as ash falls and pyroclastic flows, debris flows are usually contained in valley bottoms and follow predictable paths along stream channels, thus making hazard mitigation practical through delineation of possible inundation zones and real-time monitoring of debris flow channels.

Susceptibility and potential triggers for debris flows can be determined for a volcano and the potential triggering activity monitored. The presence of a crater lake, significant amounts of snow or ice, or structurally unsound rock, such as material that has been physically and chemically altered by volcanic gases and fluids, can be assessed through geologic field work and mapping. Field studies can also reveal debris flow deposits from previous eruptions, providing perspective on the potential local and regional hazards. Debris flow deposits can sometimes extend for tens of miles from a volcano.

For additional information on slope instability, see the chapter on monitoring slope movements.

Selected Methods for Monitoring Slope Movement

The elements or vital signs of monitoring slope movement relevant to volcano monitoring include (1) determination of types of landslides, (2) monitoring of landslide triggers and causes, (3) lahar hazard delineation, and (4) real-time lahar monitoring. The first two vital signs are covered in the chapter on slopes. Two methods are described below to monitor lahar hazards and movements.

Level 3, Method 1: Lahar Hazard Delineation

LAHARZ is a rapid, objective, and reproducible method utilizing a geographic information system (GIS) with digital elevation models (DEMs) to delineate lahar inundation zones (Iverson et al., 1998). The U.S. Geological Survey developed the method for volcanoes where data, time, funding, or personnel are inadequate to apply traditional geologic mapping methods. Both LAHARZ and traditional mapping methods are based on the same principles: (1) inundation by past lahars provides a basis for predicting inundation by future lahars; (2) distal lahar hazards are confined to valleys that head on volcano flanks; (3) lahar volume largely controls the extent of inundation downstream; (4) voluminous lahars occur less often than small lahars; and (5) no one can foretell the size of the next lahar to descend a given drainage.

The LAHARZ GIS program is an automated method that combines statistical analyses of lahar-inundation data from nine volcanoes to develop quantitative equations that predict the valley cross-sectional area and planimetric area that would be inundated by lahars with various volumes. The GIS method simultaneously delineates inundation areas for a variety of lahar volumes, thereby depicting gradations of the inundation hazard. Inundation hazard is greatest in valley bottoms close to a volcano and diminishes as elevations above valley floors and distances from the volcano increase. Automated portrayal of gradations in hazard is one of the chief advantages of this GIS methodology. The method requires a DEM of sufficient accuracy and resolution combined with a working knowledge of GIS programs. The LAHARZ program is available from the U.S. Geological Survey Cascades Volcano Observatory.

Level 3, Method 2: Real-time Monitoring of Lahars

Real-time detection of lahars close to their sources can provide timely warnings to people in delineated inundation zones, if adequate communication systems and evacuation plans exist. Continuous, automated debris flow monitoring can also provide information useful in identifying specific weather conditions that increase the likelihood of rainfall-triggered lahars or

meltwater-triggered glacial outburst floods. Scientists at the U.S. Geological Survey have developed an inexpensive, durable, portable, and quick-to-install system to detect and continuously monitor the arrival and passage of debris flows and floods in valleys draining volcanoes (LaHusen, 1996). This automated system, the **Acoustic Flow Monitor (AFM)**, senses and analyzes ground vibrations with a compact, solar-powered unit that is installed near specific channels where lahars may travel. It uses a rugged sensor and an on-site microprocessor to continuously analyze vibration signals and detect debris flows and floods based on frequency, composition, amplitude, and duration of the vibration signal. A two-way radio system communicates between each sensing unit and a base station through a radio network. An AFM system is in place to detect large-scale lahars that might occur at Mount Rainier; see http://ic.ucsc.edu/~syschwar/eart3/exercises/Rainier_warning_sys.html.

Each AFM station measures the amplitude of the ground vibration signal every second and sends data by radio to the base station at regular intervals—typically 15 minutes. If the instrument senses vibrations that exceed a certain threshold value (adjustable for each individual site) for longer than 40 seconds, the AFM transmits immediate alert messages. It continues to send alert data at 1-minute intervals for as long as the signal remains above the threshold level. When the signal drops below the threshold level, the AFM resumes normal operation, transmitting at less-frequent intervals. The AFM system has distinct advantages over other detection systems: (1) the sensor and microprocessor are set to analyze specifically the peak vibrations typically produced by debris flows and floods, and screen out other noise or tremor that would affect normal seismographs; (2) flows are monitored as they approach, and recede from, individual monitored sites; and (3) the equipment is ready to detect subsequent flows immediately without any additional maintenance.

Typically two or three AFM stations are positioned in each selected drainage so that lahar velocity can be determined from arrival times between stations; this provides a robust, redundant system. One or more hilltop radio repeaters may be needed to relay the signals downstream to a base station where appropriate actions can be initiated. The cost for installing a basic AFM monitoring system is about $50,000 per drainage covered.

MONITORING TECHNIQUES USED FOR NUMEROUS VITAL SIGNS

Method 1. Remote Sensing via Satellite

Description

Satellite remote sensing is useful to monitor and measure a variety of volcanic phenomena, including thermal emissions, volcanic ash and gas clouds, and surface deformation. Typically, satellites using infrared sensors are used to detect and track volcanic activity, and ultraviolet and radar sensors are used to measure gases and ground surfaces. Many volcanic processes emit heat. Processes that emit heat as part of an eruption are termed **active sources**. Examples include pyroclastic flows, lava flows, lava domes, and lava fountains. Processes that emit heat for long periods of time but that do not normally indicate an impending eruption are termed **passive sources**. Examples include hot springs, geysers, fumaroles, fractures, and crater lakes.

For less explosive volcanic phenomena, such as lava flows and lava fountains, satellite remote sensing can aid in the interpretation of seismic data, especially for remote or difficult to access volcanoes. Remote sensing may determine whether a type of seismic signal typically observed during an eruption (volcanic tremor) is related to a relatively slow process such as magma rising in a conduit, or a more hazardous explosive eruption. In other cases (e.g., Kīlauea, Mount Etna), remote sensing has been used to detect changes in lava flow character, from the type fed from a subsurface tube system to a surface flow (Harris et al., 1997a), as well as lava effusion rates (Harris et al., 2000). Although this change in flow character may not be apparent in seismic data, it can signal a transition in the type and location of lava flow hazard.

Thermal remote sensing of active processes has in some instances successfully identified precursors to hazardous volcanic activity and aided in the short-term forecasting (days to weeks) of hazardous explosive volcanic activity (Schneider et al., 2000; Dehn et al., 2002; Dean et al., 2004). For example, as magma intrudes into a lava-dome, its flanks can become oversteepened, leading to collapse. This generates hot block and ash flows (pyroclastic flows) which can be detected in satellite imagery. A large dome collapse can trigger a larger-volume explosive eruption as underlying, gas-rich magma is rapidly depressurized, leading to eruption columns and ash clouds traveling thousands of kilometers.

Explosive volcanic eruptions can inject large volumes of volcanic ash and gas into the atmosphere, where they are dispersed by winds. Volcanic ash is an unconsolidated mixture of sand- to dust-sized fragments of rock, crystals and glass, which pose a severe hazard to aircraft and machinery. From 1973 through 2003, nearly 100 encounters of aircraft with airborne volcanic ash have been documented, several of which nearly resulted in loss of the aircraft. Typical costs per encounter range from several tens of thousands of dollars to as much as $80,000,000 (Marianne Guffanti, U.S. Geological Survey, 2005, personal commun.). Drifting ash clouds (those that have detached from the vent) are undetectable by an aircraft's onboard radar, and are difficult to see in low light and at night. Satellite detection and tracking of drifting ash clouds, cloud dispersion forecast modeling, and prompt communication of analyses are used to mitigate the volcanic ash hazard. In addition to the airborne hazard, ash fall can occur as a result of an eruption cloud. This can range from a light dusting to thick deposits of ash, even at great distances from the volcano (Houghton et al., 2000). Satellite tracking and modeling of ash plumes also helps to predict ash fall. Forecasts and modeling of typical ash-fall patterns can help managers mitigate the effects of ash load on human and animal health, machinery, and structures.

Volcanic gases are also emitted during an explosive eruption, with water, carbon dioxide and sulfur dioxide being the most

abundant. Although these gases do not pose an acute hazard to aircraft, in large quantities they can be a chronic hazard to health, infrastructure and the environment. Once sulfur dioxide is emitted into the atmosphere, it combines with water to produce a sulfuric acid (sulfate) aerosol. In large quantities, these acid droplets can affect global climate by reflecting incoming solar radiation. Sulfuric acid droplets are very small, so they can remain airborne for months to years. Structures or aircraft in areas that contain sulfate aerosol could sustain chronic damage, such as crazing of acrylic windows, corrosion of the supports and rubber seals, and accumulation of deposits within air-handlers or engines. These affects are difficult to document because they can occur slowly over a period of years. Satellite remote sensing offers the capability to detect and quantify the amounts of sulfur dioxide released during an eruption, as well as the resulting sulfate aerosol. This includes non-explosive degassing of sulfur dioxide, which has been successfully monitored at Kīlauea for years. Although ground-based gas measurements are the most useful for routine monitoring, satellite analysis provides a synoptic overview of the extent of the gas plume, and aids in visualizing and measuring the volcanic fog ("vog") cloud produced from the vent, or by the entrance of lava from Kīlauea into the ocean (See Sutton et al., 1997).

Routine thermal monitoring of passive sources using satellite technology has, in a few instances, identified eruption precursors during volcanic unrest, when measurable increase in thermal emissions provided evidence for magma intrusion and the subsequent release of hot gases (Sparks, 2003). However, in practice, passive sources are difficult to monitor by satellite because their temperatures are low and their features are generally too small to be resolved by available thermal sensors, which typically have a spatial resolution of 60 m.

Monitoring Methods

Satellite remote sensing can monitor volcanic activity frequently and at low to moderate cost (Harris et al., 1997b). Much of the satellite data are available in near real-time online, so in many cases the expenses do not include receiving stations to downlink data. Satellite remote sensing and seismic monitoring can be symbiotically combined to determine the type and potential hazard of an erupted ash. The satellite imagery also provides information on phenomena that cannot be observed in any other way, such as thermal anomalies, large-volume gas emission, and hazardous volcanic ash clouds. A variety of complementary satellite data (Table 2) are available to make these observations. These data can be generally classified as (1) frequent, near real-time, low spatial resolution, such as Advanced Very High Resolution Radiometer (AVHRR), Moderate Resolution Imaging Spectroradiometer (MODIS), and Geostationary Operational Environmental Satellite (GOES) sensors; or (2) infrequent, non-real-time, high spatial resolution images, such as land remote sensing satellite (Landsat) and Advanced Spaceborne Thermal Emission Reflection Radiometer (ASTER) sensors. The combined use of both types of satellite data provides a robust method for detecting volcanic activity and mapping volcanic landforms and eruption deposits.

Some satellite sensors measure light at wavelengths not visible by the human eye. The most useful for monitoring volcanoes are infrared wavelengths, just longer than those humans can see. Most infrared wavelengths are absorbed by the Earth's atmosphere, except for a few "atmospheric windows" where absorption of infrared rays is minimal.

One useful atmospheric window is the short-wave infrared (SWIR) with wavelengths between 3 and 5 microns. SWIR is used to monitor high-temperature thermal features such as lava or pyroclastic flows. The hotter an object is, the more energy it will emit, and at shorter wavelengths. For example, an object with a temperature of 25 °C, such as the Earth's surface, has a peak emission at a wavelength of ~10 microns. However, a volcanic feature with a temperature of 800 °C has a peak emission at ~3 microns. Many volcanic features are sub-pixel in size, meaning they cover an area smaller than 1 km on a side for AVHRR or MODIS. The temperature recorded by the satellite is a complex mixture of the temperatures of a hot and cold component, and their respective areas. If multiple channels of data are available at different wavelengths, it is possible to take advantage of these relationships to estimate both temperature and area of a hot volcanic component (Rothery et al., 1988).

Another useful atmospheric window is the thermal infrared (TIR) with wavelengths between 8 and 14 microns. Data at these wavelengths are used to detect volcanic ash and sulfur dioxide clouds. The most common method of discriminating volcanic ash clouds from meteorological clouds is the "split-window" method. Here the brightness temperature difference (BTD) is compared between 2 satellite channels at 11 and 12 micron wavelengths. Semitransparent volcanic clouds generally have negative BTDs while meteorological clouds generally have positive BTDs (Prata, 1989). Though many factors affect the magnitude of the BTD signal, including (but not limited to) cloud opacity; the amounts, size and distribution of ash and water in the cloud; and the temperature contrast between the cloud and background surface; the amount of volcanic ash can be estimated from satellite data using a complex radiative transfer model (Wen and Rose, 1994). A similar method is utilized to detect and measure sulfur dioxide clouds from either passive degassing (using ASTER), or from explosive eruptions (using MODIS) by using wavelengths at 7.3 or 8.6 microns, where there is absorption due to sulfur dioxide (Watson et al., 2004).

Real-time satellite data analysis and monitoring requires rapid and reliable access to large amounts of satellite data. Useful data sets include AVHRR and GOES sensors on meteorological satellites operated by NOAA, and MODIS on research satellites operated by NASA. Direct reception of satellite signals is the most reliable, but also the most expensive method of data acquisition. A satellite receiving station costs between $50,000 and $150,000. A separate receiving dish and associated computer hardware is needed for each data stream, which increases the costs by $25,000 to $50,000 per dish. Installation costs vary depending upon the infrastructure needs and assets of a particular site and could range from $5,000 to $15,000. A dedicated station

TABLE 2. SUMMARY OF SENSOR CHARACTERISTICS
FOR INSTRUMENTS TYPICALLY UTILIZED IN REMOTE SENSING OF VOLCANIC PHENOMENA

Satellite sensor	Volcanic phenomena detected	Channels (microns)	Spatial resolution	Temporal resolution
Polar orbiting sensors, low spatial resolution				
AVHRR (Advanced Very High Resolution Radiometer) NOAA satellites	Thermal anomalies Volcanic ash	5 Channels b1-2 Visible b3 SWIR b4-b5 TIR	1100 m (all bands)	6–12 images/day
MODIS (Moderate Resolution Imaging Spectroradiometer) NASA satellites	Thermal anomalies Volcanic ash Sulfur dioxide	36 Channels b1, b3-4 Visible b8-14 Visible b2, b5, b26 NIR b15-19 NIR b6-7, 20-25 SWIR b27-28 SWIR b29-36 TIR	250–500 m Visible 1000 m IR	2–6 images/day
Geostationary satellites				
GOES (Geostationary Operational Environmental Satellite) NOAA satellites	Thermal anomalies Volcanic ash	5 Channels b1 Visible b2-3 SWIR b4-b5 TIR	1000 m Visible 4000 m IR	48–96 images/day
High-resolution polar orbiting sensors				
ETM + (Enhanced Thematic Mapper Plus) NASA Landsat satellite	Thermal anomalies	7 Channels b1-3 Visible b4 NIR b5-6 SWIR b7 TIR	15 m Visible 30 m VNIR 60 m TIR	Every 8–16 days
ASTER (Advanced Spaceborne Thermal Emission Reflection Radiometer) NASA satellites	Thermal anomalies Volcanic ash Sulfur dioxide	14 Channels b1-2 Visible b3 NIR b4-9 SWIR b10-14 TIR	15 m VNIR 30 m SWIR 90 m TIR	Every 8–16 days

Note: NOAA—National Oceanic and Atmospheric Administration; NASA—National Aeronautics and Space Administration; IR—infrared; NIR—near infrared; SWIR—short-wave infrared; TIR—thermal infrared; VNIR—visible and near infrared.

manager operates the systems and archives the data. Salaries of remote sensing scientists and data analysts are further costs.

Satellite data can also be acquired online from government agencies and universities at a cost of around $10,000 to $20,000 per year. Approximately $10,000 is also needed for specialized computer software, plus costs of computer workstations and large storage devices to store data received at a rate of many gigabytes per day. A robust, reliable computer network capable of handling this volume of data is also needed.

Non-real-time data from satellites such as Landsat and ASTER are still lower cost alternatives. Data from Landsat and ASTER can reveal smaller features (15–90 m) than satellites that provide near real-time data (1 km). Therefore, Landsat and ASTER data are used primarily to improve interpretation of real-time data described above. This approach has advantages over near real-time data, such as lower cost ($50 to $300 per scene covering ~34,000 km^2), higher spatial resolution, and the ability to detect smaller regions of elevated surface temperature and measure non-eruptive emissions of sulfur dioxide gas. Furthermore, all data processing is done with desktop computers using specialized, but relatively inexpensive software ($500 to $2,000).

The disadvantages are limited data availability and cloud cover. Presently, Landsat and ASTER data are available only every 8–16 days. Cloud cover, however, is the main disadvantage. In cloud covered areas, volcanic ash and gas clouds produced by explosive eruptions can only be observed once they rise above the weather clouds. Any thermal activity at the surface is partially or completely obscured by the presence of clouds.

In summary, to create an effective near-real time volcano monitoring system via satellite, the primary goal is repeat observations at adequate temporal resolution to match the volcanic process being observed. Long term precursors (e.g., deformation, gradual heating) permit us to use the higher resolution data sets. Lava flows and explosions where changes occur on the scale of minutes require the coarse spatial resolution of polar-orbiting or geostationary satellites providing imagery every hour.

EMERGING VOLCANO MONITORING TECHNIQUES

Introduction

Volcano monitoring techniques are rapidly evolving as a consequence of technological innovation and our expanding understanding of the processes that cause eruptions. This section describes three examples of new remote-monitoring methods that are being used to monitor active volcanoes. The first uses unmanned aerial vehicles (UAVs) to access hazardous areas, the second uses repeat measurements of the distance between a satellite and the ground (InSAR), and the third senses low-frequency sound waves (infrasound) to detect explosions.

All of the more traditional monitoring methods are also changing. For example, the rapid expansion of small-footprint satellite communications and internet technology is driving a revolution in the way that volcanoes are monitored. Currently, seismic, gas, deformation, and even visual imagery is monitored at remote volcanoes, some located thousands of kilometers from base stations, using satellite and internet communications. In addition, new low-cost solid-state accelerometers, GPS, and wireless local-area radio systems allow rapid helicopter deployment of small sensors with real-time data communication, even within the craters of active volcanoes

Volcanic gas monitoring is also rapidly changing, and new instruments, such as the Fourier transform infrared spectrometers (FTIR) are now available, which can remotely measure gas species, such as chlorine, that have previously only been possible to detect using more dangerous direct sampling from vent areas; these instruments provide a better understanding of the gas contents and potential explosivity of volcanoes.

Level 3, Method 1: Unmanned Aerial Vehicles (UAVs)

The development of autonomous UAVs has allowed scientists to explore uncharted anomalies in places that are difficult to reach or hazardous to access. Volcano monitoring promises to benefit from the development UAVs. In late September 2004, Mount St. Helens began its first sustained eruption since 1986, and for the first time UAVs were sent into the crater of an erupting volcano (McGarry, 2005; Patterson et al., 2005). This experiment demonstrated that small (2.45 m wingspan) and relatively inexpensive unmanned aircraft can be precisely navigated to less than a kilometer above an active volcanic vent and held on station for extended periods using pre-programmed routes and computer-stabilized flight. The UAVs delivered real-time optical and infrared imagery data to a mobile base station 10 km from the crater (Figs. 11 and 12). These data were used to monitor visible and thermal changes in the active lava dome and vent, such as growth and collapse of the new lava dome, and the extent and growth of hot areas. UAVs also offer potential advantages for use in sensitive and hazardous areas. Noise levels are typically lower than manned aircraft; at altitudes of more than a thousand feet, the small UAVs used at Mount St. Helens typically cannot be heard over background and wind noise. Since no pilot is needed and little fuel is used (there are many fuel options—alcohol, gasoline, or heavy fuels), the lower risks, costs, and environmental impacts offer significant advantages over other monitoring methods.



Figure 11. Unmanned aerial vehicle mounted on the pneumatic launching catapult in the parking lot at the Johnson Ridge Observatory at Mount St. Helens, where it was launched and recovered.

UAVs with varying payload and aeronautical capabilities are now becoming available or are under development for civilian and government use. These include both fixed-wing and rotorcraft configurations, and a range of power plant types and sizes, payloads, and flight range/duration capabilities. Because of the low cost, current availability, and ability to launch from small and remote locations, the smaller fixed-wing and rotorcraft types of UAVs offer considerable potential for unobtrusive volcano monitoring.

The 2.45 m, man-portable class of fixed-wing UAV used at Mount St. Helens cost approximately $25,000 per plane with an autopilot, onboard radio telemetry, and flight tracking/data relay computer. These aircraft are capable of carrying a payload of up to 4 kg, but larger models can accommodate payloads up to 10 kg. The maximum smaller model payload volume is ~10 cm diameter × 20 cm cross-sectional area, whereas the larger models have a payload dimension of ~45 × 28 × 12 cm. As in any aircraft, there are trade-offs between velocity, payload and duration. However, durations of 10–20 hours at 30–60 knots at day or night, and ranges of up to 1000 km with preprogrammed routes and autonomous GPS tracking are possible, although real-time data relay is typically limited to 30 km line-of-sight distance without radio repeaters. Because these aircraft are unmanned, in certain high-risk/high-benefit conditions they are considered expendable. A complete mobile base station with radio telemetry, flight controller, data acquisition/processing, and portable (30 kg) launch catapult costs about $85,000. Flight support services such as those outlined above are commercially available.

The use of UAVs for volcano monitoring is currently limited by the availability of small lightweight sensors. Only optical and



Figure 12. Still images taken from video captured from an unmanned aerial vehicle of the new lava dome ~300 m long. The left image shows an enhanced image, which accentuates the topography, thereby giving volcanologists a sense of the steepness of the lava dome. (The steepness determines the likelihood of a collapse, which could generate hazardous pyroclastic flows.) The right image is an inverted-grayscale infrared image, in which the deeper shades of gray and black represent hotter material. This image shows the hot (black) U-shaped area where new lava is being extruded (indicated by V). It also shows that the recent ash deposits (A), so prominent in the left-center of the image on the left, are relatively cold.

uncalibrated infrared cameras were tested at Mount St. Helens, although several new miniature sensors are being developed or modified for UAV use. For example, the latest generations of light-weight sulfur dioxide (SO_2) spectrometers are readily adaptable to UAV use, and will provide an alternative method for volcanic gas monitoring. Another off-the-shelf application is the use of high-resolution digital still photography and stereo imaging to document, monitor, and measure changes, such as characteristics of hazardous vent areas, and extents of lava flows and other eruptive products. One of the promises offered by UAV-based volcano monitoring is in providing observations during poor weather; however, this is also one of the greatest challenges. Currently, available GPS tracking and autonomous flight allow operation of UAV aircraft in cloudy weather, although operation in icing conditions could be problematic. A greater technical challenge is in developing sensors that can see through clouds. Researchers are currently testing a lightweight UAV-based radar system, which offers promise for observations in poor weather conditions.

To date, most UAV development and testing have taken place in military airspace, where civilian flight is prohibited or closely monitored. A principal concern about UAV operation in civilian airspace is providing separation between the UAV and commercial and private aircraft that are operating in the same area. UAV operations at Mount St. Helens were permitted under a certificate of authorization granted by the FAA to the UAV operator for flight in temporary flight restriction zone surrounding the volcano.

Level 3, Method 2: Interferometric Synthetic Aperture Radar (InSAR)

Interferometric synthetic aperture radar (**InSAR**), developed in the mid-1990s, is the most recent advancement in detecting deformation of the Earth's surface. InSAR uses two satellite radar images of the same area on the ground acquired from an identical point in space at different times. Radar range measurements, which contain information about the distance between the satellite and ground, from the later image are subtracted from the earlier to form an interferogram, which shows how much surface deformation occurred in the interval between the acquisition of the two images (Helz, 2005). Surface displacements as small as one cm can be identified in a single interferogram. When multiple interferograms are combined, displacements as small as a few mm may be recognized. A more comprehensive explanation is available from http://volcanoes.usgs.gov/insar/.

InSAR has two primary advantages over other monitoring methods. First, InSAR provides high spatial resolution along swaths that are 100 km wide and as long as thousands of kilometers. Second, the method needs no equipment on the ground. Thus, remote or isolated volcanoes may be monitored using InSAR without visiting the field area. These two characteristics combine to make InSAR particularly useful for detecting deformation at poorly monitored volcanoes. For example, until recently, South Sister volcano in Oregon was not well monitored because it showed no obvious signs of unrest, such as seismic activity or gas emissions. However, InSAR studies of the volcano in 2001 indicated that an area immediately west of the volcano was inflating ~3 cm per year, probably because magma was accumulating below the surface. As a result, the U.S. Geological Survey began annual GPS and leveling surveys at South Sister and installed continuous GPS and seismic instruments. Now any signs of an impending eruption should be recognized well in advance.

InSAR, however, has some significant drawbacks. In its present state of development, InSAR is not an operational tool for monitoring most volcanoes showing significant unrest, threatening to erupt, or actually erupting. Present limitations in satellite

availability and tasking priorities create long intervals between repeat image acquisitions, which constrain InSAR's present role to supporting long-term characterization of deformation, similar to survey-mode measurements like leveling or survey GPS. An InSAR image can be taken only when a satellite is overhead, typically on an average of a few times per month.

Atmospheric effects, including storms or cells with high concentrations of water vapor, can also introduce error to InSAR measurements. Such conditions do not lead to incoherence, but rather introduce biased signals to the data that may be incorrectly interpreted as deformation. Thus, it is important to confirm the results of any single interferogram with other data, including terrestrial deformation measurements or other temporally independent interferograms.

InSAR only images surface displacements that occur in the same direction as the radar's line-of-sight, which is usually inclined 15°–45° from vertical. Thus, an interferogram contains a combination of horizontal and vertical deformation components. Converting InSAR measurements into separate horizontal and vertical displacements, similar to those provided by GPS, requires at least two interferograms that cover the same time period and image the ground from different points in space. Such conditions are difficult to satisfy; thus, it is best to use InSAR in combination with other methods that unambiguously monitor horizontal, vertical, or both components of surface deformation.

While InSAR may be cheaper than other monitoring methods for remote volcanoes, data acquisition and analysis can still be quite expensive. Data processing requires specialized software that can include free software, which comes without technical support and therefore requires an expert already trained in its use, or technically supported software, which may cost as much as $30,000 and still requires an operator with a good background in working with radar data. Radar scenes generally cost about $100 per 100 km^2 frame, depending on how they are acquired. As of 2008, only the Canadian, European, and Japanese Space Agencies operate satellites with InSAR capabilities, so all data must be purchased from those organizations.

Variations in surface characteristics between satellite passes caused by ice, snow, and vegetation cause the radar signal to break down in some areas, preventing recovery of a deformation measurement. This "incoherence" is a significant problem on ice- and snow-covered or vegetated volcanoes, such as Mount Rainier, so InSAR is not presently a reliable monitoring tool at such sites. Future satellite missions and new signal processing techniques may reduce this problem in the coming decade.

Level 3, Method 3: Monitoring Volcanic Explosions with Infrasound

Many natural phenomena and human activities create sound waves in the atmosphere at sub-audible frequencies, generally between 1–25 Hz. Termed **infrasound**, it is generated by sources such as wind, ocean waves, heavy industry, rockfalls, aircraft, meteors, and explosions. Infrasonic waves can travel long distances through the atmosphere and, because the atmosphere has a relatively simple structure compared to the heterogeneous Earth, infrasonic waves are far less distorted by their trip through the atmosphere than are seismic waves by their trip through the Earth. Thus, infrasonic signals created by a volcanic source such as an explosion can be much simpler, and therefore easier to interpret, when received at an infrasonic sensor (such as a microphone or microbarograph) than seismic waves generated by the same explosion when received at a seismograph. Explosions in particular produce very characteristic infrasonic signals, and infrasonic sensors installed around active volcanoes have proven useful in distinguishing between explosions and other seismic sources such as rockfalls, avalanches, and wind gusts (Johnson et al., 2003).

Explosions are often recorded on seismic stations as well. For example, two explosions that occurred at Mount St. Helens in 2005 were detected first by seismic stations. However, seismographs can be so swamped by seismic waves from local earthquakes that any ground-shaking produced by explosions can be completely obscured. During the first two weeks of the 2004–2005 eruption of Mount St. Helens, earthquake activity was so intense that explosions could only be detected visually. Thus another key benefit of infrasonic monitoring at volcanoes is that explosions will still show up on infrasonic sensors when intense earthquake activity has made seismic stations all but useless for explosion detection.

What Can Be Learned

The most important question that infrasonic monitoring can answer at a volcano is, "Are explosions presently occurring?" Therefore, data from infrasonic sensors must be transmitted to observatories in real time. Having two or more infrasonic sensors at the same site greatly improves the ability to assess whether a given signal is infrasonic (traveling at the speed of sound) or subsonic (such as wind gusts, which travel at a fraction of the speed of sound).

Secondary questions include, "Where is the explosion source located?" and possibly, "What is the explosion's size?" (Although, in some instances, no direct correlation between the size of an infrasonic signal from an explosion and the size of an explosion has been found [Johnson et al., 2005].) To answer these secondary questions, two or more sets of arrays, each consisting of at least four infrasonic sensors, are needed.

Infrasonic Monitoring—Mechanics

Infrasonic sensors detect minute pressure changes in the atmosphere over a time scale ranging from milliseconds to minutes or longer and at sub-audible frequencies—generally less than 25 Hz. Infrasonic stations can consist of single sensors (commonly co-located with a seismometer; see Fig. 13) or arrays of sensors which, through array analysis techniques, can provide information on source location. Signals from these stations are typically telemetered to a volcano observatory where they are recorded, digitized, stored, and analyzed. For volcano monitoring, three to four infrasonic sites are generally sufficient to adequately monitor all sectors of a volcano, but the actual

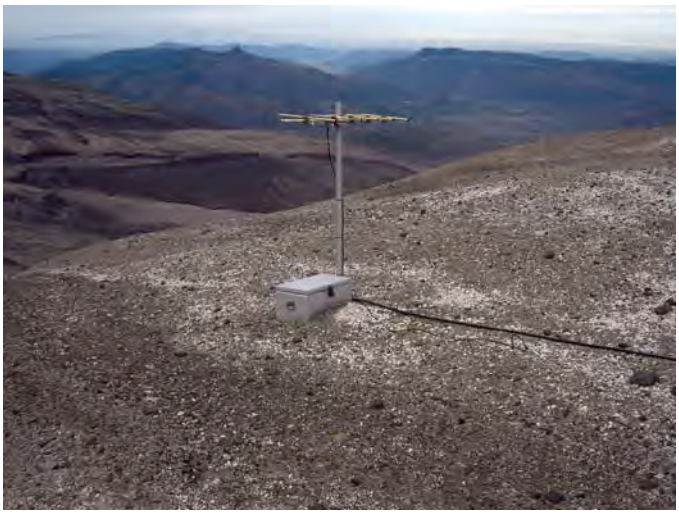


Figure 13. Typical single-microphone station at Mount St. Helens in 2004. This site is ~2 km north-northeast of the vent, but did not record any explosion-related infrasonic signals from the two explosions that occurred after its installation. The microphone is located inside the metal box. Soaker hose extending from the box helps reduce (but not eliminate) wind noise. Photo by Seth Moran (U.S. Geological Survey).

number will vary depending upon size and characteristics of the individual volcano. Infrasonic sensors can be placed at distances of 20 km or greater from a volcano, so it is feasible to install such equipment near a restless volcano without exposing field personnel to hazardous conditions.

Individual microphones cost between $1,000 and $10,000, depending upon the amount of noise reduction and sensitivity desired. Additional equipment, such as radios or satellite dishes for transmitting data, and batteries and solar panels for powering the site, cost an additional $4,000 to $10,000. Total installation costs range from $5,000 for a single telemetered microphone to more than $50,000 for a four-microphone array with associated solar panels, batteries, infrastructure, and satellite telemetry.

For a low-power, telemetered site with a single low-sensitivity microphone, a typical installation includes: an analog radio, an equipment enclosure (typically a ~0.3 m × 0.3 m × 1 m metal box) with a single 100 A–hour lead-acid battery and an electronics box, an antenna mast, antenna, solar panel, microphone (packaged in PVC pipe), and ~7–10 m of soaker hose (to reduce wind noise). For a site with an array of four high-quality microphones, a typical installation would include a radio or satellite modem to transmit data, an equipment enclosure somewhat larger than the single-microphone site, with as many as ten 100 A–hour batteries, and sufficient infrastructure to mount several solar panels and a radio antenna.

An observatory to which telemetered data are sent needs its own receiver and equipment to process and store the signals. Equipment costs are about the same as for an infrasonic sensor site, minus the cost of the sensor. If the infrasonic sensor site and the observatory are not line-of-site, then additional repeater stations will be needed.

The principal goal is explosion detection in real time. Trained analysts can examine incoming signals, or computers can send automated alarm messages to on-call staff when an explosion is detected. However, infrasonic signals from single microphones can be confused with wind noise or other non-volcanic sources. Wind noise (if it does not saturate individual sensors) can be easily distinguished from true infrasonic signals by looking at the difference in arrival times of a given signal at two or more infrasonic sensors in an array. Because wind gusts move at the speed of air, the time differences will be much greater for wind gusts than for infrasonic signals (which move at the speed of sound). Data from arrays of four or more sensors in an array can be processed in near real time to identify coherent phases sweeping across the array from a given azimuth undetectable to the naked eye. To locate explosions, at least two array sites are required. Because volcanoes are generally windy environments, multiple infrasonic sites at different points around the volcano improve the chances that one site will record an explosion free of wind noise.

Infrasonic monitoring is not needed at inactive volcanoes. However, a cache of sensors and equipment for infrasonic stations should be maintained to facilitate rapid deployment when a volcano awakens. Typical field installations require one to three people, while periodic maintenance of field stations requires one or two persons. Monitoring is best done at an observatory where data from infrasonic sensors can be viewed simultaneously with data from seismographs, remote cameras, GPS instruments, and other monitoring equipment. The best locations for most infrasonic monitoring sites are off road, so helicopter access is needed a minimum of every few years to replace heavy batteries. More frequent maintenance visits are often required for high-altitude sites.

Infrasound does have a few drawbacks. Wind noise can completely obscure infrasonic signals from explosions, so site selection is critical in mitigating wind noise. For as-yet unexplained reasons, not all explosions produce infrasound (Johnson et al., 2005). Finally, because infrasound is produced by explosions, it is only useful as an explosion detector. The method cannot therefore assist in forecasting future explosions or other volcanic events.

STUDY DESIGN

The U.S. Geological Survey has the primary responsibility for monitoring volcanoes in the United States, as mandated by the Stafford Act. That mandate, and extensive experience in volcano monitoring, makes the USGS the lead agency for development of study designs. Effective volcano monitoring requires specialized scientific expertise and instrumentation, and appropriately timed data collection and analysis. A volcano's threat level determines the degree of monitoring needed to protect lives, property, and infrastructure from volcanic activity.

Land managers and civil authorities responsible for public safety should work with the USGS to target volcano monitoring, provide necessary access to volcanoes and their surroundings,

and facilitate emplacement of monitoring equipment. Monitoring, combined with studies of a volcano's hazards and eruptive history, can reduce risk by warning of impending activity and its potential nature and scope. Land managers should plan appropriate responses to future volcanic activity, so that they then can take timely actions to protect life and property when activity is imminent.

CASE STUDY

Mount Rainier, Washington

Geologic studies at Mount Rainier, Washington, illustrate many volcano monitoring methods. The volcano is built almost entirely of andesite and dacite lava flows, with subsidiary pyroclastic flow deposits, very sparse tephras, and only one known lava dome (Sisson et al., 2001). Its lava flows extend as far as 20 km from the summit and have individual volumes up to 9 km^3. Most of its lava flows are much smaller, extending 5–10 km from the summit, with individual volumes of a few hundredths to a few tenths of a km^3. Though these lava flows were too small to reach now heavily populated areas, they lie within a region of extensive glacial ice. Similar future eruptions of mobile lavas will lead to glacial melting, with consequent downstream flooding and debris flows capable of reaching densely populated areas.

When hot pyroclastic flows erupted from the volcano, these flows commonly traversed glaciers, where they scoured, entrained, and melted ice, transforming the pyroclastic flows directly into mobile lahars. This process is fast, and little warning can be given for debris flows created by suddenly erupted pyroclastic flows, although hazards assessments can indicate likely inundation areas. The hazards potentially associated with this eruption type are illustrated by the 1985 eruption of Nevado del Ruíz (Colombia), in which a relatively small eruption melted ice and snow in the summit area, generating lahars that flowed tens of kilometers down flank valleys, killing more than 22,000 people—history's fourth largest single-eruption death toll. In addition, portions of upper Mount Rainier have been transformed to relatively weak, clay-rich rocks through the action of circulating hot acidic waters (a process known as hydrothermal alteration) (Fiske, et al., 1963; Crowley and Zimbelman, 1997; Finn et al., 2001). In the past, large areas of altered rocks have collapsed, producing voluminous, highly mobile lahars. One such collapse 5600 years ago removed the volcano's summit, core, and northeast slope, creating the Osceola Mudflow that now underlies much of the southern Puget Sound lowlands south of Seattle and east of Tacoma (Crandell and Waldron, 1956; Vallance and Scott, 1997). Another collapse of altered rock 500 years ago, called the Electron Mudflow, suddenly buried the area now occupied by the town of Orting, Washington, (population 4,000) with mud, boulders, and downed timber from several meters to several tens of meters thick (Crandell, 1971; Scott et al., 1995). No conventional building can withstand such a lahar. During the past 10,000 years, Mount Rainier has produced at least 60 lahars of various sizes, including the aforementioned large events with deposits extending into the Puget Sound lowland. Currently, ~150,000 people live in areas that were swept by lahars from Mount Rainier or by associated flooding induced by laharic sediments (Sisson et al., 2001).

Evaluating hazards from Mount Rainier is a priority because of the potential for large loss of life and property from future eruptions and debris flows. Geologic mapping and age measurements show that the modern volcano began to grow ~500,000 years ago atop the deeply eroded remains of an earlier one (Sisson et al., 2001). The volcano's construction occurred during four or perhaps five alternating stages of fast and modest growth. Well-defined fast growth stages extended from 500,000 to 420,000 years ago and from 280,000 to 180,000 years ago. These episodes of fast growth saw the assembly of a high edifice and the eruption of nearly all of the far-traveled, large-volume lava flows. Fast growth stages were also episodes of widespread hydrothermal alteration. During modest growth stages, the high edifice was eroded extensively and may have been reduced in elevation. Volcanic output has been mostly modest since 180,000 years ago, but the eruption rate increased notably 40,000 years ago, constructing much of the present upper Mount Rainier. This increase in eruption rate could mark the beginning of a fifth stage of fast growth, or it could be a fluctuation within the range typical of the modest growth stages.

Mount Rainier's Holocene tephra deposits preserve additional readily quantified evidence of episodic eruptions. Eleven eruptions in the past 10,000 years cast ash, pumice, scoria, and denser rocks high enough into the air to deposit distinctive tephra layers that can be recognized across a wide area (Mullineaux, 1974). Besides these, there are an additional 15–25 thin, fine-grained ash layers restricted to close to the volcano. These fine-grained ashes are products of weakly explosive eruptions, such as small explosions during the release of lava flows, or fine-grained ash billowing up from small pyroclastic flows. The exact number of these thin ashes is hard to determine because they are similar to each other in appearance and because they erode readily, therefore, various layers are missing in one locality or another. The eruptions that created these fine-grained ashes were clustered in time. For example, there are five recognizable subgroups of thin ashes deposited during the period ~2700–2200 yr B.P., followed closely by a sizeable pumice eruption 2200 yr B.P. (J. Vallance and T. Sisson, unpublished results). Each subgroup consists of from one to perhaps as many as five ash layers similar in chemical composition. Each subgroup probably represents the deposits of an eruptive phase consisting of multiple explosive events. Multiple lahars, one known pyroclastic flow, and two groups of lava flows correlate with the fine-grained ash deposits. During this 500-year period, significant eruptive phases took place every 100 years, on average, and each phase consisted of multiple explosive events. This highly active period was preceded by a nearly 2000-year span with no known eruptive deposits. Before this apparent dormant span, the volcano was in another period of frequent eruptions that commenced shortly before the major edifice collapse 5600 years ago that created the Osceola Mudflow.

That eruptive period has not been studied in detail, but included the eruption of pumice and ash concurrent with the Osceola edifice collapse event, as well as at ~4700 and 4500 years ago (Mullineaux, 1974). Another period of frequent eruptions was between roughly 7600–6600 years ago, preceded by a period of dormancy, or only small eruptions of close to 2000-year duration (Sisson et al., 2001).

The eruptive periods 5600–4500 and 2700–2200 years ago were dominated by effusions of lava that almost completely filled the crater left by the Osceola collapse event. Subsequent eruptions took place 1600 and 1100 years ago, although the last was very small. The eruption 1600 years ago is inferred mainly from lahar deposits, and the eruption 1100 years ago was probably of a pyroclastic flow that transformed to a lahar (Hoblitt et al., 1998), although no primary pyroclastic flow deposit is preserved. The major flank collapse 500 years ago that produced the Electron Mudflow has no known associated eruptions.

Based on the historic record, at least three dozen glacial outburst floods have occurred in the twentieth century at Mount Rainier. Glacial outburst floods are unrelated to volcanic activity at Mount Rainier. Glacial outburst floods result from the sudden release of water from glaciers and mainly form during hot weather or heavy rainfall in late summer or early fall, when snowpack has been reduced by summer melting (Walder and Driedger, 1994b). In the absence of snow cover, meltwater or rainfall move over and through the glaciers rapidly. The water bursts or surges from the glacial terminus, entraining loose sediments from channel walls and banks and thereby can transform to a lahar as the surge moves downstream. These outburst floods pose a serious hazard to facilities along stream valleys close to the volcano. Bridges, roads, and visitor facilities have been destroyed or damaged on ~10 occasions since 1926.

The time necessary to perform geologic mapping to understand the past eruptive behavior of a volcano or volcanic system depends on the detail needed to understand the system, and the size and logistical issues of a particular area. In a relatively flat area with many roads traversing it, the mapping of 150 km^2 might be done in a few weeks. Office time to compile the map in a geographic information system (GIS), prepare rocks for chemical analysis, and perform age dating would require another few weeks. These actual work times are spread out over a couple to a few years, because the process of geologic mapping is iterative between field, office, and lab work, and mapping is frequently done on many quadrangles making up the area of interest. The nominal time for geologic mapping can be extended by many times as the complexity of the geology increases, or as access becomes difficult because of fewer roads, steep terrain, or wilderness constraints. Mount Rainier, for example, requires technical mountaineering skills for safe working. In some areas, helicopter use can mitigate access issues, but this is not always possible in all protected areas. Geologic mapping requires that rock samples be collected for chemical analysis and petrographic study. During eruptions, mapping of lava flows and dome extrusion can be done by aerial photography and/or LIDAR imagery with results put in a GIS, but results can take a few weeks. Short active lava flows can be mapped by walking the contact with a GPS unit and coordinates put in a GIS. Longer active lava flows can be mapped with a GPS unit in a helicopter, and both methods have proven very effective for the ongoing eruption in Hawai‘i Volcanoes National Park.

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SUGGESTED FURTHER READING—GAS EMISSION AT GROUND LEVEL

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