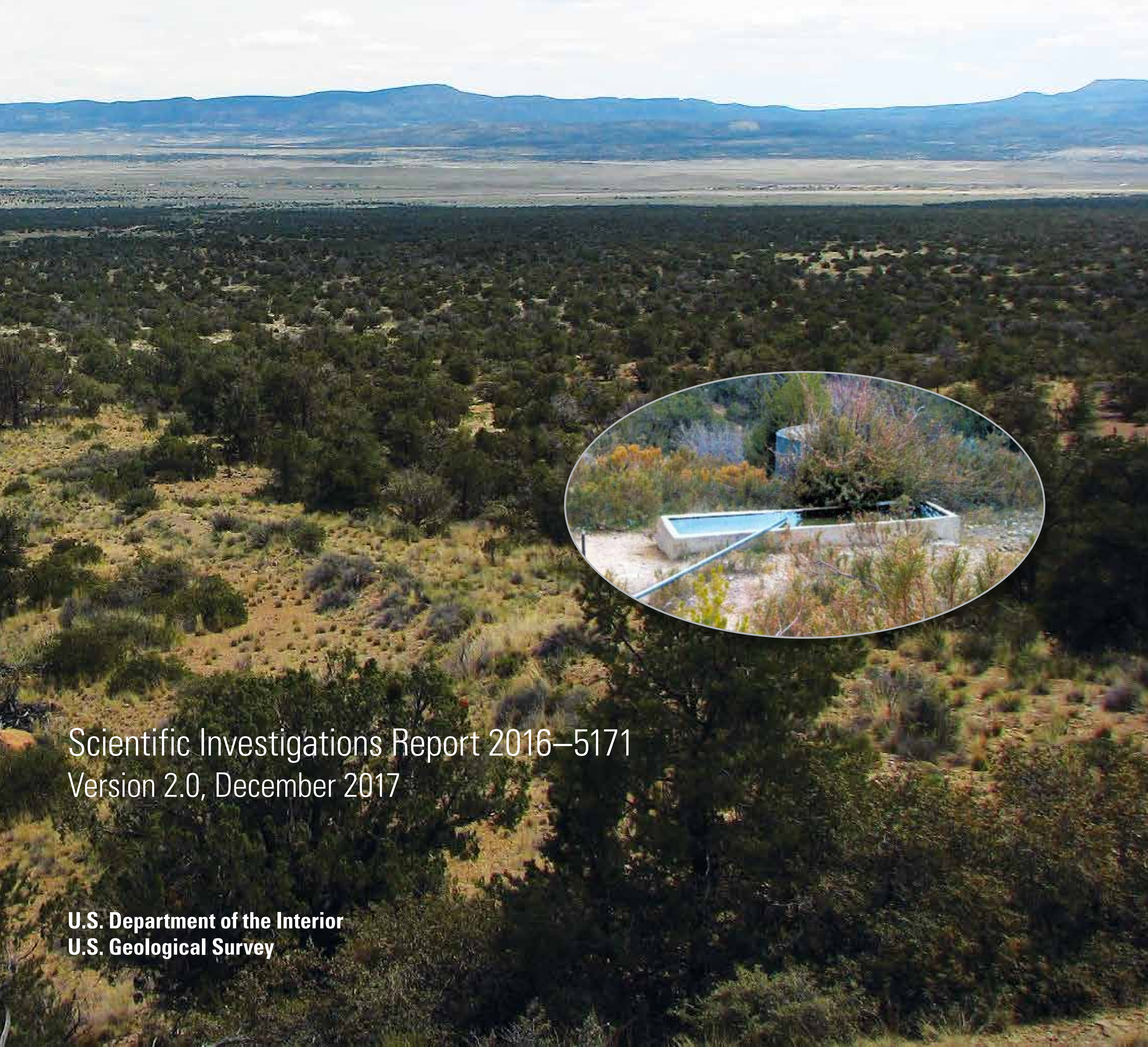
Prepared in cooperation with the Bureau of Reclamation

Hydrogeologic Framework and Characterization of the Truxton Aquifer on the Hualapai Reservation, Mohave County, Arizona



Scientific Investigations Report 2016–5171

Version 2.0, December 2017

U.S. Department of the Interior
U.S. Geological Survey

Cover. Photograph looking south showing Truxton Valley on the Hualapai Reservation, Mohave County, Arizona (by D.J. Bills, U.S. Geological Survey, 2015). Inset photograph shows Whitewater Spring and "drinker" at the base of the Music Mountains, Hualapai Reservation (by Alex Cabrillo, Hualapai Department of Water Resources, 2014).

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	0.003785	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
	Flow rate	
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as

°C = (°F – 32) / 1.8.

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1929 (NAVD 29).

Horizontal coordinate information is referenced to the North American Datums of 1927 and 1983 (NAD 27 and NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Abbreviations and Acronyms

ADWR	Arizona Department of Water Resources
BCM	Basin Characterization Model
BIA	Bureau of Indian Affairs
CSAMT	controlled source audio-frequency magnetotellurics
D	depth of investigation
DOI	Department of the Interior
ET	evapotranspiration
ET	evapotranspiration from groundwater
EVI	enhanced vegetation index
E_x	parallel electrical-field strength
E_y	perpendicular electrical-field strength
f	frequency
H_x	parallel magnetic-field strength
HDNR	Hualapai Department of Natural Resources
H_y	perpendicular magnetic-field strength
H_z	vertical magnetic-field strength
I	recharge from infiltration of precipitation
IHS	Indian Health Service
MODIS	Moderate Resolution Imaging Spectroradiometer
MT	magnetotelluric
NRCE	Natural Resources Consulting Engineers
PRISM	Parameter-Elevation Relationships on Independent Slopes Model
Q_s	base-flow discharge to streams and springs
Q_w	groundwater withdrawals from wells
R	infiltration from losing streams
r	separation between the transmitter and receiver
S	skin depth
SWAB	Southwest Alluvial Basins
U_i	underflow from adjacent aquifers
U_o	underflow to adjacent aquifers
USGS	U.S. Geological Survey
ΔS	the change in storage
ρ_a	apparent resistivity

Hydrogeologic Framework and Characterization of the Truxton Aquifer on the Hualapai Reservation, Mohave County, Arizona

By Donald J. Bills and Jamie P. Macy

Abstract

The U.S. Geological Survey, in cooperation with the Bureau of Reclamation, developed this study to determine an estimate of groundwater in storage in the Truxton aquifer on the Hualapai Reservation in northwestern Arizona. For this study, the Truxton aquifer is defined as the unconfined, saturated groundwater in the unconsolidated to semiconsolidated older and younger basin-fill deposits of the Truxton basin overlying bedrock. The physical characteristics of the Truxton aquifer have not been well characterized in the past. In particular, the depth to impermeable granite bedrock and thickness of the basin are known in only a few locations where water wells have penetrated into the granite. Increasing water demands on the Truxton aquifer by both tribal and nontribal water users have led to concern about the long-term sustainability of this water resource. The Hualapai Tribe currently projects an increase of their water needs from about 300 acre-feet (acre-ft) per year to about 780 acre-ft per year by 2050 to support the community of Peach Springs, Arizona, and the southern part of the reservation. This study aimed to quantitatively develop better knowledge of aquifer characteristics, including aquifer storage and capacity, using (1) surface resistivity data collected along transects and (2) analysis of existing geologic, borehole, precipitation, water use, and water-level data.

The surface resistivity surveys indicated that the depth to granite along the survey lines varied from less than 100 feet (ft) to more than 1,300 ft below land surface on the Hualapai Reservation. The top of the granite bedrock is consistent with the erosional character of the Truxton basin and exhibits deep paleochannels filled with basin-fill deposits consistent with the results of surface resistivity surveys and borehole logs from wells. The estimated average saturated thickness of the Truxton aquifer on the Hualapai Reservation is about 330 ft (with an estimated range of 260 to 390 ft), based on both resistivity results and the depth to water in wells. The saturated thickness might be greater in parts of the Truxton aquifer where paleochannels are incised into the granite underlying the basin-fill sediments. The estimated groundwater storage of the Truxton aquifer on the Hualapai Reservation ranges from 420,000 to 940,000 acre-ft and does not include groundwater storage in the aquifer outside the Hualapai Reservation boundary. In addition, the calculation of total storage in the Truxton aquifer does not determine nor indicate the availability and sustainability of that groundwater as a long-term resource. These results compared well with studies done on alluvial-basin aquifers in areas adjacent to this study. The part of the Truxton aquifer on the Hualapai Reservation represents about 20 percent of the entire aquifer.

Introduction

The Truxton aquifer is an unconfined groundwater-flow system in Upper Cretaceous to Pliocene aged unconsolidated to semiconsolidated younger and older basin-fill deposits of the Truxton basin, one of several structural basins located in the northwestern part of Arizona (fig. 1; Billingsley and others, 2006). The aquifer supports groundwater discharge from a few springs at the margins of the Truxton basin, the intermittent base flow of Truxton Wash in Truxton Canyon at the west end of the basin, and groundwater discharge from Peach Springs in the Peach Springs Wash watershed. Throughout the 20th century, groundwater use from this aquifer has been minor, consisting mostly of small community public supply, domestic, agricultural, and limited industrial uses (railroad). The northern part of the Truxton aquifer underlies the southern part of the Hualapai Reservation and is the main source of water supply for the tribal community of Peach Springs, Arizona (fig. 1). The aquifer also provides part of the livestock water supply for this area of the reservation. The Redwall-Muav aquifer is the only other aquifer system on the southern part of the Hualapai Reservation. It is located at the northern and eastern margins of the Truxton aquifer and consists of partly saturated Mississippian and Cambrian aged Redwall and (or) Muav Limestone (Twenter, 1962).

The physical characteristics of the Truxton aquifer are not well known. In particular, the depth to bedrock, thickness of the structural basin, and its groundwater-storage capacity are known in only a few locations where water wells have penetrated to bedrock. Given the future water needs projected by the Hualapai Tribe, there is concern that the Truxton aquifer might not be a sustainable source of water supply for the community of Peach Springs and the Hualapai Tribe.

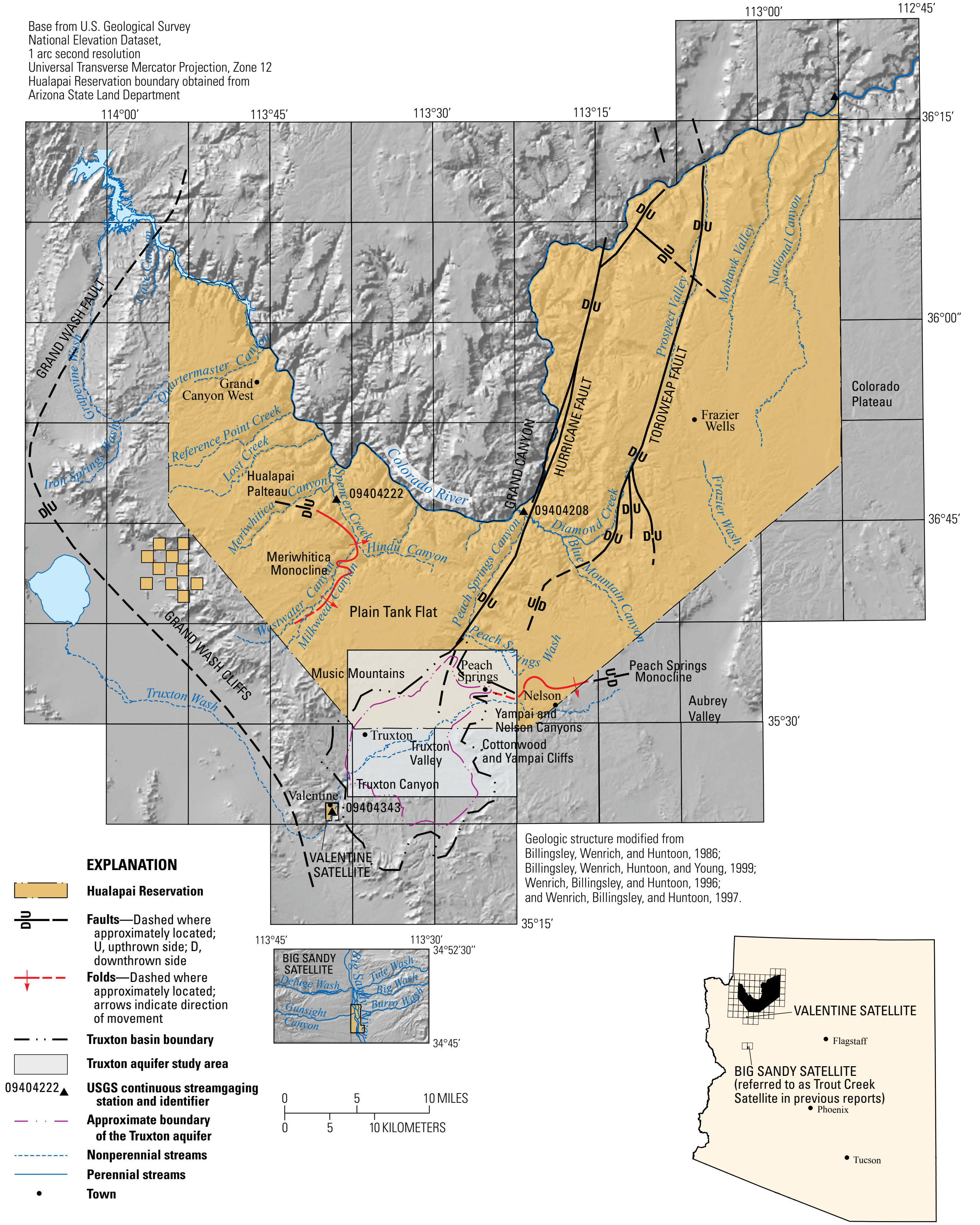


Figure 1. Map of the Hualapai Reservation in northwestern Arizona showing the approximate boundaries of the Truxton basin, the Truxton aquifer, and the study area.

Water use from the entire Truxton aquifer increased from about 50 acre-feet per year (acre-ft/yr) in the first half of the 20th century to about 200 acre-ft/yr by the 1970s (Anning and Duet, 1994; Indian Health Service, 1997, written commun.). Recent (2011) water use for the Truxton aquifer was reported by the Hualapai Tribe as about 300 acre-ft/yr (Hualapai Department of Natural Resources, 2015). The increased water use is attributed to a slow but steady increase in population both on and off the reservation and increasing agricultural use in the western part of the basin off of the reservation. The increases in water use have resulted in small but measurable groundwater-level declines of a few feet in observation wells in the area (Arizona Department of Water Resources, 2009; Natural Resources Consulting Engineers, 2011). These declines have raised concern on the part of the Hualapai Tribe about the availability, storage, and sustainability of the Truxton aquifer on the Hualapai Reservation to meet the long-term water supply needs for the community of Peach Springs and the southern part of the reservation.

The main source of water supply for the community of Peach Springs consists of three water wells located to the west of the community of Peach Springs and developed in the Truxton aquifer, as well as the recently redeveloped Peach Springs, located to the north of the community of Peach Springs in Peach Springs Wash (Hualapai Department of Natural Resources, 2015). Hualapai Department of Natural Resources estimated water demand to increase to about 780 acre-ft/yr by 2050 for the Truxton basin on the Hualapai Reservation and the Peach Springs Wash watershed parts of the reservation (Hualapai Department of Natural Resources, 2015).

In 2015, the Bureau of Reclamation requested that the U.S. Geological Survey (USGS) evaluate the part of the Truxton aquifer underlying the Hualapai Reservation as a potential long-term source of water supply for the community of Peach Springs. This study was proposed to provide an improved understanding of the hydrogeologic framework of the Truxton aquifer where it underlies the southern part of the Hualapai Reservation by gathering information on the depth to bedrock and an estimate of the storage capacity of the aquifer on the reservation. Surface geophysical data collection was determined to be the best method for obtaining additional subsurface geologic and related hydrogeologic information about the aquifer. Surface geophysical techniques provide useful information about physical-property contrasts in the subsurface that correlate to bedrock contacts and lithologic characteristics of the rocks, which are useful for evaluating the extent and saturation of a groundwater-flow system. When combined with existing well, water-level, and other hydrogeologic information available from previous studies, aquifer storage can be approximated.

In the State of Arizona, the terms “basin” and “watershed” are often used interchangeably to refer to either a surface-water drainage, a groundwater aquifer or zone, or a combination of both (Arizona Department of Water Resources, 2009). This usage can create confusion because regional groundwater aquifers can extend beyond the boundaries of surface watersheds. In the context of this report, “basin” refers to a geologic structural basin, “watershed” refers to a surface-water drainage, and the Truxton aquifer is the groundwater-bearing zone in the Truxton basin both on and off of the Hualapai Reservation.

Purpose and Scope

The purpose of this report is to (1) present the findings of an evaluation of the Truxton aquifer where it underlies the southern part of the Hualapai Reservation and (2) provide a refined conceptual model of the hydrogeology and preliminary estimates of groundwater storage in the Truxton aquifer underlying the southern Hualapai Reservation. This report describes the collection and evaluation of surface geophysical data combined with traditional analysis of existing geologic, borehole, precipitation and recharge estimates, water use, and water-level data to develop better knowledge of aquifer characteristics. These data are used to estimate the storage of groundwater in the Truxton aquifer and the depth to impermeable granitic and metamorphic bedrock. The occurrence and extent of the regional Redwall-Muav aquifer is discussed as it relates to the Truxton aquifer.

Previous Investigations

The Hualapai Reservation was established in 1883 with the Colorado River as its northern boundary for about 108 miles from National Canyon to the upper end of present day Lake Mead (fig. 1). In spite of its reservation lands bordering the Colorado River, the Hualapai Tribe was not included as a party to the 1923 Colorado River Compact (Hualapai Water Resources Program, 1999).

Early work on the geology of the Hualapai Reservation was conducted as reconnaissance by a number of USGS geologists—Newberry (1861), Dutton (1882a, b), Lee (1908), Schrader (1909), Darton (1910, 1915, 1925), and McKee (1934, 1938, 1945). Koons (1945; 1948a, b) described the Tertiary gravel beds, major faults, and volcanic rocks at the western edge of the Colorado Plateau. Additionally, the Arizona Geological Survey produced a geologic map of Mohave County in 1959 and a geologic map of Arizona in 1969, which has been revised several times since (Wilson and Moore, 1959; Reynolds, 1997; Richards and others, 2000). Several of these geologists commented on the occurrence of springs flowing from different rock units found on the Hualapai Reservation. At the time, water needs of the reservation were very minor and met by development of springs near population centers. The Atlantic, Topeka, and Santa Fe Railroad (herein, the Santa Fe Railroad), which passed through the reservation in the early 1880s, developed springs (including Peach Springs) along and near its right-of-way as watering stations. After the turn of the 20th century, the Santa Fe Railroad had only partial success developing wells closer to their tracks in the community of Peach Springs. Although some of these wells yielded about 50 gallons per minute (gal/min), others were dry or only capable of yields of a few gallons per minute (Indian Health Service, 1972; Natural Resources Consulting Engineers, 2011).

Working with the Bureau of Indian Affairs (BIA), the USGS developed two water resources studies for the Hualapai Tribe from the 1940s to 1960s. In 1942, the USGS worked with the Hualapai Tribe to locate and evaluate sites for the development of livestock water on the reservation (H.V. Peterson, written commun., 1942). In 1962, the USGS, in cooperation with the BIA, evaluated the geology and promising areas for groundwater development in the Hualapai Reservation (Twenter, 1962).

Throughout the mid-1970s, the community of Peach Springs obtained all of its water supply from Peach Springs, located about 3.5 miles (mi) north of the community, via a conveyance system owned and operated by the Santa Fe Railroad (Indian Health Service, 1972). The spring discharges from gravel and sediment deposits of the Truxton basin that are faulted against a dry to partly saturated Muav Limestone (Indian Health Service, 1972; Billingsley and others, 2006).

By 1973, it became clear that Peach Springs would not be sufficient to meet peak summer demands. The basin-fill deposits of Truxton Valley to the west of the community of Peach Springs were recommended as having the greatest potential for expansion of the water system to support current and future growth of the community (Indian Health Service, 1972; Devlin, 1976). In the early 1970s, the BIA drilled two wells, and in the mid to late 1970s, the Indian Health Service drilled two additional wells in the Truxton area of the reservation as identified by Twenter (1962). One of these wells was never used, another only for livestock, and the remaining two were developed for public supply (Devlin, 1976). Additional recommendations for water management and development were made by Boyer (1977, 1978). These recommendations were made based on an inventory of stock ponds on the reservation, discharge measurements of large springs, and evaluation of selected wells. Recommendations focused on the importance of maintaining good information on precipitation, streamflow, spring flow, and water levels in wells throughout the reservation. The collection of additional and more detailed geophysical data was mentioned as a means of developing better information on areas of groundwater supply.

Throughout the 1970s and 1980s, the Arizona Department of Water Resources (ADWR) and USGS cooperated on a series of groundwater condition maps for Arizona. Two of these maps most relevant to this study are groundwater conditions of the Hualapai Basin and groundwater conditions of the Peach Springs Basin (Remick, 1981; Myers, 1987). The Truxton basin sits on the east and southwest boundaries of the Hualapai and Peach Springs Basins, respectively. In the mid-1980s, the USGS developed generalized distribution of aquifer material and predevelopment hydrologic conditions maps for alluvial basins of Arizona and adjacent parts of California and New Mexico (Freethey and others, 1986; Freethey and Anderson, 1986). The annual predevelopment inflow and storage volumes for the entire Truxton aquifer in the Truxton basin in Freethey and others (1986) are estimated as 4,000 acre-ft/yr and 11,000,000 acre-ft, respectively. This predevelopment inflow reported by Freethey and others (1986) is two to three times the value developed by Devlin (1976). Freethey and others (1986) and Freethey and Anderson (1986) used the ADWR standard for accessible groundwater, based on a maximum depth of development of 1,200 ft. Well data from the Truxton basin through the 1980s indicated the depth of basin fill was roughly half this value. In 1994, as part of its water atlas for the state, ADWR estimated groundwater in storage for the Truxton basin to be about 1,000,000 acre-ft, again based on basin-fill depths of up to 1,200 ft (Arizona Department of Water Resources, 2009). For comparison, ADWR referred to a report by the Arizona Water Commission (1975) that estimated groundwater storage for the basin as greater than 4,000,000 acre-ft. Although these storage estimates seem large for such a small basin, they are reasonable and comparable given the limited data available at the time.

In 1994, in cooperation with the Hualapai Tribe, the USGS began to collect streamflow data at three USGS streamflow-gaging stations—Truxton Wash near Valentine, AZ (09404343); Spencer Creek near Peach Springs, AZ (09404222); and Diamond Creek near Peach Springs, AZ (09404208). The purpose of these streamflow-gaging stations is to measure the runoff and base-flow discharge from different parts of the reservation, including Truxton Valley and through the Valentine satellite part of the reservation (fig. 1). Also in the mid-1990s, the USGS, in cooperation with the BIA and the Hualapai Tribe, began a water-resources assessment of the reservation. As part of this study, the USGS and the Hualapai Department of Natural Resources (HDNR) visited, measured flow rates, and collected water samples from most of the springs and selected wells on the reservation. These data are provided in a series of U.S. Environmental Protection Agency 305(b) water-quality assessment reports (Hualapai Water Resources Program, 1999, 2004, 2009).

The USGS, in cooperation with the BIA and the Hualapai Tribe, reevaluated the surface geology and geologic structure of the Hualapai Reservation in relation to mineral resource potential in the mid-1990s. This series of four 1:48,000 geologic maps have greatly improved the detail and understanding of surface geology on reservation lands (Billingsley and others, 1986 and 1999; Wenrich and others, 1996 and 1997). These maps have been combined into the 1:100,000 geologic map of the Peach Springs area that serves as one of the base-map references for this study (Billingsley and others, 2006).

Access to sustainable quantities of good quality water has been a goal of the Hualapai Tribe for decades. Slowly but steadily increasing population combined with developing tourist- and natural-resources-based business have stretched the reservation's developed water resources infrastructure to, and occasionally beyond, its limits in recent years. Since 2000, the Hualapai Tribe, working with private consultants and Federal agencies, has developed a series of water-resource assessments and water-management plans. These studies are designed to provide the tribe with better information on the reservations quantity and quality of water and identify strategies to meet current and future water needs. Young (2007) described perched groundwater resources contained in the river gravels and semiconsolidated sediments of the Westwater Canyon area, to the north of the Truxton basin, that have been developed as a source of water for the growing Grand Canyon West development. This tourist destination currently serves about 500,000 visitors per year (Hualapai Department of Natural Resources, 2010). The Hualapai Tribe has also developed a new well in the Truxton basin (New Mud Tank well) to supplement water from the Westwater Canyon area being supplied to Grand Canyon West (Hualapai Department of Water Resources, 2010). Working with the Bureau of Reclamation (Reclamation), HDNR completed water management plans for the Western Hualapai Plateau and Spencer Creek watersheds and the Truxton Canyon Wash and Peach Springs Canyon watersheds, respectively (fig. 1; Hualapai Department of Natural Resources, 2010, 2015). Both of these reports identify the basin sediments, basalt, and lacustrine (lakebed) deposits as the most productive and accessible water-bearing zones for groundwater development. Natural Resources Consulting Engineers (NRCE) provided the Hualapai Tribe with an evaluation of the community of Peach Springs groundwater supply to describe the adequacy of the existing water-supply system to meet current domestic, commercial, and municipal water needs and recommend action to expand the water supply system (Natural Resources Consulting Engineers, 2011). The NRCE report recognizes the unconsolidated basin-fill water-bearing zones of the Truxton aquifer as areas with the most potential for continued groundwater development. NRCE also points out that existing well data show that not all locations in these unconsolidated sediments can produce usable quantities of water (Natural Resources Consulting Engineers, 2011). Among NRCE's recommendations for further study are (1) to use geophysical studies to provide a better characterization of the Truxton aquifer and (2) to locate areas that have potential for greater groundwater yields.

Setting

The study area for this report is the Truxton basin and surrounding areas of the southern part of the Hualapai Reservation (fig. 1). The main part of the Hualapai Reservation includes about 993,000 acres of land (about 1,490 square miles) south of the Colorado River and upstream of Lake Mead at the western end of the Grand Canyon region. The only community on the reservation is Peach Springs, home to about 1,500 full-time residences, Tribal government facilities, and several Federal agencies. The community of Peach Springs is located at the northeastern end of the Truxton basin, the main focus of this study, at an altitude of 4,790 ft. The Hualapai Tribe maintains Grand Canyon West, a tourist destination on the west side of the reservation, and a fish hatchery and water-hauling station at Frazier Wells on the east side of the reservation. Scattered homes occur throughout the rest of the reservation.

Physiography

The Truxton basin, partly in the southern end of the Hualapai Reservation, is a relatively small, 47,800-acre structural basin located at the northern edge of the Transition Zone. The Transition Zone is a geologic province in central Arizona, transitional between the mostly layered sedimentary rocks of the Colorado Plateau to the northeast and the heavily faulted, folded, and eroded Basin and Range Province to the west (Fenneman, 1931). The Transition Zone shares characteristics of both of these major physiographic provinces. The Truxton basin is located in the Peach Springs Basin, a water planning region designated by ADWR (Arizona Department of Water Resources, 2009). The Truxton basin is surrounded by the Music Mountains to the northwest and the Cottonwood and Yampai Cliffs to the south and east. The principal drainages in the Truxton basin are Truxton Wash and Peach Springs Canyon (fig. 1). Truxton Wash flows from east to west across the basin from headwater areas in the Yampai and Nelson Canyons to Truxton Canyon at the west end of the basin where it flows into Hualapai Valley, a closed basin adjacent to the west edge of the study area (fig. 1). Peach Springs Canyon drains the northeastern part of the basin, flowing from its headwaters near the community of Peach Springs northward toward the Grand Canyon. The Truxton basin has an average altitude of about 4,300 ft, with about 700 ft of relief from east to west. Mountains surrounding the basin have altitudes up to about 6,500 ft. About 20 percent of the basin directly underlies the southern part of the Hualapai Reservation.

Vegetation cover on the Truxton basin can generally be classified as light semidesert scrub (National Park Service, 2016). Lower elevations are a mix of desert grasses, brush, and some scattered cacti species. Moderate to dense stands of cottonwood and sycamore trees and other riparian vegetation occur at the western edge of the basin where the water table is close to the land surface and groundwater discharge supports the perennial flow of Truxton Wash. Riparian vegetation also occurs in Peach Springs Canyon near the community of Peach Springs. As the basin slopes up to the surrounding mountains, vegetation transitions to light to moderate stands of pinion and juniper. The part of the Truxton basin on the Hualapai Reservation is about a 50/50 mix of pinion and juniper stands at higher elevations and, at lower elevations, sparse grasses, brush, and cacti.

Climate

Climate of the Hualapai Reservation is classified as moderate to arid and generally correlates to altitude (Twenter, 1962). Average annual temperature, precipitation, and evaporation ranges for the Hualapai Reservation are shown on figure 2 (PRISM Climate Group, 2015). There are only two climate reporting stations on the reservation—one located in the community of Peach Springs near the northeast end of the Truxton basin (period of record, 1948 to 2006) and the other located in Truxton Canyon at the BIA Truxton Canon Agency, Valentine, Ariz., at the western end of the Truxton basin (period of record, 1901 to 1980; Western Region Climate Center, 2015). Both of these stations report an average annual precipitation of about 11 inches (in.).

Hualapai Reservation average daily maximum temperatures vary from the mid-90s during the summer to the mid-50s during the winter. Temperature extremes of 110 °F in the summer and below 0 °F in the winter have been recorded. Most of the precipitation occurs during isolated monsoonal thunderstorms in the summer months (Western Region Climate Center, 2015). Substantial accumulations of snow can occur in the winter

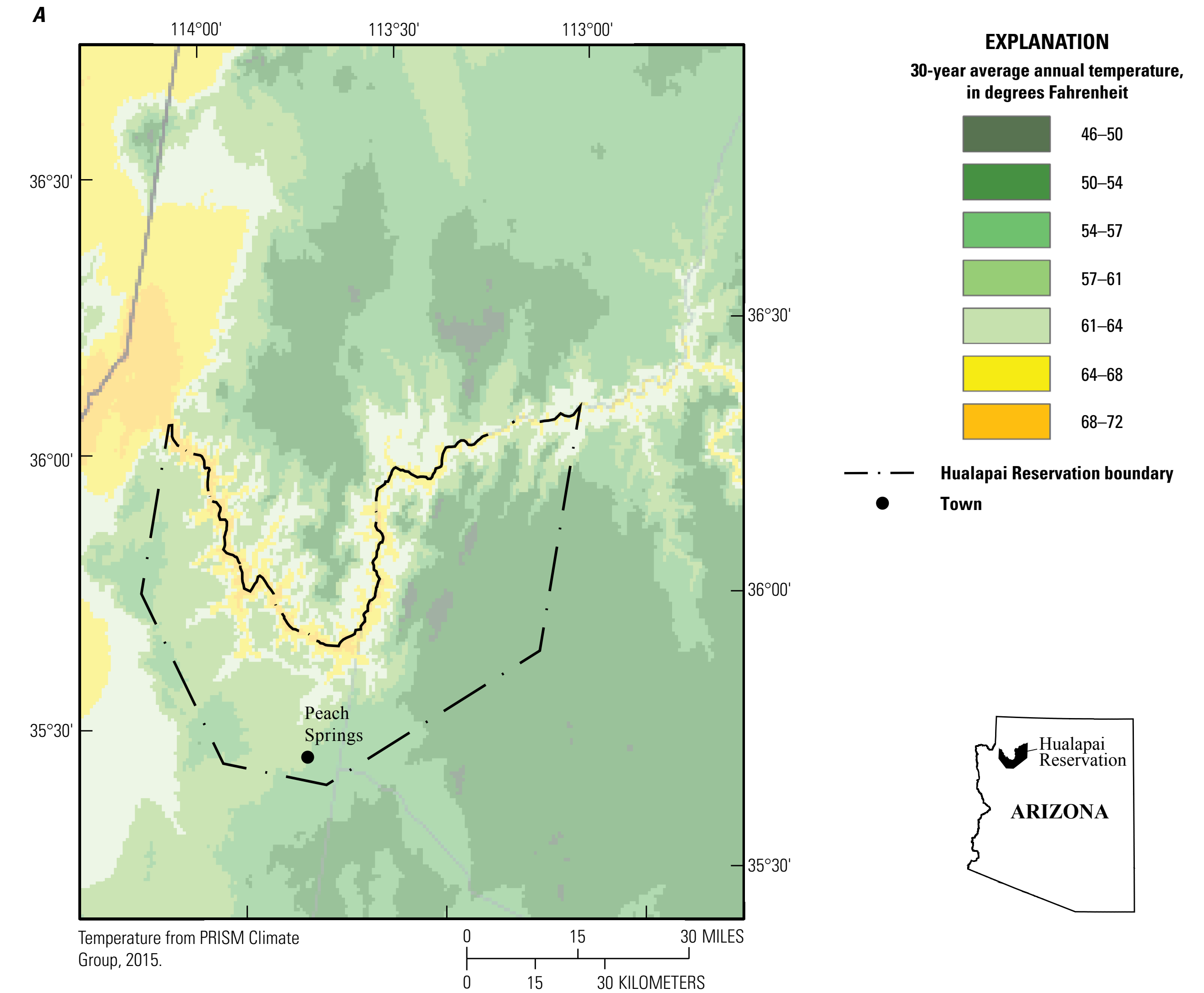


Figure 2. Map of (*A*) 30-year average annual temperature and (*B*) average annual precipitation and average annual evaporation on the Hualapai Reservation, Arizona.

months at higher elevations. Occasional warm winter storms that produce rain on snow have resulted in some of the largest runoff events in the Peach Springs Basin of which the reservation is a part (Sellers and others, 1985; Arizona Department of Water Resources, 2009). As with other areas of the Colorado Plateau, the Hualapai Reservation experiences drought conditions that can last for several years to decades interspersed with or followed by much shorter periods of above normal to extremely wet weather. Currently, the Hualapai Reservation, like much of the rest of the southwest, is in the midst of a long-term dry cycle that began in the mid- to late 1990s (Hereford and others, 2002). Precipitation at the community of Peach Springs from 1995 to 2006 has been less than the average annual of about 11 in. for 10 years of the 12-year period (Western Region Climate Center, 2015). No meteorological data are reported for the community of Peach Springs or the BIA Truxton Canon Agency from 2007 to present. However, Hereford (2014) suggests that since 2006 there have been only three additional years where the annual precipitation has been above the long-term average (based on climate analysis of the Flagstaff, Ariz., area). Because most of the Truxton basin at the southern end of the Hualapai Reservation is lower in elevation than the reporting climate stations, temperature and precipitation values are likely to be higher and lower, respectively.

Precipitation that does not run off directly as surface flow infiltrates at the land surface and leads to either evapotranspiration (ET) or groundwater recharge. Evapotranspiration is water removed by evaporation from the land surface and soil and by transpiration from plants. Using methods developed by Kohler and others (1959), Farnsworth and others (1982), and Arizona Meteorological Network (2010), evaporation estimates for the Hualapai Reservation of about 60 to 70 inches per year (in/yr) are far in excess of the average annual precipitation of about 11 in/yr (fig. 2*B*; Farnsworth and others, 1982).

Better estimates of ET are made possible by ET models that use Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data and enhanced vegetation index (EVI) data with

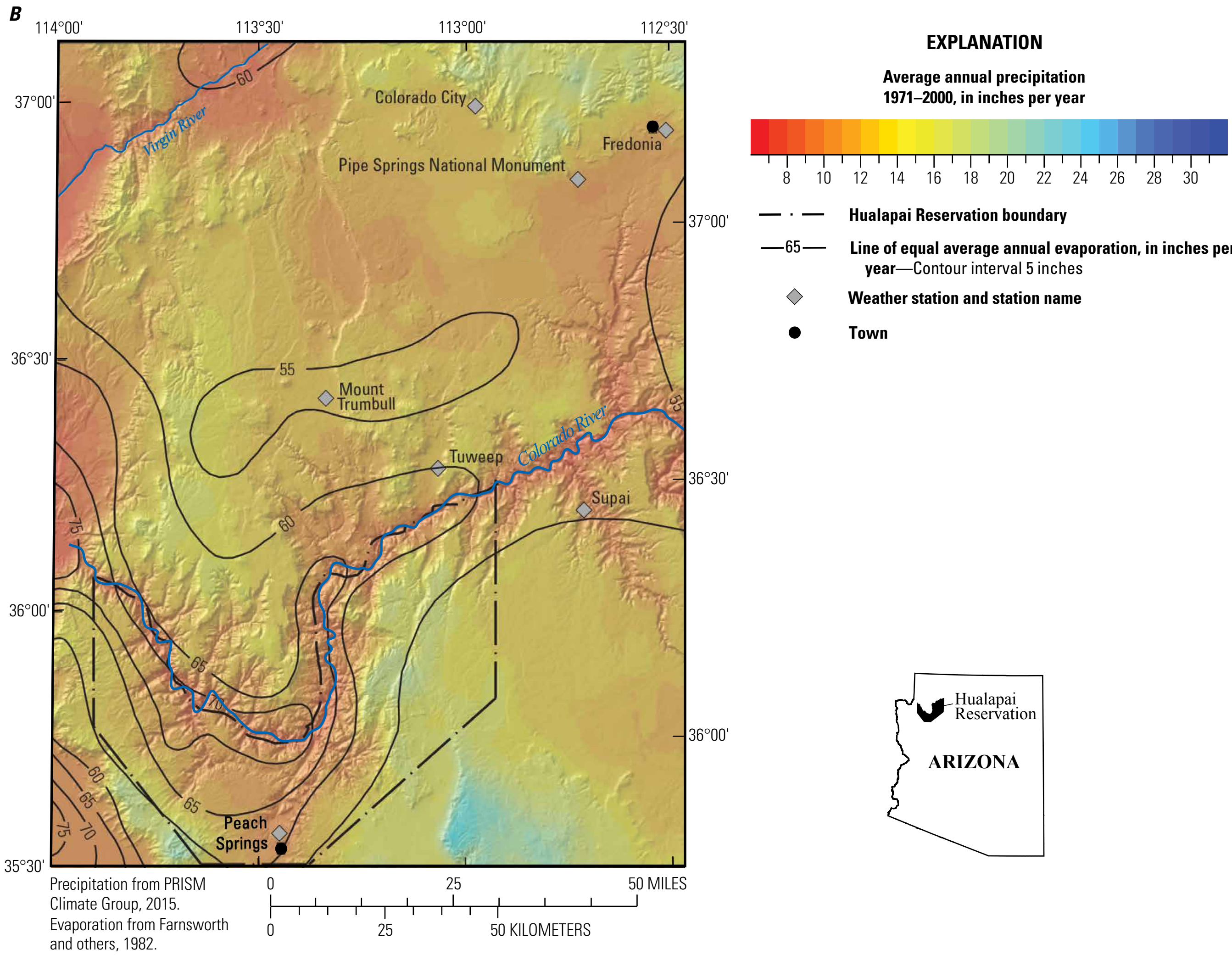
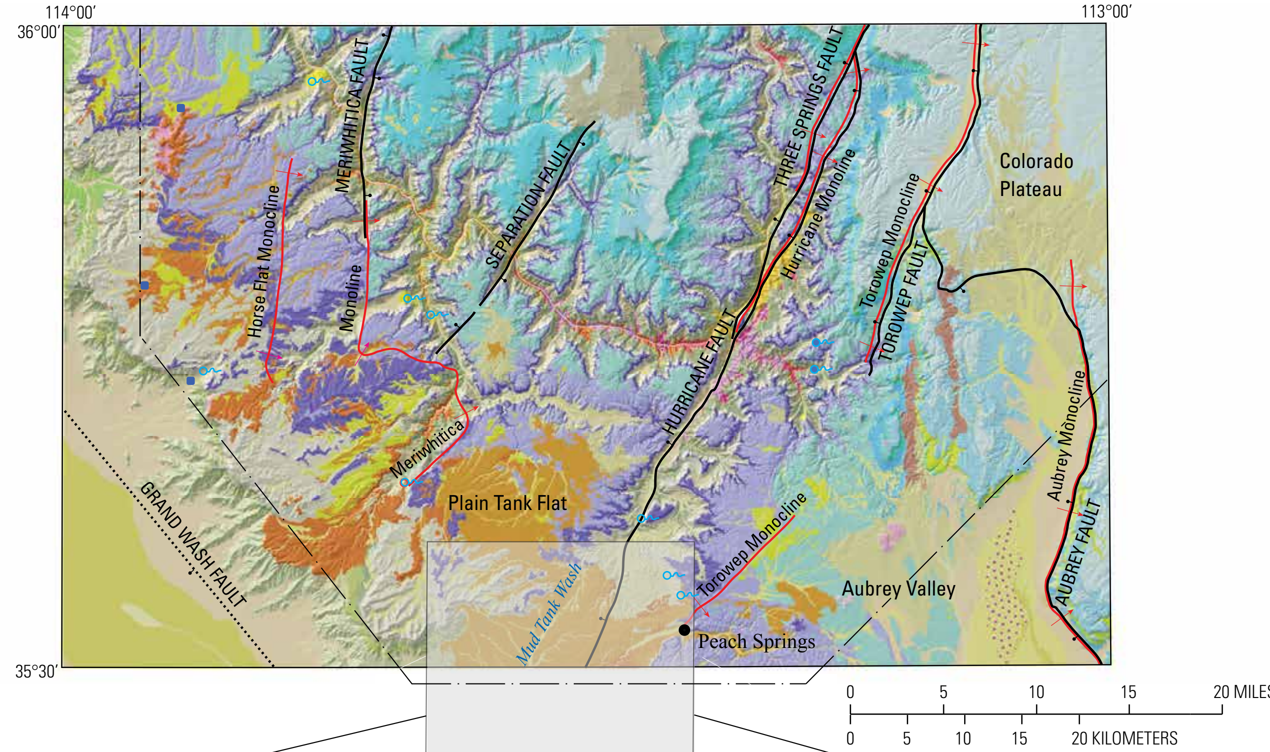


Figure 2.—Continued

water-balance, climate, and land-cover regression equations (Sanford and Selnick, 2013). The result is an estimate of the average annual ratio of ET to actual precipitation. Using this method, Sanford and Selnick (2013) estimate a ratio for Mohave County, Ariz., of 0.8 to 0.89 and estimated average annual ET that ranges from 8.2 to 12.2 in/yr for the years 1971–2000. Tillman and others (2011), using this method, developed similar ET values for alluvial basins in Arizona, including the Peach Springs watershed, where this study area is located. Because the Truxton basin is at lower elevation than much of Mohave County or the Peach Springs watershed, ET values are expected to be at the high end of the range or slightly greater owing to a greater average annual temperature.

Geology

The geology of the Hualapai Reservation consists of Precambrian igneous and metamorphosed sedimentary rocks; layered Paleozoic to Cenozoic sedimentary rocks; Tertiary to Quaternary lakebed (lacustrine) deposits, fluvial deposits, and volcanic rocks; and recent (Holocene) alluvial deposits. Structural features such as folds and faults are also present (fig. 3). The Proterozoic igneous (granitic) and metamorphic rocks generally are exposed in the bottoms of deeply incised canyons and along the Colorado River, its tributaries, and around the western and southern edge of the Truxton basin. Paleozoic and Cenozoic sedimentary rocks are layered sandstones, shales, limestones, and siltstones typical of the sequence found in the Grand Canyon proper (fig. 3). Paleozoic and Cenozoic rock units also make up the high plateau and cliff areas of the Music Mountains and the Cottonwood and Yampai Cliffs to the northwest and east of the Truxton basin. The Miocene to Pleistocene lakebed and fluvial deposits (basin-fill sediments) are coarse-grained, well-rounded cobbles, gravels, and sands, semiconsolidated to poorly consolidated, of locally derived sandstones, limestones, and volcanic rocks (Billingsley and others, 1999). These Miocene to



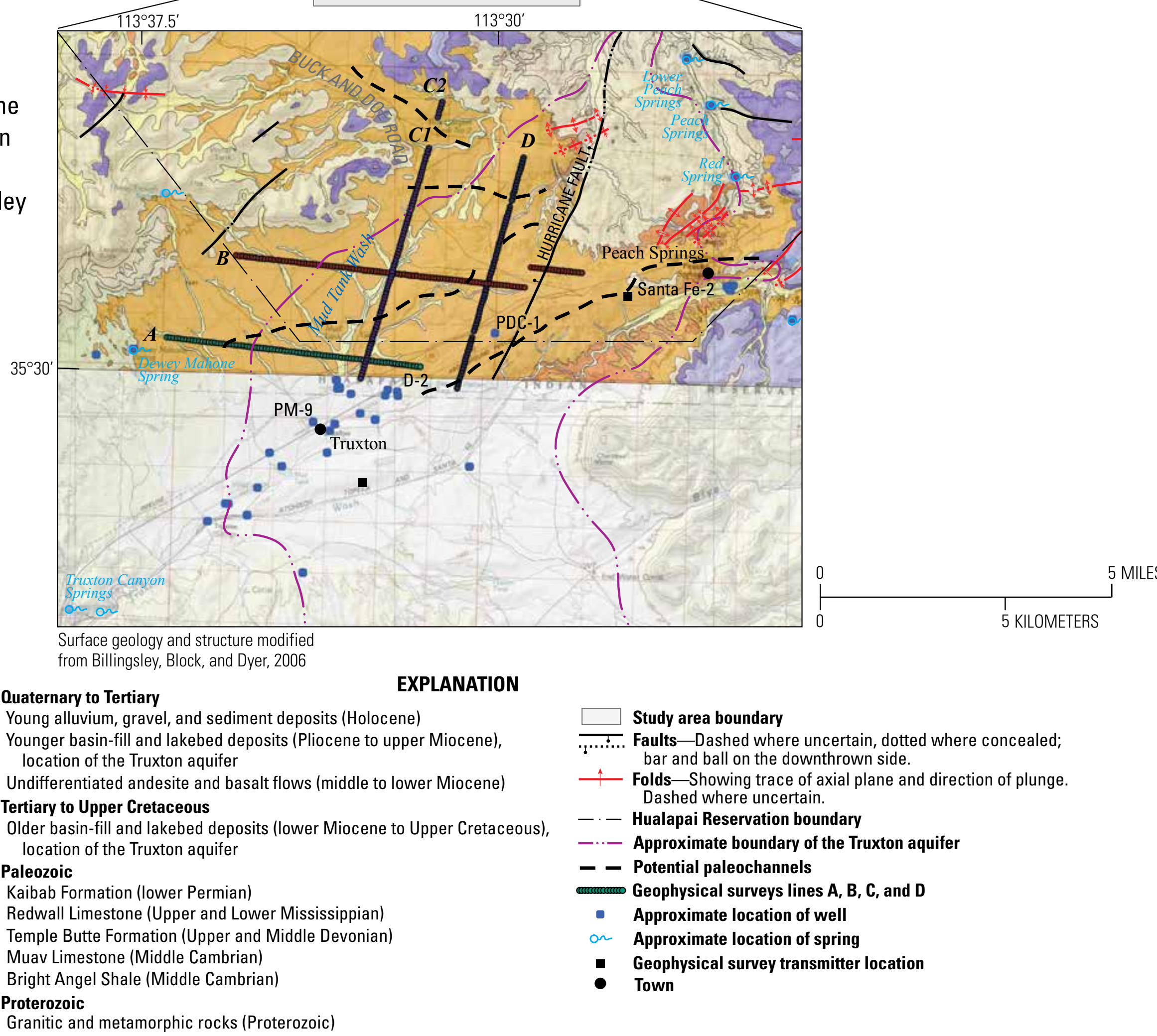


Figure 3. Map of the surface geology and geologic structure of the Hualapai Reservation in northwestern Arizona (modified from Billingsley and others, 2006).

Pleistocene basin-fill rock units are found mainly on the plateaus of the southwestern, southern, and southeastern parts of the reservation. The northern fifth of the Truxton basin underlying the southern end of the reservation consists mostly of these basin-fill sediments (fig. 3).

The surface geology and structure of the Truxton basin south of the Hualapai Reservation has not been mapped in detail except for general geologic descriptions provided by the Mohave County and State geologic maps of Wilson and Moore (1959) and Richard and others (2000). These maps indicate that the Cenozoic and younger sediments of the Truxton basin generally unconformably overlying Proterozoic granites and metamorphic rocks to the west and south. Quaternary basalts are also mapped to the west and in a small area of the south-central part of the basin. The Cambrian Tapeats Sandstone underlies the Truxton basin to the east, south, and west.

Surface geologic mapping of Hualapai Reservation lands in the 1990s has greatly improved the understanding of surface geology and structure of this part of the western Grand Canyon (Billingsley and others, 1999; Billingsley and others, 2006). The Truxton basin is now recognized as part of an old drainage and paleocanyon system eroded into the surface of Proterozoic and Paleozoic rocks. The Proterozoic and Paleozoic rocks that underlie the Truxton basin generally dip 1–3° from the southwest to the northeast and to east. This erosional surface was created during regional Laramide uplift of the southwest Colorado Plateau margin from the Late Cretaceous to Eocene (Young, 1966, 1987). The uplift resulted in northeast flowing streams that created deeply incised (1,500 to 2,000 ft) paleochannels and paleocanyons that are still visible today. Occasional damming of these channels with sediments from debris flows and volcanic deposits allowed the paleochannels to fill with fluvial sediments and lake deposits throughout the late Tertiary until they were again breached. Ongoing Basin and Range Province extension and uplift beginning in the Miocene to Pliocene (9 to 6 million years ago) and continuing into the present has caused reversal of the Truxton Wash drainage which now flows to the west-southwest. At the western end of the Truxton basin, adjacent to the Hualapai Reservation, land-surface exposures of impermeable granite cause the Truxton aquifer to discharge groundwater to Truxton Wash.

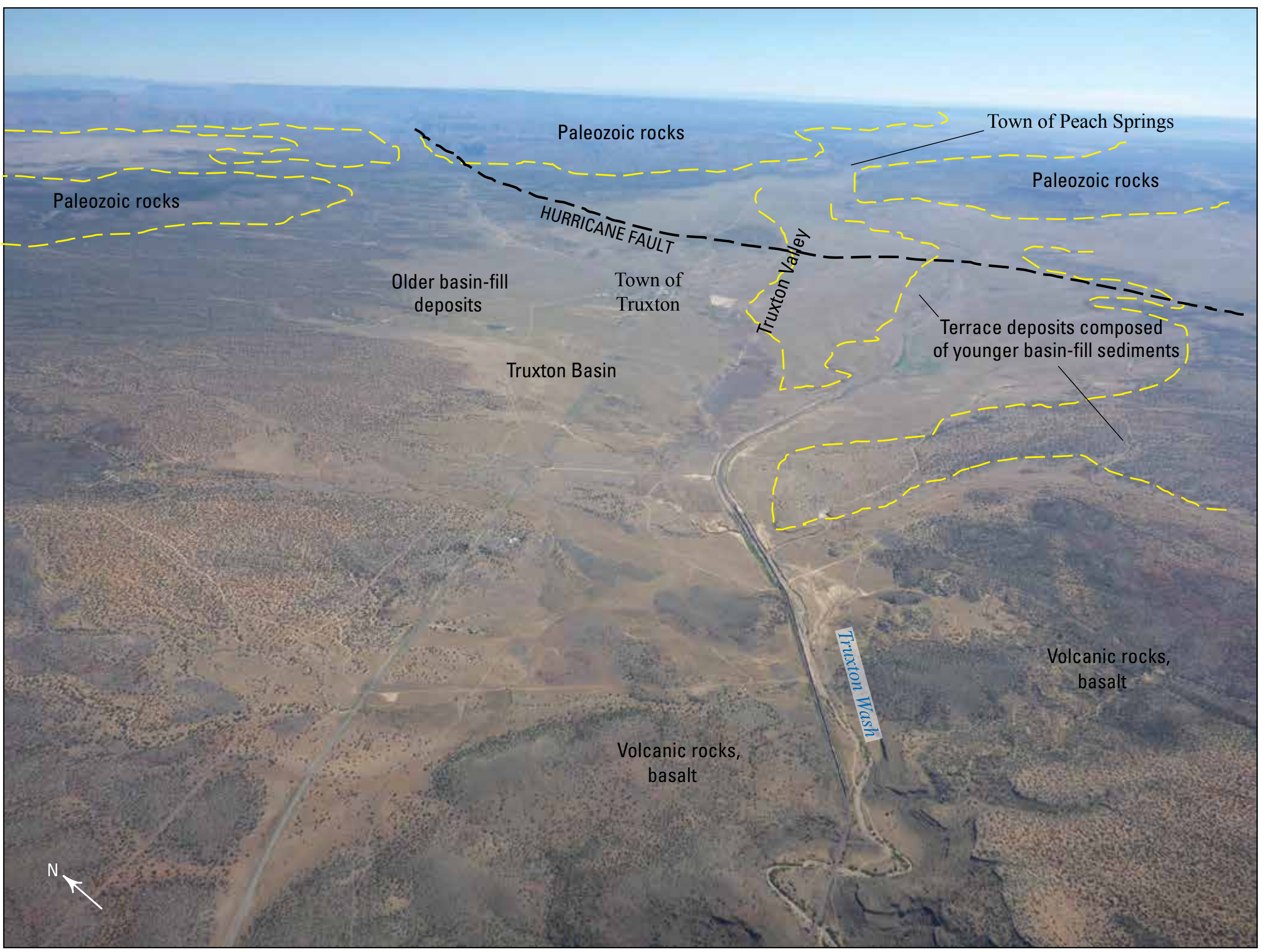


Figure 4. Aerial photograph of the Truxton basin, Arizona. Yellow dashed lines are approximate boundaries between labeled surface geologies. (Photograph by Jon Mason, U.S. Geological Survey, July 2015.)

The older (late Tertiary) gravel, sedimentary, and lakebed deposits include the Music Mountain Formation, West Water Formation, Hindu Fanglomerate, and the Buck and Doe Conglomerate (Young, 1999). These units consist of partly consolidated to partly unconsolidated coarse-grained sandstones and siltstones with gravelly, sandy, silty, and clayey sediments from Tertiary paleocanyon drainages eroded into the Hualapai Plateau, 40 to 220 ft in thickness where exposed (Young, 1999; Billingsley and others, 2006). Some limestone deposits within this unit are characteristic of lakebed deposits. An example of these deposits can be found in the upper end of Peach Springs Canyon at the northeast end of the Truxton basin and probably extend to the southwest under younger (Pliocene age) sediments of the basin (figs. 3 and 4). These older basin sediments generally represent deposition in a closed-basin environment deformed by normal faulting (Freethey and others, 1986; Billingsley and others, 2006).

Terrace deposits, younger gravels and sediments, basalts, limestones, and Paleozoic rocks are found in the Truxton basin on the Hualapai Reservation. Gravel and sediment deposits of late Tertiary to early Quaternary age are a poorly sorted and partly consolidated mix of clay, silt, sand, pebbles, cobbles, and small boulders that form the surface of much of the Truxton basin on the Hualapai Reservation. These units range from 20 to 200 ft in thickness around the margins of the basin. Some of these deposits appear to have been transported from the Hualapai Plateau to the northwestern part of the Truxton basin through an eroded paleochannel in the Paleozoic rocks into the upper end of Peach Springs Canyon. These deposits also occur at the western end of Aubrey Valley to the east of Truxton basin. There they appear to have been deposited in another old paleochannel extending to the east of the Truxton basin (Billingsley and others, 2006). Calcrete soil is common in the upper 3–6 ft of these sediments, and the rest of the unit is partly consolidated with gypsum and calcite cement (Billingsley and others, 2006). The mix of sediments is typically reworked older and younger gravelly sediment units and volcanic rocks. In the Truxton basin, where volcanic rocks are not present in the subsurface, it is difficult to distinguish between these younger and older basin-fill sediments. The younger basin-fill sediments were typically deposited during and after transition to an integrated drainage (Freethey and others, 1986; Billingsley and others, 2006).

Billingsley and others (2006) identified andesite and basalt flows around the north and east margins of the Truxton basin from 3 to 240 ft thick where exposed. These flows, Miocene to Pleistocene in age, are correlated to the Mount Floyd Volcanic Field about 40 miles to the east. Based on a few water well geologic logs, andesite and basalt flows are known to occur as a layer between older and younger basin-fill sediments in the east end of the Truxton basin (Arizona Department of Water Resources, 2016).

Younger alluvial-fan deposits, Pleistocene to Holocene in age, are mostly present-day channel deposits consisting of mud, silt, sand, gravel, cobbles, and boulders. These deposits are subject to extensive sheet wash erosion, arroyo erosion, and flash-flood debris-flow accumulations (Billingsley and others, 2006). Thickness can vary from 3 to 100 ft.

Geologic structures with the greatest influence on the Truxton basin on the Hualapai Reservation are the Hurricane Fault, the Toroweap Monocline, and a number of small discontinuous faults and anticlinal and synclinal structures scattered around the north margin of the basin (fig. 3). The high-angle, normal Hurricane Fault trends northeast to southwest along Peach Springs Canyon and through the Truxton basin to the west of the community of Peach Springs with a displacement of about 210 ft downthrown to the west. The Toroweap Monocline trends northeast to southwest at the eastern edge of the Truxton basin. The Toroweap Monocline displaces strata up to the southeast, slopes down to the northwest, and has several splayed anticlinal, synclinal, and fault segments just to the east of the community of Peach Springs (Billingsley and others, 2006). The small faults that occur at the northern edge of the Truxton basin typically trend northeast to southwest and occasionally trend west to east. Basin and Range Province extension to the west, beginning in the Miocene to Pliocene, reactivated many of the surface faults and deep-seated faults that control folding of structure on the Hualapai Reservation. The result is general down-to-the-west extension along most structures around the Truxton basin. Offset of young alluvial deposits along the Hurricane Fault in the Truxton basin indicate this structure is still active (Billingsley and others, 2006).

Structural features are significant to the groundwater resources of the southern reservation area. In addition to affecting the occurrence and movement of groundwater in the basin, they also impact groundwater-storage potential because they offset the impermeable granite and metamorphic bedrock higher or lower in the subsurface of the basin creating greater or lesser amounts of potential storage space. Faulted and folded structures can serve as either conduits or barriers to groundwater flow depending on the type and activity of the structures and the type of surrounding geologic rock units. The areas around these structures also can affect the local water quality (that is, pathways for surface contaminates into the aquifer) and can be associated with moderate- to high-yield groundwater withdrawals.

Hydrology and Hydrogeology

The hydrology and hydrogeology of the Hualapai Reservation is still poorly understood in spite of a number of studies conducted since the 1960s (Twenter, 1962; Devlin, 1976; Boyer, 1977; Boyer and others, 1978; Remick, 1981; Meyers, 1987; Young, 1966, 1978, 1999, 2007; Hualapai Department of Natural Resources, 2010 and 2015; Hualapai Department of Water Resources, 1999, 2004, 2005; and Natural Resources Consulting Engineers, 2011). This is partly due to the sparse population and water use of the area, and the limited available flow data for both surface water and groundwater resources. Most surface-water drainages on the Hualapai Reservation are ephemeral or intermittent in nature, flowing only in response to significant precipitation events. A few drainages have perennial reaches that are supported by groundwater discharge from springs. Springs represent the most significant source of surface water on reservation lands. However, many of the springs are located in remote, deeply incised canyons that limit their access to determine origin of flow, flow variability, and water quality. Most of the groundwater wells on reservation lands are located on the southern half of the reservation where depths to water make drilling wells economically feasible.

The principal drainages of the Truxton basin on the southern part of the Hualapai Reservation are Peach Springs Wash and Truxton Wash (fig. 1). Peach Springs Wash is ephemeral from its headwaters at the community of Peach Springs to Peach Springs. Groundwater discharge at Peach Springs (4,210 ft altitude) and Lower Peach Springs (3,970 ft altitude) provide an estimated perennial base flow to Peach Springs Wash of about 141 acre-ft/yr (table 1). Peach Springs Wash is perennial from Peach Springs downstream to its confluence with Peach Springs Canyon where the drainage again becomes ephemeral. Groundwater discharge from Peach Springs is derived from older sediments and lakebed deposits of the Truxton aquifer along a short segment fault, with offset down to the south, whereas Lower Peach Springs discharges from the Muav Limestone just to the south of a north-plunging, unnamed monocline (Billingsley and others, 2006). Flow from Peach Springs varies seasonally and annually. Discharge measurements made by the USGS from 1993 to 1995 indicate the flow rate can double or triple in volume depending on antecedent conditions and annual precipitation (table 1; Hualapai Department of Water Resources 1999, 2004, and 2005). The Hualapai Tribe recently redeveloped Peach Springs for water supply and is currently using about 43,200 gallons per day (about 5.0 acre-ft/yr) to supply the community of Peach Springs (Hualapai Department of Natural resources, 2015). All of the base flow not captured for municipal and recreational use evaporates or is transpired by plants downstream along the Peach Springs Wash.

Truxton Wash is an ephemeral stream from its headwaters at the Yampai Cliffs in the Yampai and Nelson Canyon areas to the east of the Truxton basin, to Truxton Canyon at the west end of the Truxton basin (fig. 1). Several small springs are located in the upland areas to the north and east of the basin on the Hualapai Reservation. These springs typically discharge a few to less than 1 gal/min each from the Muav Limestone or granite rubble supporting local livestock and wildlife use (table 1). Any excess water is evaporated and used by plants. Truxton Wash is perennial for a short reach at the west end of the basin where it has eroded a channel through the basin sediments into impermeable granite basement rocks from Truxton Canyon to the Valentine Satellite part of the reservation (fig. 1). Several springs (for example, Truxton Spring) emerge here (4,020 ft altitude) from the older basin-fill sediments of the Truxton aquifer, and they discharge a combined flow of about 531 acre-ft/yr (about 330 gal/min; table 1; Arizona Department of Water Resources, 2009; from estimates of flow made on or before 1943). The USGS maintains a streamflow-gaging station at Truxton Wash near Valentine, AZ (09404343), about 2 mi downstream from Truxton Spring (fig. 1). The base-flow rate at the streamflow gage varies annually, ranging from about 1,380 acre-ft/yr (during an unusually wet winter in water year 2005) to zero (2002–2004 and 2013–2015), as inferred from the winter base-flow data (fig. 5, table 1). The average winter base flow was determined by averaging the base flow for the months of November to February during the period of record from 1994 to 2015. Runoff events were removed from this period by hydrographic separation.

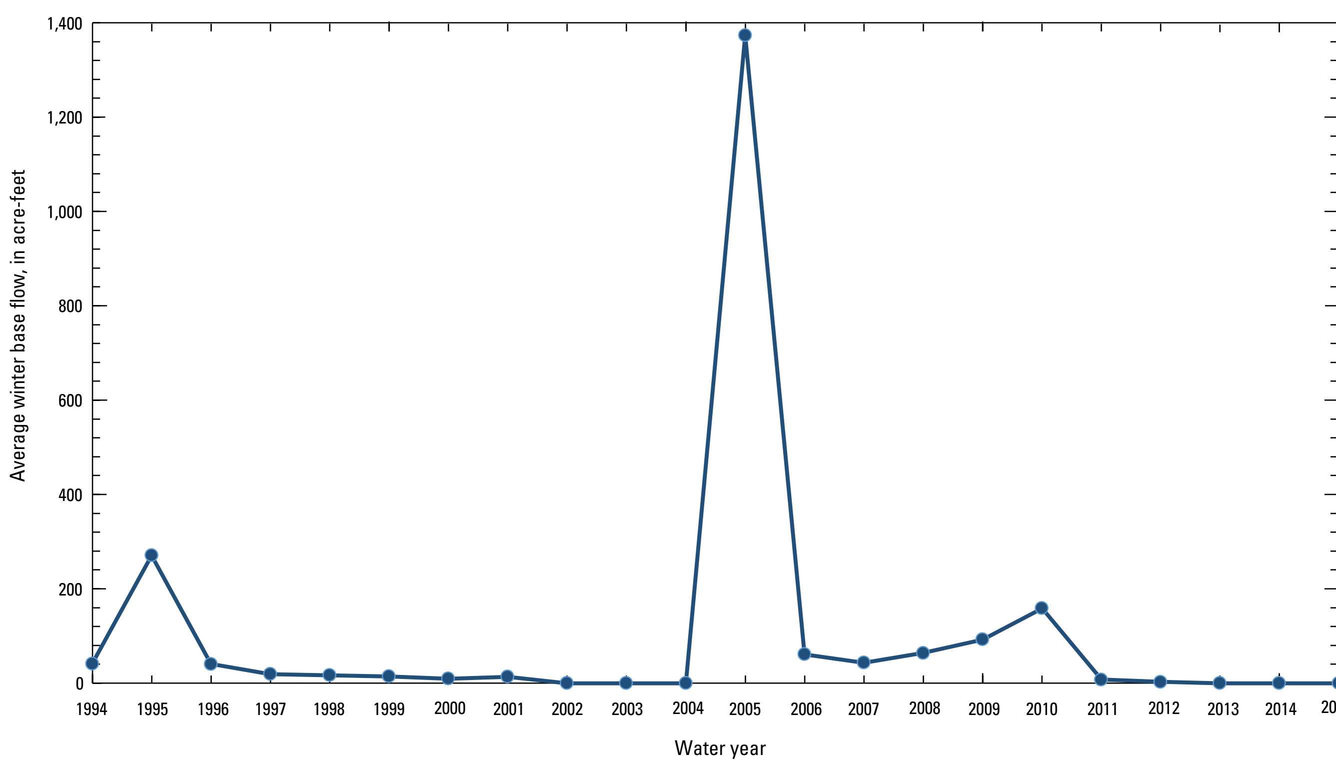


Figure 5. Graph showing the recorded average winter (November to February) base flow for U.S. Geological Survey streamflow-gaging station Truxton Wash near Valentine, AZ (09404343).

Table 1. Spring and stream discharge data for the Truxton aquifer on and adjacent to the Hualapai Reservation, Arizona.

[NAD 27, North American Datum of 1927; E, estimated; 122SMDR, Miocene sedimentary rocks; 330RDLL, Pennsylvanian Redwall Limestone; 374MUAV, Middle Cambrian Muav Limestone; --, no data]

Statin name	USGS site identification number	Latitude, decimal degree (NAD 27)	Longitude, decimal degree (NAD 27)	Altitude, feet above sea level	Discharge, gallons per minute	Date measured	Aquifer code	Estimated discharge, acre-feet per year	Remarks
Peach Springs	353445113255000	35.579	113.431	4,210	76.2	May 3, 1993	122SDMR(?)	122.70	
	--	--	--	--	92	--	--	148.14	
	--	--	--	--	28[2]	November 2, 1993	--	454.10	
	--	--	--	--	84.4	June 4, 1994	--	135.91	
	--	--	--	--	71.8	September 7, 1994	--	115.62	
	--	--	--	--	49.4[2]	March 31, 1995	--	79.58	107.63, average of Peach Springs miscellaneous measurements May 1993 to March 1995, in acre-feet per year.
Lower Peach Springs	--	35.592	113.440	4,020	0.1	March 17, 1977	374MUAV	0.16	
	--	--	--	--	10 E	June, 2015	--	16 E	
Red Spring	353333113251801	35.559	113.423	4,540	1–1.5 E	March 17, 1977	122SDMR	1.9–2.9	
	--	--	--	--	0.6	March 29, 1995	--	0.97	
Horse Trough Spring	--	35.550	113.619	5,181	0	May 5, 2002	374MUAV	0.00	
Dewey Mahone Spring	--	35.506	113.629	4,670	--	--	374MUAV	--	
Surprise Spring	353109113240201	35.536	113.401	5,120	4.00	August 6, 1992	330RDLL	6.44	
	--	--	--	--	<1 E	June 29, 1994	--	1.5 E	
	--	--	--	--	0.45	March 29, 1995	--	0.72	
Estimated sum of Truxton basin springs that discharge north to Peach Springs Canyon	--	--	--	--	67.9	--	--	110	
Crozier Spring[1]	--	35.454	113.654	4,311	--	--	--	--	
Walnut Spring[1]	--	35.441	113.683	4,406	--	--	--	--	
Crozier Canyon Spring	--	35.432	113.648	4,058	--	--	122SDMR	--	
Truxton Canyon Springs[1]	--	35.435	113.631	4,088	330	--	--	532	Tillman and others (2011)
Sum of all Truxton Basin springs	--	--	--	--	193	--	--	311.31	Arizona Department of Water Resources (2009)
Truxton Wash near Valentine, base flow	09404343	--	--	--	400	--	--	644.11	Arizona Department of Water Resources (2009)
Truxton Wash near Valentine, base flow	09404343	--	--	--	695	May 28, 1993	--	1119.14	Hualapai Water Resources Program (1999)
Truxton Wash near Valentine, base flow	09404343	--	--	--	188	December 11, 1994	--	302.73	Hualapai Water Resources Program (1999)

[1]North American Datum of 1983 (NAD 83)

[2]Does not include flow diverted to the community of Peach Springs.

ADWR estimated the average annual runoff from precipitation for the Peach Springs Basin, of which the Truxton basin is a part, as about 0.1 in. (3,250 acre-ft/yr), based on flood frequency and streamflow-gage analysis data from 1951–1980 (Arizona Department of Water Resources, 2009, sec. 4.1, Big Sandy Basin, p. 53–92, sec. 4.8, Peach Springs Basin, p. 354–389). More recently, annual runoff estimates were developed for Southwest Alluvial Basins (SWAB) by Tillman and others (2011) using Parameter-Elevation Relationships on Independent Slopes Model (PRISM) data as the basis for precipitation, a Basin Characterization Model (BCM; Flint and Flint, 2007a, b), and a multiple-regression equation to estimate runoff and recharge. Annual runoff values were averaged over 10-year periods from 1940 to 2006. For each southwest basin, runoff was determined for both total areas and mountain-front areas. Values for the Peach Springs Basin were 0.15 and 0.19 in., respectively (4,875 and 6,175 acre-ft/yr). Because the Truxton basin makes up about 9.0 percent of the area of the Peach Springs Basin and about 20 percent of Truxton basin occurs on the Hualapai Reservation, the average annual runoff derived from the PRISM and BCM method for the part of the Truxton basin on the reservation can be estimated as ranging from 87–111 acre-ft/yr.

The occurrence and movement of groundwater in the Truxton aquifer is strongly influenced by the porosity, permeability, lithology, and geologic structure of the rocks. The porosity of an aquifer is the volume of open space, or pores, to the total volume of the rock. The permeability of an aquifer is its ability to transmit water under a hydraulic gradient. Sediments with very small particle size (for example, clays, silt, siltstones, and mudstones) have very high porosity but very low permeability. The many small pore spaces create a high storage potential in the sediments or rock but limit their ability to release that water under gravity flow. Rock or sediments with low to moderate porosity (for example, sand, sandstone, gravel, and cobbles) have generally lower storage potential but have much higher permeability, allowing the water in them to release more easily under gravity flow.

Twenter (1962) provided the first comprehensive description of the Cenozoic gravel, fluvial beds, lakebed deposits, and volcanic rocks that make up most of the Truxton basin, parts of the Hualapai Plateau to the north, and Aubrey Valley to the east. Based on this geologic evaluation, spring data, and limited well data, Twenter recommended the Truxton basin as one of the areas of the Hualapai Reservation where additional water supplies probably could be developed. The lithology (texture, grain size, and composition) of the Truxton basin, basin-fill sediments that comprise the Truxton aquifer vary considerable from clay, mud, silt, sand, gravel, and cobbles to small boulders and interbeds of basalt. The consolidated rock units that are adjacent to and underlie the Truxton aquifer are typically (1) permeable Paleozoic limestones around the north and east margins of the Truxton basin and (2) impermeable granite and metamorphic rocks underlying the aquifer (fig. 3). Faults and monoclines add additional complexity to the occurrence and movement of groundwater in the Truxton aquifer by either creating barriers to groundwater flow and (or) increasing basin storage. The younger basin-fill sediments exposed at the land surface are largely unsaturated but at least moderately permeable. Well logs (appendix) reveal that younger basin-fill sediments tend to be a more poorly sorted mix of finer-grained material (mud, silt, and fine sand) that grades to coarser grained material at depth. These coarser-grained sediments near the base of the younger basin-fill sediment units tend to be water bearing in the parts of the Truxton aquifer on the Hualapai Reservation. They are separated in places from the partly to fully saturated older basin-fill sediments by dry to partly saturated basalt. Older basin-fill sediments of the Truxton basin that make up the largest part of the aquifer are also a poorly sorted mix of medium- to coarser-grained material (medium to coarse sand, silt, gravel, and cobbles), with low to moderate amounts of clay. This lithology provides porosity and permeability characteristics sufficient for water well development of the aquifer (Twenter, 1962; Natural Resources Consulting Engineers, 2011).

Faults and fractures also have considerable effect on the occurrence and movement of groundwater in the Truxton aquifer. Up to 210 ft of offset along the Hurricane Fault, which bisects the Truxton basin, has created a greater thickness of older and younger basin-fill sediments to the west of the fault (figs. 3 and 8). The potential for greater saturated thickness of the Truxton aquifer to the west of the Hurricane Fault would also result in greater storage potential. Well logs from the railroad wells near the community of Peach Springs, and Truxton Wash, indicate that the older and younger basin-fill sediments are dry in this area and groundwater is found in the underlying Redwall or Muav Limestones that comprise the Redwall-Muav aquifer (figs. 3 and 8; appendix). Alluvial sediments and the older and younger basin-fill sediments that underlie Truxton Wash likely receive water infiltrating from the streambed during runoff events. However, there are currently no wells in this area to determine if these sediments are at least partly saturated in the vicinity of the town of Peach Springs. Other smaller segment faults, folds, and the Toroweap Monocline to the north and east of the Truxton basin are areas where small springs are discharging from The Redwall-Muav aquifer into the Truxton basin. At the north end of the Truxton basin, Peach Springs and a few other smaller springs discharge northward into Peach Springs Wash from a combination of the older and younger basin-fill sediments and the Redwall-Muav Aquifer (fig. 3 and table 1).

Annual groundwater recharge rates for the Hualapai Plateau have been estimated by Huntoon (1977) as about 1 percent of the average annual precipitation. Devlin (1976) estimated an upper end for the annual groundwater recharge rate as about 2 percent of average annual precipitation, on the basis of spring discharge measurements on the reservation. These estimates of annual groundwater recharge are likely low because they assume all recharge discharges at springs and disregard ET derived from groundwater (Natural Resources Consulting Engineers, 2011). Natural Resources Consulting Engineers (2011) used water-balance methods to determine an annual groundwater recharge value of about 3 percent of the average annual precipitation for the reservation, with the greatest groundwater recharge occurring in mountain-front areas like the Music Mountains at the north end of the Truxton basin. Because of the low average annual precipitation coupled with high average annual ET and the limited surface area of the Truxton aquifer under the Hualapai Reservation, little water is available for groundwater recharge on the reservation. Additional groundwater recharge occurs on parts of the Truxton basin outside of reservation lands that, once a part of the Truxton aquifer, can be accessed by wells on the reservation. The good porosity and permeability characteristics of the Truxton aquifer also enhance groundwater recharge from the surface of the Truxton basin (Natural Resources Consulting Engineers, 2011).

The BCM average annual groundwater recharge estimates for the Peach Springs Basin are based on the available water remaining after adjustments for ET, runoff, and the field capacity of soils and rock based on hydraulic-conductivity values (Tillman and others, 2011). The average annual groundwater recharge estimate for the Peach Springs Basin is determined as the product of the area and the BCM estimate of about 0.32 in., about 24,620 acre-ft/yr, which accounts for about 3 percent of an 11.0 in/yr annual average precipitation. The part of the Truxton basin on reservation lands would receive about 120 acre-ft/yr of this value. Most of this groundwater recharge occurs mainly in the winter months when ET is lowest and precipitation is highest.

The usable storage volume of an aquifer is a product of the area, saturated thickness, and the specific yield (effective porosity) of the water-rock matrix of the aquifer. Specific yield (in unconfined aquifers) and storativity (in confined aquifers) are dimensionless values usually determined from pumping tests and aquifer tests. Storage values cannot be accurately determined from single well pumping tests; the only pumping test available for the Truxton aquifer assumed a specific yield estimate of 15 percent for a mostly sand and gravel matrix (Natural Resources Consulting Engineers, 2011). Intermediate and coarse basin-fill sediments in areas adjacent to the study area have estimated specific yields that range from 5 to 25 percent (Freethey and others, 1986).

Methods

To develop a better understanding of the storage potential and sustainability of the Truxton aquifer on the Hualapai Reservation, this study used surface geophysical surveys combined with existing well, water-level, and other hydrogeologic information available from previous studies. The surface geophysical method chosen as best suited for this study was controlled source audio-frequency magnetotellurics (CSAMT). Existing well, water-level, and other hydrogeologic information were used to develop a generalized water budget and improve the conceptual model of the aquifer.

Controlled Source Audio-Frequency Magnetotelluric Survey

CSAMT is an electromagnetic sounding technique that has proven useful for hydrogeological and groundwater studies (Zonge, 1992). CSAMT is also a geophysical method that can provide electrical resistivity in the subsurface to depths of about 3,000 meters (m, about 9,800 ft) below land surface. Because the electrical resistivity varies with rock types and water content, this method may provide an indication of subsurface structure (strata, faults, and fractures) and presence of groundwater (Simpson and Bahr, 2005). This low-impact, nonintrusive technique has been used extensively by the minerals, geothermal, hydrocarbon, and groundwater exploration industries since 1978 when CSAMT equipment systems first became commercially available (Zonge, 1992).

Description of Method

CSAMT provides the electrical resistivity of the subsurface along a receiver profile by measuring electric and magnetic fields introduced into the earth by transmitting a controlled current at several frequencies a specified distance away (fig. 6). Grounded dipoles at the receiver site detect the electric field parallel to the transmitter, and a magnetic-coil antenna senses the magnetic field perpendicular to the transmitter (fig. 6). The ratio of the orthogonal- and horizontal-electric field magnitudes to magnetic-field magnitudes yields the apparent resistivity. CSAMT uses a remote, grounded electric-dipole transmitter as an artificial signal source. The transmitter source provides a stable signal, resulting in higher precision and faster measurements than what can be obtained from natural source audio-frequency magnetotellurics (Zonge, 1992). Typically, the source for a CSAMT survey is separated from the survey line by about five times the depth of investigation because a plane wave is advantageous (fig. 6).

CSAMT measurements typically are made at frequency ranges from 1 to 8,000 hertz in binary incremental steps. The frequencies used for the surveys in this report were 2, 4, 8, 16, 32, 64, 128, 256, 512, 1,024, 2,048, 4,096, and 8,192 hertz. CSAMT measurements consist of orthogonal and parallel components of the electric (E) and magnetic (H) fields at a separation of 5 to 15 kilometers (km, 3.1 to 9.3 mi) from the source (Sharma, 1997). CSAMT measurements can be taken in a number of different arrays depending on the type of information warranted. This study used what is termed a “reconnaissance” type of CSAMT array, which consists of one electric (E_x) and one magnetic (H_y) component for each measurement (Zonge, 1992), as opposed to a more involved survey, which collects vector and tensor measurements by measuring two electric-field components (E_x and E_y) and three magnetic-field components (H_x, H_y, and H_z). Multiple electric fields are measured concurrently during reconnaissance CSAMT surveys. This study used a six-channel receiver, with the capability of simultaneously measuring five electric fields for every one magnetic field. Because the magnetic field does not change much over the same distance that substantial electric-field changes occur, fewer magnetic-field measurements are required. The magnetic-field measurement is used to normalize the electric fields and calculate the apparent resistivity and phase difference (Zonge, 1992). Grounded dipoles at the receiver site measure the electric field parallel to

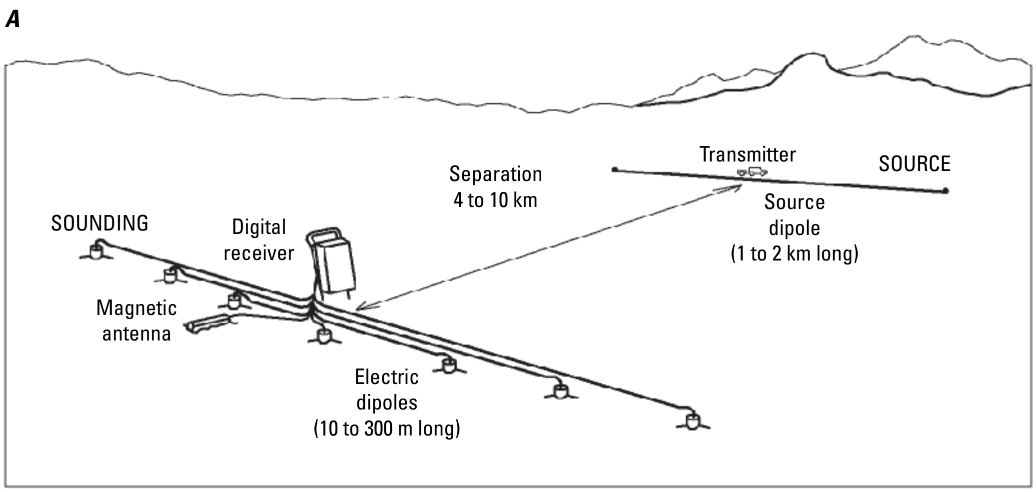
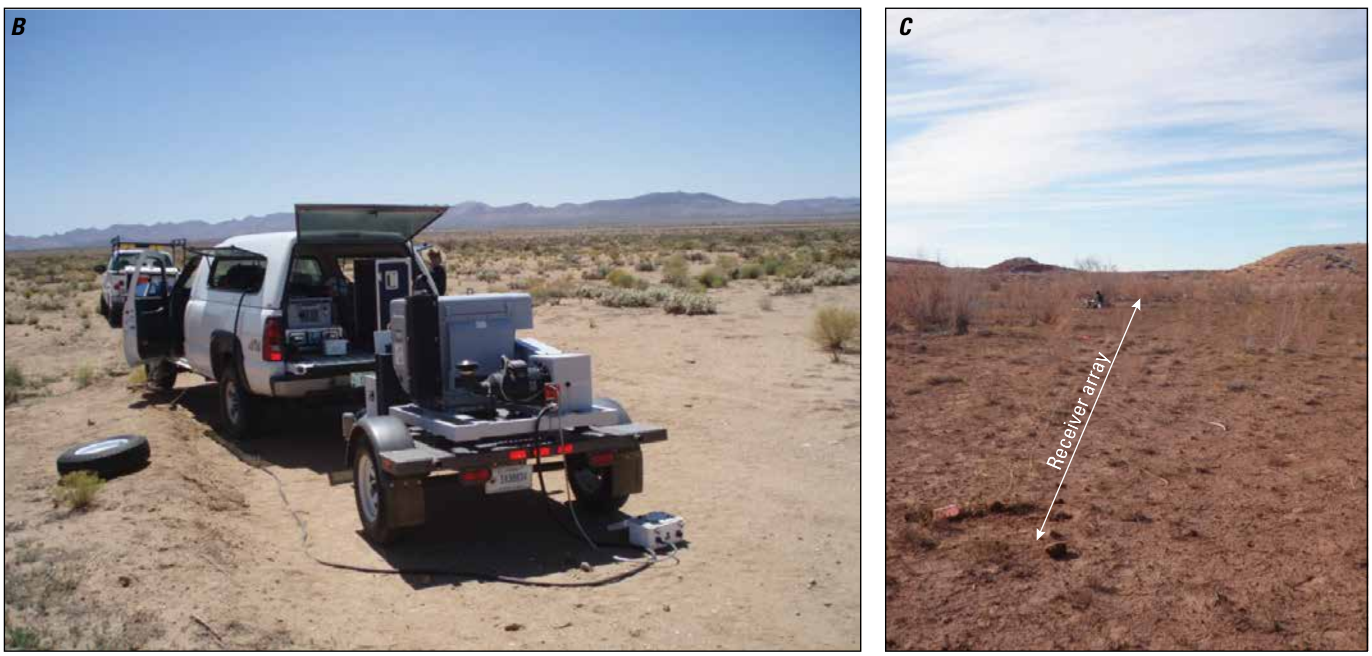


Figure 6. Diagram (*A*) and photographs (*B*, *C*) showing controlled source audio-frequency magnetotelluric setup used to study the Truxton Aquifer on the Hualapai Reservation, Mohave County, Arizona. Diagram (*A*) modified from Zonge, 1992; photographs by D.J. Bills (*B*) and Jon Mason (*C*) of the U.S. Geological Survey. m, meter; km, kilometer.



the transmitter (E_x), and a magnetic coil antenna measures the perpendicular magnetic field (H_y). The ratio of the E_x and H_y magnitudes yields the apparent resistivity (equation 1; Zonge, 1992; Simpson and Bahr, 2005):

$$\rho_a = \frac{1}{5} f \left[\frac{E_x}{H_y}\right]^2, \qquad (1)$$

where

- ρ_a is the apparent resistivity,
- f is the frequency,
- E_x is the parallel electrical-field strength, and
- H_y is the perpendicular magnetic-field strength.

The penetration of CSAMT into the subsurface and the depth of investigation are determined by the skin depth (equation 2):

$$S = 503\sqrt{\rho_a \div f}\ , \qquad (2)$$

where

- S is the skin depth,
- ρ_a is the measured apparent ground resistivity in ohm-meters, and
- f is the signal frequency (Zonge, 1992; Simpson and Bahr, 2005).

The skin depth is the depth at which the amplitude of a plane wave signal has dropped to 37 percent of its value at the surface (Zonge, 1992). The skin depth is pertinent because CSAMT data are most commonly interpreted using simplified magnetotelluric (MT) equations based on the assumption that the electric and magnetic fields behave as plane waves. Unlike MT soundings, where the source of telluric current (distant lightning strikes or atmospheric interaction with solar winds) is considered infinitely distant and nonpolarized, the CSAMT source is finite in distance and distinctly polarized (Sharma, 1997). The separation, *r*, between the transmitter and receiver for CSAMT surveys must be greater than three skin depths for the current driven into the ground to behave like plane waves (termed "far field"). When *r* is less than three skin depths at the frequency being measured, the electric and magnetic fields no longer behave as plane waves and become curved (termed "near field") such that the equation for apparent resistivity (equation 1) no longer applies. CSAMT measurements from this study were examined for near- and far-field effects before modeling by plotting the apparent resistivity versus the frequency for a given set of soundings. All data from this study used for modeling are measured in the far field. The minimum distance between the source and receiver was 5 km (3.1 mi), yielding an *r* of greater than three skin depths (Zonge, 1992).

When the *r* between the receiver and transmitter is greater than three skin depths, the equation for depth of investigation is (Zonge, 1992) the following:

$$D = 356\sqrt{\rho_a \div f}. \quad (3)$$

The depth of investigation (*D*) of a CSAMT survey can range from 20 to 3,000 m (66 to 9,800 ft), depending on the resistivity of the ground and the frequency of the signal. Lower frequency signals have a greater depth of investigation than higher frequency signals.

Collection of Controlled Source Audio-Frequency Magnetotellurics Data

CSAMT data were collected in the Truxton basin on the Hualapai Reservation from September 15 to December 18, 2015. A Zonge GGT-30 geophysical transmitter powered by and connected to a 25-kilowatt trailer-mounted generator and a Zonge XMT-32 transmitter controller were used to transmit the electrical source through a 1-kilometer-long (0.62 mi) dipole. A Zonge GDP-32II multichannel geophysical receiver was connected to six porous pot electrodes arranged in 100-m (328-ft) dipoles and a Zonge ANT6 high-gain mu-metal core magnetic antenna to measure the Earth's response to the transmitted signal. Each CSAMT field measurement consisted of one magnetic-field measurement (*Hy*) with five accompanying electric-field measurements (*Ex*).

Four CSAMT lines were surveyed as a part of this project—lines A, B, C, and D (fig. 3). A total of 34 km (21.1 mi) of survey lines were measured in the Truxton basin. Five different transmitter locations were used to survey four lines (fig. 3). The separation between transmitter and receiver locations ranged from about 5 km to 8 km (3.1 to 5.0 mi). Once survey lines were complete, data were processed and analyzed using Zonge Engineering's DATPRO suite of software (Zonge Engineering, Tucson, Ariz.). Raw CSAMT data were first averaged using Zonge's CSAVG program. Averaged data were reviewed for near-field and far-field effects by plotting the apparent resistivity versus the frequency (equation 2) for a given set of soundings. The lowest far-field frequency was determined, and data below that frequency, which violated the plane wave approximation because of an insufficient separation, *r*, were not used in the analysis. Typically for the surveys in the Truxton basin, 32 hertz was the lowest far-field frequency used for analysis. After determining the lowest far-field frequency, 32 to 8,192 hertz data were averaged and entered into Zonge's SCS2D software for inversions. The averaged data were inverted by Zonge's SCS2D software to provide a two-dimensional resistivity profile for each survey line. The profiles were then examined for errors and adjusted as appropriate. Additional adjustments were made to the inversion models in areas where the subsurface geology was known from lithologic logs for wells; line A near the Hualapai water supply wells and line D near well PCD-1 were areas where CSAMT surveys passed close enough to wells to make these adjustments. Final inversion models presented in the "Results" section of this report represent the best fit to subsurface resistivity.

Groundwater-Storage Calculations

Groundwater-storage estimates require a generalized conceptual model of the groundwater-flow system that includes areal extent, saturated thickness, and estimates of the specific yield of the aquifer material. For the study area, existing well data, water-level information, and other hydrogeologic information from wells and geologic maps were used to develop a generalized conceptual model of the aquifer as a tool to estimate storage. An approximation of the areal extent of the Truxton aquifer on the Hualapai Reservation was determined from (1) the surface geologic maps that characterize the extent of basin-fill deposits that contain the Truxton aquifer (U.S. Geological Survey, 2015; Billingsley and others, 2006; Wilson and others, 1959), (2) results of CSAMT surveys that infer the extent of partly saturated to fully saturated basin-fill deposits, and (3) area calculations using a geographic information system to estimate the aquifer boundary on the reservation as shown on figure 3.

Saturated thickness of the Truxton aquifer was estimated from CSAMT profiles and compared to well-log data. For this study, there appears to be a relation between low modeled resistivity (high conductivity, 2–16 ohm-meters [ohm-m]) and saturated, older basin-fill sediments; unsaturated, younger basin-fill sediments tend to have a higher resistivity (18–261 ohm-m). Saturated clays tended to have very low resistivity, below 2.0 ohm-m, and the granitic and metamorphic bedrock tend to have very high resistivity, greater that 398 ohm-m. For each profile, the band of resistivity that correlated to saturated older and younger basin-fill sediments was averaged. The final estimate of average saturated thickness of the Truxton aquifer on the Hualapai Reservation was the result of the average of all of the individual CSAMT profiles.

Aquifer specific yield is the ratio of the volume of water that can be drained from a unit volume of aquifer or water-bearing zone under the force of gravity or be pumped out by a well. Specific yield is typically estimated from well pumping tests and (or) aquifer tests. Only one pumping test exists for wells in the study area (Natural Resources Consulting Engineers, 2011). Other sources of specific-yield estimates were from studies of basin aquifers with similar hydrogeologic conditions in areas adjacent to the Truxton aquifer (Freethey and Anderson, 1986; Freethey and others, 1986; Arizona Department of Water Resources, 2009; Truini and others, 2013; Tillman and others, 2011). The estimated storage of the Truxton aquifer on the Hualapai Reservation was calculated as the product of the aquifer saturated volume in the basin-fill deposits multiplied by the estimated specific yield.

Generalized Groundwater Budget

A groundwater budget is one tool that can be used to evaluate the effect of changes in aquifer inflow or outflow on aquifer storage. With accurate inflow and outflow data, a groundwater budget will show if storage is increasing or decreasing. When calculated over time, the results can provide some estimate of aquifer sustainability.

A groundwater budget simply states that the rate of change in groundwater stored in an aquifer is balanced by the rate at which water flows into and out of the aquifer (fig. 7). The basic inflow components in a groundwater budget are infiltration from precipitation (recharge), water from losing stream channels, and (or) underflow from adjacent aquifers. Outflow components in a groundwater budget are discharge to streams or springs, evapotranspiration from the near-surface part of the aquifer, groundwater withdrawals by wells, and (or) underflow to adjacent aquifers. These components can be expressed as shown in equation 4:

$$(I+R+U_i) - (Q_s+ET+Q_w+U_o)=\Delta S, \quad (4)$$

where

I is recharge from infiltration of precipitation,
R is infiltration from losing streams,
U_i is underflow from adjacent aquifers,
Q_s is base-flow discharge to streams and springs,
ET is evapotranspiration from groundwater,
Q_w is groundwater withdrawals from wells,
U_o is underflow to adjacent aquifers, and
ΔS is the change in storage.

For this study, available information on the groundwater inflow and outflow components of the Truxton aquifer and an available Basin Characterization Model (BCM) were used to refine estimates of recharge. Recharge is difficult to measure directly and seldom done. Recharge estimates are commonly derived as a percentage of precipitation, the product of a water budget, or the result of modeling exercises. Recharge has not been previously estimated for the study area. Although recharge is not the focus of this study, an estimate for the study area was made using a generalized water budget to compare with values determined for areas adjacent to the study area. Estimated storage for the aquifer was derived from surface geophysical data and available well lithology. Other existing well, water-level, spring, and hydrogeologic information were used to develop a generalized water budget and improve the conceptual model of the aquifer.

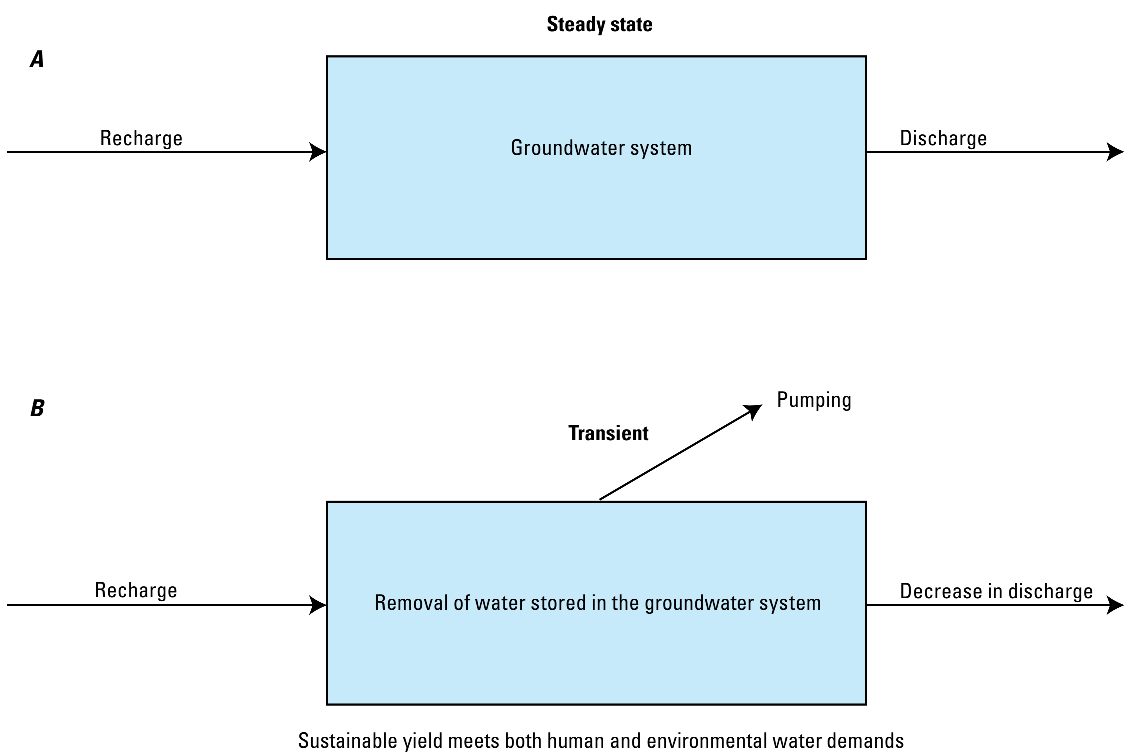


Figure 7. Diagrams illustrating water budgets for a groundwater system for (*A*) predevelopment and (*B*) development conditions (modified from Alley and others, 1999).

Results of Surface Geophysics and Evaluation of Hydrological Data to Estimate Storage of the Truxton Aquifer on the Reservation

Evaluations of surface geophysical and well borehole data were used to determine the depth to bedrock and estimate the saturated thickness of the Truxton aquifer on the Hualapai Reservation. Other existing well, geologic, and hydrologic information were used with the geophysical data to develop a generalized water budget and conceptual model of the aquifer to provide a better understanding of the hydrogeology of the Truxton aquifer on the Hualapai Reservation and estimate storage on the reservation.

Well Lithology and Surface Geophysics

The lithologic information from individual driller's logs for wells is very generalized. However, when compared with formal geologic descriptions of rock types from geologic maps (Billingsley and others, 2006) there are enough similarities to group the well lithologies into units consistent with the mapped rock types. In the upper parts of the boreholes, most driller's logs describe unconsolidated to semiconsolidated sand, gravel, clay, and silt that are tan, light brown, to reddish-brown in color (fig. 8). Underneath this material, wells in Truxton Valley generally encounter a sequence of brown to reddish-brown clay and sandy and silty clay. Both of these rock types are consistent with the younger basin-fill deposits, Pleistocene to Miocene in age, described by Billingsley and others (2006), Young (1999), and Twenter (1962). These younger basin-fill sediments are typically dry except near the bottom of the sediments as encountered in a few wells.

Below the younger basin-fill sediments, some but not all wells encounter interbeds of volcanic material that are typically described in well cuttings as cinders, tuff, or basalt. These rocks are consistent with the middle to lower Miocene volcanic rocks of the Hualapai Plateau described by Billingsley and others (2006). The volcanic rocks predate the younger basin-fill sediments encountered in boreholes and can be interbedded with the upper parts of older gravel and basin sediments and lakebed (lacustrine) deposits deeper in the subsurface. Where encountered in wells, the volcanic rocks are typically fully saturated, although driller's report they yield little to no water to wells.

From about the middle to the bottom of wells developed in Truxton Valley, boreholes encounter a sequence of partly consolidated to consolidated, reddish-brown to brown gravel and sand with varying amounts of clay (fig. 8 and appendix). Descriptions in driller's logs are consistent with the older basin-fill sediments described as filling basins and paleochannels from the Late Cretaceous to the middle to late Miocene (Billingsley and others, 2006; Twenter, 1962). Just to the north of the study area on the Hualapai Plateau, Young (1999) named these units the Buck and Doe Conglomerate. In the Truxton basin on the Hualapai Reservation, these rock units are almost always fully saturated and represent the main part of the Truxton aquifer (fig. 8*B*). The underlying basement granites and metamorphic rocks, Proterozoic in age, are encountered in wells drilled deep enough in the Truxton basin and do not contain water (fig. 8 and appendix); the lithologic log shown for well D-2 on figure 8*A* is an example.

The Hurricane Fault strikes northeast to southwest through the eastern half of the Truxton basin on the Hualapai Reservation (fig. 8*A* and *B*). The Hurricane Fault is a near-vertical, normal fault with about 210 ft of offset downthrown to the west. In the Truxton basin on the Hualapai Reservation to the east of the fault, this offset has probably placed about 210 ft of granitic rocks opposite of the older basin-fill sediments to the west of the fault in the subsurface. Pleistocene and Holocene erosion of these sediments would have reduced their thickness by similar amounts to the east of the fault resulting in less apparent offset at the surface. Paleozoic rocks exposed at the eastern edge of the Truxton basin on the Hualapai Reservation appear to be erosional with on-lapping older and younger basin-fill sediments consistent with channel and basin development in the Tertiary and early Quaternary periods (fig. 3; Billingsley and others, 2006; and Young, 2007). At the east end of the Truxton basin near the community of Peach Springs, several wells were drilled by the Santa Fe Railroad Company in the Truxton Wash drainage in the early part of the 20th century. These wells encounter older and younger basin-fill sediments that range from about 150 to more than 800 ft thick (fig. 8 and table 1-2; Natural Resources Consulting Engineers, 2011). Below these units, the railroad wells encountered limestones consistent with the Muav Limestone, claystone and shale consistent with the Bright Angel Shale, and then an interbedded sandstone and conglomerate unit consistent with the Tapeats Sandstone (Santa Fe-2, fig. 8*C*). All of the railroad wells encountered granite in the bottom of the boreholes. The older and younger basin-fill sediments are dry in these wells, and groundwater is first encountered in the Muav Limestone that comprise the Redwall-Muav aquifer in this area. To the north of the community of Peach Springs in the Peach Springs Wash watershed, Red Spring, and part of the flow from Peach Springs discharge from the partly saturated older basin-fill sediments to the east of the Hurricane Fault (Billingsley and others, 2006).

Based on spring data and limited well-log data on the Hualapai Reservation to the west of the Hurricane Fault, the average saturated thickness of basin-fill sediments ranges from about 135 ft to about 323 ft (fig. 8, table 1, and appendix). Driller's logs and lithologic data from wells and surface geologic maps for the study area were used to compare with and interpret the CSAMT data. CSAMT allowed the reasonably well-constrained lithology at wells to be extended to areas where well data were unavailable resulting in an estimated saturated thickness for a much larger portion of the Truxton aquifer on the Hualapai Reservation.

Controlled Source Audio-Frequency Magnetotellurics Results

The resistivity data collected along four CSAMT survey lines were inverted and modeled to display as cross sections (figs. 9–12). The lowest far-field frequency used for analysis was 32 hertz. The profiles were examined and adjusted for data errors, and topographic adjustments were applied. Once additional adjustments were made to the inversion models in areas where the geology was known, a very good fit of the expected subsurface hydrogeology was determined. Inversion results from all four lines indicate four electric layers that correlate to unsaturated and saturated lithologic layers at depth. The first layer is shallow, ranging in thickness from 0 to about 40 m (0 to 131 ft), and is moderately conductive (20 to 40 ohm-m); this layer represents the uppermost unsaturated younger basin-fill sediments and includes surface alluvium and channel deposits. The second layer, ranging in thickness from 100 to 150 m (328 to 492 ft), is highly resistive (greater than 100 ohm-m). This layer includes the partly saturated younger basin-fill and volcanic rocks. The third layer—highly conductive (5 to 40 ohm-m) and about 100 m (328 ft) in thickness—correlates to older basin-fill sediments. The fourth layer is highly resistive (greater than 100 ohm-m) granite and metamorphic bedrock at the bottom of the Truxton basin. As expected, the bedrock layer imaged is a very irregular erosional surface with incised paleochannels infilled by the older and younger basin-fill sediments and basalt. The surface of the imaged basin sediments and volcanic rocks are also irregular, indicating additional erosional and depositional events.

Controlled Source Audio-Frequency Magnetotellurics Line A

CSAMT line A trends west to east from about Dewey Mahone Spring in the west to Route 66 in the east (fig. 9). Line A is about 8 km (4.9 mi) in total length, and the receiver dipole spacing is 100 m (328 ft). Inversion results from line A indicate four layers in the middle of the cross section and two layers at the east and west ends (fig. 9). In the middle of the cross section, between electrode stations 245 and 535, the first layer is found from an altitude of about 1,370 to about 1,345 m (4,500–4,410 ft) and is a moderately conductive layer, 20 to 40 ohm-m (green), that represents the younger basin-fill (fig. 9). The second layer is a highly resistive layer, greater than 100 ohm-m (yellow to red), found from an altitude of 1,300 to almost 1,200 m (4,265–3,940 ft; fig. 9). Based on lithologic logs, this layer appears to be (1) dry clay, (2) lacustrine (lakebed) deposits, and (3) interbedded, partly saturated to dry volcanic rocks found throughout the Truxton basin. The third layer is a highly conductive 100-m (328-ft) layer, 5 to 40 ohm-m (blue to green), found from an altitude of about 1,200 to 1,100 m (3,940–3,610 ft; fig. 9). Based on lithologic logs, the third layer represents saturated, older basin-fill sediments and lakebed deposits moderate too rich in clay. The fourth layer is highly resistive, greater than 100 ohm-m (yellow to red), and is found at altitudes less than 1,100 m (3,610 ft) in the middle section of line A (fig. 9). Based on outcrops at the west end of the Truxton basin and lithologic logs, the fourth layer represents granite and metamorphic bedrock at the bottom of the Truxton basin (figs. 8 and 9).

In the western part of line A, between electrode stations 55 and 225, inversion results indicate only two layers. The uppermost layer is moderately conductive, 20 to 40 ohm-m (green), and is found above 1,300 m (4,265 ft) in altitude (fig. 9*A*). The uppermost layer here is a thin layer of unsaturated, younger basin-fill (fig. 9*C*). Below 1,300 m (4,265 ft) altitude, a highly resistive layer, greater than 100 ohm-m (yellow to red), represents granite bedrock and basalt interbeds that outcrop further to the west (figs. 8 and 9*C*). The basin is much shallower in this area of line A, except between the electrode stations 178 to 231. Here, the highly resistive layer is not imaged at about 1,000 m (3,280 ft) altitude, the depth of the survey. Instead, less resistive materials are imaged, consistent with saturated, younger and older basin-fill sediments. These types of sediments are consistent with paleochannels described by Young (1999, 2007) and Billingsley and others (2006). On other parts of the Hualapai Reservation, such as the Grand Wash Cliffs and Westwater Canyon, these infilled paleochannels can range from 457 to 610 m (1,500 to more than 2,000 ft) in thickness (Young, 1987, 1999, and 2007).

The resistivity profile in the eastern part of line A, between electrode stations 535 and 735, also indicates two layers. The uppermost layer is conductive to moderately conductive, 5 to 40 ohm-m (blue to green), and found from 1,350 to 1,150 m (4,429 to 3,773 ft; fig. 9*A*). This layer is a mix of older and younger basin-fill sediments reworked by erosion and partly saturated. Below 1,150 m (3,773 ft) elevation is granite bedrock represented as highly resistive material, greater than 100 ohm-m (yellow to red, fig. 9*B* and *C*).

Controlled Source Audio-Frequency Magnetotellurics Line B

CSAMT line B is a west-east transect located about 3 km (1.86 mi) north of line A (fig. 10). Line B is about 10.5 km (6.52 mi) in total length, and the receiver dipole spacing is 100 m (328 ft). The last 0.9 km (2,950 ft) of line B on the east end was offset about 300 m (984 ft) to the northeast to avoid signal noise generated by a housing development along Buck and Doe Road. Inversion results from line B were similar to those in line A, with four layers in the middle of the cross section and two layers on the west and east sides of the cross section.

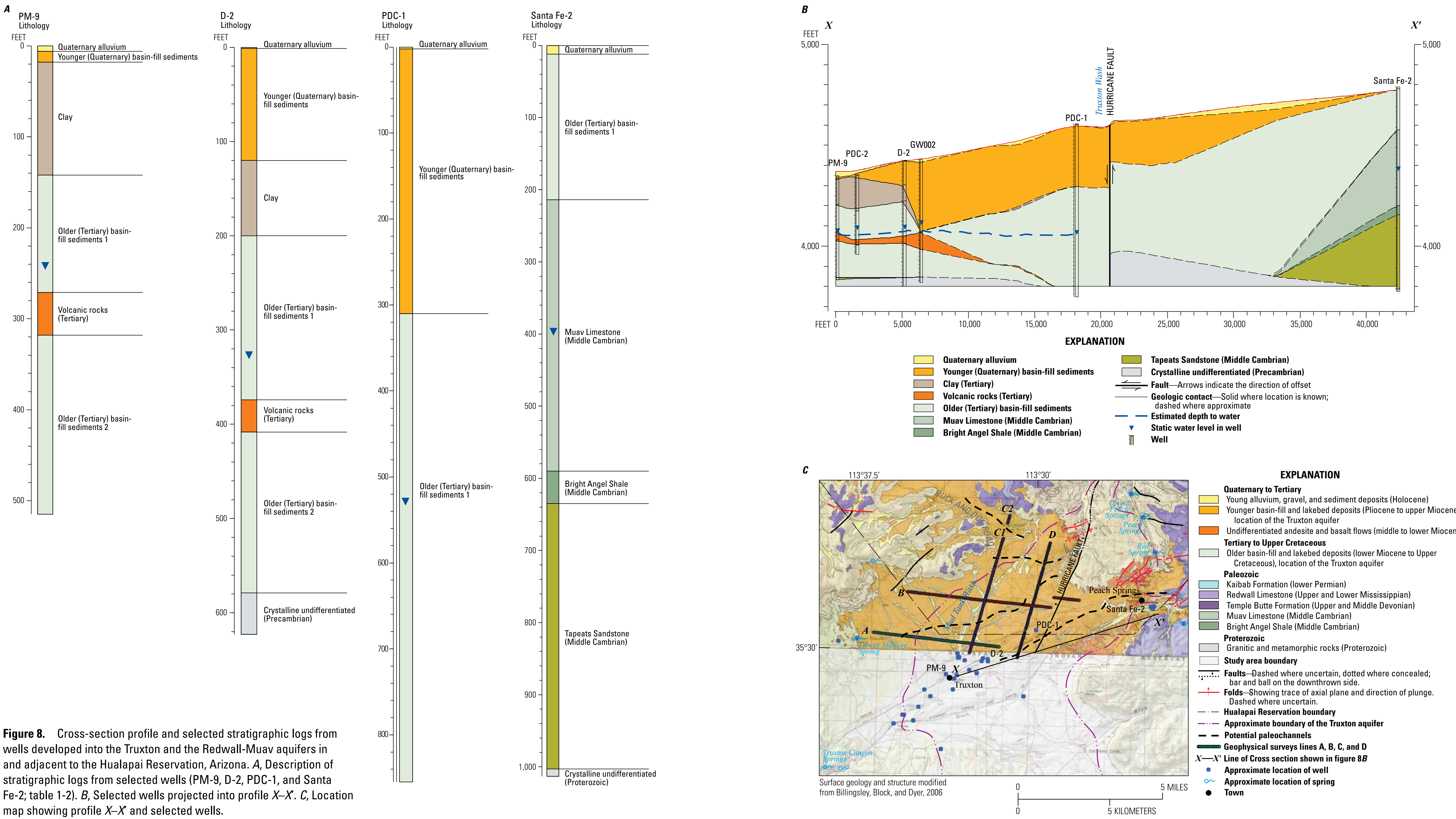
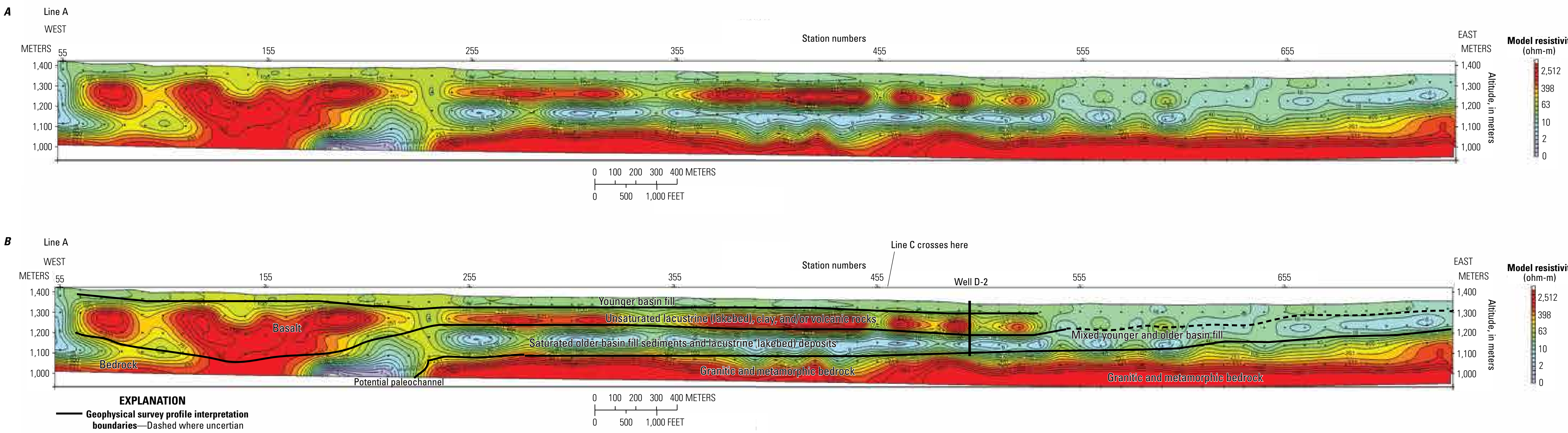


Figure 8. Cross-section profile and selected stratigraphic logs from wells developed into the Truxton and the Redwall-Muav aquifers in and adjacent to the Hualapai Reservation, Arizona. *A*, Description of stratigraphic logs from selected wells (PM-9, D-2, PDC-1, and Santa Fe-2; table 1-2). *B*, Selected wells projected into profile *X*–*X*′. *C*, Location map showing profile *X*–*X*′ and selected wells.



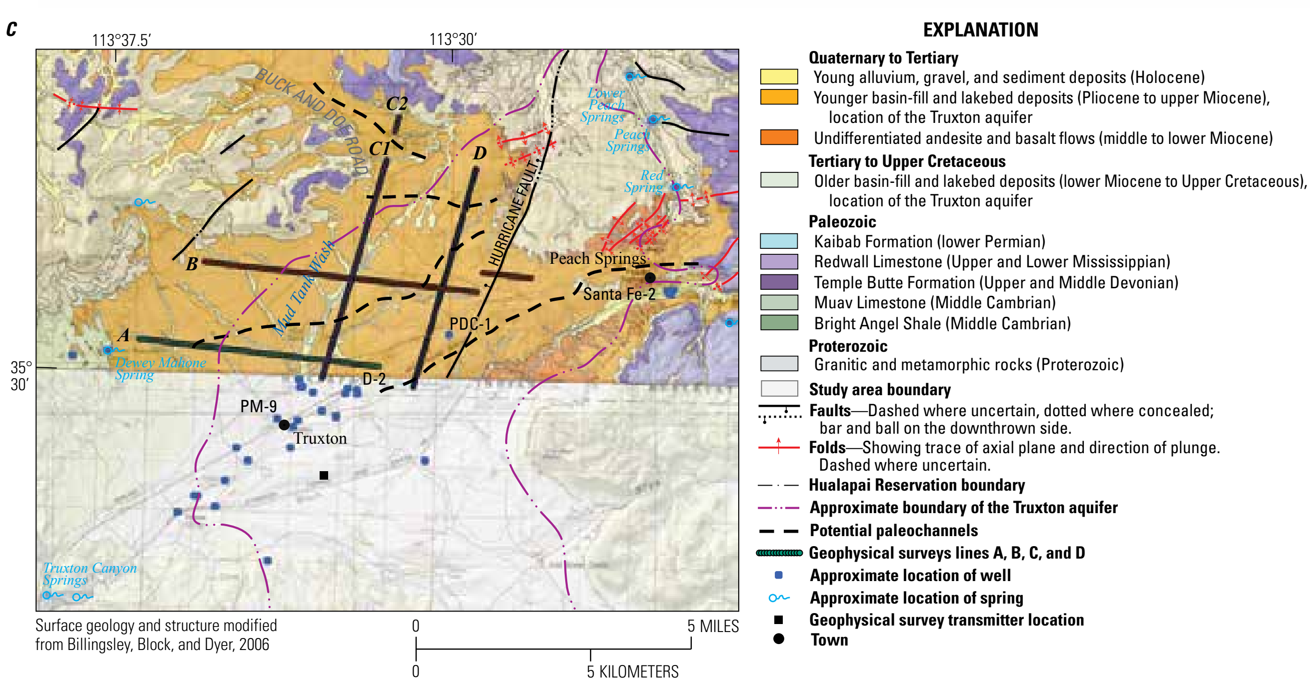
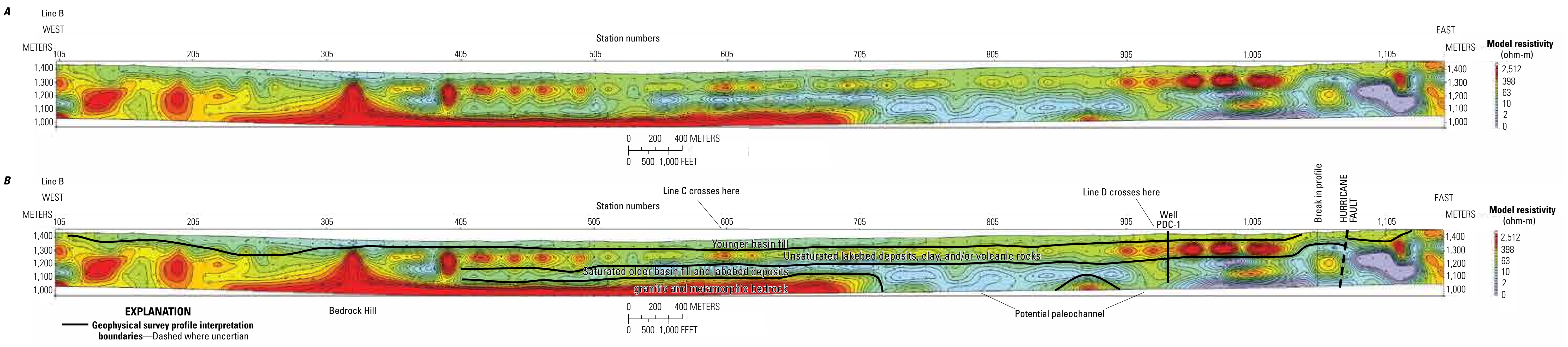


Figure 9. Controlled source audio-frequency magnetotelluric (CSAMT) survey profile (line A) from the Hualapai Reservation, Arizona. *A*, CSAMT line A profile; *B*, CSAMT line A profile with interpretations; and *C*, map showing location of CSAMT line A. ohm-m, ohm-meter.

In the middle of the cross section, between electrode stations 355 and 755, the first and second layers are found from an altitude of about 1,380 (land surface) to about 1,240 m (4,530 to 4,070 ft) and are moderately conductive layers, 20 to 60 ohm-m (green), that represent the upper, younger basin-fill and alluvial sediments (fig. 10*B*). The third layer is a low-resistivity (highly conductive) 100-m (328-ft) layer, 5 to 40 ohm-m (blue to green), found below about 1,200 m altitude (3,937 ft; fig. 10*B*). The third layer represents saturated, older basin-fill sediments, with moderate amounts of clay in some places. The fourth layer is highly resistive, greater than 100 ohm-m (yellow to red), and is found at depths greater than 1,100 m altitude (3,609 ft) in the middle cross section of line B (fig. 10*B*). The fourth layer represents granitic and metamorphic bedrock at the bottom of the Truxton basin.

At the eastern part of the cross section, at about electrode station 1050, the Hurricane Fault is intersected. Offset on this normal fault, as imaged by the very resistive (0 to 3 ohm-m, purple) saturated clay, appears to be about 60 m (200 ft) downthrown to the west, consistent with offsets determined by Billingsley and others (2006). The water well PDC-1 projects into the cross section at about electrode station 960, and CSAMT line D intersects the cross section at about electrode station 950. The lithologic log for well PDC-1 (fig. 8 and table 1-2) corroborates the layers as imaged, as does CSAMT line D where it crosses line B. Between electrode stations 705 and 1125, there is a large area where bedrock was not imaged at or below 1,100 m (3,609 ft) altitude. The bedrock in this area appears to be deeper than the total depth of the survey. Instead, the area from electrode stations 705 to about 980 is characterized by conductive to moderately conductive material at depth (blue to green) that is consistent with the saturated, older basin-fill sediments imaged throughout the study area. At a total depth of 260 m (855 ft), the well PDC-1 still did not penetrated bedrock. As with CSAMT line A, these deeper basin-fill sediments are likely associated with paleochannels that characterize the bottom of the Truxton basin. CSMAT line



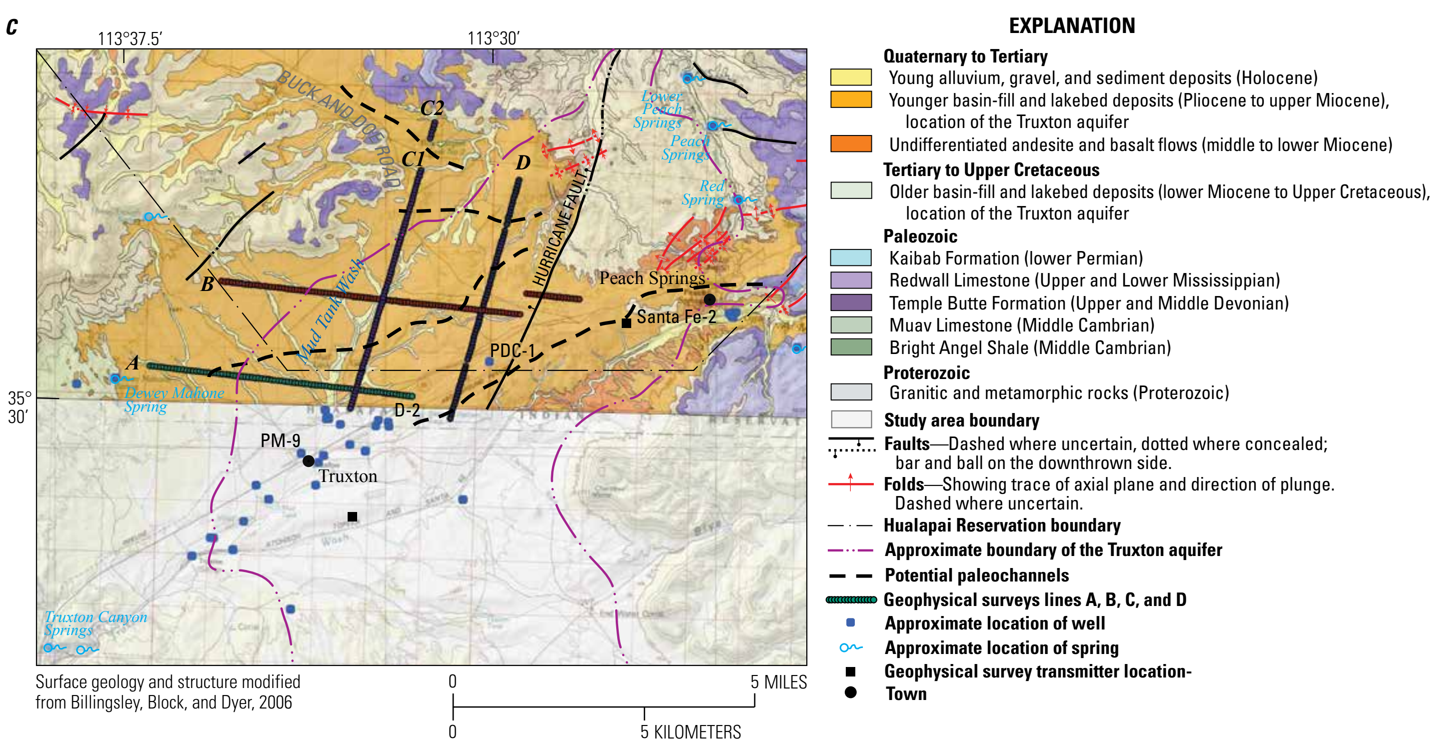


Figure 10. Controlled source audio-frequency magnetotelluric (CSAMT) survey profile (line B) from the Hualapai Reservation, Arizona. *A*, CSAMT line B profile; *B*, CSAMT line B profile with interpretations; and *C*, map showing location of CSAMT line B. ohm-m, ohm-meter.

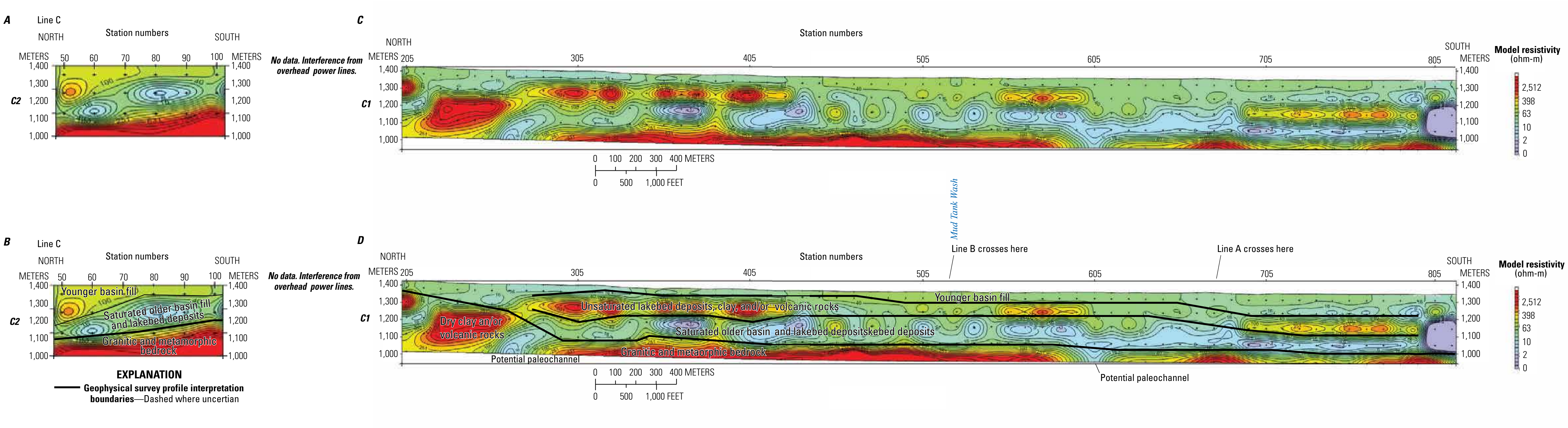
C intersects line B at electrode station 800 and has a comparable depth-resistivity profile (figs. 10 and 11).

Similar to CSAMT line A (station 250 to about 530), a resistive layer greater than 100 ohm-m (yellow to red) is imaged in line B from station 400 to about 705 at an altitude of 1,400 to 1,300 m (4,593 to 4,265 ft; fig. 10*B*). This layer represents dry, younger basin-fill sediments and unsaturated volcanic material above the water table. To the west of about electrode station 400, all three of these sedimentary rock units begin to thin out as they on lap granites and Paleozoic sediments at the west edge of the Truxton basin (fig. 10*B*). Of note is a bedrock hill that nearly breaches the surface at electrode station 315, further evidence of the erosional nature of the base of the Truxton basin.

Controlled Source Audio-Frequency Magnetotellurics Line C

CSAMT line C is a north-south transect that converges with Mud Tank Wash at about electrode station 515 (fig. 11*D*). Mud Tank Wash is incised about 7 to 8 m (23 to 26 ft) where it crosses line C, exposing the younger basin-fill sediments of the Truxton basin. The main segment of line C (C1) is about 7.5 km (4.7 mi) long. Interference from a high-voltage power line near the northeast end of line C1 resulted in about a 500-m (1,640-ft) gap in line C1. There is an additional 500-m segment of the profile, line C2, to the northeast that crosses part of a gap in the Paleozoic sediments between the Truxton basin and the Plain Tank area to the north on the southern Hualapai Plateau (fig. 11*E*). This is an area where there is the potential for groundwater in saturated basin-fill sediments of the Plain Tank area to flow down-gradient into basin-fill sediments of the Truxton basin.

Inversion results from line C1 are similar to CSAMT lines A and B, with four distinct layers throughout the cross section except for the north part of line C1, where only two layers can be resolved. This section of line C1 (electrode station 205 to 275) shows very resistive layers much closer to the surface than the rest of line C1 and thinner, undifferentiated, older and younger basin-fill sediments with some saturation potential (fig. 11*D*). A potential paleochannel occurs at about station 250. Figure 11*D* shows this part of line C1 very close to outcrops of Paleozoic bedrock to the west. Line C2 is about 500 m (1,640 ft) to the north of line C1. The highly resistive layer below 1,100 m (3,609 ft) altitude in line C2, as indicated by the inversion, correlates with the highly resistive bedrock granites indicated in line C1 and is similar to those indicated in lines A and B, where well lithologic logs indicate granite at depth. At station 110 of line C2, the bedrock imaged by the inversion appears to be



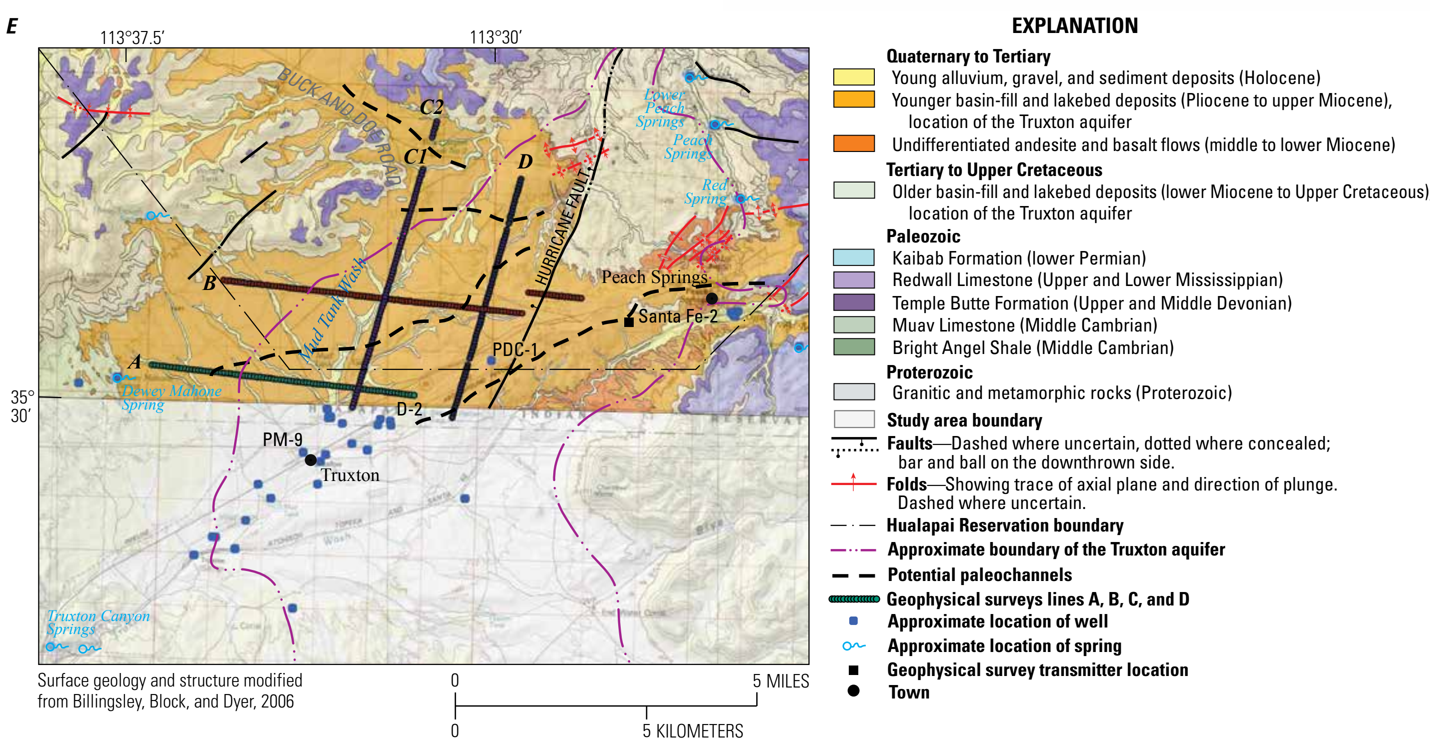


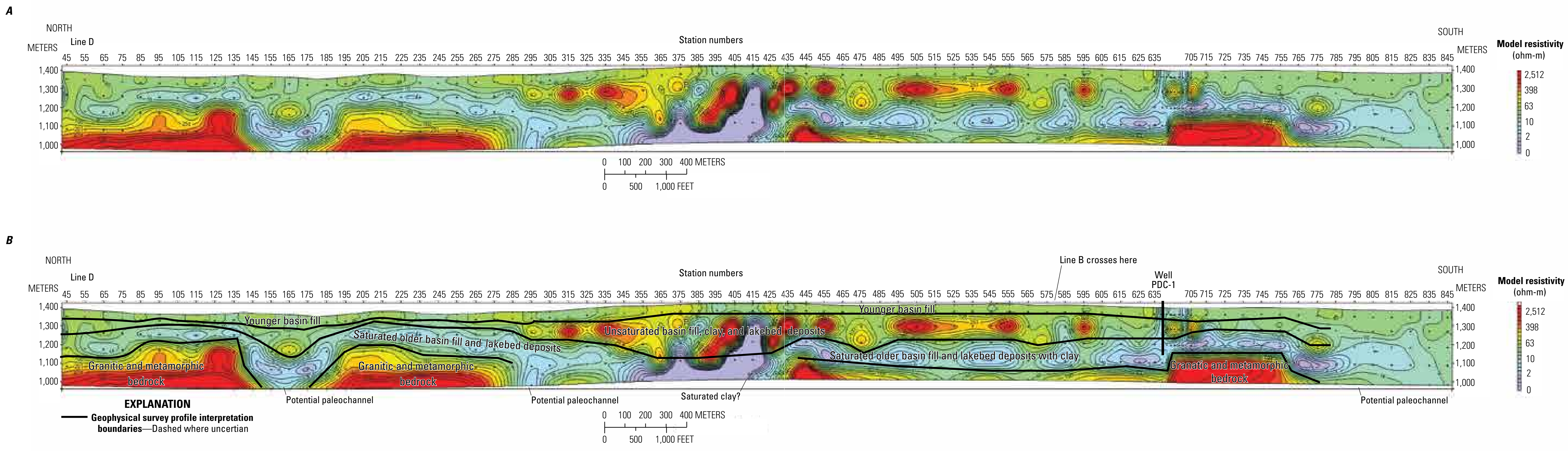
Figure 11. Controlled source audio-frequency magnetotelluric (CSAMT) survey profiles (lines C1 and C2) from the Hualapai Reservation, Arizona. *A*, CSAMT line C2 profile; *B*, CSAMT line C2 profile with interpretations; *C*, CSAMT line C1 profile; *D*, CSAMT line C1 profile with interpretations; and *E*, map showing location of CSAMT line C1 and C2. ohm-m, ohm-meter.

rising steeply out of what could be the north end of the paleochannel suggested at the north end of line C1. Additional CSAMT data collection in this area would be needed to better define this potential paleochannel and characterize its connectivity to perched water-bearing zones just to the northwest of the Truxton Basin on the southern Hualapai Plateau. Development of a test well would also provide depth-to-water information and an estimate of the underflow that could be present.

The majority of line C1, between electrode stations 275 and 815, has four layers. The first layer is moderately resistive, 20 to 40 ohm-m (green), and is located from 1,420 m to about 1,300 m altitude (4,659 to 4,265 ft; fig. 11*D*). This layer correlates to the uppermost, younger basin-fill sediments and unconsolidated alluvium. The second layer has moderate to high resistivity, greater than 10 ohm-m (green and yellow to red), and is found from an altitude of 1,300 to almost 1,200 m (4,265 to 3,937 ft; fig. 11*D*). This layer appears to be the dry clay and younger basin-fill sediments found throughout the Truxton basin. The third layer has a much lower resistivity, 5 to 40 ohm-m (blue to green), and is found from an altitude of about 1,200 to 1,100 m (3,937 to 3,609 ft; fig. 11*D*). The third layer is consistent with saturated, older basin-fill sediments, in some cases with moderate amounts of clay. The fourth layer is highly resistive, greater than 100 ohm-m (yellow to red), and is found at depths greater than 1,100 m (3,609 ft) altitude along the bottom of most of line C1 (fig. 11*D*). The fourth layer represents the granitic and metamorphic bedrock at the bottom of the Truxton basin. Paleochannels are indicated in line C1 at about electrode stations 250 and 650, where highly conductive material (blue and green) is imaged extending beyond the bottom of the profile. The inversion of line C2 to the north of line C1 differentiated three layers, consistent with the image of line C1 to the south. The first layer is moderately resistive, 40 to greater than 250 ohm-m (green to orange), and is found from 1,400 to about 1,200 m altitude (4,593 to 3,937 ft; fig. 11*B*). This layer consists of undifferentiated, young channel alluvium found at the north end of line C2 mixed with the younger basin-fill sediments. The potentially saturated, older basin-fill sediments are imaged as a low resistivity layer, 4 to 20 ohm-m (blue to green), from 1,350 to 1,060 m altitude (4,430 to 3,480 ft); this layer slopes to the north (fig. 11*B*). The resistivity and inversion of this layer on line C2 is similar to that of older basin-fill sediments imaged in line C1.

Controlled Source Audio-Frequency Magnetotellurics Line D

CSAMT line D is a north-to-south transect about 7.5 km (4.66 mi) long, parallel to and about 3 km (1.86 mi) east of CSAMT line C (fig. 12*C*). Inversion results from line D are similar to lines A, B, and C, but there are some irregularities.



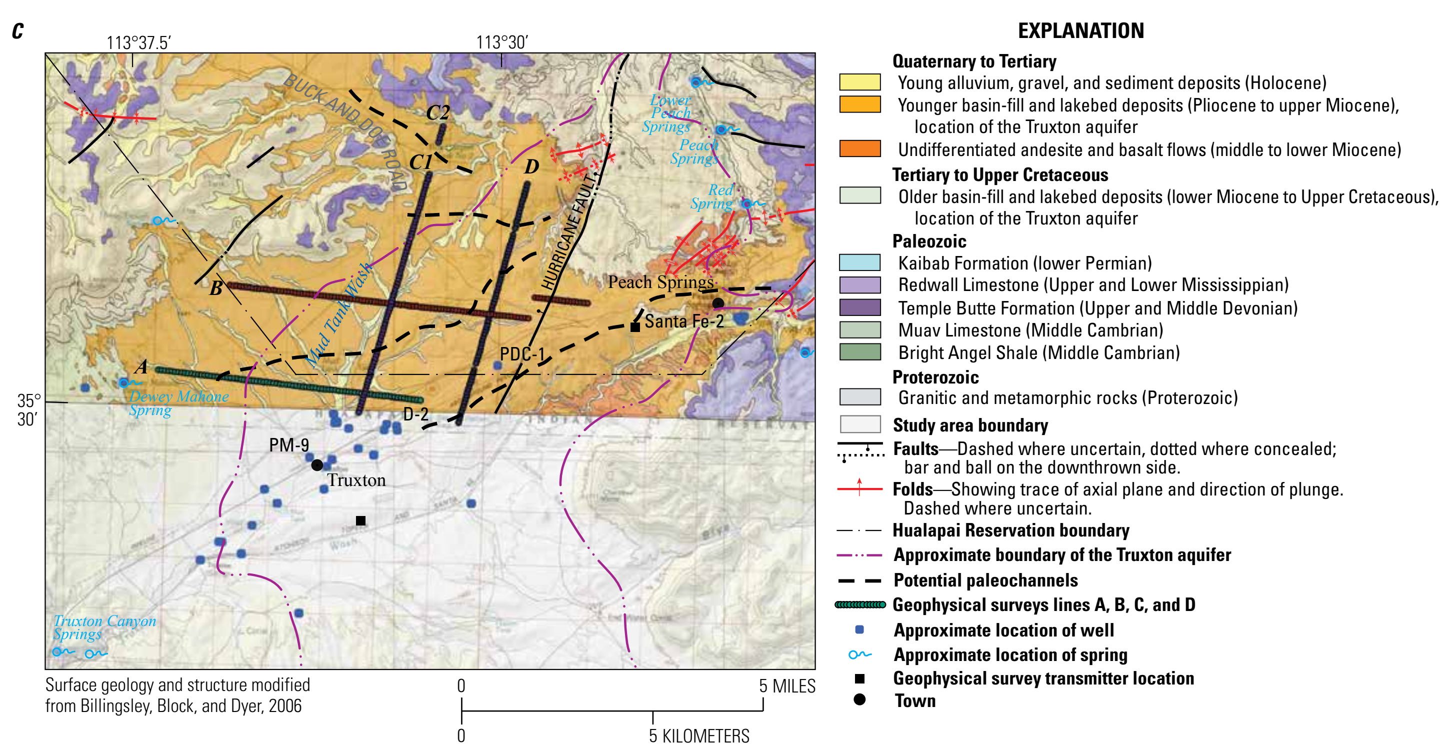


Figure 12. Controlled source audio-frequency magnetotelluric (CSAMT) survey profile (line D) from the Hualapai Reservation, Arizona. *A*, CSAMT line D profile; *B*, CSAMT line D profile with interpretations; and *C*, map showing location of CSAMT line D. ohm-m, ohm-meter.

There are four layers in line D; the first layer is found from an altitude of 1,420 to about 1,300 m (4,659 to 4,265 ft). This layer is moderately resistive at 20 to 40 ohm-m (green, fig. 12*A*). As with the other survey lines, this layer correlated to the upper alluvial sediments and younger basin-fill sediments (fig. 12*B*). The second layer is resistive, greater than 100 ohm-m (yellow to red), and is found from 1,300 to almost 1,200 m in altitude (4,265 to 3,937 ft; fig. 12*B*). This layer correlates to the older and younger basin-fill sediments found throughout this part of the Truxton basin, as imaged by lines A–C. The third layer is highly conductive with low resistivity (5 to 40 ohm-m, blue to green) and is found from about 1,200 to 1,100 m (3,937 to 3,609 ft) in altitude (fig. 12*A*). The third layer represents the saturated parts of the older basin-fill sediments that contain no to moderate amounts of clay (fig. 12*B*). The fourth layer is highly resistive, greater than 100 ohm-m (yellow to red), and found at depths greater than 1,100 m (3,609 ft) in altitude (fig. 12*B*). The fourth layer correlated to the granitic and metamorphic bedrock at the bottom of the Truxton basin and is consistent with the same material imaged in lines A–C. Similar to the other surveyed lines, several paleochannels are imaged on line D. These are centered on electrode stations 165, 295, and 815 (fig. 12*B*). At all of these sites, the lower bedrock layer can be interpreted as sloping steeply into a channel of saturated, older basin-fill sediments that extend beyond the depth of the survey. In the center of the section, from electrode station 365 to 425, there is an area of very low resistivity, 5 ohm-m or less (blue), interspersed with higher resistivity (fig. 12*A* and *B*). This could be an area of thick, saturated clay interfering with the signal returns.

The results from inversion models of the four CSAMT surveys indicate an average saturated thickness of the Truxton aquifer on the Hualapai Reservation of about 100 m (328 ft), calculated as an average of the saturated, older basin-fill sediments from all four survey lines. Comparison with well-log information indicates that average saturated thickness can vary by 20 percent resulting in a range of from 80 to 120 meters (262 to 394 ft). The CSAMT data verify the presence of a number of paleochannels in the Truxton basin on the reservation that extend deep into the underlying granite bedrock (fig. 12*C*). The saturated thickness of the Truxton aquifer will be much thicker in these paleochannels than the average calculated for the rest of the aquifer from the survey. The saturated thickness of Truxton aquifer to the east of the Hurricane Fault is thinner as shown in figure 10 and is dry in the area along Truxton Wash at the community of Peach Springs, as indicated by the railroad wells (appendix). However, because Red Spring at the upper end of Peach Springs Wash and at least a part of the flow to Peach Springs both discharge from older basin-fill sediments, the Truxton aquifer east of the Hurricane Fault and north of the community of Peach Springs is at least partially saturated in places. It is also reasonable to expect that the saturated thickness of the Truxton aquifer south of the Hualapai Reservation could also be thicker or thinner based on the erosional character of this part of the basin basement rocks.

Estimated Storage and Generalized Water Budget

The areal extent of the Truxton aquifer on the Hualapai Reservation, estimated by digitizing the aquifer area shown on figures 1 and 3 using tools in a geographic information system, was estimated to be 32,000 acres. Some parts of the CSAMT profiles indicated areas where granitic and metamorphic bedrock were 100 ft or less below land surface, whereas in other parts of the CSAMT profiles, depth to bedrock was greater than the 1,300-ft profile depth. One well, PDC-1, has a total depth of 855 ft, a static water level of 532 ft, and did not penetrate granite (fig. 8*A*). This well correlated to CSAMT line D (fig. 12*B*) in an area where bedrock is absent at the depth of the survey (about 1,300 ft). These data are consistent with the description of the Truxton Valley as an erosional basin with deep paleochannels developed before basin-fill sediments were deposited (Twenter, 1962; Young, 1999; and Billingsley and others, 2006). These paleochannels may represent areas where a significant amount of groundwater storage occurs in the basin. Using the results of the CSAMT surveys and spring and borehole data from the aquifer on the reservation, we assumed the average saturated thickness of the aquifer to be about 330 ft with an estimated uncertainty of 20 percent (range from 260 to 390 ft).

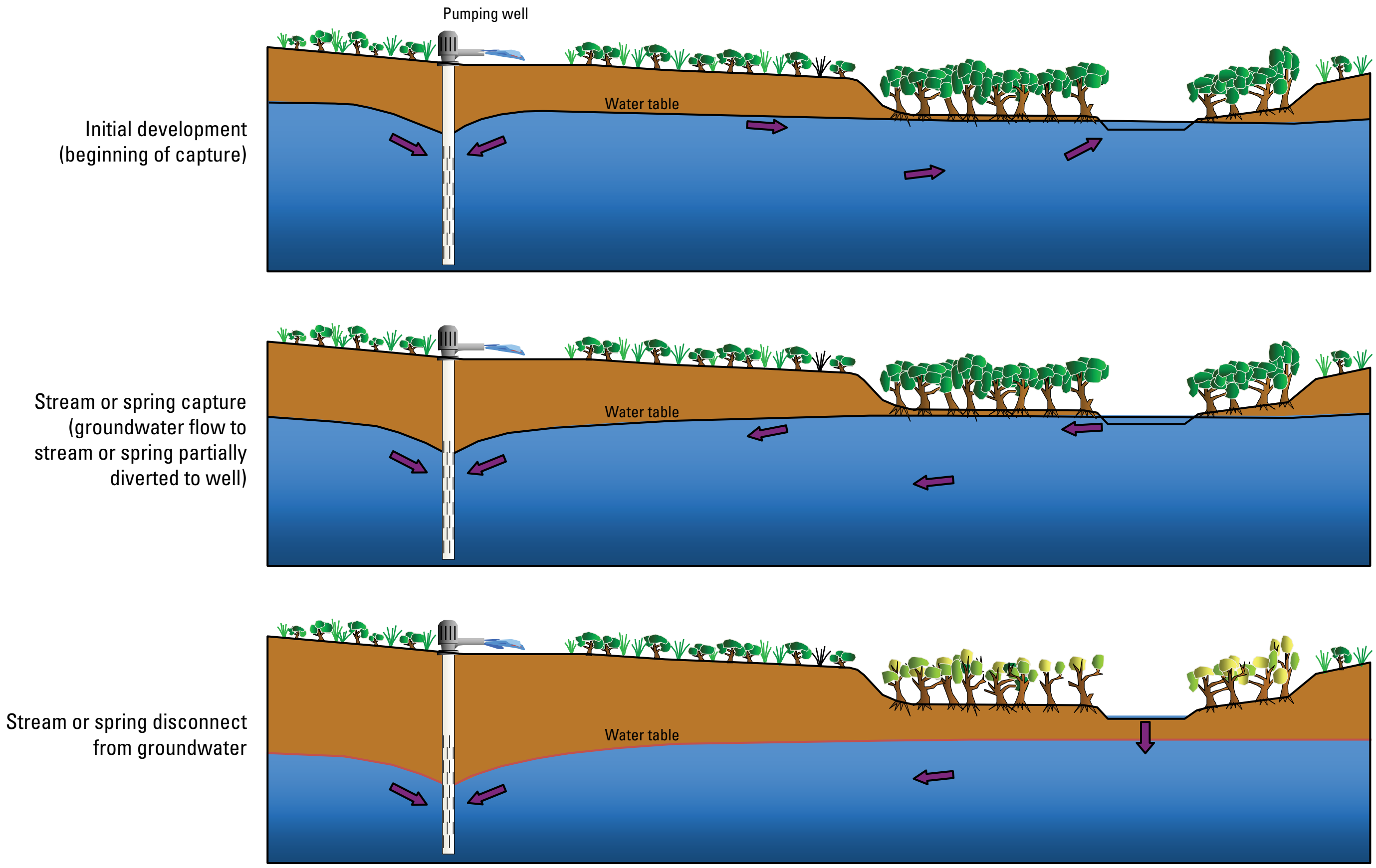
A range of values was used for specific yield as a conservative approach to estimating storage. The upper end of the range is 0.15, as suggested by NRCE, based on porosity estimates of typical basin-fill material—sand, gravel, and cobbles (Natural Resources Consulting Engineers, 2011). On review of available driller’s logs, however, it was noted that a number of drillers indicated low to moderate clay content in the older, saturated sediments, which would indicate higher porosity but a lower specific yield. Basin aquifers in adjacent areas with similar lithology—clay mixed with sand, gravel, and cobbles—typically use specific yields of 0.05 to 0.30 to estimate groundwater storage (Freethey and others, 1986; Truini and others, 2013; Tillman and others, 2011). Based on the presence of clays in the saturated older basin-fill of the Truxton aquifer on the Hualapai Reservation, a more conservative range of specific yield of 0.05 to 0.075 was used in the storage estimate.

Groundwater-storage potential of the Truxton aquifer on the Hualapai Reservation, based on values of area, saturation thickness, and specific yield, was estimated to be between 420,000 and 940,000 acre-ft. These estimates do not include groundwater storage in the aquifer outside the Hualapai Reservation boundary. Also, this calculation of estimated storage in the Truxton aquifer on the Hualapai Reservation does not determine nor indicate the availability and sustainability of that groundwater as a long-term resource. This groundwater-storage estimate, although greater than past estimates, compares with similar values determined by previous studies (Twenter 1962; Indian Health Service, 1976; and Devlin 1976).

The amount of aquifer storage is independent of the long-term water-resource sustainability of the aquifer (Barlow and Leake, 2012). In an aquifer in steady-state condition, without pumping, recharge from precipitation is balanced by discharge to evapotranspiration, streams, and springs (fig. 7*A*). When pumping is introduced, the amount of groundwater pumped is eventually balanced by a reduction in aquifer discharge to streams and springs, and the uptake of groundwater by plants, regardless of the amount of groundwater in storage (fig. 7*B*; Barlow and Leake, 2012). Inflow and outflow components of groundwater-flow systems—recharge from infiltration, runoff from streams, underflow from areas adjacent to the aquifer, discharge from the aquifer to springs and streams, evapotranspiration, and groundwater withdrawals—add complexity to and affect the overall sustainability of aquifers both temporally and spatially. When all of these elements are combined, a generalized water budget for the aquifer can be developed. However, the degree of uncertainty increases significantly when just considering sustainability of one part of the aquifer.

This study evaluated groundwater storage for the 20 percent of the Truxton aquifer underlying the Hualapai Reservation. Groundwater in the Truxton aquifer underlying the Hualapai Reservation is hydraulically connected to and responds to groundwater-level changes in the remaining 80 percent of the aquifer south of the reservation. As groundwater levels decline to the south of the reservation, groundwater levels and discharge to springs would likely decline on the reservation and vice versa. The schematic drawing in figure 13 illustrates this concept. ADWR indicated that water-level declines in observation wells to the south of the reservation measured from 1990 to 2004 were from 1 to 15 ft (Arizona Department of Water Resources, 2009). Table 1-1 shows water-level changes in monitored wells both on and off the reservation from +75 to −23 ft, with most monitored sites in the +4.0 to −11 ft range. Model scenarios by NRCE for wells on the reservation projected as much as 7 to 8 ft of decline by 2050, more than 1 mi away from individual wells, owing to pumping alone (Natural Resources Consulting Engineers, 2011). Less recharge from precipitation is another factor that could contribute to declining water levels. Direct evidence for a drying climate trend in the historical record is sparse, because the two reporting meteorological stations on the reservation have been discontinued. However, Hereford and others (2002) showed that the western part of the Colorado Plateau that includes the Hualapai Reservation is being affected by the ongoing early 21st century drought. The Hualapai Water Resources Program (1999, 2004, and 2009) showed that there is a correlation of greater and lesser spring discharge during wetter and dryer years in other parts of the reservation.

A water budget can be a useful tool to account for the human activities on groundwater-flow systems. One factor common to all aquifers is that the total amount of water entering, leaving, and stored in a system must be conserved (Alley and others, 1999).



Groundwater withdrawal rates, distance in feet or miles, and changing lithology affect timing of capture. Arrows indicate generalized groundwater flow directions.

Figure 13. Generalized illustration showing the effects of groundwater development on aquifer storage (modified from Barlow and Leake, 2010).

Theis (1940) concluded that “all water discharged by wells is balanced by a loss of water somewhere. This loss is always to some extent and in many cases largely from storage in an aquifer.” Theis goes on to note that “after sufficient time has elapsed . . . further discharge from wells will be made up in part by a [sic; “decline”] in natural discharge.” Konikow and Leake (2014) continued to refine these concepts by characterizing how “capture” must be recognized as a crucial factor in assessing water budgets, groundwater-storage depletion, and sustainability of groundwater development.

Table 2 shows a generalized water budget from the entire Truxton aquifer representing two conditions—predevelopment (pre-1975) and postdevelopment (2011). Water budgets from several other reports that describe basin or watershed conditions are provided for comparison (Freethey and Anderson, 1986; Arizona Department of Water Resources, 2009; Natural Resources Consulting Engineers, 2011; Tillman and others, 2011). The ADWR (Arizona Department of Water Resources, 2009) and Tillman and others (2011) data have been reduced by about 27 percent to be comparable with the part of the Truxton basin in the Peach Springs Basin for which those reports apply.

When the aquifer was in near equilibrium, predevelopment (pre-1975), the inflows and outflows were about 295 acre-ft annually. Minimal amounts of groundwater withdrawals (estimated as less than 10 acre-ft/yr) began in the early 1900s to support the railroad and the community of Peach Springs and did not increase until after 1975. At the southwest end of the basin, the aquifer thins to extinction against impermeable granite at an altitude of about 4,040 ft, resulting in groundwater in that part of the basin discharging to springs in Truxton Canyon. In the northeast part of the basin, Peach Springs and Lower Peach Springs discharge to Peach Springs Canyon at altitudes of 4,230 and 3,960 ft respectively. Near the community of Peach Springs, underflow into the Truxton aquifer can be inferred from the general relation of the Truxton basin sediments on-lapping Paleozoic sediments to the southeast of the community of Peach Springs and to the northwest along the Buck and Doe Road where paleochannels are incised into the Paleozoic rocks (figs. 3 and 11). Because sediments of the Truxton basin directly overlap water-bearing parts of the Paleozoic rocks to the north and east, it is possible for these two aquifers to be in hydrologic contact. That would allow for underflow from the partly saturated Paleozoic rocks to flow into the Truxton aquifer. By rearranging the water budget to calculate underflow as the sum of all the other components in equation 4, we estimated underflow as about 155 acre-ft annually to the part of the Truxton aquifer on the Hualapai Reservation (table 2).

The 2011 calendar year was selected as representative of a postdevelopment period for the Truxton aquifer from 2006 to 2014. Inflow data are consistent with that used for predevelopment conditions and result in a total inflow of about 295 acre-ft/yr. Groundwater withdrawals calculated by HDNR were added to the outflow components, resulting in a total outflow of 585 acre-ft/yr (Hualapai Department of Natural Resources, 2015). This is consistent with data reported by NRCE, showing two to five times greater drawdown potential locally around the Hualapai supply wells (Natural Resources Consulting Engineers, 2011).

Evaluating Future Groundwater Conditions

Figure 13 is a generalized schematic representation of a groundwater-flow system similar to the Truxton aquifer on the Hualapai Reservation and in areas adjacent to the reservation. In a predevelopment condition, groundwater is recharged throughout the basin with most of the recharge occurring in upland areas. Groundwater moves from these high-elevation recharge areas to low-elevation discharge areas represented by the stream channel in figure 13, not unlike Peach Springs Wash at the northeast end of the Truxton basin and Truxton Wash at the southwest end of the Truxton basin. As a well in the schematic basin described in figure 13, which represents the Truxton basin, is developed and pumped, some of the groundwater flow is directed toward the pumping well(s), resulting in declining groundwater levels. As well(s) in the Truxton basin continue to pump and more wells are developed both on and off reservation, some of the groundwater flow that supports discharge in spring or stream areas is captured, as shown by the schematic on figure 13. As pumping continues, aquifer-wide drawdown results in springs and perennial streams being decoupled from groundwater flow as groundwater storage declines. This process will occur regardless of the natural recharge occurring in the system, as figure 7 illustrated. Future study of the entire Truxton aquifer by use of the same methods applied in this study will lead to a greater understanding of the impacts of development and sustainability of the Truxton aquifer both on and off the reservation.

As the Hualapai Tribe and other water users adjacent to the reservation continue to develop new wells, the new well information is likely to improve and potentially change the conceptual model of the entire Truxton aquifer. Such new well data could facilitate development of a depth to water map of the entire Truxton aquifer, both on and off the reservation. Such a water-level map would help refine the accuracy of the saturated thickness estimate and groundwater-storage estimate for the aquifer. Water-level data from additional observation wells in the Truxton aquifer would also provide a better understanding of the spatial and temporal variability of the flow system. The collection of time-lapse gravity data could provide refined specific-yield estimates, in addition to those available from well pumping tests. Collection of CSAMT data for this study was very effective in characterizing the depth to bedrock and saturated zones along survey lines. The next step would be to extend this type of ground-based geophysics and the use airborne electromagnetic surveys to characterize the rest of the Truxton basin and aquifer in areas adjacent to the reservation. With the more complete data, these surveys could provide depth to bedrock, and saturated thickness maps can be developed for the entire Truxton aquifer.

Finally, development of a groundwater-flow model can be useful for further evaluation of the hydrogeologic framework and the effect of new water wells on groundwater discharge to streams and springs. By comparing a groundwater model to the real-world system, a better understanding of the entire Truxton aquifer can be achieved. The groundwater-flow model can then be used to better evaluate aquifer sustainability in response to a number of natural and human-caused stresses.

Summary

The Truxton aquifer is an unconfined groundwater-flow system located in Tertiary to Quaternary age unconsolidated to semiconsolidated basin-fill sediment deposits in the Truxton basin, one of several structural basins located in the western part of Arizona. The aquifer supports groundwater discharge from a few springs at the margins of the Truxton basin and the intermittent base flow of Truxton Wash, where it passes through Truxton Canyon at the west end of the basin. These springs include Peach Springs and Lower Peach Springs to the northeast and Truxton Spring to the southwest. Throughout the 20th century, groundwater use from this aquifer has been minor, consisting mostly of small community public supply, domestic, agricultural, and limited industrial uses (railroad). The northern part of the Truxton aquifer underlies the southern part of the Hualapai Reservation and is the main source of water supply for the tribal community of Peach Springs. The aquifer also provides some livestock water for this part of the reservation. Increase in water use from the Truxton aquifer is attributed to a slow but steady increase in population both on and off the reservation and increasing agricultural use in the western part of the Truxton basin off of the reservation. The increases in water use have resulted in small but measurable groundwater-level declines in observation wells of a few feet per year. This has raised some concern on the part or the Hualapai Tribe about the availability, storage, and sustainability of the Truxton aquifer to meet the long-term water supply needs for the community of Peach Springs and the southern part of the reservation.

Currently, three wells developed in the Truxton aquifer and the recently redeveloped Peach Springs are the main source of water supply for the community of Peach Springs. The most recent water-use information from 2011 indicate that the community of Peach Springs and surrounding area

Table 2. Generalized annual water budget for the Truxton aquifer on the Hualapai Reservation, Arizona, in acre-feet.

[acre-ft/yr, acre-feet per year; ADWR, Arizona Department of Water Resources; NRCE, Natural Resources Consulting Engineers; E, estimate; --, no data]

This study			Other studies			
Water-budget components	Inflow to aquifer (acre-ft/yr)	Outflow from aquifer (acre-ft/yr)	Freethey and Anderson, 1986, Peach Springs Basin[1] (acre-ft/yr)	ADWR, 2009, Truxton Basin, estimated as 27 percent of the Peach Springs Basin (acre-ft/yr)	NRCE, 2011, Truxton Basin (acre-ft/yr)	Tillman and others, 2011, Truxton Basin, estimated as 27 percent of the Peach Springs Basin (acre-ft/yr)
Predevelopment (pre-1975)						
Recharge from infiltration	120[2]	--	4,000[3]	119[2]	--	600[2]
Recharge from streams	20	--	0	1,330	0	400
Underflow from adjacent areas	155 E[4]	--	0	0	--	300
Total inflow	295	--	4,000	1,449	9,800	1,300
Baseflow discharge to streams and springs northward into Peach Springs Canyon	--	110	--	193	142	--
Evapotransporation	--	65[2]	--	660	--	324
Groundwater withdrawals	--	>10 E[5]	--	750	--	<300
Underflow south of the reservation boundary estimated as about 20 percent of the discharge from Truxton Canyon Springs	--	110 E	0	0	--	0
Total outflow	--	295 E	4,000	1,603	--	--
Postdevelopment (2011)						
Recharge from infiltration	120[2]	--	--	--	--	--
Recharge from streams	20	--	--	--	--	--
Underflow from adjacent areas	155 E[4]	--	--	--	--	--
Total inflow	295	--	--	--	--	--
Baseflow discharge to streams and springs northward into Peach Springs Canyon	--	110	--	--	--	--
Evapotransporation	--	65[2]	--	--	--	--
Groundwater withdrawals	--	300[6]	--	--	--	400
Underflow south of the reservation boundary estimated as about 20 percent of the discharge from Truxton Canyon Springs	--	110 E	--	--	--	--
Total outflow	--	585	--	--	--	--

[1] Values obtained from unpublished tabular data. Plates in report show only qualitative ranges of values.
[2] Product of Basin Characterization Model (Flint and Flint, 2007 a,b).
[3] Estimated from precipitation recharge relationship.
[4] Calculated as the sum of inflows and outflows for pre-development conditions.
[5] U.S. Geological Survey data pre-1975.
[6] Hualapai Department of Natural Resources, 2015.

are using about 300 acre-ft per year (acre-ft/yr, table 2). The HDNR has estimated water demand to increase to about 780 acre-ft/yr by 2050 for the Truxton and Peach Springs Basins on reservation lands (Hualapai Department of Natural Resources, 2015).

The physical characteristics of the Truxton aquifer are not well known. Before this study, the depth to bedrock and the thickness of the Truxton basin were known in only a few locations where water wells penetrated to bedrock at varying depths. To develop a better understanding of the groundwater-storage potential of the Truxton aquifer on the Hualapai Reservation, this study used CSAMT surveys to evaluate the depth to bedrock and the thickness of the Truxton aquifer. The surveys included four profile lines—two north-south and two east-west lines. Results of the CSAMT surveys indicated that the depth to bedrock along the survey lines varies from less than 100 ft to more than 1,300 ft, the maximum depth of the survey profiles. This is consistent with the erosional character of the Truxton basin; deep paleochannels characterize the deeper parts of the basin. Lithologic log data from wells projected into the CSAMT profiles compare well with the geophysical survey results. The estimated average saturated thickness of the Truxton aquifer on the reservation is about 330 ft (with an estimated range of 260 to 390 ft), based on both CSAMT results and the depth to water in wells. The saturated thickness might be greater in parts of the Truxton aquifer where paleochannels are incised into the bedrock underlying the basin-fill sediments.

Groundwater storage of the Truxton aquifer on the Hualapai Reservation was calculated as the product of the surface area of the aquifer, the saturated thickness, and an estimate of the specific yield of the aquifer. The surface area of the Truxton aquifer on the Hualapai Reservation was determined to be about 32,000 acres. In unconfined aquifers, the specific yield is the amount of water that will drain from an aquifer under the force of gravity. The specific yield of aquifers in groundwater basins adjacent to the Truxton aquifer ranges from 0.05 to 0.3 (5 to 30 percent), based on the clay, sand, and gravel content of rock units that contain the aquifers in these areas. A specific yield of 0.15 has only been determined for one pumping well in the Truxton aquifer. However, evaluation of lithologic logs in the Truxton aquifer indicates a significant clay component to the saturated thickness part of the aquifer. Specific yields of 0.05 and 0.075 were used in groundwater-storage calculations to accommodate moderate to high clay content found in the basin-fill sediments. The resulting groundwater-storage estimates of the Truxton aquifer on the Hualapai Reservation range from about 420,000 to 940,000 acre-ft, and do not include groundwater storage in the aquifer outside the Hualapai Reservation boundary nor indicate the availability and sustainability of that groundwater as a long-term resource.

The amount of groundwater in storage in an aquifer is not the only component of a groundwater-flow system that affects its availability. As discussed in past reports on the Truxton aquifer, the location of potential wells is crucial to their efficiency and long-term yield as a source of public water supply. Groundwater withdrawals off reservation, seasonal and long-term climate influences, and recharge to and natural discharge from groundwater to springs and streams of the aquifer will also have an effect on the availability and sustainability of groundwater on the reservation.

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Appendix—Well Data for the Truxton Aquifer on the Hualapai Reservation and Adjacent Areas

Table 1-1. Well data on and adjacent to the Southern Hualapai Reservation, Arizona.

[USGS, U.S. Geological Survey; NRCE, Natural Resources Consulting Engineers; ADWR, Arizona Department of Water Resources; ADOT, Arizona Department of Transportation; BIA, Bureau of Indian Affairs; PSC, Peach Springs community; RR, railroad; SEC, section; E, estimated; #, number; NO, number; PM, public municipal. Primary use of water: Z, destroyed; U, unused; S, stock; D, dewatering; N, industrial; P, public supply; K, mining; H, domestic; I, irrigation. Type of finish: F, gravel pack with perforations; P, perforated or slotted; X, open hole. Primary aquifer code and geologic code: 110ALVM, alluvium; 112SDMR, sedimentary rocks; 330RDLL, Redwall Limestone; 374MUAV, Muav Limestone; 400GRNT, Precambrian Granite. NGVD29, National Geodetic Vertical Datum of 1929. --, no information]

Source agency	Local well number	Site identifer	Well name[1]	Date of construction[2]	Primary use of water	Diameter of casing (inches)	Type of finish	Well depth (feet)	Altitude of land surface (feet)	Altitude datum	Water level (feet)	Water level date[2]	Discharge (gallons per minute)	Date discharge measured	Draw-down (feet)	Saturated thickness (feet)	Primary aquifer code	Geologic code
USGS	B-26-10 07DCD	353848113225700	--	--	Z	--	--	--	4,100	NGVD29	--	--	2.0	05–18–1993	--	--	122SDMR	122SDMR
--	B-26-10 07DCD	353848113225700	--	--	Z	--	--	--	--	--	--	--	3.1	06–06–1994	--	--	--	--
NRCE	B-26-11 02ACB	--	--	--	--	--	--	--	3,002	--	--	--	--	--	--	--	--	--
USGS	B-26-11 25ACB	353643113241000	--	--	U	--	--	--	3,670	NGVD29	--	--	1.8	05–18–1993	--	--	374MUAV	374MUAV
--	B-26-11 25ACB	--	--	--	U	--	--	--	--	--	--	--	5.4	06–08–1994	--	--	--	--
NRCE	B-26-11 34DBC		--	--	S	--	--	--	4,048	--	--	--	--	--	--	--	--	--
USGS	B-26-13 11BCC	353912113390200	--	--	Z	--	--	--	3,900	NGVD29	--	--	1,023.0	05–18–1993	--	--	374MUAV	374MUAV
--	B-26-13 11BCC	--	--	--	Z	--	--	--	--	--	--	--	1,023.0	05–18–1993	--	--	--	374MUAV
--	B-26-13 11BCC	--	--	--	Z	--	--	--	--	--	--	--	0.2	06–08–1994	--	--	--	--
USGS	B-26-13 20CCB	353713113421800	--	--	S	--	--	--	4,710	NGVD29	--	--	13.5	08–05–1992	--	--	122SDMR	122SDMR
--	B-26-13 20CCB	--	--	--	S	--	--	--	--	--	--	--	110.0	05–27–1993	--	--	--	--
--	B-26-13 20CCB	--	--	--	S	--	--	--	--	--	--	--	83.5	12–10–1993	--	--	--	--
--	B-26-13 20CCB	--	--	--	S	--	--	--	--	--	--	--	22.5	06–04–1994	--	--	--	--
NRCE	B-25-10 10	--	Tank Well	00-00-1964	--	--	--	82	5,225	--	Dry	--	--	--	--	--	--	--
ADWR	B-25-10 23DAA	--	--	--	D	8	--	--	--	--	--	--	--	--	--	--	--	--
ADWR	B-25-10 26CDA	--	Lime Plant	05–20–1973	N	20		1,652	5,141	--	758.0	--	37.0	--	--	894.0	374MUAV	--
USGS	B-25-10 26CDA	353104113185801	PSC	05–20–1973	N	20	P	1,652	5,150	NGVD29	878.0	09–01–1973	37.2	09–00–1973	--	774.0	--	--
--	B-25-10 26CDA	--	--	--	N	10.75	--	--	--	--	878.0	09-00-1973	--	--	--	--	--	--
--	B-25-10 26CDA	--	--	--	N	--	--	--	--	--	918.0	01–01–1986	--	--	--	--	--	--
--	B-25-10 26CDA	--	--	--	N	--	--	--	--	--	1,462.5	01–14–1986	--	--	--	--	--	--
--	B-25-10 26CDA	--	--	--	N	--	--	--	--	--	917.7	04–29–1986	--	--	--	--	--	--
--	B-25-10 26CDA	--	--	--	N	--	--	--	--	--	928.8	04–22–1987	--	--	--	--	--	--
NRCE	B-25-10 29ACA	--	New Shipley Well	05–01–1972	U	13	--	202	4,967	NGVD29	49.2	--	--	--	--	152.8	374MUAV	--
USGS	B-25-10 29ACA	353134113215501	PSC	01–05–1972	U	13	P	202	4,960	NGVD29	52.6	05–20–1980	--	--	--	149.4	--	--
--	B-25-10 29ACA	--	55-62971	--	U	--	--	--	--	--	44.0	01–01–1986	--	--	--	--	--	--
--	B-25-10 29ACA	--	--	--	U	--	--	--	--	--	44.4	01–14–1986	--	--	--	--	--	--
--	B-25-10 29ACA	--	--	--	U	--	--	--	--	--	46.6	04–22–1987	--	--	--	--	--	--
--	B-25-10 29ACA	--	--	--	U	--	--	--	--	--	--	--	--	--	--	--	--	--
NRCE	B-25-10 29BBD1	--	Grand Canyon Caverns	--	P	16	--	--	4,947	--	192.3	--	--	--	--	--	374MUAV	--
USGS	B-25-10 29BBD1	353135113222601	Shipley Well	--	P	16	--	--	4,950	NGVD29	188.0	09–24–1980	--	--	--	--	--	--
--	B-25-10 29BBD1	--	PSC	--	P	14	--	--	--	--	186.9	06–12–1984	--	--	--	--	--	--
--	B-25-10 29BBD1	--	55-627216	--	P	--	--	--	--	--	184.8	01–14–1986	--	--	--	--	--	--
--	B-25-10 29BBD1	--	--	--	P	--	--	--	--	--	188.8	04–22–1987	--	--	--	--	--	--
--	B-25-10 29BBD1	--	--	--	P	--	--	--	--	--	--	--	--	--	--	--	--	--
--	B-25-10 29BBD1	--	--	--	P	--	--	--	--	--	--	--	--	--	--	--	--	--
NRCE	B-25-10 29BBD2	--	Shipley Well	--	S	8	--	851	4,977	--	103.0	--	--	--	--	748.0	374MUAV	--
NRCE	B-25-10 35BBB	--	Nelson Well	00-00-1948	K	--	--	1,043	5,111	--	451.3	--	10 E	--	--	591.7	374MUAV	--

Table 1-1.—Continued

Source agency	Local well number	Site identifer	Well name[1]	Date of construction[2]	Primary use of water	Diameter of casing (inches)	Type of finish	Well depth (feet)	Altitude of land surface (feet)	Altitude datum	Water level (feet)	Water level date[2]	Discharge (gallons per minute)	Date discharge measured	Draw-down (feet)	Saturated thickness (feet)	Primary aquifer code	Geologic code
USGS	B-25-10 35BBB	353035113192201	PSC	--	K	--	--	1,043	5,115	NGVD29	460.0	01–01–1986	--	--	--	583.0	--	--
--	B-25-10 35BBB	--	55-627216	--	K	--	--	--	--	--	460.5	01–14–1986	--	--	--	--	--	--
--	B-25-10 35BBB	--	--	--	K	--	--	--	--	--	471.2	04–22–1987	--	--	--	--	--	--
--	B-25-10 35BBB	--	--	--	K	--	--	--	--	--	--	--	--	--	--	--	--	--
--	B-25-10 35BBB	--	--	--	K	--	--	--	--	--	--	--	--	--	--	--	--	--
ADWR	B-25-11 02CBC	--	Peach Springs (BIA#1)	06–10–1982	--	336	--	16	--	--	0.0	--	--	--	--	16.0	374MUAV	--
USGS	B-25-11 02CBC	353444113254901	PSC	--	S	--	--	--	4,230	NGVD29	--	--	70.2	06–15–1984	--	--	--	--
--	B-25-11 02CBC	--	55-627229	--	S	--	--	--	--	--	--	--	--	--	--	--	--	--
--	B-25-11 02CBC	--	--	--	S	--	--	--	--	--	--	--	--	--	--	--	--	--
--	B-25-11 02CBC	--	--	--	S	--	--	--	--	--	--	--	--	--	--	--	--	--
--	B-25-11 02CBC	--	--	--	S	--	--	--	--	--	--	--	--	--	--	--	--	--
USGS	B-25-11 03DAA	353445113255000	--	--	P	--	--	--	4,210	NGVD29	--	--	76.0	05–27–1993	--	--	122SDMR	122SDMR
--	B-25-11 03DAA	--	--	--	P	--	--	--	--	--	--	--	49.0	03–31–1995	--	--	--	--
--	B-25-11 03DAA	--	--	--	P	--	--	--	--	--	--	--	28.0	11–19–1993	--	--	--	--
--	B-25-11 03DAA	--	--	--	P	--	--	--	--	--	--	--	85.0	06–04–1994	--	--	--	--
NRCE	B-25-11 03DAD	--	--	--	S	--	--	--	4,239	--	--	--	--	--	--	--	--	--
USGS	B-25-11 14BAA	353333113251801	PSC	--	S	--	--	--	4,540	NGVD29	--	--	0.3	06–15–1984	--	--	110ALVM	110ALVM
--	B-25-11 14BAA	--	--	--	S	--	--	--	--	--	--	--	0.6	03–29–1995	--	--	--	--
--	B-25-11 14BAA	--	--	--	S	--	--	--	--	--	--	--	--	--	--	--	--	--
--	B-25-11 14BAA	--	--	--	S	--	--	--	--	--	--	--	--	--	--	--	--	--
ADWR	B-25-11 25DBD	--	--	--	--	--	--	--	5,216	--	--	--	--	--	--	--	--	--
USGS	B-25-11 25DBD	353109113240201	PSC	--	U	--	--	--	5,120	NGVD29	--	--	0.1	09–24–1980	--	--	330RDLL	330RDLL
--	B-25-11 25DBD	--	--	--	U	--	--	--	--	--	--	--	4.0	08–06–1992	--	--	--	--
--	B-25-11 25DBD	--	--	--	U	--	--	--	--	--	--	--	1.0	12–10–1993	--	--	--	--
--	B-25-11 25DBD	--	--	--	U	--	--	--	--	--	--	--	1.0	06–28–1994	--	--	--	--
--	B-25-11 25DBD	--	--	--	U	--	--	--	--	--	--	--	0.3	03–29–1995	--	--	--	--
NRCE	B-25-11 26B	--	Santa Fe#4	00-00-1917	Z	--	--	992	4,787	--	420.0	--	6.0	--	--	572.0	374MUAV	--
NRCE	B-25-11 26B	--	Santa Fe#2	00-00-1907	Z	--	--	1,013	4,789	--	402.0	--	--	--	--	611.0	374MUAV	--
NRCE	B-25-11 26B	--	Santa Fe#6	00-00-1925	Z	--	--	836	4,800	--	410.0	--	--	--	--	426.0	374MUAV	--
NRCE	B-25-11-26AAB	--	Santa Fe#3	00-00-1913	U	12	--	1,003	4,800	--	410.0	--	34.0	--	--	593.0	374MUAV	--
USGS	B-25-11 26BAA	353141113251901	PSC	--	K	14	--	350	4,800	NGVD29	--	--	--	--	--	--	--	--
--	B-25-11 26BAA	--	55-627228	--	K	--	--	--	--	--	--	--	--	--	--	--	--	--
--	B-25-11 26BAA	--	--	--	K	--	--	--	--	--	--	--	--	--	--	--	--	--
--	B-25-11 26BAA	--	--	--	K	--	--	--	--	--	--	--	--	--	--	--	--	--
--	B-25-11 26BAA	--	--	--	K	--	--	--	--	--	--	--	--	--	--	--	--	--
USGS	B-25-11 26BAD	353137113252001	Santa Fe#1	00-00-1903	P	6	--	924	4,795	NGVD29	337.1	09–24–1980	25 and 34	--	--	586.9	374MUAV	--
--	B-25-11 26BAD	--	PSC	--	P	--	--	--	--	--	271.8	06–15–1984	--	--	--	--	--	--
--	B-25-11 26BAD	--	55-627227	--	P	--	--	--	--	--	272.0	01–01–1986	--	--	--	--	--	--
--	B-25-11 26BAD	--	--	--	P	--	--	--	--	--	272.4	01–14–1986	--	--	--	--	--	--
--	B-25-11 26BAD	--	--	--	P	--	--	--	--	--	262.3	04–22–1987	--	--	--	--	--	--
NRCE	B-25-11 26BAD	--	Santa Fe#5	00-00-1923	S	6	--	851	4,787	--	300.0	--	40.0	--	--	551.0	374MUAV	--

Table 1-1.—Continued

Source agency	Local well number	Site identifer	Well name[1]	Date of construction[2]	Primary use of water	Diameter of casing (inches)	Type of finish	Well depth (feet)	Altitude of land surface (feet)	Altitude datum	Water level (feet)	Water level date[2]	Discharge (gallons per minute)	Date discharge measured	Draw-down (feet)	Saturated thickness (feet)	Primary aquifer code	Geologic code
ADWR	B-25-11 31BBB	--	Truxton Well PCD-1	01-01-1972	U	6 and 10	--	855	4,642	--	532.0	--	--	--	--	323.0	--	--
USGS	B-25-12 36ACB	353044113301701	PSC	00-00-1972	U	10	P	855	4,590	NGVD29	535.4	04–23–1980	60.0	--	213.0	319.6	--	--
--	B-25-12 36ACB	--	--	--	U	--	--	--	--	--	534.1	06–15–1984	--	--	--	--	--	--
--	B-25-12 36ACB	--	--	--	U	--	--	--	--	--	535.0	01–01–1986	--	--	--	--	--	--
--	B-25-12 36ACB	--	--	--	U	--	--	--	--	--	535.1	01–14–1986	--	--	--	--	--	--
--	B-25-12 36ACB	--	--	--	U	--	--	--	--	--	533.9	04–22–1987	--	--	--	--	--	--
--	B-25-12 36ACB	--	--	--	U	--	--	--	--	--	533.7	02–27–1992	--	--	--	--	--	--
--	B-25-12 36ACB	--	--	--	U	--	--	--	--	--	532.2	10–27–1992	--	--	--	--	--	--
--	B-25-12 36ACB	--	--	--	U	--	--	--	--	--	532.9	10–13–1997	--	--	--	--	--	--
ADWR	B-25-13 07ACA	--	55-640822	06–14–1984	H	8	--	34	--	--	1.1	11–08–1995	--	--	--	--	--	--
ADWR	B-25-13 35DC	--	--	01–26–1980	S	8	--	150	4,783	--	8.0	--	5.0	--	--	142.0	--	--
USGS	B-25-13 35DC	353015113382701	SEC 35 WELL	02–26–1980	--	8	X	150	4,780	NGVD29	8.0	01–26–1980	30.2	01–26–1980	--	142.0	--	--
ADWR	B-25-13 36CAC	--	Dewey Mahoney Spring windmill	--	U	72	--	--	--	--	3.0	--	--	--	--	--	--	--
USGS	B-25-13 36CAC	353022113374001		--	U	72	--	--	4,680	NGVD29	3.0	05–20–1980	--	--	--	--	--	--
USGS	B-24-12 02BDC	352944113321601	WELL NO 1	--	P	12	--	--	4,442	NGVD29	329.1	04–23–1987	--	--	--	--	--	--
--	B-24-12 02BDC	--	PSC	--	P	--	--	--	--	--	--	--	--	--	--	--	--	--
--	B-24-12 02BDC	--	--	--	P	--	--	--	--	--	--	--	--	--	--	--	--	--
--	B-24-12 02BDC	--	--	--	P	--	--	--	--	--	--	--	--	--	--	--	--	--
--	B-24-12 02BDC	--	--	--	P	--	--	--	--	--	--	--	--	--	--	--	--	--
NRCE	B-24-12 02CBB	--	D-2-1	01–01–1976	P	8	--	623	4,423	--	332.9	--	119.0	--	--	290.1	--	--
USGS	B-24-12 02CBB	352942113322501	WELL NO 2	01–00–1976	H	8	F	623	4,412	NGVD29	354.3	01–20–1976	119.2	01–20–1976	47.7	268.7	--	--
--	B-24-12 02CBB	--	PSC	--	H	--	--	--	--	--	354.3	01–26–1976	--	--	--	--	--	--
--	B-24-12 02CBB	--	--	--	H	--	--	--	--	--	332.9	04–23–1987	--	--	--	--	--	--
--	B-24-12 02CBB	--	--	--	H	--	--	--	--	--	--	--	--	--	--	--	--	--
--	B-24-12 02CBB	--	--	--	H	--	--	--	--	--	--	--	--	--	--	--	--	--
NRCE	B-24-12 03BCD1	--	--	--	U	6	--	--	4,341	--	254.1	--	--	--	--	--	--	--
USGS	B-24-12 03BCD1	352948113332301	PSC	--	U	6	--	--	4,343	NGVD29	252.0	04–23–1987	--	--	--	--	--	--
--	B-24-12 03BCD1	--	--	--	U	--	--	--	--	--	--	--	--	--	--	--	--	--
--	B-24-12 03BCD1	--	--	--	U	--	--	--	--	--	--	--	--	--	--	--	--	--
--	B-24-12 03BCD1	--	--	--	U	--	--	--	--	--	--	--	--	--	--	--	--	--
ADWR	B-24-12 03BCD2	332947113332301	--	--	P	6	--	--	4,337	--	261.5	--	--	--	--	--	--	--
USGS	B-24-12 03BCD2	352947113332301	PSC	--	P	6	--	104	4,343	NGVD29	--	--	--	--	--	--	--	--
--	B-24-12 03BCD2	--	--	--	P	--	--	--	--	--	--	--	--	--	--	--	--	--
--	B-24-12 03BCD2	--	--	--	P	--	--	--	--	--	--	--	--	--	--	--	--	--
--	B-24-12 03BCD2	--	--	--	P	--	--	--	--	--	--	--	--	--	--	--	--	--
NRCE	B-24-12 03BDC	--	Old Mud Tank Well (PM-9)	00-00-1964	--	12 and 14	--	515	4,347	--	265.0	--	20.0	--	--	250.0	--	--
NRCE	B-24-12 03CAB	--	PDC-2	03-00-1972	S	10.75		397	4,360	--	261.6	--	76.0	--	--	135.4	--	--
USGS	B-24-12 03CAB	352942113330901	PSC	00-00-1972	U	10	P	397	4,357	NGVD29	264.7	03–10–1972	76.2	03–10–1972	53.0	132.3	--	--
--	B-24-12 03CAB	--	--	--	U	10.75		--	--	--	259.1	09–14–1980	--	--	--	--	--	--

Table 1-1.—Continued

Source agency	Local well number	Site identifer	Well name[1]	Date of construction[2]	Primary use of water	Diameter of casing (inches)	Type of finish	Well depth (feet)	Altitude of land surface (feet)	Altitude datum	Water level (feet)	Water level date[2]	Discharge (gallons per minute)	Date discharge measured	Draw-down (feet)	Saturated thickness (feet)	Primary aquifer code	Geologic code
--	B-24-12 03CAB	--	--	--	U	--	--	--	--	--	259.1	09–24–1980	--	--	--	--	--	--
--	B-24-12 03CAB	--	--	--	U	--	--	--	--	--	261.0	01–01–1986	--	--	--	--	--	--
--	B-24-12 03CAB	--	--	--	U	--	--	--	--	--	260.7	01–14–1986	--	--	--	--	--	--
--	B-24-12 03CAB	--	--	--	U	--	--	--	--	--	259.8	04–23–1987	--	--	--	--	--	--
--	B-24-12 03CAB	--	--	--	U	--	--	--	--	--	260.7	10–27–1992	--	--	--	--	--	--
NRCE	B-24-12 03DCC	--	Goldenstien-3	09–23–2004	--	6.5	--	355	4,365	--	259.0	--	40.0	--	--	96.0	--	--
NRCE	B-24-12 03DDD	--	Hatch valley water company	03–20–2012	P	6	--	381	4,406	--	294.0	--	25.0	--	--	87.0	--	--
NRCE	B-24-12 05CBB	--	Mohr and Leap	06–10–1998	--	7	--	510	--	--	360.0	--	16.0	--	--	150.0	--	--
NRCE	B-24-12 05CCB	--	Robinson	03–15–20002	--	--	--	480	--	--	--	--	--	--	--	--	--	--
NRCE	B-24-12 05DDB	--	Dooda	03–11–2002	--	--	--	355	--	--	320.0	--	--	--	--	35.0	--	--
NRCE	B-24-12 05DDB	--	Moore	03–19–2002	--	--	--	405	--	--	370.0	--	--	--	--	35.0	--	--
ADWR	B-24-12 08DAC	--	--	--	U	--	--	--	4,324	--	--	--	--	--	--	--	--	--
USGS	B-24-12 08DAC	352840113344801	--	--	U	--	--	--	4,325	NGVD29	--	--	--	--	--	--	--	--
NRCE	B-24-12 09ABB	--	--	--	--	5	--	430	4,325	--	242.0	--	40.0	--	--	188.0	--	--
ADWR	B-24-12 09ADD	--	--	--	P	--	--	385	4,301	--	222.5	--	--	--	--	162.5	--	--
USGS	B-24-12 09AAD	352904113333401	--	--	P	--	--	385	4,302	NGVD29	225.0	01–01–1986	--	--	--	160.0	--	--
--	B-24-12 09AAD	--	--	--	P	--	--	--	--	--	225.0	01–14–1986	--	--	--	--	--	--
--	B-24-12 09AAD	--	--	--	P	--	--	--	--	--	225.2	04–23–1987	--	--	--	--	--	--
--	B-24-12 09AAD	--	--	--	P	--	--	--	--	--	220.1	10–27–1992	--	--	--	--	--	--
--	B-24-12 09AAD	--	--	--	P	--	--	--	--	--	220.5	10–25–1993	--	--	--	--	--	--
--	B-24-12 09AAD	--	--	--	P	--	--	--	--	--	221.0	10–31–1994	--	--	--	--	--	--
--	B-24-12 09AAD	--	--	--	P	--	--	--	--	--	220.8	11–10–1995	--	--	--	--	--	--
--	B-24-12 09AAD	--	--	--	P	--	--	--	--	--	220.9	10–28–1996	--	--	--	--	--	--
--	B-24-12 09AAD	--	--	--	P	--	--	--	--	--	221.2	10–13–1997	--	--	--	--	--	--
--	B-24-12 09AAD	--	--	--	P	--	--	--	--	--	221.1	10–19–1998	--	--	--	--	--	--
--	B-24-12 09AAD	--	--	--	P	--	--	--	--	--	221.4	10–18–1999	--	--	--	--	--	--
--	B-24-12 09AAD	--	--	--	P	--	--	--	--	--	222.2	10–16–2000	--	--	--	--	--	--
--	B-24-12 09AAD	--	--	--	P	--	--	--	--	--	221.9	10–15–2001	--	--	--	--	--	--
NRCE	B-24-12 09BBB	--	McPherson	09–08–1999	--	7	--	385	--	--	335.0	--	30.0	--	--	50.0	--	--
NRCE	B-24-12 09CCC	--	Goldenstien-1	09–25–2004	--	6.5	--	380	4,300	--	202.0	--	40.0	--	--	178.0	--	--
NRCE	B-24-12 09DAD	--	Chamberlan	09–22–2004	--	5	--	355	4,310	--	213.0	--	--	--	--	142.0	--	--
NRCE	B-24-12 10BBB	--	ADOT	--	U	8	--	--	--	--	--	--	--	--	--	--	--	--
NRCE	B-24-12 12 DCA	--	Robinson	09–01–1973	S	8	--	100	4,449	--	61.7	--	--	--	--	38.3	--	--
USGS	B-24-12 12DCA	352831113303901	PSC	09–01–1973	S	8	P	100	4,445	NGVD29	69.1	04–23–1980	15.2	09-00-1973	--	30.9	--	--
--	B-24-12 12DCA	--	55-614901	--	S	--	--	--	--	--	62.0	12–06–1985	--	--	--	--	--	--
--	B-24-12 12DCA	--	--	--	S	--	--	--	--	--	62.0	01–01–1986	--	--	--	--	--	--
--	B-24-12 12DCA	--	--	--	S	--	--	--	--	--	61.6	04–23–1987	--	--	--	--	--	--
--	B-24-12 12DCA	--	--	--	S	--	--	--	--	--	61.8	10–16–1992	--	--	--	--	--	--
NRCE	B-24-12 02BDC	352944113321601	School	--	P	12	--	--	4,423	--	329.1	--	--	--	--	--	--	--
ADWR	B-24-12 17ACB	--	--	--	U	--	--	--	4,265	--	180.3	--	--	--	--	--	--	--
USGS	B-24-12 17ACB	352804113350201	PSC	--	S	--	--	--	4,261	NGVD29	178.7	04–21–1980	--	--	--	--	--	--

Table 1-1.—Continued

Source agency	Local well number	Site identifer	Well name[1]	Date of construction[2]	Primary use of water	Diameter of casing (inches)	Type of finish	Well depth (feet)	Altitude of land surface (feet)	Altitude datum	Water level (feet)	Water level date[2]	Discharge (gallons per minute)	Date discharge measured	Draw-down (feet)	Saturated thickness (feet)	Primary aquifer code	Geologic code
--	B-24-12 17ACB	--	55-609481	--	S	--	--	--	--	--	178.7	12–06–1985	--	--	--	--	--	--
--	B-24-12 17ACB	--	--	--	S	--	--	--	--	--	179.0	01–01–1986	--	--	--	--	--	--
--	B-24-12 17ACB	--	--	--	S	--	--	--	--	--	178.9	04–23–1987	--	--	--	--	--	--
--	B-24-12 17ACB	--	--	--	S	--	--	--	--	--	180.1	10–26–1992	--	--	--	--	--	--
ADWR	B-24-12 17CBC	--	--	--	U	--	--	440	4,247	--	147.8	--	--	--	--	292.2	--	--
USGS	B-24-12 17CBC	352740113355501	PSC	--	U	--	--	440	4,255	NGVD29	146.9	07–23–1953	--	--	--	293.2	--	--
--	B-24-12 17CBC	--	55-609483	--	U	--	--	--	--	--	146.1	10–05–1954	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	147.5	02–05–1955	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	145.8	11–09–1955	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	147.1	06–19–1956	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	146.2	10–24–1956	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	146.1	05–30–1957	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	146.3	02–22–1958	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	145.6	01–29–1959	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	144.8	03–09–1960	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	145.7	04–19–1961	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	144.9	04–05–1962	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	145.1	02–12–1963	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	144.5	01–28–1965	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	145.4	02–15–1967	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	144.5	01–16–1968	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	144.2	01–25–1969	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	144.0	01–26–1970	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	143.9	03–11–1971	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	143.4	01–31–1972	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	143.6	02–07–1973	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	145.5	02–04–1974	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	143.5	03–27–1975	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	142.9	02–04–1976	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	143.6	01–25–1977	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	144.2	02–03–1978	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	141.7	03–27–1979	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	144.2	03–06–1980	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	143.8	04–09–1981	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	143.9	01-1201982	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	144.3	02–17–1983	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	144.6	01–25–1984	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	144.5	01–24–1985	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	144.6	02–06–1985	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	145.0	01–01–1986	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	145.1	02013-1987	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	145.3	04–23–1987	--	--	--	--	--	--

Table 1-1.—Continued

Source agency	Local well number	Site identifer	Well name[1]	Date of construction[2]	Primary use of water	Diameter of casing (inches)	Type of finish	Well depth (feet)	Altitude of land surface (feet)	Altitude datum	Water level (feet)	Water level date[2]	Discharge (gallons per minute)	Date discharge measured	Draw-down (feet)	Saturated thickness (feet)	Primary aquifer code	Geologic code
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	145.0	01–14–1988	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	144.6	01–10–1989	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	145.3	01–16–1990	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	145.3	11–06–1990	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	146.8	10–29–1991	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	146.6	10–27–1992	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	144.7	10–25–1993	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	145.2	11–06–1995	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	146.0	10–28–1996	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	146.0	10–13–1997	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	146.8	10–19–1998	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	147.2	10–18–1999	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	147.1	10–16–2000	--	--	--	--	--	--
--	B-24-12 17CBC	--	--	--	U	--	--	--	--	--	147.2	11–15–2001	--	--	--	--	--	--
ADWR	B-24-12 17CDD	--	--	--	U	8	--	--	4,265	--	133.9	10–26–1992	--	--	--	--	--	--
USGS	B-24-12 17CDD	352736113351401	PSC	--	U	8	--	442	4,240	NGVD29	149.4	04–21–1980	--	--	--	292.6	--	--
--	B-24-12 17CDD	--	55-609484	--	U	--	--	--	--	--	150.4	12-00-1985	--	--	--	--	--	--
--	B-24-12 17CDD	--	--	--	U	--	--	--	--	--	150.0	10–10–1986	--	--	--	--	--	--
--	B-24-12 17CDD	--	--	--	U	--	--	--	--	--	151.1	04–23–1987	--	--	--	--	--	--
--	B-24-12 17CDD	--	--	--	U	--	--	--	--	--	133.9	10–26–1992	--	--	--	--	--	--
	B-24-12 18DAA	--	--	--	S		--	--	4,251	--	--	--	--	--	--	--	--	--
ADWR	B-24-12 19ABB	--	--	--	S	12	--	--	4,216	--	122.2	--	250.0	--	--	--	--	--
USGS	B-24-12 19ABB	352729113360301	PSC	--	S	--	--	--	4,215	NGVD29	122.3	04–21–1980	--	--	--	--	--	--
--	B-24-12 19ABB	--	55-609482	--	S	--	--	--	--	--	124.0	12–06–1985	--	--	--	--	--	--
--	B-24-12 19ABB	--	--	--	S	--	--	--	--	--	124.0	01–01–1986	--	--	--	--	--	--
--	B-24-12 19ABB	--	--	--	S	--	--	--	--	--	124.3	04–23–1987	--	--	--	--	--	--
--	B-24-12 19ABB	--	--	--	S	--	--	--	--	--	125.4	10–26–1992	--	--	--	--	--	--
ADWR	B-24-12 21DCC	--	55-501865	10–14–1981	U	8	--	320	4,357		267.5	--	12.0	--	--	52.5	--	--
USGS	B-24-12 08DAC	352843113344801	WQ 32	09–25–1979	U	7	X	1,624	4,325	NGVD29	--	--	--	--	--	--	--	--
USGS	B-24-13 07DCA	352827113421701	--	--	S	--	--	--	5,120	NGVD29	--	--	2.2	00–00–1965	--	--	--	--
NRCE	B-24-13 13DDD	--	Schneider	06–17–1998	--	6	--	220	--	--	90.0	01–10–2000	--	--	--	130.0	--	--
USGS	B-24-13 18CAD	352744113423101	--	--	U	--	--	--	4,740	NGVD29	--	--	3.2	00–00–1965	--	--	--	--
--	B-24-13 18CAD	--	--	--	U	--	--	--	--	--	--	--	0.2	09–23–1980	--	--	--	--
USGS	B-24-13 19BBA	352728113425301	--	--	S	--	--	--	4,560	NGVD29	--	--	2.5	09–23–1980	--	--	--	--
USGS	B-24-13 34ADD1	352522113385601	--	--	U	--	--	--	3,885	NGVD29	--	--	--	--	--	--	--	--
USGS	B-24-13 34ADD2	352522113385701	55-642156	--	H	6	--	397	--	NGVD29	55.6	03–24–1980	--	--	--	341.4	--	--
--	B-24-13 34ADD2	--	WIK	--	H	--	--	--	--	--	51.0	01–01–1986	--	--	--	--	--	--
--	B-24-13 34ADD2	--	BIS	--	H	--	--	--	--	--	51.3	01–13–1986	--	--	--	--	--	--
--	B-24-13 34ADD2	--	--	--	H	--	--	--	--	--	--	--	--	--	--	--	--	--
--	B-24-13 34ADD2	--	--	--	H	--	--	--	--	--	--	--	--	--	--	--	--	--
USGS	B-24-13 35B1	352435113391001	--	00–00–1919	N	16	P	101	4,030	NGVD29	24.0	07–01–1919	20.0	--	--	77.0	400GRNT	400GRNT
	B-24-13 35B1		--	--	N	--	--	--	--	--	24.0	07-00-1919	--	--	--	--	--	--

Table 1-1.—Continued

Source agency	Local well number	Site identifer	Well name[1]	Date of construction[2]	Primary use of water	Diameter of casing (inches)	Type of finish	Well depth (feet)	Altitude of land surface (feet)	Altitude datum	Water level (feet)	Water level date[1]	Discharge (gallons per minute)	Date discharge measured	Draw-down (feet)	Saturated thickness (feet)	Primary aquifer code	Geologic code
USGS	B-24-13 35B2	352436113391001	--	00–00–1920	N	16	P	62	4,080	NGVD29	12.0	08–27–1920	37.0		31.0	50.0	400GRNT	400GRNT
USGS	B-24-13 35C	352505113383001	--	--	I	--	--	--	3,880	NGVD29	--	--	330.2	10-00-1943	--	--	--	--
ADWR	B-24-13 35DCB	--	55-633212	01–01–1962	I	12	--	184	--	--	8.2	--	--	--	--	175.8	--	--
USGS	B-24-13 35DCB	352505113382901	PSC	00–00–1962	I	12	--	184	3,927	NGVD29	8.2	03–24–1980	--	--	--	175.8	--	--
--	B-24-13 35DCB	--	55-633212	--	I	--	--	--	--	--	--	--	--	--	--	--	--	--
--	B-24-13 35DCB	--	--	--	I	--	--	--	--	--	--	--	--	--	--	--	--	--
--	B-24-13 35DCB	--	--	--	I	--	--	--	--	--	--	--	--	--	--	--	--	--
--	B-24-13 35DCB	--	--	--	I	--	--	--	--	--	--	--	--	--	--	--	--	--
NRCE	B-23-11 09BCC	--	--	01–01–1968	U	8	--	299	5,082	--	192.4	--	--	--	--	106.6	--	--
NRCE	B-22-11 02CBC	--	--	--	S	--	--	--	4,239	--	--	--	--	--	--	--	--	--
NRCE	--	--	Music Mountain	--	--	--	--	35	--	--	--	--	--	--	--	--	--	--
NRCE	--	--	Music Mountain	--	--	--	--	45	--	--	--	--	--	--	--	--	--	--
NRCE	--	--	Truxton/Ground Livestock Company	--	--	--	--	280	--	--	156.0	--	--	--	--	124.0	--	--
NRCE	--	--	Truxton/Hatch Valley Water Company	1961/1962	--	--	--	465	--	--	220.0	--	500.0	--	--	245.0	--	--
NRCE	--	--	New Water	06–00–1971	--	--	--	719	--	--	Dry	--	--	--	--	--	--	--
NRCE	--	--	Truxton/WF Cattle	00–00–1953	--	--	--	500	--	--	145.0	--	--	--	--	355.0	--	--
NRCE	--	--	Crozier/Valentine Ranch	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
NRCE	--	--	Truxton/WF Cattle	--	--	--	--	--	--	--	146.0	--	300.0	--	--	--	--	--
NRCE	--	--	Truxton/WF Cattle	--	--	--	--	--	--	--	147.0	--	300.0	--	--	--	--	--
NRCE	--	--	New West Water Well	--	--	--	--	--	4,914	--	--	--	--	--	--	--	--	--
NRCE	--	--	GW003	11–20–1989	P	8	--	660	4,422	--	324.0	--	250.0	--	--	336.0	--	--
NRCE	--	--	GW002	00–00–1976	P	8	--	609	4,429	--	--	--	--	--	--	--	--	--
NRCE	--	--	New Mud Tank (3 wells)	11–11–2002	S	6	--	320	4,354	--	266.0	--	25.0	--	--	54.0	--	--

[1]Numbers (for example, 55-62971) are ADWR well registry number.

[2]Date format is month–day–year. 00 in either the month or day indicated unknown date for month or day.

Table 1-2. Selected borehole driller's logs for the Truxton aquifer on the Hualapai Reservation and adjacent water-bearing zones, northwestern Arizona.

[NRCE, Natural Resources Consulting Engineers; ADWR, Arizona Department of Water Resources; #, number; &, and; @, at; brn, brown; w/, with; gal/min, gallons per minute; ft., feet; in., inch; med., medium; --, no data]

Well name	Altitude of land surface (feet)	Depth below land surface (feet)		Unit description	Remarks
		From	To		
PDC-1	4,640	0.0	2.0	Topsoil	NRCE (2011)
--	--	2.0	310.0	Tan conglomerate	--
--	--	310.0	855.0	Reddish-brown conglomerate	NRCE (2011)
PDC-2	4,360	0.0	6.0	Top soil	--
--	--	6.0	180.0	Brown clay	--
--	--	180.0	335.0	Conglomerate	--
--	--	335.0	350.0	Basalt	--
--	--	350.0	365.0	Conglomerate	--
--	--	365.0	375.0	Red sandstone	--
--	--	375.0	397.0	Red conglomerate w/ some clay	--
PM-9 (Old Mud Tank well)	4,347	0.0	6.0	Top soil	NRCE (2011), ADWR (2016)
--	--	6.0	18.0	Cemented conglomerate	--
--	--	18.0	50.0	Sandy clay	--
--	--	50.0	142.0	Silty clay–some fine sand	--
--	--	142.0	233.0	Cemented sand and gravel	--
--	--	233.0	262.0	Gray sandstone (hard)	--
--	--	262.0	271.0	Red sandstone	--
--	--	271.0	291.0	Black volcanic rock (basalt)	--
--	--	291.0	318.0	Brown volcanic rock (basalt)	--
--	--	318.0	326.0	Silt and sandy conglomerate	--
--	--	326.0	332.0	Broked sandstone, conglomerate	--
--	--	332.0	343.0	Sandstone, basalt, conglomerate	--
--	--	343.0	515.0	Cemented sand conglomerate	--
D-2	4,420	0.0	1.0	Soil	NRCE (2011)
--	--	1.0	25.0	Semiconsolidated sand and gravel w/ light brn clay	--
--	--	25.0	31.0	Semiconsolidated sand and gravel w/ tan clay	--
--	--	31.0	47.0	Tan clay with sand and gravel	--
--	--	47.0	90.0	Semiconsolidated sand and gravel w/ brn clay	--
--	--	90.0	120.0	Consolidated gravel and sand w/ brn clay	--
--	--	120.0	200.0	Reddish-brown clay	--
--	--	200.0	245.0	Consolidated sand and small gravel w/reddish-brn clay	--
--	--	245.0	275.0	Consolidated sand and gravel w/ gray clay	--
--	--	275.0	309.0	Consolidated sand and gravel w/ reddish-brn clay	--
--	--	309.0	353.0	Consolidated sand, gravel, and cobbles w/ light brn clay	--
--	--	353.0	374.0	Consolidated gravel and basalt boulders w/ white & gray clay	--
--	--	374.0	404.0	Basalt	--
--	--	404.0	408.0	Dark gray basalt	--
--	--	408.0	446.0	Consolidated sand and gravel w/ reddish-brn clay	--
--	--	446.0	455.0	Consolidated sand and gravel w/ less reddish-brn clay	--
--	--	455.0	502.0	Consolidated sand and gravel, hard	--
--	--	502.0	528.0	Consolidated sand and gravel w/ brown clay	--

Table 1–2.—Continued

Well name	Altitude of land surface (feet)	Depth below land surface (feet)		Unit description	Remarks
		From	To		
--	--	528.0	540.0	Consolidates coarse sand and fine gravel, rust stained	--
--	--	540.0	571.0	Silty sand, minor gravel increasing toward bottom	--
--	--	571.0	579.0	Consolidated sand and gravel w/ green-gray clay	--
--	--	579.0	581.0	Coarse crystalline granite	Transition, granite
--	--	581.0	615.0	Green-gray clay w/ granite boulders	Granite basement
--	--	615.0	623.0	Coarse crystalline granite	--
Sante Fe #1	4,797	0.0	200.0	--	NRCE (2011)
--	--	--	200.0	Cemented gravel	--
--	--	200.0	587.0	Limestone	--
--	--	587.0	592.0	Gravel	--
--	--	592.0	617.0	Clay	--
--	--	617.0	637.0	Blue clay	--
--	--	637.0	924.0	Sandstone	--
Sante Fe #2	4,789	0.0	12.0	Clay soil	NRCE (2011)
--	--	12.0	215.0	Cemented gravel	--
--	--	215.0	590.0	Limestone	--
--	--	590.0	635.0	Clay	--
--	--	635.0	935.0	Sandstone	--
--	--	935.0	1,003.0	Quartz	Granite basement?
--	--	1,003.0	1,013.0	Granite	--
Sante Fe #3	4,800	0.0	15.0	Soil	NRCE (2011)
--	--	15.0	167.0	Conglomerate, gravel	--
--	--	167.0	345.0	White limestone	--
--	--	345.0	410.0	Red sandstone	--
--	--	410.0	420.0	Fine brown sand	--
--	--	420.0	445.0	Red limestone	--
--	--	445.0	470.0	Yellow clay	--
--	--	470.0	485.0	Limestone	--
--	--	485.0	505.0	Clay	--
--	--	505.0	570.0	Limestone	--
--	--	570.0	580.0	Gray shale	--
--	--	580.0	660.0	Sandstone	--
--	--	660.0	765.0	Sandstone and quartzite	Granite?
--	--	765.0	890.0	Sandstone	Granite?
--	--	890.0	910.0	Clay	Granite?
--	--	910.0	1,003.0	Sandstone and quartzite	Granite?
Sante Fe #4	4,787	0.0	15.0	Sub soil	NRCE (2011)
--	--	15.0	135.0	Cemented gravel	--
--	--	135.0	155.0	Sand and gravel	--
--	--	155.0	175.0	Sandy shale	--
--	--	175.0	240.0	Limestone	--
--	--	240.0	320.0	Sandy limestone	--
--	--	320.0	330.0	Yellow clay	--
--	--	330.0	340.0	Sandy limestone	--
--	--	340.0	395.0	Sandy yellow clay	--

Table 1–2.—Continued

Well name	Altitude of land surface (feet)	Depth below land surface (feet)		Unit description	Remarks
		From	To		
--	--	322.0	373.0	Gray lime	--
--	--	373.0	424.0	Conglomerate	--
--	--	424.0	434.0	Soft clay, sand, and gravel	--
--	--	434.0	449.0	Red clay	--
--	--	449.0	456.0	Red clay	--
--	--	456.0	478.0	Yellow clay	--
--	--	478.0	501.0	Sandstone	--
--	--	501.0	519.0	Conglomerate	--
--	--	519.0	576.0	Blue shale	--
--	--	576.0	610.0	Gray lime, streaks w/ shale	--
--	--	610.0	651.0	Gray lime	--
--	--	651.0	672.0	Shale	--
--	--	672.0	686.0	Lime	--
--	--	686.0	705.0	Conglomerate	--
--	--	705.0	710.0	Hard sand	--
--	--	710.0	716.0	Conglomerate	--
--	--	716.0	722.0	Shale	--
--	--	722.0	747.0	Gray lime	--
--	--	747.0	800.0	Conglomerate	--
--	--	800.0	810.0	Cemented sand	--
--	--	810.0	836.0	Clay and gravel	--
GW002	4,429	0.0	2.0	Topsoil	NRCE (2011), ADWR (2016)
--	--	2.0	15.0	Topsoil w/ moist clay	--
--	--	15.0	20.0	Small gravel w/ clay & silt, some fine sand	--
--	--	20.0	30.0	Red & white clays, fine sand, w/ lite gravel	--
--	--	30.0	40.0	Coarse gravel	--
--	--	40.0	70.0	Red sand w/ pebbles	--
--	--	70.0	80.0	Coarser gravel	--
--	--	80.0	95.0	Coarse gravels & less sand	--
--	--	95.0	97.0	More sand, less gravel	--
--	--	97.0	115.0	Complete lost circulation & caving zone, seems to be gravel	--
--	--	115.0	130.0	Healed very fine sand, w/ lite gravel (lost circulation)	--
--	--	130.0	145.0	Flour-like sand w/ lite gravel, high red clay content	--
--	--	145.0	175.0	Mostly tan clay w/ very lite gravel, high red clay content	--
--	--	175.0	205.0	Reddish-brown & tan clays (hole very free)	--
--	--	205.0	210.0	Same but drills faster	--
--	--	210.0	240.0	Same but few pebbles	--
--	--	240.0	270.0	Pebbles w/ tan clay, small angular gravel, more gravel toward bottom	--
--	--	270.0	318.0	Tan clay w/ lite gravels	--
--	--	318.0	325.0	Coarse gravel & less sand	--
--	--	325.0	360.0	Angular coarse & fine gravels	--
--	--	360.0	380.0	Medium gray basalt	--
--	--	380.0	410.0	Finer (basalt) chips, gray angular w/ reddish matrix grading to reddish rock	--

Table 1–2.—Continued

Well name	Altitude of land surface (feet)	Depth below land surface (feet)		Unit description	Remarks
		From	To		
--	--	410.0	445.0	Mostly basalt (1 gal/min water production)	--
--	--	445.0	510.0	Mixed gravel & clay (water increasing at 500 ft)	--
--	--	510.0	535.0	Green clay & mixed gravel (more water)	--
--	--	535.0	550.0	Coarse to fine sand (more water)	--
--	--	550.0	565.0	Green clay w/ gravels (more water)	--
--	--	565.0	580.0	Lots of sand, green & brown clay (more water)	--
--	--	580.0	583.0	Mixed gravel & medium sand (more water)	--
--	--	583.0	600.0	Crystalline granite (no change in water)	Granite basement
--	--	600.0	609.0	Crystalline granite	--
GW003	4,422	0.0	20.0	Hard brown clay & sand	NRCE (2011), ADWR (2016)
--	--	20.0	35.0	Dry green & blue clay	--
--	--	35.0	340.0	Alluvial conglomerate, sandy, red & brn cemented	--
--	--	340.0	440.0	Harder, more rock, less sand & gravel	--
--	--	440.0	480.0	Sand & silt, 1/4-in. round gravel	--
--	--	480.0	595.0	Well rounded gravel & sand	--
--	--	595.0	640.0	Decomposed granite	Granite basement?
--	--	640.0	660.0	Harder, tighter granite	--
DNR #2	--	0.0	140.0	Brown clay	NRCE (2011)
--	--	140.0	190.0	Cemented sand & gravel	--
--	--	190.0	230.0	Gray sand	--
--	--	230.0	250.0	White powder dirt	--
--	--	250.0	260.0	Gray sand	--
--	--	260.0	270.0	Red powder dirt	--
--	--	270.0	290.0	Dark gray sand	--
--	--	290.0	300.0	Gravel & sand	--
--	--	300.0	320.0	Brown clay	--
Dewy Mahoney Windmill	--	0.0	3.0	Granite, red, med. hard	ADWR (2016)
--	--	3.0	18.0	Granite, red, hard	--
--	--	18.0	19.0	first water (trickle in crack in red rock)	--
--	--	19.0	48.0	Granite, red, hard	--
--	--	48.0	50.0	Water pick-up, 6 gal/min, crack	--
--	--	50.0	82.0	Granite, red, hard	--
--	--	82.0	84.0	Water pick-up, 12 gal/min	--
--	--	84.0	122.0	Granite, red, hard	--
--	--	122.0	138.0	Water pick-up, 30 gal/min	--
--	--	138.0	150.0	Granite, red, hard	--
Goldenstien-1	4,300	0.0	185.0	Clay	ADWR (2016)
--	--	185.0	215.0	Clay, basalt	--
--	--	215.0	275.0	Clay, gravel	--
--	--	275.0	305.0	Basalt	--
--	--	305.0	330.0	Clay, altered basalt	--
--	--	330.0	380.0	Clay, alluvium	--
Chamberlan	4,310	0.0	65.0	Clay	ADWR (2016)
--	--	65.0	170.0	Clay, alluvium	--
--	--	170.0	240.0	Clay, sand, alluvium	--
--	--	240.0	300.0	Clay, altered basalt	--

Table 1–2.—Continued

Well name	Altitude of land surface (feet)	Depth below land surface (feet)		Unit description	Remarks
		From	To		
--	--	300.0	355.0	Clay, alluvium	--
Hatch Valley Water Company	4,406	0.0	15.0	Clay	ADWR (2016)
--	--	15.0	20.0	Volcanic, lava	--
--	--	20.0	300.0	Volcanic	--
--	--	300.0	320.0	Grey volcanic	--
--	--	320.0	340.0	Brown volcanic	--
--	--	340.0	370.0	Gray volcanic	--
--	--	370.0	381.0	Granite	--
Goldenstien-3	4,365	0.0	230.0	Clay, sandstone	ADWR (2016)
--	--	230.0	340.0	Clay, altered black basalt	--
--	--	340.0	355.0	Clay, alluvium	--
Goldenstien-2	4,365	0.0	300.0	Clay, altered limestone (1 gal/min @ 300 ft)	ADWR (2016)
--	--	300.0	380.0	Clay, altered basalt (10 gal/min @ 380 ft)	--
--	--	380.0	430.0	Clay Alluvium (30 gal/min @ 390 ft)	--
McPherson	--	0.0	15.0	Overburden	ADWR (2016)
--	--	15.0	175.0	Clay	--
--	--	175.0	210.0	Basalt	--
--	--	210.0	235.0	Clay	--
--	--	235.0	255.0	Basalt	--
--	--	255.0	275.0	Rhyolite	--
--	--	275.0	280.0	Red clay	--
--	--	280.0	305.0	Rhyolite	--
--	--	305.0	320.0	Basalt	--
--	--	320.0	335.0	Red clay	--
--	--	335.0	355.0	Gravel (30 gal/min)	--
--	--	355.0	385.0	Red clay	--
Mohr and Leap	--	0.0	195.0	Clay	ADWR (2016)
--	--	195.0	510.0	Decomposed granite	--

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