National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Groundwater Monitoring Protocol and Standard Operating Procedures

Sonoran Desert, Chihuahuan Desert, and Southern Plains Networks, Version 1

Natural Resource Report NPS/SODN/NRR—2014/787



ON THE COVER

Measuring depth to water. National Park Service photograph.

Groundwater Monitoring Protocol and Standard Operating Procedures

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Natural Resource Report NPS/SODN/NRR—2014/787

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March 2014

U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

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Please cite this publication as:

Filippone, C. L., K. Beaupré, D. Angell, M. H. Reiser, E. Gwilliam, J. A. Hubbard, K. Gallo, M. D. Jacobson, and H. Sosinski. 2014. Groundwater monitoring protocol and standard operating procedures: Sonoran Desert, Chihuahuan Desert, and Southern Plains networks, version 1. Natural Resource Report NPS/SODN/NRR—2014/787. National Park Service, Fort Collins, Colorado.

NPS 960/124186, March 2014

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Abstract

Groundwater monitoring provides a window into a vital resource that knows no political or jurisdictional boundaries. The knowledge gained through groundwater monitoring has direct application in the planning and sustainable management of all NPS ecosystem resources. The groundwater-monitoring program of the Sonoran Desert, Chihuahuan Desert, and Southern Plains inventory and monitoring networks are designed to provide water-level data for tracking long-term depth to water and water-level elevation. In combination with climatic and surficial monitoring, these data provide improved understanding of local water balance and groundwater dynamics, and support interpretation of the results of surface monitoring of biotic and abiotic resources.

The monitoring program summarized here includes both point-in-time measurements and water-level time-series using sensors equipped with recording capabilities. Data management procedures developed to facilitate access, quality assurance, sharing within and outside the National Park Service, and long-term archiving are also described.

Acronyms

ADWR	Arizona Department of Water Resources
AMA	active management area
bgs	below ground surface
BIBE	Big Bend National Park
CAGR	Casa Grande Ruins National Monument
CHDN	Chihuahuan Desert Network
CHIR	Chiricahua National Monument
CORO	Coronado National Memorial
FGDC	Federal Geographic Data Committee
FOBO	Fort Bowie National Historic Site
GICL	Gila Cliff Dwellings National Monument
GPS	Global Positioning System
GRD	Groundwater Resource Division
GUMO	Guadalupe Mountains National Park
GWSI	Groundwater Site Inventory
I&M	inventory and monitoring
MOCA	Montezuma Castle National Monument
MP	measuring point
NHP	national historical park
NHS	national historic site
NIST	National Institute of Standards and Technology
NM	national monument
NMEM	national memorial
NP	national park
NPS	National Park Service
NRA	national recreation area
NWIS	U.S. Geological Survey National Water Information System
ORPI	Organ Pipe Cactus National Monument
PHDI	Palmer Hydrological Drought Index
QA/QC	quality assurance/quality control
SAGE	Saguaro National Park (Rincon Mountain District)
SAGU	Saguaro National Park
SAGW	Saguaro National Park (Tucson Mountain District)
SODN	Sonoran Desert Network
SOP	standard operating procedure
SOPN	Southern Plains Network
SWNC	Southwest Network Collaboration
TONT	Tonto National Monument
TWDB	Texas Water Development Board
TUMA	Tumacácori National Historical Park
TUZI	Tuzigoot National Monument
TWDB	Texas Water Development Board
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
UTC	Coordinated Universal Time
WRD	Water Resources Division
WSR	Wild and Scenic River

Acknowledgements

As is always the case, this protocol reflects the contributions of many. We are especially indebted to the scientists and National Park Service personnel who have dedicated themselves to the understanding of hydrological processes in the arid and semiarid southwestern United States.

Special thanks are extended to Larry Martin, of the National Park Service Water Resources Division, who has generously shared his time, expertise, and overall support to the understanding and protection of National Park Service groundwater resources for many years. Thanks are extended to Don Bills, of the U.S. Geological Survey, Flagstaff Science Campus, for his cooperation in locating information on the cleaning and calibration of sounders. Thanks also to Nina Chambers, of the Chihuahuan Desert Network, for her helpful review and edits.

Protocol Narrative

Revision History Log						
Previous Version #	**Revision date**	**Author**	**Changes made**	**Section and paragraph**	**Reason for change**	**New Version #**

1 Background

The core mission of the National Park Service (NPS), as outlined in the agency's 1916 Organic Act, is the protection and preservation of natural and cultural resources for future generations. Responding to criticism that it lacked basic knowledge of natural resources within parks, the NPS initiated the Inventory and Monitoring (I&M) Program to detect long-term changes in ecosystems (NPS 1992). Parks with significant natural resources were assigned to one of 32 monitoring networks, each based on ecological similarity and geographic proximity. Each network was charged with developing a monitoring program capable of detecting long-term changes in physical and biological resources within its assigned park units.

1.1 The Southwest Network Collaboration

This protocol has been developed and is being implemented as a joint protocol of the Southwest Network Collaboration (SWNC). SWNC is a joint effort between the natural resource I&M programs of the NPS and U.S. Fish and Wildlife Service (USFWS). The NPS partners are the Sonoran Desert Network, Chihuahuan Desert Network, and Southern Plains Network (Figure 1-1). The USFWS partners are the Sonoran and Chihuahuan Deserts Zone and Plains and Playas Zone. Through this collaboration, the programs share monitoring protocols as well as data collection and reporting duties. The goal of the SWNC is to improve effectiveness and efficiency across all five networks.

Under the SWNC, the networks, in varying combinations, share protocols, training, data management, and reporting responsibilities for eight different protocols: air quality, climate, invasive exotic plants, groundwater, landbirds, surface water (streams and seeps/springs/tinajas), and terrestrial vegetation & soils, as well as trail cameras. In some cases, field crews are shared across the programs. For protocols shared across programs, the methods and datasheet templates used by field crews are uniform. Data management duties are shared among the networks' data management staff. The data for all programs collaborating on a given protocol are stored in a central database accessible to all of the networks. In most cases, analysis and reporting duties are assigned to a single network.

1.2 Participating networks

The three NPS SWNC networks are collaborating on this groundwater monitoring protocol. (The USFWS partners are in the early stages of groundwater program development.)

The Sonoran Desert Network (SODN) includes 11 parks in southern Arizona and New Mexico (Figure 1-1, Figure 1-2, Table

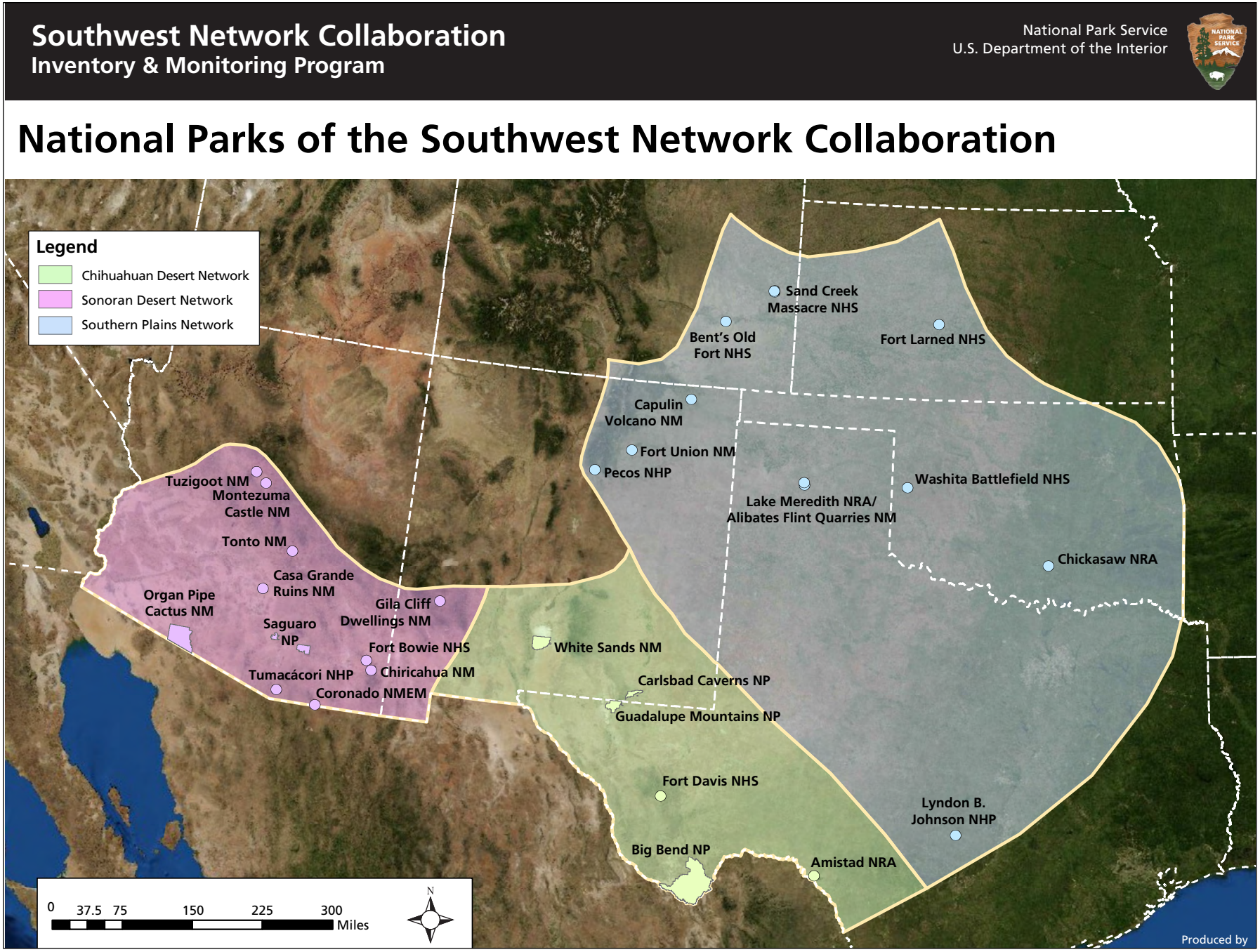


Figure 1-1. National park units of the Southwest Network Collaboration.

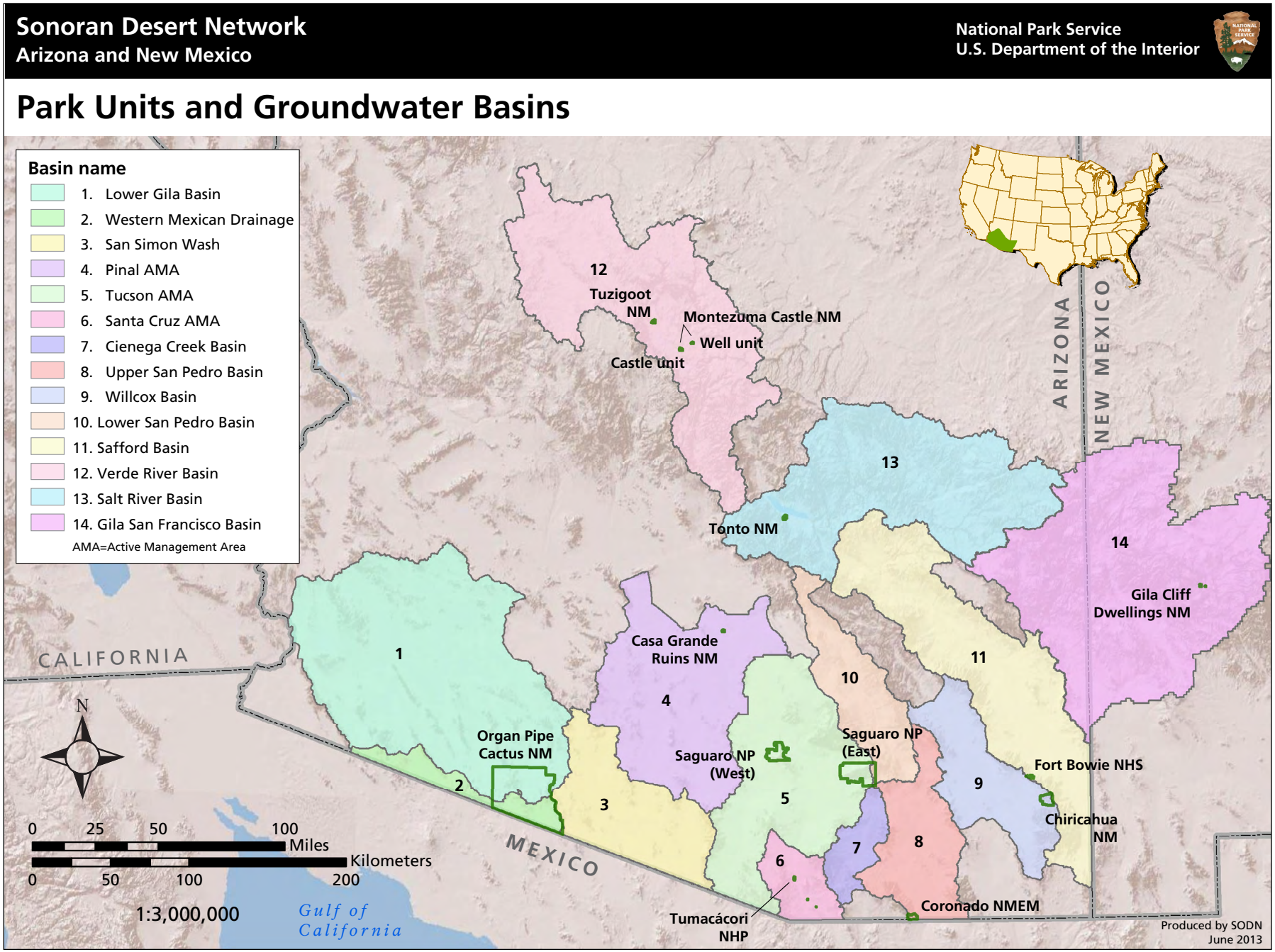


Figure 1-2. National park units and groundwater basins of the Sonoran Desert Network.

Table 1-1. Parks of the Sonoran Desert Network.

Park*	Park code	Regional aquifer/Ecoregion1 (State)	Area	
			ac[2]	ha
Casa Grande Ruins NM	CAGR	Basin and Range basin-fill aquifer/Sonoran Desert (AZ)	473	191
Chiricahua NM	CHIR	Basin and Range basin-fill aquifer/Apache Highlands (AZ)	11,985	4,850
Coronado NMEM	CORO	Other rocks (minor aquifer, not a principal aquifer or confining unit)/ Apache Highlands (AZ)	4,830	1,955
Fort Bowie NHS	FOBO	Other rocks (minor aquifer, not a principal aquifer or confining unit)/ Apache Highlands (AZ)	999	404
Gila Cliff Dwellings NM	GICL	Other rocks (minor aquifer, not a principal aquifer or confining unit)/ Arizona-New Mexico Mountains (NM)	533	216
Montezuma Castle NM	MOCA	Basin and Range basin-fill aquifers/Apache Highlands (AZ)	859	348
Organ Pipe Cactus NM	ORPI	Basin and Range basin-fill aquifers/Sonoran Desert (AZ)	330,689	133,825
Saguaro NP	SAGU	Basin and Range basin-fill aquifers/Sonoran Desert and Apache Highlands (AZ)	91,442	37,005
Tonto NM	TONT	Basin and Range basin-fill aquifers/Sonoran Desert (AZ)	1,120	453
Tumacácori NHP	TUMA	Basin and Range basin-fill aquifers/Apache Highlands (AZ)	360	146
Tuzigoot NM	TUZI	Basin and Range basin-fill aquifers/Apache Highlands (AZ)	812	329

[1] Regional aquifer based on http://nationalatlas.gov/mapmaker. Ecoregions based on The Nature Conservancy (2008).

[2] Acreage from NPS (2012).

*see page vii for acronyms

1-1), ranging in size from 146 hectares (ha) (Tumacácori National Historical Park; NPS 2012) to 133,825 ha (Organ Pipe Cactus National Monument). Groundwater monitoring will be conducted at Chiricahua National Monument (NM), Coronado National Memorial (NMEM), Fort Bowie National Historic Site (NHS), Montezuma Castle NM, Organ Pipe Cactus NM, Saguaro National Park (NP), Tonto NM, Tumacácori National Historical Park (NHP), and adjacent to Casa Grande Ruins NM and Tuzigoot NM.

The Chihuahuan Desert Network (CHDN) includes seven parks located from south-central New Mexico through southwest Texas (Figure 1-1, Table 1-2, Figure 1-3). These units range in size from 212 ha (Fort Davis NHS) to 324,220 ha (Big Bend NP). Collectively, these parks represent most of the ecological communities present within the greater Sonoran and Chihuahuan Desert ecoregions (NPS 2005; NPS 2010). Groundwater monitoring will be conducted in Big Bend NP, Carlsbad Caverns NP, Fort Davis NHS, Guadalupe Mountains NP, and White Sands NM.

The Southern Plains Network (SOPN) includes 11 parks in Colorado, Kansas, New Mexico, Oklahoma, and Texas (Figure 1-1, Table 1-3, Figure 1-4), ranging in size from 127 ha (Washita Battlefield NHS) to 18,202 ha (Lake Meredith National Recreation Area; NRA). Groundwater monitoring is ongoing at Chickasaw NRA and Bent's Old Fort NHS. Opportunities for monitoring at Pecos NHP and other SOPN parks are being investigated.

Prior to the start of monitoring, staff from each network completed a monitoring plan that identified "vital signs" selected from a diverse range of natural resources, including air, water, climate, soils, plants, invertebrates, and vertebrates (NPS 2005; CHDN 2010). The intent of the NPS I&M Program is to track a subset of physical, chemical, and biological elements of park ecosystems, called vital signs, that are selected to represent the overall health or condition of park resources, known or hypothesized effects of stressors, or elements that have important human values. The status of each vital sign is tracked using systematic, repeated data collection, or monitoring, developed to track the overall condition of the natural resource represented by the vital sign. Hydrology workgroups at each network evaluated high-priority water resource issues and identified candidate vital

signs on the basis of ecological significance, feasibility, and relevance to management (NPS 2005; CHDN 2010). Groundwater quantity was considered among the most important and feasible hydrological parameters for long-term monitoring at each of the NPS SWNC networks.

Table 1-2. Parks of the Chihuahuan Desert Network.

Park	Park code	Regional aquifer/Ecoregion1 (State)	Area	
			ac[2]	ha
Amistad NRA	AMIS	Edwards-Trinity aquifer system/Tamaulipan Thornscrub (TX)	58,500	23,674
Big Bend NP	BIBE	Other rocks (minor aquifer, not a principal aquifer or confining unit)/Chihuahuan Desert (TX)	801,163	324,220
Carlsbad Caverns NP	CAVE	Other rocks (minor aquifer, not a principal aquifer or confining unit)/Chihuahuan Desert and Arizona-New Mexico Mountains (NM)	46,766	18,926
Fort Davis NHS	FODA	Other rocks (minor aquifer, not a principal aquifer or confining unit)/Chihuahuan Desert (TX)	523	212
Guadalupe Mountains NP	GUMO	Rio Grande aquifer system/Chihuahuan Desert and Arizona-New Mexico Mountains (TX)	86,367	34,952
Rio Grande WSR	RIGR	Edwards-Trinity aquifer system/Chihuahuan Desert (TX)	9,600	3,885
White Sands NM	WHSA	Rio Grande aquifer system/Chihuahuan Desert (NM)	143,733	58,167

[1] Regional aquifer based on http://nationalatlas.gov/mapmaker. Ecoregions based on The Nature Conservancy (2008).

[2] Acreage from NPS (2012).

*see page vii for acronyms

Table 1-3. Parks of the Southern Plains Network.

Park	Park code	Regional aquifer/Ecoregion[1] (State)	Area	
			ac[2]	ha
Alibates Flint Quarries NM	ALFL	Other rocks (minor aquifer, not a principal aquifer or confining unit)/Southern Shortgrass Prairie (TX)	1371	555
Bent's Old Fort NHS	BEOL	Other rocks (minor aquifer, not a principal aquifer or confining unit)/Central Shortgrass Prairie (CO)	799	323
Capulin Volcano NM	CAVO	Other rocks (minor aquifer, not a principal aquifer or confining unit)/Southern Shortgrass Prairie (NM)	793	321
Chickasaw NRA	CHIC	Other rocks (minor aquifer, not a principal aquifer or confining unit)/Crosstimbers and Southern Tallgrass Prairie (OK)	9,899	4,006
Fort Larned NHS	FOLS	Other rocks (minor aquifer, not a principal aquifer or confining unit)/Central Mixed-Grass Prairie (KS)	718	291
Fort Union NM	FOUN	Other rocks (minor aquifer, not a principal aquifer or confining unit)/Southern Shortgrass Prairie (NM)	721	292
Lake Meredith NRA	LAMR	Other rocks (minor aquifer, not a principal aquifer or confining unit)/Southern Shortgrass Prairie (TX)	44,978	18,202
Lyndon B. Johnson NHP	LYJO	Edwards-Trinity aquifer system/Edwards Plateau (TX)	1,570	636
Pecos NHP	PECO	Other rocks (minor aquifer, not a principal aquifer or confining unit)/Southern Shortgrass Prairie (NM)	6,703	2713
Sand Creek Massacre NHS	SAND	Other rocks (minor aquifer, not a principal aquifer or confining unit)/Central Shortgrass Prairie (CO)	12,583	5,092
Washita Battlefield NHS	WABA	Other rocks (minor aquifer, not a principal aquifer or confining unit)/Central Mixed-Grass Prairie (OK)	315	127

[1] Regional aquifer based on http://nationalatlas.gov/mapmaker. Ecoregions based on The Nature Conservancy (2008).

[2] Acreage from NPS (2012).

*see page vii for acronyms

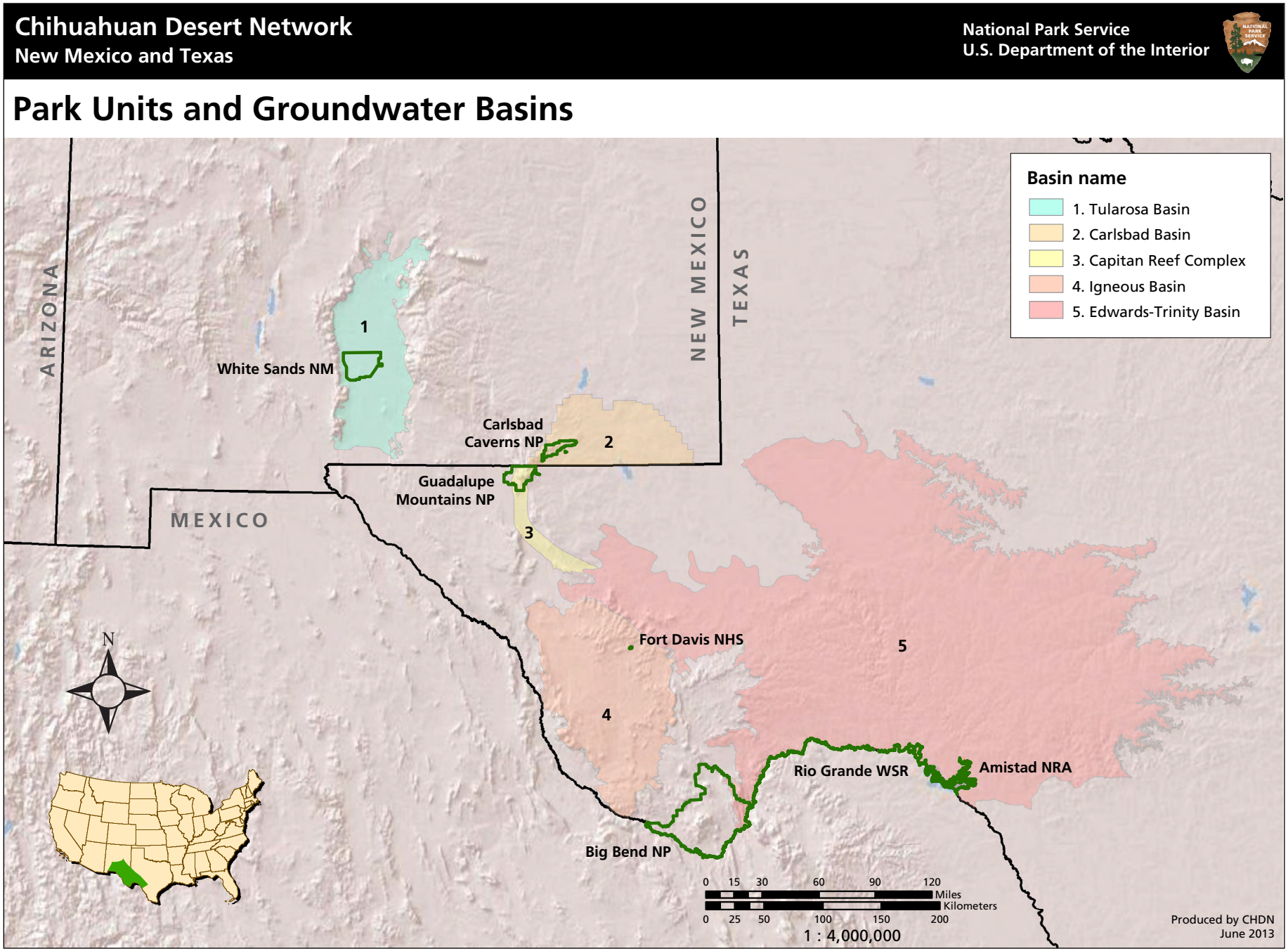


Figure 1-3. National park units and groundwater basins of the Chihuahuan Desert Network.

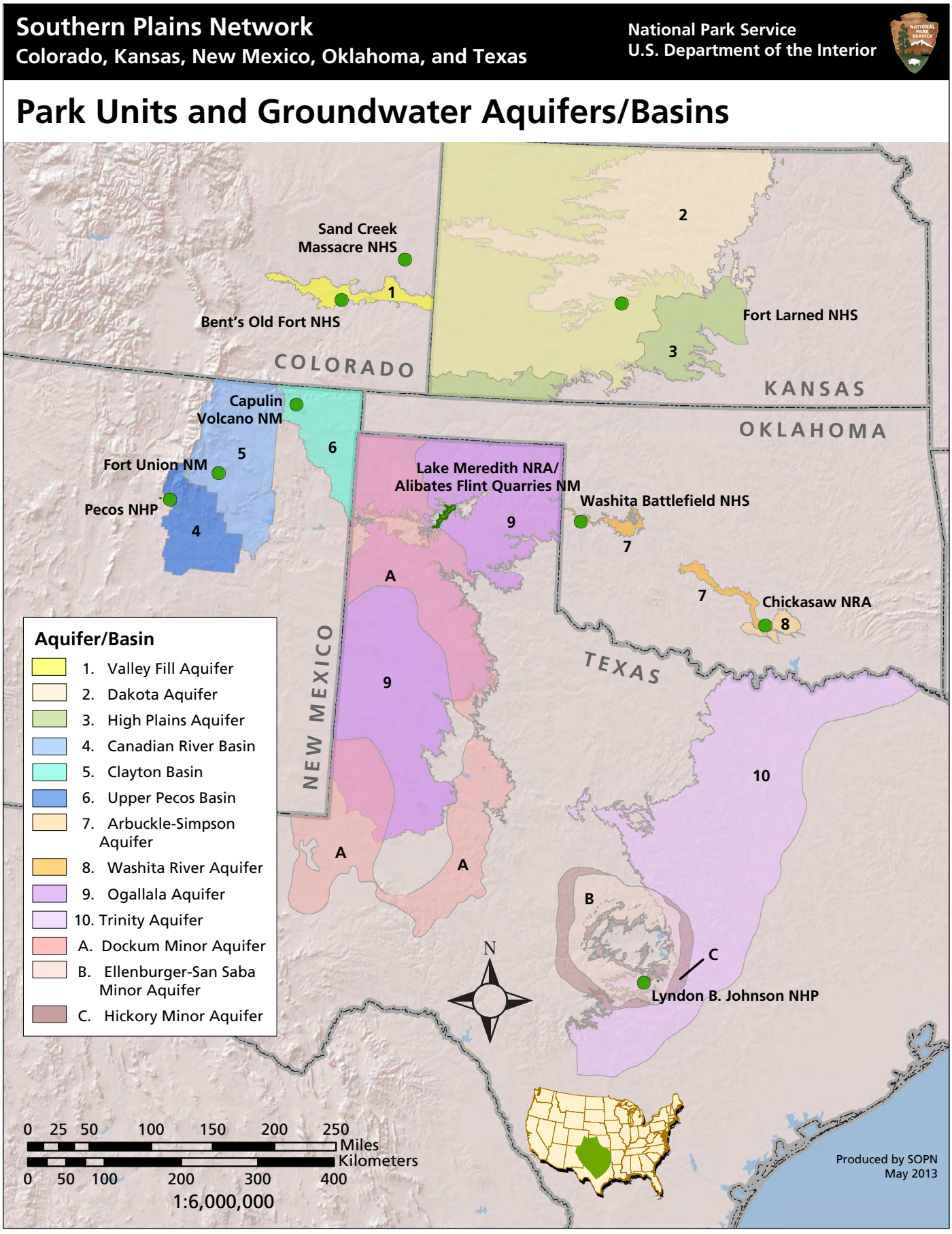


Figure 1-4. National park units and groundwater aquifers/basins of the Southern Plains Network.

2 Program Overview

2.1 Program goals

The goals of the groundwater monitoring program are to provide resource managers with the information needed to:

- Quantify status and trends of NPS groundwater resources through a program of high-quality data collection, archiving, and analysis;
- Understand and communicate present and future threats to NPS groundwater resources and groundwater-dependent surface waters;
- Provide park managers with information relating to best management practices for resource protection and sustainability;
- Support interpretation of the results of surface biotic and abiotic monitoring; and
- Facilitate groundwater data accessibility to park managers and the public.

These goals will be achieved by monitoring groundwater status, identifying local changes in groundwater quantity, interpreting data, and facilitating the integration of SWNC groundwater data with data from other parks and external partners and agencies.

2.2 Program objectives

The central objective of SWNC groundwater monitoring is to quantify piezometric (hydraulic) head* in the zone of water saturation at designated monitoring locations. This monitoring will be conducted at frequencies determined by site-specific goals, as described below, and will be reported as depth to water and as water-table elevation in English units of feet. Minimum frequency of monitoring will be once per year.

Detailed objectives of SWNC groundwater monitoring include:

1. Inventory wells, document and archive well metadata and groundwater level data at parks in each network in a format consistent with national interagency groundwater database standards.
2. Identify selected wells for monitoring and identify areas where new monitoring wells may be needed to achieve program goals.
3. Work with NPS staff to obtain high-quality groundwater data using standardized methods and procedures for activities occurring as part of this protocol.
4. Document and report groundwater levels and trends at wells selected for monitoring.
5. Document and report groundwater resource status at parks for water-supply planning purposes as needed.
6. Support and complement the interpretation of physical and biological surface-monitoring results.
7. Support the development of water-balance analyses at parks, including relationships between groundwater and surface-water resources, land use, biota, and climate.
8. Identify potential threats or stressors to groundwater resources through analysis of groundwater status and factors affecting water resources in and around NPS units.
9. Facilitate access to groundwater data through NPS and other federal data-sharing portals.
10. Interpret park groundwater status and water balance in the context of regional climate and hydrologic trends.
11. Assess and/or monitor site suitability for riparian habitat or other special uses.
12. Support legal protection of groundwater and surface water resources.

*Hydraulic or piezometric head is a measure of the energy associated with pressure and elevation at a point in an incompressible liquid. It can also be described as the stored energy due to the weight of the water column above an outflow point plus the energy associated with the elevation of the outflow point above a reference datum.

3 Groundwater as a Focus for Monitoring Efforts

Processes that affect groundwater resources occur mostly out of sight and over long time periods. Knowing the status and trends of groundwater resources is of paramount importance for land managers charged with protecting natural resources in perpetuity for future generations. As pointed out by Taylor and Alley (2001), groundwater is one of the most important natural resources of this country, providing drinking water, irrigating crops, and sustaining rivers and streams across the nation.

Water resources of the Sonoran Desert, Chihuahuan Desert, and Southern Plains networks occur as shallow or deep groundwater; perennial, intermittent, or ephemeral streams; and tinajas, springs, seeps, cienegas (wetlands), and ponds. Each of these occupies an important niche in sustaining ecosystems in arid and semiarid regions.

Despite longstanding lay perspectives of groundwater and surface waters as separate entities, these resources are one and the same, and this is nowhere more evident than in arid and semiarid regions. Ephemeral flows vanish below the desert surface, only to re-emerge months, years, decades, or even centuries later as precious perennial and intermittent streams, springs, and tinajas, which are sustained through dry seasons and drought years by these same waters. Changes in surface characteristics, such as plant cover and soil integrity, affect runoff, infiltration, and evapotranspiration. Increased runoff results in reduced infiltration, which limits the amount of water available for groundwater and groundwater-dependent surface waters. In one way or another, all ecological communities—from the desert floor to sky-island mountaintops—are influenced by the status of groundwater.

Groundwater resources are vulnerable to impacts associated with drought, climate change, increasing consumption by a burgeoning population and economy, and changes in land use and watershed integrity. Groundwater response to stresses can occur rapidly or may take place over extended time periods of decades to centuries. Where there is hydraulic connectivity, groundwater pumping will result in the gradual capture of springs and other surface waters. Depletion of surface flows can continue to increase even decades after pumping has stopped (Alley et al. 1999; Barlow and Leake 2012). Because humans, vegetation, and wildlife all require access to water, understanding groundwater dynamics is basic to understanding, managing, and protecting present and future ecosystem function and health.

All but three of the 29 SWNC parks depend on groundwater as a source of potable water (A. Kramer, personal communication). Systematic observation of groundwater levels is the primary means of gaining the information needed for understanding, protecting, and maintaining the security of park water sources into the future. The applicability of groundwater data collected outside park boundaries to understanding groundwater status at parks depends on the geologic context of the area and the details of well construction. Where appropriate, groundwater-level data from wells located outside park boundaries may be included in this protocol or may serve as a surrogate for measurements made within a park. Analysis of trends in water levels throughout a region can provide a broad-scale, integrated perspective of the impacts of environmental factors that stress groundwater resources.

3.1 Groundwater and climate change

Climate change and long-term drought are stressors with regional, rather than local, footprints. The southwestern United States is experiencing some of the most rapid warming in the nation and projections are for continued strong warming (Seager et al. 2007; Thomas 2009). Drought and changes to water cycles are expected to have substantial impacts on biological diversity and protected areas in the coming decades. Anticipated water-cycle shifts, including increased storm intensity, reductions in spring precipitation, increased winter precipitation falling as rain instead of snow, and increased temperature and evaporative losses, all have implications for the long-term sustainability of groundwater resources in the arid Southwest. In combination with projected increases in

consumptive use for agriculture, industry, and domestic supply, the potential for conflict between interests competing for dwindling groundwater resources will intensify.

Monitoring and reporting on groundwater resource status benefits the understanding of local groundwater dynamics and the relationship between climatic factors, current water levels, and past groundwater conditions at national parks and their surrounding regions. In the face of climatic uncertainty, these data have broad application for informing land managers about what may be expected under a range of future scenarios.

3.2 Groundwater and key ecological communities

In deserts and semiarid high plains, water is typically the limiting resource that defines the range of potential life on the surface, and the influence of groundwater permeates the desert landscape. Groundwater discharge to streams, springs, and tinajas sustains perennial and intermittent flows in arid and semi-arid environments. Depth to groundwater is a key determinant of ecosystem type on the surface. In combination with ecological monitoring, groundwater data contribute to the understanding of "peak ecological water," defined by Gleick and Palaniappan (2010) as "the point beyond which the total costs of ecological disruptions and damages exceed the total value provided by human use of that water." Groundwater data provide the foundation for park managers to work with partners and neighbors toward maintaining groundwater resources needed to sustain key ecological communities.

A study in Arizona's San Pedro River valley determined that out of 12 environmental variables, depth to groundwater exerted the greatest influence on plant assemblage composition (Stromberg et al. 1996). As depth to water decreases, ecological productivity increases. Arid-region riparian ecosystems are located at the interface between terrestrial and aquatic ecosystems along the banks of rivers, streams, ponds, springs, and meadows (Baker et al. 2004). Groundwater plays a vital role in sustaining riparian communities during dry seasons and times of drought. Due to limits on the ability of phreatophytes to extend roots deeper when water levels decline, depth to water is a critical parameter for riparian vegetation.

All Sonoran Desert Network parks, except for Casa Grande Ruins NM, include highly valued riparian habitat. Extensive riparian habitats are found in all Chihuahuan Desert Network parks except for Fort Davis NHS. Riparian habitats are found in all Southern Plains Network parks except for Capulin Volcano NM. Riparian habitats in SOPN parks range from small, isolated wetlands (Fort Union NM) to perennial rivers and reservoirs (Chickasaw and Lake Meredith NRAs).

Throughout the Basin and Range ecological province, deep alluvial basins between mountain ranges harbor groundwater—often hundreds of feet below the land surface. Extensive lowland desert-shrub communities populated by creosote, bursage, and palo verde–mixed-cactus communities thrive under these conditions. Water levels deep below the surface in these basins may fluctuate with little or no effect on surface communities. They are sustained by direct precipitation and soil moisture, and are adapted to survive lengthy dry periods. These deep basins are often tapped to provide water to thirsty communities. It must be remembered that declining water levels in basins will propagate upstream, and groundwater overdraft will eventually result in capture of distant surface waters. Declining water levels in basins also causes subsidence, land settling that ruptures the surface and results in permanent compaction of some soil types.

3.2.1 Stressors to groundwater systems

Groundwater stressors are processes associated with sustained declines in groundwater levels. Sustained water-level declines result from decreased recharge and/or increased discharge from groundwater systems that formerly fluctuated within a quasi-equilibrium range at a given location. A decline in groundwater levels indicates a reduction in water stored in the subsurface as changes in the water balance propagate through the hydrologic system. Lowered water tables result in greater distance to water for plant roots; loss or degradation of riparian habitat; reduced discharge to springs, streams, and tinajas; subsidence of sediments within alluvial

basins; and reductions in water available for wildlife and human consumption.

Groundwater stressors can be natural and/or human-induced. Factors that lower water tables by reducing recharge include drought, decreased infiltration, increased consumptive uses or manipulation of rivers and streams, climate and land-use changes, and alterations to physical and/or biological systems on the surface. Factors that increase discharge are primarily related to groundwater pumping, channel incision and gullying, and increased evapotranspiration. Because water flows downgradient, effects related to lowered water tables in one location will eventually impact all hydraulically connected water bodies. This is the mechanism by which capture of flow from streams and springs occurs.

Groundwater withdrawals for human uses—including domestic, industrial, and agricultural—are a major cause of groundwater decline. With the exception of interbasin transfers, this stressor tends to be localized within the aquifers near population centers and industrialized and agricultural areas, although water-level declines in one area can eventually result in impacts far from the source of the water extraction. Increasing demand for water in the western United States has resulted in projects and proposals for large-scale interbasin water transfers that have the potential to—and do—result in significant impacts within the originating (donor) watersheds. Dependence on these projects increases the vulnerability of population centers to supply interruption that could originate in a number of ways.

Diversion of streams and rivers, and changes to watershed drainage patterns and land-cover characteristics, stress groundwater resources by decreasing infiltration and recharge to aquifers. Understanding local and regional groundwater dynamics and stressors makes it possible to formulate questions and seek answers about the drivers behind changes in groundwater status. Long-term monitoring data from parks can be analyzed in conjunction with groundwater data obtained outside park boundaries to differentiate between local and regional trends in the data. This constitutes a significant value-added result for the wider community.

3.3 Review of groundwater monitoring programs

The following sections discuss groundwater monitoring programs that are active in the greater SODN, CHDN, and SOPN areas. The data forthcoming from these programs are of significant value to NPS groundwater monitoring goals associated with larger-scale and longer-term processes affecting groundwater dynamics, including climate change, land use and land cover, and basin-wide water balance.

3.3.1 State and regional

Multiple state agencies are involved in the management of water resources in Arizona, Colorado, Kansas, New Mexico, Oklahoma, and Texas (Table 3-1). These agencies are some of the first sources that should be investigated in any search for information related to groundwater and wells. The following paragraphs discuss some of these agencies as they are involved with groundwater.

3.3.1.1 Arizona

The Arizona Department of Water Resources (ADWR) Basic Data Unit maintains an annual groundwater-level monitoring program of about 1,800 index wells statewide. Annual data from four ADWR index wells are included in the SODN groundwater monitoring program. The Basic Data Unit has also deployed automatic water-level monitoring at over 100 wells statewide. The data from these wells allow for an improved understanding of factors behind both short-term and longer-term changes in groundwater status. SODN and ADWR staff coordinated the instrumentation of two wells at Tumacácori NHP by ADWR as part of this state program.

Recent and historical water-level data from the ADWR Basic Data Unit, together with site metadata, are available from ADWR as the Groundwater Site Inventory (GWSI) database, and are available at no cost on the Internet. In addition, well-drilling and construction data are available for many wells registered with the state through the ADWR Imaged Records database. Additional information on these programs may be found by following links from the main ADWR website (see Table 3-1).

Table 3-1. State water management agencies for Arizona, Colorado, Kansas, New Mexico, Oklahoma, and Texas.

State	Agency
Arizona	Arizona Department of Water Resources Arizona Department of Environmental Quality
Colorado	Colorado Division of Water Resources Colorado Water Conservation Board Colorado Department of Public Health and Environment Colorado Department of Natural Resources Colorado Department of Public Health and Environment, Water Quality Control Division
Kansas	Kansas Department of Agriculture Kansas Department of Agriculture, Division of Water Resources Kansas Department of Health and Environment Kansas Water Office
New Mexico	New Mexico Office of the State Engineer New Mexico Environment Department
Oklahoma	Oklahoma Department of Environmental Quality Oklahoma Department of Environmental Quality, Water Quality Division Oklahoma Water Resources Board
Texas	Texas Water Development Board State of Texas Texas Commission on Environmental Quality

Source: http://www.westgov.org/wswc/links.html

3.3.1.2 Colorado

The Colorado Division of Water Resources operates a statewide network for monitoring groundwater levels in cooperation with local groundwater management districts. The division works with the Colorado Ground Water Commission, a regulatory body authorized by the state's general assembly, to manage and control groundwater resources within eight Designated Ground Water Basins in eastern Colorado. The division monitors more than 1,500 wells to assist in projecting groundwater levels and aid in the administration of groundwater.

3.3.1.3 Kansas

In Kansas, wells are monitored by a variety of organizations, with data centralized in the WIZARD database, operated by the Kansas Geological Survey. The WIZARD database is a repository of information on freshwater wells completed in Kansas aquifers. Although WIZARD consolidates information formerly maintained by several local, state, and federal agencies, most of its data are taken from the U.S. Geological Survey's GWSI.

3.3.1.4 New Mexico

Information about wells and well logs in New Mexico can be found at the website of the New Mexico Office of the State Engineer.

Groundwater-level data collected by the State of New Mexico are archived with the U.S. Geological Survey (USGS) New Mexico Water Science Center in Albuquerque. Some of these data are made available to the public through the USGS National Water Information System (NWIS) at http://waterdata.usgs.gov/nwis. A significant number of data may not be posted on the web; persons interested in a specific area should contact the center and inquire about the availability of additional data.

3.3.1.5 Oklahoma

The Oklahoma Water Resources Board annually monitors more than 750 groundwater wells throughout Oklahoma. The Water Well Level Mass Measurement Program has been managed in cooperation with the USGS since the 1950s, and is used to predict water use trends and groundwater availability throughout Oklahoma.

3.3.1.6 Texas

The Texas Water Development Board (TWDB) provides water planning, data collection and dissemination, financial assistance, and technical assistance services to the citizens of Texas. Its Groundwater Resources Division (GRD) is responsible for all aspects of groundwater studies in the state. The GRD monitors groundwater levels and groundwater quality in nine major and 21 minor aquifers, conducts regional-scale groundwater modeling, and houses and maintains water-well records. They also review and approve groundwater management plans. CHDN park units are located in three different TWDB Groundwater Management Areas and three different Groundwater Conservation Districts. The TWDB groundwater database has records from more than 135,000 wells located throughout the state. Six wells with state-operated automatic water-level monitoring (daily recorded water levels) are located in or near CHDN parks (Big Bend NP, Fort Davis NHS, Guadalupe Mountains NP). Data from these observation wells, which are included in the CHDN groundwater monitoring program, will help improve our understanding of factors behind changes in groundwater status.

Recent and historical water-level data from the TWDB and its cooperators are publicly available on the Internet. In addition, well-drilling and construction data are available for many wells registered with the state through the TWDB database. Additional information on these programs may be found by following links from the main TWDB website provided above.

3.3.2 U.S. Geological Survey

A limited number of wells in and near SWNC parks are currently monitored by the USGS. Data collection at these wells is related to specific programmatic objectives; the USGS groundwater program is not intended to provide statewide coverage. However, USGS water-level monitoring in areas around parks is valuable to the NPS for interpretation of local groundwater conditions. Recent and historical USGS groundwater data are available through the NWIS web portal (see Section 3.3.1.4). Many USGS groundwater data for Arizona are also available via the State of Arizona's ADWR GWSI system.

USGS groundwater monitoring in and near SWNC parks includes three wells located within a half-mile of Carlsbad Caverns NP, in New Mexico, and locations in the upper San Pedro River basin and the upper Verde River valley, in Arizona. Except for one well at Coronado National Memorial, none of the wells currently monitored by the USGS are located within SODN units. Additional work is needed to determine if there are other wells monitored by USGS in or near parks in the wider SWNC area.

3.3.3 Sonoran Desert Network

Table 3-2 provides a summary of ongoing groundwater monitoring at SODN parks. Every park in the network except for Gila Cliff Dwellings NM is included in the groundwater program. Of the park units included in the current program, SODN staff conduct monitoring at three units, park staff conduct monitoring at three units, and water levels at or nearby five units are monitored by the ADWR or USGS. SODN staff process all of the data and incorporate them into the SODN database.

The Organ Pipe Cactus National Monument Ecological Monitoring Program (EMP) has included quarterly water-level monitoring at up to 14 wells since 1987. Seven of those wells are no longer monitored due to casing collapse, burial by debris flow, or the decline of water levels below the well bottoms. EMP groundwater data have documented steep groundwater declines attributable to pumping in the Lukeville–Sonoita area and, since about 2000, shown declines in groundwater levels across the park that correlate to reduced precipitation and large-scale anthropogenic changes over that period (Filippone et al. 2006, 2012).

At Saguaro NP, park staff and volunteers monitor groundwater levels at 10 wells within the Rincon Creek drainage in the Rincon Mountain District. This effort originated in 2005, with data collection in support of a water-rights application for instream flow in the drainage. Chiricahua NM staff conduct water-level monitoring at three wells within the Bonita Creek drainage.

Additional monitoring programs in the Sonoran Desert Network region are maintained

Table 3-2. Summary of wells selected for monitoring groundwater conditions in the Sonoran Desert Network.

Local well designation	State and/or USGS well ID	Monitoring schedule (Manual/Automated)	Total depth (ft)	Aquifer/Groundwater basin	Monitoring entity (data source)*
Casa Grande Ruins National Monument					
D-05-08 17BBB2 (off park)	55-621935	Annual	820	Unconsolidated basin fill sediments/Eloy Basin Pinal AMA	ADWR (ADWR GWSI)
Chiricahua National Monument					
Headquarters	55-629081	Monthly/hourly	78	Shallow Alluvium of Bonita Canyon/Willcox Basin	NPS-CHIR (SODN)
Faraway	55-629083/55-629145	Monthly	120	Shallow Alluvium of Bonita Canyon/Willcox Basin	NPS-CHIR (SODN)
Campground-1	55-629082	Monthly	116	Shallow Alluvium of Bonita Canyon/Willcox Basin	NPS-CHIR (SODN)
Coronado National Memorial					
X2	55-509098	Quarterly/4x per day	320	Middle Piedmont Huachuca Mtns/Upper San Pedro Basin	SODN (SODN)
SX1	55-507448	Quarterly/4x per day	300	Middle Piedmont Huachuca Mtns/Upper San Pedro Basin	SODN (SODN)
ACA2	55-509095	Quarterly/4x per day	340	Middle Piedmont Huachuca Mtns/Upper San Pedro Basin	SODN (SODN)
Water Supply-2 (Water Tank)	55-909747	Quarterly/2x per hour	683	Huachuca granite/Upper San Pedro Basin	SODN (SODN)
Baumkirchner #3	55-633158 (USGS 312044110141901)	Quarterly/4x per day	125	Middle Piedmont Huachuca Mtns/Upper San Pedro Basin	USGS/SODN (USGS/SODN)
Headquarters	55-629139	Quarterly	98	Alluvium Montezuma Canyon/Upper San Pedro Basin	SODN (SODN)
Fort Bowie National Historic Site					
WSW-2	55-582902	Quarterly/hourly	220	Fractured Horquilla Limestone/San Simon Valley Basin	SODN (SODN)
Siphon Canyon	55-629136	Annually	102	Alluvium of Siphon Canyon/limestone bedrock/San Simon Valley Basin	SODN (SODN)
Montezuma Castle National Monument (Castle unit)					
MOCA water supply well	55-629124	Annually	160	Verde Formation Limestone /Verde River Basin	ADWR (ADWR GWSI)
Montezuma Castle National Monument (Well unit)					
ADWR Index Well 343924111454901 (off park)	A-15-05 25DDD 55-514006	Annual	300	Unknown/Verde River Basin	ADWR (ADWR GWSI)
USGS 343852111460301 (off park)	A-15-05 36DAB	Daily	189	Unknown/Verde River Basin	USGS (NWIS)

Table 3-2. Summary of wells selected for monitoring groundwater conditions in the Sonoran Desert Network, cont.

Local well designation	State and/or USGS well ID	Monitoring schedule (Manual/Automated)	Total depth (ft)	Aquifer/Groundwater basin	Monitoring entity (data source)*
Organ Pipe Cactus National Monument					
Alamo Wash (destroyed by flood in 2012)	55- 629154	Quarterly	17/21	Shallow Alluvium of Alamo Canyon/Lower Gila Basin	NPS-ORPI (ORPI/SODN)
Bates (obstructed; replaced by East of Bates, October 2010)	55- 629121	Quarterly	67/80	Shallow Alluvium of Growler Wash/Lower Gila Basin	NPS-ORPI (ORPI/SODN)
East of Bates	unknown	Quarterly		Shallow Alluvium of Growler Wash/Lower Gila Basin	NPS-ORPI (ORPI/SODN)
Bonita	USGS 320115112573001/ C-16-07 27BAD UNSURV 55-629153	Quarterly	37/40	Shallow Alluvium of Aguajita Wash/Western Mexican Drainage Basin	NPS-ORPI (ORPI/SODN)
Corner	USGS 315743113050201/ C-17-08 09ADD UNSURV	Quarterly	97/101	Lower Piedmont of Quitobaquito Hills/Western Mexican Drainage Basin	NPS-ORPI (ORPI/SODN)
Kalil	USGS 315254112490201/ C-18-05 06DCD	Quarterly	187	Lower Piedmont of Ajo Mountains/Western Mexican Drainage Basin	NPS-ORPI (ORPI/SODN)
Stack	USGS 315313112490701/ C-18-05 06DBB	Quarterly	206 (?)	Lower Piedmont of Ajo Mountains/Sonoyta Valley/ Western Mexican Drainage Basin	NPS-ORPI (ORPI/SODN)
USGS #1 Camino Dos Republicas	USGS 315257112475301/ C-18-05 05DDC	Quarterly	250	Lower Piedmont of Ajo Mountains/Western Mexican Drainage Basin	NPS-ORPI (ORPI/SODN)
USGS #2 Lukeville	USGS 315232112475501/ C-18-05 08ACA	Quarterly	238/250	Lower Piedmont of Ajo Mountains/Western Mexican Drainage Basin	NPS-ORPI (ORPI/SODN)
USGS #3 Salsola	USGS 315056112424301/ C-18-04 19AAC UNSURV	Quarterly	278/300	Lower Piedmont of Ajo Mountains/Western Mexican Drainage Basin	NPS-ORPI (ORPI/SODN)
Headquarters No. 5 North	55-629090 C-17-05 17ABC	Annual	420	Western Mexican Drainage Basin	ADWR (GWSI)
Saguaro National Park (Rincon Mountain District)					
Madrona Pack Base Well	55-629099	Quarterly/hourly?	117	Alluvium of Chiminea Creek/Upper Santa Cruz Basin Tucson AMA	NPS-SAGU (SAGU/SODN)
Hope Camp Well	Unknown/unregistered	Semi-Annual/4x per day	50.1	Southern flank of Tanque Verde Ridge in the Rincon Valley/Upper Santa Cruz Basin Tucson AMA	NPS-SAGU (SAGU/SODN)
Lunt Well	55-633106	Quarterly/hourly?	455	Pantano Formation /Upper Santa Cruz Basin Tucson AMA	NPS-SAGU (SAGU/SODN)
RC-1	55-206881	Quarterly/15 min	8.5	Alluvium of Rincon Creek/Upper Santa Cruz Basin Tucson AMA	NPS-SAGU (SAGU/SODN)

Table 3-2. Summary of wells selected for monitoring groundwater conditions in the Sonoran Desert Network, cont.

Local well designation	State and/or USGS well ID	Monitoring schedule (Manual/Automated)	Total depth (ft)	Aquifer/Groundwater basin	Monitoring entity (data source)*
RC-2	55-206882	Quarterly/15 min	13.0	Alluvium of Rincon Creek/Upper Santa Cruz Basin Tucson AMA	NPS-SAGU (SAGU/SODN)
RC-3	55-206883	Quarterly/15 min	17.0	Alluvium of Rincon Creek/Upper Santa Cruz Basin Tucson AMA	NPS-SAGU (SAGU/SODN)
RC-4	55-206880	Quarterly/15 min	9.0	Alluvium of Rincon Creek/Upper Santa Cruz Basin Tucson AMA	NPS-SAGU (SAGU/SODN)
RC-5	55-206879	Quarterly/15 min	11.5	Alluvium of Rincon Creek/Upper Santa Cruz Tucson Basin AMA	NPS-SAGU (SAGU/SODN)
RC-6	55-206878	Quarterly/15 min	10.0	Alluvium of Rincon Creek/Upper Santa Cruz Basin Tucson AMA	NPS-SAGU (SAGU/SODN)
RC-7	55-206877	Quarterly/15 min	10.0	Alluvium of Rincon Creek/Upper Santa Cruz Basin Tucson AMA	NPS-SAGU (SAGU/SODN)
Saguaro National Park (Tucson Mountain District)					
SAGW WSW-1	55-629094	Quarterly/4x per day	560	Tucson Mountains west bajada/Avra Valley Basin Tucson AMA	SODN (SAGU/SODN)
Tumacácori National Historical Park					
MW-1-Deep	55-551438	Quarterly/4x per day	120	Santa Cruz River Floodplain aquifer/Older Alluvium/Upper Santa Cruz Basin Santa Cruz AMA	ADWR (ADWR GWSI)
MW-1-Shallow	55-551439	Quarterly/4x per day	65	Santa Cruz River Floodplain aquifer/Younger Alluvium/Upper Santa Cruz Basin Santa Cruz AMA	ADWR (ADWR GWSI)
TUMA Water Supply Well	ADWR Index 313408111025601 D-21-13 30DCA	Annual	150	Santa Cruz River Floodplain aquifer/Older Alluvium/Upper Santa Cruz Basin Santa Cruz AMA	ADWR (ADWR GWSI)
Tuzigoot National Monument					
Kauzlarik ADWR Index Well (off park)	A-16-03 22DCD 55-629211	Annual	1,400	Verde Formation local aquifer/Verde River Basin	ADWR (ADWR GWSI)
City of Cottonwood Index Well #1 (off park)	A-16-03 34AAD 55-609076	Annual	300	Verde formation local aquifer/Verde River Basin	ADWR (ADWR GWSI)
State Land Department (off park)	A-16-03 36CDC 55-614257	3x/year/4x per day	1,200	Verde Formation local aquifer/Verde River Basin	ADWR (ADWR GWSI)

Well locations at and near each park unit are shown in Appendix B.

*see page vii for acronyms

by local water providers around population centers, including Tucson, Phoenix, Prescott, Flagstaff, and Sierra Vista. Data from these programs are generally not readily available unless included in the state groundwater-level database.

3.3.4 Chihuahuan Desert Network

Staff at Big Bend, Carlsbad Caverns, and Guadalupe Mountains NPs and White Sands NM have been monitoring groundwater levels for the past few years, and will continue to do so with CHDN support. All wells monitored in the CHDN are located in these parks, and each park has a dedicated water-level sounder. In the event of staff turnover, CHDN staff will assist with training of new staff as needed.

Over the last century, more than 100 wells have been dug or drilled in what is now Big Bend NP. However, just 29 of those wells currently represent the park's most important sources (or potential sources) of water and/or hydrogeologic information relevant to park managers, water-resource planners, and hydrologists. Twelve of those 29 wells are observation wells, including one well maintained by the TWDB (Porter et al. 2009). Park staff continuously monitors 10 wells with pressure transducers, and another 34 "open" observation wells are monitored at least once a year (K. Crawford, pers. comm., August 8, 2012). Eleven observation wells in Big Bend NP have been selected for inclusion in this long-term groundwater monitoring protocol (Table 3-3). Those 10 wells were selected from the full list of potential sites by first eliminating wells that were the second of a pair and those that were deteriorating. Wells were then selected (1) to cover the spatial extent of the park, (2) to represent the park's three types of local aquifers located (igneous, Upper Cretaceous, and Lower Cretaceous), and (3) to represent the common threats to groundwater (e.g., water-supply wells).

Staff at Carlsbad Caverns NP conducts water-level monitoring at the only well in the park, near Rattlesnake Springs. For 60 years, Rattlesnake Springs has provided irrigation water for NPS property and privately owned land nearby, such as Washington Ranch. Water at this site is piped from a 118-ft deep water-supply well to park headquarters near the main cavern through a pipeline completed in 1935. This well taps the same coarse alluvial aquifer that sustains Rattlesnake Springs (Porter et al. 2009). The recorded history of water levels at Rattlesnake Springs well is longer (60 years) than that of any other well in the CHDN. The data from this well will be included in the CHDN groundwater database.

At Fort Davis NHS, the Oak Grove well, used for irrigation of a culturally and historically significant cottonwood grove, may be monitored as a part of CHDN's groundwater monitoring efforts. There are two other groundwater wells in the park, and an additional three observation groundwater wells adjacent or nearby to the park that are a part of Jeff Davis County's groundwater monitoring system. The two wells nearest the park have been monitored by the county since the mid-1960s (Porter et al. 2009).

Although 10 wells have been documented within Guadalupe Mountains NP, none has a history of known water levels prior to April 2009, when NPS Water Resources Division (WRD) staff conducted a groundwater monitoring assessment for the park (Martin 2009). Beginning in April 2010, monitoring of three wells (Signal Peak, PX, and Lemonade) was initiated (Table 3-3). Each of these three wells is monitored manually on a quarterly basis, and is also instrumented with a sensor that records water level and temperature on a 6-hour schedule (Filippone 2011). The monitoring data are collected by Guadalupe Mountains NP staff and are processed, reported, and archived by CHDN. Three other observation wells are located between six and 40 miles of the park, for which long-term water-level records are available beginning in 1954 (Porter et al. 2009). The TWDB is investigating the hydrogeology of the Capitan Aquifer and is developing a groundwater availability model to help guide future groundwater development from that aquifer. TWDB personnel take annual water-level measurements at several wells in the area—usually in the winter months, when groundwater pumping is minimal (Martin 2009).

As of 2012, there were 15 known wells in White Sands NM. Six of those wells have been monitored from 1997 to the present. In addition, six piezometers (most are six feet

Table 3-3. Summary of wells selected for monitoring groundwater conditions in the Chihuahuan Desert Network (to date).

Local well designation	State and/or USGS well ID	Monitoring schedule (Manual/Automated)	Total depth (ft)	Aquifer	Monitoring entity (data source)*
Big Bend National Park**					
Gambusia Well 72-49-508 (park #)	None	Bimonthly/4x per day	290	Cretaceous aquifer	NPS BIBE (BIBE/CHDN)
Contractor's Well 73-46-704 (park #)	None	Bimonthly/4x per day	234		NPS BIBE (BIBE/CHDN)
Oak Springs Well #1/TB-5/73-46-706 (park #)	None	Bimonthly/4x per day	118	Igneous Intrusive Volcanics	NPS BIBE (BIBE/CHDN)
TH-10/I-50/73-47-201 (park #)	None	Bimonthly/4x per day	445	Aguja	NPS BIBE (BIBE/CHDN)
K-Bar #6 Observation Well/Panther Junction #6 Observation Well/73-47-508 (park #)	None	Bimonthly/4x per day	165	Aguja	NPS BIBE (BIBE/CHDN)
K-Bar #7 Observation Well/73-47-511 (park #)	None	Bimonthly/4x per day	130	Aguja	NPS BIBE (BIBE/CHDN)
Gallery Well 73-52-905 (park #)	None	Bimonthly/4x per day	26	Unconsolidated alluvial deposits	NPS BIBE (BIBE/CHDN)
T-3/Well 37/73-47-101 (park #)	None	Bimonthly/4x per day	136 (blocked)	Aguja	NPS BIBE (BIBE/CHDN)
Deep Fault Well 72-49-5 (park #)	None	Bimonthly/4x per day	798	Cretaceous	NPS BIBE (BIBE/CHDN)
Reynolds Well 73-47-799 (park #)	None	Bimonthly/4x per day	90		NPS BIBE (BIBE/CHDN)
Gallery Well 73-52-905 (park #)	None	Bimonthly/15 minutes	26	Rio Grande alluvium	NPS BIBE (BIBE/CHDN)
Guadalupe Mountains National Park					
Signal Peak	4710201	Quarterly/4x per day	1500	Capitan Reef Complex Aquifer	NPS GUMO (GUMO/CHDN)
PX	4701201	Quarterly/4x per day	300	Local aquifer	NPS GUMO (GUMO/CHDN)
Lemonade	unknown	Quarterly/4x per day	51	Shallow alluvium of the Salt Basin Flat	NPS GUMO (GUMO/CHDN)

Well locations at and near each park unit are shown in Appendix B.

*see page vii for acronyms

**Source: K. Crawford, pers. comm., March 7, 2013.

deep and a few extend to 13 feet) and four water wells have been in place at the park as part of two other projects: LiDAR dune dynamics monitoring and ongoing hydrologic studies by researchers from the New Mexico Bureau of Geology and Mineral Resources. Recording water-level sensors have been installed in piezometers, shallow monitoring wells (25 to 30 feet deep), and two deep wells 200 feet deep. Results of the hydrologic study have provided information leading to improved understanding of the groundwater system in the vicinity of White Sands NM.

3.3.5 Southern Plains Network

Southern Plains Network parks that utilize groundwater as a primary source of potable water include Alibates Flint Quarries NM and Lake Meredith NRA, Bent's Old Fort NHS, Capulin Volcano NM, Fort Larned NHS, Fort Union NM, Lyndon B. Johnson NHP, Sand Creek Massacre NHS, and Pecos NHP. Monitoring of groundwater resources at each of these parks is recommended as a primary means of informing park managers on the status of this vital resource.

Implementation of the groundwater protocol in SOPN parks is in its early stages. In past years, there has been limited monitoring of groundwater levels within SOPN parks, and a well inventory is in process for this network (E. Gwilliam, pers. comm.). Chickasaw NRA is the only one of SOPN's 11 park units that actively monitors groundwater (EARDC 2007). NPS personnel at Chickasaw NRA monitor groundwater levels at four wells (East, West, South, and North) associated with this park unit. All but the North Well are located inside park boundaries. Groundwater in the vicinity of Lake Meredith NRA and Alibates Flint Quarries NM are currently monitored by the Canadian River Municipal Water Authority.

Southern Plains Network staff monitors groundwater levels at Bent's Old Fort NHS, and water levels were measured at the park during March–September 2001 via 15 hand-augured and well-point driven piezometers (EARDC 2007). This effort was conducted as part of a study by Woods and others (2002). Periodic high water tables in the Arkansas River valley have caused concern for the foundations and subterranean rooms at Bent's Old Fort NHS (Fran Pannebaker, Chief of Natural Resources, pers. comm.).

The SWNC hydrologist and aquatic ecology leads have developed a recommended workplan for implementing the SOPN groundwater monitoring protocol (Appendix A).

4 Implementation

Implementation of groundwater monitoring will generally proceed along the following steps:

- Determine that collection of groundwater data is a priority for the network and the park
- Clarify objectives and goals of the proposed program as they apply to the network and the park
- Identify candidate park units and discuss groundwater monitoring with park staff
- Inventory and gather metadata and historical water-level data for wells within and adjacent to park units
- Obtain equipment, check calibrations, enter into equipment-tracking spreadsheets
- Conduct and document field assessments of candidate wells
- Collect hydrogeologic reports and data relevant to candidate park units within the network
- Select monitoring locations and identify measurement schedules consistent with goals and objectives for each location
- Survey monitoring-location measuring points and ground-surface elevations
- Develop and implement a "Green-Amber-Red" (GAR) safety plan for monitoring at each park in conjunction with park staff
- Initiate monitoring
- Process and archive data as it becomes available
- Revisit monitoring plans for each park as data are processed and analyzed to evaluate need for any revisions
- Develop hydrogeological summary and text for reporting of data at monitored park units

4.1 Sampling design

Sampling design includes both spatial and temporal aspects of monitoring. Sampling design is determined by program objectives, availability of suitable monitoring locations, hydrogeologic setting, and park and programmatic resources, including staff time and funds for equipment, travel, and data processing and management.

4.1.1 Location selection

4.1.1.1 Background

Selection of groundwater monitoring locations is typically relatively straightforward because available groundwater monitoring locations (wells) are limited. Groundwater monitoring sites are primarily determined by the presence, construction, and accessibility of existing wells and the applicability of those wells to the goals of the monitoring program. Typical criteria for assessing whether a well is appropriate for monitoring include consideration of the following questions:

- Is the monitoring location safely accessible?
- Is the monitoring location located on NPS property, or has the landowner provided written permission to allow the NPS to monitor at that location?
- Does the configuration of the wellhead allow the access required for monitoring?
- Is the well an active water supply well?
- Is the well the only available option for monitoring at the park unit?
- Are construction specifications known for the well?
- Is a well log available?
- Are there historical water levels from this well?
- Is the well currently monitored by another party?
- Is the well appropriately constructed to allow collection of high-quality data in a hydrologically suitable location?
- Are nearby wells already being monitored by another agency that would render this location redundant?

- Are there other nearby wells that would be more suitable?
- Is there any reason to believe the well may be contaminated?
- Are there existing water quality data from the well?

Even when a potentially suitable well is available, access difficulties or other issues may rule out the use of the site. In cases where multiple wells are potential monitoring sites, selection will be governed by available resources and the capacity of data from each well to contribute to meeting program-specific objectives. Determination of a well's suitability should be made by program managers in concert with a hydrologist and park staff after a review of local hydrologic and geologic conditions has been completed.

In the determination of suitability and interpretation of water-level data, knowledge of well construction and geologic log data are important. However, if the well was constructed prior to the implementation of requirements for reporting this information, these data are often not available. When construction and/or geologic log data are not available, knowledge of site conditions and general well situation, such as total depth and geologic setting, may be sufficient to provide information needed to determine suitability and interpret water levels recorded in those wells. Depending on need and available resources, supplemental well data may be obtained by use of borehole video methods, borehole flow meter studies, water quality analyses, and/or pumping tests.

4.1.1.2 SWNC groundwater monitoring sites

Tables 3-2 and 3-3 summarize sites currently selected for groundwater monitoring at or near SODN and CHDN parks. The wells listed are either monitored by NPS park or network staff, or are monitored by an outside agency and the data are obtained from the Internet. Appendix B shows the locations of the wells monitored at and near SODN parks, and at Guadalupe Mountains NP.

4.1.2 Installation of new wells

Protection of high-value resources, including springs, streams, and riparian habitats in particularly sensitive or threatened areas, may warrant construction of groundwater monitoring wells or piezometers for data collection. In cases where unique, highly valued and particularly vulnerable resources are or may be threatened, installation of monitoring wells for data-collection purposes should be afforded serious consideration. For example, installation of monitoring wells or piezometers near the Quitobaquito Springs and pond complex at Organ Pipe Cactus NM has been recommended (Filippone 2006). To date, all groundwater monitoring included in the SWNC groundwater protocol has been conducted at existing wells and piezometers.

4.1.3 Measurement schedules

Water-level monitoring is conducted using both manual (direct) and automated (indirect) methods.

4.1.3.1 Manual measurement

Manual measurements require a site visit for data collection and are scheduled according to availability of staff and park-specific monitoring objectives. Quarterly data are suitable for identification of long-term trends and, to a lesser extent, seasonal effects in the data. In addition, manual water-level measurements provide essential quality-control reference points for the data recorded by automated water-level sensors.

4.1.3.2 Automated measurement

Background—. The use of automated methods is beneficial when monitoring objectives are best met by data collection at more frequent intervals than can reasonably be achieved by site visits. Data from datalogging sensors are downloaded during site visits.

When scheduling automated measurements, it is important to consider the burden of long-term data management, and to minimize the number of data points collected while fulfilling the information need. If the only goal is to identify long-term trends, then quarterly monitoring is generally adequate. However, resource managers wanting to understand why trends are occurring, or interested in identifying actions they may wish to take in response to trends, will benefit from a richer dataset that can provide greater insight to the causes of changes—that is, the larger-scale water-balance dynamics of the groundwater system.

While the complete datasets needed to develop a detailed water budget are rarely available, data on some variables are typically available and others may be estimated with greater or lesser degrees of certainty. Some of the datasets that would be applied to a water-balance analysis* include groundwater levels, precipitation, potential evaporation, temperature, evapotranspiration, stream flow, infiltration, and pumping, as well as hydrologic parameters that would contribute to a meaningful water-balance analysis. Of these, a number are already monitored at most parks.

Water levels are known to fluctuate in response to many types of natural and anthropogenic perturbations, including groundwater pumping, channel incision, and reduced infiltration due to evapotranspiration, earth tides, and barometric air-pressure fluctuations. Some of these perturbations are cyclic, with daily, seasonal, or annual periods, while others follow less predictable patterns. Temporal spacing of recorded water levels should be designed to capture the most transient phenomena determined to be important for the specific objectives at each site.

If the phenomenon of interest is cyclic, then determination of monitoring frequency will rely on an analysis of the phenomenon of interest and the desired resolution, with consideration given to limiting the resulting data management burden. In addition to site-specific objectives, some factors that may be considered when establishing manual and automated measurement schedules include:

- Availability of resources required to conduct site visits, including staff time, travel support, and equipment
- Availability of resources to carry out data management, develop site documentation and metadata, and hydrogeologic setting information and reporting
- Availability and nature of historical data
- Other nearby wells monitored
- Understanding of hydrogeology in the area (good/fair/poor)
- Hydrogeologic setting
- Shallow water table-deep water table
- Location relative to recharge/discharge zones
- Proximity to streams/springs/riparian habitats
- Nearby pumping or recharge facilities
- Different groundwater basins or watersheds

***SWNC schedule*—.** The default schedule for automated groundwater level and barometric pressure measurements in SWNC parks is four times daily, programmed as follows: 12:00 AM, 6:00 AM, 12:00 PM, and 6:00 PM. This schedule is sufficient to discriminate daily or longer-period cyclic signals. More frequent data collection does occur at selected sites when local objectives require.

Current SODN and CHDN groundwater monitoring schedules are shown in Tables 3-2 and 3-3. In each case, the data-collection schedule has been established by, and to meet the needs of, the primary user. Where monitoring is conducted by NPS staff, the primary user is the respective park, and data collection is conducted by either park or network staff. In the case of wells monitored by state agencies or the USGS, the primary users are those respective agencies and the NPS is a secondary user of those data.

A well inventory, list of monitoring locations, and schedules for SOPN parks were being developed at time of writing. Several shallow wells at Bent's Old Fort NHS are in the early stages of monitoring.

4.1.3.3 Time conventions

All sensors and data are maintained on local (Central or Mountain) Standard Time year-round, regardless of local daylight time conventions. This system is equivalent with Coordinated Universal Time (UTC), which does not change with the seasons. Times programmed to sensors and times recorded for manual readings are referenced to time originating with the National Institute of

*A water-balance analysis attempts to quantify the total amount of water entering and leaving a system, together with the change in stored water. Such analyses can be used to develop estimates of components that are difficult or impossible to measure, such as actual evaporation and transpiration.

Standards and Technology (NIST) in Colorado. Time from NIST can be easily located on cell phones, and can also be found at www.time.gov. NIST time is consistent with UTC within fractions of a second. When local daylight savings time is in effect, an hour should be subtracted from the local time to maintain all readings in the standard time framework. Where cell phones will not receive a signal, a reliable timepiece should be synchronized with cell-phone time prior to going to the field. As a reference, Mountain Standard Time is equivalent with UTC -7 (i.e., 7 hours earlier than the reference), and Central Standard Time is equivalent with UTC -6.

4.2 Preparation for monitoring

After a park is identified for monitoring, preparations begin, including program planning, data management preparation, fieldwork scheduling, and purchasing and maintenance of equipment. Inventory and development of the well files, field folders, and site metadata constitute significant preparation efforts for fieldwork that are documented in SOP #1. The files and field folders will require ongoing updates but the majority of this effort will occur in the early stages of implementation.

Preparation activities for monitoring site visits and equipment lists are described in SOP #2. Key activities include staff training; development and review of safety procedures; assembling, cleaning, and calibrating equipment and supplies; and arranging logistical details for each site visit. All work will be conducted in conformance with established network safety procedures (CHDN 2013; SOPN 2012; SODN 2012). More information on each of these topics can be found in SOP #2.

Equipment management and tracking is an important component of the groundwater program. A spreadsheet-based inventory of groundwater instrumentation acquired and deployed by the network is maintained and updated as purchases are made or equipment is loaned, deployed, repaired, upgraded, relocated, replaced and/or retired. These spreadsheets/databases are designed to track monitoring hardware deployed in parks over time, providing information on both historical and currently installed instrumentation. The spreadsheets also provide an independent means of associating data with instrumentation if one should be needed.

Equipment purchased for use in the groundwater program is documented and tracked upon receipt on an "intake" spreadsheet by fiscal year. As sensors, software, or communications hardware are deployed at park units, or as monitoring hardware, such as sounders or sensor downloaders, are loaned to park units, a notation to that effect is made in the hydrologic instrumentation intake tracking spreadsheet, and a corresponding notation is made on the park-specific worksheet in the same workbook. As field equipment is loaned, deployed, repaired, upgraded, relocated, replaced and/or retired, entries to that effect are noted, so that it is possible to track equipment from reception to retirement. Examples of network intake and park-equipment spreadsheets are provided as attachments to SOP #5.

4.3 Field methods

For the purposes of this protocol, the principal method of quantifying hydraulic head is by measurement of the distance from a fixed point to the water surface in equilibrium with the atmosphere in a well, piezometer, or open borehole under static conditions. It must be understood that site conditions, including geology, flow regimes, and well construction, will determine what that measurement actually represents; see Bear (1972) for a further discussion of the interpretation of water-level data. In locations where artesian conditions are present, hydraulic head may be determined by measurement of confined pressure.

As described in Section 4.1.3, field methods may be grouped into two categories: manual (direct) and automated (indirect). Wells monitored by CHDN and SODN are measured by direct methods on the schedules shown in Tables 3-2 and 3-3. As described above, some of the wells are also monitored using indirect methods.

4.3.1 Direct field measurements

Direct field measurements of depth to water, also known as "tape-down" or manual measurements, are the most fundamental water-level data element and are the standard

against which indirect data are compared and adjusted. In a tape-down measurement, the observer measures depth to water in a well from a fixed measuring point (MP) at the surface. Direct field measurements are typically made using a graduated electrical sounder or a chalked steel tape. SOP #3 provides details for obtaining and recording direct depth-to-water data using manual measurements.

Quality control for water-level sounder measurements includes scheduled verification of sounder-tape markings using a survey-grade steel tape with 0.01-foot markings and temperature-compensation scale. Methods for calibrating the water-level sounder are provided in the USGS document AR-2010-1.7, "Methods for calibration of graduated steel and electric tapes for measuring water levels," which is included with SOP #2. A datasheet for sounder calibration is included with SOP #2.

Preventing contamination of wells by chemical or biological agents is a high priority. A comprehensive equipment-cleaning and disinfection procedure is required between uses at different park units. During a single site visit, the water-level sounder or tape is disinfected following each manual water-level measurement prior to use at another well. Procedures for cleaning and disinfecting water-level instrumentation are provided in SOP #4.

Under some conditions, alternative methods requiring specialized equipment may be required. Alternative methods for measuring water level/hydraulic head, such as using sonar or air pressure (or water pressure under artesian conditions), are not described as part of this narrative or the accompanying SOPs. Methods for measuring water levels in very deep wells are discussed by Garber and Koopman (1978). Additional information relating to alternative methods of water-level measurement may be found in Cunningham and Schalk (2011).

4.3.2 Indirect field measurements

Indirect methods of measuring depth to groundwater, such as the use of sensors equipped with recording capabilities, offer many benefits to the SWNC groundwater program—including the ability to collect measurements on a daily or more frequent schedule and the opportunity for flexibility in scheduling site visits. Recording sensors are able to capture data that represent dynamic, shorter-term ecohydrologic and surface water-groundwater interaction processes in addition to long-term trends in groundwater levels. They typically also record water temperature—an added benefit.

Automated, or "continuous" measurements are typically obtained using a data-logging pressure transducer (hereafter referred to as the "sensor") installed at a known position in the well. As water levels change, the varying weight of the water column above the transducer is recorded at a prescribed time interval. From these data, the height of the water column above the sensor, depth to water from the surface, and water-level elevation can then be calculated at each measurement time. Data from submersible sensors are verified against manual measurements and adjusted as needed for quality-assurance purposes. Procedures for downloading and maintenance of the water-level sensors currently in use at SWNC parks are described in SOP #6.

4.3.2.1 Selection of sensors

Background—. The planning and installation of data logging water-level sensors depend on site- and manufacturer-specific configurations. Specific sensors, and configuration of water-level monitoring instrumentation, are determined by site-specific physical parameters and by the goals and objectives of monitoring at each site. When considering alternative pressure sensors and comparing costs, some of the key factors that may be helpful to keep in mind include:

1. Size and physical configuration of the sensor and well access
2. Measurement pressure range
3. Accuracy and resolution of measurement
4. Battery life or power source, if external
5. Warranty period
6. Ease of programming, downloading, and processing of data
7. Method(s) available for downloading

sensor

8. Cost of software and licensing requirements
9. Cost of field downloaders and cables
10. Cost of computer connection hardware
11. Cost of sensors
12. Vented or unvented options
13. Cost of barometric pressure sensor (needed for unvented sensors)
14. Memory size of sensors
15. Flexibility in programming time steps, start-stop, etc.

SWNC sensors—. The Sonoran Desert, Chihuahuan Desert, and Southern Plains networks have found that the use of unvented submersible pressure transducers, compensated for changes in atmospheric pressure with a nearby barometric pressure sensor, have met network needs. Unvented sensors do not require maintenance of air lines using dessicant, and may be deployed using less costly cable than that required for vented sensors. The unvented water-level sensors require data compensation for barometric pressure changes, which is easily accomplished using software developed for this purpose. Data from a single barometric pressure sensor may be used to compensate data from pressure transducers within a range of 20 horizontal miles and 1,000 vertical feet (Solinst 2011). However, experience has shown that use of barometric readings measured nearby and in a similar environment as the sensor to be compensated will result in the best quality compensation.

For purposes of data consistency, most efficient use of hardware and accessories, and uniformity in training and operating procedures, CHDN, SODN and SOPN have elected to use a single type of recording water-level sensor for groundwater monitoring. This hardware is available for purchase from several U.S. General Services Administration-registered suppliers. The sensor system is supplied from the manufacturer with support in the form of user's manuals and technical support by telephone as needed. Alternative water-level sensor systems are available and used as needed when site-specific conditions warrant.

For further information on selection and deployment of water-level sensing instrumentation, the reader is referred to NPS staff with experience in this area. Technical staff are available for consultation on this topic at the NPS-WRD and within the networks. Additional guidance may be found in Freeman and others (2004) and Cunningham and Schalk (2011).

4.3.2.2 Deployment of groundwater-level sensors

Specific procedures for deploying groundwater-level sensors are not included in this protocol due to the variety of site conditions and instrumentation options that may be encountered. The groundwater program lead is responsible for determining what, where, when, and how to install instrumentation as part of the groundwater program. For guidance on this topic, the reader is referred to I&M hydrologists and NPS-WRD or other NPS hydrology staff as a source of information and technical support. In addition, the reader is referred to Cunningham and Schalk (2011) and Freeman and others (2004) for additional information.

SOP #5 describes the steps for documenting the installation of continuous water-level monitoring instrumentation in wells. SWNC staff uses the datasheet, "Document Groundwater Monitoring Instrumentation" (SOP #5) to record details and guide data collection during installation of water-level sensors.

4.3.2.3 Deployment of barometric-pressure sensors

The recommended deployment location for a barometric-pressure sensor used to compensate data from an unvented water-level sensor is within a well that is not sealed airtight, a few feet or more below the ground surface at a depth that will not be threatened by submersion if water levels rise. Alternatively, barometric-pressure sensors may be deployed on the surface within a building with ample air leakage and without heating or air conditioning, such as a storage shed or maintenance workshop. Deploying a barometric-pressure sensor inside an airtight and/or heated or air-conditioned building will introduce unwanted air pressure fluctuations

related to heating, cooling, and human activity. Also, deployment in a location affected by wind will potentially introduce significant pressure fluctuations that do not affect water levels within the wells in the same way, and should be avoided.

4.3.2.4 Quality assurance/quality control

Use of automated data collection requires careful attention to data quality so that any issues may be recognized and corrected, or the data flagged accordingly, in a timely manner. Depending on specific accuracy requirements of the program, greater or lesser degrees of quality control are required. The SWNC groundwater program strives to meet accuracy standards of 0.01-ft in manual and automated water-level data.

While pressure transducers are manufacturer-calibrated prior to delivery to the consumer, problems can arise between the office/laboratory and the sensor installation point. For this reason, each sensor should be tested prior to installation to verify accurate calibration in the office/laboratory and again in the field. Detailed guidance on testing and calibration of transducers can be found in Freeman and others (2004) and Cunningham and Schalk (2011).

When wells are instrumented with water-level pressure sensors, measurements may be recorded at regularly spaced time intervals and downloaded by either park or network staff at convenient times. Manual groundwater-level measurements are taken at the time of each download or more frequently, as time allows. The manual water-level data provide an essential reference point against which to verify the accuracy of the recorded water-level data. Potential issues with water-level sensing instrumentation data include drifting of the pressure transducer, installation at different depths between deployments due to the cable or attachment apparatus snagging or hanging up on something inside the well, battery failure, and changes in the length of the suspension cable or cord due to stretching, kinking, or temperature changes.

4.3.3 Photographic site record

Obtaining photographs of each well site at least annually is included as part of this protocol. The photographs should be documented using photographic metadata methods described in the respective network guidelines (CHDN 2012; SODN 2009).

4.4 Monitoring follow-up

The principal tasks immediately following a monitoring event include transfer of data to computer networks, cleaning and maintenance of equipment, and data processing. Following data processing, interim reports to parks are developed, consisting of a graph of all data (including the most recent) and a sentence or two of comment about the information shown on the graph. After the end of the water year, final quality assurance/quality control, analysis, and reporting are conducted.[1]

4.4.1 Equipment cleaning and disinfection

Following a site visit for groundwater monitoring at a single park, equipment (including the empty cable reel) must be thoroughly cleaned, disinfected, and returned to storage prior to use at another park. When monitoring multiple wells within the same park, disinfection of equipment is recommended between wells, and always required prior to use of equipment at water supply wells. SOP #4 provides details on the steps to follow for cleaning and disinfection of sounders, empty reels, and any other equipment that has come into contact with the inside of well casing(s). Equipment that is not cleaned promptly upon return to the base of operations should be tagged as unclean. Equipment should not be returned to its assigned storage location or go into the field at another location until it has been fully cleaned and disinfected.

4.4.2 Data processing

Data processing begins with the transfer of raw data files from field downloaders and

[1] For CHDN, SODN and SOPN purposes, a water year has been designated as the period from October 1 to September 30.

handwritten datasheets to field folders and digital formats compatible with Microsoft Excel and Access. Data processing should occur promptly upon returning to the office following each data-collection event. Steps for processing raw data and data obtained from sources outside the NPS are outlined in SOP #7. Master files that archive cumulative groundwater data for each location will be stored as described in SOP #7.

Details of data management, particularly as related to the groundwater database and handling of field datasheets, are provided in Section 5.

Table 5-1. Groundwater protocol annual schedule.

Quarter	Month	Fieldwork	Data management	Data certification	Analysis & reporting	Administrative	Month	Quarter
1	OCT	All groundwater parks/ sounder QA/QC	4th quarter data management, QA/QC (previous water year)	All data certified for previous water year (October 31)	Assemble and QA previous water year data		OCT	1
	NOV				Integrate data from previous water year		NOV	
	DEC		1st quarter data management, QA/QC (current water year)		Integrate current-year groundwater data, perform analysis and interpretation for previous water year (annual report)		DEC	
2	JAN	All groundwater parks			Final annual report on previous water year		JAN	2
	FEB				Verify report standards & product deliverables/product dissemination		FEB	
	MAR		2nd quarter data management, QA/QC (current water year)		Integrate current-year groundwater data	Evaluation and close-out meeting (previous water year)	MAR	
3	APR	All groundwater parks					APR	3
	MAY						MAY	
	JUN		3rd quarter data management, QA/QC (current water year)		Integrate current-year groundwater data		JUN	
4	JUL	All groundwater parks				Kickoff and planning meeting (upcoming water year)	JUL	4
	AUG					Purchasing for upcoming water year	AUG	
	SEP		4th quarter data management, QA/QC (current water year)		Integrate current-year groundwater data	Preparation for upcoming field season	SEP	

5 Analysis and Reporting

Analysis and reporting responsibilities will be handled by each network using common procedures and formats. Analysis and reporting of groundwater monitoring activities for each park will be conducted annually as per the protocol schedule shown in Table 5-1. Analysis and reporting will focus on the goals identified in Section 2.1 of this document.

Guidelines for data analysis and the development of the annual report for the groundwater protocol are provided in SOP #8. The groundwater annual report will include a narrative description of the data and a discussion of the hydrogeologic setting for each well. This section is not expected to change significantly from year to year but may be supplemented or modified as additional data become available. The report will discuss the groundwater data record as it relates to other water-balance components for which data are available.

The report will also include graphs showing both the manual measurements and time-series data recorded by sensors in wells for the water year of the report. Manual water-level data will be reported in tables as both depth to water and water-level elevation. In addition, the entire dataset of record for the monitored locations will be presented graphically as a separate plot. When available, daily precipitation totals, cumulative precipitation and evapotranspiration demand, and/or maximum and minimum daily temperatures will be presented graphically, along with water levels and the monthly regional Palmer Hydrologic Drought Index (PHDI). PHDI data are available at http://www1.ncdc.noaa.gov/pub/data/cirs/.

A quantitative analysis of the data record will be presented to the extent that available data allow. The minimum analysis would describe the range of the fluctuation in the water table over the year and historically, and cumulative annual precipitation at the site. Higher levels of quantitative analysis will be possible for data recorded by sensors at more frequent intervals (e.g., daily/hourly), and at locations where multiple monitoring locations allow calculation of hydraulic gradients. For example, the higher levels of analysis may identify relationships between groundwater levels and evapotranspiration demand, pumping in the area, flow direction, response to extreme events, or seasonal and longer-term climatic conditions. When available from other sources, information relative to surrounding regional groundwater conditions will also be incorporated either directly or by reference in the report.

6 Data Management

For this protocol, data management will be handled consistently across the three networks using a shared database. Effective data management to ensure data quality, interpretability, security, longevity, and availability is critical to the success of the groundwater monitoring program. Data management for this monitoring effort is a cyclic process that starts with a kickoff meeting in August of the preceding water year and ends in February of the second year following the kickoff meeting, when the final report is completed and data are permanently archived off-site. The cycle is repeated each year as monitoring data are collected.

This section presents an overview of the monitoring database and general procedures for organizing, entering, verifying, validating, certifying, documenting, distributing, and archiving the data collected under this protocol. Additional information and context may be found in each network's data management plan. Further details and instructions for the tasks in each stage of the data management cycle are contained in SOP #9.

6.1 Data organization

This long-term monitoring project generates large quantities of data and numerous products, and a well-organized digital file structure is critical to avoid confusion and potential data corruption. Any organization that implements this monitoring project should have a formalized directory structure to manage ongoing data collection. Appropriate staff and partners involved in this project are granted edit access to data for the current field season. At the end of each field season, certified data, completed products, and other seasonal files are transferred to the permanent project folder where they are stored in read-only format. Each network or organization should and will provide documentation and training on its own specific directory structure, its purpose and use, and links to other information relevant to the project.

6.2 Data model

To appropriately manage groundwater data, the dataset should be stored and managed in a normalized relational database. This protocol may also leverage other databases common to workflow throughout the office. These database solutions could include (1) a database containing the data tables that store core groundwater data and (2) a database(s) containing other data relevant to operational and project needs, which are integrated through a user interface. This configuration allows for improvements and revisions to the database user application without altering the actual data structure or any of the records in the back-end database data tables.

The database containing the core groundwater data is being developed with indicators to represent where data are in the data life cycle. The database also incorporates an automated log file that tracks the users who access it, as well as any modifications users make to either the database structure or data. The database is accompanied by metadata or documentation that articulates the data dictionary, management of the database, and versioning procedures.

The user interface includes forms for data entry and modification; queries for verification, validation, and data export; and code for creating custom features designed to maintain efficient workflow. The application has documentation that articulates procedures for management and versioning, as well as easy-to-understand user instructions.

The database created by the authors of this protocol is based on the NPS Natural Resource Database Template (a set of relational database tables in Microsoft Access recommended by the NPS I&M program for these types of databases). The design includes standardized core tables for elements (such as Locations and Events) that are common to most monitoring datasets, as well as a field data table that can be duplicated and customized to meet individual project data requirements.

The project leader should have a thorough understanding of the project database structure and procedures for using the application. Any and all documentation requested by the project lead, staff, or partners should be made available in read-only format.

6.3 Data-entry procedures

Sampling data for groundwater are acquired as specified in the protocol SOPs, using two different methods: (1) data are manually recorded on paper field datasheets, and (2) recorded data are downloaded from automated sensors. A third method, in which manual measurements of water level data are entered directly into the project database on ruggedized field laptop computers, is available but not utilized for this protocol.

Paper field data-entry forms serve as the primary portal into the database. Location and sampling event information are entered first. Then, field-trip notes, metadata describing wells, and data on manual depth-to-water measurements and well-hardware maintenance data may be entered.

Data recorded on paper field datasheets are copied and the originals placed into the "To Be Entered" data folder in the Groundwater file drawer. These data are entered into the digital database as soon as possible following collection. Copies of datasheets are provided to the groundwater lead. Beginning data entry after the field season ends is not acceptable. This is an essential step since keeping current with data entry facilitates finding and correcting errors while the information is still fresh in the minds of the field staff. To facilitate accuracy, QA/QC (quality assurance/quality control) mechanisms are built into the database to eliminate as many potential data-entry errors as possible. The "Groundwater Monitoring Database User Guide" contains more information on these mechanisms.

Data downloaded from electronic sensors are processed following the procedures outlined in SOP #7. An SOP describing groundwater data management and QA/QC procedures for continuous data using Aquarius software to process time series data from sensors is planned for development.

6.4 Data-certification process

Data verification is the process of checking the accuracy of digital data against copies of the original paper datasheets. Data recorded on paper datasheets and entered into the groundwater database requires verification (refer to SOP #9 for guidance on QA/QC procedures for paper datasheets).

Data validation is the process of reviewing digital data for range and logic errors. Although some validation features, such as range limits, are built into the database itself via data-entry forms (see above) and queries, the project lead or another person familiar with the data further reviews the dataset for these types of errors. Spatial data are validated according to the procedures specified in SOP #9 using the latest version of NPS-sanctioned geospatial software.

Data certification is the process of ensuring that the dataset (i.e., the database containing all of the records for that year) has been verified and validated for accuracy, is complete, and is fully documented. Data certification is completed annually for all tabular and spatial data and photographs. This process should be documented by the project leader in order to notify the data manager that data are ready for archiving and storage. After the dataset is certified, it can be used in analysis and reporting.

6.5 Data metadata procedures

Any data produced by the groundwater monitoring protocol should have accompanying metadata. Metadata help users to locate and use their own data resources and those of others. Metadata also help to preserve data history, allow the data life cycle to be effectively managed, identify the effective and administrative limits of data use, and instill data accountability by requiring producers to state what they do and do not know about the dataset.

At the most basic level, metadata ensure the longevity and usability of the dataset. When changes in personnel cause an organization to lose institutional knowledge, undocumented data can lose its value. Subsequent employees may be left with minimal understanding of the contents and uses of a digital database and may be unable to trust the results generated from those data. Also, lack of knowledge about data produced by other organizations can lead to duplication of effort. For these reasons, in the long term, data metadata are well worth the investment of time and resources required to generate them (FGDC 2013).

For geographic metadata, the "SODN Metadata Development Guidelines" incorporate best practices according to NPS and Federal Geographic Data Committee (FGDC) standards. Database objects (e.g., tables, fields) are defined and documented in a data dictionary and/or in Section 5 of an FGDC-compliant metadata file. Both spatial and non-spatial metadata records are uploaded to the NPS Natural Resource Information Portal, where they are available to the public. All metadata records are updated as needed whenever additional data are collected and added to the dataset.

6.6 Product integration and distribution

Multiple products will be generated from this dataset, including annual groundwater data, field summaries, data summaries, status reports, and synthesis-and-trend reports. All data will be assessed for sensitive content or proprietary purposes. All data, metadata, and reports judged to be non-sensitive and non-proprietary will be made available to any interested parties. Other datasets, including those containing sensitive data, may be requested in writing from the data steward. Sensitive data are released only with a signed confidentiality agreement. Each network or organization is responsible for ensuring that data are stored in the appropriate location and format, and are obtainable by all person(s) interested and authorized to access the dataset(s).

6.7 Data maintenance and archiving

The groundwater databases are archived on a secure server with regularly scheduled backups. To ensure data compatibility with other existing or newly developed software programs, each database will be exported to an ASCII file. These ASCII files are stored on a secure server drive. All archived files are designated as read-only.

Before making revisions to either the front- or back-end database, a copy of the current version is stored to facilitate tracking of changes over time. The file name for the database includes a number indicating the version of the database (e.g., Groundwater_be_v100.mdb) appended to the file name. After storing the copy, the version number of the database undergoing revision is changed and "_Draft" is added to the end of the file name. When the revisions have been approved, the "_Draft" designation is removed. Frequent users of the data are notified of the updated version by data management staff.

After the data have been certified and archived, any data editing must meet the following conditions: (1) users may only make changes that improve or update the data while maintaining data integrity, (2) all changes must be documented in the database change/version log, and (3) users must be prepared to recover from mistakes made during editing. Printed data records are not altered, and they are reconciled to the database through the use of the edit table. Any editing of archived data is accomplished jointly by the project leader and data manager.

7 Personnel Requirements and Training

Personnel involved in executing this protocol include network staff, park staff, and volunteers. Fixed network staffing needs include a groundwater program lead and data management staff, as well as geospatial and administrative support staff. Additional network staffing needs depend on details of the planned groundwater program for each network, including number and distribution of sites, frequency of monitoring, and availability of park and/or volunteer staff to conduct fieldwork at the monitoring locations. Personnel training requirements depend on the respective tasks each will perform.

Park staff and volunteers provide essential "boots on the ground" support by collecting manual depth-to-water measurements and downloading water-level sensors deployed in wells. Availability of park staff and volunteers significantly reduces costs associated with network travel time and expenses. Typical tasks carried out by field staff require specific training in conducting and recording accurate tape-down measurements as well as downloading and performing maintenance on water-level sensors. The essential tasks for field personnel are described in detail in SOPs #1–6. Training for park staff and volunteers includes reading and becoming well-versed in the field protocols, safety procedures (CHDN 2012; SODN 2012), and SOPs. Staff-in-training are accompanied by the groundwater lead or another qualified network staff member during initial monitoring events to verify procedures and understanding of the protocol, SOPs, and datasheets.

Network personnel requirements include staff for planning and preparation, fieldwork and equipment management, data processing, data management, analysis, reporting, and administration. Fieldwork includes one-time or occasional tasks, such as surveying and site-metadata inventory, as well as repeated events, such as measuring depth to water manually at monitoring sites and installing, maintaining, troubleshooting, and downloading recording sensors at selected locations.

With the possible exception of installation of sensors, field efforts related to groundwater monitoring for wells with water levels not greater than 1,000 ft bgs (below ground surface) can generally be accomplished by one person. Measurement of deeper water levels may require more than one person. Where sites are remote or other situations exist, safety considerations may dictate that a minimum of two persons should conduct the monitoring.

Planning the installation of recording sensors and the reporting and analysis of groundwater data requires training in hydrogeology and groundwater hydraulics. Interpretation of groundwater data within local and regional contexts requires formal training in hydrology. However, presentation of water-level data, even without interpretation, will allow park staff to arrive at general conclusions regarding groundwater status and trends.

7.1 Roles and responsibilities

The groundwater program lead is responsible for implementing this protocol and reporting to the network coordinator. Protocol implementation will be conducted by network, regional, and park staff in cooperation with and under the guidance of the groundwater program lead for each network. Volunteers are coordinated by staff from the respective parks where they serve. Data managers are responsible for data management activities.

At the start of the water year, the groundwater program lead will develop an annual work plan in coordination with the network streams protocol and other network fieldwork. The protocol leads will tentatively schedule fieldwork and will coordinate with other network staff to implement the plan.

Network field personnel are responsible for assembling equipment, ensuring that it is cleaned and in working order, and coordinating visits and well access with park staff. In cases where field sensors will also be accessed, the field staff should verify that the required software for that hardware is

loaded onto the laptop or downloader as needed and is functional. In the field, data identifying the observer, well, date, time, depth to water, and equipment used will be entered directly into the groundwater field datasheets, along with field notes (SOP #3).

Where field monitoring is conducted by park staff or volunteers, groundwater field datasheets will be used for documentation of fieldwork. These sheets will be transmitted to the program manager by e-mail of scanned datasheets, fax, or postal mail following completion of each monitoring effort.

All digital field data from water-level sensors will be transferred in raw format from parks via e-mail or downloaded from network hardware and filed in a dated folder on the vital-signs drive under the appropriate groundwater folder as described in SOP #7.

At the end of the field season, the groundwater program lead is responsible for directing a thorough review of all data entered. The data manager is responsible for designing a suitable database, updating the database, and archiving and disseminating groundwater data. The groundwater program lead will summarize, analyze, and report annual groundwater data to the network coordinator.

7.2 Qualifications and training

Staff must be able to perform the activities described in this document. Recommended qualifications and training of staff implementing the groundwater protocol are detailed below.

The network hydrologist, physical scientist, or aquatic ecologist acts as the program lead, organizes and oversees the groundwater monitoring effort, and reports to the network coordinator. The program lead must have in-depth knowledge of this protocol and associated SOPs to successfully plan and execute the protocol. Ability to train field staff is required of the program lead. Formal training in geology and groundwater hydrology is required to complete the analysis and reporting requirements of SOP #8.

Qualifications required of field personnel include communication and interpersonal skills needed to interact with park and network staff, and physical ability to access monitoring locations while transporting equipment that may weigh up to 25 lbs. and to operate field instrumentation, such as water-level sounders and cable reels. Ability to (1) use the relevant computer software and the equipment described in this protocol and the various groundwater SOPs, and (2) troubleshoot problems in the field and follow safety guidelines are of paramount importance. Field personnel must also be able to download data when back in the office, maintain and troubleshoot equipment, enter data into the groundwater database correctly and with minimal supervision, and communicate via verbal, digital, and written means.

8 Operational Requirements

Operational requirements for implementation of this protocol include personnel; office space; tools, equipment, and instrumentation for manual and automated water-level monitoring; computers, servers, datasheets, notebooks, and filing facilities for maintaining and archiving the data; printing, facsimile, copying, and scanning capabilities; telephone and Internet service; transportation to and from the monitoring sites; and computing and archiving facilities at network offices.

9 Revising the Protocol

This sampling protocol consists of a protocol narrative and 10 standard operating procedures (SOPs). The protocol narrative provides the history and justification for the program and an overview of the approach and methods used. The protocol narrative will be revised only if major changes are made to the protocol. The SOPs, in contrast, are specific, step-by-step instructions for performing each task. They are expected to be revised more frequently than the protocol narrative.

Careful documentation of such revisions, including an archive of previous versions, is essential for maintaining consistency in data collection, analyses, and reporting. To summarize changes, the monitoring database for each component contains a field to identify the protocol version used to gather and analyze data. The steps for changing any aspect of the protocol are outlined in SOP #10. The narrative and each SOP contain a Revision History Log that should be completed each time the narrative or an SOP is revised. The purpose of this log is to explain why changes were made and to track document version numbers. Former and active versions of the protocol narrative and SOPs are stored on separate drives on the network server.

The SWNC networks use a Master Version Table and Version Key number (VK#) to track which versions of the narrative and SOPs are used in each version of the monitoring protocol. The VK# is essential if project information is to be properly analyzed and interpreted. ***The protocol narrative, SOPs, and data should never be distributed independently of the Master Version Table.***

10 Program Review

A thorough analysis and review of the monitoring protocol will be conducted every 10 years under the direction of the CHDN, SODN, and SOPN program managers and the regional I&M coordinator. This review may include external experts and will focus on the monitoring approach, methods, and results obtained using the protocol, in much the same manner as the initial external review required of all NPS I&M protocols.

At the close of each field season, network groundwater staff and cooperators will complete a less-formal review of the protocol in the context of the field season for the purposes of evaluating operating procedures. If significant concerns are identified, this informal review may trigger a more formal internal or external review as described above, at the discretion of the CHDN, SODN, and SOPN program managers.

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Appendix A. Recommended Workplan for Implementing Groundwater Monitoring in Southern Plains Network Parks

The SWNC hydrologist and aquatic ecology lead have developed the following workplan recommended for implementing groundwater monitoring in Southern Plains Network parks.

1. Develop an inventory of and metadata for all wells at and near Bent's Old Fort NHS and Pecos NHP (including wells already monitored by the USGS or the states of Colorado or New Mexico). Collect and archive any existing water levels or water quality records at wells in or near the parks by examining park files, place an inquiry with Larry Martin at the NPS WRD, search USGS websites for groundwater data from the wells identified, and contact the USGS New Mexico Water Science Center to inquire about unpublished data.

2. Install and monitor logging pressure transducers at selected monitoring wells at Bent's Old Fort NHS, and one at Pecos NHP, for at least one year. Instrumented wells will be monitored manually when sensors are downloaded quarterly.

3. Identify any wells monitored by other agencies that will provide information on groundwater status at and in the immediate vicinity of network parks.

4. Collect quarterly manual groundwater levels from monitoring locations, including the instrumented monitoring wells at Bent's Old Fort NHS and Pecos NHP.

5. Develop "master" data spreadsheets for the monitored wells as per the SWNC groundwater protocol and incorporate measurements as they become available.

6. Enter the monitored wells into the SWNC groundwater database.

7. Create an implementation plan for Alibates Flint Quarries NM, Chickasaw NRA, Washita Battlefield NHS, Fort Union NM, and Sand Creek Massacre NHS.

Bent's Old Fort National Historic Site

Currently, four shallow wells are monitored by manual and automated methods as per the SWNC groundwater protocol. An initial year of instrumentation (logging pressure transducers) is underway to help understand groundwater dynamics in the system. After a year, the transducer data will be assessed for correlation and the number of transducers will be continued, or decreased, and deployed elsewhere. The objectives of groundwater monitoring at this park are to understand groundwater dynamics via measured water levels as they impact the fort's subterranean resources, the source for the Arch wetlands, and the dynamic relationship between the water level in the Arkansas River and adjacent groundwater levels.

Capulin Volcano National Monument

A USGS index well located south of the park is recommended for tracking via the NWIS site (USGS 364444104000201). The park's water-supply well (USGS 364643103583701) should be monitored semi-annually or at least once per year on a relatively fixed schedule following a no-pumping period of at least 24 hours. Consolidation of metadata and existing records by examination of park files and a data request to the NPS-WRD is recommended.

Chickasaw National Recreation Area

Prior to implementing a specific groundwater monitoring plan, investigation into existing data and NPS Water Rights Branch reports, as well as ongoing monitoring, will be conducted. Also, SOPN must determine exactly what equipment the park already has in its possession and what additional equipment may be provided by the network. Two USGS index wells are located in the park, USGS 343017096561501 01S-13E-01 ABA 1 CNRA GW WELL 2 and USGS 343022096565701 01S-03W-01 BBB 1 CNRA GW WELL 1. The North, South, East, and West wells in the Travertine Creek area should be monitored

on a schedule to be determined by available park and network resources.

Fort Larned National Historic Site

No monitoring is in place or planned at this time, although consolidation of existing records may improve our understanding of regional groundwater dynamics. The USGS monitors a well south of the park that may be a source of surrogate data (USGS 381015099132702 22S 17W 05BBC 02).

Fort Union National Monument

Records indicate that the only well at this park is a drinking-water production well for the visitor center. If no other wells are available for monitoring, then manual monitoring on a quarterly or semiannual basis following a period of no-pumping of at least 24 hours is recommended for this well. A review and consolidation of well records in files at the park and at the NPS-WRD is recommended. SWNC staff will investigate opportunities for groundwater monitoring at the park and assess the feasibility of monitoring at this site.

Lake Meredith National Recreation Area/Alibates Flint Quarries National Monument

No monitoring is planned at this time, although consolidation of existing records may improve understanding of regional groundwater dynamics.

Lyndon B. Johnson National Historical Park

No monitoring is planned at this time, although consolidation of existing records may improve our understanding of regional groundwater dynamics.

Pecos National Historical Park

The park includes a total of 10 wells (NPS-WRD 1995). It is recommended that the trading post well be monitored with a sounding tape at least quarterly. Deployment of a logging transducer at this well is under consideration. SWNC staff will assess the value of monitoring other park wells and develop a work plan for monitoring.

Sand Creek Massacre National Historic Site

An extensive network of piezometers was installed in the riparian zone during previous studies (Martin 2006). Deeper wells are not known to exist. The existing well infrastructure and the proximity of this site to Bent's Old Fort NHS make it logistically possible to include this park in monitoring operations. We recommend that the well infrastructure be assessed to measure whether it could meet the protocol objectives and whether it would be feasible to incorporate this park into future work plans.

Washita Battlefield National Historic Site

During water year 2013, it was recommended that the existing well infrastructure be assessed at this site. Several unused agricultural and monitoring wells (Marston and Halihan 2007) are present at this site and would be excellent choices for further monitoring. Since SWNC staff would not be able to visit this site at a frequency that would fulfill the objectives of this protocol, SWNC staff will need to work with staff from this park (or possibly Chickasaw NRA) to ensure timely monitoring and quality data. It is recommended that the SWNC pay for one pay-period of park (or Chickasaw NRA) staff time to ensure that monitoring tasks would be completed in fulfillment of groundwater monitoring protocol objectives. The SOPN water quality monitoring account would incur this expense.

Appendix B. Locations of Wells Monitored in and Near Sonoran Desert Network Parks, and at Guadalupe Mountains National Park

Maps start next page

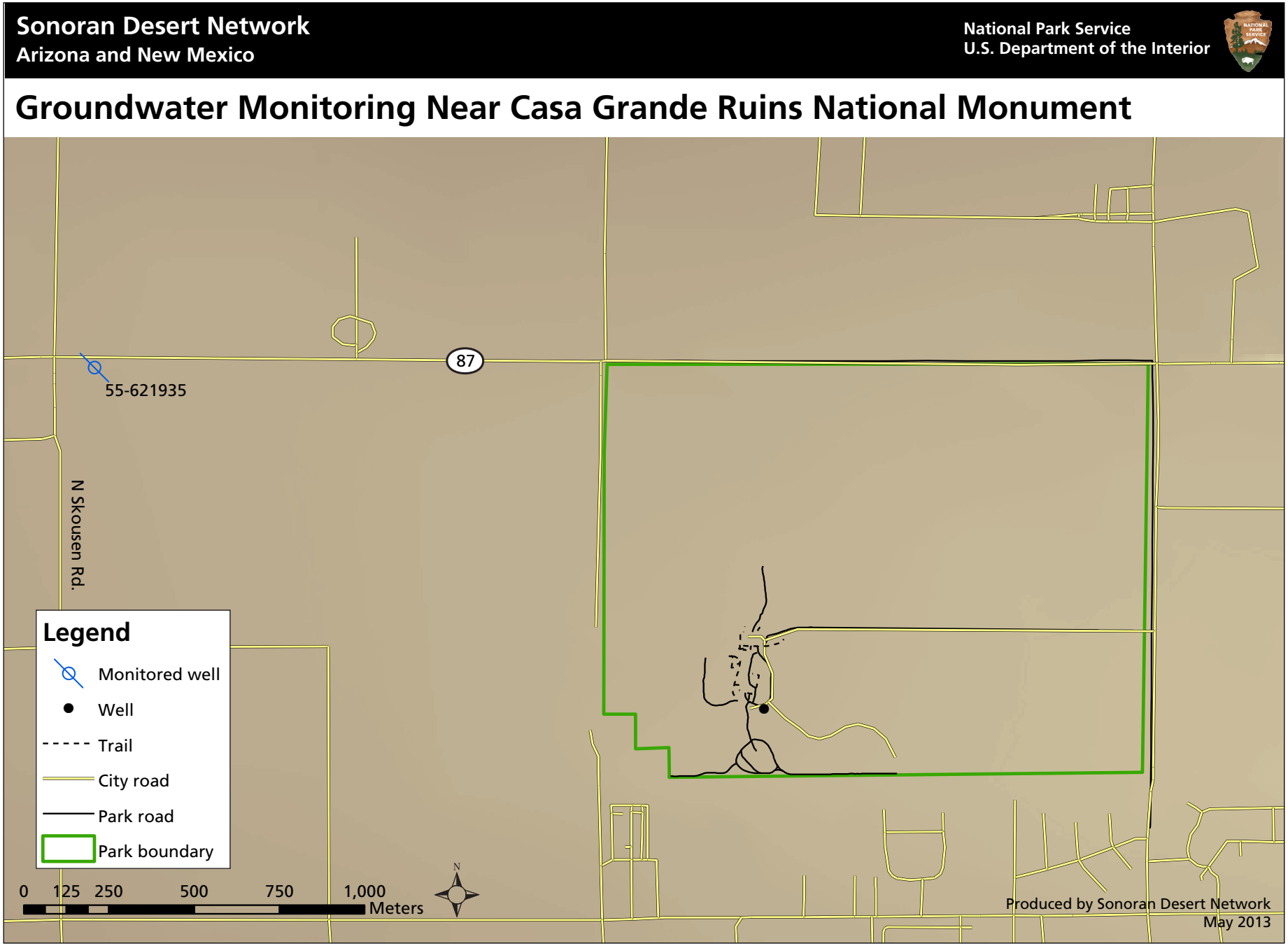


Figure B-1. Groundwater monitoring wells near Casa Grande Ruins National Monument.

Groundwater Monitoring in Chiricahua National Monument

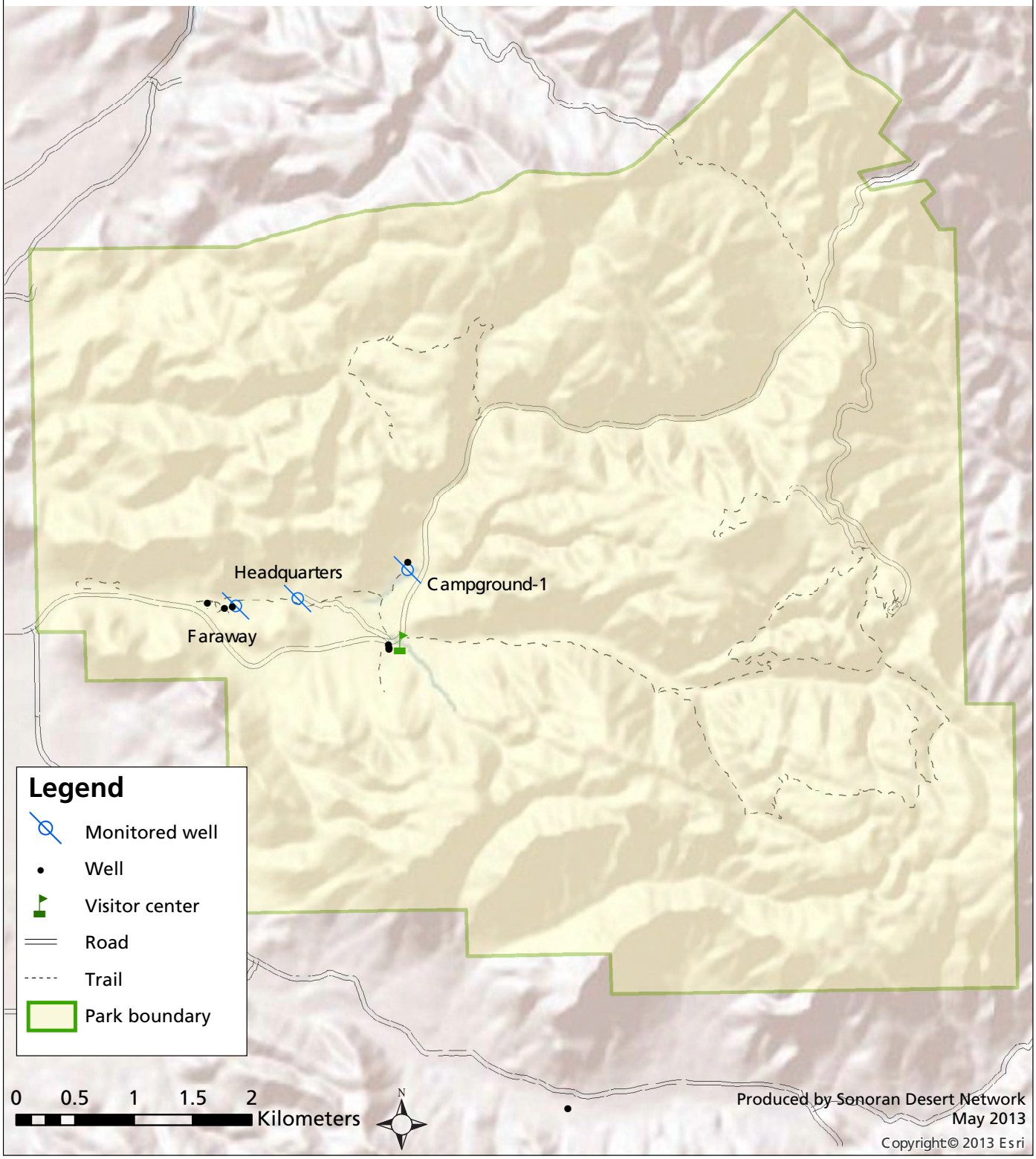


Figure B-2. Groundwater monitoring wells in Chiricahua National Monument.

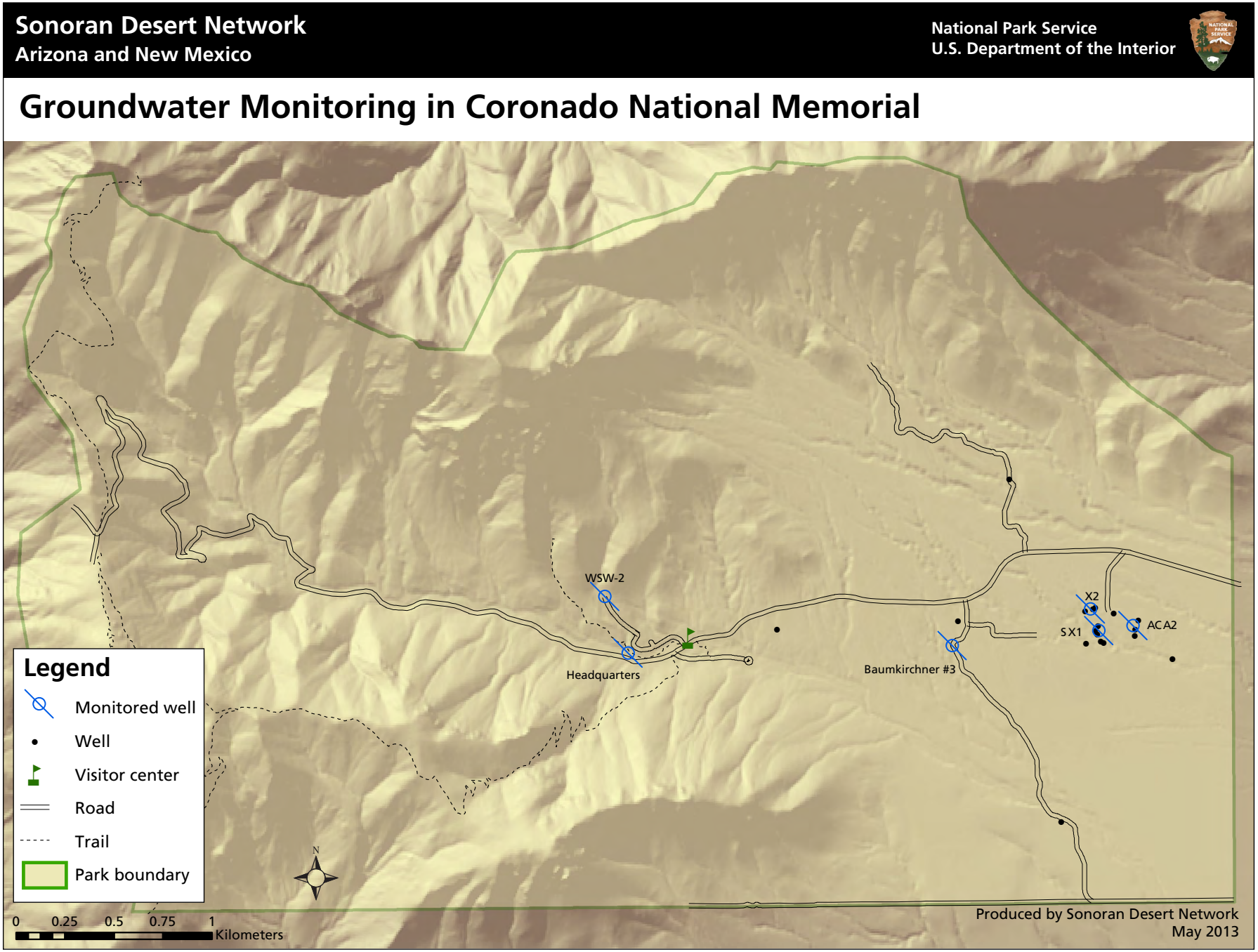


Figure B-3. Groundwater monitoring wells in Coronado National Memorial.

Groundwater Monitoring in Fort Bowie National Historic Site

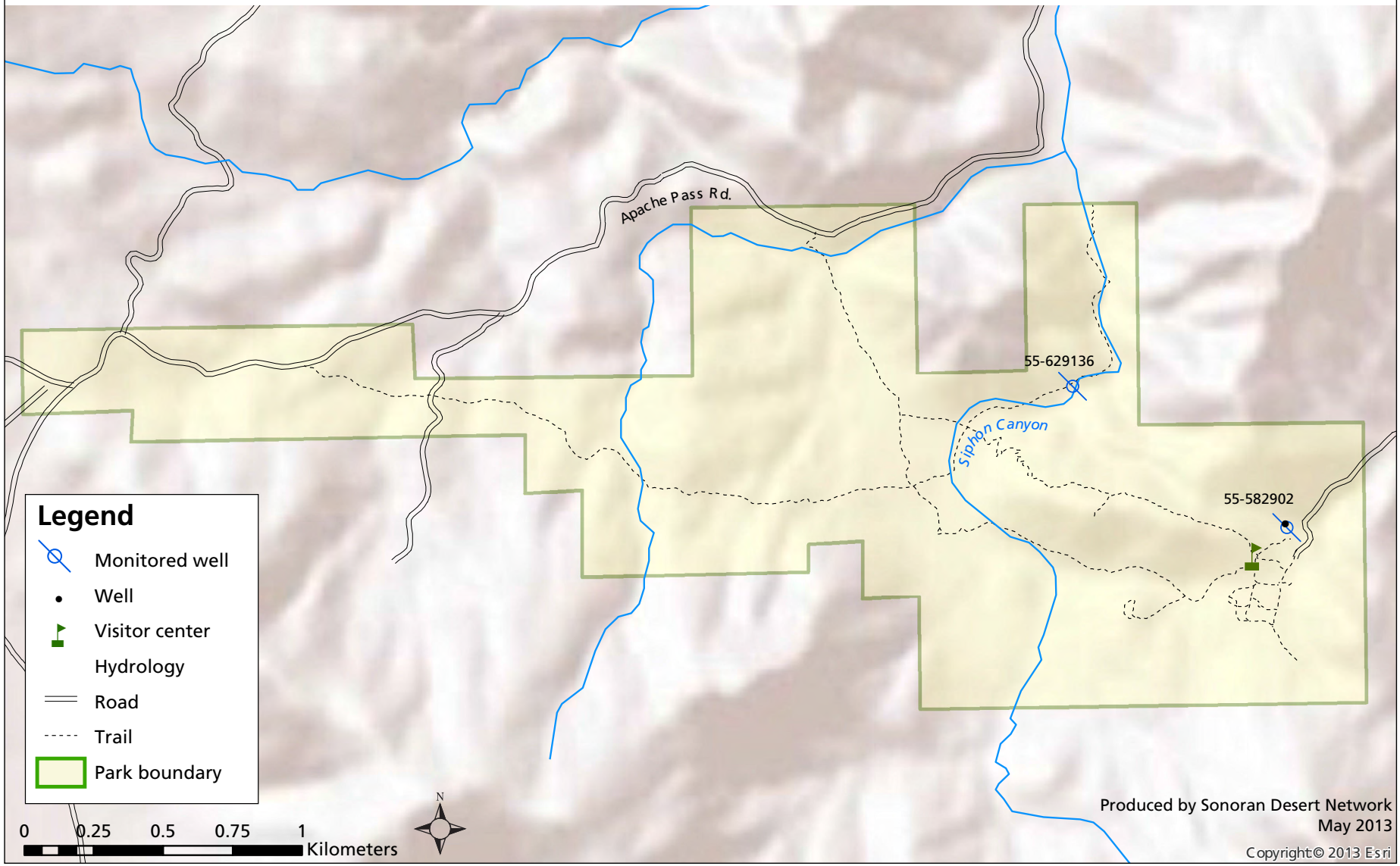


Figure B-4. Groundwater monitoring wells in Fort Bowie National Historic Site.

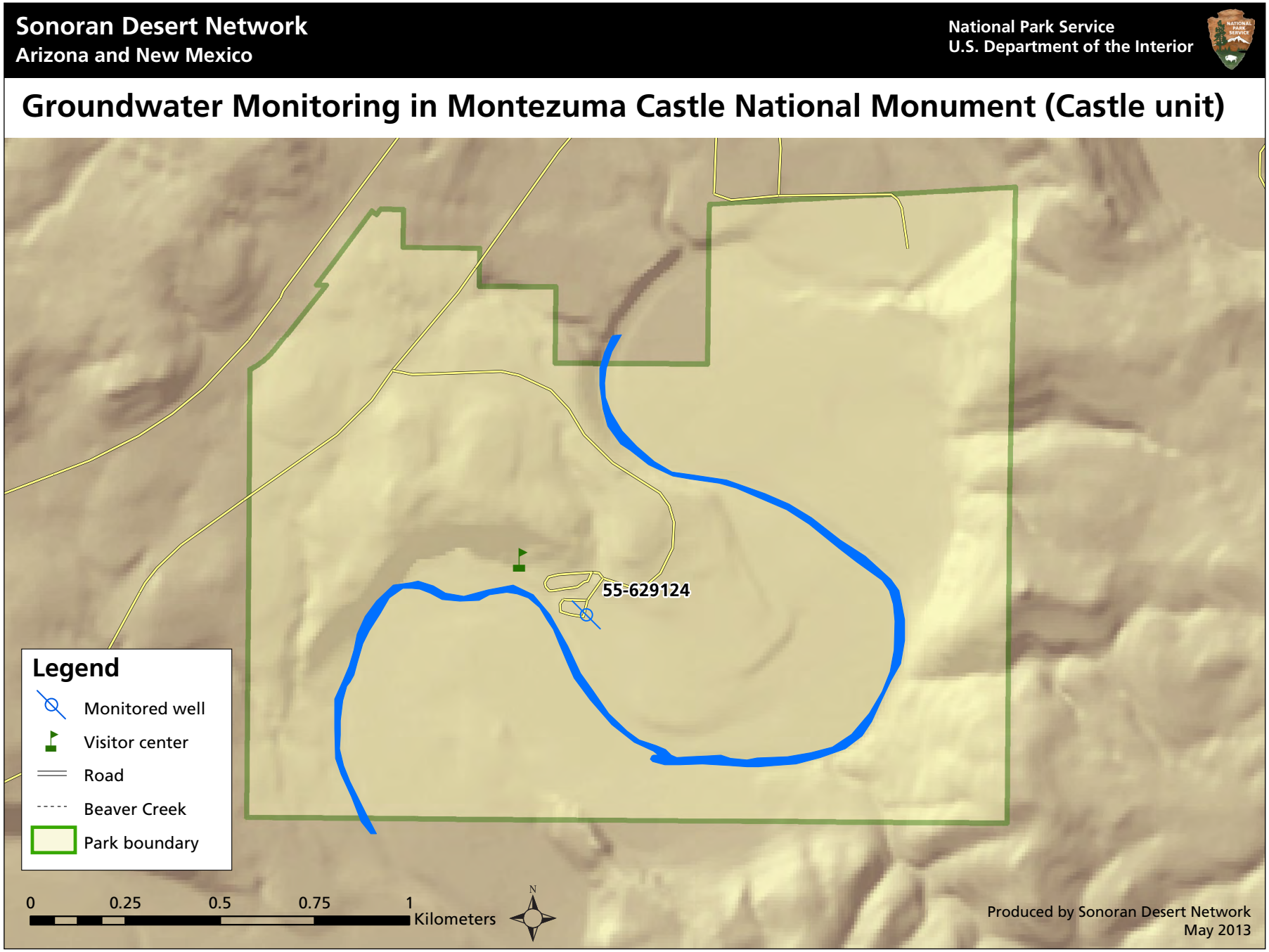


Figure B-5. Groundwater monitoring wells in Montezuma Castle National Monument (Castle unit).

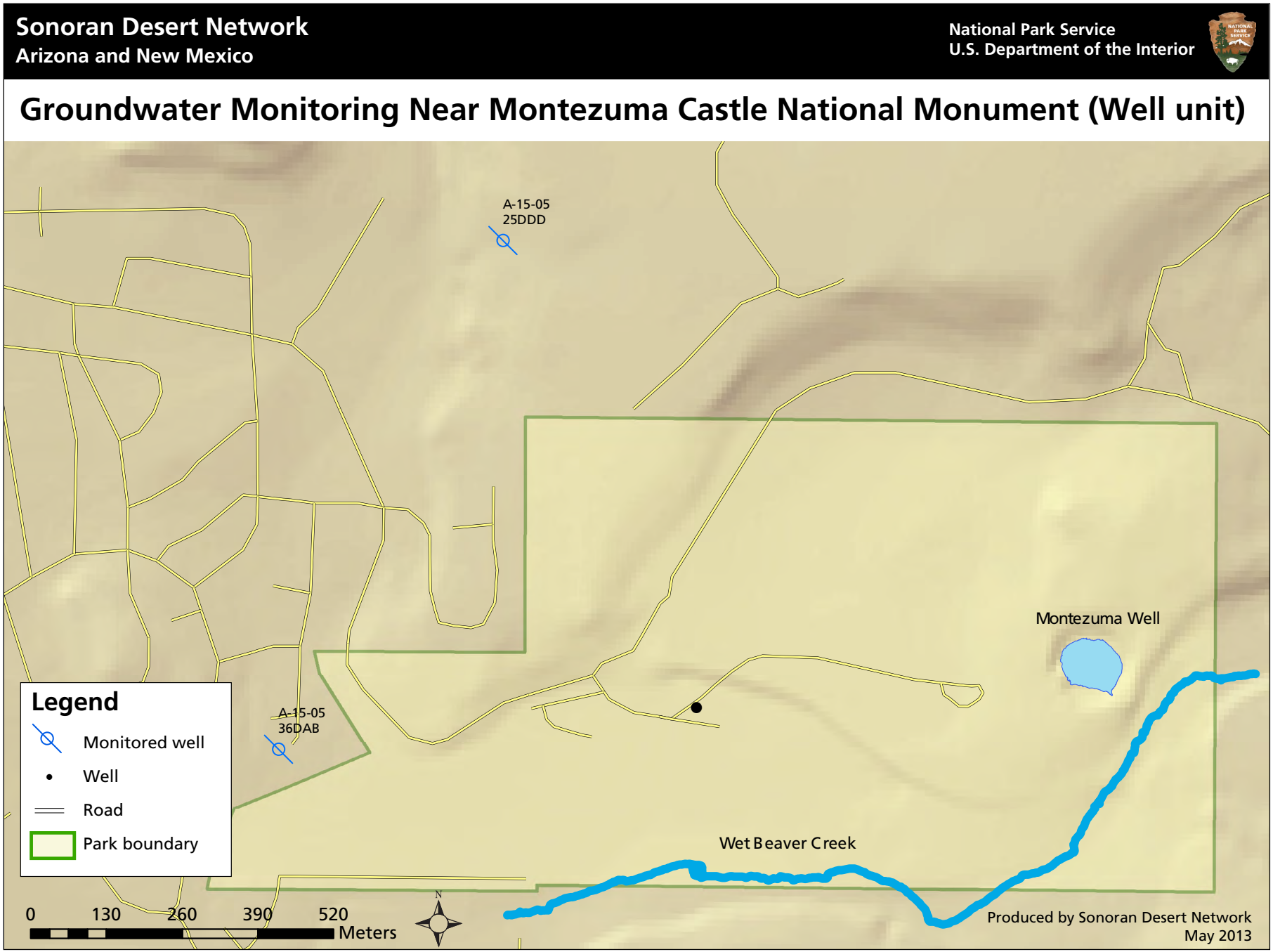


Figure B-6. Groundwater monitoring wells near Montezuma Castle National Monument (Well unit).

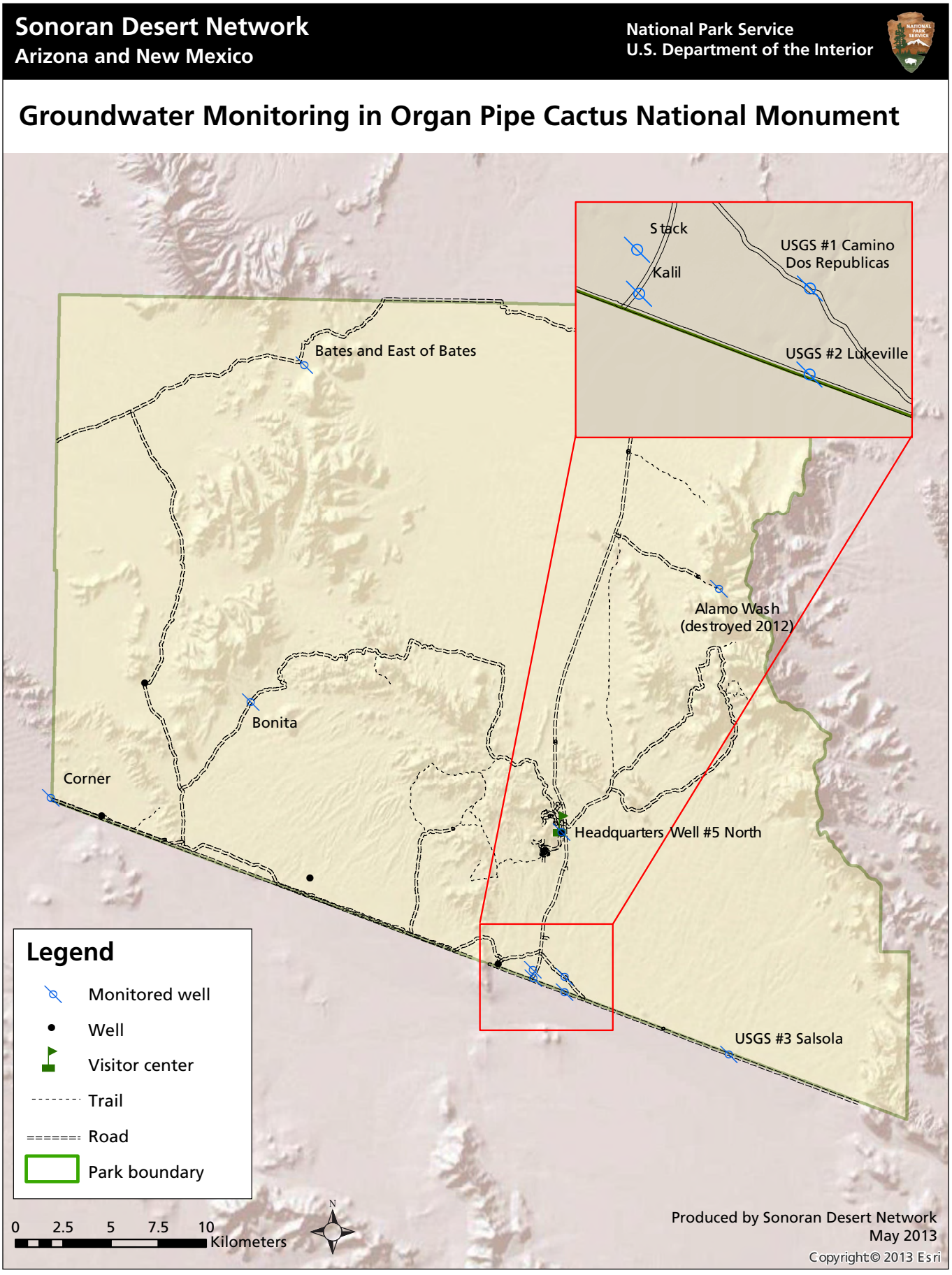


Figure B-7. Groundwater monitoring wells in Organ Pipe Cactus National Monument.

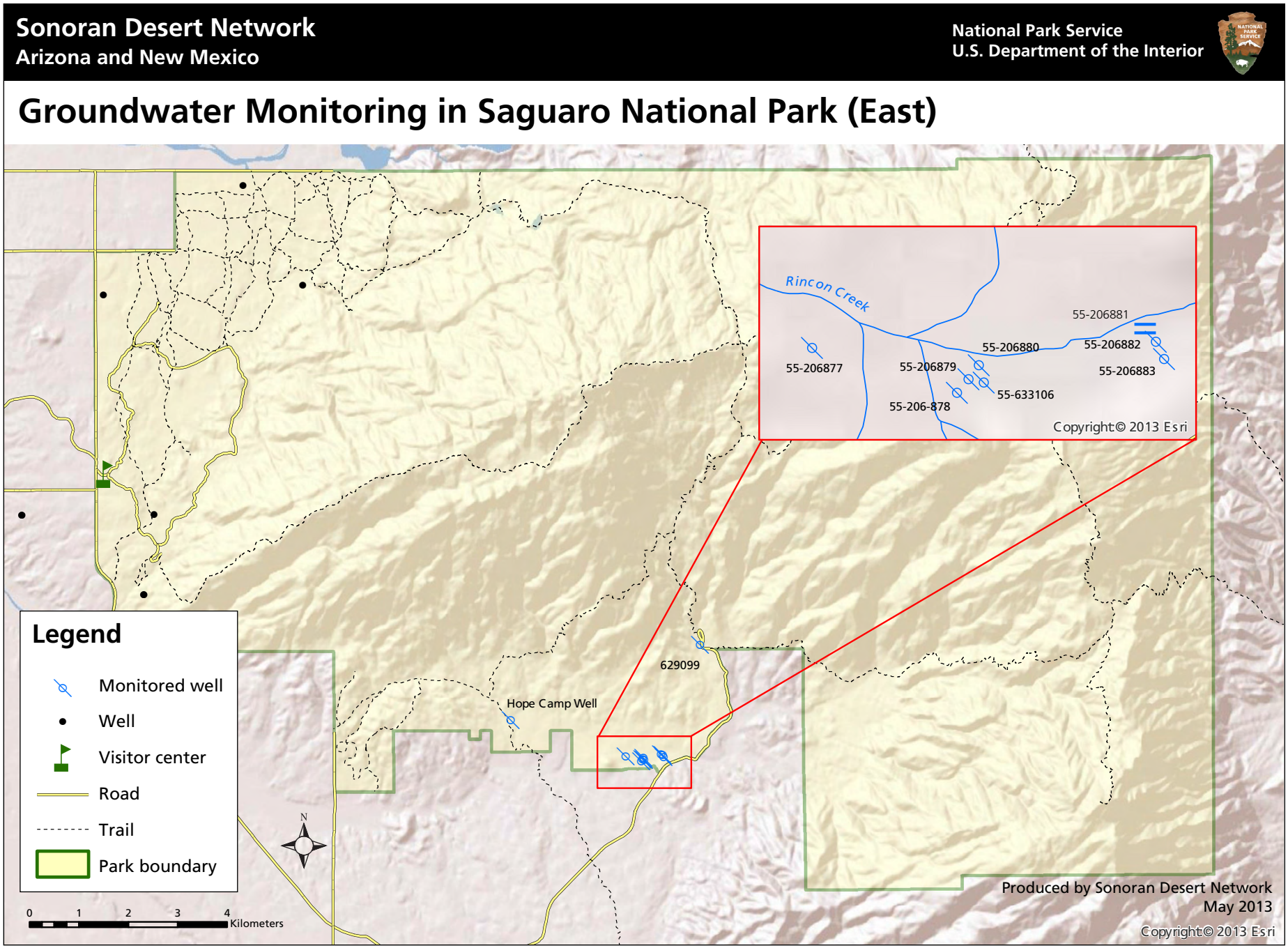


Figure B-8. Groundwater monitoring wells in Saguaro National Park (East).

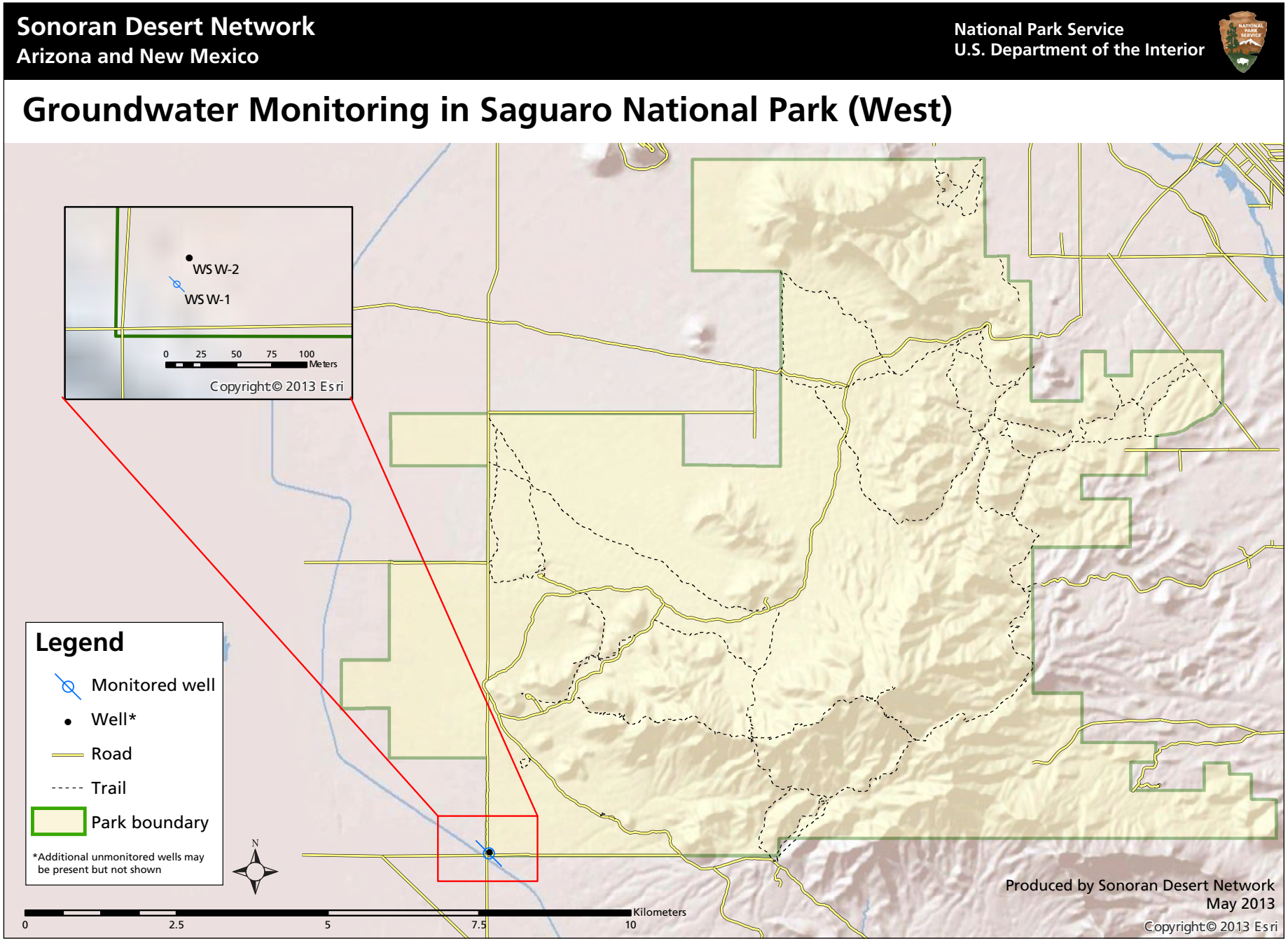


Figure B-9. Groundwater monitoring wells in Saguaro National Park (West).

Groundwater Monitoring in Tumacácori National Historical Park (Mission unit)

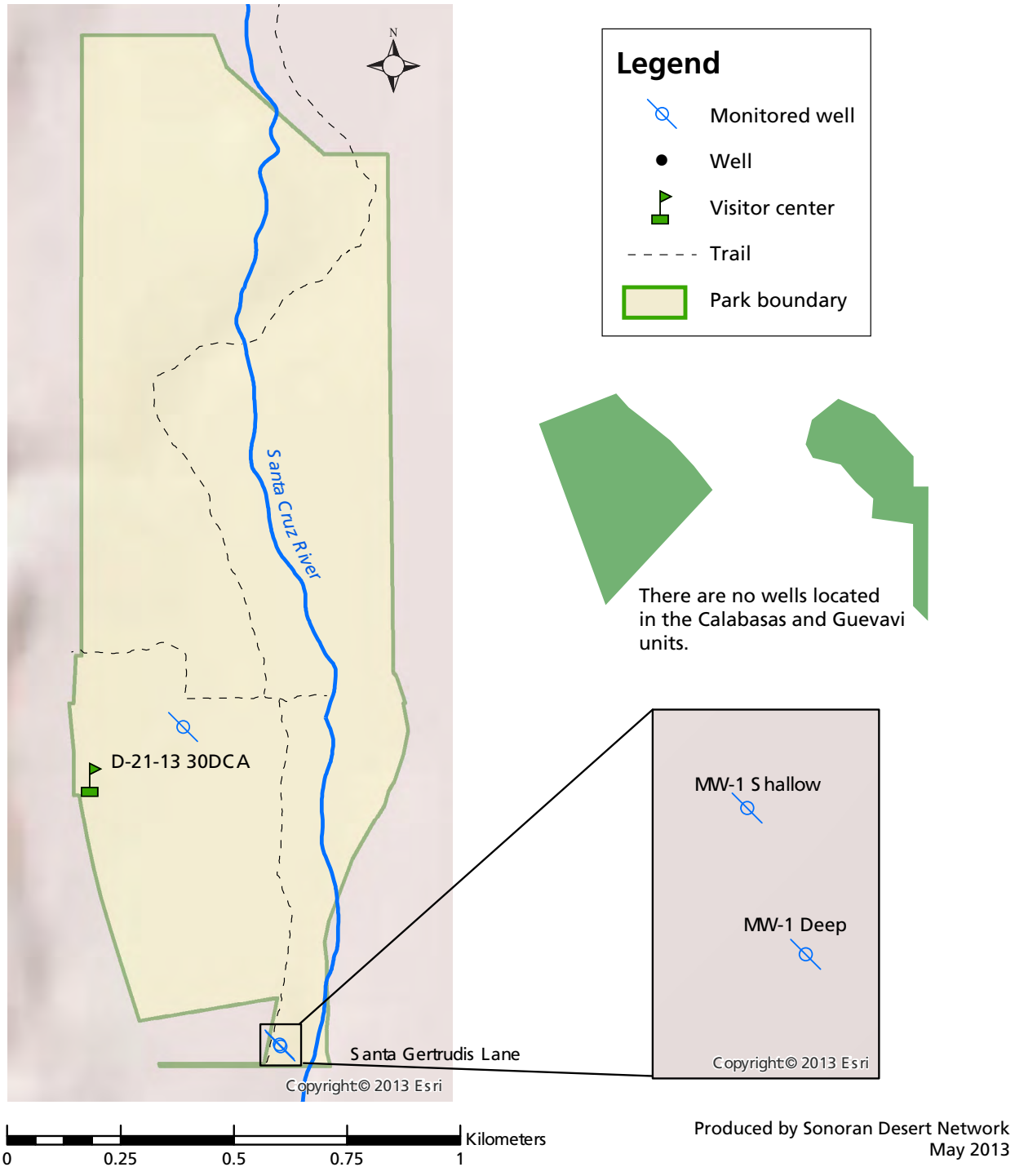


Figure B-10. Groundwater monitoring wells in Tumacácori National Historical Park.

Groundwater Monitoring Near Tuzigoot National Monument

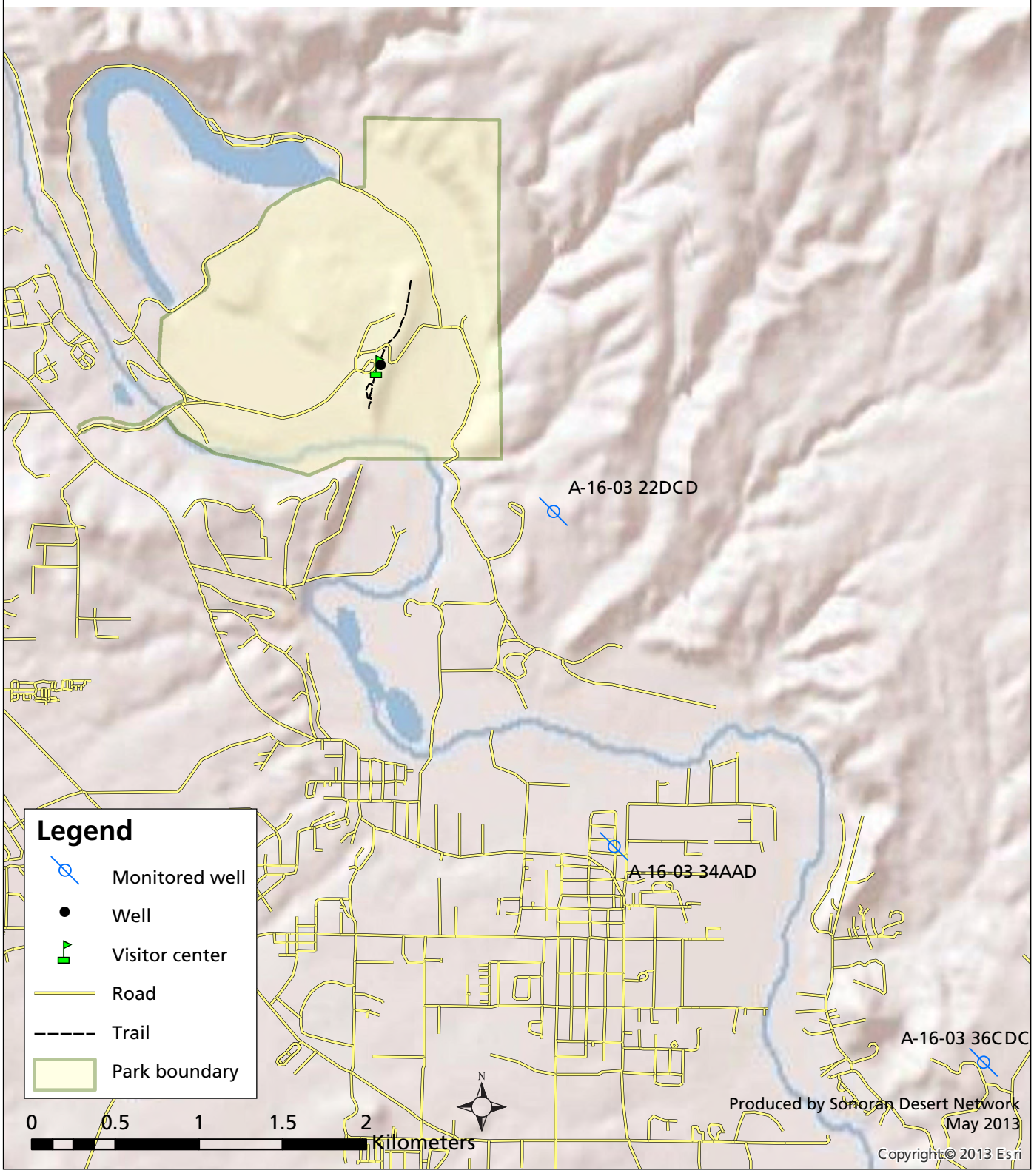


Figure B-11 Groundwater monitoring wells near Tuzigoot National Monument.

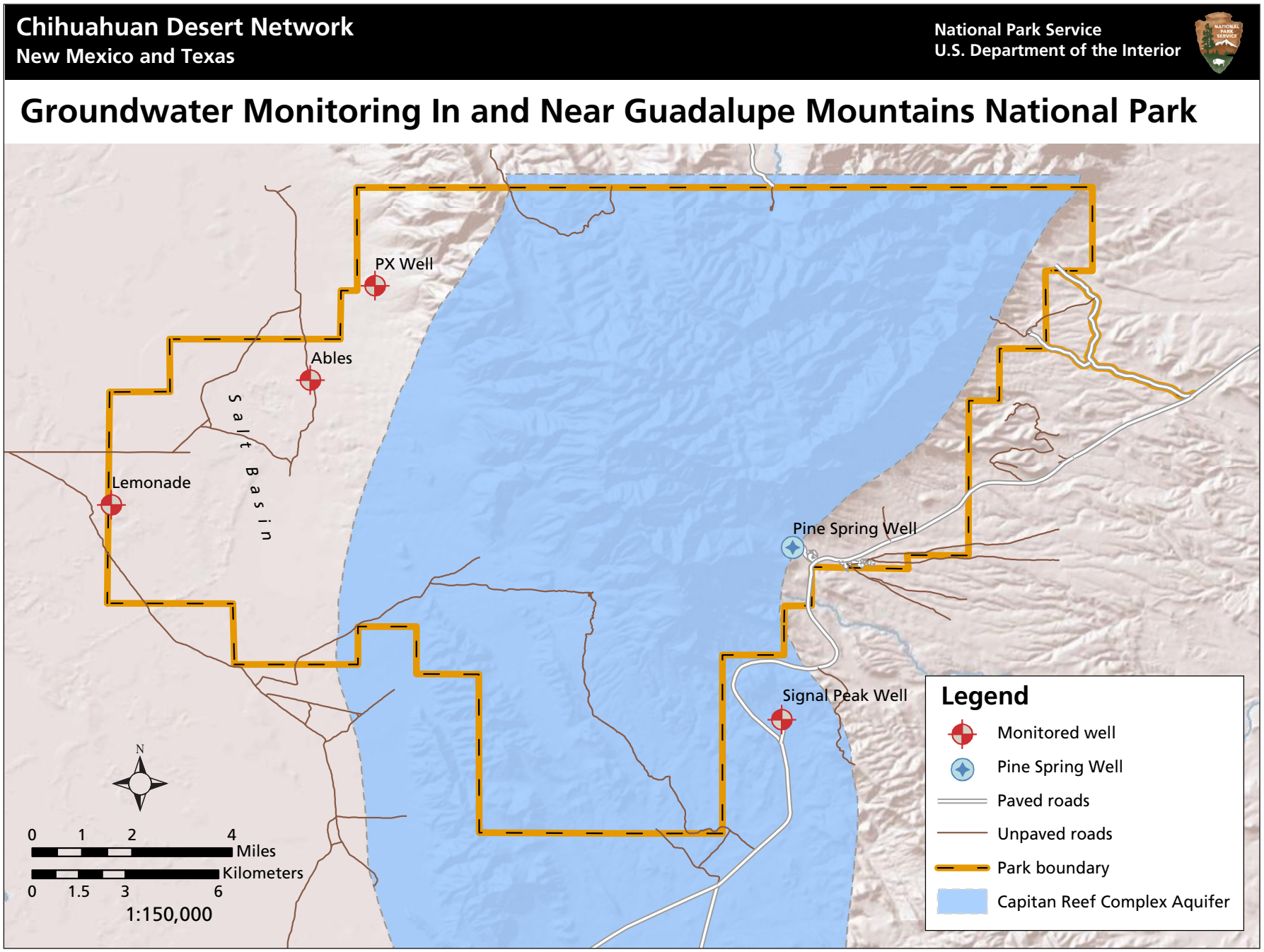


Figure B-12. Groundwater monitoring wells in and near Guadalupe Mountains National Park.

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

NPS 960/124186, March 2014

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