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Redwood Creek Watershed Studies

Summary of Geomorphic Research at Redwood National Park

Natural Resource Report NPS/REDW/NRR—2021/2228





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ON THIS PAGE
View of logging on east side of Redwood Creek, a site that was later included in Redwood National Park, circa 1970
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ON THE COVER
Left: Lost Man Creek, circa 1990
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Right: Clearcut logging in Bridge Creek, 1973
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Natural Resource Report NPS/REDW/NRR—2021/2228

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Executive Summary

The story of Redwood National Park (RNP) is one of landscape disturbance, recovery and resilience, uniquely documented by 50 years of observations and measurements. Old-growth coastal redwood forests (*Sequoia sempervirens*), encompassing the tallest trees in the world, once stretched along 450 miles of California coastline. By 2016, following widespread timber harvest, only 5% of the original primeval redwood forests remained, much of it protected within Redwood National Park. This report summarizes decades of studies of physical processes, both natural and human-influenced, affecting the terrestrial and aquatic ecosystems in Redwood National Park. The long-term monitoring has provided a rare opportunity to assess how a forested watershed responds to and recovers from large-scale perturbations. These studies have been used by many agencies and organizations to guide management decisions on forested lands, and results have been widely cited nationally and internationally.

Coastal redwood has long been considered an iconic species in California. Efforts to establish a national park to protect uncut stands of redwoods began in the early 1900s, but it was not until 1968 that the U.S. Congress approved the creation of Redwood National Park. Redwood National Park encompasses redwood forest stands in the downstream third of the Redwood Creek watershed, a steep basin where unstable geology and high rainfall produce a landscape highly susceptible to the effects of land use and large storms. Even after Park establishment, widespread logging continued upslope and upstream of Park boundaries. Large floods combined with recent timber harvest exacerbated naturally high erosion rates, resulting in severe erosion and sedimentation impacts on Park resources. In the 1970s, many studies meticulously documented the damage from land use activities outside of Park boundaries. So, to better protect old-growth redwood trees from excessive erosion and sedimentation associated with timber harvest and road construction, Congress expanded Park boundaries in 1978. As part of the 1978 legislation, Congress instructed the National Park Service to "…conduct erosion and sedimentation studies in the Redwood Creek basin." This unique mandate from Congress led to the establishment of a federal scientific team to examine an extensive array of hillslope and river channel processes that might affect the health of the redwood ecosystem. Consequently, the Redwood Creek watershed is one of the few sites in the United States that has a long-term (> 45 years) monitoring program of river channel responses to hillslope disturbances.

Initially, Redwood National Park focused on two major branches of study. The first was to assess sources and causes of hillslope erosion in the Redwood Creek watershed, track the movement and storage of sediment resulting from such erosion, and quantify the amount of sediment flushed out of the watershed by Redwood Creek. Sediment sources were inventoried through field mapping, aerial photograph analysis, and measurements of streamflow and sediment, especially during storms, in Redwood Creek and its tributaries. Large floods in the 1960s and 1970s initiated hundreds of landslides and road failures in the Redwood Creek basin, contributing immense volumes of sediment to Redwood Creek and its tributaries. Gullies from roads also brought in large amounts of sediment to creeks. As a result of this widespread hillslope erosion, much of it associated with unmaintained logging roads, the Redwood Creek channel filled by up to 25 ft. of gravel and sand in many reaches. As the river channel filled, streamflow was diverted against riverbanks, causing a positive feedback

of even more streambank erosion and landslides. The river channel widened, pools became scarcer and shallower, and channel substrate became finer.

Since 1975, Redwood Creek has downcut through thick deposits of sand and gravel. As sediment was flushed downstream, the upstream reaches of Redwood Creek recovered more rapidly than downstream reaches and steep tributaries recovered more rapidly than the mainstem of Redwood Creek. Pools became more frequent and deeper, and the channel bed coarsened. Although the most rapid period of stream channel recovery occurred within the first decade of disturbance, the impact of excess sediment has persisted for more than 40 years. Extensive monitoring of channel changes shows that channel widening, and excess sediment are still present in some stream reaches as of 2020.

The second major focus of RNP geomorphic efforts, based on the sediment source inventory, was the removal of abandoned logging roads on disturbed federal lands. RNP began its pioneering watershed restoration program in 1977, and road removal techniques evolved greatly over the next four decades. Since 1978, RNP has decommissioned about 255 miles of abandoned logging roads from Park lands. Road removal has been effective in reducing erosion problems, although not eliminating them entirely. In a large storm in 1997, abandoned logging roads that had been decommissioned exhibited less than one-third the erosion than untreated roads. In cooperation with landowners upstream of Park boundaries, watershed restoration efforts were expanded to private lands, where 181 miles of logging roads have been removed or upgraded. Road treatments have greatly reduced the potential for road-related erosion in the future. RNP's road removal program has been emulated in many other forested regions in the United States.

Key findings of RNP studies address many forest management issues, including landslide mechanisms, gully formation, streamflow and sediment yield regimes, channel erosion and sedimentation, stream temperature, large in-channel wood and changes in aquatic habitat. The long-term monitoring efforts in the Redwood Creek watershed have documented landscape damage from timber harvest and road construction activities as well as partial recovery of hillslopes and stream channels. Removal of logging roads, revegetation of hillslopes, and improvement in timber harvest practices have led to decreased sediment yields from 1975 levels. Road removal also sequesters carbon as soil erosion decreases, road surfaces revegetate, and soil organic carbon accumulates. As part of these efforts, innovative restoration and monitoring techniques were developed, tested, and implemented. Lessons learned from RNP studies have been incorporated into management policies of many government agencies, including revisions of California Forest Practice Rules.

Several challenges to full ecosystem recovery remain. The loss of old-growth trees along Redwood Creek, through timber harvest and bank erosion, has reduced both shading and the input of large wood to the river channel, as well as decreasing the sediment-filtering effect of streamside vegetation. Summer low flows have decreased since the 1970s. During drought years, up to 1.5 miles of lower Redwood Creek dry out completely. The effect of water diversions from illegal cannabis plantations on decreased flows is unknown. Stream temperatures during summer low flows exceed those preferred by salmonids along much of the length of Redwood Creek, especially in the middle basin. Several juvenile fish kills have been documented in Redwood Creek since 2006. Timber

harvest and private residential development will continue upstream of Park boundaries. Diseases, pests, pathogens, invasive species, wildfire, and climate change will likely continue to affect forest stands. Funding for actions to meet these threats is a continual challenge.

Monitoring road removal sites has shown that to date some of the desired outcomes of restoration have been achieved in terms of decreased erosion and sedimentation. The Redwood Creek basin has served as a laboratory to study the trajectories of watershed recovery. Nevertheless, the recently restored landscape has yet to be tested by intense storms, which were common from 1953 to 1975. Climate modeling predicts increased storm intensity in the future. Adaptive land management requires a continuous evaluation of what works and what doesn't work, and of unintended consequences. Thus, long-term monitoring of restoration and land use activities is needed to guide future actions under varying climatic and land use scenarios.

Acknowledgments

The almost-50 years of work summarized in this report was only possible because of the dozens of field crews, students, volunteers, private landowners, state and federal agencies, non-governmental organizations, and technical reviewers. In particular, we appreciate the USGS researchers that laid the groundwork for many of the Redwood Creek watershed studies including: Richard Janda, K Michael Nolan, Deborah Harden, Richard Iverson, James Duls, and Tom Stephens. Project leaders, restoration geologists, and technical support staff who contributed much to watershed restoration and related data collection and interpretation are listed in Appendix A. Cooperators and funding agencies are listed in Appendix B. Tamara Wolski assisted with bibliographic research and copyediting. Dave Van de Mark helped with restoring old photographs. Efforts by Vicki Ozaki and Rachel Truesdell of the NPS were critical in obtaining data sets and in-house reports, creating maps and graphics, and other logistical support. Thoughtful reviews by K. Michael Nolan, Andre Lehre and Greg Bundros improved the clarity and organization of this effort. Redwood Parks Conservancy facilitated the production of this report.



Dr. Richard J. Janda, Lead scientist for the USGS Forest Geomorphology Project. In memoriam 1939–1992 (USGS/WILLIAM SCOTT).

List of Acronyms, Abbreviations, and Units

Some agency and other acronyms or abbreviations used throughout this manuscript include:

API: Antecedent Precipitation Index

BOF: California Board of Forestry

CAL FIRE: California Department of Forestry and Fire Protection

CDFW: California Department of Fish and Wildlife; until 2013, known as CDFG: California Department of Fish and Game

CDPR: California Department of Parks and Recreation

CFPR: California Forest Practice Rules

DOI: U.S. Department of Interior

EPA: U.S. Environmental Protection Agency

GIP: GeoScientists-in-the-Parks

GIS: Geographic Information Systems

HSU: Humboldt State University

MOU: Memorandum of Understanding

MWMT: Maximum weekly maximum temperature (the seasonal high of the average daily maximum temperatures for each seven-day period)

NPS: National Park Service

NCWAP: North Coast Watershed Assessment Program

PPZ: Park Protection Zone

RNP: Redwood National Park

RNSP: Redwood National and State Parks

THP: Timber harvest plan

TMDL: Total Maximum Daily Load

USFS: United States Forest Service

USFWS: United States Fish and Wildlife Service

USGS: United States Geological Survey

WSP: Watershed Stewards Program

WY: Water Year; a water year runs from October 1 to the following September 30 and is designated by the calendar year in which it ends. Thus, the year ending September 30, 1999 is called the "1999" water year.

XS: Cross Section

Units and Conversions

cfs = cubic feet per second

Mg = megagrams = 1,000,000 grams = 1 metric tonne = 1.1 English tons

mg =milligram = 1/1000 of a gram

mg/L = milligram per liter, equivalent to parts per million

mm = millimeter = 0.039 inch. (25.4 mm = 1 inch)

ppm – parts per million

Glossary

Adventitious root: A root growing from a location other than the underground, descending portion of the axis of a plant, as from a stem or trunk.

Aggradation: The increase in channel bed elevation in a river due to the deposition of sediment.

Basin, hydrographic (also called a **drainage basin or watershed**)**:** An area of land where rainfall and snowfall collect and drain off into a common outlet, such as into a stream, river, or bay.

Bedload: Particles in a flowing river that are transported by rolling, bouncing, or dragging along the channel bed.

Benthic macroinvertebrates: Small aquatic animals and the aquatic larval stages of insects which live on a river channel bed, commonly attached to rocks, vegetation or logs. They are commonly used as indicators of the biological condition of waterbodies.

Berm: An earthen. linear mound bordering a river channel, commonly composed of sand and gravel.

Coherent unit (KJfl): Resistant assemblage of sandstone and mudstone, characterized by steep and rugged topography.

Colluvium: Unconsolidated, unsorted earth material being transported or deposited on hillslopes by mass movement rather than by flowing water.

Crowning: A crowned road is gently sloped to both sides of the centerline of the road surface, and drains to both sides of the crown. It includes an inboard ditch.

Cutslope (or Cutbank): The artificial face or slope, formed during road construction, cut into soils or rock along the inside of a road.

Debris slide: A landslide in which movement occurs along a well-defined, planar slip face roughly parallel to the ground surface and is not channelized.

Debris torrent (or debris flow): Rapid, channelized flows of saturated, poorly sorted soil, weathered bedrock, and organic debris.

Discharge: The volume of stream flow that is transported through a given channel cross-sectional area in a given length of time. A common metric of discharge is cubic feet per second.

Earthflow: A slow-moving downslope viscous flow of fine-grained materials, typically resulting from very wet or saturated soil conditions.

Evapotranspiration: The process of transferring moisture from the earth to the atmosphere by evaporation of water from soil and transpiration from plants.

Flume: An artificial channel used to measure water flow and sediment transport under controlled conditions.

Geomorphic: Relating to the form of the landscape and the physical processes that shape a landscape feature.

Harvest unit: The area encompassed by a timber harvest plan in which trees may be cut by various silvicultural techniques.

Headwater: A tributary stream of a river close to or forming part of its source.

Hummocky: Terrain characterized by an uneven or undulating surface texture which contains subdued and rolling landforms.

Hydrologically connected road: A road segment that has a continuous surface flow path to a natural stream channel during a storm runoff event.

Inboard ditch: A ditch at the base of a cutslope running parallel to a road, which conveys water to a culvert or other drainage feature.

Incoherent unit (KJfc): A fine-grained sandstone and shale assemblage that has been pervasively sheared by tectonic processes. Soils developed on this bedrock are typically clay rich and highly susceptible to landsliding.

Landing: A location at the side of a logging road where logs are stored temporarily after trees are harvested. Here the logs are bucked (cut into shorter lengths) and loaded onto a truck to go to a mill.

Longitudinal profile (or Thalweg profile): A graphic presentation of water surface elevation and channel bed elevation plotted against river channel distance.

Outslope: An outsloped road has a driving surface that gently slopes from the cutslope to the outside road edge and has no inboard ditch.

Peak flow: The maximum rate of water discharge during the period of runoff caused by a storm or snowmelt. The maximum discharge of the year is the annual peak flow.

Recontouring, full: In addition to the methods used in road decommissioning, the road bench and road fill are reshaped to mimic the original hillslope morphology as much as possible as well as uncovering and retrieving topsoil.

Recontouring, partial: In addition to the methods used in road decommissioning (see below), the road bench and road fill are partially reshaped to mimic the original hillslope morphology.

Recurrence interval: (or Return interval): A probability of flood occurrence. For example, a 10-year return interval flood has 1/10 = 0.1 or 10% chance of being exceeded in any one year.

Redd: A nest for spawning built by salmon and steelhead into streambed gravels.

Refugia: Areas in a river where aquatic organisms can survive through a period of unfavorable conditions, such as high stream temperatures.

Riffle: A shallow portion of a stream with fast-moving water.

Riparian: Plant communities adjacent to a stream, affected by surface and subsurface streamflow.

Road decommissioning: Heavy equipment (bulldozers, excavators, dump trucks, etc.) is used to excavate buried stream channels, remove drainage structures, recontour streambanks, and decompact road surfaces.

Road prism: The area of ground encompassing the driving surface as well as road drainage ditches, shoulders, cutbanks, and fillslopes.

Rolling dip: Smooth, angled depressions constructed in the roadbed to convey surface runoff off the road surface.

Scour: The removal of sediment such as sand and gravel from a location in a river bed caused by swiftly moving water.

Sediment budget: An organizational tool used to assess sediment sources, transport, and storage within a river system.

Sediment yield: The amount of sediment per unit area removed from a watershed by flowing water during a specified period of time. A common metric of sediment yield is "tons of sediment per square mile per year."

Spawning: The act or process of a fish producing and depositing eggs in the streambed.

Stream crossing (also called **road-stream crossing):** The location where a road crosses a natural watercourse or stream. Water generally flows either under the road through a culvert or bridge or across the road through a ford.

Stream diversion: If a culvert or other drainage feature becomes plugged and no longer conveys water across the road into a stream channel, flow may be diverted down the adjacent road, possibly causing gullies, road fill failures, and/or landslides.

Suspended sediment: The portion of the sediment load in a river that stays in suspension by the turbulence of flowing water. It generally consists of fine particles (clay, silt, and fine sand).

Swale: A shallow, open depression in unconsolidated materials which lacks a defined channel but can funnel overland or subsurface flow into a stream channel.

Thalweg: A line drawn to join the lowest points along the length of a stream bed, defining its deepest channel.

Tree throw: The process of uprooting and tipping over of trees by strong winds, commonly resulting in a small depression from which the root-ball is displaced, and an adjacent mound is built from the soil sloughed from the root ball.

Tributary: A small stream or river that flows into a larger stream or mainstem river.

Turbidity: The relative clarity of water measured by the amount of light that is scattered by material in the water. Material that causes water to be turbid includes clay, silt, fine inorganic and organic matter, algae, and dissolved organic compounds.

Waterbar: A road construction feature built on a diagonal across the road consisting of a small ditch and ridge designed to divert surface water off the road

Watershed: see “Basin.”

Introduction

Many visitors who enter the primeval forests of Redwood National and State Parks (RNSP), a World Heritage Site, are in awe, entranced by the cathedral redwoods and rugged green hills. The majesty of ancient redwoods, which have endured so much over millennia, lead people to believe in the forest's resistance and timelessness. Yet, following European settlement of California, less than 5% of uncut redwood stands remains from their original extent. Despite appearances of resilience, many redwood landscapes have been greatly disturbed in the past 75 years, and we have much to learn about the devastation and recovery of these lands. The tranquil scenery of the redwoods belies the tremendous power and energy underlying the land, which only become evident during extreme events. Shattering magnitude 9 earthquakes flex the land and create powerful tsunamis, described in the oral histories of our local Yurok, Tolowa Dee-ni' Nation and Wiyot tribes. Damaging distant source tsunamis have also repeatedly struck the north coast, but between events many local residents become complacent. Decades of moderate winters lull people into comfortable lives on floodplains, instilling historical amnesia about the several epic floods in the last two centuries. The combination of these two forces, tectonic uplift and intense rainfall, leads to acre-size or larger landslides tumbling off the hillslopes and smothering stream channels. But humans too have shaped the landscape. Adding to these natural forces, timber harvest, road construction, gravel mining, and other human activities have greatly exacerbated naturally high erosion rates in this environment, even on Park lands. Scars from past land changes are common.

Much of ecosystem recovery following large disturbances is incremental, and only by observing a system for decades can trends in recovery be understood. Lessons learned from studying such recovery can then be applied to other disturbed sites to accelerate healing of the land. Despite several books being written on the natural and cultural history of the redwoods, there has been no comprehensive summary of the scientific studies which were integral to the establishment of Redwood National Park and its pioneering watershed restoration program. The purpose of this paper is to summarize what we know about natural processes and man-made disturbance of those processes and subsequent recovery in this dynamic environment, with a focus on a half-century of studies of erosion and sedimentation in the Redwood Creek watershed.

History of Scientific Studies

Redwood National Park (RNP) in north coastal California was established in 1968, but the present boundary of RNP (Figure 1) was set only after decades of political controversy and scientific studies. Logging of redwood forests in Humboldt and Del Norte counties began in the 1850s and ramped up by the 1890s. In response to the loss of redwoods in California, several women's clubs vigorously promoted the idea a national redwood park in the early 1900s (Wasserman and Wasserman, 2019). The Save the Redwoods League, established in 1918, supported the idea of such a park and led an effort to protect remaining old-growth redwoods from widespread logging. Many decades of Congressional inaction followed, however. After World War II, harvest of redwoods skyrocketed as a building frenzy took hold in the U.S., but it was not until the 1960s that the White House seriously considered establishing a redwood national park. In 1963 the National Geographic Society commissioned a study of California's coast redwoods to analyze whether additional preservation of redwood forests was needed. Based on that study, in 1964 Secretary of the Interior Stewart Udall advised President Lyndon B. Johnson of an urgent need to preserve old-growth redwoods in a national park. Several years of frequently contentious meetings among government agencies, Congress, timber companies, conservation organizations, and interested citizens followed, until President Johnson signed the Redwood National Park Act on October 2, 1968.

Nevertheless, after RNP was created in 1968, controversy continued. The Park included a 0.5-mile-wide riparian corridor along the downstream third of Redwood Creek, sometimes called "the Worm" (Figure 2). The floodplain in this corridor, which included the Tall Trees Grove, supported some of the largest old-growth redwood trees within Park boundaries. Although the trees themselves were protected from being logged, several citizen groups and organizations were concerned that timber harvest upstream and adjacent to the Worm was threatening the redwood trees and Redwood Creek.

Stone and others (1969) evaluated the need for "…buffers and watershed management practices that can protect the Park from hazardous inputs generated outside the Park." The Sierra Club pressed the U.S. Department of Interior (DOI) on this issue of external threats. The Secretary of Interior responded, "The integrity of the park is in no danger at the present time as a result of logging activities on private lands outside the park" (Schrepfer, 1983). DOI authorized two studies, by Earth Satellite Corporation and by Dr. Richard Curry, to support its stance. Contrary to DOI's expectations, however, the two studies concluded that logging outside of park boundaries (primarily by tractor-yarded clearcutting) did indeed have negative impacts on park resources.

The Sierra Club then forced the DOI to make the Curry report public under the Freedom of Information Act and charged that the National Park Service (NPS) was not fulfilling the congressional mandate to "preserve significant examples of the primeval coastal redwood (*Sequoia sempervirens*) forests and the streams…with which they are associated" (Wayburn, 1975). In response, DOI authorized Dr. Richard Janda of the United States Geological Survey (USGS) to conduct a three-year study of sedimentation and erosion in Redwood Creek (Spence, 2011). This USGS Forest Geomorphology Project assessed the impacts of several large floods and upslope and upstream logging activities on Redwood Creek and its forested floodplains. The USGS research was

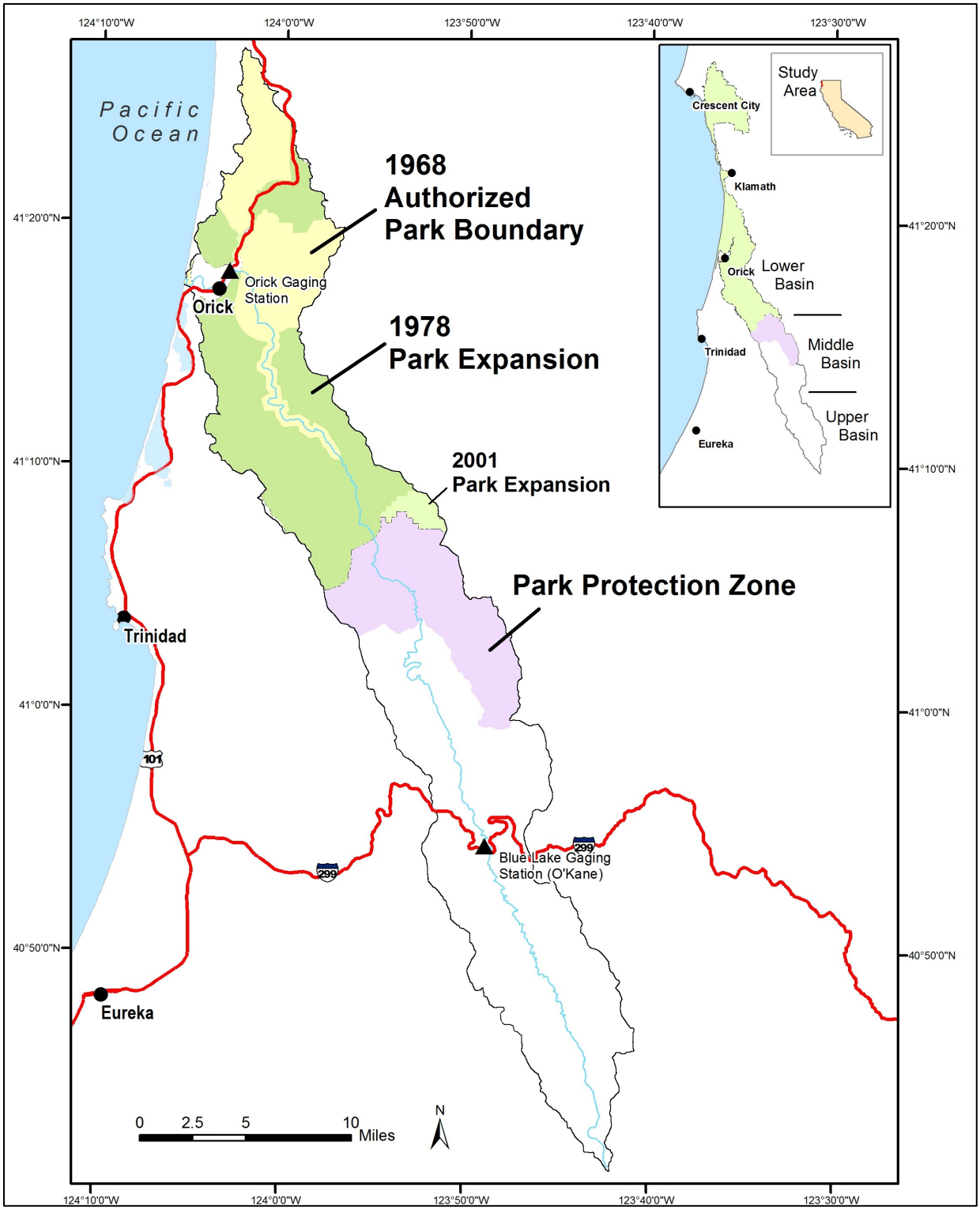


Figure 1. Location map showing the 1968 and 1978 boundaries and the Park Protection Zone.



Figure 2. 1976 aerial photograph of Redwood Creek looking east. The Tall Trees Grove lies in the bend in the river in the lower left. The "Worm" boundary is delimited by the recent clearcuts on the hillslope above the Tall Trees Grove (© DAVE VAN DE MARK).

critical in the effort to expand RNP. Streamflow and sediment discharge were measured at many locations, both in uncut and harvested areas, during many storms (synoptic storm sampling) (Nolan and Janda, 1995) and sequential aerial photographs documented the extent of logging and the occurrence of landslides throughout the basin (Harden *et al*., 1978). The many reports by the USGS in the 1970s provided clear evidence of the impact of timber harvest on the Park's forest and aquatic resources (Janda, 1975; 1976; 1977; Janda *et al*., 1975; Nolan *et al*., 1976). They highlighted not only the effects of past timber harvest but also the threat of on-going and planned harvest on private lands. Dr. Janda provided extensive scientific testimony explaining these findings before the Federal Court and the U.S. Congress (Janda, 1976). It took several more years of Congressional hearings, meetings among representatives of the lumber industry, government agencies, environmental activists, and concerned citizens before Public Law 95-250 (the Redwood National Park Expansion Act) was signed in 1978. The Act added 48,000 acres (about 38,000 of which had been logged) to the Park.

Three critical parts of the Expansion Act, which were unique for national park legislation, directed future scientific studies and erosion control activities within the Redwood Creek basin:

1. “The Secretary shall undertake and publish studies on erosion and sedimentation originating within the hydrographic basin of Redwood Creek with particular effort to identify sources and causes, including differentiation between natural and man-aggravated conditions, and shall adapt his general management plan to benefit from the results of such studies.”

2. “The Secretary…is further authorized…to initiate, provide funds, equipment, and personnel for the development and implementation of a program for the rehabilitation of areas within and upstream from the park contributing significant sedimentation because of past logging disturbances and road conditions, and, to the extent feasible, to reduce risk of damage to streamside areas adjacent to Redwood Creek and for other reasons.”

3. “…the Secretary is authorized...to enter into contracts and cooperative agreements with the owners of land on the periphery of the park…to assure that the consequences of forestry management…will not adversely affect the timber, soil, and streams within the park.” A 26,000-acre Park Protection Zone (PPZ) was established upstream and adjacent to Park boundaries, so that Park staff could participate in timber harvest plan reviews and provide recommendations to prevent erosion. (A small portion of the PPZ in upper Coyote Creek was later transferred to RNP in 2001.) In 1994 three California state parks (Jedediah Smith, Prairie Creek, and Del Norte Coast Redwoods) joined with RNP to cooperatively manage 120,000 acres of forested lands. This partnership is referred to as Redwood National and State Parks (RNSP).

Consequently, several decades of studies have addressed these three directives. Hundreds of reports and journal articles written about RNP hydrology and geomorphology have been used and cited by scientists and land managers, both nationally and internationally (Appendix D). This review summarizes the lessons learned from geomorphic studies in the Redwood Creek basin and the implications for land management. A review of other RNP reports on estuarine and coastal processes, water quality, fisheries, and vegetation management were beyond the scope of this project.

Scientific studies played an integral role in the effort to establish, and later expand, Redwood National Park. Congress directed the NPS to study erosion and sedimentation, initiate a watershed rehabilitation program, and work with adjacent landowners to protect Park resources.

Site Description

Redwood National Park is located in the downstream third of the Redwood Creek watershed in north coastal California and was established in 1968 to preserve ancient stands of coast redwood (*Sequoia sempervirens*). The Redwood Creek basin is located in the northern Coast Ranges of California, USA. It is the ancestral home of the Chilula and the Whilkut tribes. Redwood Creek drains an area of 282 mi^2 and total basin relief is 5,300 ft. It lies within a tectonically active region with high uplift rates (the Cascadia subduction zone; CSZ) and subject to large earthquakes. Tsunami deposits and other evidence indicate a magnitude 9 earthquake occurred on the CSZ in 1700. These great earthquakes generate large tsunamis that inundate our coast areas and change the coastline with some areas dropping in elevation and others rising.

The climate of the Redwood Creek watershed is Mediterranean, with mild, wet winters, and warm, dry summers. The climate is moderated by the proximity of the Pacific Ocean, which maintains a fairly constant temperature year-round. Prevailing winds are northwesterly, bringing cool, moist air and frequent fog to the lower basin. The middle and upper basins are less affected than the lower basin by marine influences. Mean annual basin-wide precipitation is roughly 80 in. Most precipitation falls as rain. Snow falls fairly frequently at altitudes greater than 1,600 ft. and rarely at lower altitudes. Rainfall is strongly seasonal, with most rain falling between November and March. The long dry summer conditions are eased by persistent fog in the lower basin. Fog condensation adds measurably to soil moisture during the dry summer months (Janda *et al.*, 1975; Dawson, 1998).

The basin is underlain by the highly erodible rocks of the Franciscan Assemblage, mostly sandstones, mudstones, and schist (Harden *et al.,* 1981) (Figure 3). The Grogan Fault bisects the basin and separates schist (west) from coherent sandstone and incoherent sandstone-mudstone units (east). Schist slopes on the west side are gently convex, hillslope gradient averages 25%, ridges are broad and flat, and streams are typically shallowly incised. Conversely, on the east-side resistant sandstone, sharp ridge crests, steeper slopes, and narrow V-shaped canyons prevail. The incoherent unit has subdued and rolling topography and less deeply incised drainages. Locally, a break-in-slope separates the gentler upper hillslopes from steeper (> 65%) streamside hillslopes, which are called inner gorges (Kelsey, 1988). Streamside landslides are common on these steep, lower hillslopes.

Redwood Creek, a gravel-bed river 61 miles long, enters the Pacific Ocean near Orick, CA. Channel gradients range from 12% in the headwaters to 0.1% in the lower reaches. Channel gradient is less than 2% in the lowest 50 miles of Redwood Creek and the riverbed morphology is characterized by pools and riffles. Most tributaries are steep (> 4%), but the four largest tributaries have low-gradient reaches with well-developed pool-riffle morphology like that in the mainstem. Floodplain development is limited in the Redwood Creek watershed, and many reaches of Redwood Creek and its tributaries are highly constrained (valley width is less than two channel widths). Redwood Creek is listed as sediment- and temperature-impaired by the U.S. Environmental Protection Agency (EPA).

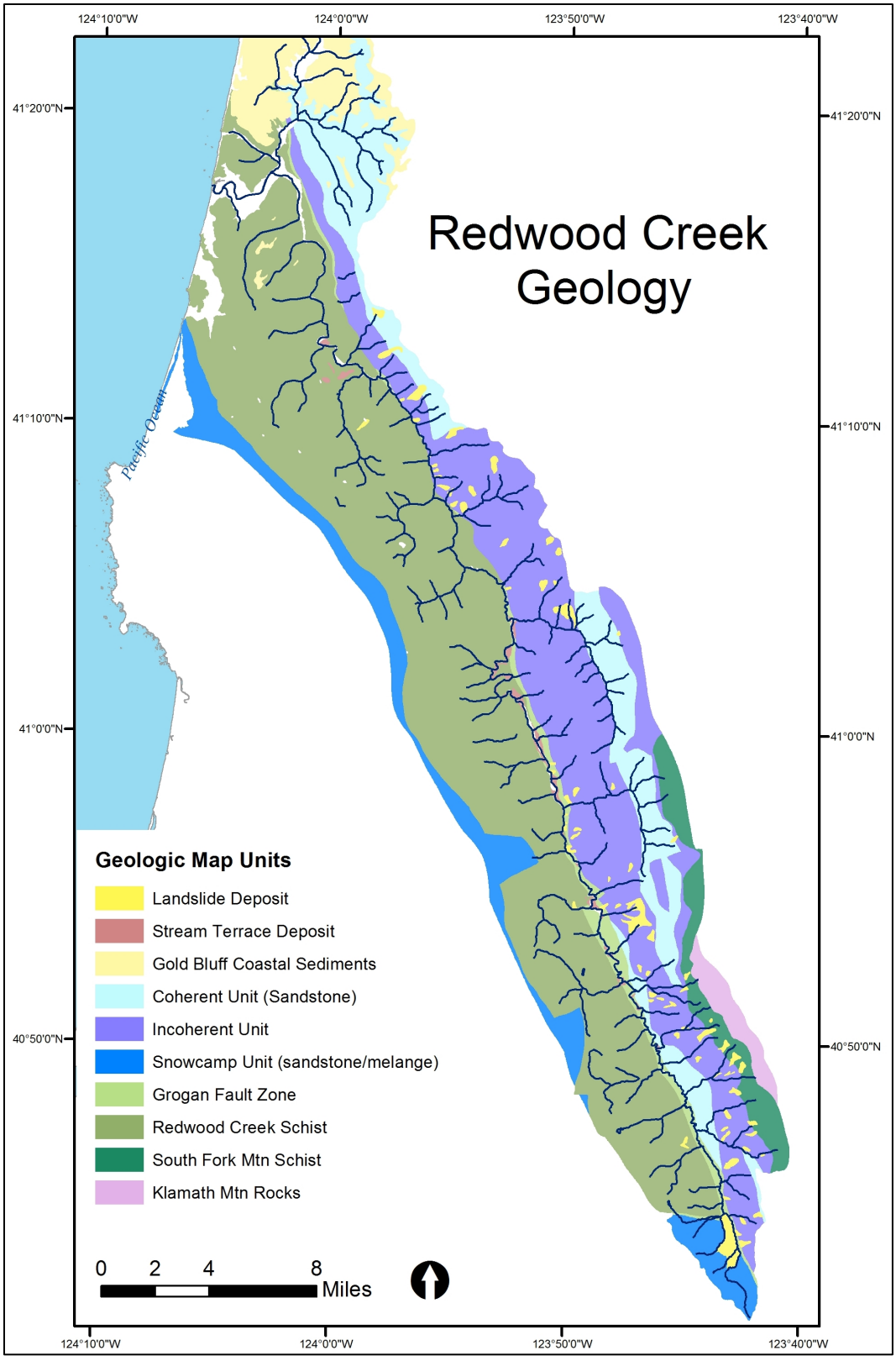


Figure 3. Geologic map of the Redwood Creek basin (based on Harden *et al*., 1981).

Prior to 1945, 85 percent of the Redwood Creek basin was blanketed with virgin redwood (*Sequoia sempervirens*) and Douglas-fir (*Pseudotsuga menziesii*) forest stands (Best, 1995). Scattered grasslands and oak-woodlands lined the eastern ridgetops. Redwood and Douglas-fir trees can reach more than 300 ft. in height and 15 ft. in diameter, and the large wood contributed by fallen trees influenced channel morphology in many streams. By 1997, 80 percent of the original coniferous forest (not including the Prairie Creek basin) had been logged. The primary silvicultural method was clearcut logging with tractor yarding, which resulted in extensive ground disturbance and large areas of bare soil. Widespread construction of haul roads and dense patterns of skid trails accompanied the timber harvest activities (see cover photos). Currently, park lands encompass most of the remaining old-growth forests in the basin.

In 1978, RNP was expanded by 48,000 acres to encompass recently logged lands adjacent to the 1968 Park boundaries. Most of the redwood forest on this land had been tractor logged, which resulted in an extensive network of unpaved haul roads and tractor trails (skid roads). The newly expanded Park included more than 415 miles of abandoned haul roads and 3,000 miles of skid roads, which were causing accelerated erosion (Janda *et al*., 1975; RNSP, 2000). The road removal program began when, as part of the Park expansion in 1978, Congress passed Public Law 95-250, which directed the NPS to reduce human-induced erosion on the newly acquired lands. Since then, about 255 miles of roads have been treated within Park boundaries.

The Redwood Creek basin is located in a tectonically active zone with high uplift rates and high rainfall. Widespread timber harvest and road construction greatly exacerbated naturally high erosion rates in the watershed.

Storm and Flood History

Most erosion and sediment movement in north coastal California takes place during intense rainstorms and large floods. Storms and floods are critical events for the resources of Redwood Creek because they erode hillslopes, reshape channels, and transport large proportions of river sediment loads. Consequently, any analysis of geomorphic events such as landsliding, sediment transport, and floodplain sedimentation needs to account for the storm and flood history during the period of interest.

In the 1970s, the USGS established a network of stream gaging stations along Redwood Creek and several tributaries, and then RNP added stations in the Prairie Creek subbasin in the 1990s (Figure 4). Many of the stations are now discontinued. Appendix C contains a full list of monitoring stations and dates of operation.

Measurements of river flow in Redwood Creek at Orick cover the period of 1953 to the present. Discharge is reported as cubic feet per second (cfs). Between 1953 and 1975, five years had peak flows of 50,000 to 50,500 cfs (Figure 5A). The December 1964 flood peak was the highest measured flow on record. However, since 1975 only one flood, in December 1996, exceeded a five-year recurrence interval flood level (https://streamstatsags.cr.usgs.gov/gagepages/html/11482500.htm).

The series of flood-producing storms between 1953 and 2017 was preceded by more than 60 years during which only moderate or localized storm events occurred. Limited precipitation records in the late 19th century document several large storms in 1852, December 1861-January 1862, 1879, 1881, 1888, and 1890. Newspapers report damage, such as bridge washouts and damage to farm buildings along Redwood Creek, from floods associated with these storms, but no quantitative information on the magnitude of the flood peaks is available (Harden *et al.,*1995). Anecdotal evidence suggests that floods in 1861–62 and 1867 were as large or larger than the 1964 flood (Coghlan, 1984). Rainfall amounts during the period of recent large floods in 1953, 1955, 1964, 1972 (two floods), and 1975 were not unusually large in comparison to long-term records (Janda *et al.,* 1975). The flood-frequency study of Coghlan (1984) supported this conclusion and indicated that storms such as those that produced large floods in the 1950s to 1970s are a normal climatic feature.

Other factors besides rainfall affect river peak flows. When soils are near saturation because of previous rainfall, more runoff is generated for a given amount of new rainfall. This is evaluated by using an Antecedent Precipitation Index (API), which accounts for rainfall in the days preceding a large storm. Harden (1995) and Curry (2007) analyzed available records that showed since 1953, the highest four API's were for storms in January 1953, December 1996, March 1972, and December 1964. Snowmelt during a storm can also contribute to peak flows, but snowfall records in the Redwood Creek basin are spotty.

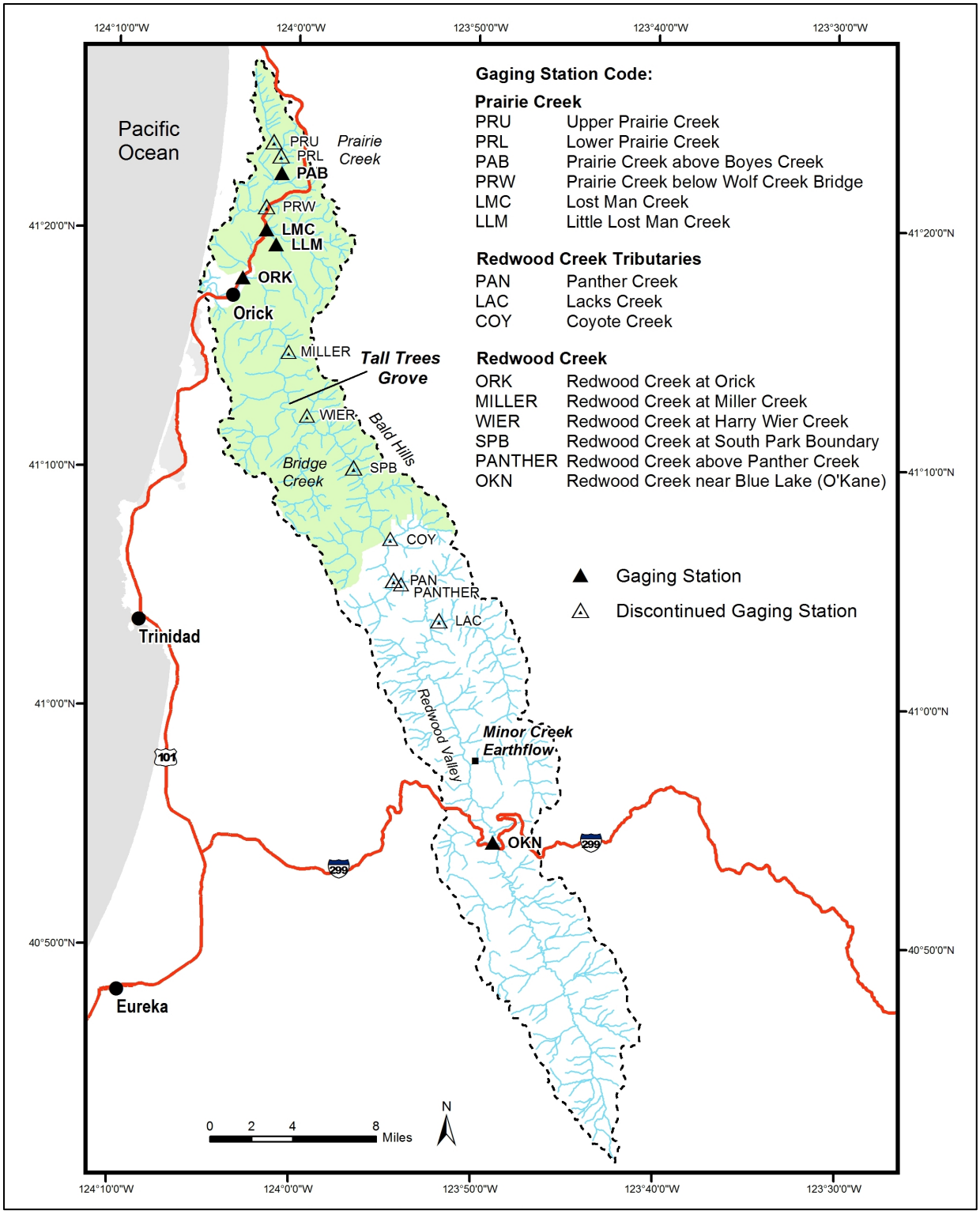


Figure 4. Stream monitoring stations in the Redwood Creek watershed.

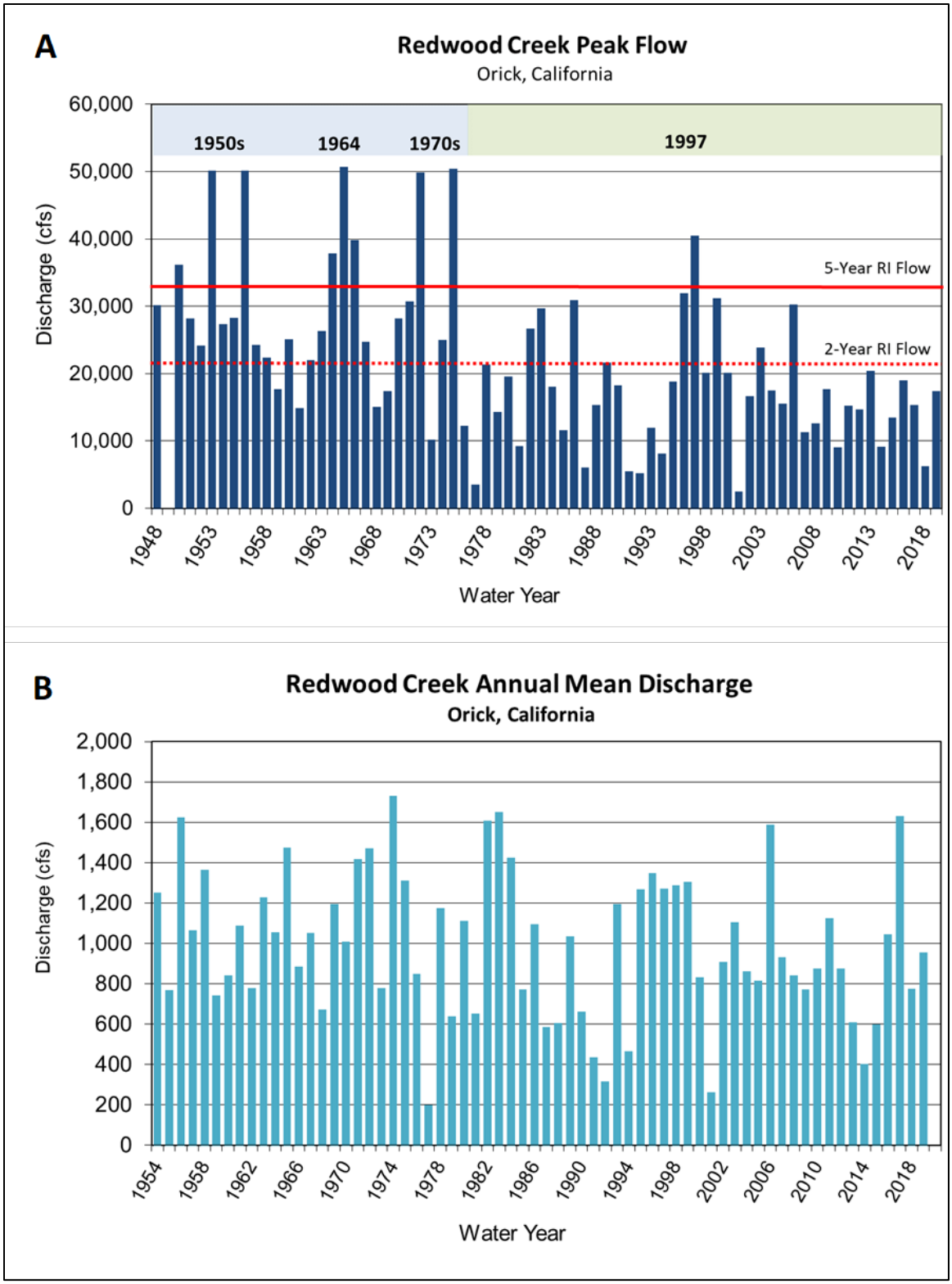


Figure 5. A) Annual peak flow at Redwood Creek at Orick gaging station. B) Annual runoff (mean annual discharge) at Redwood Creek at Orick gaging station.

Some storms were focused on inland areas, whereas other storms were more coastal. For example, the December 1964 flood was more intense in the inland portions of the Redwood Creek basin, when 17.5 inches of rain fell between December 18–30. In contrast, from March 15–24, 1975, 23.8 inches of rain was recorded in lower Redwood Creek (Harden, 1995). The differences in rainfall distribution affected the distribution of landslide activity in both space and time.

The 1964 flood was especially damaging to aquatic resources in the Redwood Creek basin. Post-World War II logging and road construction on steep hillslopes in upper Redwood Creek made the land very susceptible to erosion. Of the 1,852 landslides occurring between 1954 to 1980, the majority of them occurred during the 1964 event and were associated with roads and timber harvest (Kelsey *et al.,* 1995). Up to 25 ft. of sediment filled the Redwood Creek channel at many locations, filling in pools and burying streamside trees. Channel widening and streambank erosion were widespread, which also caused the loss of redwood trees. Effects from this flood persist to today (discussed in more detail later).

Hillslope conditions can also increase the volume of runoff during a given storm. Timber harvesting and roads can increase storm runoff by reducing canopy interception, decreasing evapotranspiration, compacting soil, intercepting subsurface flow at road cutbanks, and channeling overland flow along roads and skid trails. Land use probably increased streamflow in Redwood Creek during and shortly after the period of intensive harvesting in the 1960s and 1970s (Nolan and Janda, 1981b).

Sustained moderately high river flows do not change river channels as much as intense, short-term peak flows, but are important in influencing aquatic ecology. The total volume of streamflow in a year (annual runoff) does not necessarily reflect years with high peak flows (Figure 5B). For example, in Water Year (WY) 2017, even though no large floods occurred, average runoff was 1624 cfs, higher than in the flood years of 1975 (1304 cfs) or WY 1965 (1467 cfs). (A WY runs from October 1 to September 30.)

It is important to note that, since RNP was expanded in 1978 and since the initiation of the watershed restoration program, the highest flood peak was only 40,300 cfs (a 12-year recurrence interval flood). The Tall Trees Grove has not been inundated since the 1975 flood, but the probability of a flood of that size occurring in the next ten years is 50%. The effect of a future 50,000 cfs flood on Redwood Creek channel and floodplain is unknown. Likewise, the effects of a large, intense rainstorm on recently harvested or revegetated hillslopes and on restored logging roads remain to be seen. The recurrence interval of recent floods may be different from the recurrence interval of their associated erosion events, due to land use disturbances; that is, the erosion associated with floods in the 1960s and 1970s was greater than the erosion from previous floods of the same size (Nolan and Marron, 1995). In addition, in light of climate change, the probability of occurrence of floods based on past records may not be indicative of flood frequency in the future. Recently, a study of megastorms in California (dubbed “atmospheric rivers”) suggests a higher number of such intense storms in the future (Dettinger and Ingram, 2013).



View of the mouth of Redwood Creek during the 1950 flood (PINKY ZUBER)

Large storms and floods are important drivers of geomorphic change. Several major floods occurred in the Redwood Creek basin between 1953 and 1975, causing extensive erosion and sedimentation, but no flood has exceeded a 12-year recurrence interval since then.

Project Summaries and Lessons Learned

Sediment Budget Approach

To develop land use policies for watersheds and to guide watershed restoration, land managers need to understand sources of sediment entering river systems, the timing and magnitude of sediment input and output, and the role of humans in accelerating erosional processes. As a first step in developing a watershed restoration plan, RNP adopted a sediment budget approach to quantify these aspects in order to prioritize erosion problems in the basin. In its simplest version, a sediment budget is:

$$\text{Input} \pm \text{Storage} = \text{Output}$$

The following discussion focuses on these three elements of the budget. Each element has several sub-elements that were quantified by teams of researchers. The budget was based on a combination of field work, monitoring and stream gaging, interpretation of aerial photographs, and extrapolation of results from other studies. The time period chosen (1954–1980) encompassed five large floods in the basin (in 1955, 1964, January and March 1972, and 1975), and was bracketed by the availability of air photos in 1954 and 1978. Field mapping in 1980 filled in many gaps in the air photo interpretation. Appendix E describes the methodology in more detail.

Sediment Input

Sediment enters rivers through a variety of processes. Many sediment sources (input) are active in the Redwood Creek basin and were inventoried for various time periods through a combination of field mapping and air photo analysis. Soil erosion in this watershed is driven mainly by the forces of gravity and water. Some processes are triggered mainly by gravity whereas others require intense rainfall and river flow to initiate erosion. Both gravity and water are involved in moving sediment downslope and downstream. The following describes studies of both hillslope and in-channel erosion processes.

Erosion of Hillslopes by Water

Surface Erosion on Logged Hillslopes

In undisturbed temperate rain forests, such as the redwood biome, most rainfall soaks into the spongy ground instead of flowing over the ground surface (that is, the infiltration capacity of the soil is higher than rainfall intensity). Conditions change, however, when the soil is compacted during road construction or timber harvest, especially in tractor-logged operations. Under these disturbed conditions, overland flow can transport sand, silt, and clay downslope and to channels. Surface erosion was measured with erosion-deposition pins on forested and logged hillslopes. Ground surface lowering was minor (0.01 in/yr) on forested sandstone slopes, forested schist slopes, and logged sandstone slopes, but was much higher (0.18 in/yr) on tractor-yarded schist slopes (Marron *et al.*, 1995). Overall, surface erosion on disturbed ground represented <1% of total sediment input.

Erosion from Road Prisms and Road Crossings

Unpaved logging roads (both haul roads and smaller skid trails) contribute sediment to stream channels through several processes: cutbank erosion and failures, surface erosion from unpaved roads, erosion of inboard ditches, and erosion of road fill at stream crossings (Figure 6) (road fill and

landing failures are included under "Mass Movement," discussed as a separate component below). The older the road and the more storms it has weathered, the higher the probability that a crossing will have failed. Various field inventories in portions of the Redwood Creek basin quantified the volume and timing of stream crossing failures (Weaver and Hagans, 1987; Klein *et al*., 2005*;* Spreiter, RNP files; Best *et al.,* 1995), and these measurements were then extrapolated to the entire watershed. The Redwood Creek Watershed Analysis (RNP, 1997) and U.S. EPA Total Maximum Daily Load analysis (1998) describe the measurements and estimates used to quantify sediment sources from road prisms. Erosion from road prisms, not including mass movement, represented 15% of sediment input.



Figure 6. Failure of a rusted culvert causing erosion of road fill (2006; NPS).

Gullies and Stream Diversions

Gullies are another type of hillslope erosion and were inventoried in detail at nine study sites in lower Redwood Creek. They are defined as newly formed, narrow channels that usually carry water only during and after storms. Most gullies were caused by diversion of streamflow from first- and second-order streams on unmaintained logging roads (Best *et al.,* 1995) (Figure 7). The highest amount of post-harvest gully erosion occurred in areas underlain by incoherent bedrock and soils low in clay or in rock fragments (Weaver *et al*., 1995). Many gullies were the result of stream diversions on logging roads. Gullies and stream diversions represented 21% of sediment input.



Figure 7. Culvert on ridgeline directed runoff onto unchanneled hillslope, causing a gully (Manez Prairie, Bald Hills, 1981; NPS).

Hillslope Processes (Mass Movement)

Mass movement is the process by which soil and rock move downslope and can be slow or fast moving. High seasonal rainfall, steep topography, and deep weathering on highly fractured bedrock make the hillslopes in the Redwood Creek basin very susceptible to several styles of mass movement (Nolan *et al.,*1976). Shallow landslides strip off the soil layer and frequently some of the weathered bedrock as well. Deep-seated failures such as earthflows may incorporate even more weathered bedrock. The Redwood Creek basin displays several types of mass movement and distinguishing the effects of timber harvest and road construction on landslide rates was a focus of many studies. Areas of active mass movement occupy about 16 percent of the total area of the Redwood Creek watershed, and sites of inactive mass-movement features occupy an additional 15 percent (Harden *et al*., 1995). The following describes the dominant types of mass movement in the Redwood Creek basin.

Soil Creep

Soil creep is the slow, downslope movement of soil and weathered bedrock under the influence of gravity. Frost-heaving, wet-dry cycles, tree-throw, and animal activity contribute to creep. It is most rapid on steeper slopes. Creep typically supplies sediment to streambanks, where it enters the river by bank erosion, or to colluvial hollows (these inputs are quantified below). Creep is particularly active

on slopes underlain by sheared and foliated schists on the west side of the Redwood Creek basin. Movement rates range from 0.03 to 0.1 inch/yr and responds primarily to rainfall (Swanston *et al.*, 1995).

Debris Torrents

Colluvium (soil and weathered bedrock) accumulate in swales called colluvial hollows (see Soil Creep). These colluvial hollows were mapped by examining places where roadcuts exposed the stratigraphy of the swale. The hollows slowly fill with soil and rock fragments through soil creep and episodically discharge the sediment by debris torrents at intervals of centuries or even millennia. Debris torrents (or debris flows) are rapid, channelized flows of saturated, poorly sorted soil and organic debris. The torrents scour streambanks and the channel bed of most organic and inorganic material (Figure 8). Old-growth trees provide some resistance to the flow, whereas the torrents tend to travel farther in cutover areas. Carbon dating was used to determine the age of debris torrent scars in RNP (Marron, 1982).

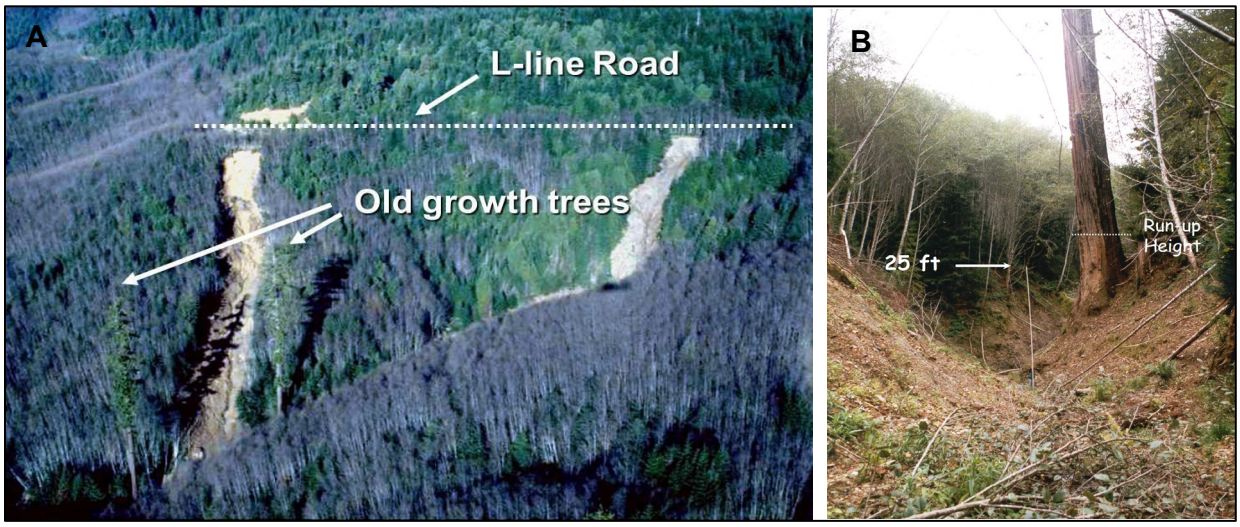


Figure 8. A) Debris torrent originating from an abandoned logging road (1997; NPS). B) View of same debris torrent track showing 25 ft. of channel bank and streambed scour (NPS/OZAKI).

Colluvial hollows and their associated debris torrent scars are more common on slopes underlain by the relatively coherent graywacke and shale found on the east side of Redwood Creek than on the schist slopes of the west side. Best *et al.*, (1995) mapped road-related debris torrents which occurred in the Garrett Creek subbasin from 1956 to 1980. Curry (2009) mapped torrents on schist terrain that were generated in the 1997 storm. Results from these studies were used to extrapolate rates of debris torrents throughout the basin. Debris torrents represented 3.5% of sediment input during the sediment budget period.

Earthflows

Earthflows in the Redwood Creek basin are deep-seated, slow-moving landslides, with hummocky surfaces vegetated with grasses and shrubs. They mostly occur on areas underlain by intensively sheared shale-rich units in the Franciscan Complex. Many earthflows feed into Redwood Creek and

its tributaries, especially in the middle basin area. From 1975 to 1980 earthflow movement was measured at several sites near Counts Hill Prairie on the east side of Redwood Creek. Here annual movement ranged from 0.12 in. to 5.2 in. (Swanston *et al.,* 1995). In addition, the Minor Creek earthflow, several miles upstream, was monitored intensely from 1973 to 2001 (Iverson, 1984; Iverson and Major, 1987; Nolan and Janda, 1995b; Mark *et al.*, 2002). Thickness of the Minor Creek earthflow varied from about 12 ft. along the margins of the earthflow to about 20 ft. in the center. The earthflow showed miniscule movement during the dry summer months (0.04 to 0.15 in/month) but accelerated 10 to 100 times faster in the wet winter months. In 1980 the toe of the slide moved almost 50 ft. as Minor Creek undercut its base, and 64% of total displacement occurred in only three winters. Interestingly, the timing, duration, and speed of movement had no consistent relationship to the timing and amount of rainfall. Instead, local groundwater circulation patterns seemed to govern patterns of overall earthflow movement. Gullies on the earthflow surfaces delivered less than 10% of the sediment contributed to streams from earthflow complexes. The effect of grazing, road construction, or other land management activities on earthflow movement is unknown. During the study period earthflows only represented 3.4% of sediment input.

Forested Block Slides

Earlier mapping by Nolan *et al*., (1976) and Harden *et al*., (1982) suggested there were few deep-seated landslides within areas underlain by schist; however, more recent mapping has identified numerous large landslides in schist units. These forested block slides are deep-seated, translational landslides ranging in size from 1 to 5 acres, and the depth to failure zone ranges from 10 to 20 ft. (Sonnevil *et al*., 1987; Swanston *et al.*, 1995; Falls *et al*., 2003). Annual surface displacement measured on three block slides between 1981 and 1987 was 0 to 22 ft. Unlike earthflows, movement of monitored block slides was episodic and storm related. Common to nearly all block slides is a preferential failure zone in a highly sheared, carbonaceous schist (Sonnevil *et al.,* 1987). During the study period, forested block slides represented <1% of sediment input.

Debris Slides

Debris slides are shallow, fast-moving landslides which contribute sediment directly to Redwood Creek and its tributaries (Figure 9). They mostly occur on steep slopes in the inner gorge and are triggered by large storms (Falls *et al*., 2003). Debris slides dating from the 1964 storm were concentrated in the upper basin, whereas the 1972 and 1975 storms caused more debris slides in the mid-to-lower basin. Almost half the material delivered to tributary channels during the period of 1954 to 1980 occurred in the 1964 flood (Pitlick, 1995). An assessment of 1,850 debris slides that were active in this study period showed that the largest 10 percent of landslides accounted for 60 percent of the total volume (Kelsey *et al*., 1995).

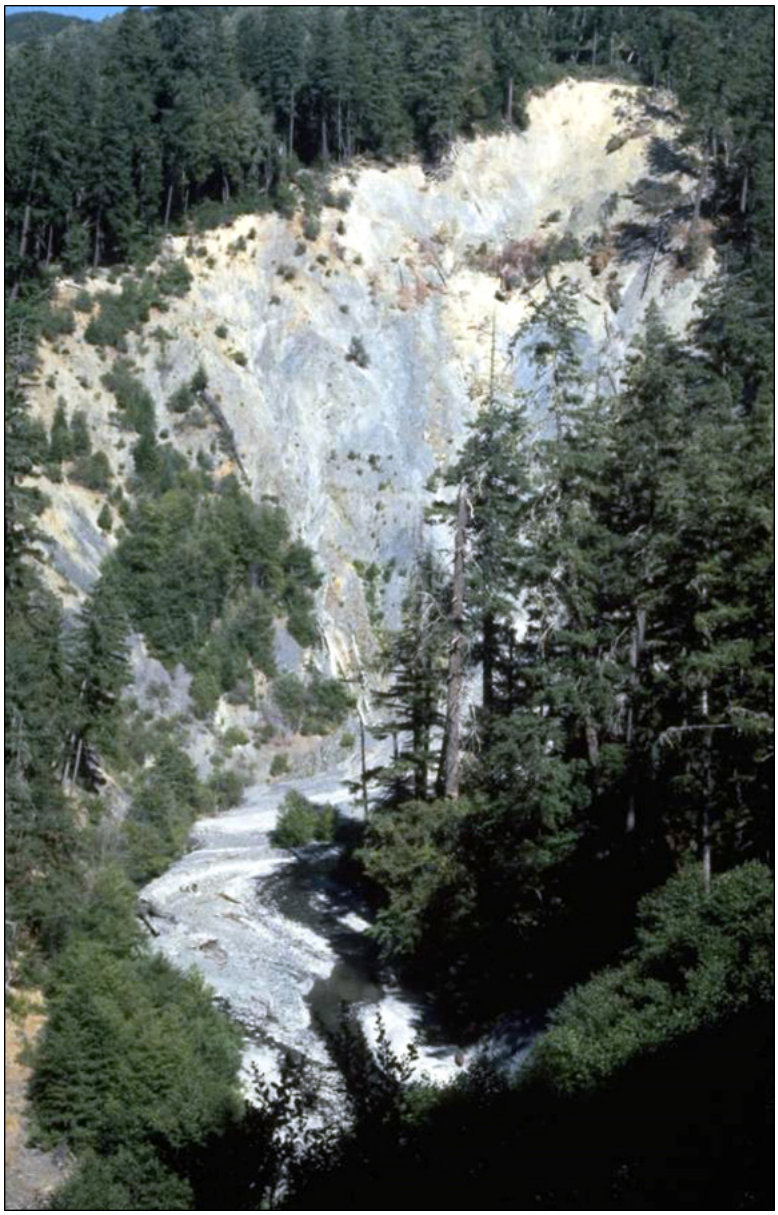


Figure 9. Debris slide along Redwood Creek (1980; NPS).

A large storm in 1997 initiated another 250 new debris slides. Landslide input from inner gorge areas containing harvest units was over three times greater on a per unit length basis than in inner gorge areas not containing harvest units. Eighteen miles of the inner gorge was harvested from 1977 to 1997. If the inner gorge had not been harvested, there could have been a reduction of 11% of the sediment that was delivered to the study area. A majority of the slides (63%) was associated with roads. Landslides associated with roads contributed 2.6 times more sediment to Redwood Creek and its tributaries on a per unit area basis than the basin average (Curry, 2007).

Debris slides are the largest source of sediment to Redwood Creek, and from 1954 to 1980 they contributed about 40% of the total sediment input to Redwood Creek and its tributaries. Landslides

associated with roads and those initiated on cutslopes accounted for 50 to 80% of total landslide-related erosion during that period (Pitlick, 1995; Kelsey *et al.,* 1995).

In-Channel Sediment Sources

Streambank Erosion

Streambanks line the base of hillslopes or terraces. A river erodes its streambanks, especially on the outer bends of meanders, while depositing sediment on point bars on the inside of the bends. When rivers fill with sediment, they tend to widen and increase the rate of bank erosion in places that are not buttressed by bedrock. Consequently, a positive feedback loop develops in which a streamside debris slide can aggrade the channel, which in turn causes more streamside debris slides and further aggradation (Colman, 1973). Streambank failures, in contrast to the larger debris slides described above, seldom extend more than 150 ft. upslope from the channel edge (Figure 10). They contribute sediment and large wood to both the tributaries and the mainstem of Redwood Creek, but are most common in the lower part of the basin. The sediment contribution from streambank erosion (15%) is significant, but much less than that of debris slides (Kelsey *et al*., 1995). Figure 11 summarizes sediment inputs to Redwood Creek.



Figure 10. Streambank erosion along Redwood Creek upstream of Tall Trees Grove (1980; NPS).

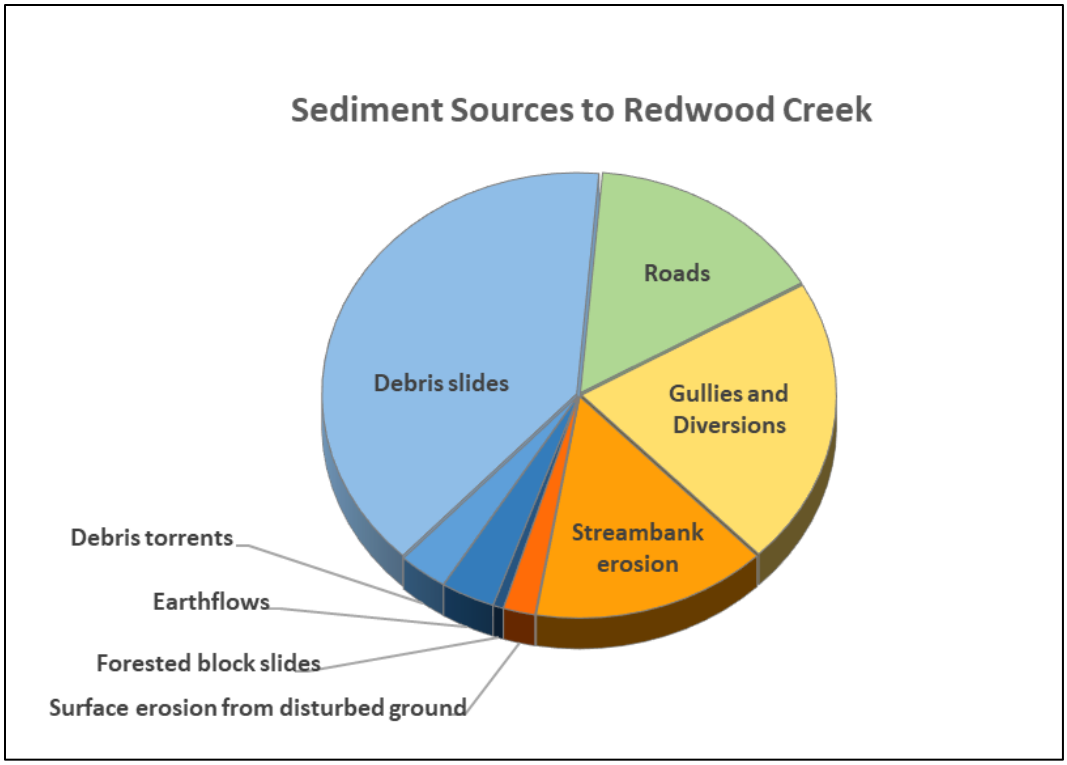


Figure 11. Sediment inputs to Redwood Creek, based on sediment source inventories.

Channel Bed Erosion

Rivers cutting through sediment deposits lower the river channel bed and transport the sand and gravel downstream. Consequently, historical sedimentation can be a source of sediment to downstream reaches as the river downcuts through older sediment deposits. This scenario has been repeated many times in Redwood Creek and its tributaries. For example, in the period 1980 to 1990, removal of previously deposited sediment in the channel accounted for about 25 percent of the total sediment load measured at the Redwood Creek at Orick gaging station (Madej and Ozaki, 1996). Because this sediment has already been accounted for in the above categories, it is not considered an additional sediment input in the sediment source inventory.

Sediment source inventories showed that landslides, stream diversions, and gullies were the largest contributors of sediment to Redwood Creek, and many of these features were associated with roads. Consequently, the focus of RNP's watershed restoration program became the removal of abandoned forest roads and upgrading drivable roads.

Sediment Storage

Once sediment reaches a stream channel, it can be stored in the channel bed for short or long periods of time, or transported downstream, eventually to the ocean. Because of the severe impact of excess sedimentation on redwood trees and fish habitat in Redwood Creek, a major focus of RNP studies was the fate of sediment deposited in the channel bed.

In 1973, the USGS established a network of 50 permanent cross-sectional survey transects along the length of Redwood Creek to assess channel changes, described later in more detail in the "Channel Response to Sediment Pulses" section. In addition, detailed field mapping of stored sediment in the mainstem of Redwood Creek and major tributaries quantified the volume and relative mobility of various modes of sediment storage (such as gravel bars, log jams, floodplains, and terraces) (Madej, 1995; Pitlick, 1995). The depth of channel-bed scour during high streamflows, the age of vegetation growing on the sediment deposit, historical information on sediment mobility from aerial photographs, and even partly buried car bodies were all used to categorize channel-stored sediment by its level of mobility.

Four levels of mobility were identified (Figure 12). Active sediment is frequently mobilized during moderate flows (those with a 20 to 50% chance of occurring each year). Vegetation on active sediment is absent or sparse. Data from scour chain installations and channel bed measurements during winter flows define the depth of the active layer. Active sediment is also found in bars less than 3 ft. high that are composed of pebbles, sand, and some cobbles. Semi-active sediment is mobilized during higher flows, such as a 5 to 20% chance flood. At such flows, sediment covered with shrubs and young trees is mobilized, as well as some cobble and boulder deposits. Inactive sediment is stationary until 1 to 5% chance floods occur, unless the river channel shifts and laterally erodes these deposits. Stable sediment has not been mobilized historically and constitute most floodplain and terrace deposits. Fine-grained deposition occurs on theses surfaces during high flow, but the bulk of the sediment persists for centuries, unless streambanks are eroded.

Baseline channel conditions were assessed using air photos dating from 1947. Excess sediment in Redwood Creek is defined as the increase of sediment over 1947 levels. As of 1964, about 10 million tons of excess sediment had been deposited in Redwood Creek (equivalent to burying a football field a half-mile deep.) Even though sediment in the active channel in upper Redwood Creek was largely flushed out in the 10 to 15 years following the 1964 flood, much of the remaining excess sediment is stored in inactive gravel berms and will probably persist for decades (Madej, 1995) (Figure 13). In 2002, crews remapped sediment storage in upper Redwood Creek and found many of the remaining sediment deposits were then well vegetated.

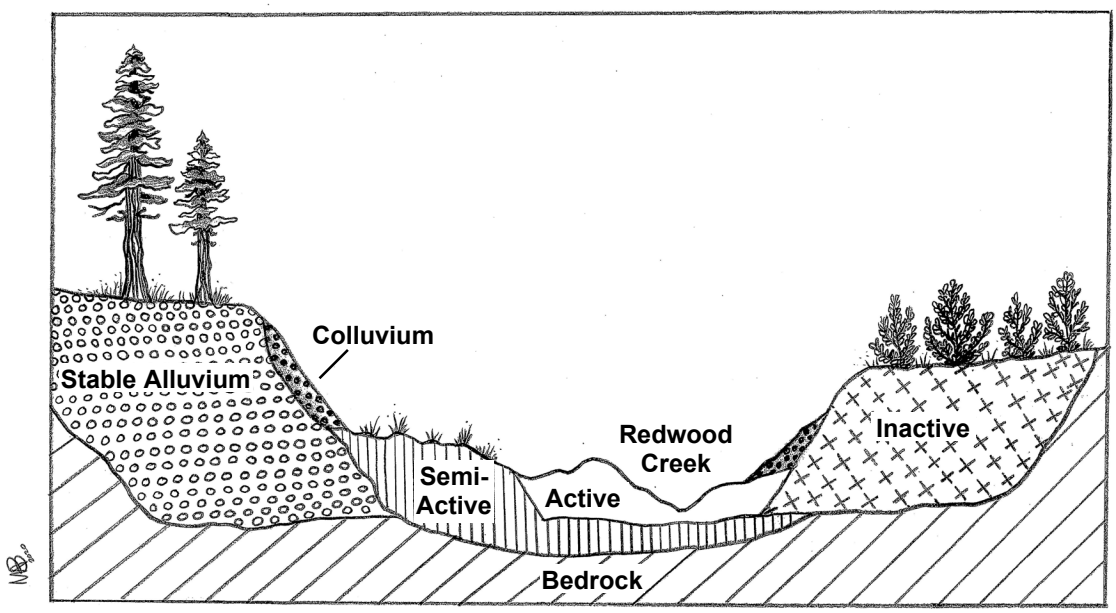


Figure 12. Schematic cross section of four sediment categories in Redwood Creek: active, semi-active, inactive, and stable.



Figure 13. 1964 flood deposits in the headwaters of Redwood Creek. Since 1964 the river has flushed most of the sediment in the active channel to sites downstream, whereas deposits plastered against the valley wall will likely remain for decades (1980 /NPS).

In contrast to the upper reach, where the active channel cut through 1964 flood deposits within a decade, the lower reach of Redwood Creek still stored 6.5 million tons of excess sediment in 1980. The residence time of this sediment is predicted to be decades for active sediment, to centuries or more for sediment in stable units (Kelsey *et al.,* 1987; Madej, 1987).

Tributary streams also received large sediment inputs during floods. Steep tributaries are efficient sediment transporters, and they rapidly flushed out excess sediment. By 1980, only 22% of landslide-derived sediment remained in Douglas-fir-dominated basins, while 49% of excess sediment remained in redwood-dominated high-relief basins (Pitlick, 1995). The 1980 tributary channel mapping has not been updated, but limited data from cross-sectional surveys in tributaries indicate that many channels continued to downcut post-1980, and had mostly stabilized by 2004 (Madej *et al.*, 2006). Lower Bridge Creek showed the most dramatic channel bed degradation, with about 10 ft. of channel lowering since 1975.

Large floods in 1964, 1972, and 1975 filled the channel beds of Redwood Creek and its tributaries with tremendous amounts of sediment. Steep reaches flushed out most sediment within 10 years of the floods, but sediment stored in gentle gradient reaches or deposited on floodplains will persist for much longer.

Sediment Transport and Output

The third element of the sediment budget, after input and storage, is sediment output (sediment yield). During high winter flows, Redwood Creek exports large amounts of sediment to the ocean (Figure 14). Sediment output assessed in RNP studies focused on two types of loads: suspended sediment and bedload. Suspended sediment consists of sand, silt, and clay particles distributed throughout the water column. Fine sediment carried in suspension is of concern primarily because of its effects on aquatic biota and habitat. Fish-feeding efficiency decreases as water becomes more turbid. As flows decrease, fine sediment can settle out and infiltrate streambed gravels, leading to less oxygen reaching salmon redds. Bedload is the coarser fraction of the sediment load, and consists of sand, gravel, and boulders. Bedload moves by bouncing and rolling along the channel bed. Bedload transport is responsible for changes in the channel bed, for example, by filling or scouring out pools.

A third way that material is transported to the ocean is by dissolution of soluble minerals by water via groundwater and rivers. In fresh water, the major dissolved solids consist of the cations calcium, magnesium, sodium, and potassium, and the anions bicarbonate, carbonate, sulfate, chloride, and fluoride. A two-year study (September 1973-September 1975) found total dissolved-solids concentrations ranging from 25 to 139 milligrams per liter in Redwood Creek and several tributaries.

Exposure of soils to the elements in areas logged or having naturally sparse vegetation accelerated chemical weathering and increased dissolved-solids concentrations (Bradford and Iwatsubo, 1978). Based on the values of average runoff from 1954 to 1980 and this range of solute concentration, dissolved load in Redwood Creek at Orick was 26,000 to 145,000 tons/year (92 to 517 tons/mi^2/yr), a small fraction of the material exported as suspended load or bedload (discussed below). Little work on solute transport has been conducted in RNP since.



Figure 14. Sediment plume entering Pacific Ocean at mouth of Redwood Creek (circa 1982; NPS).

The amount of sediment removed each year from a watershed by flowing water is commonly reported as an annual sediment yield, in units of sediment per unit area per year (e.g., tons/mi^2/yr). Annual suspended sediment yields from rivers in northwestern California are among the highest recorded in the United States outside of areas draining active volcanoes or glaciers (Milliman and Syvitski, 1992). In the 1970s annual sediment yields in Redwood Creek reached 10,300 tons/mi^2, compared to an average of 185 tons/mi^2 for rivers in the conterminous United States (Nolan *et al.*, 1987).

Sediment yield from Redwood Creek is measured at two gaging stations. Redwood Creek at O'Kane (also called Redwood Creek near Blue Lake) is located in the upper basin and measures flow and sediment output from a 67.7 mi^2 drainage area (which represents 24% of the entire Redwood Creek watershed). Suspended sediment, streamflow, and some bedload at this station have been measured

since 1973 (Figure 15), but monitoring will be discontinued in 2020. The gaging station called Redwood Creek at Orick is near the mouth of Redwood Creek, and measures output from a drainage area of 277 mi^2. Suspended sediment has been measured here from 1973 to the present, and bedload was measured from 1973 to 1992. Total suspended sediment output from Redwood Creek from 1954 to 2016 was calculated to be 54.5 million tons of sediment. Sediment output is highly episodic. Large infrequent flows transport a relatively large proportion of the sediment in these rivers, including



Figure 15. Measuring streamflow and sediment transport at the O'Kane Redwood Creek gaging station (circa 1982; NPS).

Redwood Creek. For example, in WY 1965 (which includes the December 1964 flood), suspended sediment output from Redwood Creek at Orick was 4.3 million tons, which was more than the sediment load of the lowest 26 flow years in the monitoring record combined. To compare relative

amounts of sediment load from watersheds of different sizes, sediment yield, expressed as tons/mi^2/yr, reflects how much sediment is being exported for every square mile of drainage area (Figure 16). Not surprisingly, sediment yields are highest during years with higher than average flows (mid-1970s, 1982–1983, and 1995–1997). Of note, however, is that during the high runoff years of 1974–1975, the upper basin accounted for 25 to 30% of the total suspended sediment output from Redwood Creek. In contrast, in the high runoff years of 1995–1997, the upper basin accounted for a much higher fraction of the total load (31 to 42% of the total suspended sediment output). This could reflect improving hillslope conditions in lower Redwood Creek.

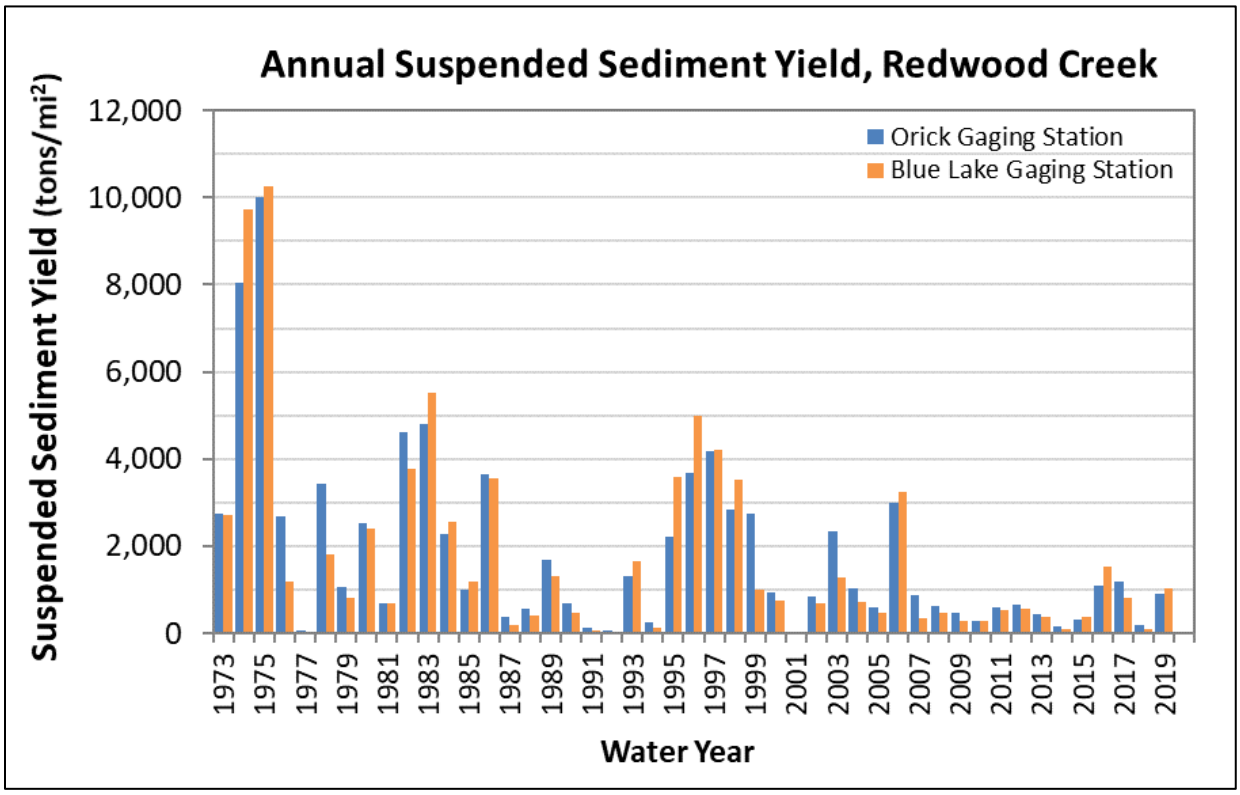


Figure 16. Annual suspended sediment yield, Redwood Creek.

Another way to assess sediment trends is to see if a given level of streamflow (say 5,000 cfs, a moderate winter flow) carries more or less sediment over time. Such sediment trends are evaluated by the use of sediment rating curves, which plot suspended sediment concentration (measured in mg/l) in a river against water discharge (Figure 17). Shifts in the curves over time can be an indication of the impact of land use changes and watershed management on sediment yield. In the case of Redwood Creek, there has been a significant downward shift in these curves through time. Suspended sediment concentrations were much higher in the 1970s and this relationship has been in decline ever since (Madej *et al.*, 2006; Warrick *et al.*, 2013). This may be attributed to reforestation of clearcuts, road removal projects, and improved land use practices, but it may also be influenced by the lack of a large (greater than 25-year) flood since 1975.

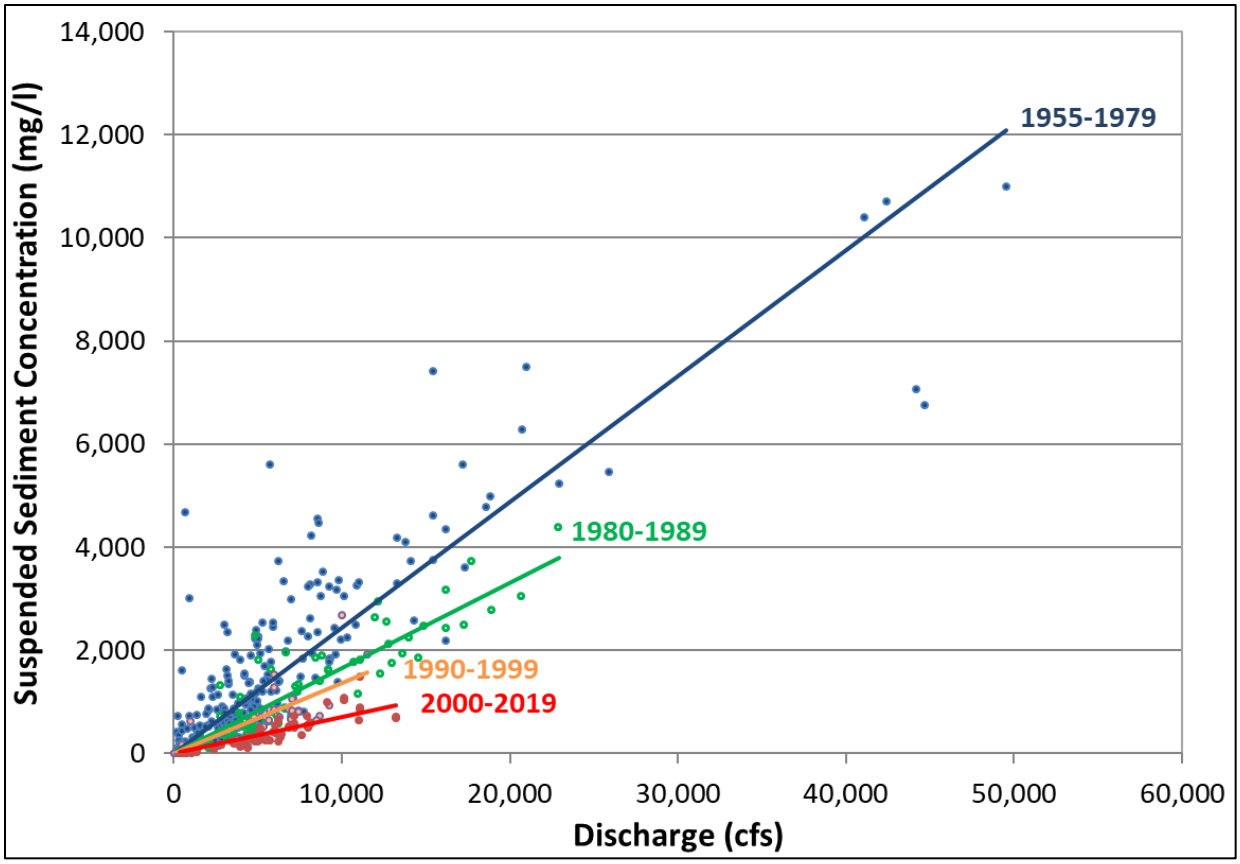


Figure 17. Suspended sediment rating curves from the Orick gaging station on Redwood Creek.

Streamflow and suspended sediment have also been measured at several tributary streams during various time periods (Figure 18, Appendix C). Three stations in the PPZ (Lacks, Coyote, and Panther creeks) were established by the USGS about 1980, and RNP continued monitoring them in the 1990s (Figure 4). In general, the east side of the Redwood Creek basin (underlain by sandstones and mudstones), represented by Lacks Creek and Coyote Creek, had higher average annual sediment loads (700 to 1000 tons/ mi^2) than the west side (underlain by schist), represented by Panther Creek (500 tons/mi^2) (Klein and Marquette, 2010). All three of these basins have been heavily logged in the past. In addition, RNSP began operating another network of gaging stations in Prairie Creek in 1990 to assess the impacts and persistence of fine sediment transported into Prairie Creek from the Highway 101 Prairie Creek Bypass construction project (discussed below), and later to assess impacts from road removal projects, especially in Lost Man Creek. At present, RNP operates three long-term gaging stations: at Little Lost Man Creek (pristine), Lost Man Creek at the Hatchery (logged and most roads recently removed), and Prairie above Boyes Creek (pristine). Little Lost Man Creek, a Research Natural Area, is useful as a control in sediment studies. This small tributary (3.5 mi^2) has a long record of flow and sediment records (1975 to 2019), and average annual suspended sediment load is ~100 tons/mi^2. No shifts in sediment rating curves through time are evident in this stream (Warrick *et al*., 2013), which supports the view that landscape recovery in the broader Redwood Creek basin is responsible for the decline in sediment loads displayed in Figure 19.



Figure 18. Measuring streamflow on Little Lost Man Creek (2017/NPS).

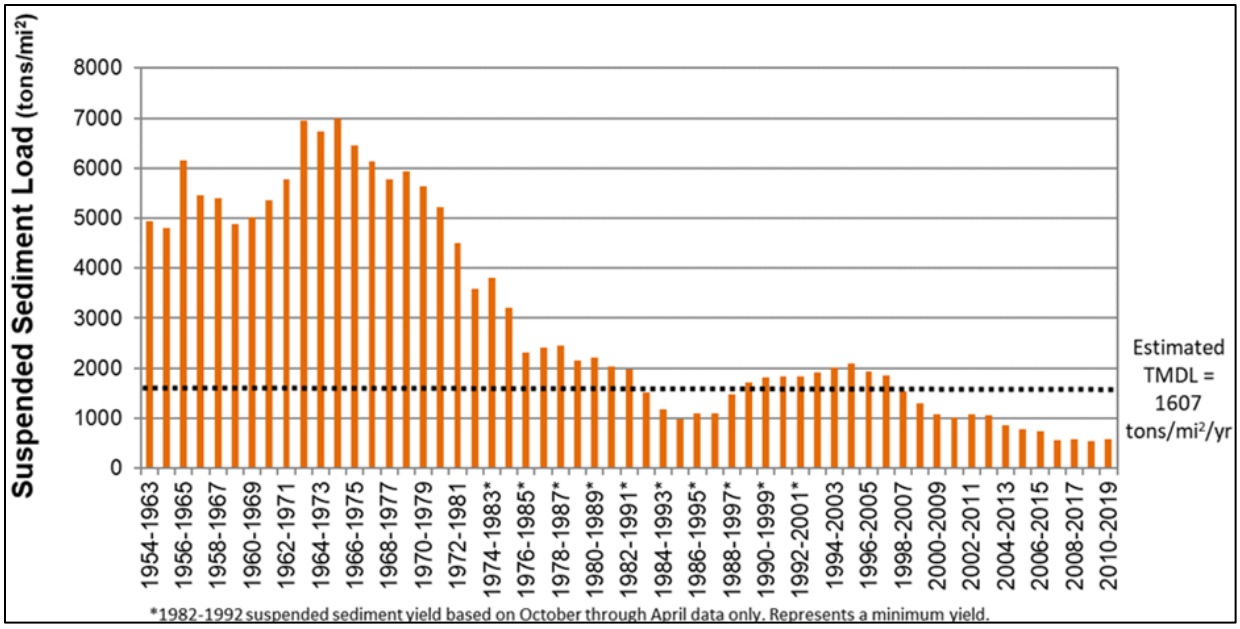


Figure 19. Ten-year rolling average of the suspended sediment yield for Redwood Creek at Orick and the TMDL target.

The U.S. Environmental Protection Agency (EPA) established a Total Maximum Daily Load (TMDL) standard for Redwood Creek in 1998. This sediment TMDL for the Redwood Creek watershed was developed primarily to promote activities that protect aquatic and riparian habitats and water quality from sedimentation associated with land use. The TMDL, with considerable Park input, identified logging roads as the major source of controllable sediment. The TMDL estimated the total annual sediment loading in Redwood Creek to be about 4,750 tons per square mile per year, and that the total allowable suspended sediment load to be 1,607 tons per square mile per year (an allowable load is the maximum amount of a pollutant, in this case sediment, that a stream can receive while still meeting water quality standards.) To allow for temporal variation, the allowable load was expressed as a 10-year rolling annual average. Redwood Creek greatly exceeded the TMDL target in the 1960s and 1970s, but the annual sediment load has decreased since then (Figure 19). Controllable sources of sediment have been reduced by road decommissioning and upgrading projects both within the Park and on private lands. The last decade has been a time of lower-than-average peak flows, which also contributes to lower sediment yields in recent years.

Sediment yield from Redwood Creek has decreased since the 1970s, but is still elevated over background (natural) rates.

Channel Response to Sediment Pulses

Several large floods in the 1950s, 1960s, and 1970s changed many characteristics of the Redwood Creek channel. Aerial photographs, field observations, and accounts by local residents documented that the river channel widened, pools filled in, channel bed material became finer, and the channel bed aggraded up to 25 ft. at some sites (Nolan and Marron, 1995; Madej, 1995). Then, the 12-year flood in 1997 initiated 250 new landslides in the Redwood Creek basin, which caused additional localized channel aggradation in parts of Redwood Creek. Understanding how abrupt increased sediment inputs (sediment pulses) in a river network are flushed out through time is key to predicting the persistence of sediment effects on a river system. Monitoring channel response to high sediment loads in Redwood Creek used three primary methodologies: cross-sectional surveys, thalweg profile surveys, and channel bed particle size analysis (pebble counts).

Cross-Sectional Surveys

In 1973, the USGS established about 50 cross-sectional transects along the length of Redwood Creek (labeled 'XS' on Figure 20). Cross sections are set perpendicular to streamflow direction. Cross sections were resurveyed by the USGS and RNP annually from 1973 to 1987, and periodically since then. Cross sections were monumented with steel rebar reinforced by concrete and referenced to at least two other triangulation points. Changes in cross-sectional area due to channel scour, fill, and streambank erosion were calculated by comparing plots of successive cross-sectional surveys. The change in mean streambed elevation was calculated as the change in cross-sectional area, referenced to permanent endpoints, divided by bankfull width, which results in a streamflow-independent value. For each survey year, the cumulative change in mean streambed elevation was calculated to show trends at individual cross sections over time.

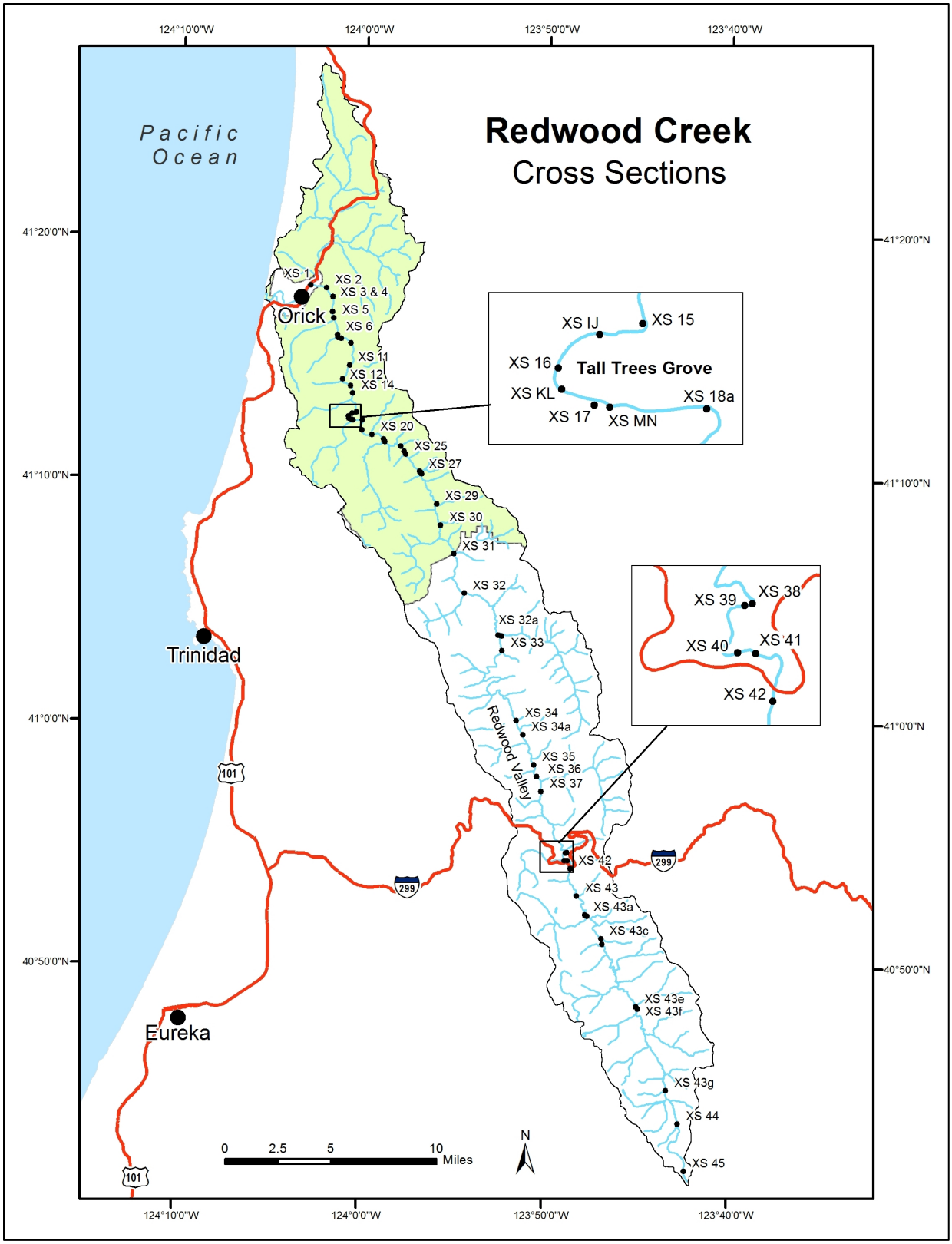


Figure 20. Location map of channel cross sections in the Redwood Creek basin.

In general, cross-section surveys document downcutting in the Redwood Creek channel since the start of data collection (1973–1975). Figure 21 is an example of a cross section (XS 25) located several miles upstream of the Tall Trees Grove, where the elevation of the deepest part of the channel bed has downcut over 13 feet since 1973, and was still actively cutting through sediments as of 2017. Some reaches of Redwood Creek have downcut even more (20 ft. or greater) (Figures 22 and 23). A compilation of cross-sectional survey data is available online at Sciencebase.gov (https://doi.org/10.5066/P9G0N0TN).

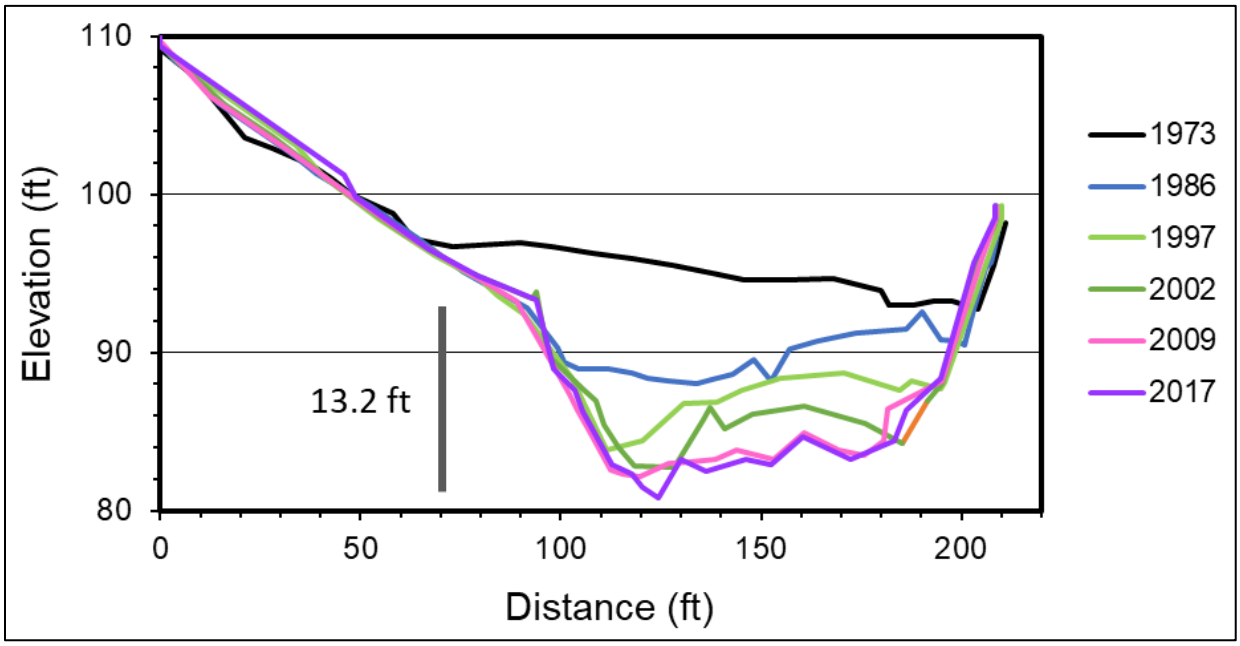


Figure 21. Example of cross-sectional transect on Redwood Creek showing ~13 ft. of downcutting in the channel bed from 1973 to 2017.

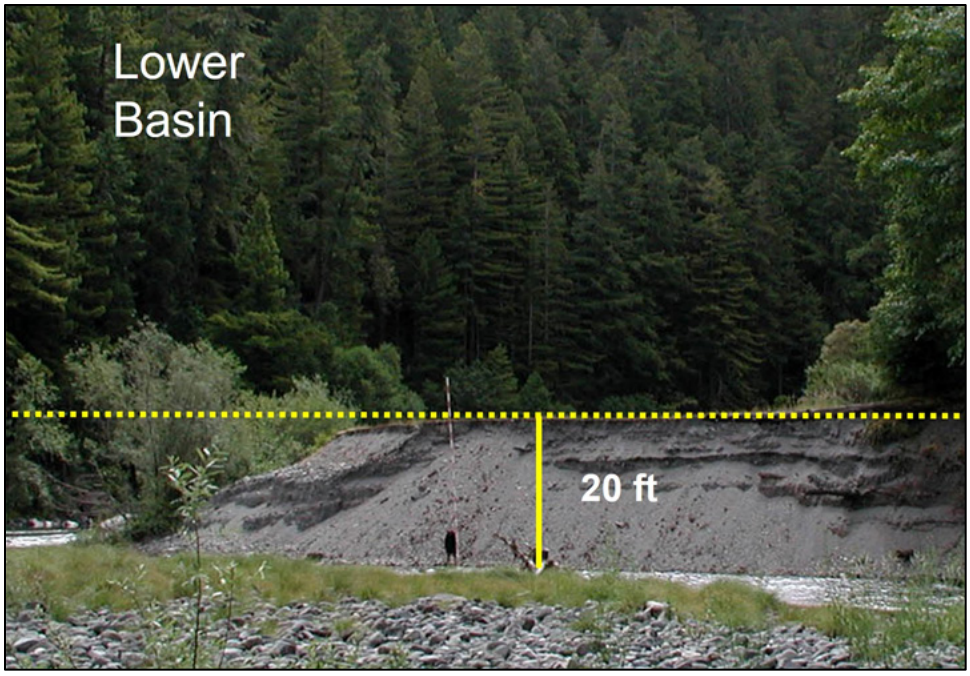


Figure 22. Remnants of 1964 flood deposits that buried the headwater channels of Redwood Creek with 22 to 25 ft. of sand and gravel, killing riparian forests. Since then the river has flushed most of that sediment downstream (1980; NPS).

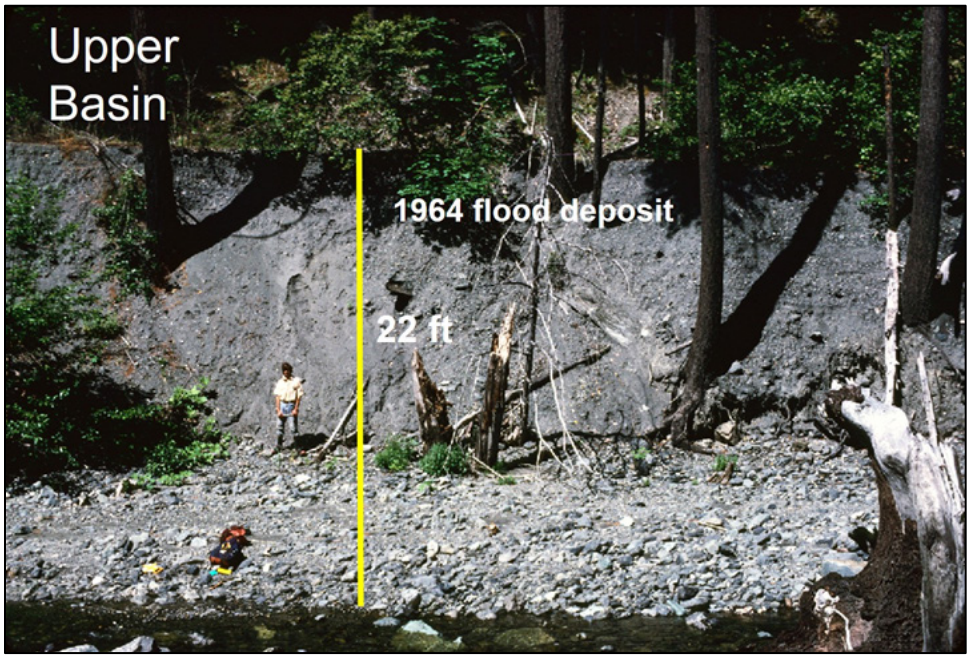


Figure 23. Cross Section 23 in lower Redwood Creek showing 20 ft. of downcutting through flood deposits (circa 2010). Sand and gravel were deposited during floods in 1964, 1972, and 1975. The top of the flood deposits was the active channel in the 1970s. (NPS/OZAKI).

Channel response varied based on timing of peak aggradation. Channel-stored sediment was evacuated rapidly from the upstream third of the Redwood Creek channel and the channel bed reached a stable bed elevation by 1985 as the bed coarsened (Figure 24, XS 40**)**. Currently only narrow remnants of flood deposits remain, which are now mostly well vegetated. In the middle basin (e.g., XS 35), Redwood Creek continued to downcut until about 2006, when the channel bed elevation started to show signs of stabilizing. At XS 25 (upstream of Dolason Creek) aggradation peaked in 1975 and the channel has been downcutting since then. In the downstream reach (e.g., XS 6), channel aggradation peaked in the 1990s, and the channel is still incising. Channel bed elevations throughout the watershed showed an approximate exponential decrease with time, but decay rates were highest in areas with the thickest flood deposits (Madej and Ozaki, 2009).

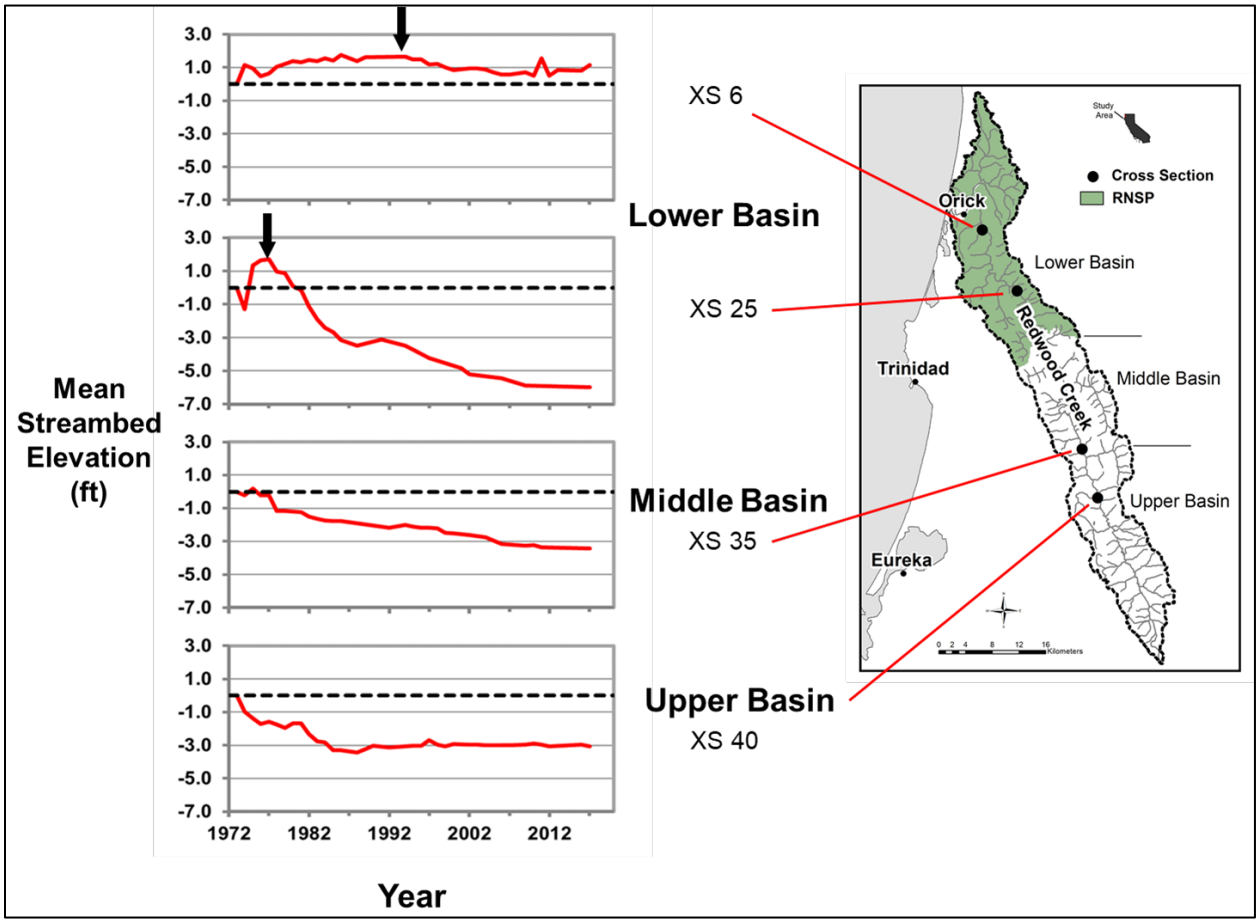


Figure 24. Change in mean streambed elevation at four representative cross sections (XS) along Redwood Creek. Dashed line is zero, i.e., the bed elevation at the beginning of the surveys in 1973. Arrows denote peak of aggradation.

Remnants of sediment deposited in Redwood Creek during floods in the 1960s and 1970s still persist in the river channel 50 years later. This channel aggradation has impacted many life cycles of salmon.

Thalweg Profiles

Important aquatic habitat features, such as pools, riffles, and runs, are monitored using thalweg profiles. Thalweg profiles are longitudinal surveys of the deepest part of the river channel, which follow the direction of streamflow (Figure 25). Several profiles in lower Redwood Creek have been surveyed by the USGS and RNP from 1977 to the present. All major morphologic features (i.e., top, middle, and base of pools, runs, and riffles) and breaks-in-slope were surveyed. The length of each surveyed profile was 20 to >30 channel widths.

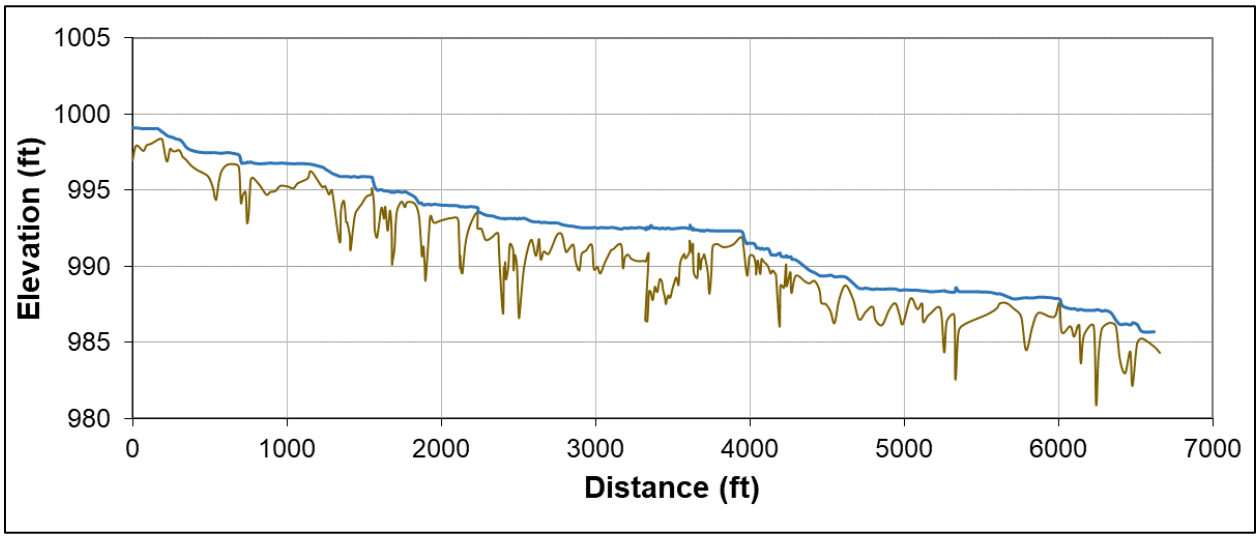


Figure 25. Example of Redwood Creek thalweg profile, surveyed in 1997 downstream of Cross Section 14 showing the water surface (blue line) and channel bed (brown line).

In the earliest survey, in 1977, Redwood Creek was severely impacted by channel aggradation, and the channel bed was flat and featureless. No pools deeper than 3 ft. were observed (Figure 26). As Redwood Creek began to flush excess sediment out of the system, pools began to develop, and by 1995 surveys detected 31 pools deeper than 3 ft. in the monitored reach. The flood of 1997 filled in some pools, but as of 2006 they mostly have recovered. Upstream of the Tall Trees Grove, where aggradation peaked in 1975, pools were deeper and more frequent than in a downstream reach, where channel in-filling peaked in the mid-1990s and where the channel has had less time to recover. The dominant pool-forming mechanism in lower Redwood Creek was scour around bedrock outcrops or large boulders, but about one-quarter of the pools were formed by scour around large wood (Madej and Ozaki, 2009). As Redwood Creek recovers from extensive sedimentation, in addition to deeper

pools, average water depth also has increased, and bed topography has become more variable and complex (Madej, 2001b).

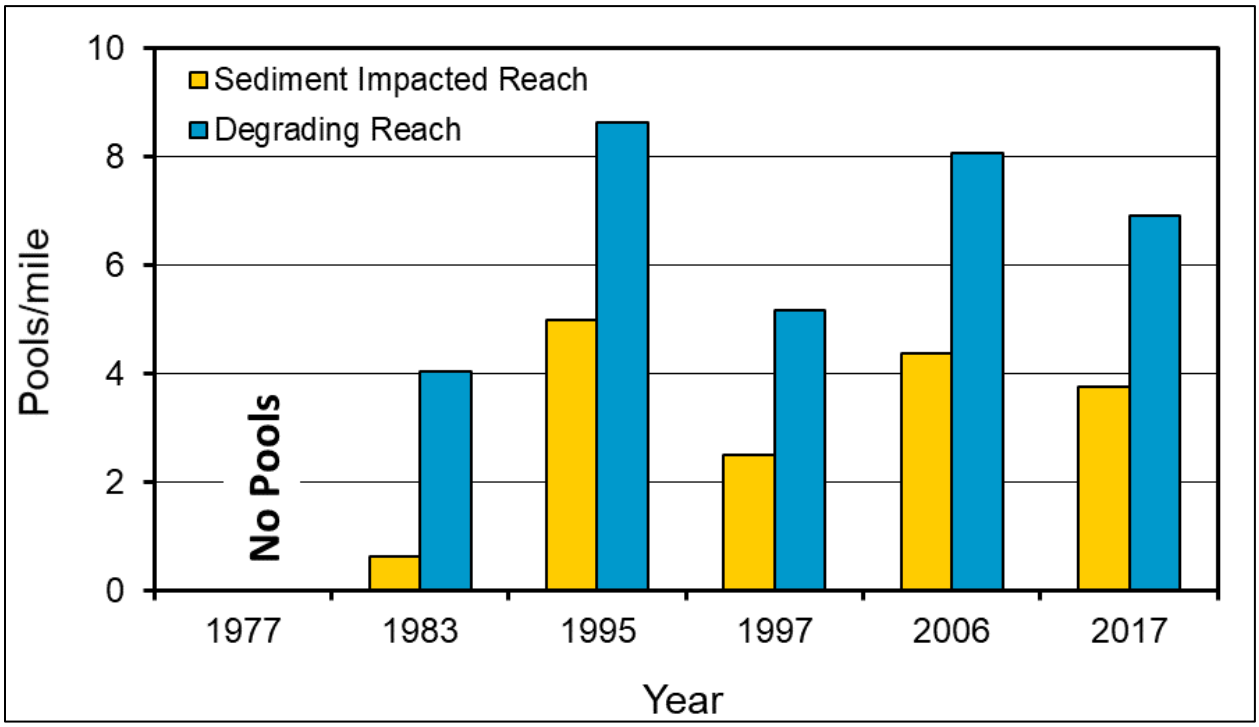


Figure 26. Frequency of pools > 3 ft. deep in two reaches of Redwood Creek, RNP, 1977–2017. The degrading (scouring) reach is downstream of Dolason Creek (near XS 23), and the sediment-impacted reach is downstream of Elam Creek (XS 6).

Pools, an important habitat feature in salmon-bearing rivers, were largely absent in lower Redwood Creek when the channel was severely aggraded. Pools are becoming deeper and more frequent as Redwood Creek recovers from past sedimentation.

Particle Size of Redwood Creek Channel Bed

Salmon and other aquatic life are sensitive to the size of gravels and sand in a river channel, in which they spawn and rear. How much of a channel bed is mobilized during a flood is related to the size of the bed particles. As particle size decreases, bed mobility increases for a given flow. If a bed is too mobile, salmon redds may be scoured out during high flows. A common response to increased sediment loads in gravel-bed rivers is the fining of the channel bed, with smaller gravel and sand becoming more prevalent and the bed becoming more mobile (Lisle *et al.,* 2000).

The particle sizes at cross sections in Redwood Creek were determined using the Wolman pebble count methodology (Wolman, 1954). Five transects perpendicular to the stream channel were measured, with the center transect located on the cross section. The length of streambed sampled equaled the active channel width and transects were spaced a quarter-channel width apart. The 'B' or intermediate axis was measured for 20 particles selected at regular intervals along each transect for a total of 100 particles. This standard grid spacing assured that the same area of channel bed was sampled in each survey. Class sizes ranged from < 2 mm (<0.1 in.) (sand) to > 256 mm (> 10 in.) (boulders).

Pebble counts have been conducted since 1979. The dominant particle size on the channel bed, D_{84}, decreases in a downstream direction, from 165 mm (6 in.) in the headwaters to about 40 mm (<2 in.) in the lower river ($D_{84\ is}$ the 84th percentile of the surface bed particle sizes) (Figure 27). Notably, D_{84} increased at most cross sections from 1979 to 2006. At many cross sections, the D_{84} doubled during this period. In general, the channel bed has coarsened as the channel has downcut (Madej and Ozaki, 2009).

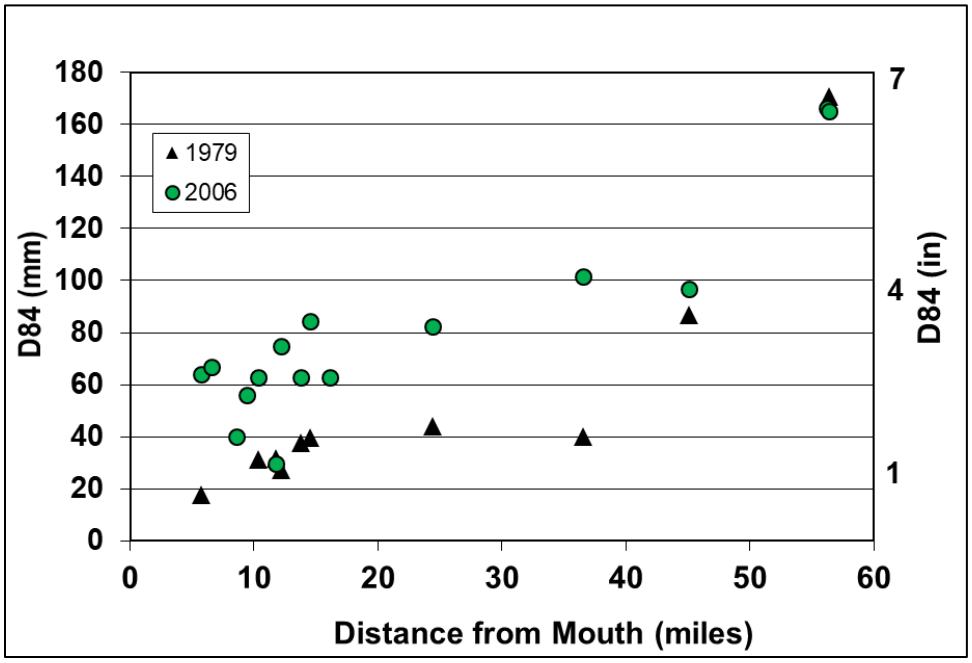


Figure 27. Dominant particle size (D84) calculated from pebble counts conducted at cross sections in 1979 and 2006.

As Redwood Creek flushes excess sand and fine gravel out of its channel, the channel bed has coarsened, improving salmon spawning habitat.

Flume Experiments

Because river channel adjustment processes may persist for decades, flume experiments, lasting just a few weeks, were used to model years of changes in Redwood Creek (Figure 28). Responses to various sediment loads were assessed. Changes in channel bed texture, morphology, water surface slope, sediment transport rates, and particle sizes were measured, which can help to predict channel dynamics in sensitive settings (Madej *et al*., 2009).

The results showed that full channel recovery after severe aggradation, in terms of channel width, bed elevation, and median particle size, did not occur. Consequently, some channel condition targets proposed by regulatory agencies may not be realistic. Nevertheless, if recovery is defined as a return to an armored, single-thread channel with low sediment transport rates, a stable channel did eventually develop.



Figure 28. Flume experiment modeling sediment transport and channel change in Redwood Creek (2007; USGS).

Tall Trees Grove

The Tall Trees Grove is a stand of uncut redwoods growing on a streamside terrace, or alluvial flat. It is located on a meander bend on the east side of Redwood Creek about eight miles upstream of Orick, California. In 1964, the National Geographic Society published results of surveys of tree heights in California redwood groves, including the tallest redwood measured up to that date (367.8 ft.) located in the Tall Trees Grove along Redwood Creek (Grosvenor, 1964; Zahl, 1964) (A more recent measurement of another redwood tree in RNSP exceeded 379 ft.). The discovery of the tallest

known redwood brought national attention to the Grove, inspiring efforts to establish a national park (see “History of Scientific Studies” in previous section). In 1963, the hillslopes to the west of the Tall Trees Grove were being logged, and the Georgia-Pacific Corporation was dredging gravel from Redwood Creek to use for surfacing of logging roads. An estimated 80,000 to 100,000 yd^3 was excavated each year from the bed of Redwood Creek from about 1951 to 1968 (Milestone, 1978).

Stream processes can affect the health of redwoods on alluvial flats in several ways. Slow-moving overbank flood waters can deposit beneficial fresh silt deposits, into which a redwood develops a new root system (adventitious roots) that sustains the redwood as flood-deposited silt builds up around its base (Stone and Vasey, 1968). In contrast, streambank erosion can expose roots, eventually undermining a tree and causing it to topple. The creation of a flood channel across the alluvial flat (avulsion) can also undermine and weaken root structures of trees growing on the flat, causing them to fall. Rapid channel aggradation can lead to deposition of coarse gravel at the base of trees, which can physically abrade tree trunks or inhibit the formation of adventitious roots, which eventually kills the tree. Channel aggradation also raises the water table level, and, if rapid and high enough, can drown the root zone of trees.

The attention directed towards this special stand of trees led to several detailed studies of the Grove. According to local accounts, the Tall Trees Grove was inundated in the floods of 1953, 1955, 1964, 1972, and 1975. Silty floodwaters impregnated rough-textured redwood bark with mudlines, providing evidence of these recent flood heights in the Grove (Figure 29). Flood waters deposited overbank sediment, mostly silt and fine sand, throughout the grove, and in 1978 Milestone mapped several fresh flood berms deposited on the terrace surface. A detailed plane-table map of surface topography was completed in 1982 (Varnum, RNP files). The Tall Trees Grove abuts a terrace riser, and at least four older terraces form subtle stair-stepped topography above the present floodplain. In 1986, floodplain sediments up to 25 ft. deep were sampled in 13 soil cores, streambank exposures, and five backhoe pits, and charcoal remnants found in the sediment were dated by carbon-14 analysis. Soil horizons were characterized by color, texture, thickness, the presence or absence of sedimentary structures, particle size and gravel content, organic content, and the geometry and orientation of the depositional unit. About 5 ft. of sediment was deposited over a period of 810 years ($\pm$ 50 years) through a minimum of five major episodes of flood deposition. Seventeen overbank flood packets were identified, and charcoal found at a depth of 10 ft. was dated at 3,520 years before present (Hagans, RNP files). No dates are available for sediment below 10 ft. At 22 ft., the soil corer encountered coarse channel sediment (likely a point-bar deposit).



Figure 29. Six-foot high flood marks on redwood tree, Tall Trees Grove, RNP (circa 2008; NPS).

Six permanent channel cross-sectional transects were established along the Tall Trees Grove reach, from upstream of the mouth of Tom McDonald Creek to the downstream end of the meander bend (Figure 20). The transects have been surveyed since 1973, but reports by local foresters and road construction crews provide evidence of up to 10 ft. of channel aggradation in this reach occurring before 1973 (Nolan and Marron, 1995). The highest channel bed elevation was measured in 1975. By 2017 average bed elevation near Tom McDonald Creek had decreased by about 4 ½ ft (Figure 30). The thalweg (the deepest part of the channel bed) downcut even more and was 6 ft. lower in 2017 than in 1975.

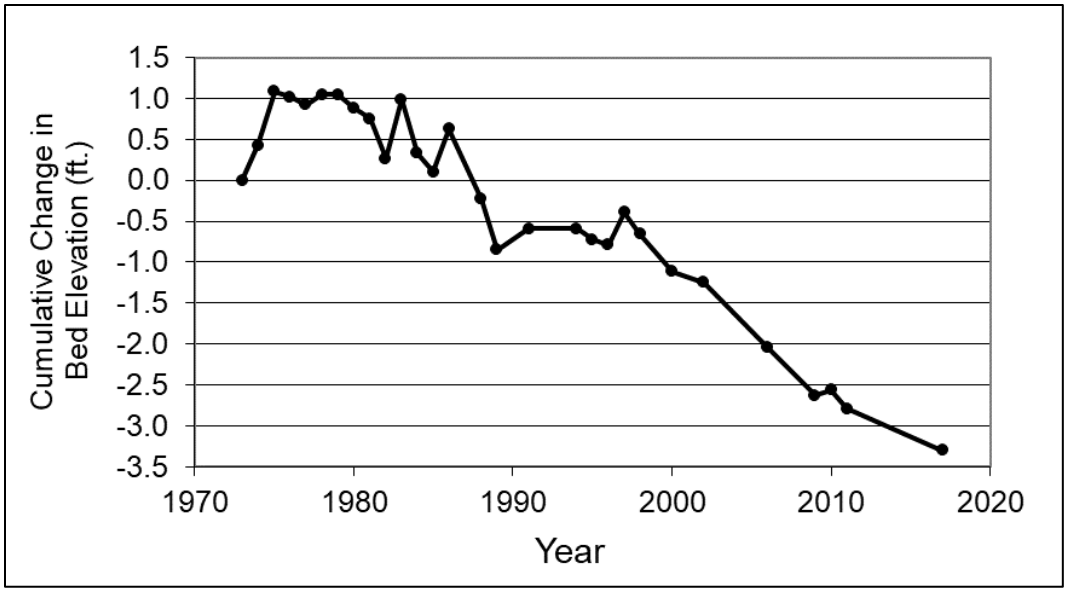


Figure 30. Cumulative change in average channel bed elevation at Cross Section 17, at the upstream end of the Tall Trees Grove.

The concern that channel aggradation can raise water table levels and harm redwood roots was investigated using a network of groundwater wells on three alluvial flats, including the Tall Trees Grove. In 1976, 18 piezometers (13 of which were equipped with digital recorders) were driven about 20 ft. deep into terrace sediments. The bottom foot of the well tubes was perforated to allow the entrance of groundwater. In these wells, water level rose to a level equal to the water table. Three piezometers, located between 75 and 250 ft. from the bank of Redwood Creek at Cross Section 19 (one mile upstream of the Tall Trees Grove), were intensely monitored through WY 1981. The terrace sediments had good hydraulic connection with Redwood Creek, with the water table surface closely and quickly mimicking the level of surface water in Redwood Creek (McFadden, 1983). The years of monitoring were characterized by only low to moderate runoff, however, and the effects of high flows on groundwater levels is unknown. McFadden also found that at times in the summer of 1981 the groundwater table was lower than the water surface in Redwood Creek, meaning the river was losing surface flow to the groundwater. Because the channel bed in 2018 was several feet lower than in 1981, Redwood Creek may no longer be a losing stream, but no data are available to validate this.

The Tall Trees Grove in Redwood National Park is vulnerable to damage by flooding, streambank erosion, and sedimentation, although river channel conditions are slowly recovering from past disturbances.

Riparian Condition

Riparian vegetation is intimately linked to the stream and river channels along which it grows. Riparian vegetation can retard movement of sediment, water, and floated organic debris on floodplains during floods. It increases bank stability. Riparian vegetation is an important source of organic matter and nutrients to streams and contributes large wood to channels, which in turn influences important aquatic habitats such as pools and riffles. The condition of riparian habitat has changed greatly since the 1940s, primarily due to timber harvest. Changes in dominant riparian composition (conifer or hardwood) and tree sparsity along the length of Redwood Creek were assessed using six sets of aerial photographs dating from 1948 to 1997 (Urner and Madej, 1998). A subsample of eight miles was field checked in 1998 to verify air photo interpretation, with additional field mapping in 2002. The earliest complete set of air photos that were available are dated 1948, and by this time 8 percent of the coniferous forest in the watershed had been cut, representing 6 percent of the basin area (Best, 1995). Most logging occurred after 1940, so it is assumed that most of the Redwood Creek riparian zone was uncut and conifer-dominated before 1948. A set of 1936 photos supports this assumption, especially in areas upstream of State Highway 299, where a closed conifer canopy over Redwood Creek was common.

Figure 31A shows the significant changes in riparian condition since 1948, from uncut conifer stands to hardwood-dominated stands. A combination of streamside timber harvest, channel widening, and sediment deposition resulted in fewer conifer trees since 1948. Reaches with sparse riparian vegetation (mostly grass and shrubs) increased after large floods in 1955 and 1964, but the riparian stand density (mostly hardwoods) has increased since then (Urner and Madej, 1998) (Figure 31B). Riparian trees are an important source of in-channel wood, a critical component of aquatic habitat (discussed in the following section). Hardwood and conifer stands, especially outside of the Park, are relatively young. They do not currently contain the size (length and diameter) of trees needed for functional and stable in-channel large wood. Similar observations regarding riparian species, size classes, and recruitable large wood were noted by Bundros, *et al*. (2003) and Cannata *et al*. (2006).

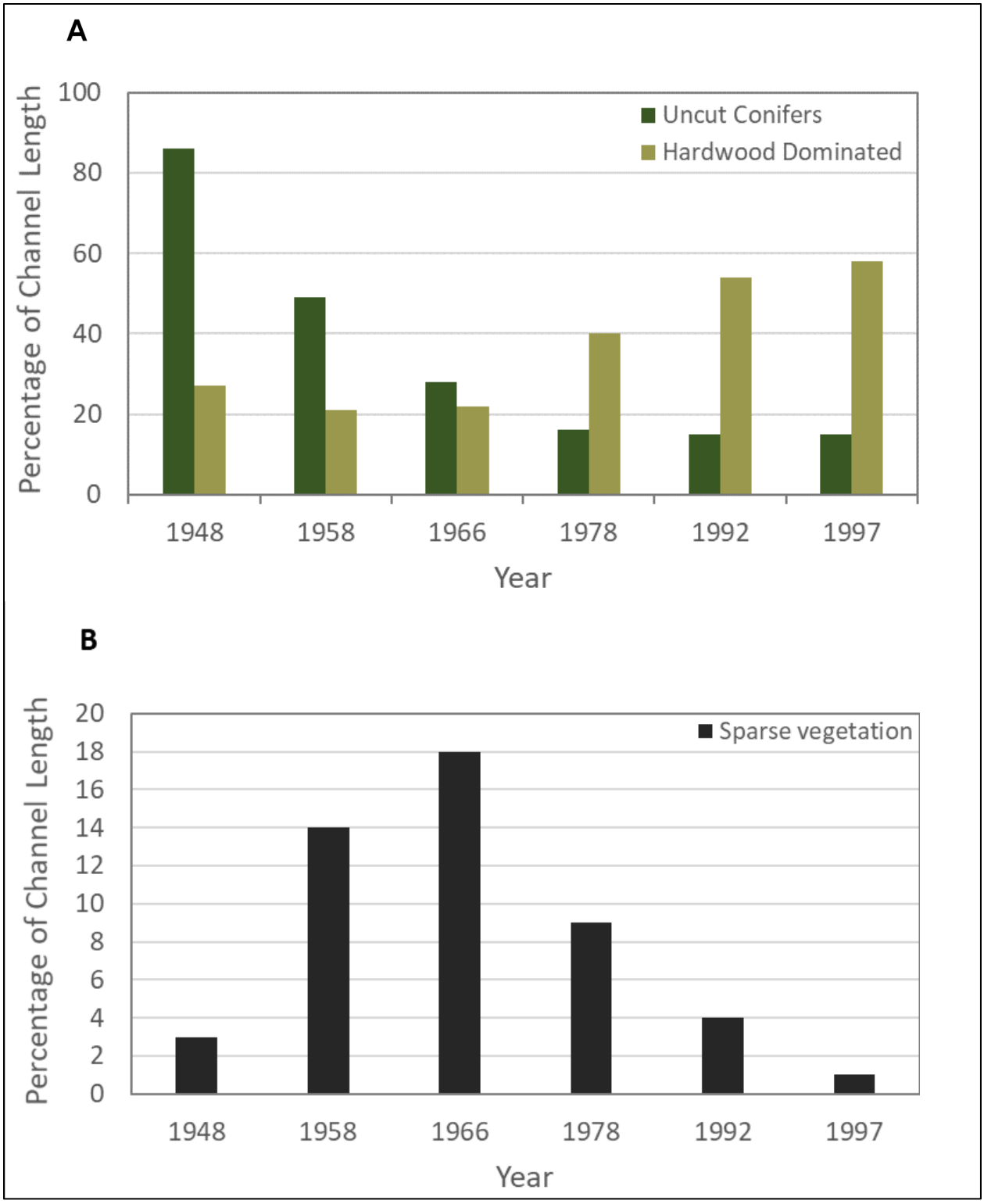


Figure 31. A) Changes in the amount of uncut riparian zones and hardwood-dominated riparian zones along Redwood Creek, 1948–1997. B) Length of Redwood Creek exhibiting sparse riparian vegetation, 1948–1997.



Figure 32. Air photo comparisons of lower Bridge Creek canopy closure in 1978 and 1997.

Riparian canopy cover was also measured in 15 tributaries within RNSP in 2005, using a hand-held spherical densiometer. Riparian canopy cover in these tributaries ranged from 67 to 98% (Madej *et al.,* 2006). In addition, an examination of air photos showed an increase in canopy cover in many of these streams since 1978 (Figure 32).

Conifer-dominated riparian forest stands along Redwood Creek and its tributaries decreased greatly after 1950 and will take decades to recover.

Large In-Channel Wood

Old-growth redwood trees have extremely large biomass, with trunk wood volumes of 900 to 1300 yd^3, and are very decay resistant (Noss, 2000). Consequently, when trees fall into a river channel, they have a large and persistent influence on in-channel wood loading (Figure 33).



Figure 33. Fallen redwoods in Redwood Creek control channel shape, promote pool formation, and influence streamflow (USGS).

Residence times for individual pieces of in-channel wood can exceed 200 years (Keller and Tally, 1979). Large wood is a major control on pool formation. The percentage of pools formed by large wood is highest in small streams, but large wood is still important in larger streams and rivers in influencing pool development. Large wood also influences sediment storage in headwater streams. For example, in Little Lost Man Creek, a volume of sediment equivalent to about 100 to 150 years of average annual bedload is stored in wood-related sites (Keller *et al.*, 1995). On average, Redwood Creek tributaries draining redwood forests have a higher proportion of sediment stored by large wood than tributaries draining Douglas-fir forests, even though sediment production from landslides is much higher in Douglas-fir basins (Pitlick, 1995). Although large wood is important in storing channel sediment in Redwood Creek tributaries, debris jams in the mainstem of Redwood Creek store less than 1 percent of the total stored sediment. Jams that span the channel width, and thus form effective sediment traps, only occur in the upstream-most seven miles of Redwood Creek (Madej, 1995). Many of the Douglas-fir log jams that were emplaced during floods in the 1960s and 1970s have now decayed and no longer trap sediment.

A common practice for many decades was to remove large wood from streams, in the thought that log jams prevented fish migration. However, when wood is removed, sediment is released downstream and can reduce salmon habitat as spawning gravels are dispersed and deep, wood-formed pools diminish. Large wood removal in the Redwood Creek basin commonly followed this pattern (Klein *et al.*, 1987; MacDonald and Keller, 1987). By 1980 the beneficial effect of large in-channel wood was recognized, and wood removal became rare.

Large wood in steep streams dissipates streamflow energy, so it can reduce channel incision. Trees enter a channel through windfall, streambank erosion, or landslides, and, depending on channel conditions and the size of the tree, they may remain in place or be transported downstream. Wood loading tends to be higher in steep, narrow streams where large logs get lodged tightly on the streambanks and channel bed and are not easily transported downstream. Several surveys of wood loading were conducted on tributaries of Redwood Creek between 1978 and 2005. These surveys in RNSP include stream habitat in: old-growth redwood (Keller *et al*.,1995; Benda *et al*., 2002; Kramer and Klein, 1999); second-growth redwood (Keller *et al*., 1995; Madej, 2010); and excavated stream crossings (Maurin, 2008). Wood loading varies widely, but streams draining old-growth redwood forests have higher loadings than those draining second-growth forests (Figure 34). Streams in a logged forest but with a buffer of streamside redwoods had wood loading intermediate between those two conditions. An additional large wood survey in Prairie Creek and its tributaries in 2014–2015 reported high wood loading of 228 to 575 pieces/km of stream (different units than in Figure 34) (Wilzbach and Ozaki, 2017).

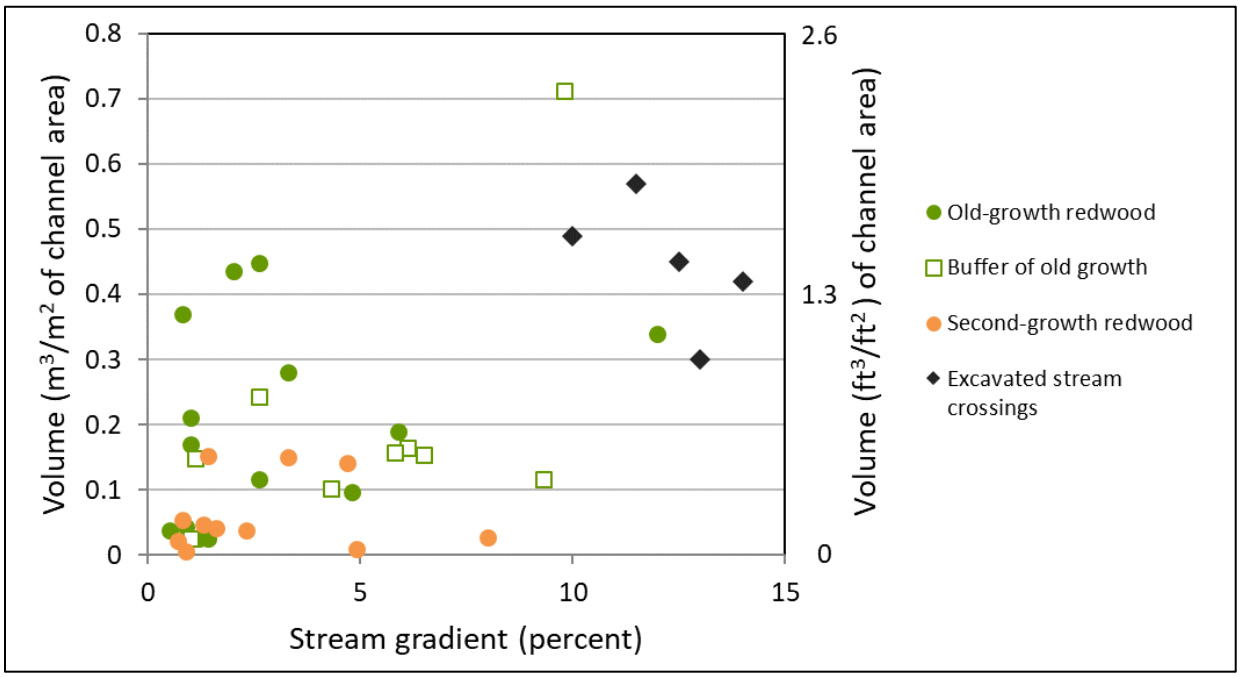


Figure 34. Volume of large wood in tributaries of Redwood Creek, CA.

Another type of wood loading was to intentionally place wood in small stream channels during road restoration to protect the channel from downcutting. RNP experimented with introducing large amounts of wood to stream channels as abandoned forest roads were decommissioned. Stream crossings that were excavated during road restoration work and armored with wood pieces have higher wood loading than most streams with a buffer of old-growth trees or streams draining second-growth forests (Figure 34). Nevertheless, the architecture of this wood placement following road restoration differs from a natural step-pool structure, the wood is much smaller than in natural streams, and the species composition contains more hardwoods (Madej, 2010). Future research is

needed to assess the long-term effectiveness of such wood placement in restoring channel stability and improving aquatic habitat, especially after a large flood.

Large wood in channels creates pools and provides shelter to fish. Wood abundance in streams is high in old-growth forests, but is diminished in streams with logged riparian areas.

Stream Temperature and Cold Pools

Water temperature influences many aspects of a salmon's life cycle, including egg development, juvenile appetite and growth, migration, and distribution. In a north coastal California stream near Redwood Creek, Welsh *et al.* (2001) reported that juvenile coho salmon were not present in streams where the seven-day average daily maximum temperature (called the maximum weekly maximum temperature, or MWMT) exceeded 18.1° C (65° F). In-channel stream temperatures have been monitored at several locations along Redwood Creek since 1997. In addition, in July 2003 a thermal infrared flight documented surface water temperature along 59 miles of Redwood Creek (Ozaki and Anderson, 2005). Figure 35 is an example of the output from this flight. Based on RNP data, Redwood Creek is currently listed as temperature-impaired under the Clean Water Act because of elevated summer water temperatures. Unlike many rivers that get warmer as they flow downstream, Redwood Creek reaches its maximum temperature in the middle basin. Channel widening, sediment accumulation, and reduced shading contribute to the warm temperatures. Here MWMTs frequently reach 80° F, and coho do not use this part of the river. Juvenile steelhead fish kills were documented in this reach by California Department of Fish and Wildlife (CDFW) in the summers of 2006, 2009, 2014, and 2015. Redwood Creek becomes cooler farther downstream, where coastal fog, shading by old-growth redwood trees in the riparian zone, and the presence of cold springs contribute to the cooling trend. Maximum water temperature in lower Redwood Creek on foggy days is 3–5° F cooler than on sunny days (Madej, 2012). Nevertheless, MWMTs range from 68 to 74° F, still higher than the preferred temperature for coho.

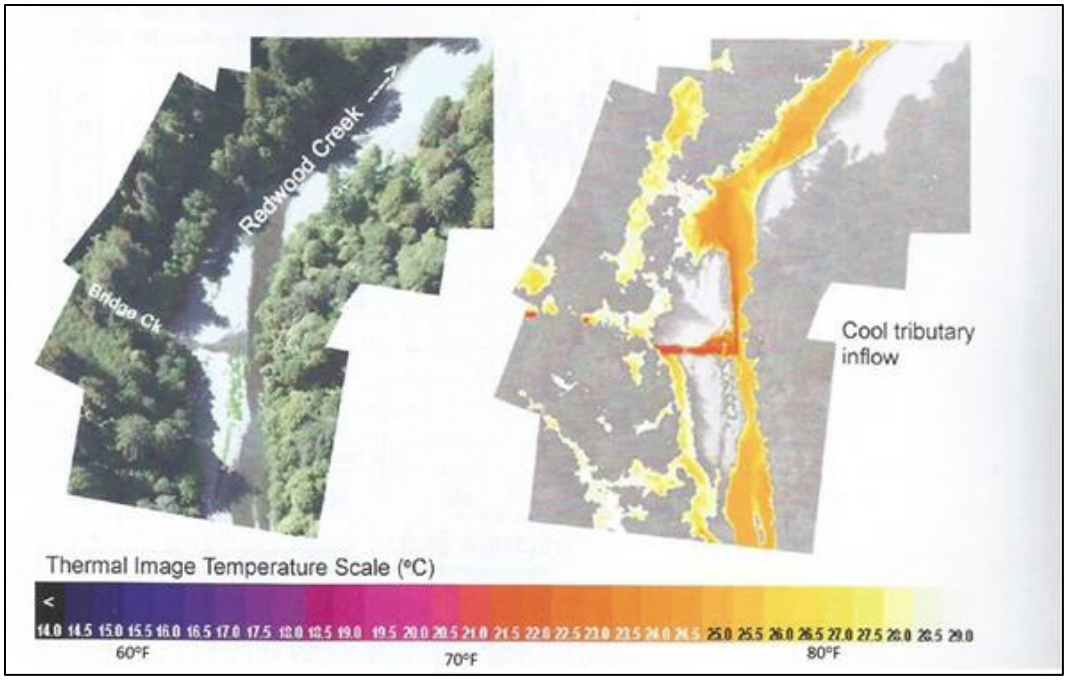


Figure 35. Thermal image of the confluence of Bridge Creek and Redwood Creek. Tributary inflow is cooler than mainstem water, but both are above the preferred temperature for salmonids.

Cold pools are thermally stratified pools with summer water temperatures more than 5° F cooler than temperatures in the main flow of Redwood Creek. Because they offer a cool refuge during hot summers, more fish occupy these pools than in adjacent pools with warmer temperatures (Keller and Hofstra, 1983). In Redwood Creek, cold pools were only found downstream of Emerald Creek (Harry Wier Creek) in wide, aggraded stream reaches (Moses, 1984). Cold pools develop where cool tributary flow or mainstem intragravel flow, and to a lesser extent, groundwater seeps, enter a side channel that is isolated from the main flow. A gravel bar is essential to isolate large volumes of cold water and to prevent thermal mixing with mainstem flow, as large wood on its own is not sufficient to retard mixing (Ozaki, 1988). Cold pools are ephemeral features because the Redwood Creek low flow channel shifts from year to year and conditions necessary for cold pool formation are not always present in the same locations over time. The coldest water is found in the deepest part of pools. In addition, the longer and narrower the pool, the colder the pool water (Ozaki, 1988).

Summer water temperature in the main flow of Redwood Creek is many degrees warmer than that preferred by salmon. Although few in number, cold pools provide important summer refugia for fish.

Episodic Drying of Lower Redwood Creek

Summer low flows in Redwood Creek have declined significantly since the 1970s (Madej, 2011) even when adjusted for differences in precipitation (Asarian and Walker, 2016). Several factors contribute to this trend: second-growth forests are becoming more prevalent as clearcut hillslopes revegetate, which increase water demand; sand and gravel accumulation in the channel bed allows more streamflow to go subsurface; legal and illegal water diversions for residential and agricultural use have increased; and a trend of higher air temperature and possible decrease in fog increases evapotranspiration demands.

Anecdotal observations report that lower Redwood Creek has gone dry at least four times since 2002 (Figure 36). The most recent incidence occurred during three consecutive summers starting in the 2014 drought. Park staff mapped the extent of dry channel upstream of Prairie Creek. The dry channels persisted from late summer into early fall and extended between 1.2 and 1.5 miles upstream of the confluence with Prairie Creek (Figure 37). Because the Redwood Creek at Orick gaging station is located downstream of the confluence of Prairie Creek with Redwood Creek, the gage reported flowing water from Prairie Creek even though Redwood Creek upstream of the gage was dry. Pools then became isolated pockets of warm, stagnant water. When flow was not continuous, juvenile salmon and steelhead, as well as other aquatic species, became stranded in these pools and faced poor water quality and increased predation from birds, raccoons, and other animals as they were concentrated into smaller and shallower pools.



Figure 36. The dry channel bed of lower Redwood Creek showing isolated pools (August 2002; NPS/OZAKI).

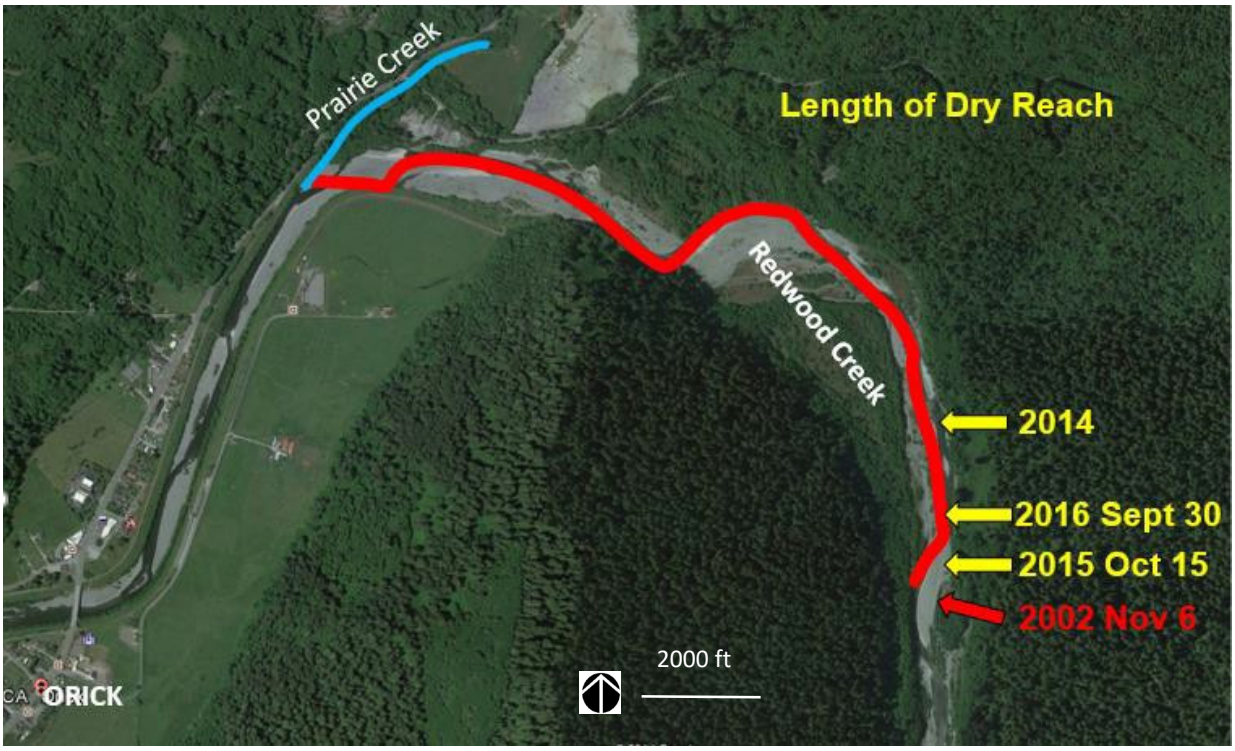


Figure 37. Map of dry reaches of Redwood Creek upstream of Prairie Creek.

In low rainfall years, lower Redwood Creek dries out in late summer, leaving only isolated pockets of warm, stagnant water in the channel and stranding fish.

Carbon Export and Sequestration

Human activities such as burning fossil fuels and clearing forests have caused a substantial increase in the concentration of carbon dioxide (CO_2) in the atmosphere, which contributes greatly to global warming. Carbon sequestration, on the other hand, helps to offset carbon emissions. This can be accomplished through restoring forests, preventing soil erosion, and reducing fossil fuel emissions. Soil is a major component of carbon (C) budgets because large amounts of organic matter are sequestered in soil layers. Consequently, soil erosion and sedimentation influence carbon fluxes in a watershed. Vegetation, especially large trees such as old-growth redwoods, also store a large amount of carbon. Landslides provide a mechanism to strip vegetation and soil off a hillslope and deliver carbon directly to the stream network. Although landslide deposits have the potential to bury and preserve soil carbon, in Redwood Creek the steep topography and direct delivery of landslide material to streams promote the export of carbon to the estuary and ocean instead. Landslides in 1964, 1972, and 1975 contributed roughly 310,000 tons C to the river network. An additional 22,000 tons C was delivered by landslides in 1997 (Madej, 2010), contributing to the total suspended

sediment yield in 1997 of 1,160,000 tons in Redwood Creek. Organic carbon is typically a minor component of the sediment load in Redwood Creek (only 1 to 2% of the suspended sediment load). In contrast, in pristine upper Prairie Creek, which drains old-growth forests, organic carbon is 13 to 33% of the suspended sediment load, which are some of the highest percentages reported in the global literature.

Watershed restoration activities (discussed in more detail in a later section) also affect carbon export and sequestration. The removal of roads decreases landslide frequency and promotes revegetation of disturbed road prisms. As soils develop on the former road surfaces, soil organic carbon accumulates, increasing carbon sequestration, or "savings" (Seney and Madej, 2015). Road removal involves a carbon cost, though, through heavy equipment and vehicle fuel emissions, short-term soil loss, and clearing of vegetation (Figure 38). In balance, the total carbon cost for treating 255 miles of road was 25,000 tons C, and the total savings from that work as of 2009 was 75,000 tons C (Madej *et al*., 2013). Carbon sequestration will continue to increase as trees grow and soil carbon accumulates (Van Mantgem *et al*., 2013).

Soil organic carbon is a major component of carbon budgets. Land management activities, through their influence on soil, affect both carbon export and sequestration in the Redwood Creek basin. Over the long term, road removal represents a carbon savings.

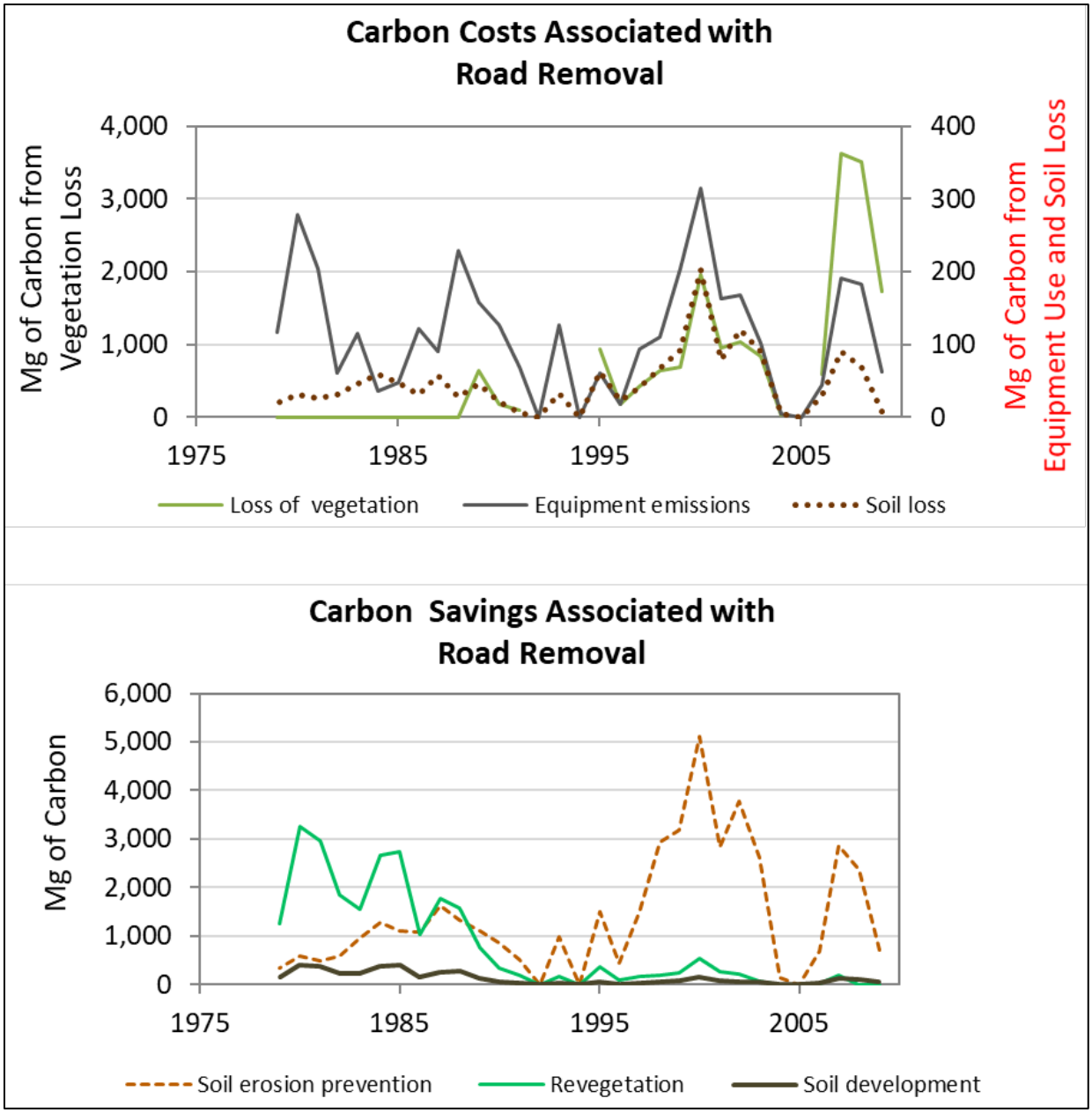


Figure 38. Carbon costs and savings associated with removal of logging roads in Redwood National Park, 1979 to 2009 (1 Mg = 1.1 ton).

Gravel Mining

After the 1964 flood severely damaged the town of Orick, the U.S. Army Corps of Engineers constructed flood control levees along the lowermost 3 1/2 miles of Redwood Creek in 1968. The County of Humboldt then became responsible for maintaining the river channel bed at a specified design elevation between the levees. In 1987 and 1988 gravel was extracted from this reach of river for use in the construction of the Highway 101 bypass project, with the anticipation that gravel mining would lower the bed of Redwood Creek to near the design elevation. Extraction was limited to the gravel replenishment rate, based on the average annual bedload transport estimated from the

1954 to 1980 data at the USGS Orick gaging station. Because of concern over potential impacts on fish habitat and possible undermining of the flood levees due to bed scour, in 1987 RNP initiated a monitoring program to: 1) determine gravel extraction and replenishment rates, 2) document changes in channel shape and slope, and 3) provide management recommendations and guidelines for future gravel extraction proposals. Twenty-six cross sections were surveyed before and after gravel extraction from the confluence of Redwood Creek with Prairie Creek downstream to the last meander bend in Redwood Creek before it reaches the estuary. Cross sections were then resurveyed annually through 1995.

Between 1987 and 1990 extraction volumes (214,000 yd^3) exceeded replenishment values (109,000 yd^3). Gravel offtake lowered mean bed elevations at the surveyed transects from 1 to 4 ft. After four years, less than half the volume of gravel extracted had been replaced (although streamflows were lower than average during this period) (Collins and Dunne, 1990). Gravel bars were able to rebuild only a fraction of the topography removed by mining in the previous summers, and some bars were rebuilt along the opposite banks from their original location. Channel scour proceeded upstream of the mined reach. As of 1995, when the monitoring program ended, average channel bed elevation in the mined reach was still ~1 ft. lower than pre-extraction levels.

Consequently, the California Department of Fish and Game (now Department of Fish and Wildlife) revised the mining guidelines, and restricted mining to one-half the channel width and focused mining on the low-water channel. The County of Humboldt continues to monitor river bed elevations and levee conditions, although minimal mining has occurred since 1990. Subsidence of parts of the levees and possible piping of flow through the earthen levees are additional concerns regarding the stability of the flood control structure.

Gravel mining in lower Redwood Creek in 1987 and 1988 exceeded the gravel replenishment rate and changed channel and gravel bar configurations, which persisted for several years.

Highway 101 Bypass Construction

In October 1989, an unprotected highway construction alignment in the Prairie Creek watershed was subjected to a large storm, resulting in tons of fine sediment entering Prairie Creek and many of its tributaries. A layer of silt and clay settled on the surface of streambeds and infiltrated into subsurface gravels. Because infiltration of large amounts of fine sediment into salmonid redds can reduce reproductive success and decrease intragravel water flow and availability of dissolved oxygen, RNP initiated a monitoring program to assess the possible damage to Park resources from this sedimentation. Several stream gaging stations were established in Prairie Creek (Figure 4) to measure streamflow and sediment discharge, some of which continue operating at present. Artificial salmonid redds were constructed to test permeability, fine sediment infiltration, and survival of steelhead eggs (Meyer *et al.*, 1993). Fine sediment infiltration was greatest in Brown Creek, a tributary of Prairie

Creek, which received direct input of sediment from the highway alignment. Gravel permeability was lower in redds exposed to sediment inputs from Brown Creek. Dissolved oxygen concentrations decreased over the winter but were still above 5 ppm (concentrations < 5ppm have been reported to cause egg mortality (Meyer *et al.*, 1993)).

Mean egg survival-to-hatching rate in artificial redds over four years of study was about 40%, except where oligochaete worm infestation was present. Egg survival to hatching was largely unaffected by fine sediment or changes in permeability; instead, worm infestation seemed to be responsible for cases of high mortality (<2% egg survival). The relation between the presence of worms and amount of fine sediment is unknown, however (Meyer *et al.*, 1994).

Effectiveness of Watershed Restoration Efforts

As part of the Redwood National Park Expansion Act, Congress authorized $33,000,000 for watershed rehabilitation. The sediment budget, described earlier, clearly showed that abandoned logging roads caused significant erosion problems. Consequently, the main focus of watershed restoration was road decommissioning or removal, which has been on-going since pilot studies began in 1977. The goal of such work is to reduce sediment input to streams from road-related erosion problems, which may lead to improved conditions for fish and other aquatic biota.

Forest roads are significant sources of sediment (Janda *et al*., 1975; Best *et al*., 1995). Road cuts and drainage structures, such as culverts, can disrupt natural drainage patterns. Stream crossings fail when culverts plug with sediment or wood, or are too small to convey storm discharge, and road fill at the stream crossing is eroded (Figure 6). When drainage structures fail to function properly, streams can divert out of their natural channel onto hillslopes, causing gullies and landslides (Figure 7). Road cuts can intercept groundwater and increase the amount of surface runoff. In addition, widespread surface runoff from the road bench and cutbanks flows into inboard ditches, which commonly deliver fine sediment to channels (Figure 39).

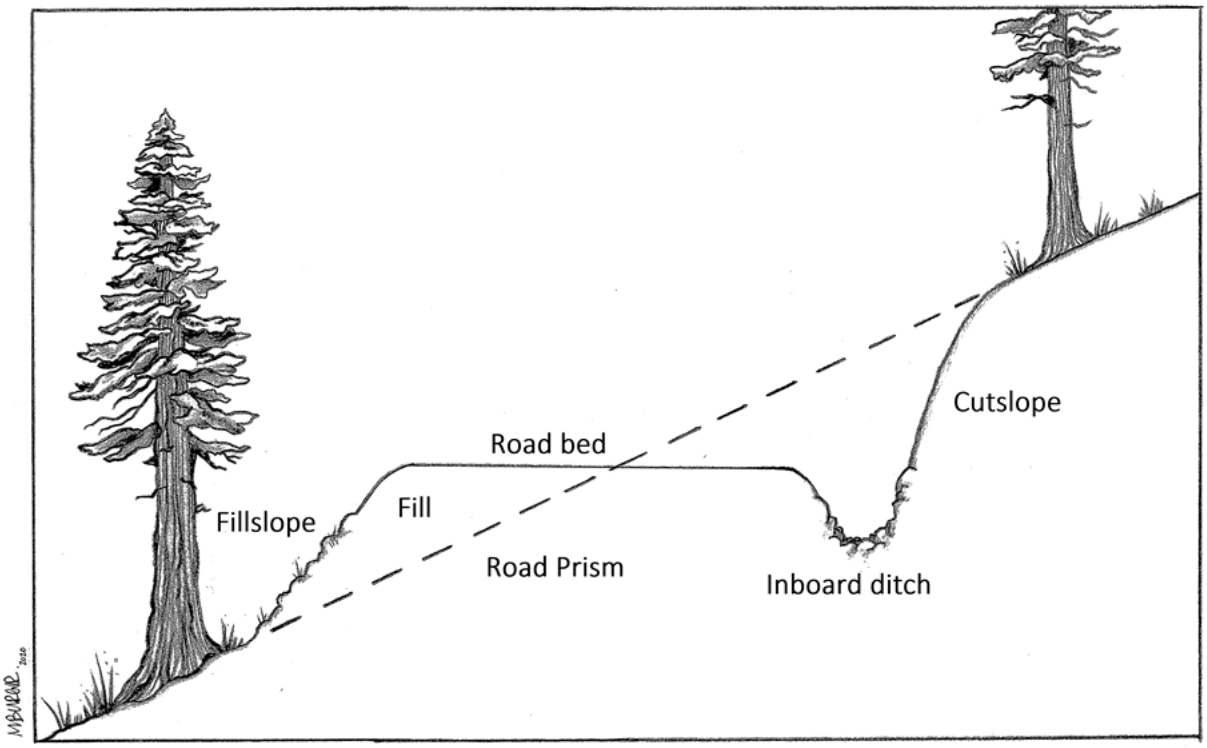


Figure 39. Components of a road. Dashed line represents original hillslope configuration (after Switalski *et al.*, 2004).

Because of the importance of road-related erosion, RNP developed a Watershed Rehabilitation Plan (1981) designed to assess needs on a landscape scale. Roads were prioritized for treatment based on several criteria, listed in order of importance below:

- The amount of sediment yield from the tributary basin in which the site occurs. The higher the estimated sediment yield, the higher the priorities for the treatment of sites in the tributary basin.
- The proximity of sites to perennial stream channels: The closer the sites to perennial streams, the higher the priority.
- The condition of logging roads: The more serious the state of disrepair of the roads, the higher the priority.
- The date of logging: Recently logged areas were more accessible, and the erosional problems were easier to detect and not as well developed, therefore these areas were scheduled to be treated first, before conditions worsened.
- The past logging method: Tractor-yarding resulted in greater ground disturbance than cable-yarding, so the former areas had a higher priority for treatment.
- The accessibility of the site: Sites at the ends of dead-end logging roads were treated first because road removal precluded reasonably easy access to the site for treatment.

- The amount of drainage area upslope from the site: If a certain site was selected for treatment, all the drainage area immediately upslope to the watershed divide needed to be treated at the same time so that small watersheds on the slope were rehabilitated as a physiographic unit.

The original Watershed Rehabilitation Plan included a timeline of 10 years to complete road removal work (excluding roads in Prairie Creek). However, as work progressed, Park staff realized that watershed restoration and ecological healing would be a much slower and longer process. Also, as the restoration program progressed, other prioritizing factors were considered, such as presence of threatened or endangered species; access for road maintenance, prescribed fire, second-growth thinning and other resource management activities; prairie restoration, wildfire control; and visitor access (Ozaki *et al.,*1997).

Typical road treatments include decompacting the road surface, removing drainage structures, excavating road fill from stream channels and exhuming the original streambed and streambanks, excavating unstable sidecast fill from the downslope side of road benches or landings, and filling in or draining the inboard ditch. Treatment styles in RNP have evolved since 1978. In the first years, hand crews built waterbars, check dams, and other labor-intensive erosion control features, assisted by small heavy equipment such as backhoes. Park geologists soon realized that the same large heavy equipment that was used to construct roads was needed for efficient removal of roads, and hand crews were phased out. Treatments in the early 1980s used heavy equipment such as bulldozers and excavators to decompact road surfaces and construct drains perpendicular to the road alignment to dewater inboard ditches. Following this treatment, the roads were mulched with straw, seeded, and replanted with native vegetation (Figure 40). As the RNP program progressed, Park geologists began to use more intensive treatment methods, which included partially recontouring the road surface by excavating fill from the outboard edge of the road and placing the material in the inboard ditch at the base of the cutbank. This technique required more earth moving. By the 1990s geologists commonly prescribed full recontouring of the road bench, in which the cutbank was covered by excavated fill, original topsoil from the outboard edge of the road was replaced on the newly shaped road surface where possible, stream channels were excavated to the original channel bed elevation, and streambanks were extensively reshaped (Figure 41). Because of the extensive reshaping for the road prism, full recontouring involves moving much more road fill than earlier techniques. Export outsloping, in which unstable road fill is transported to stable locations, involves even more earth moving than full recontouring.



Figure 40. Typical stream channel excavation in the 1980s. A) Abandoned logging road with intact culvert before treatment. B) Immediately following stream crossing excavation. In this case, rock armor and check dams were installed on the channel bed to prevent downcutting. C) Less than one year later, revegetation of the streambanks is well underway. D) Three years after treatment, alders have revegetated most of the ground disturbed during treatment (NPS).

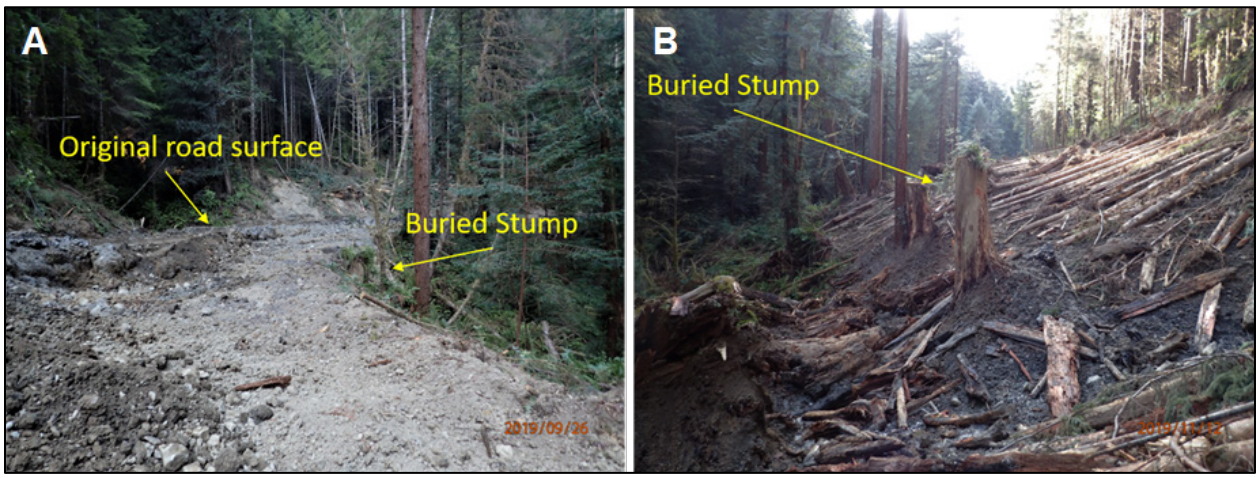


Figure 41. An example of more intensive road removal (full recontouring). A) Abandoned logging road before treatment. B) The road bench is obliterated and the hillslope is recontoured. Stumps (at arrow) uncovered during excavation indicate the location and elevation of the original hillslopes (NPS\YOUNGBLOOD).

From 1978 to 2009, RNP treated 255 miles of road within Park boundaries (Figure 42). Roads treated on private lands are discussed in a later section. During the period from 1979 to 1989, 170.5 miles of road were treated (an average of 15.5 miles per year). This represents two-thirds of total length of road removal as of 2009 (Figure 43). Then as the restoration program shifted focus, with more intense treatment implemented on shorter lengths of road, the volume of road fill excavated from each mile of road increased. During this later period of 1996 to 2002 only 42 miles of road were removed, but about 2.3 million cubic yards were excavated from road-stream crossings and by export outsloping (Figure 43). This represents almost half of all road fill excavated during the entire road restoration program. So, although fewer miles of road were treated during the later period, more road fill was removed from unstable locations. The focus of road removal in recent years has been in the Lost Man Creek subbasin. As of 2019, all 29 miles of abandoned logging roads were removed, and the remaining 15 miles of road will be maintained as service roads. Contract costs for all road restoration work totaled $20.5 million (not adjusted for inflation). (Park staff time is not included.) Summary reports and cost analyses for individual restoration projects are on file at RNSP. Future road removal work will focus on the Prairie Creek area, through “Redwood Rising,” a collaboration of the Save the Redwoods League, CDPR, and RNP. The collaborative proposes to remove 54 miles of abandoned roads in a 9200 acre lower Prairie Creek project area by 2030.

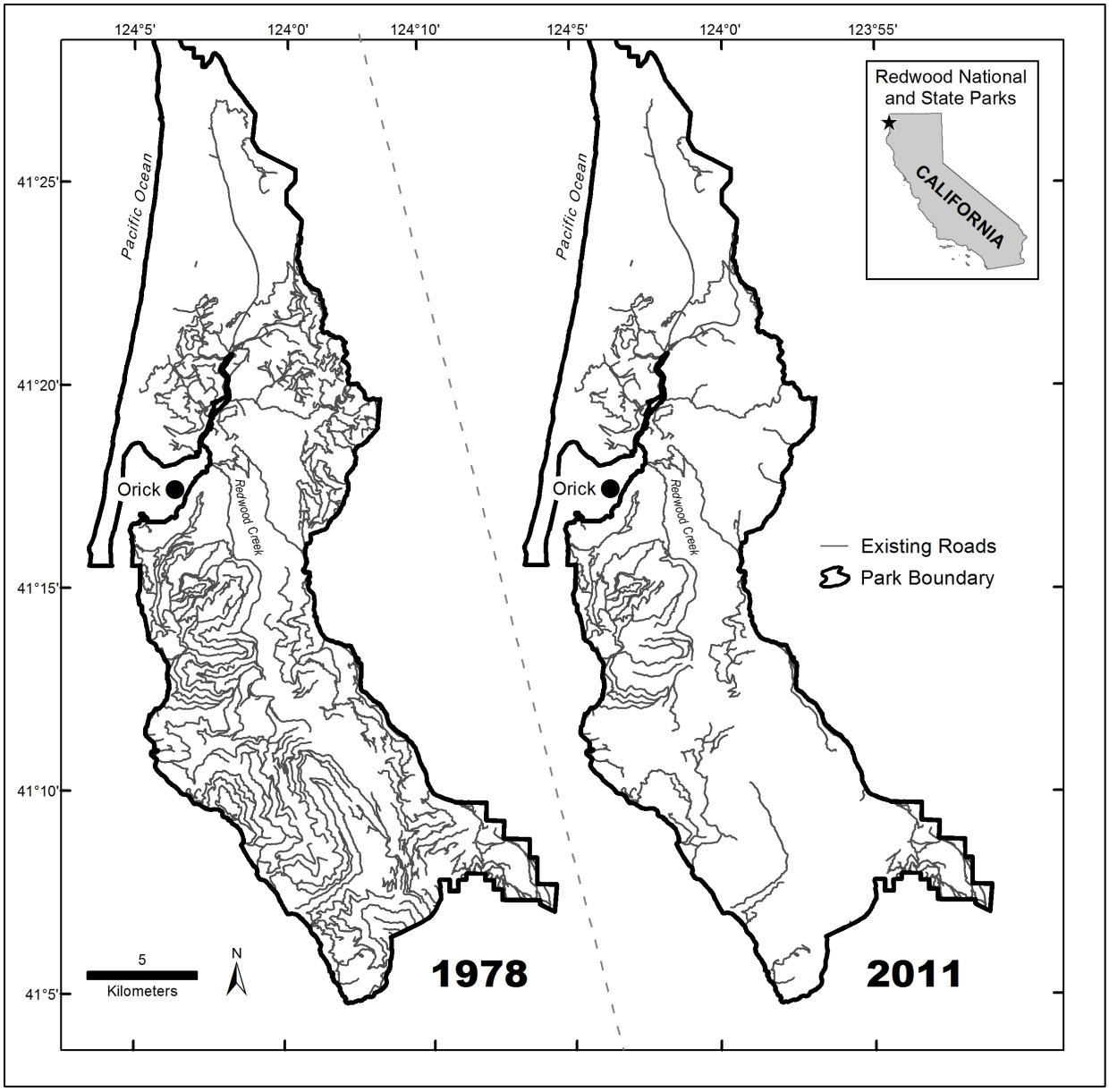


Figure 42. Map showing existing roads in 1978 and 2010 in Redwood National Park, California. The decrease in road density in 2010 represents roads which have been removed.

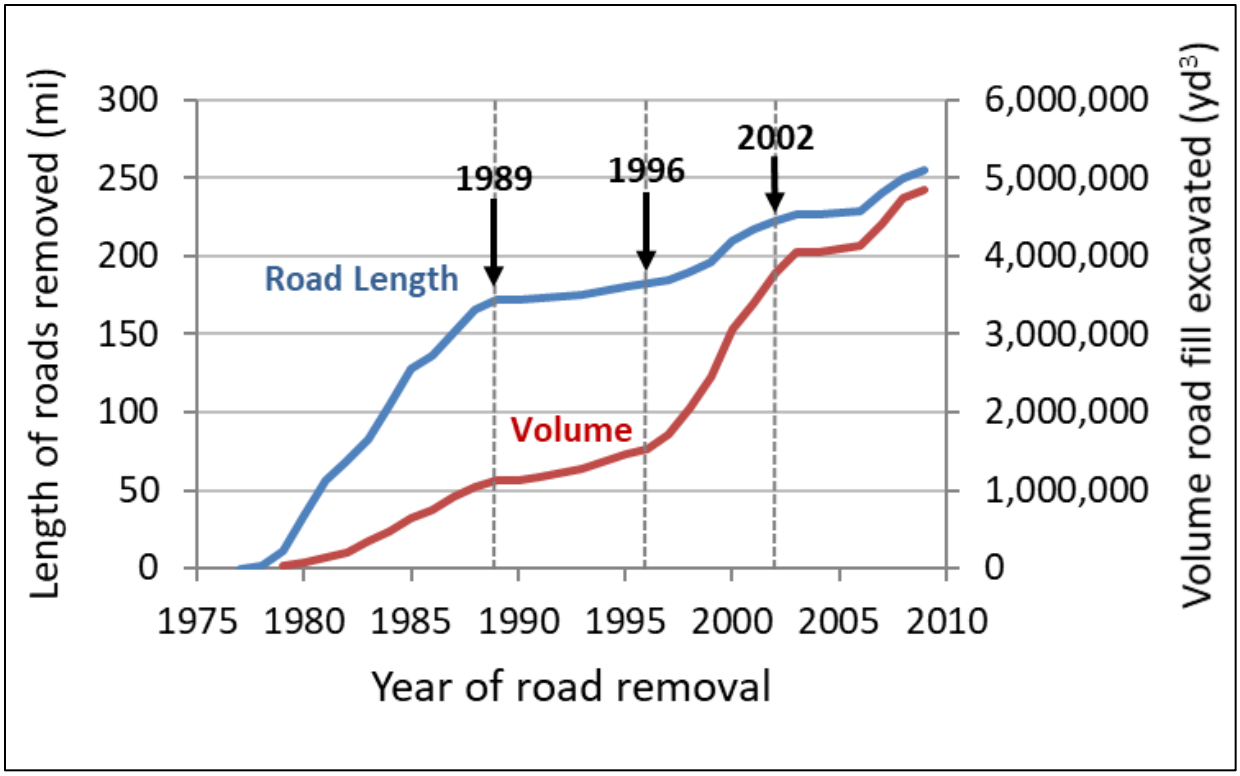


Figure 43. Cumulative length of roads removed and volume of road fill excavated from 1979 to 2009. About 70% of road length removed occurred by 1989. Few roads were removed between 1990 and 1996. Post-1996, road treatments focused more on excavating road fill than treating long stretches of road.

Success of watershed restoration can be measured in several ways. Many studies have addressed the effectiveness of road removal work in terms of sediment production over a several-year time period (Weaver *et al.*, 1987; Klein, 1987; Bloom, 1998; Madej, 2001a). Because road removal involves heavy equipment work and the removal of vegetation, there is commonly a short-term increase in erosion at the site until the newly excavated streambanks settle and become revegetated. Most post-rehabilitation erosion is generated either by adjustments of excavated stream crossings during the first one or two winters, or results from road fill failures on treated road prisms. Post-treatment erosion in RNP was assessed following a 12-year storm in 1997. Erosion in excavated stream crossings was found to be related to stream power and the volume of fill excavated from the crossings—the larger the excavation and the higher the stream power, the more the crossing eroded. Post-treatment erosion on road prisms was related to method of treatment and hillslope position, with lower slope roads having 50 times the amount of erosion than upper slope roads (Madej, 2001a). Treated roads exhibited less than one-third the erosion than untreated roads during the 1997 storm (Switalski *et al.,* 2004). Erosion from 190 miles of treated roads contributed less than 2% of the total sediment load of Redwood Creek during the period 1978 to 1998 (Madej, 2001a).

More recently, erosion and turbidity associated with road removal were monitored in Lost Man Creek, where over 50 miles of road and associated stream crossings had been removed by 2009.

Excavated stream crossings contributed high sediment loads initially, but contributions decreased rapidly over time (Klein, 2012).

The effectiveness of watershed restoration can also be evaluated by the health of stream biota. A full biological assessment is beyond the scope of this review, but in general some recovery has been noted. Between 1973 and 1975 the USGS collected aquatic biological data at 50 sites (mostly in disturbed streams) in the Redwood Creek watershed. Those sites, many of which had had road restoration work in the 1980s, were resampled in 2004 and 2005. In terms of benthic macroinvertebrates, diversity index values were higher in 2004 than in the 1970s. Long-lived species, which can be indicative of more stable channel conditions, were more abundant in the 2004–2005 period. Periphyton growth rates were lower, probably due to the increase in canopy cover. Stream reaches in undisturbed redwood forests had significantly higher biomass and density of tailed frogs (*Ascaphus truei)* than streams with restoration work, suggesting recovery of headwaters amphibian assemblages may be suppressed for many decades after disturbances (Madej *et al.*, 2006).

Monitoring road removal sites has shown that to date some of the desired outcomes of restoration have been achieved. Nevertheless, the recently restored landscape has yet to be tested by intense storms, which were common from 1953 to 1975. Climate modeling suggest increased storm intensity in the future. Adaptive land management requires a continuous evaluation of what works and what doesn't work, and of unintended consequences. Thus, long-term monitoring of restoration activities is needed to guide future actions.

RNP's restoration program has removed 255 miles of road and moved 4.8 million cubic yards of road fill from unstable locations to more stable sites. These road treatments have greatly reduced the potential for road-related erosion in the future.

Additional Studies and New Methodologies

Many other studies in RNP have involved geomorphic monitoring and assessment. In the flood of 1975 landslides from a harvested area deposited a large amount of logging slash into Bridge Creek, a major tributary of Redwood Creek. The jam was modified in 1984 and again in 1990 to allow better fish passage. Many cross-sectional and longitudinal channel surveys documented channel changes from 1984 to 1997 (Klein *et al.,* undated; Smith, 1994). Likewise, channel monitoring documented changes in Lost Man Creek following the removal of a 7-ft. high concrete dam in 1989 and its associated sediment. Sediment that had accumulated upstream of the dam was excavated and deposited on the adjacent floodplain; consequently, post-dam removal channel changes were minimal. A landslide in the Emerald Creek (Harry Wier Creek) tributary basin was intensely monitored for several years (Babcock *et al.*, 1982). Soil mapping in RNP compared relationships between soil type and geomorphic setting (Popenoe, 1985; Popenoe *et al.,*1992). The USGS analyzed solute transport and streamflow patterns in a pristine tributary, Little Lost Man Creek (Bencala *et al.,*

1984; Triska *et al.*, 1995; and in streams affected by logging (Bradford, 1995). The Redwood Creek estuary, which has been heavily modified by flood control levees, has many years of channel bed and sand spit surveys.

In the early 1980s RNP implemented many physical monitoring techniques that were considered new and experimental at the time. Automatic data loggers, slope movement indicators to monitor downslope movement of landslides, pressure transducers, and piezometers to measure groundwater elevations on unstable slopes were all tested in many areas of RNP. Surface erosion was measured with erosion pins, erosion bridges, and erosion plots with sediment collection troughs. In small steep streams, standard stream gaging techniques needed to be modified to monitor stream hydrographs in remote areas, and irregular channels typically required the construction of special flumes for accurate flow measurements. Stereo ground photography documented pre- and post-restoration land conditions. Relocatable scour chains revealed the annual depth of channel bed scour and fill in Redwood Creek. Pebble counts, grab sampling, freeze-core sampling of channel beds, and digitization of close-up vertical photographs were all used successfully to quantify particle sizes of river channels and streambanks. More recently, new metrics for analyzing pool and riffle distributions were developed (Madej, 1999). Genetic algorithms and dynamic programming were incorporated into a decision support system to assess road decommissioning priorities (Eschenbach *et al*, 2005). Landslide susceptibility was modeled using a geographic information system (Hare, 2003). Tremendous advances in remote sensing, especially the development and acquisition of Lidar imagery, have increased the accuracy of mapping streams, roads, and landslides. Fish population studies benefited from the geomorphic monitoring data base (Madej *et al.,* 2012). These new and modified methodologies have been used by many other researchers and land managers in many other regions.

Land Management Implications

Private Lands Program

In response to legislative mandates stated by Public Law 95-250 in 1978 (see “History of Scientific Studies”), RNP undertook studies to measure and assess erosion, sedimentation, and sediment transport in the Redwood Creek basin. Some of these assessments occurred on private lands upstream of Park boundaries, which influenced land management through three main approaches: reviews of timber harvest plans (THPs), involvement with revising CA Forest Practice Rules (CFPR), and the development of cooperative erosion control efforts with private landowners.

In 1976 a Redwoods Agreement was negotiated between the Department of the Interior, the Department of Justice, and the three major industrial timberland owners in the Redwood Creek basin. The agreement stipulated that each company would submit their plans for annual timber harvesting in Redwood Creek to the NPS for review and comment. A multidisciplinary team of NPS hydrologists, geologists and foresters was assembled in 1976 to begin field reviews of proposed THPs (U.S. Secretary of the Interior, 1987). Following RNP expansion in 1978, Park geologists continued to actively participate in reviews of timber harvest plans (THPs) on private lands in the 26,000-acre Park Protection Zone (PPZ) in the Redwood Creek basin, and occasionally on lands farther upstream. A first review of a THP, submitted by a Registered Professional Forester, was conducted in the office by a multi-agency team that included the California Board of Forestry (BOF) and Fire Protection (CAL FIRE), the California Department of Fish and Game (now Fish and Wildlife), the California Regional Water Quality Control Board, the California Geological Survey, RNP, and other agencies as needed. On most THPs a review team then conducted a pre-harvest field inspection to examine the proposed logging site. Initially when Park geologists joined the review team, plan inspections engendered some suspicion and misgivings among the various parties involved. Guidelines developed by the Park for the PPZ were one of the first attempts to quantify erosion hazards, and then modify management actions based on these risk assessments. For example, in 1983 Park staff developed a Mass Movement Checklist and Mass Erosion Hazard Rating for PPZ lands, and in 1984 they developed "Land Use Guidelines for the Park Protection Zone" (Weaver, 1984). Eventually, over a period of several years, landowners, agency personnel, and government scientists developed more trust in their mutual relationships, and Park staff were considered a resource rather than an adversary. Erosion control recommendations that were once a hard sell became standard practice through time, and the process of working with landowners fostered cooperative erosion control efforts throughout the watershed (described below). In 1995 and again in 2000, Memoranda of Understanding (MOUs) between the National Park Service and individual private landowners were signed to facilitate these cooperative efforts.

The review of timber harvest plans ensured that: 1) new roads were built on appropriate ground to decrease erosion and road failures; 2) poorly placed roads were removed under approved timber harvest plans, when appropriate; 3) Park staff were viewed as a resource by both agencies and landowners; and 4) best management practices were used to minimize or prevent erosion. Park involvement in THPs also kept personal relationships with upper basin landowners and their foresters and other review agencies current and in good standing (Bundros, personal communication). From

1984 through 2016, 386 THPs were filed for the Redwood Creek basin, and Park staff reviewed 47 percent of all THPs through 2010 averaging seven plans per year (Figure 44). In 2011, due to reduction in staff, the park began prioritizing THP review based on proximity to the park. From 2011 through 2015, 34 % of all THPs were reviewed, an average of about 4 plans per year (Short, 2017). During this period, 218 miles of new road were constructed as part of the timber harvest process, of which 156 miles were seasonal roads and 62 miles were temporary roads (Short, 2017). As of 2010, more than 50,000 acres in Redwood Creek were inspected and reviewed through the THP process. In 2011, the lead geologist (Bundros) retired and the park reduced efforts reviewing THPs on private lands in the upper basin of Redwood Creek. In early 2017, when the last upper basin geologist retired, no further THPs were reviewed in Redwood Creek with the exception of Special Treatment Areas (STA) reviews which extend from the park boundary out 200 feet on to private land (Short, 2017). Between 2017 to 2019, THP reviews have focused on STAs along the park boundary and the park has commented on 18 reviews.

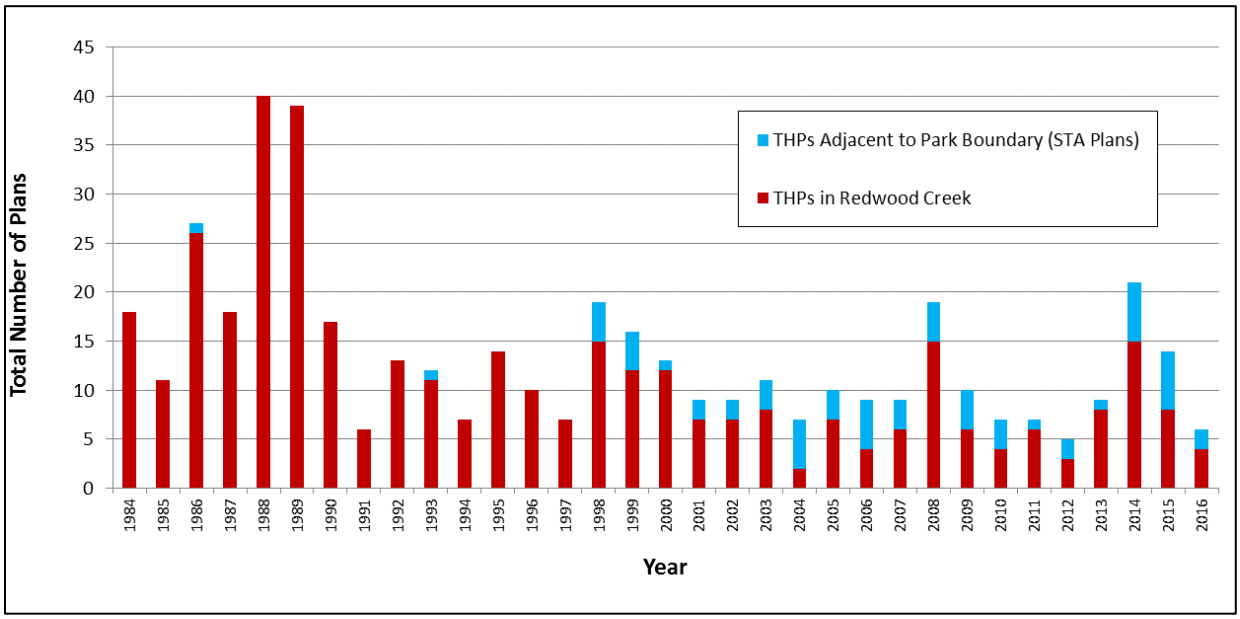


Figure 44. Timber harvest plans in the Redwood Creek watershed or adjacent to park boundaries from 1984 to 2016.

In a second approach to prevent erosion from timber harvest activities, RNP became involved with California forest practices rules. CAL FIRE is the agency responsible for the development of forest practice standards and enforcement of CFPR. State regulation of timber harvest activities began in 1945 when the CA Forest Practice Act was enacted, but this act had no road-related requirements. A major revision in forest practices occurred when the Z'Berg-Nejedly Forest Practice Act was passed in 1973 and implemented in the field as of 1975. These new rules brought increased protection to watercourses, and included requirements for timber harvest plans, road drainage, and stream protection zones, as well as limitations on logging unit size.

Lessons learned from Redwood Creek watershed studies have been instrumental in revising state-wide forest rules. Required forest practices have been upgraded continually since 1975. From the late 1970s to 2010, Park personnel served on CA BOF rules subcommittees and provided testimony, comments, and field data to support rule changes. Redwood Creek studies suggested several gully prevention techniques, such as the excavation of rolling dips near stream crossings, installation of properly sized culverts, and maintenance of roads, especially during storms. In 1983, as part of new BOF Road and Landings rules, road-stream crossings were required to accommodate 50-year floods (rather than 25-year floods), and then in 2000 the requirement became passing a 100-year flood along with debris and sediment. RNP developed a culvert-sizing tool that is still used in sizing the appropriate road drainage to pass the 100-year flood.

Correct design of road drainage features is critical to preventing erosion from forest roads, and such techniques are described by Weaver *et al*. (2015). Since initiating THP reviews in the 1970s, RNP has recommended preventing road runoff from reaching streams (hydrologic disconnection) and removing the potential for streams to divert at road drainage sites through the construction of critical dips on roads. These erosion control measures were adopted by the state in 2010 under the Anadromous Salmonid Protections Rules, for areas with listed salmonids. More recently, in 2015, updated road rules were implemented, based on a 2013 rule package. These include requirements for road maintenance and recommendations for road surface design, such as outsloping or crowning. In addition to involvement with CFPR, Park geologists have commented on waste discharge requirements and other policies of the California Regional Water Quality Control Board and Department of Fish and Wildlife.

In a third approach to erosion prevention, RNP worked with private landowners to identify potential problem areas. RNP pioneered the design and use of road erosion site inventories to locate and map significant existing and potential erosion sites on forest roads and landings. Initially the inventories were used to prescribe treatments to mitigate significant adverse impacts from abandoned forest roads on Park lands (see Appendix B in Bundros and Short (2011) for the road inventory form). From 1978 to 2009, RNP removed 255 miles of road in the Park for contract costs of $20,500,000. The road inventory approach was then expanded to cover private lands and started in earnest in 1996 with cooperative efforts with private landowners upstream of Park boundaries.

This private lands program has been a success on many levels. Of the 1,100 miles of road existing in the upper watershed at the beginning of the program, about 773 miles (70%) had been assessed as of 2011, about 120 miles of road had been upgraded and about 61 miles had been decommissioned. Significantly, 531,000 yd^3 of road-related soil erosion has been prevented by this work (Bundros and Short, 2011). Total funding for all cooperative erosion control projects in the upper watershed through 2009 was about $5.8 million. Landowners provided about $1.9 million (33%) in funding with the remainder provided by various grant sources. Park staff were instrumental in obtaining grant money for this road improvement effort.

The erosion control methodologies developed by RNP geologists are now applied to many areas with past disturbance from timber harvest activities. RNP pioneered the design and implementation of removal of abandoned logging roads. Rehabilitation of forest roads is now a commonly accepted

erosion control method used on federal, state, county, and private roads throughout the western U.S. In addition, the road inventory methodologies have been adapted by other agencies and, as of the 2013 CFPR revision, are being applied statewide.

Redwood National Park geologists also provide guidance to Park maintenance staff and other landowners for monitoring road networks, especially during storms, to check for evidence of surface erosion, rilling, downcutting, culvert plugging or overtopping, and sediment delivery to streams. If evidence of existing or potential sediment delivery exists, corrective measures can then be implemented before serious erosion occurs. Regular road maintenance on active logging roads is now required by the CFPR.

RNP's long-term involvement, through 2010, in timber harvest plan reviews and cooperation with private landowners in the Redwood Creek watershed led to decreased erosion risks in the upper basin. There, 773 miles of logging roads were assessed for erosion problems, and 181 miles of road were upgraded or removed. Also, RNP was instrumental in establishing stronger California Forest Practice Rules to provide long-term protection the Park's aquatic and riparian resources.

Sediment Savings from Road Treatment

The total amount of sediment 'saved' (i.e., soil erosion prevented) from both federal and private lands through road treatments in the Redwood Creek watershed from 1998 to 2009 is about 2.74 million tons, or about 820 tons per square mile per year (Bundros and Short, 2011). In comparison, the total sediment output for the same period in Redwood Creek was 1,800 tons per square mile per year (Bundros and Short, 2011). Although the two measurements are not directly comparable, the sediment reduction is significant in terms of total sediment input to Redwood Creek. The long-term effectiveness of road treatments still needs to be tested by a large (greater than 25-year) storm, however.

Land Management Policy Decisions

Data sets from the Redwood Creek watershed have been used in many land management policy decisions. The Park developed a draft BOF Sensitive Watershed nomination for Redwood Creek in 1994, which led to the adoption of MOUs between RNP and individual landowners. RNP produced a Redwood Creek Watershed Analysis (2000), which was used as a funding tool to obtain grants for erosion control work and as a base for EPA's Total Maximum Daily Load analysis (2000). RNP facilitated acquisition of land by the U.S. Bureau of Land Management in Lacks Creek (1997–2004),

where RNP geologists then initiated road removal projects in that area. Park staff contributed to the Report of the Scientific Review Panel on CA Forest Practice Rules and Salmonid Habitat (Ligon *et al.,* 1999), BOF's Interim Watershed Mitigation addendum (2001), University of California's Cumulative Watershed Effects review (2001), BOF Cumulative Impacts Assessment Rule Addendum (2004), the Green Diamond Resource Company Aquatic Habitat Conservation Plan (2007), BOF's Review of Forest Management Effects on Riparian Functions for Anadromous Salmonids (Liquori *et al*., 2008), and BOF Anadromous Salmonid Protection Rules (2009). The California North Coast Watershed Assessment Program (NCWAP), a multi-agency state effort in 2000–2002, used Redwood Creek as a test case because of its data richness. Key revisions of a 2014 coho protection plan (the National Marine Fisheries Service Recovery Plan for the Southern Oregon/Northern California Coast Coho Salmon Evolutionarily Significant Unit) incorporated RNP suggestions for watershed protection. RNP coordinated an Integrated Watershed Strategy for Redwood Creek (Redwood Creek Watershed Group, 2006), which was used to obtain California Proposition 50 funding for several watershed projects, including in the town of Orick. RNP also applied a slope stability model, SHALSTAB, to all of Redwood Creek hillslopes, which is used to evaluate hillslope stability during THP reviews and erosion control planning.

In recent years, RNP has shifted focus from involvement in upper basin issues to lower Redwood Creek and its tributary Prairie Creek. Restoration efforts by Redwoods Rising (a collaboration of the Save the Redwoods League, CDPR, and RNP) in this area have used background data from RNSP to guide planning of ecosystem restoration projects. Nevertheless, emerging issues on private lands upstream of RNP, such as cannabis cultivation and its associated withdrawal of water, Sudden Oak Death and other diseases, invasive species, wildfire, residential development and fragmentation of forested tracts, water demands caused by changing climatic conditions, and continued timber harvest, will continue to affect downstream and possibly threaten Park resources.

Long-Term Monitoring of Watershed Processes

The types of land use changes and disturbances discussed in this summary point to the need for continued monitoring of physical and biological resources. The Redwood Creek watershed is an important laboratory for understanding landscape response to human disturbances. Detailed geomorphic and hydrologic data have been collected in the Redwood Creek watershed since the 1970s. This long-term data set of geomorphic change and watershed dynamics is unique in the United States, and globally, in its extent and availability. Among the values of long-term monitoring are: 1) quantifying ecological responses to drivers of ecosystem change; 2) understanding complex ecosystem processes that occur over long periods; 3) providing core physical and ecological data for parameterizing and validating simulation models or developing theoretical models; and 4) providing data and understanding at scales relevant to management, thus critically supporting evidence-based policy, decision-making, and management of ecosystems. In contrast to short-term data, long-term data sets are able to capture and recognize long-term events, changes in highly variable systems, time-lagged responses, cumulative effects of stressors, and biotic responses encompassing multiple generations (Wilzbach and Ozaki, 2017). Such data sets will help interpret the effects of both climate change and of future large storms and floods on watershed processes.

Long-term monitoring programs are difficult to maintain because they exceed the length of government administrations and funding cycles. Monitoring of discharge, suspended sediment, temperature, and water quality in Redwood Creek had been supported with relatively stable funding from the National Park Service and the U.S. Geological Survey for many years, but budgets are declining, and several gaging stations have been discontinued. Many grant programs fund implementation projects but not long-term monitoring of effectiveness. Securing adequate funding for continued monitoring of watershed processes will be a large challenge for land managers in the future.

Almost 50 years of monitoring watershed processes in the Redwood Creek basin has produced a unique and rare geomorphic data set. It has aided California land managers in policy and decision-making regarding protection of natural resources. Monitoring results have been used to help secure funding for road treatment, both within and upstream of RNP. Results have been widely cited and applied to projects nationally and internationally.

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A data set of Redwood Creek cross section results is available online at: Sciencebase.gov (https://doi.org/10.5066/P9G0N0TN).

Appendix A: Project Leads and Staffing 1978–2019

Project Leaders

- James Agee, NPS
- David Best
- Gregory Bundros
- Steven Colman, USGS
- Danny Hagans
- Deborah Harden, USGS
- Terrence Hofstra
- Richard Iverson, USGS
- Richard Janda, USGS
- Edward Keller, University of California at Santa Barbara
- Harvey Kelsey
- Randy Klein
- Thomas Lisle, USFS
- Mary Ann Madej, USGS
- Donna Marron, USGS
- K. Michael Nolan, USGS
- Vicki Ozaki
- John Pitlick
- Darci Short
- Ronald Sonnevil
- Stephen Veirs
- Judy Wartella
- William Weaver

Redwood National Park Restoration Geologists

- David Burns
- Ingrid Corson
- Gilbert Craven
- Philip Freiberg
- Gregory Gibbs
- James Howard
- Louise Johnson
- Meridith Manning
- Michael Sanders
- Rebecca Smith
- Terry Spreiter
- David Steenson
- Patrick Teti
- Kenneth Utley
- Edward Wosika
- Neal Youngblood

Support Staff (surveys, mapping, GIS, water sampling, lab work, and monitoring)
All RNP unless otherwise noted.

- Brian Adkins
- Mark Alpert
- Sal Amador
- Bruce Amen
- Lisa Babcock
- Brian Barr
- Robert Belding
- Anna Bloom
- Fred Booker
- Scott Bowman, USFS
- G. Robert Brackenridge
- Charles Brown
- Monica Bueno
- Natalie Cabrera
- Scott Carroll
- Anne Choquette
- Michael Coghlan
- Kathleen Considine
- Christopher Currens
- Tera Curry
- James Duls, USGS
- Patty Egan
- Colleen Ellis
- Nicolai Erikson
- Chris Faubion
- Ashley Fairchild, WSP
- Joan Florsheim
- Van Hare
- Kelly Helstrom
- Susan Hilton, USFS
- Justin Hobart, GIP
- Jonathan Hollis, USGS

- Carrie Jones
- Deadra Knox
- Kevin Kveton
- Richard La Husen
- Laura Lalemand, USGS
- Koa Lavery
- Fred Levitan
- Nancy Marks
- Tom Marquette
- Jeannie Mayer
- James Milestone
- Julie Miller
- Matthew Morasutti, WSP
- Michael Napolitano
- Desiree Otillio, WSP
- Jayson Padgett, GIP
- James Popenoe
- Sandra Potter
- Bonnie Pryor, USFS
- Brian Rasmussen
- Cindy Ricks
- Paul Routon
- Sonette Russell, GIP
- Briana Salazar
- Michael Sandecki
- John Schlosser
- Mark Seltenrich
- Joseph Seney
- Tom Stephens, USGS
- Kendall Story, GIP
- Dianne Sutherland, USFS
- Rachel Truesdell
- Stacey Urner
- Dan Vann

- Zoe Varner, WSP
- Nick Varnum
- John Veevaert
- Dominic Vitali
- Victor Vrell
- Tom Walter
- Madeline Wilner, GIP
- Anneliese Wilson
- James Wood
- Ashley Woodford, GIP

Appendix B: Cooperators

Agencies and Nonprofits

- CA Board of Forestry
- CA Department of Fish and Game/Fish and Wildlife
- CA North Coast Regional Water Quality Control Board
- CA State Parks
- CalTrout
- County of Humboldt
- Humboldt State University
- Orick Community Services District
- U.S. Bureau of Land Management
- U.S. Environmental Protection Agency
- U.S. Fish and Wildlife Service
- U.S. Forest Service
- U.S. Geological Survey
- U.S. National Weather Service
- Western Land Conservancy
- Pacific Coast Fish, Wildlife and Wetlands Restoration Association

Other

- Pacific Watershed Associates
- Redwood Regional Watershed Center
- Redwood Creek Landowners Association
- Natural Resources Management Corporation
- Redwood Creek Watershed Group

Funders

- CA Jobs-in-the-Woods
- CA Proposition 50 – Coastal
- CA Proposition 50 – Integrated Regional Water Management CA Proposition 84
- CA Salmonid Restoration Fund CA Senate Bill 271
- National Park Service Geologic Resource Division
- National Park Service Servicewide Comprehensive Call (SCC)
- Resources Legacy Foundation
- Save the Redwoods League
- USGS Legacy Data Project

Appendix C: List of Gaging Stations and Date of Operations

Table C-1. List of Gaging Stations and Date of Operations.

Location	Gaging Station[a]	Station Code	Dates of Operation (Water Year)	Data available [b, c] (Water Year)	USGS Station #
Prairie Creek	Prairie Creek above Wolf Creek Bridge	PRW	1991–2012	• Q 1991–2012 (NPS) • Turbidity 2004–2012 (NPS) • SS 1991–2012 (NPS)	–
	Prairie Creek above Boyes Creek	PAB	2004-present	• Q **2004-present (NPS)** • Turbidity **2004-present (NPS)** • SS **2004-present (NPS)**	–
	Lower Prairie Creek below Brown Creek	PRL	1990–2004	• Q **1990–2002, 2004 (NPS)** • SS **1991–2001 (NPS)**	–
	Upper Prairie Creek above Brown Creek	PRU	1990–2012	• Q **1991–2012 (NPS)** • Turbidity **2001–2012 (NPS)** • SS **1990–2012 (NPS)**	–
Prairie Creek Tributaries	Lost Man Creek	LMC	2002-present	• Q **2002-present (NPS)** • Turbidity **2002-present (NPS)** • SS **2002-present (NPS)**	–
	Little Lost Man Creek	LLM	**1974–1989 (USGS)**, 1993-present	• Q **1974–1989 (USGS), 1993-present (NPS)** • Turbidity **2002-present (NPS)** • SS **1975–1989 (USGS), 1993-present (NPS)** • BD **1975–1982 (USGS)**	11482468

[a] The USGS ran many other synoptic and non-synoptic gaging stations from 1974–1976. Data are in Iwatsubo et al., 1975 and 1976. Gaging station locations are shown in Figure 2 of Iwatsubo et al., 1975.

[b] Q = discharge, SS = suspended sediment and BD = bedload.

[c] Monitoring agency: NPS or USGS, as noted. USGS also shown in blue text.

[d] USGS also established tributary gaging stations on Miller Creek (11482250) and Harry Wier Creek (11482225).

[e] Green Diamond Resource Company took over Panther Creek gaging station in 2012 – data are not available.

Table C-1 (continued). List of Gaging Stations and Date of Operations.

Location	Gaging Station[a]	Station Code	Dates of Operation (Water Year)	Data available [b, c] (Water Year)	USGS Station #
Redwood Creek	Redwood Creek at Orick	ORK	1911–1913 (USGS), 1954-present (USGS)	• Q 1912–1913 (USGS), 1954-present (USGS) • SS 1971-present (USGS), **1993–present (NPS)** • BD 1972–2009 (USGS)	11482500
	Redwood Creek at Miller Creek [d]	MILLER	1978–1984 (USGS)	• Q 1978–1984 (USGS) • SS 1978–1984 (USGS) • BD 1978–1984 (USGS)	11482261
	Redwood Creek at Harry Wier Creek (Emerald Creek) [d]	WIER	1974–1984 (USGS)	• Q 1974–1976 (USGS), 1978–1980 (USGS), 1982–1984 (USGS) • SS 1974–1976 (USGS), 1978–80 (USGS), 1982–1984 (USGS) • BD 1974–1976 (USGS), 1978–1980 (USGS), 1982–1983 (USGS)	11482220
	Redwood Creek South Park Boundary	SPB	1971–1981 (USGS)	• Q 1971–1981 (USGS) • SS 1971–1981 (USGS) • BD 1974–1976 (USGS), 1978–1981 (USGS)	11482200
	Redwood Creek above Panther Creek	PAN	1974–1989 (USGS)	• Q 1974–1976 (USGS), 1980–1989 (USGS) • SS 1974–1976 (USGS), 1980–1989 (USGS) • BD 1974–1976 (USGS), 1980–1989 (USGS)	11482120

[a] The USGS ran many other synoptic and non-synoptic gaging stations from 1974–1976. Data are in Iwatsubo et al., 1975 and 1976. Gaging station locations are shown in Figure 2 of Iwatsubo et al., 1975.

[b] Q = discharge, SS = suspended sediment and BD = bedload.

[c] Monitoring agency: NPS or USGS, as noted. USGS also shown in blue text.

[d] USGS also established tributary gaging stations on Miller Creek (11482250) and Harry Wier Creek (11482225).

[e] Green Diamond Resource Company took over Panther Creek gaging station in 2012 – data are not available.

Table C-1 (continued). List of Gaging Stations and Date of Operations.

Location	Gaging Station[a]	Station Code	Dates of Operation (Water Year)	Data available [b, c] (Water Year)	USGS Station #
Redwood Creek (continued)	Redwood Creek near Blue Lake (O'Kane)	OKN	1954–1958 (USGS), 1972-present (USGS)	• Q 1954–1958 (USGS), 1973–1993 (USGS), 1995-present (USGS) • SS 1973–1991 (USGS), 1993 (USGS), 1995-present (USGS) • BD 1974–76 (USGS), 1978 (USGS), 1980–1983 (USGS), 1987–1991 (USGS), 1993 (USGS), 1995–2009 (USGS)	11481500
Redwood Creek Tributaries	Coyote Creek	COY	1979–1989 (USGS), 1992–1995 (USGS)	• Q 1979–1982 (USGS), 1984–1989 (USGS), **1992–1995 (NPS)** • SS 1979–1982 (USGS), 1984–1989 (USGS), **1992–1995 (NPS)** • BD 1979 (USGS), 1981–1982 (USGS), 1988 (USGS)	11482130
	Panther Creek	PAN	1979–1991 (USGS), 1992–2011, 2012 [e]	• Q 1979–1991 (USGS), **1992–2011 (NPS)** • Turbidity **2005–2011 (NPS)** • SS 1979–1991 (USGS), **1992–2011 (NPS)** • BD 1979–1983 (USGS), 1986–1987 (USGS)	11482125
	Lacks Creek	LAC	1975–1991 (USGS), 1992–2011	• Q 1975–1976, 1978–1991, **1992–2011 (NPS)** • SS 1975 (USGS), 1978–1991 (USGS), **1992–2011 (NPS)** • BD 1978–1979 (USGS), 1981–1983 (USGS), 1988 (USGS), 1990 (USGS)	11482110

[a] The USGS ran many other synoptic and non-synoptic gaging stations from 1974–1976. Data are in Iwatsubo et al., 1975 and 1976. Gaging station locations are shown in Figure 2 of Iwatsubo et al., 1975.

[b] Q = discharge, SS = suspended sediment and BD = bedload.

[c] Monitoring agency: NPS or USGS, as noted. USGS also shown in blue text.

[d] USGS also established tributary gaging stations on Miller Creek (11482250) and Harry Wier Creek (11482225).

[e] Green Diamond Resource Company took over Panther Creek gaging station in 2012 – data are not available.

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Appendix E: Sediment Budget for the Redwood Creek Watershed, 1954–1980

Updated 2020 by M.A. Madej: This sediment budget, produced by Redwood National Park staff, is an update of the Redwood Creek sediment budget listed in the Redwood Creek Watershed Analysis (1997), based on new data collected since the 1997 flood, and supersedes previous versions.

Sediment Budget Approach

To develop land use policies for watersheds and to guide watershed restoration, land managers need to understand sources of sediment entering river systems, the timing and magnitude of sediment input and output, and the role of humans in accelerating erosional processes. As a first step in developing a watershed restoration plan after Park expansion in 1978, RNP adopted a sediment budget approach to quantify these aspects in order to prioritize treatment of erosion problems in the basin. In its simplest version, a sediment budget is:

$$\text{Input} \pm \text{Storage} = \text{Output}$$

The following discussion focuses on these three elements of the budget. Each element has several sub-elements that were quantified by teams of researchers from Redwood National Park, U.S. Geological Survey and academia. The budget was based on a combination of field work, monitoring and stream gaging, interpretation of aerial photographs, and extrapolation of results from other studies. The time period chosen (1954–1980) encompassed five large floods in the basin (in 1955, 1964, January and March 1972, and 1975), and was bracketed by the availability of air photos in 1954 and 1978. Field mapping in 1980 filled in many gaps in the air photo interpretation.

Table 1 lists sediment sources during that time period. The following sections describe how each item in Table 1 was estimated. Most of the data used was collected in the 1980s, and these values were used in various reports by Redwood National Park. However, following a large flood in 1997 and subsequent field studies plus additional years of monitoring data, some updates of probable erosion rates were made. Consequently, the values in this current version of the sediment source table differ slightly from earlier versions. A full list of resources used to develop the budget is included in Appendix C. Many different measurement units were used by various investigators in studies spanning many years. We tried to list the original measurements along with the appropriate conversions. All estimates for this sediment budget were converted to English tons (1 metric tonne (or Mg) = 1.10231 English ton). Volumes (cubic yards) were converted to mass (tons) based on measurements of bulk densities of soil, colluvium and alluvium. Estimates are rounded to the thousands of tons. This sediment budget does not differentiate sediment according to particle size, and both bedload and suspended sediment-sized particles are considered. We recognize that many of the items listed are rough estimates, and are based on extrapolations of data from small study sites to large areas. Nevertheless, we feel this method was adequate to show the relative importance of various erosional processes even if the exact volumes of sediment cannot be measured.

SEDIMENT PRODUCTION ASSOCIATED WITH ROAD NETWORKS

Unpaved logging roads are commonly a source of sediment to streams channels. Roads contribute sediment through several processes: cutbank erosion and failures, surface erosion from unpaved roads, erosion of inboard ditches, road fill failures, landing failures, gully erosion from stream diversions, and erosion of road fill at stream crossings. Although not as large as haul roads, skid roads and skid trails are more numerous and also contribute sediment to stream channels. In addition to the sources of sediment listed below, there are several unmeasured sediment sources: cutbank and road fill failures that were not included under other mass movement categories, sheetwash and cutbank erosion from skid trails, and small landing failures that did not result in large landslides. Small failures (< 400 m^2, or 0.1 acre, in area) are difficult to detect under forest cover on 1:6000 air photos (Madej, 2011). Also, features that become revegetated quickly many not be detected in air photos taken many years after the failure. Likewise, road maintenance may have fixed and obscured erosion problems on roads before the next set of air photos was taken or the next field inventory.

Cutbank erosion

Ten grids of nine erosion pins each were installed on the east side C-line in Redwood National Park in 1979 (Madej, unpublished data). Pins were 9-inch steel nails that were painted orange, and they were driven into the cutbank perpendicular to the ground surface until they were flush with the ground. Pins were spaced 18 inches horizontally from each other, above the talus pile at the toe of the cutbank. Data collection covered the period from Nov. 1979 to June 1986 (seven winters, with moderate intensity rains) at 10 sites, on both schist and sandstone terrain. Only 48 pins remained undisturbed for the seven-year period. For the 48 erosion pins that remained intact for seven years, mean depth of erosion was 1.12 inches. (1.12 in/7 years = 0.16 inch/year, or 1.6 inches (0.13 ft.) in 10 years.) There was no significant difference between sandstone and schist terrain.

Many assumptions and simplifications were used to estimate a sediment yield from cutbanks:

1. Based on erosion pin data, a rate of 0.13 ft. of cutbank retreat in 10 years was applied to all haul roads in the basin. On abandoned roads, it was assumed that 10 years after road construction, a combination of revegetation and the cessation of road grading and ditch cleaning would protect cutbanks from further significant erosion and contribution of material into inboard ditches. Without road grading and ditch cleaning, a debris apron forms at the base of cutbanks and stores material eroded from upslope cutbanks. Cutbank slides would contribute sediment over and above that recorded by erosion pins, but this factor was not measured in the field.
2. Haul roads were assumed to have only one cut bank (no through cuts were considered), with an average height of 10 ft. Skid trails were assumed to have negligible cutbank erosion.
3. All material eroded from the cutbank was assumed to reach the inboard ditch. Based on a road inventory in Redwood National Park (Spreiter, 1995) of more than 700 culverts, 70% of culverts draining inboard ditches feed into stream channels (the remainder were ditch relief culverts or drained springs). This value is considerably higher than Raines and Kelsey's value for Grouse Creek, an adjacent watershed. However, most of the 1250

miles of roads in the Redwood Creek basin were abandoned or unmaintained, with few functioning waterbars or ditch relief culverts. Therefore, we assumed that about 70% of sediment reaching the inboard ditch was delivered to a stream during the first 10 years after road construction, with no contribution to streams after 10 years.

4. About 1400 miles of road were constructed in the Redwood Creek basin by 1978.
5. A bulk density of 100 lbs/ft^3 (1.6 g/cm^3) based on soil surveys (Popenoe, 1987) was used to convert volumes of eroded cutbank material to mass. (This bulk density was used for all hillslope erosion calculations, unless noted otherwise).

The calculation used was:

10 ft. high cutbanks x 0.13 ft. retreat in 10 years x 5,280 ft/mile = 6,864 ft^3 for each mile of haul road over 10 years x 70% delivery = 4,805 ft^3/mile

4,805 ft^3/mile = 240 tons/mile of haul road over a 10-year period.

240 tons/miles of road x 1400 miles = **336,000 tons from Cutbank erosion**

This estimated yield of 240 tons/mile of road is similar to that of Reid and Dunne's measurement of cutbank erosion of 15 metric tons/km of road per yr (=26.6 tons/mile of road per yr or 266 tons/mile of road in 10 years) for logging roads on the Olympic Peninsula, Washington, but greater than Raines and Kelsey's 1991 estimate of 13.5 tons/mile/yr or 135 tons/mile per 10 year period for Grouse Creek, a 170 km^2 basin adjacent to Redwood Creek.

Surface Erosion from Unpaved Roads

Estimates of surface erosion were based on Reid and Dunne's work (1984) on logging roads in the Clearwater River, Olympic Mountains, Washington. There, under 3900 mm/yr of rainfall on sandstone and graywacke bedrock, the sediment yields from unpaved roads varied by use level:

Heavy use – 500 metric tonnes/km/yr

Moderate use – 42 metric tonnes/km/yr

Abandoned – 0.51 metric tonnes/km/yr

These values need to be adjusted for conditions in the Redwood Creek basin. For Redwood Creek, the amount of surface erosion is probably less than in the Olympics because rainfall totals and rainfall intensities are less. Raines and Kelsey (1991) accounted for the difference in precipitation between Grouse Creek and the Clearwater basin by multiplying sediment yield rates by 0.76 (the ratio of the Grouse Creek R factor (a rainfall and runoff factor) to the Clearwater R factor). Redwood Creek has about the same R-value as Grouse Creek, so the same method was used. Also, the average width of haul roads in the Redwood Creek basin is about 20 ft. (6 m) (based on road inventories of more than 150 miles of roads), which is 1.5 times the average width of roads in the Clearwater basin. Finally, only the sediment washed off from roads that drains into stream channels (via inboard ditches and culverts) should be counted in this sediment budget. From road inventories in the Redwood Creek basin (Spreiter, 1995), 70% of road drainage structures feed into stream channels (are hydrologically connected). Thus, the adjustment factor for Redwood Creek is:

0.76 x 1.5 x 0.70 = 0.80

Erosion from road surfaces is very sensitive to traffic levels (Reid and Dunne, 1984), which in turn is dependent on the type of timber harvest, length of the harvest plan, and post-harvest activities. It was assumed that during the time period 1954–1980, all roads in the Redwood Creek watershed had heavy use for one year during timber harvest, moderate use for three years, and were abandoned the remainder of the time.

1400 miles of road was constructed by 1978 = 2250 km of road.

1. Heavy use: 2250 km x 500 tonnes/km/yr x 1 yr = 1,125,000 tonnes
2. Moderate use: 2250 km x 42 tonnes/km/yr x 3 years = 283,500 tonnes
3. Abandoned: 2250 km x 0.51 tonnes/km/yr x 23 years = 26,400 tonnes

Total = 1,434,900 tonnes = 1,581,000 English tons (from the surface of roads from 1954–1980)

Adjustment factor applied to roads: 0.80 x 1,581,000 tons = **1,265,000 tons.**

If roads were actually heavily used for two years instead of one (which depends on the harvest history and log hauling routes), the total amount eroded over the 27-year period would be:

2.6 x 10^6 tonnes (2.8 x 10^6 English tons) or adjusted sediment production of 2.2 x 10^6 tons.

In Table 1, the smaller amount is listed because the level of road use is not well known.

Skid Trails

Little quantitative information was available for erosion from skid trails. Best *et al.* (1995) determined erosion due to rilling and water diversions on skid trails in the Garrett Creek watershed (this value does not include skid trail stream crossing failures or general surface lowering from sheetwash). There, on about 5 km^2 of lands with logged coniferous forests, 29,182 tonnes of sediment came from erosion on skid trails, or 5836 t/km^2. Best (1984) stated that 348 km^2 (134 mi^2) of the Redwood Creek basin upstream of the Prairie Creek confluence was tractor yarded by 1978. An additional 20.5 km^2 (7.9 mi^2) in Lost Man Creek was logged, and mostly tractor yarded. We applied the erosion rate from skid trails in Garrett Creek to all tractor-yarded lands (142 mi^2) in the Redwood Creek basin:

368.5 km^2 x 5836 t/km^2 = 2,150,566 metric tonnes = **2,371,000 tons**

Erosion from Inboard Ditches

Based on a study of Garrett Creek, a tributary of Redwood Creek (Best *et al.*, 1995),

2,086 tonnes of road material eroded from inboard ditches along 12.7 km of road, or 164 tonnes of material/km of road, from 1956 to 1980.

This erosion rate was applied to the 2,250 km of haul roads in the Redwood Creek basin:

2,250 km x 164 tonnes/km = 369,000 metric tonnes = **407,000 tons**.

Erosion from Haul Road Stream Crossings

Stream crossing failures contribute significant amounts of road fill into stream channels. Various inventories have produced several estimates of this type of erosion in different terrains. The older the road and the more storms it has weathered, the higher the probability that a crossing will have failed. Eighty percent of the roads in the Redwood Creek basin were built before the large storms in 1972 and 1975, and 66% of them were built before the 1964 flood. Many crossings failed and were rebuilt, only to fail again. Hagans and Weaver (1987) measured failures of crossings in haul roads and skid trails on 2214 ha in Redwood National Park, and the average crossing failure volume was 63 yd^3 (48 m^3). Measurements for skid trail crossings were not distinguished from haul road crossings, and this value is considered to be low for the watershed as a whole. Best (unpublished data) measured erosion at 140 stream crossings. He found the average failed crossing volume (n = 51) was 208 yd^3 (159 m^3). The Redwood National Park inventory of more than 900 stream crossings (Spreiter, 1995) listed the average volume eroded from all stream crossings as 230 yd^3 (176 m^3), which includes crossings with no failure volume. In Garrett Creek (Best *et al.*, 1995) 111 crossings were inventoried. Of these, about 50% of the crossings failed during the study period, and a typical failure volume was 74–186 m^3 (97–243 yd^3). This value could be refined if failure rates were stratified by age of road and slope position, but that task has not been completed. In the present version of the sediment budget, we assumed a failure rate of 50% during the study period (1954 to 1980) and used a value of 200 yd^3 an estimate of erosion from failed stream crossings in the Redwood Creek basin.

The next step was to estimate the number of stream crossings in the Redwood Creek basin. Field mapping and air photo interpretation during various studies (Bundros, Klein, Alpert; Redwood National Park, unpublished data) inventoried the number of stream crossings on 90 mi^2 in the lower

Redwood Creek basin (one-third of the basin area). The number of crossings ranged from 21 to 45 crossings/mi^2. For this budget an intermediate value of 30 crossings/mi^2 was used.

Upstream of park boundaries: 162 mi^2 of roaded lands x 30 crossings/mi^2 = 4,860 crossings

Park lands: 116 mi^2 − [24,315 acres of old growth, or 38 mi^2] = 78 mi^2

78 mi^2 x 30 crossings/mi^2 = 2,348 crossings

For this basin, a total of 7,200 crossings is equivalent to about 5 crossings/mile of haul road. Individual subbasins range from 2 to 14 crossings/mile of haul road, depending on the position and size of road and the drainage density of the terrain.

The estimated sediment input from haul road crossing failures during this time period is:

7,200 crossings x 50% failure rate x 200 yd^3/failed crossing = 720,000 yd^3

720,000 yd^3 x 1.62 tons/yd^3 = **1,166,000 tons** from 240 mi^2 of roaded land

(roaded lands include prairies and oak woodlands as well as forests)

(A bulk density of 1.62 tons/yd^3 (120 lbs/ft^3) was used because of the rocky composition of road fill). This estimate is equivalent to a sediment production of 4860 t/mi^2. This value is lower than that for the nearby upper mid-Grouse Creek basin measured by Raines and Kelsey (2.79 m^3/ha, or 7800

t/mi^2), but higher than that for upper Grouse Creek and Cow Creek (900 to 1000 t/mi^2) (Raines and Kelsey, 1991).

Skid Trail Crossings

Various road and hillslope inventories (Best, Alpert, Spreiter; unpublished data) documented average skid trail crossings to be 25 to 50 yd^3 in size. Several assumptions were used to estimate an erosion rate from skid trail crossing failures on tractor logged hillslopes:

1. Skid trail density was 16 to 42 km/km2 (Best, unpublished data), which is two to five times the haul road density. Some areas have skid trail densities 7.5 times haul road densities (Redwood National Park, 1981). So, we assumed skid trail crossing density was four times that of haul road crossings, or 120 crossings/mi2 of tractor-logged terrain.
2. Assumed average crossing failure volume from skid trail crossings was 25 yd3.
3. Assumed 75% of skid trail crossings failed during this time period (field observations seem to bear out a higher failure rate in skid trail crossings than in haul road crossings)
4. Best's 1984 land use report stated that about 348 km2 of the Redwood Creek basin was tractor yarded, and an additional 20.5 km2 were cut in the Lost Man area, or 368 km2 (142 mi2)

142 mi^2 x 120 crossings/mi^2 x 25 yd^3 x 75% = 321,750 yd^3 = **517,000 tons** from failures of skid trail crossings.

Surface Erosion from Disturbed Ground

Surface erosion of bare ground disturbed during logging operations is highly variable, and depends on many factors, such as soil type, slope steepness, and rainfall intensity following soil disturbance. Previously reported estimates of surface erosion have since been refined based on more recent data. Hagans and Weaver (1987) estimated the amount of material eroded from bare ground based on sediment trough data (0.05 to 0.1 cm of ground surface lowering during the first winter following ground disturbance). Hagans and Weaver stated that only 3,600 ha of bare ground (1/3 of the harvested area of 10,770 ha of Park lands) would actually contribute sediment from surface erosion to streams. Using soil maps compiled by Popenoe (1987), they estimated that surface erosion delivered 124,400 m^3 (34.6 m^3/ha) to streams from 1954 to 1980. This assumes that bare ground only contributed sediment for the first year after disturbance, because many slopes become armored and revegetated in following years.

1/3 x 10,770 ha = 3,600 ha

3,600 ha x 34.6 m^3/ha=226,000 tons

That rate of ground lowering was roughly similar to what Marron *et al.* (1995) measured from erosion pins installed on bare ground (0.03 cm to 0.46 cm/yr), although their 1995 report has a higher upper range for erosion. Because the high rate of surface erosion from Marron *et al.* (1995) report was not included in Hagans and Weaver's estimates, their 1987 estimate should be considered a minimum.

Next, the value of 34.6 m^3/ha was extrapolated to the remaining area of the drainage basin. Best (1984) stated that between 1949 and 1978, 25,445 ha (62,876 ac) of the Redwood Creek watershed was logged upstream of Redwood National Park boundaries. This estimate only includes the original logging of old-growth forests and does not include later reentries and harvest of second-growth. By 1970, 65 percent of the original coniferous forests of the basin had been logged, and practically all of that was tractor-yarded. Cable logging became more common in steep areas adjacent to streams between 1970 and 1978, but less than 6% of the watershed was cable yarded (Best, 1995). For this rough estimate of surface erosion, erosion from disturbed lands on cable yarded cuts was treated the same as on tractor-yarded areas. The assumption was that, as in lower Redwood Creek, only one-third of the disturbed ground contributed sediment to a stream channel (Hagans and Weaver, 1987). Another assumption was that soils in the upper basin eroded at similar rates at those in lower Redwood Creek.

More detailed soil surveys were completed by the U.S. Natural Resource Conservation Service (2008) and further refinements to these estimates could be made. However, current land management policy addresses surface erosion through improved road maintenance, hydrologic disconnection, and mulching freshly disturbed surfaces, so RNP has not prioritized a recalculation of surface erosion estimates.

The calculation of surface erosion from the upper basin is as follows:

1/3 x 25,445 ha = 8,400 ha

8,400 ha x 34.6 m^3/ha=290,640 m^3 = 380,500 yd^3=514,000 tons

The Lost Man Creek basin was not included in Best's 1995 study. In Lost Man Creek, approximately 2,050 ha were logged:

1/3 x 2,050 ha x 34.6 m3/ha =23,400 m3 =30,615 yd3 = 41,000 tons

Total amount of surface erosion:

41,000 tons – Lost Man Creek

226,000 tons – Redwood National Park lands upstream of Prairie Creek

514,000 tons – Land upstream of Redwood National Park boundaries.

800,000 tons

Gullies

In this study, gullies are defined as newly formed, narrow channels that usually carry water only during and after storms. In forested areas, gullies are not part of the natural hydrologic network; rather they are caused by diversion of runoff from roads or other disturbances. Natural gullies can form on unstable land, such as earthflows (discussed later), where shifting land diverts water onto unchanneled hillslopes, causing gullies.

A) Prairie gullies:

From field measurements and air photo interpretation Walter (1985) estimated the sediment production from gullies on all prairies in the Redwood Creek basin, including both natural and road-related gullies, to be 248,411 m^3 (**440,000 tons**) between 1954 and 1978.

Nolan and Janda (1995) conducted detailed gully measurements on two very active earthflows (included under "prairie" classification) from 1977 to 1982. They determined that gullies only contributed 7 to 8 % of the total sediment input from those sites, or about 60 to 2000 tonnes/km^2/yr. Prairie land in the Redwood Creek basins is ~56 km^2 (Best, 1995). Consequently, a range of gully contribution is:

60 tonnes/km^2/yr x 56 km^2 x 27 years = 90,700 tonnes = ~100,000 tons

2,000 tonnes/km^2/yr x 56 km^2 x 27 years = 3,024,000 tonnes= ~3,333,000 tons

Because the prairies in the Nolan and Janda study were eroding more actively than most prairies, based on field observations, we used Walter's estimate of 440,000 tons.

B) Forested lands

Gullies are a common erosional feature on lands that have had timber harvest and road construction. Most gullies are caused by stream diversions, where water flows across a road and down a hillslope that did not originally have a channel. Such diversions are commonly caused by plugged or misplaced culverts. Stream diversions on roads produced most of the largest gullies and the bulk of hillslope erosion from the roaded areas. For example, Weaver *et al.* (1995) documented that 94% of the total volume of hillslope erosion in the South Copper Creek study site was caused by diversions. In addition, Best *et al.* (1995) found that 66% of road-related fluvial erosion in the Garrett Creek watershed was caused by stream diversions.

1. **Within Redwood National Park boundaries:**

   Weaver *et al.* (1995) extrapolated field measurements of gully erosion on 22 km^2 of logged lands to all logged lands within the park. Their estimate of sediment derived from gully erosion is 1.74 x 10^6 tonnes **(1.92 x 10^6 tons).**

2. **Upstream of Redwood National Park's boundary:**

   Hagans and Weaver's extrapolation (1987) used soil classifications to define high, moderate and low yield terrains for gully erosion. Popenoe (personal communication) categorized Hugo and Masterson soils as those most susceptible to fluvial erosion. In the Park Protection Zone and upper basin 15,272 acres(6,180 ha) are underlain by these soil types, so the high yield rate of Hagans and Weaver (260 m^3/ha) was applied to this area. Stable soils, in terms of gully erosion, are Trailhead and Orick soil types (Popenoe, personal communication) which produce only 3 m^3/ha. Upstream of park boundaries only 476 ac (193 ha) are underlain by these soils. In the remainder of the upper basin (25,620 ha), soils were considered to be at moderate risk from gully

erosion, and we applied Hagans and Weaver's value for moderate yields (64 m^3/ha). The estimate of gully erosion for lands upstream of the park and for the Lost Man Creek basin (excluding prairies), is:

6,180 ha x 260 m^3/ha = 1,607,000 m^3

193 ha x 3 m^3/ha = 579 m^3

25,620 ha x 64 m^3/ha = 1,640,000 m^3

2,050 ha x 64 m^3/ha = 131,000 m^3 (estimate for Lost Man basin)

Total = 3,378,579 m^3 = 5,966,000 tons

Total gully yield for Redwood Creek basin:

440,000 tons – prairies

1,920,000 tons – in Redwood National Park, excluding prairies

5,966,000 tons – upstream of park, and Lost Man Basin

Total = 8,326,000 tons

STREAMBANK EROSION

Streambank erosion along tributaries

The length of stream channels of various stream orders was determined by using Redwood National Park's geographic information system, based on blueline streams shown on USGS 1:24,000 topographic maps, with extensions of small channels based on contour crenulations.

The amount of streambank erosion for each order stream was extrapolated from measurements by Raines and Kelsey (1991) in the adjacent basin of Grouse Creek. Field observations in tributary basins of Redwood Creek and cross-sectional survey data in third- and fourth-order streams (1974 to 1988, unpublished data) support these extrapolated values. These values of streambank erosion in tributaries did not include streamside landsliding (which is documented in a later section). The time frame of streambank erosion was difficult to pinpoint exactly. Undercutting of young tree roots and the prominence of bare banks suggested recent erosion, but not precise timing. The value of sediment production from tributary streambank erosion for Redwood Creek could be refined by stratifying tributaries by bedrock and land use, and by making more intensive field measurements, but this step was not done.

Table E-1. Streambank erosion along tributaries.

Stream Order	Miles of Channel (Length in Meters)	Streambank Erosion (m^3/m)*	Sediment Production (m^3)	Sediment Mass (tons)
1	1529 (2.46 x 10^6)	0.17	418,000	739,000
2	473 (761,220)	1.63	1,240,788	2,190,000
3	183 (294,510)	1.57	462,381	816,000
4	86.2 (138,725)	0.20	27,745	49,000
5	61.2 (98,492)	0.31	30,532	54,000
TOTAL				**3,848,000**

* Based on Raines and Kelsey (1991) streambank erosion values for Grouse Creek.

Mainstem bank erosion

The active channel width of Redwood Creek was defined by the width of bare or sparsely vegetated gravel bars and the low flow channel of Redwood Creek. The active channel width increased greatly in several reaches of Redwood Creek during the 1964 flood, and to a lesser extent, during the 1972 and 1975 floods (Nolan and Marron, 1995). Channel widening does not automatically translate into bank erosion, however, because much of the channel widening was due to an excessive amount of gravel being deposited on surfaces that were formerly covered with trees and shrubs. Also, streamside landslides were tabulated separately, and erosion of the toes of such slides was included under that category. Although cross section measurements yield the most accurate values for bank erosion, cross section data were not available to assess the effects of the 1964 and 1972 floods. In addition, cross section monuments were commonly established on stable points, such as bedrock outcrops, so cross section surveys may not be representative of typical bank conditions in a reach.

Bank erosion along Redwood Creek was documented in two ways. The first was by field mapping of erosion features. Field evidence of bank erosion included undercut tree roots and toppled streamside trees. This estimate is a minimum, however, because once the tree is washed away, little evidence for the amount of lateral retreat remains. The second method used sequential aerial photographs from 1954, 1958, 1965 and 1978 to measure bank erosion. The problem with using air photos is that determining accurate scales from older air photos was difficult. The exact location of streambanks was commonly obscured by shadows from large streamside conifers. It was also difficult to determine accurate bank heights. Bank height information was gleaned from the recent cross section surveys and field mapping. Channel widening through the erosion of three large gravel bars during the 1964 flood accounted for 25% of the total mainstem bank erosion. Although the alluvium in these bars originally was derived from upslope erosion processes, these were stable bars that had been deposited prior to 1954. Thus, counting erosion of these bars as sediment production during this time period is not double counting the volume of sediment. The mass of sediment derived from streambank erosion along Redwood Creek between 1954 and 1980 was **2,070,000 tons.**

MASS MOVEMENT

Streamside landslides along the mainstem of Redwood Creek

Kelsey *et al.* (1995) determined the volume of material contributed by streamside debris slides and earthflows along the mainstem of Redwood Creek. Landslide volumes were measured in the field, with supplemental measurements from air photos. Between 1954 and 1980, 4,000,100 m^3 (**7,100,000 tons**) of material entered Redwood Creek from these slides.

Landslides in tributary basins

Pitlick (1995), through a combination of field mapping and air photo interpretation, determined the contribution of streamside debris slides in 16 tributary basins in the Redwood Creek basin. Almost 90% of the slides occurred post-1954, and these slides contributed **3,900,000** tons of sediment to tributary channels. He also classified tributary basins and their associated contribution of landslide material during the period 1954–1978 as:

Redwood dominated vegetation, Low relief: – 5,000 t/km^2

Redwood dominated vegetation, High Relief: – 13,800 t/km^2

Douglas-fir dominated vegetation, High Relief: – 26,100 t/km^2

We extrapolated those rates of sediment production from streamside landslides to tributary basins which were not sampled and mapped during Pitlick's study.

Douglas-fir, High Relief basins: 142 km^2 x 26,100 t/km^2 = 3,706,200 tonnes

Redwood, Low Relief basins: 42.5 km^2 x 5,000 t/km^2 = 212,500 tonnes

Redwood, High Relief basins 2.9 km^2 x 13,800 t/km^2 = 40,020 tonnes

Lost Man Creek, also Redwood, Low Relief: (40.89 km^2 x 5000 t/km^2 = 204,450 tonnes

Total debris slide input from unsampled tributaries: 4,163,000 tonnes (**4,600,000 tons**).

Earthflows

The most areally extensive mass movement features in the watershed are earthflows (Nolan *et al.,* 1976; Harden *et al.,* 1978). The total area covered by active earthflows represents about 10% of the Redwood Creek watershed upstream of the confluence of Redwood and Prairie Creeks and very active earthflows comprise 2% of this area (~5 mi^2) (Harden *et al.,* 1978). The earthflows classified as "very active" can be considered streamside landslides in that they deliver sediment directly to major channels, but we quantified them separately from the shallow streamside landslides described above.

Earthflows are slow-moving (0 to 20 feet per year) persistent landslides. They are generally grass-covered rather than forested, and are often gullied (Gully erosion on these features was counted under "Prairie gullies.") Studies in and near the Redwood Creek watershed by Kelsey (1978; 1980), Harden *et al.* (1978), Nolan *et al.* (1979), Iverson (1984) and Iverson and Major (1987) have shown that earthflows deliver sediment to stream channels through both mass movement and fluvial processes and that earthflow movement is related to annual rainfall and patterns of groundwater flow. Movement rates vary widely in both space and time. For example, sediment yields from two

earthflows monitored from 1977 to 1982 ranged from 1,890 to 64,750 t/mi^2/yr and movement rates at the earthflow toes ranged from 0.02 to 10.25 m/yr (Nolan and Janda, 1995). This wide variation makes extrapolation of data to the entire watershed difficult. On a local scale, earthflows influence sediment input and channel morphology (Nolan and Janda, 1995). Nevertheless, on a watershed scale, earthflows contribute relatively little sediment to Redwood Creek (Kelsey *et al*., 1981; 1995). Based on air photo analysis in the 1980s, they estimated that during the period from 1954 to 1980 earthflows contributed only about 1% of the total landslide volume that they mapped in the Redwood Creek basin, or about 133,000 tons.

However, more detailed, long-term data collection at the Minor Creek earthflow since that early estimate has provided more information. The Minor Creek earthflow, a prominent earthflow in the Redwood Creek basin, has been monitored for almost 30 years. During the 1997 storm season it moved about 1.7 m (Mark *et al.,* 2002). The average width of the earthflow is 100 m and depth at the toe is about 5 m, so the earthflow contributed about 850 m^3 of sediment to Minor Creek, a tributary of Redwood Creek in 1997. Average movement of the Minor Creek earthflow is less, though, only 0.42 m/yr, with a net sediment flux of 4000 m^3 during a 27-year period (equivalent to about 10,000 tons/mi^2 of earthflow per year) (Mark *et al.,* 2002). For the sediment budget period (1954 to 1980) we applied this sediment yield rate to the 5 mi^2 of very active earthflows in the Redwood Creek basin:

10,000 tons/mi^2 x 5 mi^2 =50,000 tons per year total from earthflows

50,000 tons per year x 27 years = **1,350,000 tons**

The above estimate is based on the aerial extent of earthflows (sediment delivered on a per square mile of earthflow area). However, a long, narrow earthflow may not contribute as much material to a stream channel as an earthflow of the same area but that is short and wide. So, another approach is to assess sediment input by the length of earthflow toes actively contributing to stream channels and applying the average downhill movement of 0.42 m/yr and the average streambank height of 5 m. An air photo inventory in 1997 measured the length of streambank bordered by the toes of active earthflows (Madej, unpublished data). There are 7.2 miles of active earthflow toes in tributary basins and 4.4 miles along the mainstem of Redwood Creek.

7.2 + 4.4 = 11.6 miles of active earthflow toes (18,668 m).

18,668 m x 5 m x 0.42 m/yr = 39,203 m^3 = 51,277 yd^3

51,277 yd^3 x 1.59 tons/yd^3 = 81,531 tons/year

81,531 x 27 years = ~2,200,000 tons

So, estimates of earthflow sediment contribution during the sediment budget time period of 1954–1980 range from 133,000 to 2,200,000 tons. We used an estimate of 1,350,000 tons in Table 1 as an intermediate value. In any case, earthflows are a small percentage of total sediment input during this time period.

Forested Block Slides

Forested block slides are a type of slow-moving landslide typically located near shear zones on schist terrain. They behave somewhat like earthflows, but natural movement rates are typically slow enough to permit the establishment and maintenance of a coniferous forest. Sonnevil *et al.* (1987) estimated 64,150 m^3 (113,000 tons) of sediment was derived from block slides from schist terrain within the park between 1954 and 1980. The area of Park lands underlain by Redwood Creek schist is about 14,500 ha, or 145 km^2.

(64,150 m^3/145 km^2 = 442 m^3/km^2)

We assumed that the same rate of blocksliding occurs on the schist terrain upstream of the park boundary: 3,846 ac of South Fork Mountain schist and 42,481 ac of Redwood Creek schist. We also assumed that forested block slides will deliver sediment directly into stream channels.

46,327 ac = 18,748 ha = 187.5 km^2

187.5 km^2 x 442 m^3/km^2 = 83,000 m^3 = 147,000 tons from upstream of park + 113,000 tons – Park lands

Total = 260,000 tons

Debris torrents

The estimate of sediment production from landslides in the above section only considered those slides adjacent to high order (third to fifth order) channels. In some parts of the basin, especially those underlain by the Incoherent Unit of Coyote Creek (44,673 ac or 181 km^2), debris torrents are common higher on the hillslopes and contribute sediment into lower order stream channels. The Garrett Creek study (Best *et al.,* 1995) reported a rate of 4,021 t/km^2 of sediment from road-related debris torrents from 1956 to 1980, and in the adjacent basin of Grouse Creek Raines and Kelsey (1991) reported a similar rate for debris torrents of 4,830 t/km^2 during the same time period.

Based on the above values, an estimated yield from debris torrents for the Redwood Creek basin was:

181 km^2 of "Incoherent" terrain x 4,500 tonnes/km^2 = 814,500 tonnes = 900,000 tons

The above estimate did not include debris torrents originating on schist terrain, however. During the January 1997 storm (a 12-year return interval event) many debris torrents originated from roads built on schist terrain. We assume that such debris torrents were generated in past large storms, although we have no measurements of past torrents. Curry (2007) reported that 160,000 m^3 (335,000 tons) of material was delivered to stream channels from 91 debris torrents on schist terrain in 1997. We assume that this level of failure would have also occurred sometime during the sediment budget period. Because there were several large storms during the period covered by this sediment budget, multiple episodes of torrenting probably occurred, so this estimate may be low.

From 1954–1980, debris torrents are estimated to have produced a minimum of:

900,000 tons – sandstone terrain

335,000 tons – schist terrain

Total = 1,235,000 tons

CHANGE IN CHANNEL-STORED SEDIMENT

Change in Sediment Storage in Tributaries

Pitlick (1995) estimated the total amount of sediment stored in 74 tributaries to be 2 x 10^6 tonnes (2.2 x 10^6 tons). However, this is not a change in storage because the tributaries had already stored some sediment behind log jams and in gravel bars before the large floods of 1964, 1972 and 1975 occurred. We had no data on pre-1954 tributary sediment storage. Madej (1987) reported that 60–100% of recent flood deposits in tributaries were flushed out within 10 years of the flood, based on an analysis of tributary cross section data from 1974 to 1986. So, in this sediment budget we estimate that 80% of the amount of sediment that Pitlick measured in the tributaries was there before the flood, because the "excess" flood deposits would have been quickly flushed out of the steep tributary channels.

> 2,200,000 tons x 20% = **440,000 tons** = Net addition to storage in tributary stream channels from 1954 to 1980

Change in Sediment Storage in Redwood Creek

Based on field measurements and air photo interpretation, Madej (1995) estimated that there was a net increase of 9.4 x 10^6 tonnes (10,400,000 tons) of sediment stored in the channel of Redwood Creek from 1947 to 1980. Most of this sediment was deposited during the 1964 flood. Details of field methodology and locations of sediment storage are listed in the 1995 reports. Total addition to channel storage in the sediment budget period is about **10,400,000 tons.**

SEDIMENT OUTPUT

Bedload and suspended sediment have been measured near the mouth of Redwood Creek at the Orick gaging station since 1971. The U.S. Geological Survey publishes yearly summaries of these gaging efforts in their annual Water Resources Data reports. In addition, Knott (USGS, unpublished memo, 1981) estimated the probable sediment yields before gaging stations were established for the period of 1954 to 1971. The total sediment output for Redwood Creek, including both bedload and suspended sediment discharge, for the period 1954 to 1980 was **45,000,000 tons.**

Limitations to sediment budget calculations

Many of the estimates included in this sediment budget were based on limited field data or were extrapolated from studies conducted elsewhere. In addition, reentry of previously disturbed lands for harvest of second- and third-growth forests was not considered. More intensive field mapping since the 1980s led Park staff to identify more abandoned logging roads than in earlier estimates. Only one failure episode was considered because we could only document the most recent failure. For example, it is difficult to discern if road crossings or road reaches failed, were rebuilt, and failed again, although we know this sequence sometimes occurred on the landscape. Five large storms occurred during the sediment budget period, and evidence of earlier failures may have been destroyed by more recent events. The U.S. Geological Survey (in letter dated 1984) estimated a 20–30% accuracy of their daily suspended load measurements 95% of the time. Because there were no sediment records for the period 1954–1970, their estimates of sediment yield for that time period are necessarily subject to a greater (but unknown) error.

A sediment budget theoretically should balance; that is:

Sediment Input – Increase in Sediment Storage = Sediment Output.

The sediment budget as presented here does not balance perfectly. If we insert the numbers of sediment input, storage and output into the above equation, it may look like about 16,000,000 tons of sediment is "missing," (about a third of the total sediment output). This probably does not mean we are missing a single sediment source that contributed 16,000,000 tons of sediment, however, because there is some source of error in estimating each element of the budget. These errors can easily be in the range of 30%. Nevertheless, the budget is a useful tool to indicate of the relative magnitude of different sediment sources. For example, landslides and road-related erosion are by far the dominant sources of material entering stream channels, whereas surface erosion and streambank erosion play a smaller role. The network of unmaintained logging roads in the Redwood Creek watershed was a dominant source of preventable erosion during the sediment budget period; consequently, Redwood National Park focused its watershed restoration efforts on the removal or upgrades of these roads. Future monitoring of erosion response following large floods in Redwood Creek will shed more light on erosion and sediment dynamics in the Redwood Creek basin, as well as determining the effectiveness of watershed restoration efforts.

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