Hydrogeology and Water Chemistry of Montezuma Well in Montezuma Castle National Monument and Surrounding Area, Arizona

By A.D. KONIECZKI and S.A. LEAKE

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BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Gordon P. Eaton, Director

For additional information write to:

District Chief
U.S. Geological Survey
Water Resources Division
520 North Park Avenue, Suite 221
Tucson, AZ 85719-5035

Copies of this report can be purchased from:

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CONVERSION FACTORS

Multiply	By	To obtain
centimeter (cm)	0.3937	inch
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
cubic hectometer (hm^3)	810.7	acre-foot
cubic meter per second (m^3/s)	35.31	cubic foot per second
liter per second (L/s)	0.035	cubic foot per second
liter per minute (L/min)	0.2642	gallon per minute

In this report, temperature is reported in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by the following equation:

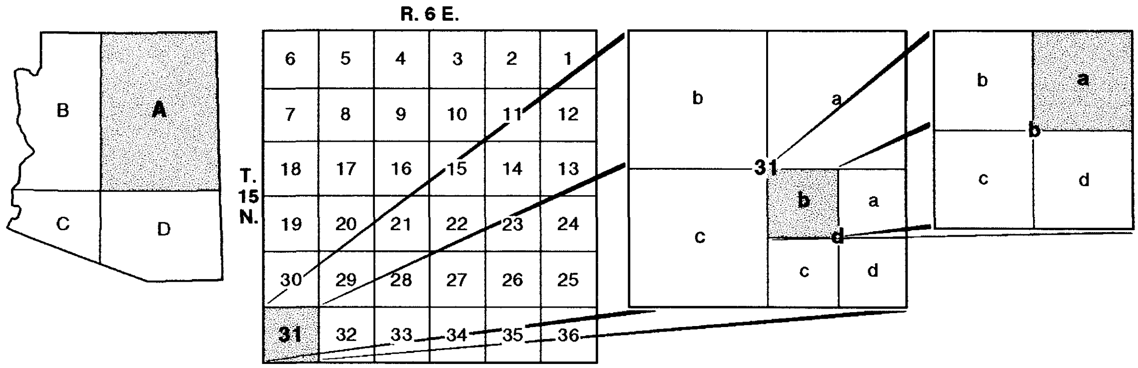
$$°F = 1.8\ (°C) + 32$$

ABBREVIATED WATER-QUALITY UNITS

Chemical concentration and water temperature are given only in metric units. Chemical concentration in water is given in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is a unit expressing the solute mass per unit volume (liter) of water. One thousand micrograms per liter is equivalent to 1 milligram per liter. For concentrations less than 7,000 milligrams per liter, the numerical value is about the same as for concentrations in parts per million. Specific conductance is given in microsiemens per centimeter (µS/cm) at 25°C. Radioactivity is expressed in picocuries per liter (pCi/L), which is the amount of radioactive decay producing 2.2 disintegrations per minute in a unit volume (liter) of water.

WELL-NUMBERING AND NAMING SYSTEM

WELL (A–15–06)31dba



Quadrant A, Township 15 North, Range 6 East, section 31, quarter section d, quarter section b, quarter section a

The well numbers used by the U.S. Geological Survey in Arizona are in accordance with the Bureau of Land Management's system of land subdivision. The land survey in Arizona is based on the Gila and Salt River Meridian and Base Line, which divide the State into four quadrants and are designated by capital letters A, B, C, and D in a counterclockwise direction, beginning in the northeast quarter. The first digit of a well number indicates the township, the second the range, and the third the section in which the well is situated. The lowercase letters a, b, c, and d after the section number indicate the well location within the section. The first letter denotes a particular 160–acre tract, the second the 40–acre tract, and the third the 10–acre tract. These letters also are assigned in a counterclockwise direction, beginning in the northeast quarter. If the location is known within a 10–acre tract, three lowercase letters are shown in the well number. Where more than one well is within a 10–acre tract, consecutive numbers beginning with 1 are added as suffixes. In the example shown, well number (A–15–06)31dba designates the well as being in the NE1/4, NW1/4, SE1/4, section 31, Township 15 North, and Range 6 East.

VERTICAL DATUM

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929—A geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called "Sea Level Datum of 1929."

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Abstract

Increasing population and associated residential and commercial development have greatly increased water use and consumption in the Verde Valley near Montezuma Well, a unit of Montezuma Castle National Monument in central Arizona. Flow from Montezuma Well and water levels in eight wells that are measured annually do not indicate that the ground-water system has been affected by development. Additional data are needed to develop an adequate ground-water monitoring program so that future effects of development can be detected. Monitoring the ground-water system would detect changes in discharge from the Montezuma Well or changes in the ground-water system that might indicate a potential change of flow to the well.

Water samples were collected, and field measurements of specific conductance, pH, temperature, and dissolved oxygen were made throughout the pond at Montezuma Well during an exploration in May 1991. The exploration included two fissures in the bottom of the pond that were filled with sand. The sand in the fissures was kept in suspension by water entering the pond. Water chemistry indicates that the ground water from the area is a mixed combination of calcium, magnesium, sodium, and bicarbonate type water. The analyses for $^{18}O/^{16}O$ and $^{2}H/^{1}H$ show that the water from the wells and springs in the area, including Montezuma Well, has been exposed to similar environmental conditions and could have had similar flow paths.

The MODFLOW finite-difference ground-water model was used to develop an uncalibrated interpretive model to study possible mechanisms for discharge of water at Montezuma Well. The study presents the hypothesis that ground water in the Supai Formation is the source of discharge to Montezuma Well because of the differences between the surface elevation of the pond at Montezuma Well and the stage in the adjacent Wet Beaver Creek. A series of simulations shows that upward flow from the Supai Formation is a possible mechanism for discharge to Montezuma Well, and that a geologic structure in the Supai Formation could play a role in the upward movement of water to Montezuma Well.

The mechanism for inflow from the Verde Formation is not understood; however, this study concludes that the Verde Formation, Supai Formation, and other underlying rock units are probably the sources of water to Montezuma Well.

INTRODUCTION

In the early 1990's, the U.S. Geological Survey (USGS) in cooperation with the National Park Service conducted a study to investigate Montezuma Well (a unit of the Montezuma Castle National Monument) and the surrounding hydrologic system. Montezuma Well is about 161 km (100 mi) north of Phoenix, Arizona, and includes a spring-fed, cup-shaped pond about 91 m (298 ft) wide by 107 m (351 ft) long, on the north side of Wet Beaver Creek. The depth of the fissures in the pond is unknown but exceeds 15 m (49.2 ft). Montezuma Well is an important resource in the Monument, which was established on April 1, 1947. There is evidence that people inhabited the area as long as 11,000 years ago. The Hohokam and the Sinagua Indians inhabited the area around 600 A.D. and 1125 A.D., respectively.

The study area is a popular retirement area, and population growth and associated residential and commercial development have resulted in increased water use that may in time affect the amount of water flowing from springs into Montezuma Well. The communities near Montezuma Well are Camp Verde, Lake Montezuma, Rimrock, and McGuireville (fig. 1). Lake Montezuma, Rimrock, and McGuireville have a total of about 2,000 residents, and the population of Camp Verde has grown from 1,100 in 1980 to 6,200 in 1990 (U.S. Bureau of the Census, 1991). Residents rely on ground water from water companies and from privately owned wells.

A significant reduction in the spring flow to Montezuma Well would affect the environment in and around the pond. National Park Service concerns for protection of spring flow include discharge, water quality, and maintenance of the natural biological status of the pond. The near constant spring flow, in conjunction with unusual water chemistry, provide a unique habitat for several endemic species.

Montezuma Well is in the Central Highlands province of Arizona, which is a transition zone between the Basin and Range province to the south and the Plateau Uplands province to the north (U.S. Geological Survey, 1969). The area is characterized by layered sedimentary rocks and volcanic rocks along the edge of the study area. The area around Montezuma Well is semiarid with mild winters and warm summers. In the winter, temperatures are from just below freezing at night and range from 16° to 21°C (61°F to 70°F) during the day. In the summer, daytime temperatures may reach 38°C (100°F). The average annual precipitation in the area ranges from about 30.5 cm (12 in.) at Montezuma Castle National Monument to about 50.8 cm (20 in.) at the headwaters of Wet Beaver Creek (Sellers, 1985). The largest amount of rainfall occurs during July and August when tropical moisture flows into the area from the south. At the higher altitudes, some of the precipitation falls as snow during the winter months.

Purpose and Scope

The purpose of the study was to determine if spring flow to the pond at Montezuma Well has been affected by development of the surrounding area and to determine the potential for future effects. Water samples were collected from the pond and springs and wells in the area from 1990 to 1991 (fig. 1). This report presents the findings from the study, and suggests a data-collection network that could be used to monitor the ground-water system for possible effects on Montezuma Well.

The study area extends from the boundary of the Central Highlands province and the Plateau Uplands province to the Verde River (fig. 1). Most of the study area is in the Coconino National Forest and only a small part of the land is privately owned.

Previous Investigations

Several studies have been made in the Verde Valley; however, few studies have investigated Montezuma Well. Feth and Hem (1963) investigated the springs in the area; and Twenter and Metzger (1963) reported on the hydrogeology of the Verde Valley. Levings and Mann (1980) presented ground-water conditions of the upper Verde River Valley, and Ross and Farrar (1980) described the geothermal characteristics of the ground water in the Verde Valley. Owen-Joyce and Bell (1983) reported on the hydrology of the upper

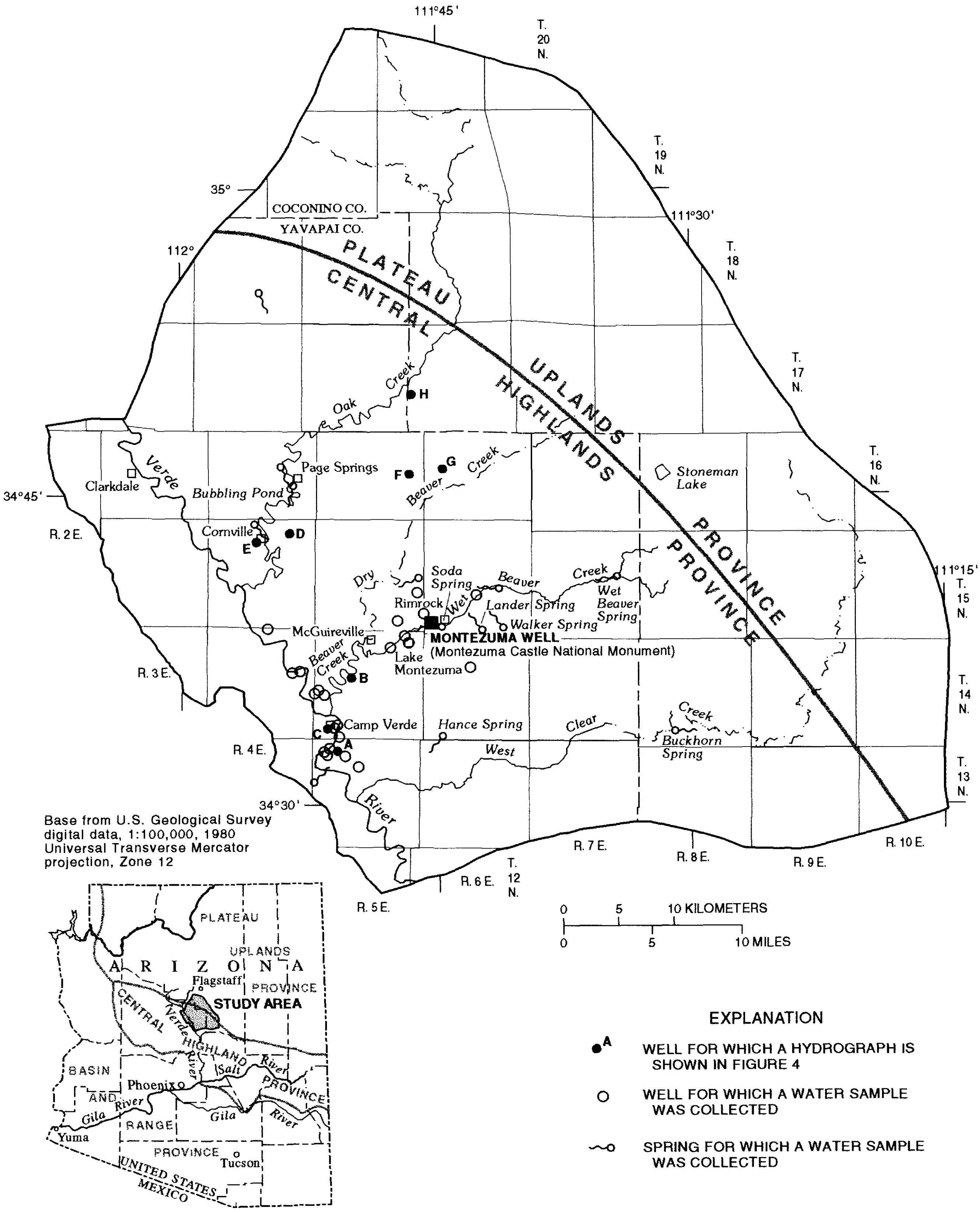


Figure 1. Location of study area, data-collection sites, Montezuma Well area, Montezuma Castle National Monument, Arizona.

Verde River area and Owen-Joyce (1984) described the stream-aquifer system near Camp Verde. Donchin (1983) described the stratigraphy in the area around Montezuma Well, Smith (1984) constructed a gravity-anomaly map of the Verde Valley, and Baldys (1990) evaluated the water-quality trends at six data collection sites in the Verde River Basin.

Collection of Data and Exploration of Montezuma Well, May 1991

Water flows from the pond through a small cave to a channel, which conveys most of the water for use by the National Park Service and for irrigation use by private individuals. In 1977, a continuously recording gaging station, Montezuma Well outlet near Rimrock, Arizona, 09505260, was installed 43 m (141 ft) downstream from the cave outlet on the outflow channel of the pond. The station was established to provide background data and to monitor spring flow. Monthly mean discharge ranged from 20 to 90 L/s (0.71 to 3.18 ft^3/s; fig. 2). Mean daily discharge for 15 years was 62 L/s (2.19 ft^3/s), or 1.96 hm^3/yr (1,590 acre-ft/yr). The discharge data did not always account for water losses from the channel, evapotranspiration, or for some of the water that flows into Wet Beaver Creek through fractures in the cave. Operation of the station was discontinued in 1992.

In May 1991, personnel of the USGS conducted an underwater diving survey to study Montezuma Well. Water samples were collected, field measurements of specific conductance, pH, temperature, and dissolved-oxygen concentration were made throughout the pond, and the bottom of the pond was investigated. A 10- by 10-meter grid was used to determine the location of each observation, field measurement, and sample (fig. 3).

Montezuma Well has dense aquatic vegetation along the edge of the pond that is anchored in 8 to 10 m (26 to 33 ft) of water. Leeches and amphipods are found throughout the pond at depths greater than 4 m (13 ft); however, large concentrations of

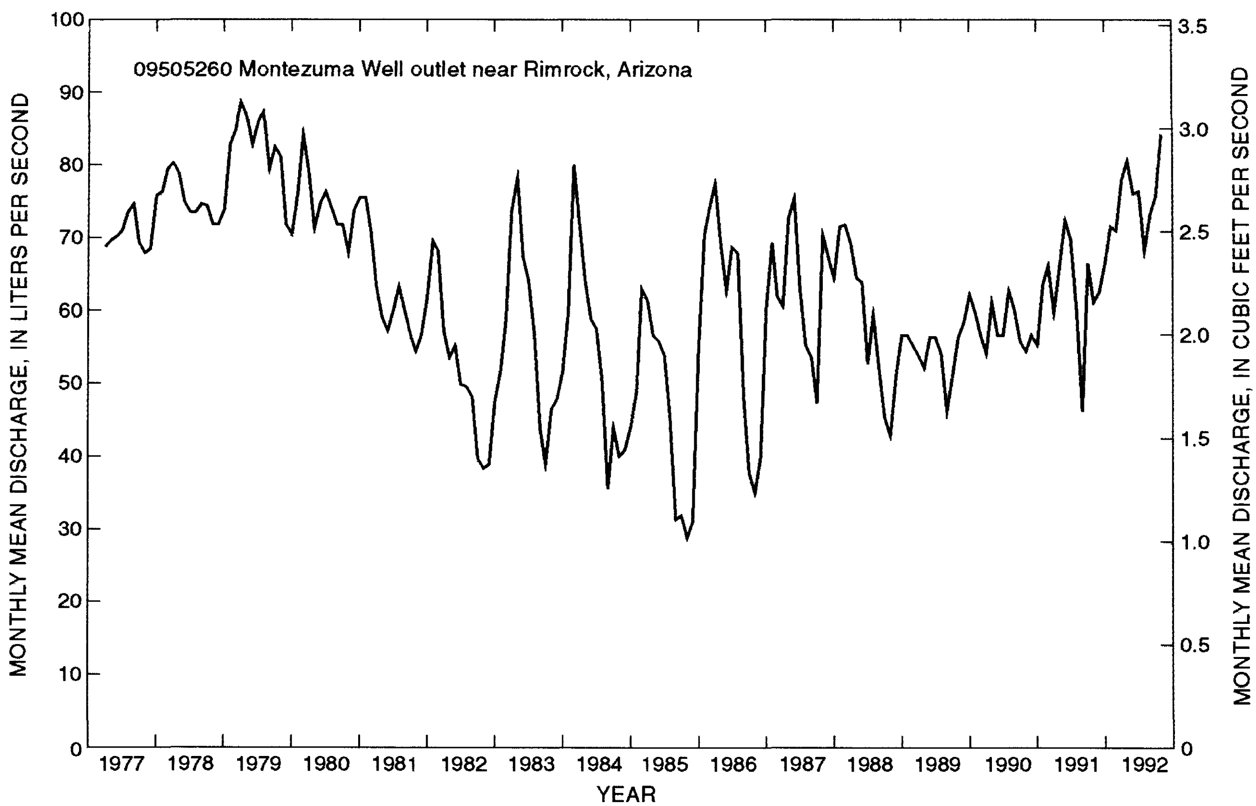


Figure 2. Monthly mean discharge, Montezuma Well outlet near Rimrock, Arizona, 1977–92.

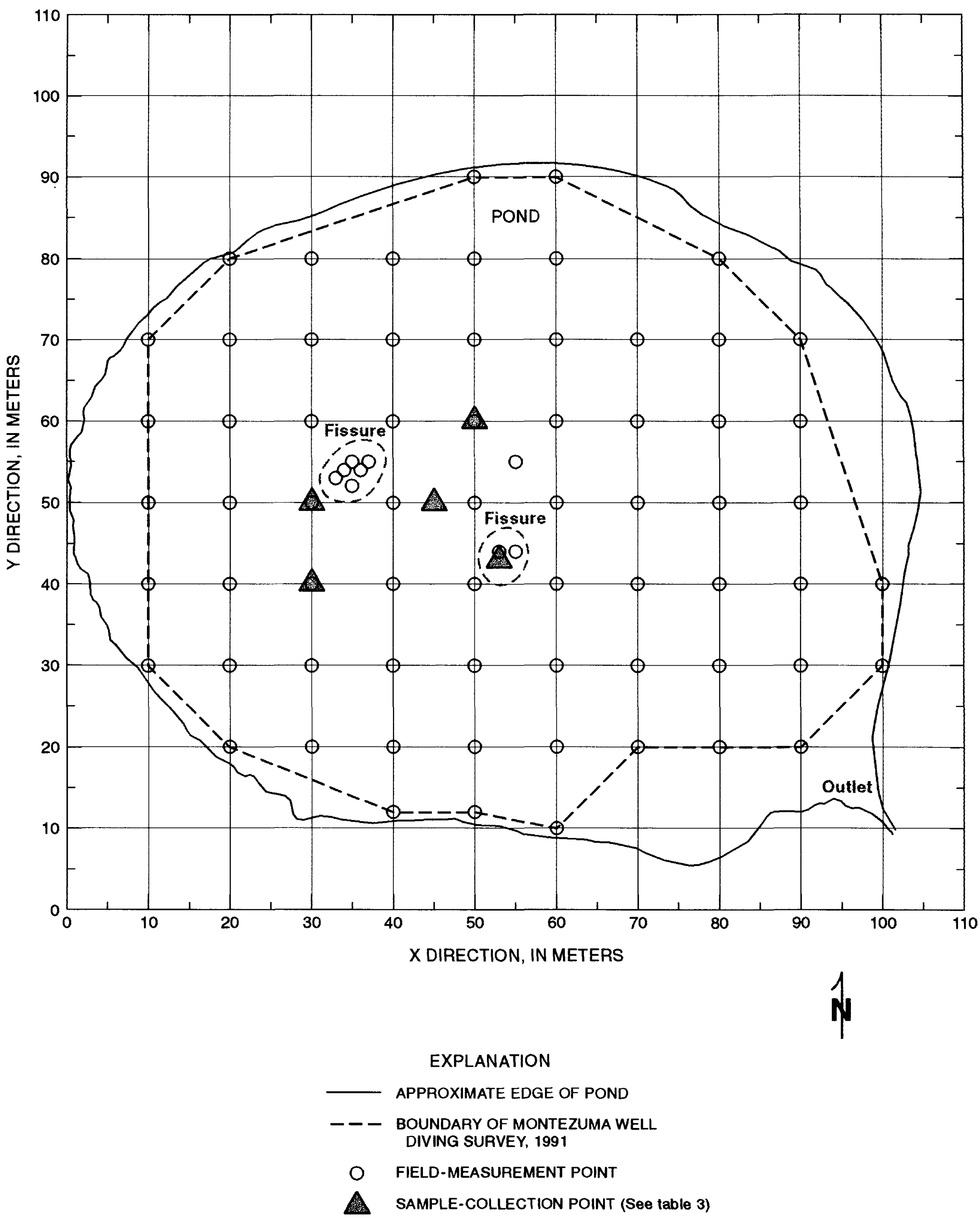


Figure 3. Sample grid, field-measurement points, and sample-collection points, Montezuma Well.

carbon dioxide prevent the survival of fish in the pond. The pond is bowl shaped, and the steeply sloping sides extend beyond a depth of 15.2 m (50 ft). The pond has a uniform sand bottom at a depth of about 15.5 m (51 ft) and has no detectable solid-rock bottom. Water enters the pond through two fissures in the bottom near the center at coordinates 35,55 and 55,44 (fig. 3). The fissures were filled with sand that was kept in suspension by water entering the pond, however, no current was detected throughout the rest of the pond. The bottom of the pond, away from the fissures, consisted of polished, very fine sand and some biologic detritus that was easily disturbed and put into suspension. An attempt was made to measure the thickness of the sediments using 4-foot probes, however, a hard bottom could not be detected. Anchors were dropped through the suspended sand to more than 30.5 m (100 ft). Less dense material, such as clay balls and pieces of wood, were observed floating on the surface of the churning sand. The divers noticed that the water was warmer in the two fissures than in the rest of the pond. Visibility was 1.5 m (5 ft) near the surface, 1 m (3 ft) at a depth of 6 to 14 m (20 to 66 ft), and 0 m beyond a depth of 14 m (66 ft). The visibility probably was affected by the motion of the divers that disturbed the material on the bottom. Lights were needed below 8 m (26 ft).

Soundings of the pond made by Feth and others (1954) indicated that the bottom of the pond was 15.2 m (50 ft) below the surface. During an exploration of the pond in 1974, the maximum depths were measured at 20 to 22.9 m (66 to 75 ft), which was 4.6 to 6.1 m (15 ft to 20 ft) deeper than the measurements in 1991. In 1974, in some places, pinnacles of hard material were found projecting from the bottom of the pond (S.Y. Harmon, Arizona State University, written commun., 1974); however, pinnacles were not observed in 1991.

Water samples were collected from the pond and cave outlets. The samples were analyzed for common ions, nutrients, and oxygen- and deuterium-isotope ratios. To further characterize the conditions in the pond, vertical profiles of temperature, pH, dissolved-oxygen concentration, specific conductance, and oxidation-reduction potential were measured using a multiparameter instrument (see section entitled "Field Measurements," table 7, at the end of the report).

Analyses of samples from the pond were compared with analyses of samples collected from springs and wells in the surrounding area. In May 1991, the pond was explored, and profiles of specific conductance, pH, temperature, and dissolved-oxygen concentration were made. Comparisons were made among data for temperature, specific conductance, and pH collected from wells and springs in the area and the data for temperature, specific conductance, and pH collected from the pond. Isotope data were used to determine the relative age of water samples and the path taken by the water to Montezuma Well. Drillers' logs and the results of previous investigations were used to interpret the geology. All water-level data available from wells in the area were compiled and supplemented with new measurements. An uncalibrated interpretive model of the area surrounding Montezuma Well was developed to study the possible mechanism for discharge of water at Montezuma Well.

HYDROGEOLOGY

Montezuma Well is in the Central Highlands province, a transition zone between the Basin and Range province to the south and the Plateau Uplands province to the north (U.S. Geological Survey, 1969). The Central Highlands province is composed mainly of layered sedimentary rocks. Near Montezuma Well, ground water occurs in the Supai and Verde Formations, volcanic rocks along the margins of the Verde Formation, and alluvium found in the stream channels and along the flood plains (table 1).

The Supai Formation of Pennsylvanian-Permian age ranges in thickness from 0 to 580 m (0 to 1,900 ft). The formation consists of upper, middle, and lower members. The upper member is composed of sandstone and siltstone and ranges in thickness from 0 to 190 m (0 to 623 ft). The middle member is mainly siltstone and mudstone and includes conglomerate, sandstone, and limestone. The middle member ranges from 0 to 90 m (0 to 295 ft). The lower member is sandstone and siltstone and ranges from 0 to 300 m (0 to 984 ft) (Owen-Joyce and Bell, 1983). The Supai

Table 1. Geologic units near Montezuma Well and their hydrologic significance

[Modified from Owen-Joyce and Bell, 1983]

System	Formation or unit	Thickness, in meters (feet)	Description	Hydrologic significance
Quaternary	Stream alluvium	0–15.2 (0–50)	Gravel, sand, silt and clay, includes streamwash	Where saturated, yields generally will be less than 3 liters per second (50 gallons per minute). In localized areas, unit may yield more. Water levels in wells may be influenced by the stage of nearby streams.
Tertiary	Verde Formation	0–550 (0–1,800)	Thick limestone facies Lower, middle, and upper limestone facies Mudstone facies Sandstone facies	Principal unit of the regional aquifer. Limestone and sandstone facies are water bearing where saturated. Well yields may be as much as 125 liters per second (2,000 gallons per minute) from the limestone facies where the unit contains solution channels and joints.
	Volcanic rocks	0–430 (0–1,400)	Basalt flows interbedded with Verde Formation	Volcanic rocks generally are above the water table and yield small amounts of water to springs and wells.
Permian	Coconino Sandstone	0–200 (0–650)	Sandstone	Principal unit of the regional aquifer east of the study area.
Pennsylvanian-Permian	Supai Formation	0–190 (0–625)	Upper member: Sandstone and siltstone; average bed thickness is 2 to 3 meters (7 to 10 feet)	Principal unit of regional aquifer east of Montezuma Well. Wells may yield as much as 20 liters per second (a few hundred gallons per minute) in the areas of fracturing and faulting.
		0–90 (0–300)	Middle member: Siltstone, mudstone, intercalated with conglomerate, sandstone, and some limestone	
		0–300 (0–1,000)	Lower member: Sandstone and siltstone	

Formation underlies the Verde Formation beneath the pond and is exposed east of the pond. Near Montezuma Well, drillers' logs indicate that the Supai Formation is overlain by the Verde Formation and stream alluvium to a depth of about 16 m (52 ft).

The Verde Formation is the predominant unit exposed at the land surface near the pond. The formation of Tertiary age is composed of lakebed sediments and some intruded basalt and fluvial conglomerate. The Verde Formation may be more than 550 m (1,800 ft) thick (Owen-Joyce and Bell, 1983). The Verde Formation is heterogeneous, and several lithologic facies have been described that include thick limestone facies; upper, middle, and lower limestone facies; mudstone facies, and sandstone facies. The limestone facies of the Verde Formation contain many joints, solution channels, and fractures and faults that act as conduits for the flow of water.

Near Montezuma Well, the Verde Formation is thin and has been removed by erosion to the east. Drillers' logs show a difference in composition of the Verde Formation between the area around Montezuma Well and the area near Camp Verde. The lithology near Montezuma Well mainly is limestone with some basalt flows, and the formation has extensive fractures and solution features.

Volcanic rocks can be found along the margins of the Verde Formation. Outcrops and logs of wells indicate that the volcanic rocks vary in thickness and may be faulted and jointed.

Stream alluvium is found in the stream channels and along the flood plains and includes boulders, gravel, sand, silt, and some clay. The unit generally is less than 15.2 m (50 ft) thick and may be saturated near streams.

Ground water flows downgradient through permeable sediments, and movement is influenced by geologic structure. Some faults may impede the horizontal flow of water, and fractures and faults may allow water to rise to the surface as springs that discharge significant amounts of water from the aquifer (table 2). Such springs include those at Montezuma Well, Page Springs, Bubbling Pond, Wet Beaver Spring, and Buckhorn Spring.

Wells in the area have been completed in the alluvium and in the Verde and Supai Formations. Most of the wells were drilled into the Verde Formation, and a few wells in the Beaver Creek drainage basin penetrate the Supai Formation. Water levels in wells completed in the Verde Formation range from flowing at the land surface to about 61.0 m (200 ft) below land surface. Well owners report that some wells drilled into the Verde Formation flow during the winter and not in the summer. Wells completed in the alluvium near Wet Beaver Creek are shallow, and water levels in the wells generally are influenced by flow in the creek.

Depth to water in wells varies widely in the study area. The depth to water depends on the local geology. Well depth may depend to some degree on the required yield. Where present, basalt flows serve as confining layers and create artesian conditions as confirmed by drillers' logs that indicated rising water levels in the boreholes when drilling penetrated the basalt flows. Well yield depends on the primary permeability of the material and secondary permeability that results from faults and fractures. Faults and fractures have affected drilling and well yields at many sites. During drilling above the water table, drillers have reported the loss of drilling fluids from the boreholes as the fluids flowed into open, dry fractures. For example, a driller reported "losing water" in a well in sec. 3, T. 14 N., R. 5 E., at a depth of 53.9 m (177 ft) in limestone. The well was drilled to 89.0 m (292 ft), and the static water level was 67 m (220 ft). Fractures and faults may act as conduits for ground-water flow and increase well yield. Some wells with shallow water levels may flow at the surface in the winter and spring when increased recharge occurs from winter rain and snow and when ground-water pumping declines because of reduced need.

The effect of the diverse lithology on the occurrence of ground water is shown in the variation of the depth to water in adjacent wells. For example, drillers reported that water levels in four wells drilled in the northeast part of sec. 2, T. 14 N., R. 5 E., ranged from flowing to 3.6 m (12 ft) below land surface. In the west-central part of sec. 2, T. 14 N., R. 5 E., well depths in four wells ranged from 49 to 76 m (160 to 250 ft) and water levels ranged from 10.4 m to 56.4 m (34 to 185 ft) below land surface. Although the deepest water level was in the deepest well, a general relation between well depth and depth to water did not exist.

Depths to water in eight wells that are measured annually range from 21.3 to 162 m (70 to 531 ft; fig. 4). The wells for which the primary contributing unit is the Supai Formation generally are north of Montezuma Well, and depth to water in the wells ranged from 111.9 to 135.7 m (367 to 445 ft). Depth to water ranged from 5.9 to 27.8 m (19 to 91 ft) in wells for which the primary contributing unit is the Verde Formation. East of Montezuma Well, development is sparse. Although a few ranches are in the area, most of the land is part of the Coconino National Forest and is unlikely to be developed. The effects of water use will come from development downstream from Montezuma Well.

WATER CHEMISTRY

Vertical profiles of temperature, pH, specific conductance, dissolved-oxygen concentration, and

Table 2. Spring discharge, Montezuma Well area

[Primary use: S, stock; U, unused; I, irrigation; H, domestic; R, recreation; Z, other. Dashes indicate no data]

Local identifier	Name of spring	Latitude, in degrees	Longitude, in degrees	Altitude of land surface, in meters	Primary use of water	Date of measurement	Discharge, in liters per second
(A-13-05)08dbb	Unnamed spring	34°31'54"	111°50'35"	927	S	10–28–81	0.06
(A-13-05)08dcd	Unnamed spring	34°31'38"	111°50'35"	920	U	11–05–80	17.0
						06–09–81	12.0
(A-13-05)08ddd	Unnamed spring	34°31'35"	111°50'15"	919	U	11–06–80	13.9
(A-13-05)16bba1	Unnamed spring	34°31'31"	111°50'02"	919	U	11–06–80	.57
(A-13-05)16bba2	Blue	34°31'25"	111°49'59"	924	U	11–06–80	13.2
						06–11–81	14.5
(A-13-05)16bbd1	Unnamed spring	34°31'22"	111°49'59"	922	U	11–06–80	5.68
(A-13-05)16bbd2	Unnamed spring	34°31'20"	111°50'01"	920	U	11–06–80	.82
(A-13-05)16bcb	Catfish	34°31'12"	111°50'03"	919	U	06–11–81	1.39
(A-13-05)18cbb	Cottonwood	34°31'02"	111°52'15"	1,079	S	07–10–59	.01
						12–13–77	.17
(A-13-06)10aad	Bull Pen Spring	34°32'14"	111°41'45"	1,219	S	10–20–59	.44
(A-14-06)29dad	Unnamed spring	34°34'25"	111°43'52"	1,172	S	05–27–81	.06
(A-14-06)32caa	Hance Spring	34°33'36"	111°44'20"	1,119	S	10–20–59	.01
						05–27–81	.25
(A-14-08)32a unsurv	Buckhorn	34°33'40"	111°31'08"	1,542	S	05–28–59	63.1
(A-15-04)04aca	Cottontail	34°43'37"	111°55'38"	1,018	I	06–09–77	.32
(A-15-05)11aab	Beaverhead	34°42'51"	111°47'01"	1,106	S	06–04–74	5.36
(A-15-06)23bdd	Beaver Creek Spring	34°40'44"	111°41'08"	1,213	I	04–20–78	.13
(A-15-06)31dba	Montezuma Well	34°38'56"	111°45'03"	1,097	I	06–19–48	66.2
(A-15-06)32cbd	Soda Spring	34°38'45"	111°44'29"	1,096	H	07–25–49	3.15
						02–06–59	.95
(A-15-06)35cac	Walker Creek Spring	34°38'47"	111°41'11"	1,256	S	07–10–59	4.73
(A-15-07)14acc	Wet Beaver Spring	34°41'16"	111°34'33"	1,521	S	10–19–59	85.2
(A-16-04)14ccc	Lolo-Mai	34°46'34"	111°54'04"	1,073	R	07–10–74	18.9
(A-16-04)15ccc	Spring Creek	34°54'03"	111°55'08"	1,090	S	12–11–51	8.64
(A-16-04)23bba	Turtle Pond	34°46'27"	111°54'04"	1,070	H	02–12–52	10.3
						07–09–52	8.52
						12–10–52	10.1
(A-16-04)23bbb	Tree Root Spring	34°46'27"	111°54'05"	1,074	Z	07–09–52	16.6
(A-16-04)23bbc	Bubbling Pond	34°46'25"	111°54'03"	1,074	--	05–20–68	245
(A-16-04)23ddc	Page Springs	34°45'42"	111°53'18"	1,067	H	08–04–49	878
(A-16-04)35abc	Lower Newell	34°44'38"	111°53'32"	1,033	--	02–04–59	32.8
(A-16-05)12add	Bell Rock	34°47'52"	111°45'52"	1,302	S	04–25–74	.06
(A-17-07)11acc	Woods Spring	34°52'10"	111°37'12"	1,932	H	12–13–60	1.58

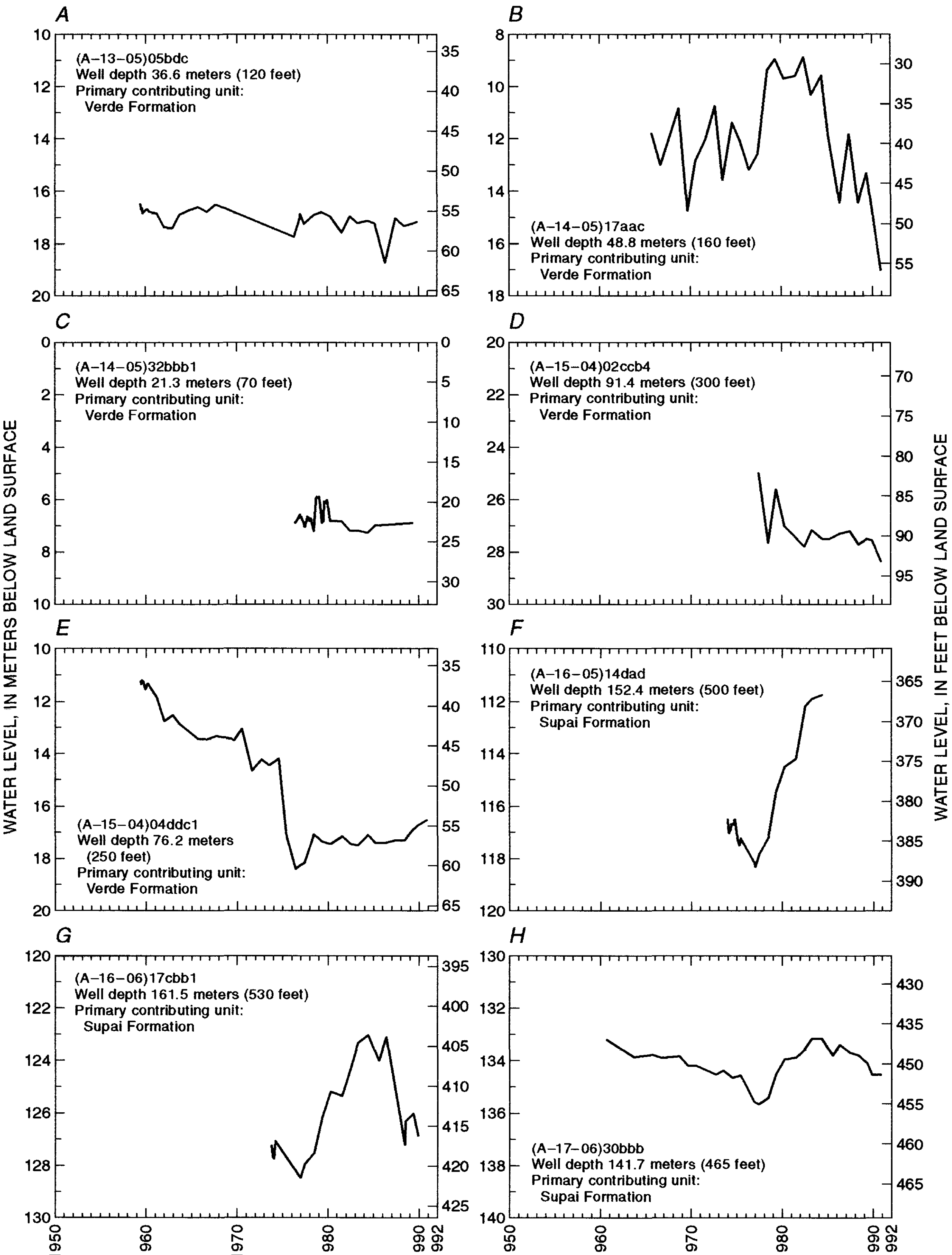


Figure 4. Water levels and well depths in selected wells.

oxidation-reduction potential in the pond were made using a multiparameter instrument in May 1991. Measurements were made at 75 locations on the 10- by 10-meter grid in the pond (see section entitled "Field Measurements" at the end of the report). In addition to the field measurements, grid coordinates, and depth also were noted. Eight water samples were collected from the pond at depths that ranged from 1 to 15 m (3 to 49 ft; table 3). Samples collected at the pond and at the cave outlets were analyzed for specific conductance, pH, major ions, nutrients, tritium, and oxygen-isotope ratio ($^{18}O/^{16}O$). During the study, 18 samples also were collected from springs and wells in the area near Montezuma Well (tables 3 and 4).

The flow path taken by ground water generally determines the chemical character of the water. Various groups of constituents can be used to evaluate the chemical character of ground water. Data on major ions, isotopic data, and field measurements of temperature, pH, and specific conductance were used to compare the water from Montezuma Well with water from other springs and wells in the area.

The overall chemistry of the pond did not change with depth; however, minor differences existed from the point where the water enters the pond and the point at which it discharges. Differences existed in concentrations of nitrogen (ammonia plus organic total), total organic carbon, chloride, iron, and alkalinity between the water from the bottom of the pond and the water at the cave outlet. Concentrations of other constituents were similar. Dissolved-solids concentrations in water samples from the pond ranged from 511 to 578 mg/L (table 3).

Field Measurements

Comparisons were made between temperature, specific conductance, and pH for wells and springs in the area and the data collected during the exploration of Montezuma Well (table 5). Samples from 92 wells and 21 springs that had been collected before this study were used in the analysis. Some of the wells and springs had been sampled more than once. The data were divided into four groups, which were based on the source of the water—Montezuma Well, stream alluvium, Verde Formation, and Supai Formation. Data for depths of 13.4 to 15.5 m (44 to 51 ft) in Montezuma Well were used to minimize the effect of the limnological environment of Montezuma Well on the chemistry and reduce the possible error of the measurements made in the suspended sand.

The mean water temperature near the bottom of Montezuma Well was at least 2°C (3.6°F) warmer than the mean water temperature of samples from the stream alluvium, Verde Formation, and Supai Formation. The mean temperatures of water from the alluvium and Supai Formation were 17.6 and 17.9°C (63.7 and 64.2°F), respectively.

The mean specific conductance of the water near the bottom of Montezuma Well was less than the mean specific conductance of water from the stream alluvium and Verde Formation, but greater than the mean specific conductance of water from the Supai Formation. Specific conductance of water from the Supai Formation was noticeably less than in water samples from the Verde Formation and alluvium.

The pH of water from Montezuma Well was less than the pH of samples from the other sources. The mean pH for samples from the alluvium, Verde Formation, and Supai Formation ranged from 7.5 to 7.9 and the mean pH for Montezuma Well was 6.6.

Profiles at the fissures were plotted to show changes with depth (figs. 5–7). Profiles for specific conductance, temperature, and pH at the fissures showed more variation than elsewhere in the pond. Specific conductance, temperature, and pH were similar between the bottom of the pond and the outlet of the pond.

The temperature in the pond ranged from 21.0 to 26.5°C (70 to 80°F). In most of the profiles, the temperature dropped about 0.5°C in the first 5 m (16 ft) below the surface and then remained constant for about 10 m (33 ft). The temperature rose about 1°C in the suspended sand. The temperature remained constant horizontally except at the fissures where the temperature increased.

Specific conductance in the pond ranged from 250 to more than 1,000 µS/cm. For depths less than 0.5 m (1.6 ft), specific conductance was over 1,000 µS/cm, and for depths greater than 15 m (49 ft) in the suspended sand, specific conductance

Table 3. Field and chemical data for water samples, Montezuma Well

[μS/cm, microsiemens per centimeter at 25°Celsius; mg/L, milligrams per liter; μg/L, micrograms per liter; pCi/L, picocuries per liter; <, less than. Dashes indicate no data. WO, well outlet; CO, cave outfall]

Date	Time	Location in pond (X–Y)	Depth to bottom from surface at sampling locations (meters)	Specific conductance (μS/cm)	pH (standard units)	Nitrogen, ammonia, dissolved (mg/L as N)	Nitrogen, ammonia, total (mg/L as N)	Nitrogen, nitrite, dissolved (mg/L as N)	Nitrogen, ammonia+ organic, dissolved (mg/L as N)	Nitrogen, ammonia+ organic, total (mg/L as N)	Phosphorus, total (mg/L as P)	Phosphorus, ortho, dissolved (mg/L as P)	Phosphorus, ortho, total (mg/L as P)	Carbon, organic, total (mg/L as C)
05–20–91	0945	45–50	1.00	978	6.8	--	0.010	<0.010	<0.20	0.30	<0.010	<0.010	<0.010	0.8
05–20–91	1015	50–60	9.00	976	6.8	--	.010	<.010	0.30	1.2	<.010	<.010	<.010	1.1
05–20–91	1025	30–40	9.00	980	6.8	--	--	--	--	--	--	--	--	--
05–20–91	1245	30–50	10.0	970	6.8	0.020	.020	<.010	<.20	<.20	<.010	<.010	<.010	.9
05–20–91	1246	30–50	10.0	968	6.8	.010	.010	<.010	<.20	.40	<.010	<.010	<.010	1.3
05–20–91	1325	30–50	15.0	963	--	.010	.020	<.010	<.20	<.20	<.010	<.010	<.010	.9
05–20–91	1400	53–43	10.0	967	6.7	--	--	--	--	--	--	--	--	--
05–20–91	1445	53–43	15.0	968	6.7	--	--	--	--	--	--	--	--	--
05–21–91	0910	WO	--	950	6.8	--	--	--	--	--	--	--	--	--
05–21–91	1005	CO	--	960	7.0	--	.010	<.010	--	--	<.010	<.010	<.010	--

Carbon, organic, dissolved (mg/L as C)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)	Fluoride, dissolved (mg/L as F)	Silica, dissolved, (mg/L as SiO_2)	Boron, dissolved (μg/L as B)	Iron, dissolved (μg/L as Fe)	Manganese, dissolved (μg/L as Mn)	Tritium, total (pCi/L)	Solids, sum of constituents, dissolved (mg/L)	$^{18}O/^{16}O$ stable isotope ratio, per mil
0.5	110	35	51	5.6	43	14	0.20	16	770	<3	<1	<1.0	573	-11.60
.5	110	36	51	5.4	46	11	.20	16	770	7	<1	--	575	--
--	110	36	51	5.6	39	12	.20	16	760	<3	<1	--	568	--
.5	110	35	49	5.6	43	12	.20	16	770	14	<1	<1.0	578	-11.60
.4	110	36	51	5.4	43	12	.20	16	760	5	<1	<1.0	573	--
.4	110	35	49	5.3	43	11	.20	16	760	7	<1	<1.0	513	-11.60
--	110	35	51	5.8	44	10	.20	16	760	5	<1	<1.0	517	-11.60
--	110	35	51	5.8	42	10	.20	16	760	3	<1	<1.0	515	-11.60
--	110	35	50	5.7	42	12	.20	16	750	4	<1	1.0	514	-11.50
--	110	35	48	5.3	41	12	.30	15	780	3	<1	<1.0	511	-11.60

Table 4. Physical properties and chemical analyses of water from selected wells and springs

[W, well; S, spring; µS/cm, microsiemens per centimeter at 25° Celsius; °C, degrees Celsius; mg/L, milligrams per liter; µg/L, micrograms per liter; pCi/L, picocuries per liter; <, less than. Dashes indicate no data]

Local identifier	Station number	Site type	Date	Time	Depth of well, total (meters)	Specific conductance, field (µS/cm)	Temperature, field (°C)	pH, field (standard units)	Alkalinity, field (mg/L as $CaCO_3$)
(A-13-05)05ddc2	343225111502601	W	03–05–89	1230	39.6	1,600	19.0	7.6	--
(A-13-05)06daa3	343247111511601	W	03–06–89	1600	14.6	--	--	--	--
(A-13-05)06dbd	343238111513201	W	03–05–89	1200	10.7	2,700	11.5	7.4	350
(A-13-05)06ddc	343230111512401	W	03–05–89	0900	48.8	--	--	--	--
(A-13-05)09dbb	343156111493201	W	03–05–89	1400	64.0	--	--	--	--
(A-13-05)18cbb	343102111521501	S	03–06–89	1730	--	--	--	--	--
			05–31–90	1624	--	--	--	--	--
			04–27–91	0730	--	--	--	--	--
(A-14-04)03bab2	343837111545501	W	03–05–89	1830	42.7	--	--	--	--
(A-14-04)13bca2	343632111530201	W	03–05–89	1700	30.5	--	--	--	--
(A-14-04)14adc2	343628111532601	W	03–05–89	1800	85.3	--	--	--	--
(A-14-05)01cba	343759111463801	W	03–04–89	1700	--	790	18.0	--	--
(A-14-05)02aad	343822111465401	W	03–04–89	1300	93.9	--	--	--	--
(A-14-05)02aad2	343818111465301	W	03–04–89	1400	--	--	--	--	--
(A-14-05)02ccd	343741111474001	W	03–04–89	1600	45.7	--	--	--	--
(A-14-05)02ccd2	343744111474301	W	03–04–89	1830	--	--	--	--	--
(A-14-05)19bcc	343528111520801	W	03–04–89	1000	76.2	--	--	--	--
(A-14-05)19bcd	343530111520601	W	03–04–89	1100	76.2	--	--	--	--
(A-14-05)19bdb	343539111515601	W	03–04–89	2000	80.8	--	--	--	--
(A-14-05)19dba	343524111513501	W	03–06–89	1430	--	--	--	--	--
(A-14-05)32bda	343356111505001	W	03–06–89	1300	--	2,500	23.5	6.9	--
(A-14-05)32bdc	343347111505701	W	03–05–89	1600	24.4	2,150	21.0	6.8	--
(A-14-05)32dcc	343322111504201	W	03–05–89	1500	39.6	--	--	--	--
(A-14-06)09dcd	343646111430201	W	06–26–91	0945	121.9	469	25.0	--	--
(A-14-06)32caa	343336111442001	S	09–08–90	1030	--	927	23.5	7.1	395
(A-14-08)32a unsurv	343340111310801	S	09–10–90	1540	--	220	33.0	8.7	98
(A-15-04)04aca	344337111553801	S	09–08–90	1540	--	--	22.0	7.1	--
(A-15-05)11aab	344251111470101	S	09–08–90	1600	--	431	22.0	7.1	162
(A-15-05)24aba	344105111460801	S	03–06–89	1100	--	--	--	--	--
			05–31–90	1200	--	--	--	--	--
			04–27–91	1300	--	--	--	--	--
(A-15-05)24dca	344024111460801	W	06–27–91	1115	121.3	732	22.0	7.6	--
(A-15-05)25ddd	343924111454901	W	08–15–91	1100	73.2	820	23.0	7.2	--
(A-15-05)35acc	343902111471701	W	06–26–91	1400	93.0	745	23.0	--	--
(A-15-06)21ddc	344019111424301	W	06–25–91	1300	39.3	419	19.5	7.0	--
(A-15-06)23bdd	344044111410801	S	06–25–91	0945	--	288	20.0	7.7	--
(A-15-06)31dba	343856111450301	S	03–06–89	0900	--	860	20.0	7.6	356
			05–31–90	1300	--	--	--	--	--
			04–27–91	1400	--	--	--	--	--
(A-15-06)32cbd	343845111442901	S	09–05–90	1400	--	1,260	24.5	6.5	582
(A-15-06)34adc	343834111420401	S	09–09–90	1300	--	417	22.0	7.6	183
(A-15-06)35cac	343847111411101	S	09–09–90	1500	--	331	21.5	7.7	158
(A-15-07)14acc	344116111343301	S	08–14–91	1020	--	255	17.0	7.6	--
(A-16-04)15ccc	345403111550801	S	09–08–90	1700	--	--	21.0	7.4	220
(A-16-04)23bba	344627111540401	S	09–06–90	1300	--	550	22.0	7.2	201
(A-16-04)23bbc	344625111540301	S	09–06–90	1400	--	--	--	--	--
(A-16-04)23ddc	344542111531801	S	05–31–90	1000	--	--	--	--	--
			09–06–90	1800	--	380	26.0	7.5	166
			04–27–91	1500	--	--	--	--	--

Table 4. Physical properties and chemical analyses of water from selected wells and springs—Continued

Local identifier	Date	Nitrogen, ammonia, dissolved (mg/L as N)	Nitrogen, ammonia, total (mg/L as N)	Nitrogen, nitrite, dissolved (mg/L as N)	Nitrogen, nitrite, total (mg/L as N)	Nitrogen, ammonia + organic, dissolved (mg/L as N)	Nitrogen, ammonia + organic, total (mg/L as N)	Nitrogen, NO_2+NO_3, total (mg/L as N)	Nitrogen, NO_2+NO_3, dissolved (mg/L as N)
(A-13-05)05ddc2	03–05–89	--	--	--	--	--	--	--	0.380
(A-13-05)06daa3	03–06–89	--	--	--	--	--	--	--	<.100
(A-13-05)06dbd	03–05–89	--	--	--	--	--	--	--	<.100
(A-13-05)06ddc	03–05–89	--	--	--	--	--	--	--	<.100
(A-13-05)09dbb	03–05–89	--	--	--	--	--	--	--	<.100
(A-13-05)18cbb	03–06–89	--	--	--	--	--	--	--	.280
	05–31–90	--	--	--	--	--	--	--	--
	04–27–91	--	--	--	--	--	--	--	--
(A-14-04)03bab2	03–05–89	--	--	--	--	--	--	--	2.00
(A-14-04)13bca2	03–05–89	--	--	--	--	--	--	--	.960
(A-14-04)14adc2	03–05–89	--	--	--	--	--	--	--	<.100
(A-14-05)01cba	03–04–89	--	--	--	--	--	--	--	.140
(A-14-05)02aad	03–04–89	--	--	--	--	--	--	--	.140
(A-14-05)02aad2	03–04–89	--	--	--	--	--	--	--	.130
(A-14-05)02ccd	03–04–89	--	--	--	--	--	--	--	2.20
(A-14-05)02ccd2	03–04–89	--	--	--	--	--	--	--	.420
(A-14-05)19bcc	03–04–89	--	--	--	--	--	--	--	.680
(A-14-05)19bcd	03–04–89	--	--	--	--	--	--	--	.690
(A-14-05)19bdb	03–04–89	--	--	--	--	--	--	--	--
(A-14-05)19dba	03–06–89	--	--	--	--	--	--	--	.490
(A-14-05)32bda	03–06–89	--	--	--	--	--	--	--	<.100
(A-14-05)32bdc	03–05–89	--	--	--	--	--	--	--	<.100
(A-14-05)32dcc	03–05–89	--	--	--	--	--	--	--	5.70
(A-14-06)09dcd	06–26–91	<0.010	0.010	<0.010	<0.010	--	--	1.10	.880
(A-14-06)32caa	09–08–90	--	--	--	--	--	--	--	--
(A-14-08)32a unsurv	09–10–90	--	--	--	--	--	--	--	--
(A-15-04)04aca	09–08–90	--	--	--	--	--	--	--	--
(A-15-05)11aab	09–08–90	--	--	--	--	--	--	--	--
(A-15-05)24aba	03–06–89	--	--	--	--	--	--	--	<.100
	05–31–90	--	--	--	--	--	--	--	--
	04–27–91	--	--	--	--	--	--	--	--
(A-15-05)24dca	06–27–91	<.010	<.010	<.010	<.010	0.30	0.30	4.10	3.80
(A-15-05)25ddd	08–15–91	<.010	<.010	<.010	<.010	<.20	.30	<.050	<.050
(A-15-05)35acc	06–26–91	<.010	<.010	<.010	<.010	<.20	<.20	.130	.130
(A-15-06)21ddc	06–25–91	<.010	.010	<.010	<.010	<.20	<.20	.410	.420
(A-15-06)23bdd	06–25–91	.010	.020	<.010	<.010	.20	<.20	.200	.200
(A-15-06)31dba	03–06–89	--	--	--	--	--	--	--	.110
	05–31–90	--	--	--	--	--	--	--	--
	04–27–91	--	--	--	--	--	--	--	--
(A-15-06)32cbd	09–05–90	--	--	--	--	--	--	--	--
(A-15-06)34adc	09–09–90	--	--	--	--	--	--	--	--
(A-15-06)35cac	09–09–90	--	--	--	--	--	--	--	--
(A-15-07)14acc	08–14–91	--	--	<.010	<.010	.40	.80	.170	.200
(A-16-04)15ccc	09–08–90	--	--	--	--	--	--	--	--
(A-16-04)23bba	09–06–90	--	--	--	--	--	--	--	--
(A-16-04)23bbc	09–06–90	--	--	--	--	--	--	--	--
(A-16-04)23ddc	05–31–90	--	--	--	--	--	--	--	--
	09–06–90	--	--	--	--	--	--	--	--
	04–27–91	--	--	--	--	--	--	--	--

Table 4. Physical properties and chemical analyses of water from selected wells and springs—Continued

Local identifier	Date	Phosphorus, total (mg/L as P)	Phosphorus, ortho, dissolved (mg/L as P)	Phosphorus, ortho, total (mg/L as P)	Hardness, total (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Sodium adsorption ratio
(A-13-05)05ddc2	03–05–89	--	--	--	470	84	62	150	3
(A-13-05)06daa3	03–06–89	--	--	--	440	82	57	180	4
(A-13-05)06dbd	03–05–89	--	--	--	440	78	60	370	8
(A-13-05)06ddc	03–05–89	--	--	--	520	76	79	600	12
(A-13-05)09dbb	03–05–89	--	--	--	540	80	83	49	.9
(A-13-05)18cbb	03–06–89	--	--	--	310	73	32	28	.7
	05–31–90	--	--	--	--	--	--	--	--
	04–27–91	--	--	--	--	--	--	--	--
(A-14-04)03bab2	03–05–89	--	--	--	1,400	170	230	40	.5
(A-14-04)13bca2	03–05–89	--	--	--	650	61	120	53	.9
(A-14-04)14adc2	03–05–89	--	--	--	270	43	40	38	1
(A-14-05)01cba	03–04–89	--	--	--	340	76	36	50	1
(A-14-05)02aad	03–04–89	--	--	--	320	76	32	41	1
(A-14-05)02aad2	03–04–89	--	--	--	330	78	33	37	.9
(A-14-05)02ccd	03–04–89	--	--	--	310	61	38	30	.7
(A-14-05)02ccd2	03–04–89	--	--	--	350	76	40	43	1
(A-14-05)19bcc	03–04–89	--	--	--	310	52	44	29	.7
(A-14-05)19bcd	03–04–89	--	--	--	310	51	45	29	.7
(A-14-05)19bdb	03–04–89	--	--	--	290	49	41	29	.7
(A-14-05)19dba	03–06–89	--	--	--	290	50	39	30	.8
(A-14-05)32bda	03–06–89	--	--	--	700	150	78	180	3
(A-14-05)32bdc	03–05–89	--	--	--	800	170	90	200	3
(A-14-05)32dcc	03–05–89	--	--	--	570	93	81	170	3
(A-14-06)09dcd	06–26–91	<0.010	<0.010	<0.010	170	42	17	42	1
(A-14-06)32caa	09–08–90	--	--	--	350	85	34	22	.5
(A-14-08)32a unsurv	09–10–90	--	--	--	92	22	8.9	4.8	.2
(A-15-04)04aca	09–08–90	--	--	--	430	90	50	31	.7
(A-15-05)11aab	09–08–90	--	--	--	170	40	18	16	.5
(A-15-05)24aba	03–06–89	--	--	--	360	76	41	38	.9
	05–31–90	--	--	--	--	--	--	--	--
	04–27–91	--	--	--	--	--	--	--	--
(A-15-05)24dca	06–27–91	.010	<.010	.010	270	55	31	41	1
(A-15-05)25ddd	08–15–91	.020	--	.010	280	62	30	69	2
(A-15-05)35acc	06–26–91	.020	.010	.020	330	83	31	42	1
(A-15-06)21ddc	06–25–91	.040	.030	.030	220	52	23	8.4	.2
(A-15-06)23bdd	06–25–91	.020	<.010	<.010	150	30	19	6.2	.2
(A-15-06)31dba	03–06–89	--	--	--	430	110	37	52	1
	05–31–90	--	--	--	--	--	--	--	--
	04–27–91	--	--	--	--	--	--	--	--
(A-15-06)32cbd	09–05–90	--	--	--	530	140	43	65	1
(A-15-06)34adc	09–09–90	--	--	--	190	36	24	9.1	.3
(A-15-06)35cac	09–09–90	--	--	--	160	29	21	6.5	.2
(A-15-07)14acc	08–14–91	.070	--	.010	110	23	12	5.7	.2
(A-16-04)15ccc	09–08–90	--	--	--	260	63	25	16	.4
(A-16-04)23bba	09–06–90	--	--	--	240	57	23	16	.5
(A-16-04)23bbc	09–06–90	--	--	--	220	52	21	11	.3
(A-16-04)23ddc	05–31–90	--	--	--	--	--	--	--	--
	09–06–90	--	--	--	170	41	17	8.5	.3
	04–27–91	--	--	--	--	--	--	--	--

Table 4. Physical properties and chemical analyses of water from selected wells and springs—Continued

Local identifier	Date	Potassium, dissolved (mg/L as K)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Boron, dissolved (µg/L as B)	Iron, dissolved (µg/L as Fe)
(A-13-05)05ddc2	03–05–89	9.3	29	470	1.0	80	400	73
(A-13-05)06daa3	03–06–89	9.4	88	360	2.8	96	440	36
(A-13-05)06dbd	03–05–89	12	240	590	3.3	110	670	220
(A-13-05)06ddc	03–05–89	17	510	890	3.5	97	1,100	160
(A-13-05)09dbb	03–05–89	8.8	9.3	430	2.6	91	750	100
(A-13-05)18cbb	03–06–89	2.8	17	83	.30	39	50	10
	05–31–90	--	--	--	--	--	--	--
	04–27–91	--	--	--	--	--	--	--
(A-14-04)03bab2	03–05–89	5.8	29	1,300	.50	72	760	30
(A-14-04)13bca2	03–05–89	4.1	67	250	.90	34	380	41
(A-14-04)14adc2	03–05–89	3.3	18	66	.60	59	220	1,200
(A-14-05)01cba	03–04–89	7.9	21	14	.50	30	450	7
(A-14-05)02aad	03–04–89	3.5	26	10	.40	25	510	6
(A-14-05)02aad2	03–04–89	4.3	26	10	.30	26	500	62
(A-14-05)02ccd	03–04–89	2.7	24	10	.20	27	310	6
(A-14-05)02ccd2	03–04–89	5.6	17	14	.40	32	480	50
(A-14-05)19bcc	03–04–89	2.9	16	41	.40	58	190	5
(A-14-05)19bcd	03–04–89	3.1	16	42	.40	60	190	8
(A-14-05)19bdb	03–04–89	3.1	16	41	.70	60	200	150
(A-14-05)19dba	03–06–89	3.1	15	38	.30	58	180	8
(A-14-05)32bda	03–06–89	13	85	400	.60	91	700	130
(A-14-05)32bdc	03–05–89	12	98	460	1.2	110	820	240
(A-14-05)32dcc	03–05–89	5.5	120	380	.60	40	840	5
(A-14-06)09dcd	06–26–91	4.6	13	6.5	<.10	21	90	8
(A-14-06)32caa	09–08–90	1.5	40	10	.20	17	--	--
(A-14-08)32a unsurv	09–10–90	4.6	3.0	1.2	<.10	30	--	--
(A-15-04)04aca	09–08–90	3.6	18	50	.10	55	--	--
(A-15-05)11aab	09–08–90	1.0	22	4.6	.10	19	--	--
(A-15-05)24aba	03–06–89	1.5	14	30	.40	39	80	78
	05–31–90	--	--	--	--	--	--	--
	04–27–91	--	--	--	--	--	--	--
(A-15-05)24dca	06–27–91	5.3	27	15	<.10	34	150	17
(A-15-05)25ddd	08–15–91	9.7	11	14	.30	39	550	73
(A-15-05)35acc	06–26–91	4.1	34	12	<.10	23	590	100
(A-15-06)21ddc	06–25–91	1.7	5.8	2.4	.10	23	10	9
(A-15-06)23bdd	06–25–91	1.7	6.0	2.4	.10	19	10	8
(A-15-06)31dba	03–06–89	2.8	33	11	.30	17	750	9
	05–31–90	--	--	--	--	--	--	--
	04–27–91	--	--	--	--	--	--	--
(A-15-06)32cbd	09–05–90	6.9	51	19	.20	17	--	--
(A-15-06)34adc	09–09–90	1.7	11	4.8	.10	23	--	--
(A-15-06)35cac	09–09–90	1.8	6.0	2.5	<.10	19	--	--
(A-15-07)14acc	08–14–91	1.2	5.2	1.1	<.10	19	10	16
(A-16-04)15ccc	09–08–90	1.1	31	13	.40	12	--	--
(A-16-04)23bba	09–06–90	1.2	31	11	<.10	14	--	--
(A-16-04)23bbc	09–06–90	1.2	17	10	.10	15	--	--
(A-16-04)23ddc	05–31–90	--	--	--	--	--	--	--
	09–06–90	1.2	9.3	2.9	.10	17	--	--
	04–27–91	--	--	--	--	--	--	--

Table 4. Physical properties and chemical analyses of water from selected wells and springs—Continued

Local identifier	Date	Manganese, dissolved (µg/L as Mn)	Tritium, total (pCi/L)	Solids, residue at 180°C, dissolved (mg/L)	Solids, sum of constituents, dissolved (mg/L)	$^2H/^1H$ stable isotope ratio per mil	$^{18}O/^{16}O$ stable isotope ratio per mil
(A-13-05)05ddc2	03–05–89	<1	--	--	1,060	--	--
(A-13-05)06daa3	03–06–89	2	--	--	1,110	--	--
(A-13-05)06dbd	03–05–89	<10	--	--	1,670	-76.0	-10.35
(A-13-05)06ddc	03–05–89	30	--	--	2,480	-75.0	-10.40
(A-13-05)09dbb	03–05–89	<1	--	--	880	-77.5	-10.75
(A-13-05)18cbb	03–06–89	<1	--	--	435	-68.5	-9.25
	05–31–90	--	--	--	--	-70.0	-9.50
	04–27–91	--	--	--	--	-70.0	-9.35
(A-14-04)03bab2	03–05–89	10	--	--	2,010	-77.5	-10.70
(A-14-04)13bca2	03–05–89	1	--	--	854	-73.5	-9.95
(A-14-04)14adc2	03–05–89	31	--	--	428	--	--
(A-14-05)01cba	03–04–89	<1	--	--	486	--	--
(A-14-05)02aad	03–04–89	<1	--	--	436	--	--
(A-14-05)02aad2	03–04–89	1	--	--	440	-78.5	-11.25
(A-14-05)02ccd	03–04–89	<1	--	--	398	-75.5	-10.40
(A-14-05)02ccd2	03–04–89	<1	--	--	482	--	--
(A-14-05)19bcc	03–04–89	<1	--	--	432	-79.0	-10.65
(A-14-05)19bcd	03–04–89	<1	--	--	436	--	--
(A-14-05)19bdb	03–04–89	1	--	--	414	-76.0	-10.84
(A-14-05)19dba	03–06–89	<1	--	--	408	--	--
(A-14-05)32bda	03–06–89	23	--	--	1,360	--	--
(A-14-05)32bdc	03–05–89	40	--	--	1,530	-81.5	-11.30
(A-14-05)32dcc	03–05–89	<1	--	--	1,140	--	--
(A-14-06)09dcd	06–26–91	<1	<1.0	--	302	--	--
(A-14-06)32caa	09–08–90	--	13	403	447	-80.0	-11.70
(A-14-08)32a unsurv	09–08–90	--	17	124	134	-25.5	-3.60
(A-15-04)04aca	09–08–90	--	.6	540	565	-62.5	-8.00
(A-15-05)11aab	09–08–90	--	<1.0	219	218	-79.5	-11.45
(A-15-05)24aba	03–06–89	24	--	--	473	-69.5	-8.95
	05–31–90	--	--	--	--	-61.0	-6.90
	04–27–91	--	--	--	--	-65.0	-7.75
(A-15-05)24dca	06–27–91	<1	3.0	--	409	-66.0	-7.75
(A-15-05)25ddd	08–15–91	180	<1.0	--	487	-87.5	-12.20
(A-15-05)35acc	06–26–91	<1	2.0	--	463	-80.0	-11.35
(A-15-06)21ddc	06–25–91	<1	6.0	--	266	-77.0	-10.90
(A-15-06)23bdd	06–25–91	<1	<1.0	--	187	-81.5	-11.45
(A-15-06)31dba	03–06–89	<1	--	--	478	-71.0	-9.85
	05–31–90	--	--	--	--	-82.0	-11.55
	04–27–91	--	--	--	--	-80.5	-11.45
(A-15-06)32cbd	09–05–90	--	1.0	706	691	-82.5	-11.75
(A-15-06)34adc	09–09–90	--	<1.0	208	219	-75.5	-10.50
(A-15-06)35cac	09–09–90	--	1.0	171	181	-79.0	-11.40
(A-15-07)14acc	08–14–91	<1	--	--	137	-79.5	-11.45
(A-16-04)15ccc	09–08–90	--	<1.0	288	293	-82.5	-11.85
(A-16-04)23bba	09–06–90	--	1.0	283	274	-81.5	-11.75
(A-16-04)23bbc	09–06–90	--	3.0	237	262	-81.5	-11.75
(A-16-04)23ddc	05–31–90	--	--	--	--	-80.5	-11.65
	09–06–90	--	3.0	191	197	-80.0	-11.70
	04–27–91	--	--	--	--	-82.5	-11.60

Table 5. Statistics for field properties, Montezuma Well area

Source of water	Number of samples	Mean	Median	Minimum	Maximum
	Field-property statistics				
Temperature, in degrees Celsius					
Pond at Montezuma Well.....	37	22.3	22.3	22.1	22.9
Stream alluvium..................	45	17.6	18.0	11.0	26.5
Verde Formation	145	20.0	20.0	11.0	27.5
Supai Formation..................	54	17.9	17.5	10.0	25.0
Specific conductance, in microsiemens per centimeter at 25 degrees Celsius					
Pond at Montezuma Well.....	37	980	980	905	1,030
Stream alluvium..................	81	1,280	1,150	435	5,600
Verde Formation	264	1,200	910	350	13,700
Supai Formation..................	80	440	420	196	710
pH, standard units					
Pond at Montezuma Well.....	37	6.6	6.6	6.3	6.6
Stream alluvium..................	57	7.6	7.5	7.0	8.1
Verde Formation	174	7.5	7.3	6.4	8.7
Supai Formation..................	43	7.9	7.6	7.0	8.7

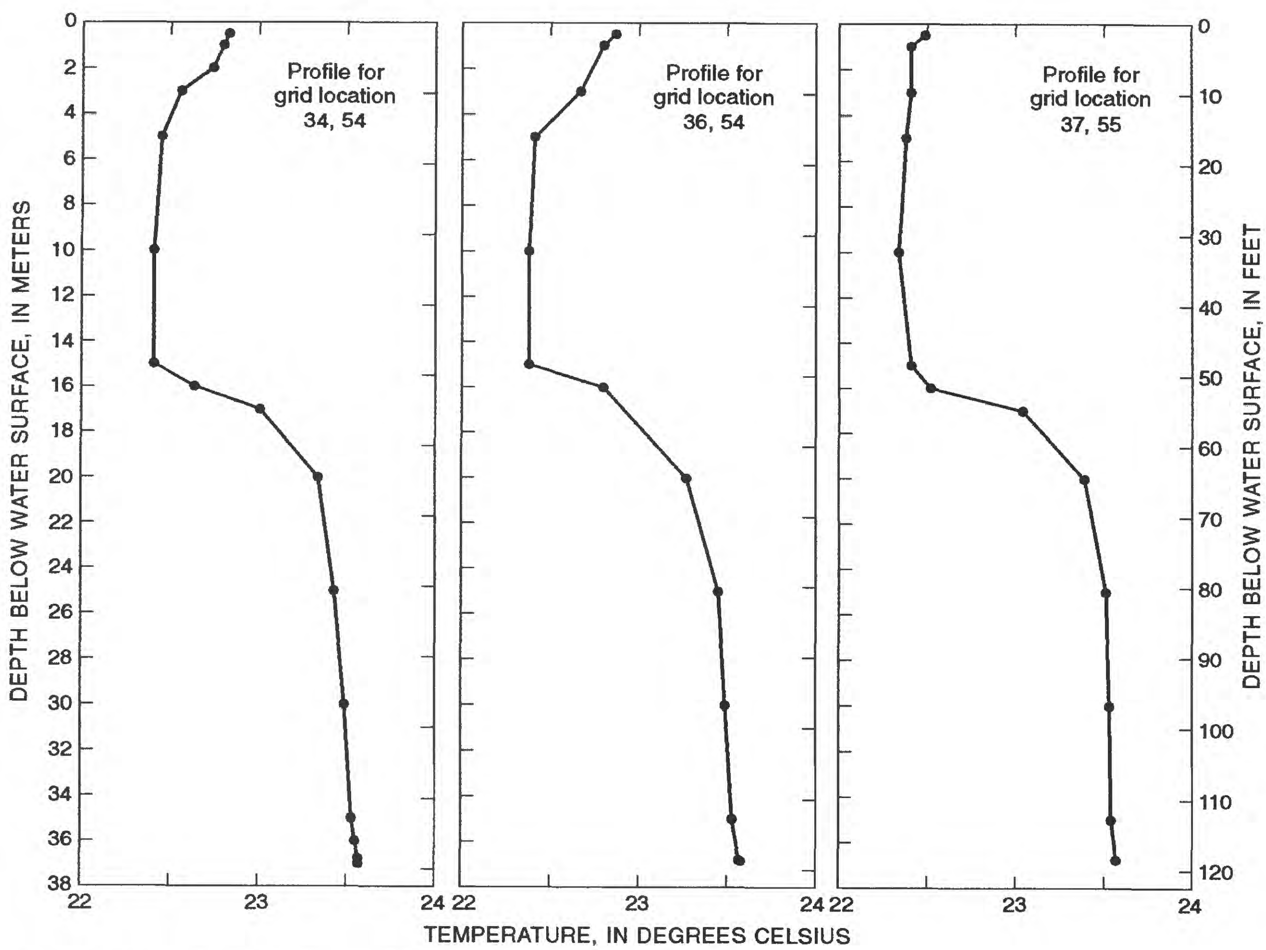


Figure 5. Temperature profiles at fissures in Montezuma Well.

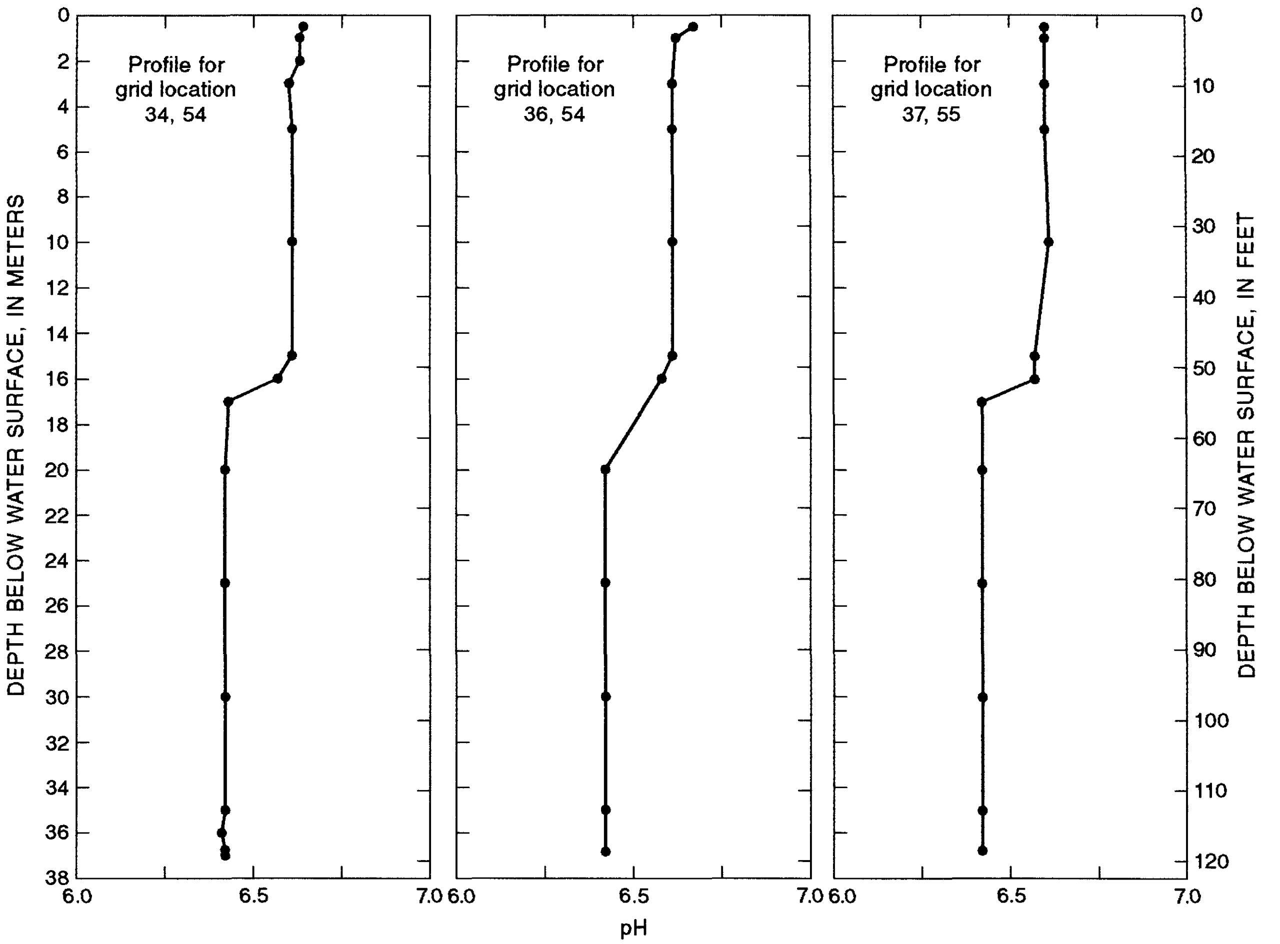


Figure 6. pH profiles at fissures in Montezuma Well.

was less than 500 µS/cm. The measurements made in water with suspended sand may be in error because of interference from the sand.

The pH in the pond ranged from 6.3 to 7.8. The pH of the water above the fissures remained constant until the probe reached the suspended sand at about 16 m (52 ft) below the surface where the pH dropped about 0.1 pH unit.

Dissolved-oxygen concentration had the greatest variability in the pond. Measurements of greater than 100-percent saturation were often made near the edge of the pond where vegetation may have had an effect.

Major Ions

Chemical analyses of water from wells and springs near Montezuma Well (table 4) exhibit ranges in concentration that suggest that the source of the ground water is from various lithologic units. The major cations in the water are calcium, magnesium, and sodium. Bicarbonate is the predominant anion in the water, but a few samples from wells near Camp Verde contained large concentrations of sulfate. Water samples east of Montezuma Well contained large concentrations of magnesium, calcium, and bicarbonate. Samples from the Verde Formation near Montezuma Well had the largest concentrations of calcium, magnesium, sodium, and bicarbonate.

Stiff and trilinear (Piper) diagrams can be used to characterize water and to group different types of water. The Piper diagrams show the relative chemical composition of a sample and can be used to show if samples from different sites have similar compositions (Hem, 1985). Piper diagrams, however, do not show the concentrations of major

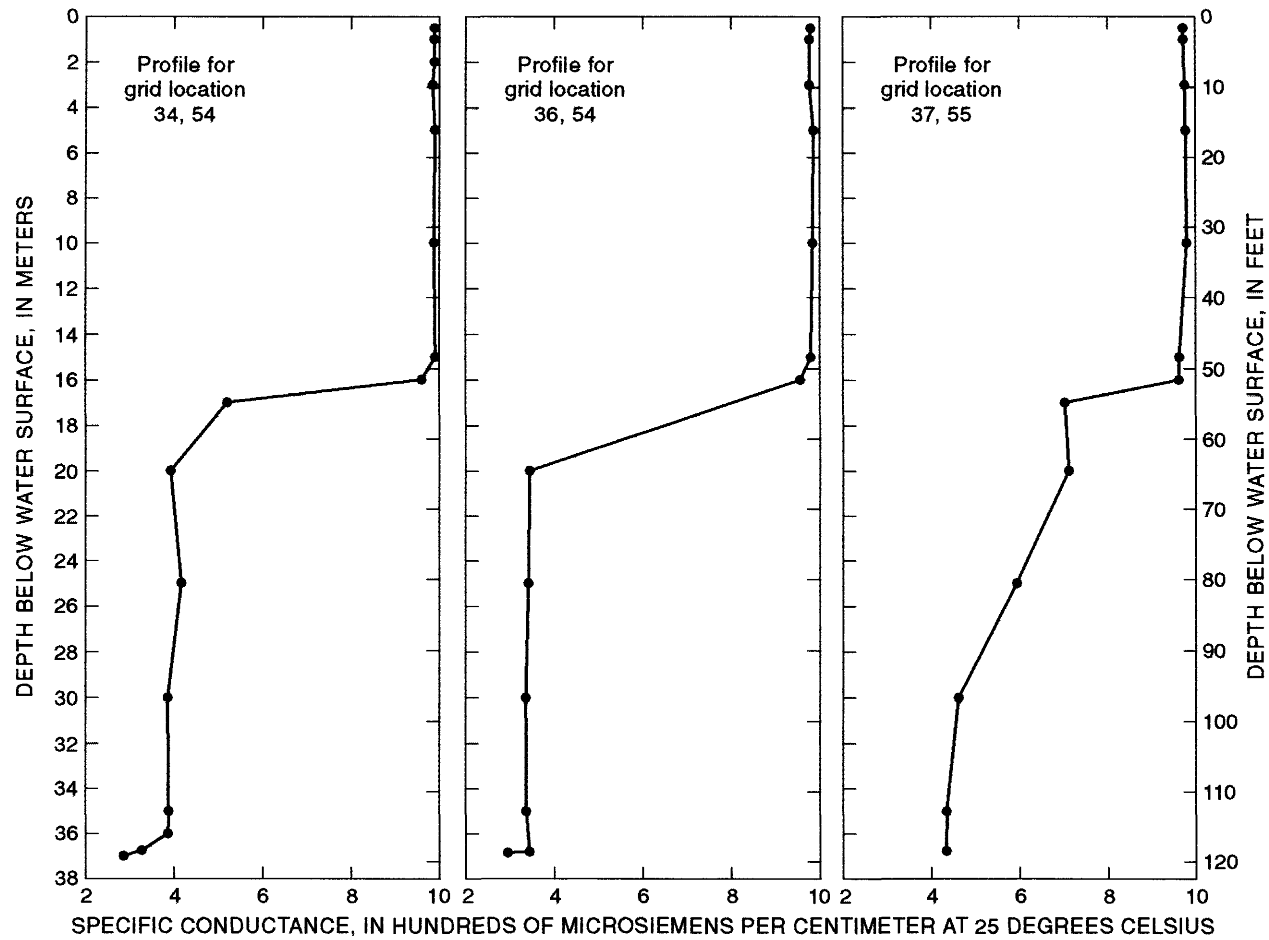


Figure 7. Specific conductance profiles at fissures in Montezuma Well.

ions that can vary significantly depending on the flow path. The plots in figures 8 and 9*A–C* were used to compare chemical analyses from wells and springs with analyses from Montezuma Well. The relative percentages of the major ions in samples from Soda Spring and several wells in the area were similar to Montezuma Well; however, the concentrations of the major ions were not necessarily the same.

Three distinct shapes indicate the relative compositions of water found in the area near Montezuma Well (fig. 8). The concentrations of chloride, fluoride, and sulfate are small throughout the area, and concentrations of magnesium, calcium, and bicarbonate are the predominant ions found in the water. The total concentrations of the major ions in the first pair of Stiff diagrams generally are smaller than in the other pairs. The second pair, which include analyses from Montezuma Well, have the largest concentrations of bicarbonate. The third pair of Stiff diagrams are similar in shape to the first pair, but contain larger concentrations of the major ions.

Chemical analyses of samples from several sites are shown in three plots (figs. 9*A–C*). The relative compositions of the water generally are similar; however, minor differences are evident. The sites represented in figure 9*A* generally are east of Montezuma Well except Page Springs. The sites represented in figure 9*B* are clustered around Montezuma Well, and sites represented in figure 9*C* are along Oak Creek, Dry Beaver Creek, and south of Montezuma Well. At these sites, the percentages of sodium plus potassium is smallest and the percentage of bicarbonate is largest (fig. 9*A*).

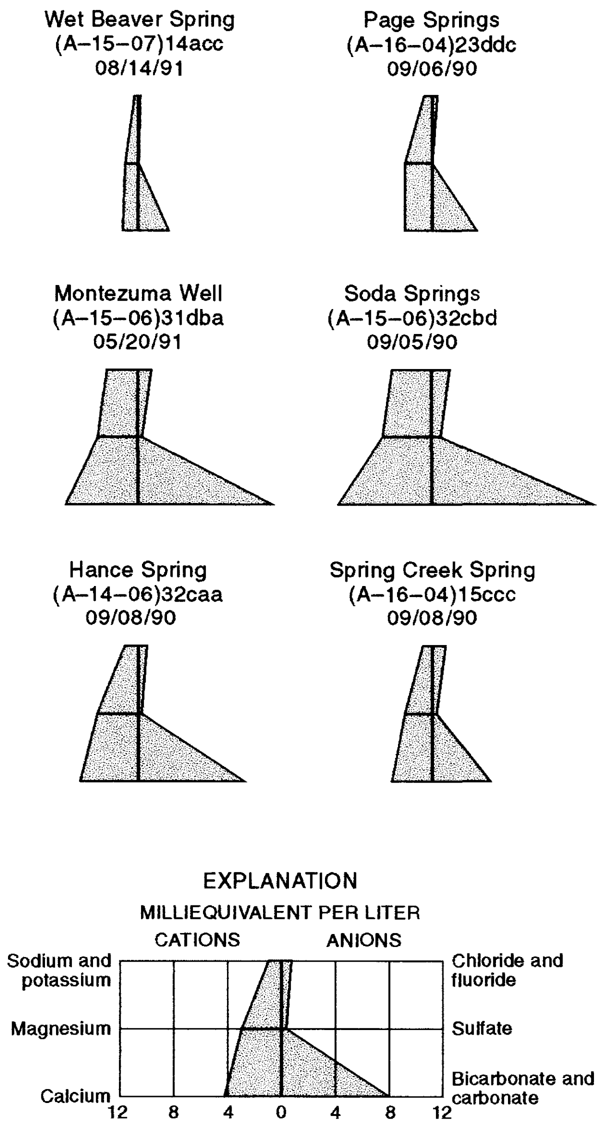


Figure 8. Chemical analyses of Montezuma Well and selected springs.

Isotopes

Tritium and stable isotopes of hydrogen and oxygen were measured to determine the relative ages of water in the study area and to determine the path taken by the water flowing to Montezuma Well. Tritium, a radioactive isotope of hydrogen, occurs naturally in the atmosphere as a result of solar winds and the interaction of cosmic rays with the atmosphere. Large amounts of tritium were added to the atmosphere in the 1950's and 1960's during testing of thermonuclear weapons. The ratio of oxygen-18 (^{18}O) to oxygen-16 (^{16}O) and the ratio of hydrogen-2 (^{2}H, deuterium or D) to hydrogen-1 (^{1}H) can be used to determine the source of water and the path of ground-water flow. Factors that affect the concentrations of oxygen and hydrogen isotopes in water are evaporation, rainfall, altitude, latitude, proximity to the ocean, and seasonal variation.

The tritium content of 1 pCi/L or less of 16 samples, including those from Montezuma Well, indicates that the water was from the regional aquifer and that ground water at these sites was not affected by local recharge. Four samples with a content of 2 to 3 pCi/L may be a mixture of the regional aquifer and more recent water. Although samples were not collected from Beaver Creek, the tritium (6 pCi/L) in water from well (A-15-06)21ddc near Beaver Creek indicates that the ground water flowing to the well probably is recharged by water from the creek. The tritium content of 13 pCi/L in samples from Hance Spring, which is in volcanic rocks, indicates water from the spring is younger than water from the regional aquifer. Water passes through volcanic rocks quickly and is likely to have a higher tritium content.

Twenty-five samples from 18 sites were collected for isotope analysis during this study; 8 samples were from Montezuma Well (table 7) and the remaining samples were from wells and springs in the surrounding area. Only the samples from Montezuma Well were analyzed for tritium and oxygen-isotope ratios. Stable-isotope analyses completed before this study also were used in the interpretations. An analysis of the water collected from Buckhorn Spring was not used in the interpretations because the anomalous results indicate that the sample may have been contaminated. Seasonal variations were not considered because samples were only collected during the late spring or summer.

During the study, 17 samples were analyzed for $^{18}O/^{16}O$ and $^{2}H/^{1}H$. The isotope ratios are expressed by delta notation (δ) in parts per mil (parts per thousand or ‰) differences relative to standard mean ocean water (SMOW). Phase changes, such as evaporation and condensation fractionate oxygen and hydrogen isotopes because of differences in mass. Lighter isotopes evaporate preferentially resulting in water enriched in ^{18}O and D, and a vapor phase enriched in ^{16}O and ^{1}H.

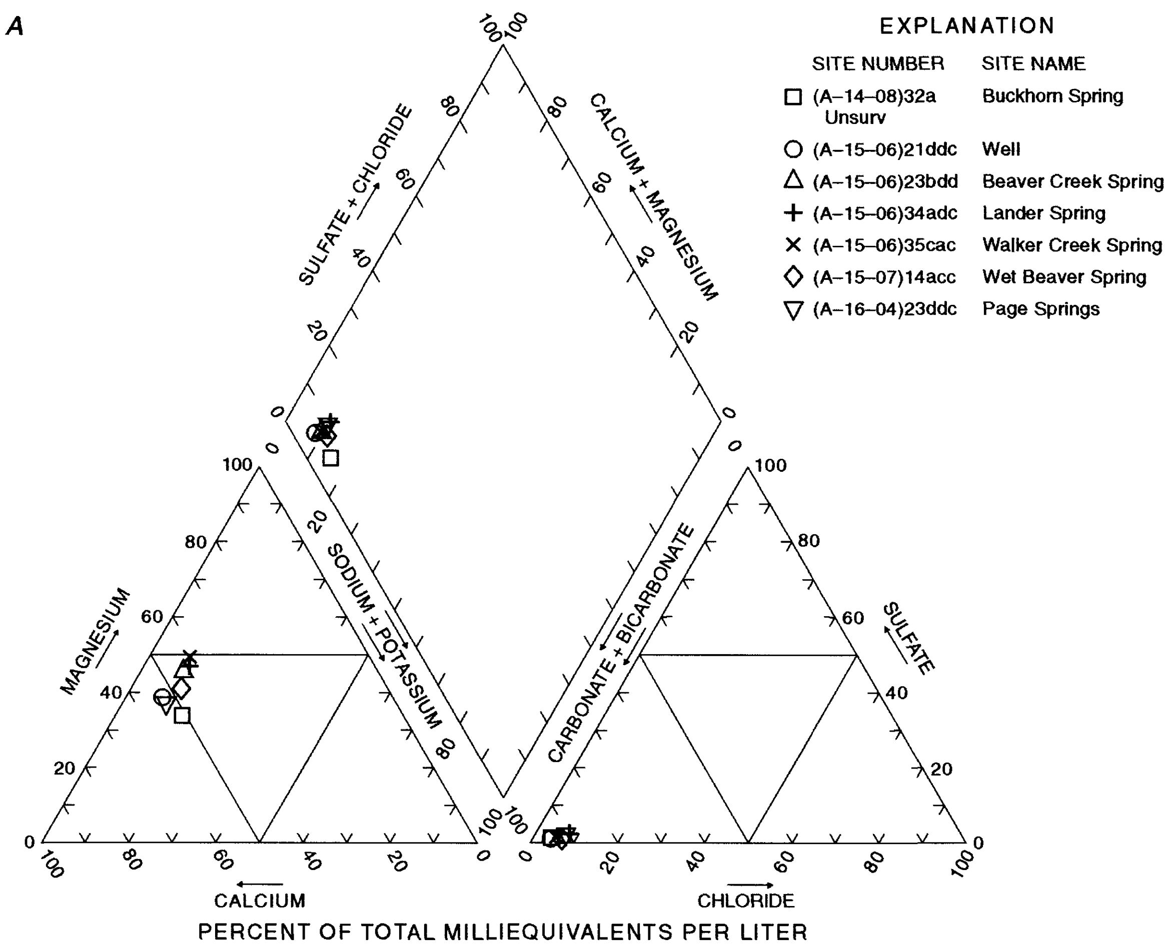


Figure 9. Relative compositions of water from Montezuma Well and selected wells and springs.

Stable isotopes of oxygen and hydrogen have conservative properties in low-temperature ground-water systems and are unaffected by chemical processes over geologically short periods of time (Muir and Coplen, 1981). These characteristics result in spatial and seasonal variations in $\delta^{18}O$ and δD values in precipitation and conservative properties in ground-water systems not subject to evaporation.

The $\delta^{18}O$ values for the samples ranged from -6.9 to -12.2 per mil and the δD values ranged from -61.0 to -81.5 per mil. The plot of the data shows that the water from the wells and springs in the area, including Montezuma Well, has been exposed to similar environmental conditions and could have had similar flow paths (fig. 10). Part of the line of regression of the analyses that plots to right of the global meteoric water line indicates that the water from several sites has been affected by evaporation. Most of the isotope data from the Verde Formation plot to the right of the global meteoric water line compared to the data from the samples from the Supai Formation that plot to the left; however, the isotope analyses could not be used to distinguish the water from the different formations because the data plot in a small group.

DEVELOPMENT OF AN INTERPRETIVE GROUND-WATER FLOW MODEL

Ground-water flow models can be valuable tools for analysis of aquifer systems. Models commonly are developed to predict responses in ground-water systems to changes in recharge or discharge. Development of ground-water models as predictive tools requires spatial information on aquifer-system hydraulic properties, head, inflow and outflow components, and geometry. For the

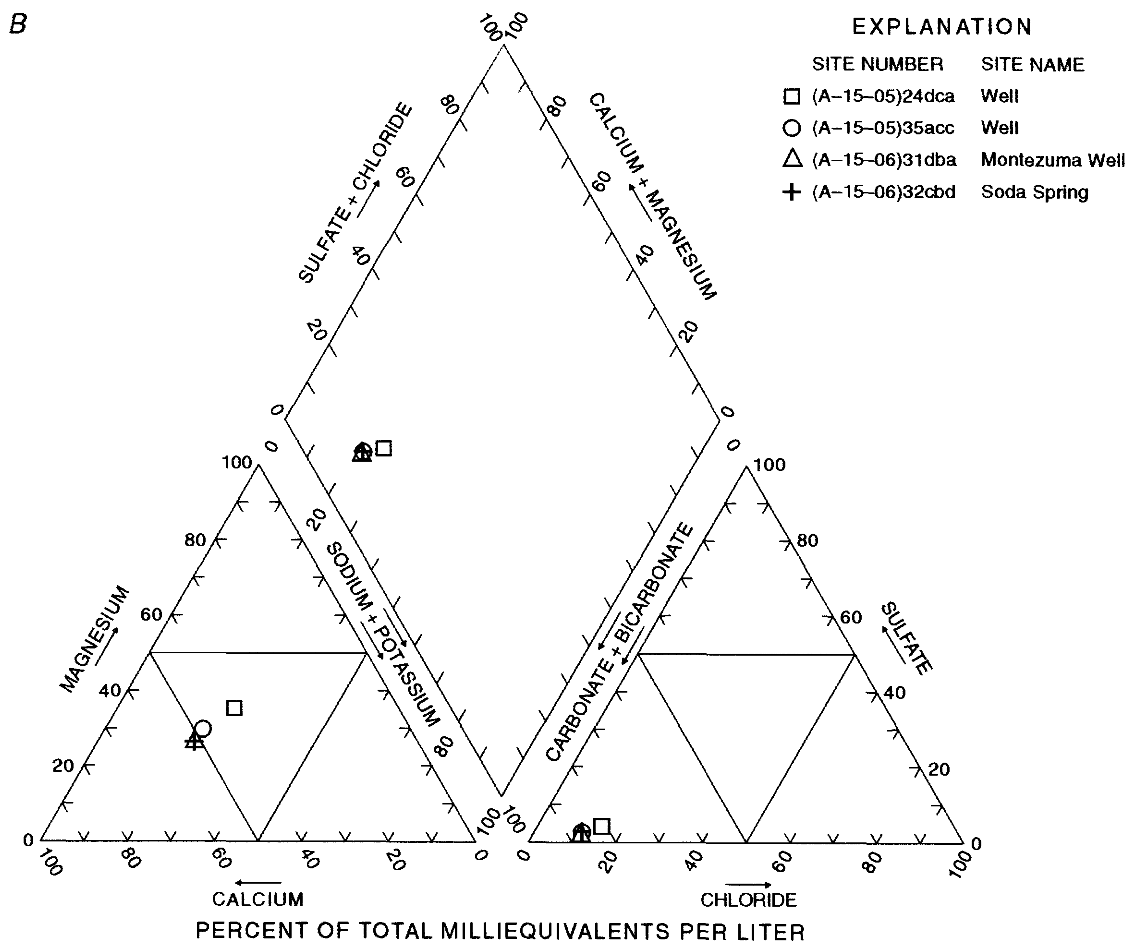


Figure 9. Continued

regional aquifer system in the Verde Valley, data are not sufficient to construct a ground-water model with which future effects could be predicted with confidence. Another use of a ground-water model, however, is to develop insight and understanding regarding interrelations of flow components in an aquifer system. Anderson and Woessner (1992, table 1.1) refer to this use as an interpretive type of modeling. For this study, an uncalibrated interpretive model was developed to study possible mechanisms for discharge of water at Montezuma Well.

Development of the interpretive model used the MODFLOW finite-difference ground-water model (McDonald and Harbaugh, 1988) to simulate, in a general sense, assumed steady-state flow conditions represented by hydrogeology presented by Owen-Joyce and Bell (1983). Although ground-water levels and system flow components vary with time in response to natural and human-induced variations in aquifer inflow and outflow, the assumption of steady-state conditions is valid for studying possible mechanisms of ground-water discharge to Montezuma Well.

Two model layers were used to represent the ground-water flow system in the Verde Valley. The upper layer represents the saturated part of the Verde Formation. In the model, the entire extent of the Verde Formation was assumed to be saturated (figs. 1 and 11). The lower layer represents saturated parts of the Supai Formation and other overlying and underlying rocks through which regional ground-water flow occurs. The areal extent of the lower layer is much larger than the areal extent of the upper layer. The outline of the study area (fig. 1) is the approximate areal extent of the lower layer of the model (fig. 11). The model boundary on the southwest is the edge of the aquifer system (fig. 11), boundaries on the northwest and southeast are flow lines, and the boundary on the east

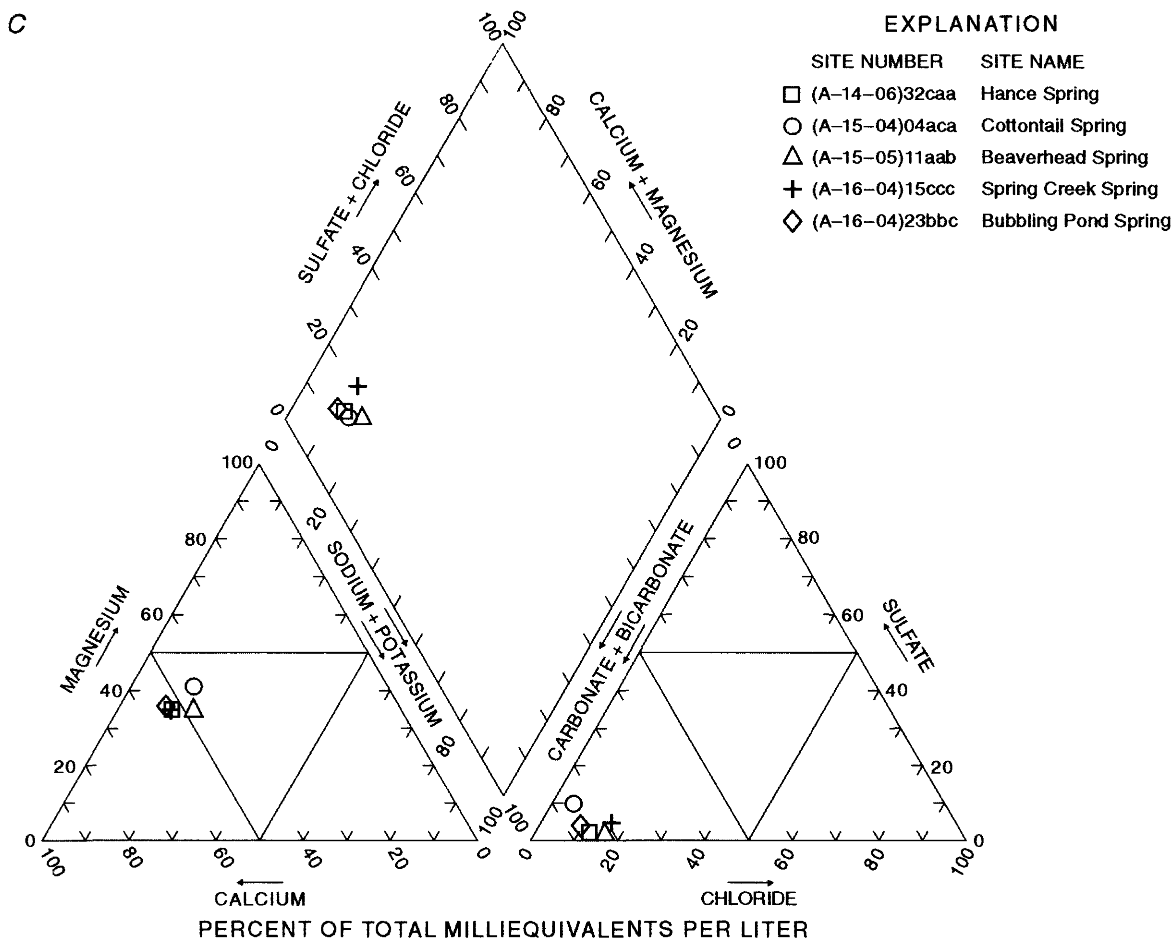


Figure 9. Continued.

and northeast is a ground-water divide. Locations of flow lines and the ground-water divide were inferred from water-level contours presented by Owen-Joyce and Bell (1983). All lateral boundaries in the upper and lower layers are no-flow boundaries.

The model was constructed using meters for length and days for time. In this report, most values involving length are given in equivalent values using metric units with equivalent English units in parentheses. Flow rates are expressed in liters per second with equivalent values given in parentheses.

In the horizontal dimensions, the model is divided into an irregular grid of 58 rows and 46 columns of finite-difference cells (fig. 11). The grid is oriented so that columns of grid cells are parallel to the trend of the Verde River in the study area. Montezuma Well is at the intersection of model row 36 and model column 22 where the grid dimensions are 500 m (1,640 ft) in each direction (fig. 12). The grid size in some areas is as large as 2,000 m (6,560 ft) square.

Aquifer thickness, hydraulic conductivity, and transmissivity of the saturated parts of the Verde Formation and Supai Formation are unknown in much of the study area. Furthermore, the quantity and distribution of recharge to the ground-water system are unknown. For steady-state flow models, such as the one constructed for this study, some hydrologic properties or quantities can be estimated if other properties or quantities are known. For example, if major components of inflow, outflow, and head in the aquifer are known, then transmissivity can be estimated as part of the modeling procedure. Similarly, if transmissivity and head are known, then flow quantities can be estimated. Because transmissivity and flow quantities are unknown for much of the area, values must be assumed for the interpretive model. The model

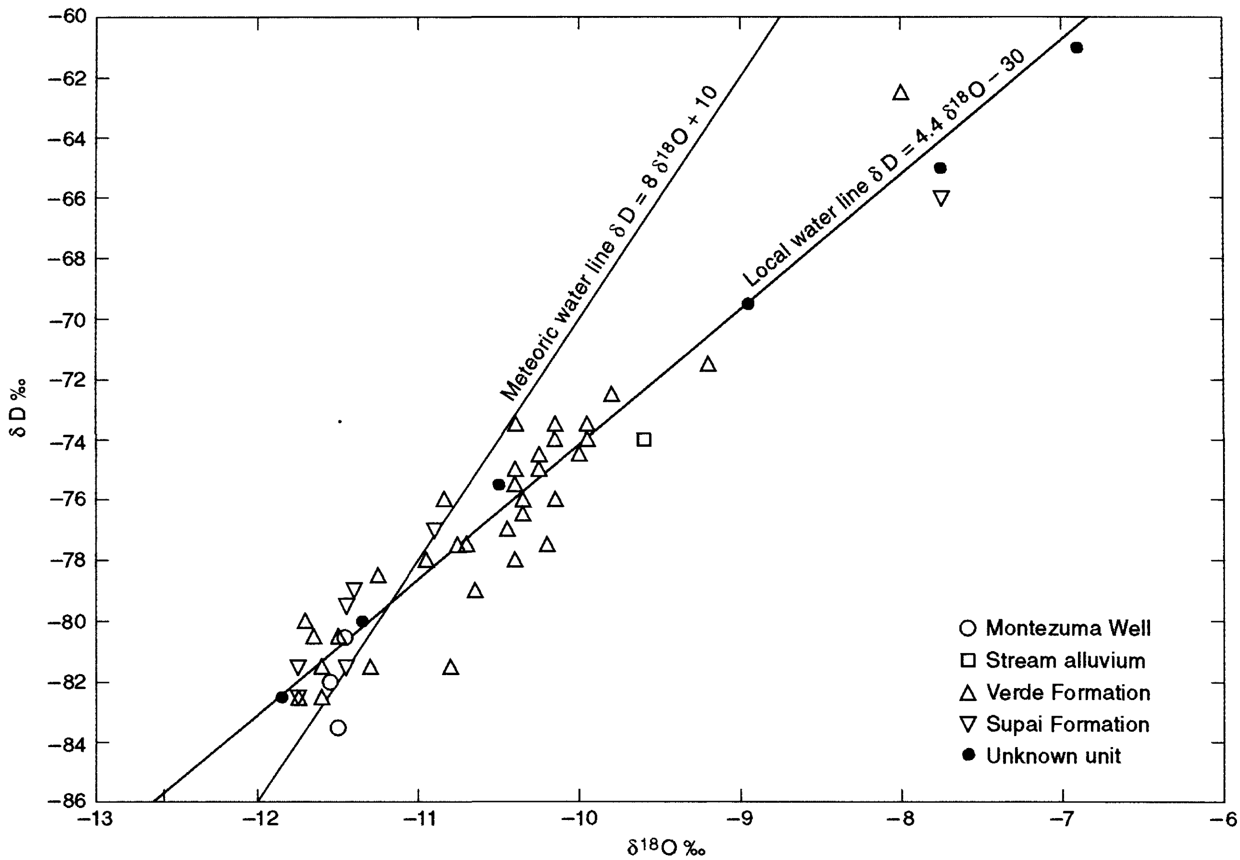
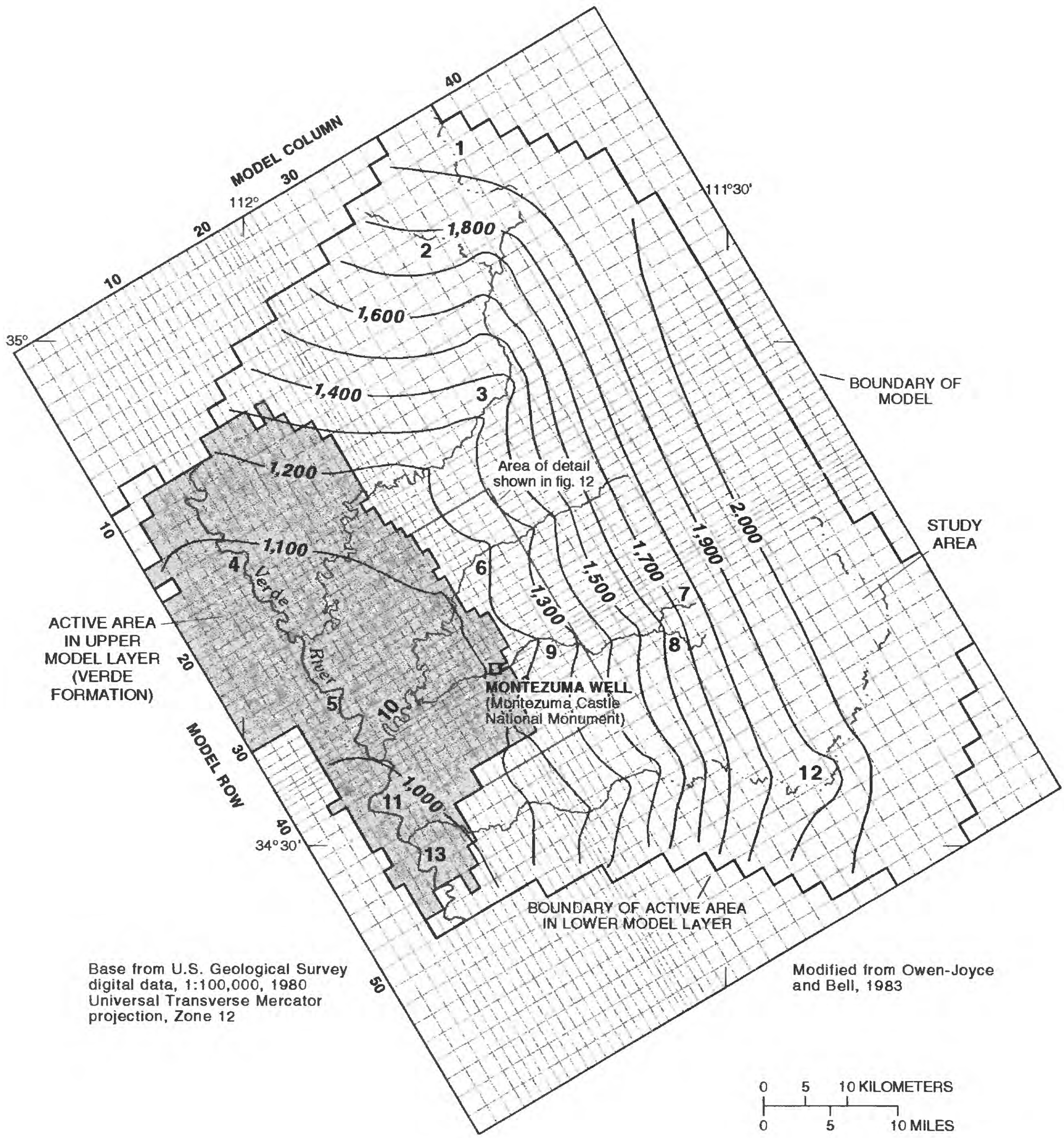


Figure 10. Deuterium and ^{18}O content of water from various sources, Montezuma Castle National Monument area, Arizona.

used the assumption that areal recharge is 10 percent of the long-term average precipitation. Twenter and Metzger (1963) estimated that ground-water recharge in the Verde Valley is about 8 percent of annual precipitation. Assumed values of precipitation were taken from an unpublished precipitation map of the area (Sandra J. Owen-Joyce, hydrologist, U.S. Geological Survey, written commun., 1993). A recharge of 10 percent of the precipitation value (fig. 13) at each model cell results in a total inflow of 62 L/s (211 ft³/s) for the entire model area.

The model uses the Stream Package for MODFLOW (Prudic, 1989) to simulate surface-water features, which include the Verde River, Oak Creek, Dry Beaver Creek, Wet Beaver Creek, and West Clear Creek, and a few washes. For this discussion, the Verde River, the four major creeks, and washes are referred to as "streams." The model input uses stream-segment numbering shown in figure 11. An inflow of 5,300 L/s (187 ft³/s) was specified for the upper end of the Verde River (segment 4). All other stream segments flow in response to ground-water inflow or inflow from upstream segments. An option in the Stream Package was selected to specify stream stage rather than calculating stage as a function of stream discharge. Stage was calculated as the sum of an assumed stream depth and the average streambed altitude within each model cell traversed by a stream (table 6). Streambed conductance for each model cell traversed by a stream was calculated as $(w_s l_s K_s)/b_s$ where w_s is an assumed stream width (table 6), l_s is the length of stream within the model cell, K_s is an assumed vertical hydraulic conductivity of the streambed of 0.1 m/d (0.33 ft/d), and b_s is an assumed streambed thickness of 1.0 m (3.3 ft). Discharge by evapotranspiration and flow to springs other than Montezuma Well was not simulated. This configuration has the



EXPLANATION

—*1,200*— GENERALIZED WATER LEVEL—Contour interval 100 meters. Datum is sea level

7 NUMBERED STREAM SEGMENT USED IN MODEL

Figure 11. Grid developed for ground-water flow model and generalized water-level contours for Montezuma Well area, Arizona.

Figure 12. Details of model grid around Montezuma Well and features used to test effects of geologic structure on upward flow to well.

effect of forcing ground water to discharge to the streams. Vertical leakance between the upper and lower model layers is unknown; however, the property is important in controlling discharge to Montezuma Well. The significance of vertical leakance is discussed further in this section. With the assumed recharge distribution, constant transmissivity values in the upper and lower layer were adjusted until head near the northeast boundary along the assumed ground-water divide in the lower layer was similar to head in the same area estimated by Owen-Joyce and Bell (1983, pl. 2). Using a transmissivity value of 75 m^2/d (800 ft^2/d) for each layer, the simulated water levels in the lower layer near the ground-water divide range from about 1,920 to 2,100 m (6,300 to 6,900 ft; fig. 11). Water

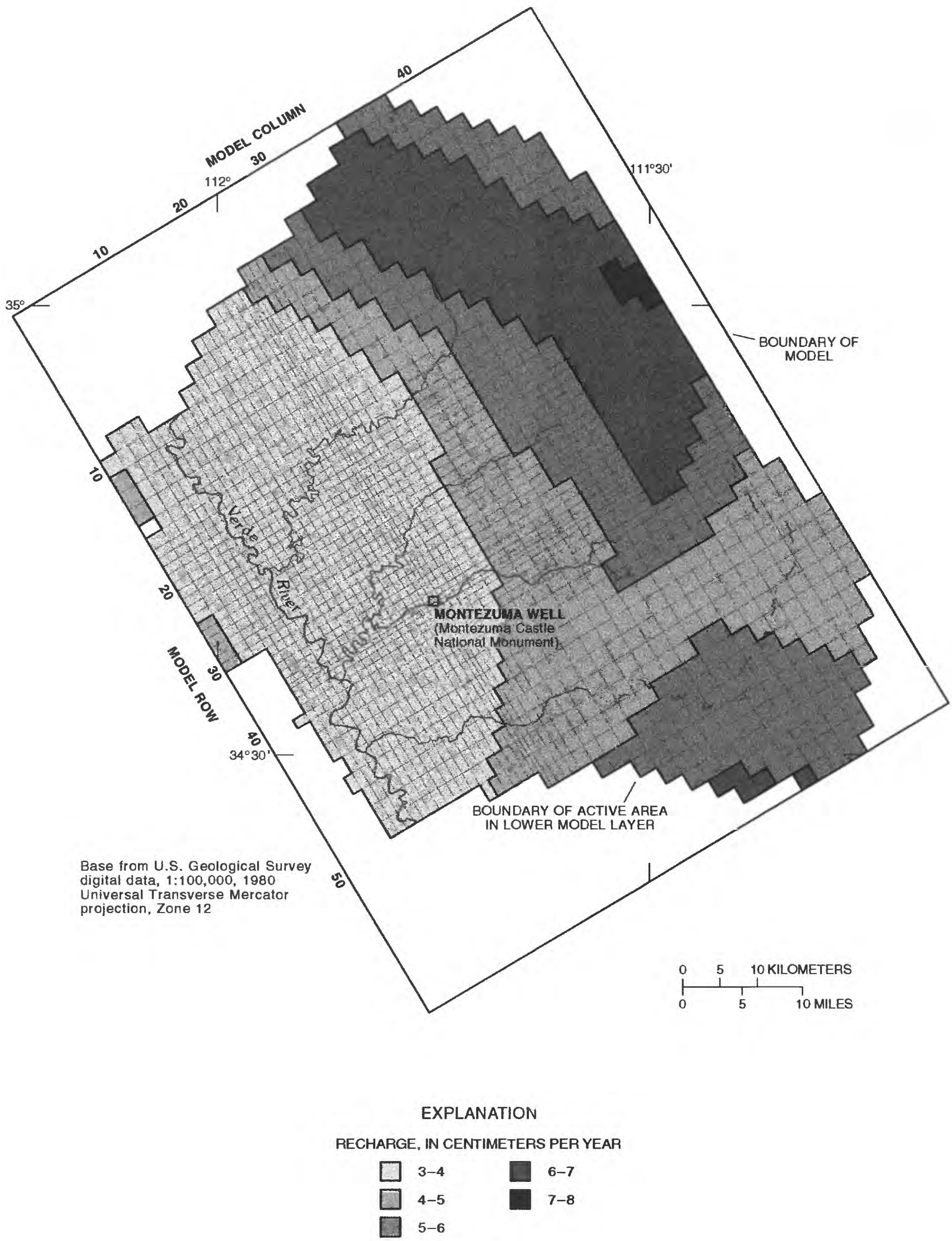


Figure 13. Recharge distribution used in interpretive ground-water model.

Table 6. Properties and conditions for stream segments represented in the model

Segment number	Name of stream	Assumed properties and conditions: Stream width, Meters	Stream width, Feet	Stream depth, Meters	Stream depth, Feet	Range in streambed altitude, Meters	Range in streambed altitude, Feet
1	Fry Canyon Wash and Oak Creek	1.0	3.3	0.3	1.0	2,195–1,633	7,203–5,357
2	West Fork Oak Creek	1.0	3.3	.3	1.0	2,064–1,624	6,772–5,329
3	Oak Creek	3.0	9.8	.5	1.6	1,600–965	5,250–3,166
4	Verde River	5.0	16.4	1.0	3.3	1,041–965	3,415–3,166
5	Verde River	5.0	16.4	1.0	3.3	965–935	3,166–3,067
6	Dry Beaver Creek	2.0	6.6	.3	1.0	1,892–988	6,208–3,240
7	Unnamed wash	1.0	3.3	.3	1.0	1,934–1,666	6,347–5,465
8	Wet Beaver Creek	1.0	3.3	.3	1.0	1,875–1,582	6,151–5,191
9	Wet Beaver Creek	2.0	6.6	.3	1.0	1,544–991	5,066–3,250
10	Beaver Creek	3.0	9.8	.3	1.0	984–936	3,230–3,070
11	Verde River	5.0	16.4	1.0	3.3	935–914	3,066–3,002
12	West Clear Creek	3.0	9.8	.3	1.0	2,341–916	7,682–3,005
13	Verde River	5.0	16.4	1.0	3.3	908–870	2,978–2,853

levels estimated by Owen-Joyce and Bell (1983, pl. 2) for the same area range from about 1,860 to 2,070 m (6,100 to 6,800 ft). In areas downgradient from the ground-water divide, the computed water levels are controlled by the altitude of streams. Estimates of ground-water levels presented by Owen-Joyce and Bell (1983, pl. 2) also were controlled by altitude of streams; therefore, simulated water-level contours are similar to the previously estimated contours for most of the simulated area.

The main purpose of the interpretive model is to test possible mechanisms for discharge of an estimated 65 L/s (2.3 ft^3/s) of ground water at Montezuma Well, which is within the area of the surface exposure of the Verde Formation. Wet Beaver Creek traverses the Verde Formation within several hundreds of feet from the pond at Montezuma Well; however, the altitude of the water surface of Montezuma Well (approximately 1,083 m (3,553 ft) above mean sea level) is about 9 m (30 ft) higher than the stage in the adjacent creek. Because of the differences in water-surface altitudes, this study presents the hypothesis that ground water in the Supai Formation is the source of discharge to Montezuma Well. The mechanism of upward flow from the Supai Formation at Montezuma Well requires (1) restriction to vertical movement of water from the Supai Formation to the Verde Formation in the area surrounding Montezuma Well and (2) a localized conduit allowing vertical movement of water from the Supai Formation to the land surface.

The restriction to vertical movement of water can be increased by lowering the vertical leakance between the upper and lower model layers. With vertical leakance in the range of 10^{-2} to 10^{0} day^{-1}, the computed head in the lower model layer at Montezuma Well is slightly less than the altitude of the water surface in Montezuma Well (fig. 14). However, as leakance is decreased, the computed head in the Supai Formation and potential driving force for upward flow to Montezuma Well is increased.

A conduit for vertical movement of water to the land surface at Montezuma Well was represented in the model with the Drain Package using a single drain cell in model layer 2, row 36, and column 22. A series of simulations were made using different values of vertical leakance, a drain conductance of 1.0×10^5 m^2/d (1.1×10^6 ft^2/d), and a drain elevation of 1,083 m (3,553 ft). The series shows that discharge to Montezuma Well can vary from zero to more than 100 L/s (3.5 ft^3/s) (fig. 14). The conclusion drawn from this analysis is that upward flow from the Supai Formation is a possible mechanism for discharge to Montezuma Well.

Geologic structure is another possible contributing mechanism to discharge at Montezuma Well and other springs in the area. An analysis of gravity data by Smith (1984) indicates a

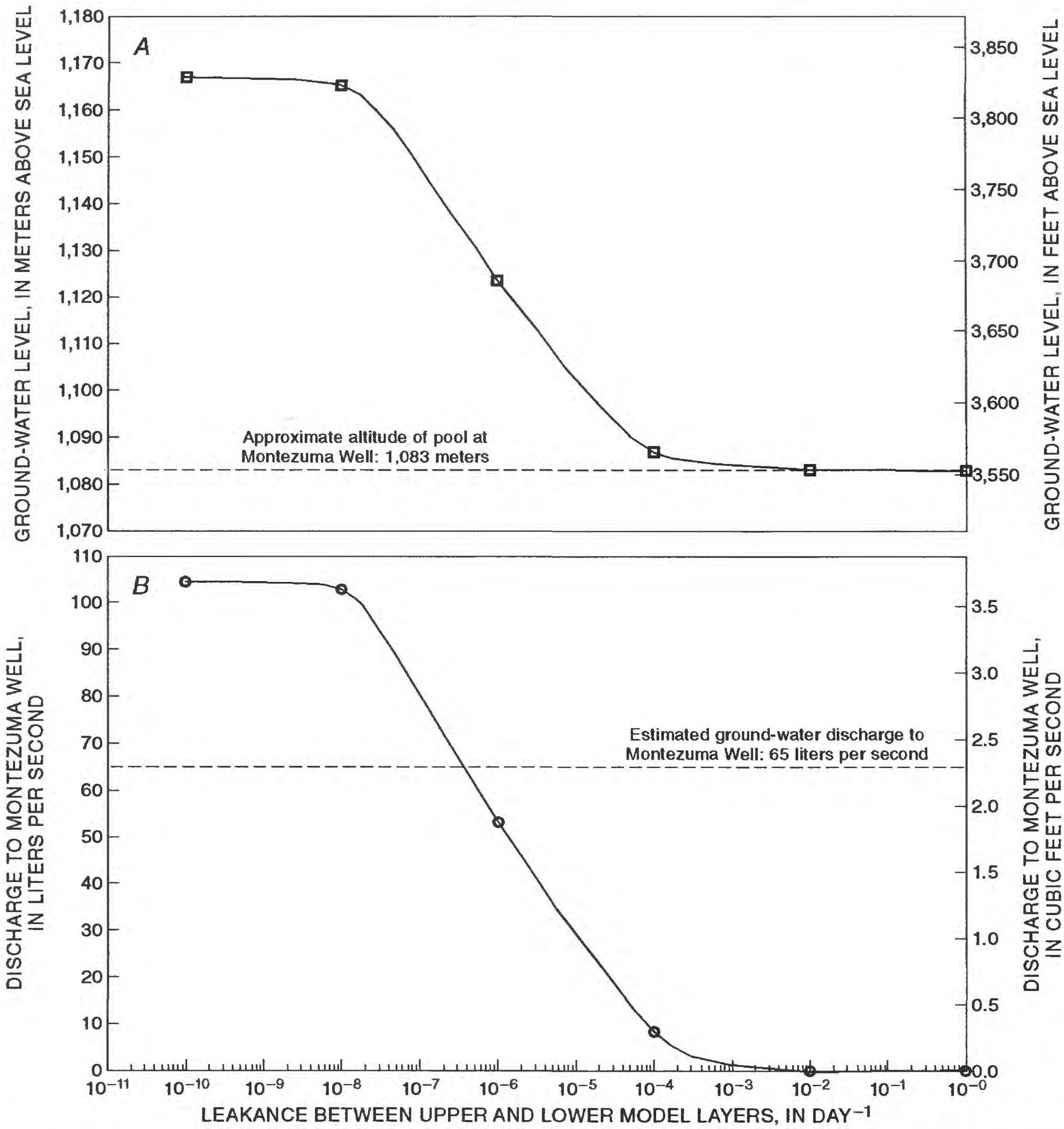


Figure 14. Effects of variations in leakance between model layers on computed water level and discharge at Montezuma Well.

north-northwestward-trending structure at or near Montezuma Well. The possible effects of the fault were simulated by placing a horizontal flow barrier (Hsieh and Freckleton, 1993) in the lower layer downgradient from Montezuma Well (fig. 12). All model properties and conditions except for vertical leakance and hydraulic properties of the flow barrier were the same as those used in previous simulations. Vertical leakance between layers was set at 1×10^{-6} d^{-1} downgradient from the flow barrier and was set at 0.0 d^{-1} upgradient from the barrier. For each segment along the barrier (fig. 12), the hydraulic characteristic (transmissivity divided by width of segment) of the barrier was set at 1.0×10^{-6} m/d (3.3×10^{-6} ft/d). The resulting discharge to Montezuma Well from the simulation is 60 L/s

($2.1 ft^3/s$). The simulation demonstrates that geologic structure in the Supai Formation could play a role in the upward movement of water to Montezuma Well.

By adjusting vertical leakance and (or) hydraulic characteristics of horizontal-flow barriers, the interpretive model could be made to simulate the estimated actual discharge to Montezuma Well. The simulation, however, would not be a "calibration" that could be used for predicting possible effects of ground-water development. Different simulations using other combinations of recharge, transmissivity, and vertical leakance could produce other representations of the flow system with appropriate discharge to Montezuma Well. More data related to system flow quantities, hydraulic properties, and physical characteristics are needed before a predictive model can be developed; however, the interpretive model presented in this report could be used in the future to help develop an improved understanding of the ground-water system in the Verde Valley.

SOURCE OF WATER IN MONTEZUMA WELL

Observations made during the diving survey of Montezuma Well indicate that upward movement of water into the pond occurs in at least two areas. The areas referred to as "fissures" in this report. A probe of a multiparameter instrument was lowered about 22 m (70 ft) below the bottom of the pond into one of the fissures and temperature, pH, and specific conductance were measured. Results of surveys in the fissures are presented in the discussion of field measurements and in figures 5–7. In comparison to water in the pond, water in the fissures had higher temperature, lower specific conductance, and lower pH. The average specific conductance of the water in the fissures was about 400 μS/cm, whereas, specific conductance of water in the pond is about 1,000 μS/cm. These values indicate concentrations of total dissolved solids of roughly 200 mg/L and 500 mg/L, respectively. The Verde Formation is not likely to be the source of the water in the fissures because higher values of total dissolved solids are typical for water in the Verde Formation; however, values around 200 mg/L are typical for ground-water in the Supai Formation. Observations made during the diving survey and measurements made within the fissures indicate that the Supai Formation and possibly other rock units underlying the Verde Formation are sources of water to the fissures.

Inflow of water with 200 mg/L of dissolved solids, however, cannot account for the water chemistry in the pond. The outflow from the pond is about 65 L/s ($2.3 ft^3/s$) of water with a total dissolved-solids concentration of about 500 mg/L. In some situations, dissolved solids can increase because of evaporation and transpiration; however, the annual average rate of evaporation plus transpiration from the pond in Montezuma Well is likely to be less than 0.3 L/s ($0.01 ft^3/s$). Because that rate is small in comparison to the rate of surface-water outflow from the pond, evaporation and transpiration cannot explain the increase in concentration of dissolved solids.

Another possible explanation for the increase in dissolved solids is dissolution of rocks adjacent to the pond after water enters through the fissures. The discharge rate of 65 L/s ($2.3 ft^3/s$) and dissolved-solids concentration of 500 mg/L indicate that the discharge of dissolved solids from the pond is about 33 g/s. If the inflow from the fissures was 65 L/s ($2.3 ft^3/s$) of water with 200 mg/L of dissolved solids, then the rate of inflow of dissolved solids would be about 13 g/s. The difference between the inflow and outflow rates would indicate a dissolution rate of about 20 g/s. Assuming a rock density of 2.7 g/cm^3, the volumetric rate of dissolution would be about 230 m^3/yr, resulting in significant changes in the rock mass adjacent to the pond over periods of decades and longer. Because those changes have not been observed, dissolution of rocks at the rate of 20 g/s is not considered to be a reasonable explanation for the increase in dissolved solids.

A third explanation for the increase in dissolved solids is that in addition to the water from the fissures entering the pond, water with a higher dissolved-solids concentration also is entering the pond. Another source of water could be the Verde Formation. In addition to relatively high concentrations of dissolved solids, water in parts of the Verde Formation is characterized by high concentrations of arsenic. The arsenic concentration of 100 μg/L for water in Montezuma Well reported by Owen-Joyce and Bell (1983) indicates the Verde Formation is a likely source of water to Montezuma Well. On the other hand, the head in the Verde Formation is thought to be lower than the altitude of the pond surface at Montezuma Well. The nearest wells to Montezuma Well that tap the Verde Formation are wells (A-15-6)31cba1 and (A-15-6)31cba2, which are adjacent to Wet Beaver Creek about 600 m (2,000 ft) downstream from the pond in Montezuma Well. From data given by Owen-Joyce and Bell (1983), the altitude of the water level in the Verde Formation can be computed to be about 1,058 m (3,470 ft) above sea level, which is lower than the pond surface and the water surface in Wet Beaver Creek (fig. 15). The possibility remains, however, that the flow system in the Verde Formation could include solution channels that transmit water to Montezuma Well from other areas within the Verde Formation. Although the mechanism for inflow from the Verde Formation is not understood, the Verde Formation and the underlying Supai Formation probably are the sources of water to Montezuma Well.

CONSIDERATIONS FOR FURTHER DATA COLLECTION

Although changes in the ground-water system that indicate impending effects on the water resources of Montezuma Well were not found during this project, further study is required to define the hydrologic system and design a long-term monitoring program, which would enable the delineation of areas outside the park where development is likely to affect park resources. Additional hydrologic and geologic information are necessary to further develop and calibrate the ground-water model. Geophysical techniques and borehole inspection are needed to investigate the gravity survey anomaly of a north-northwestward-trending structure near Montezuma Well that may form a ground-water flow barrier. Other test-well drilling and testing may be necessary to define the geology and related aquifer properties.

Application of the new information would be used to design and develop a monitoring program to detect changes in the ground-water system that might indicate a potential change in the flow or water chemistry of Montezuma Well. Potential options for monitoring include the following:

- Install a staff gage in the pond to monitor the stage of the water in the pond.
- Install a streamflow-gaging station at the cave outlet to measure the discharge. The streamflow-gaging station at Montezuma Well was discontinued in September 1992.
- Measure the discharge from several springs in the area, particularly, Soda, Walker, and

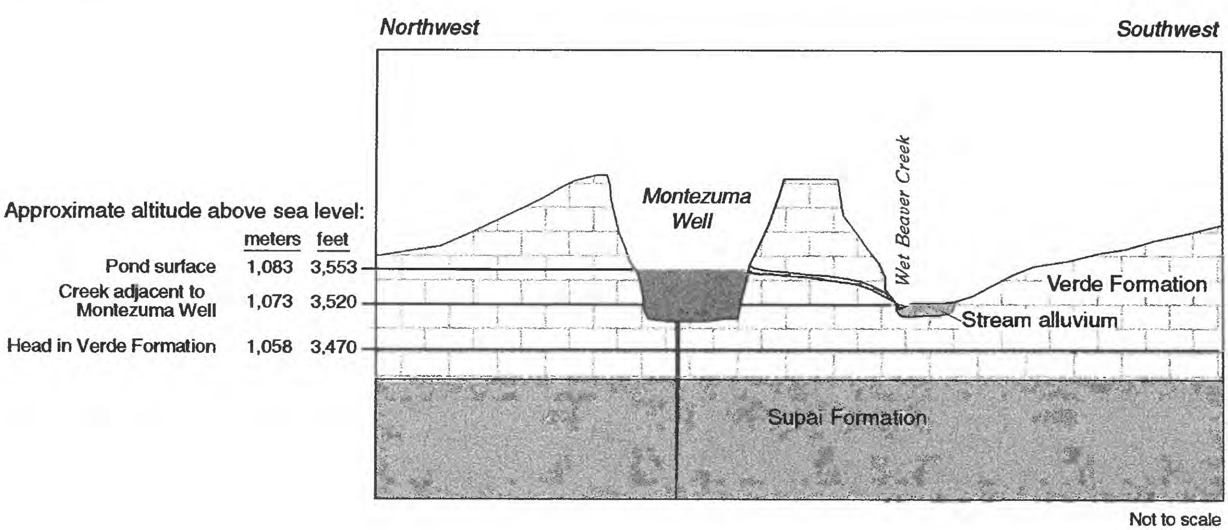


Figure 15. Idealized cross section through Montezuma Well. Head in Verde Valley Formation is from measurements in well about 600 meters (2,000 feet) from pond.

Lander Springs because of their chemistry and proximity to Montezuma Well.

- Record water levels in wells upgradient and downgradient from Montezuma Well that are drilled to various depths and that are finished in different units. Existing, privately-owned wells may be accessible for measuring water levels.
- Drill a series of monitoring wells near Montezuma Well that would represent the potentiometric heads in the area. The wells probably would have water levels ranging from less than 15 m (49 ft) to more than 90 m (295 ft) below land surface.
- Collect quarterly water samples from the observation wells and springs and have them analyzed for concentrations of major ions. Specific conductance, pH, and temperature would be measured when samples were collected.

SUMMARY

Montezuma Well, a unit of Montezuma Castle National Monument, is in the Verde Valley, a popular retirement area in central Arizona. A significant reduction in the spring flow to Montezuma Well would affect the environment in and around the pond. Nearby communities of McGuireville, Lake Montezuma, and Rimrock have more than 2,000 residents, and census figures show that Camp Verde has grown from 1,100 in 1980 to 6,200 in 1990. The increasing population and associated residential and commercial development has increased the use of water.

Data on flow from Montezuma Well and water levels in eight wells measured annually do not indicate that the ground-water system has been affected by development. The wide range in water levels generally is the result of well construction and local lithology; however, additional data are needed to monitor the ground-water system around Montezuma Well. Monitoring of the ground-water system would detect changes in discharges from the pond or changes in the ground-water system that might indicate a potential change of flow to Montezuma Well.

Water-chemistry data indicate that the ground water sampled from wells in the area is a mixture of water from the various lithologic units. Most of the water samples are a mixed cation type of calcium, magnesium, and sodium, and most are a bicarbonate type water. A few samples collected near Camp Verde are a sulfate type. The water in samples collected east of Montezuma Well is a magnesium calcium bicarbonate type. Water in samples collected from Montezuma Well and the Verde Formation near Montezuma Well is a calcium magnesium sodium bicarbonate type.

The source of the water to Montezuma Well could not be determined from isotope analyses. Tritium values only confirm that the water is from the regional aquifer and that there is no local recharge. The oxygen-isotope ratios were within the range of ratios in water from other wells and springs in the area.

The MODFLOW finite-difference ground-water model was used to develop an uncalibrated interpretive model to study possible mechanisms for discharge of water at Montezuma Well. The study presents the hypothesis that ground water in the Supai Formation is the source of discharge to Montezuma Well because of the differences between the water surface of Montezuma Well and the stage in the adjacent Wet Beaver Creek. A series of simulations show that upward flow from the Supai Formation is a possible mechanism for discharge to Montezuma Well, and that a geologic structure in the Supai Formation could play a role in the upward movement of water to Montezuma Well.

The mechanism for inflow from the Verde Formation is not understood; however, this study concludes that the Verde Formation, Supai Formation, and the underlying rock units probably are the sources of water to Montezuma Well. The Supai Formation is probably the source of the water in the fissures because the concentrations of total dissolved solids in the fissures are typical of water in the Supai Formation. Additional water, however, is assumed to be entering the well from the Verde Formation or from other rock units that have higher concentrations of dissolved solids.

More data related to system flow quantities, hydraulic properties, and physical characteristics are needed before a predictive model can be developed; however, the interpretive model presented in this report could be used in the future to help develop an improved understanding of the ground-water system in the Verde Valley.

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FIELD MEASUREMENTS

-PAGE 39 FOLLOWS-

Table 7. Field measurements, Montezuma Well

Grid coordinates, in meters X	Grid coordinates, in meters Y	Depth, in meters	Temperature, in degrees Celsius	pH	Specific conductance, in microsiemens per centimeter	Dissolved oxygen, in milligrams per liter	Saturation of dissolved oxygen, in percent	Oxidation-reduction potential	Remarks
10	30	0.25	21.57	7.84	1,031	8.88	115.1	0.292	
10	30	.50	22.30	6.86	1,006	8.43	109.3	.317	Scummy next to weeds and under ash tree. Vegetation on bottom.
10	30	1.00	22.60	6.77	995	7.25	94.7	.319	
10	30	2.11	22.64	6.67	986	7.23	93.2	.322	
10	40	.50	22.41	6.58	979	6.73	87.6	.287	
10	40	1.00	22.41	6.58	977	6.76	88.1	.291	
10	40	3.00	22.37	6.59	977	6.70	86.7	.293	
10	40	5.00	22.31	6.58	978	6.46	83.3	.296	
10	40	8.00	22.27	6.58	978	6.07	78.1	.295	
10	50	.50	22.29	6.56	977	7.25	94.5	.343	
10	50	1.00	22.26	6.56	976	7.26	94.6	.343	
10	50	3.00	22.19	6.56	977	7.14	92.8	.344	
10	50	5.00	22.15	6.56	979	7.05	91.7	.345	
10	50	8.00	22.12	6.56	979	7.02	91.2	.345	
10	60	.50	24.02	6.86	988	7.31	97.5	.309	
10	60	1.00	23.61	6.61	978	7.57	100.3	.322	
10	60	3.00	22.86	6.58	973	6.85	89.8	.328	
10	60	4.92	22.60	6.58	978	5.94	78.5	.330	
10	60	5.00	22.49	6.58	981	6.26	81.6	.331	In weeds.
10	70	.5	23.31	6.73	961	7.74	102.8	.476	
10	70	1.0	22.64	6.63	972	5.86	76.5	.436	Weeds and scum
10	70	1.2	22.45	6.57	956	3.30	41.3	.242	
20	20	.25	21.91	7.44	1,053	10.52	135.1	.306	
20	20	.50	22.56	6.80	1,004	7.72	101.7	.318	In weeds, scum and grass, rock bottom
20	20	1.00	22.70	6.76	990	7.54	98.9	.318	
20	30	.50	23.08	6.76	985	7.35	97.5	.295	
20	30	1.00	23.08	6.76	986	7.33	97.0	.295	Open water
20	30	3.00	22.97	6.63	973	7.21	95.1	.301	
20	30	5.00	22.81	6.60	973	7.22	93.7	.302	
20	30	8.00	22.45	6.59	979	6.65	86.0	.300	Bottom
20	40	.50	22.49	6.61	980	6.88	90.0	.311	
20	40	1.00	22.49	6.61	979	6.67	87.4	.313	Open water
20	40	3.00	22.45	6.59	977	6.72	87.1	.316	
20	40	5.00	22.38	6.58	977	6.52	84.9	.318	
20	40	10.00	22.30	6.59	980	6.42	83.0	.319	
20	40	12.48	22.27	6.58	980	6.12	79.2	.252	Soft bottom
20	40	12.48	22.23	6.59	984	5.51	70.3	.240	In mud bottom
20	50	.50	22.37	6.58	978	7.19	93.9	.343	
20	50	1.00	22.34	6.57	977	7.14	93.2	.344	
20	50	3.00	22.23	6.56	977	6.94	90.3	.345	

Table 7. Field measurements, Montezuma Well—Continued

Grid coordinates, in meters		Depth, in meters	Temperature, in degrees Celsius	pH	Specific conductance, in microsiemens per centimeter	Dissolved oxygen, in milligrams per liter	Saturation of dissolved oxygen, in percent	Oxidation-reduction potential	Remarks
X	Y								
20	50	5.00	22.19	6.56	978	6.89	89.5	0.345	
20	50	10.00	22.12	6.56	981	6.90	89.7	.345	
20	50	14.70	22.08	6.57	981	6.85	89.1	.314	
20	60	.50	23.83	6.80	988	7.15	95.6	.316	
20	60	1.00	23.46	6.60	971	7.95	105.7	.326	
20	60	3.00	22.90	6.58	973	7.62	98.3	.331	
20	60	5.00	22.62	6.57	977	6.41	83.5	.332	
20	60	10.00	22.43	6.57	982	5.66	73.6	.334	
20	60	11.46	22.24	6.57	985	5.80	75.3	.277	
20	70	.50	22.41	6.60	978	7.71	100.5	.325	
20	70	1.00	22.41	6.60	976	7.12	92.6	.327	Weeds; no scum
20	70	3.00	22.38	6.61	976	7.58	98.8	.328	
20	70	5.00	22.34	6.61	977	7.51	97.6	.331	
20	70	6.00	22.30	6.62	976	6.55	84.6	.299	
20	80	.50	21.94	6.87	1,007	8.98	116.3	.337	Scummy
20	80	.70	22.15	6.65	907	6.78	85.6	.280	Weeds; rock bottom
30	20	.02	23.34	7.30	1,047	18.52	247.5	.251	
30	20	.25	26.52	6.98	975	12.77	175.4	.281	
30	20	.27	24.51	6.78	972	7.29	98.4	.291	
30	20	.50	23.83	6.77	971	7.10	94.8	.294	
30	20	1.00	23.54	6.76	974	6.62	88.3	.295	
30	20	2.00	23.23	6.70	975	6.55	85.7	.298	Weedy bottom
30	20	2.40	22.86	6.53	943	2.61	32.0	.174	In bottom
30	30	.25	22.93	6.75	987	7.28	95.5	.278	Open water
30	30	.50	22.97	6.74	986	6.80	90.0	.280	
30	30	1.00	22.97	6.74	987	7.12	93.6	.282	
30	30	3.00	22.83	6.61	976	7.04	91.8	.290	
30	30	5.00	22.60	6.60	979	6.75	87.6	.292	Semisoft
30	30	7.79	22.45	6.59	983	5.42	69.9	.247	Springy bottom
30	40	.50	22.49	6.61	980	6.55	84.7	.298	
30	40	1.00	22.51	6.62	979	6.56	85.8	.310	
30	40	3.00	22.45	6.59	977	6.55	85.5	.315	
30	40	5.00	22.34	6.59	978	6.22	80.6	.317	
30	40	10.00	22.29	6.59	979	5.95	77.4	.319	
30	40	13.54	22.26	6.59	981	6.02	77.7	.300	Semisoft bottom
30	50	.50	22.41	6.60	980	7.16	93.6	.332	
30	50	1.00	22.39	6.58	977	7.06	92.3	.334	
30	50	3.00	22.30	6.56	975	6.88	89.6	.335	
30	50	5.00	22.22	6.56	979	6.86	89.2	.336	
30	50	10.00	22.15	6.56	982	6.85	89.0	.337	

Table 7. Field measurements, Montezuma Well—Continued

Grid coordinates, in meters X	Grid coordinates, in meters Y	Depth, in meters	Temperature, in degrees Celsius	pH	Specific conductance, in microsiemens per centimeter	Dissolved oxygen, in milligrams per liter	Saturation of dissolved oxygen, in percent	Oxidation-reduction potential	Remarks
30	50	15.00	22.12	6.57	981	6.81	88.3	0.336	
30	50	15.70	22.44	6.48	906	4.32	56.3	.338	
30	60	.50	23.76	6.62	984	7.17	95.8	.315	
30	60	1.00	23.55	6.58	978	7.26	97.9	.318	
30	60	3.00	22.87	6.57	977	6.33	82.6	.324	
30	60	5.00	22.64	6.56	980	5.96	77.8	.326	
30	60	10.00	22.40	6.56	986	5.98	78.2	.328	
30	60	15.00	22.30	6.57	986	5.84	75.5	.331	
30	60	15.30	22.28	6.55	964	4.98	62.9	.251	
30	70	.50	22.50	6.61	976	6.99	91.4	.326	
30	70	1.00	22.30	6.60	978	7.20	93.7	.328	Open water
30	70	3.00	22.38	6.60	976	7.36	95.9	.330	
30	70	5.00	22.34	6.60	977	7.52	97.9	.333	
30	70	9.00	22.30	6.60	978	7.99	104.2	.333	Bottom
30	70	9.00	22.29	6.61	978	7.57	99.2	.329	Bottom in mud
30	80	.50	22.41	6.63	977	8.80	114.6	.336	Weeds with scum; dense bottom
30	80	1.00	22.34	6.54	1,003	6.70	86.3	.135	
33	53	.50	22.90	6.55	981	6.99	92.0	.342	
33	53	1.00	22.90	6.53	977	7.03	92.5	.343	
33	53	3.00	22.59	6.52	970	5.88	76.8	.345	
33	53	5.00	22.47	6.53	975	5.78	75.4	.345	
33	53	10.00	22.41	6.53	974	5.84	75.6	.345	
33	53	15.00	22.34	6.53	979	5.84	76.1	.345	
33	53	15.80	22.38	6.52	967	5.89	76.9	.346	
33	53	16.23	23.08	6.43	571	5.29	69.8	.354	
34	54	.50	22.83	6.64	989	6.25	82.8	.420	
34	54	1.00	22.80	6.63	988	6.54	86.0	.420	
34	54	2.00	22.74	6.63	989	6.43	84.4	.419	
34	54	3.00	22.56	6.60	985	6.02	78.3	.417	
34	54	5.00	22.45	6.61	990	6.20	81.5	.415	
34	54	10.00	22.41	6.61	988	6.30	82.1	.413	
34	54	15.00	22.41	6.61	991	6.26	81.5	.413	
34	54	16.00	22.64	6.57	960	6.11	79.4	.415	Bottom; quicksand
34	54	17.00	23.01	6.43	520	5.80	76.2	.424	
34	54	20.00	23.34	6.42	392	5.45	72.0	.433	
34	54	25.00	23.43	6.42	416	5.37	71.1	.439	
34	54	30.00	23.49	6.42	385	5.47	72.4	.446	
34	54	35.00	23.53	6.42	387	5.31	70.5	.463	
34	54	36.00	23.55	6.41	385	5.29	70.4	.465	
34	54	36.75	23.57	6.42	326	5.36	71.2	.469	Bottom also

Table 7. Field measurements, Montezuma Well—Continued

Grid coordinates, in meters X	Grid coordinates, in meters Y	Depth, in meters	Temperature, in degrees Celsius	pH	Specific conductance, in microsiemens per centimeter	Dissolved oxygen, in milligrams per liter	Saturation of dissolved oxygen, in percent	Oxidation-reduction potential	Remarks
34	54	37.00	23.57	6.42	985	5.39	71.7	0.471	
35	52	.50	23.29	6.57	980	6.28	83.0	.352	
35	52	1.00	23.04	6.53	974	6.81	90.1	.354	
35	52	3.00	22.71	6.52	971	6.15	80.7	.354	
35	52	5.00	22.54	6.53	977	6.24	81.1	.354	
35	52	10.00	22.41	6.53	980	5.91	77.3	.354	
35	52	15.00	22.34	6.53	983	5.99	78.6	.354	
35	52	16.30	23.44	6.36	361	5.63	74.9	.370	
35	55	.50	24.07	6.63	960	6.87	92.9	.323	
35	55	1.00	23.49	6.56	957	7.12	94.6	.327	
35	55	3.00	22.98	6.54	959	6.27	82.5	.328	
35	55	5.00	22.79	6.54	963	5.78	75.6	.329	Soft bottom at 16
35	55	10.00	22.56	6.53	965	6.02	78.3	.329	
35	55	15.00	22.42	6.54	969	5.95	76.8	.328	Possible boiling sand, no large drop in dissolved oxygen
35	55	16.10	23.20	6.37	369	6.10	80.7	.337	
35	55	16.31	23.34	6.37	357	6.09	80.9	.338	
36	54	.50	22.87	6.67	980	7.10	93.4	.398	
36	54	1.00	22.80	6.62	977	7.04	92.7	.400	
36	54	3.00	22.67	6.61	977	7.62	99.4	.400	
36	54	5.00	22.41	6.61	986	5.79	75.2	.403	Bottom at 16 meters
36	54	10.00	22.38	6.61	984	6.08	78.8	.402	
36	54	15.00	22.38	6.61	980	6.19	80.7	.404	Resistance on retrieval of probe
36	54	16.00	22.80	6.58	956	6.11	79.9	.408	
36	54	20.00	23.27	6.42	344	5.70	75.4	.420	
36	54	25.00	23.45	6.42	341	5.59	74.9	.427	
36	54	30.00	23.49	6.42	335	5.81	77.5	.434	
36	54	35.00	23.53	6.42	336	6.22	82.3	.440	
36	54	36.80	23.57	6.42	343	5.75	76.5	.451	Bottom
36	54	36.84	23.58	6.42	294	5.72	76.1	.456	
37	55	.50	22.49	6.60	973	6.12	79.6	.378	Vent
37	55	1.00	22.41	6.60	973	6.24	81.1	.375	
37	55	3.00	22.41	6.60	976	6.29	81.9	.375	
37	55	5.00	22.38	6.60	978	6.27	82.0	.374	
37	55	10.00	22.34	6.61	980	6.21	81.3	.372	
37	55	15.00	22.41	6.57	963	6.29	81.5	.372	
37	55	16.00	22.52	6.57	962	5.79	75.2	.370	Bottom; quicksand
37	55	17.00	23.04	6.42	703	5.75	75.7	.381	
37	55	20.00	23.39	6.42	712	5.44	72.2	.390	

Table 7. Field measurements, Montezuma Well—Continued

Grid coordinates, in meters X	Grid coordinates, in meters Y	Depth, in meters	Temperature, in degrees Celsius	pH	Specific conductance, in microsiemens per centimeter	Dissolved oxygen, in milligrams per liter	Saturation of dissolved oxygen, in percent	Oxidation-reduction potential	Remarks
37	55	25.00	23.51	6.42	594	6.29	83.7	0.399	
37	55	30.00	23.53	6.42	462	6.30	83.7	.408	
37	55	35.00	23.54	6.42	435	6.22	82.7	.414	
37	55	36.76	23.57	6.42	434	5.78	76.8	.433	Bottom
40	12	.02	23.42	7.18	1,020	7.85	101.4	.228	Grass; scum
40	12	.25	24.63	6.71	1,010	6.92	94.1	.277	Rock bottom
40	20	.04	25.05	7.28	401	17.30	246.1	.266	
40	20	.25	25.64	6.81	986	13.20	179.0	.288	
40	20	.50	24.71	6.74	964	9.66	126.5	.292	
40	20	1.00	23.93	6.70	964	7.26	96.8	.291	Very weedy bottom
40	30	.50	22.94	6.72	985	7.19	94.7	.253	Open water
40	30	1.00	22.71	6.73	988	7.22	95.0	.259	
40	30	3.00	22.67	6.59	977	6.66	86.3	.269	
40	30	5.00	22.52	6.58	981	6.82	88.6	.273	
40	30	7.89	22.41	6.59	982	6.16	79.3	.272	Semifirm bottom
40	40	.50	22.51	6.61	980	6.74	88.1	.327	
40	40	1.00	22.49	6.59	979	6.49	85.0	.327	
40	40	3.00	22.42	6.58	978	6.58	85.8	.329	
40	40	5.00	22.38	6.58	984	6.42	83.4	.330	
40	40	10.00	22.30	6.58	984	6.31	81.8	.331	
40	40	14.66	22.27	6.58	982	6.18	78.9	.283	Bottom
40	50	.50	22.56	6.59	980	6.97	90.8	.351	
40	50	1.00	22.52	6.57	977	6.91	89.9	.351	
40	50	3.00	22.34	6.56	978	5.96	77.4	.350	
40	50	5.00	22.23	6.56	983	6.38	82.6	.349	
40	50	10.00	22.19	6.56	987	6.22	80.4	.348	
40	50	15.00	22.13	6.57	984	6.21	80.1	.348	
40	50	15.64	22.71	6.40	907	2.41	31.3	.310	
40	60	.50	23.87	6.73	988	6.47	86.7	.307	
40	60	1.00	23.34	6.58	974	7.59	100.7	.318	
40	60	3.00	22.93	6.57	972	7.40	96.3	.320	
40	60	5.00	22.56	6.56	980	6.10	79.5	.324	
40	60	10.00	22.41	6.56	986	6.08	78.9	.326	
40	60	15.00	22.31	6.56	985	6.14	80.0	.325	
40	60	15.56	22.87	6.39	905	4.00	52.0	.269	About 6 centimeters ooze
40	70	.50	22.27	6.61	983	6.79	87.9	.270	
40	70	1.00	22.38	6.60	980	6.62	86.0	.279	Open water
40	70	3.00	22.38	6.59	978	6.54	84.3	.285	
40	70	5.00	22.34	6.60	978	6.41	83.0	.291	

Table 7. Field measurements, Montezuma Well—Continued

Grid coordinates, in meters X	Grid coordinates, in meters Y	Depth, in meters	Temperature, in degrees Celsius	pH	Specific conductance, in microsiemens per centimeter	Dissolved oxygen, in milligrams per liter	Saturation of dissolved oxygen, in percent	Oxidation-reduction potential	Remarks
40	70	9.28	22.30	6.60	978	5.57	71.8	0.296	Solid bottom
40	80	.50	22.53	6.62	977	9.31	121.7	.310	Weeds; scum
40	80	.89	22.27	6.55	1,022	7.18	93.5	.164	Dense weeds bottom
50	12	.25	24.06	6.66	998	4.51	58.9	.213	In grass
50	20	.02	24.29	7.04	1,077	16.98	229.6	.264	In bubbly foam on surface
50	20	.25	25.96	6.83	997	10.47	145.9	.281	
50	20	.50	24.40	6.75	966	7.22	97.0	.289	
50	20	1.00	23.92	6.73	966	6.85	91.8	.290	Weedy scum
50	20	3.00	23.38	6.63	965	6.61	87.6	.295	
50	20	3.79	22.83	6.60	972	5.27	68.5	.207	Dense weeds bottom
50	20	4.00	22.56	6.51	979	1.06	12.0	.143	In bottom
50	30	.50	22.90	6.71	984	7.00	91.9	.263	Open water
50	30	1.00	22.90	6.71	984	7.02	92.8	.266	
50	30	3.00	22.72	6.60	978	6.92	90.8	.274	
50	30	5.00	22.56	6.59	981	6.93	90.2	.279	
50	30	10.00	22.41	6.58	989	6.32	82.5	.284	
50	30	12.45	22.34	6.58	988	5.92	76.9	.244	Soft bottom
50	30	12.48	22.34	6.58	988	4.37	53.9	.251	In bottom
50	40	.50	22.49	6.62	983	6.70	87.6	.316	
50	40	1.00	22.49	6.61	982	6.55	86.2	.318	Open water
50	40	3.00	22.41	6.58	985	6.34	82.2	.321	
50	40	5.00	22.34	6.58	987	6.48	84.2	.323	
50	40	10.00	22.30	6.58	986	6.27	81.6	.324	
50	40	15.00	22.27	6.59	988	6.31	81.9	.327	
50	40	15.39	22.26	6.59	988	5.97	77.7	.230	Real soft bottom
50	40	15.5	22.52	6.35	952	.86	10.7	.118	Boiling sand
50	40	15.6	22.64	6.45	950	1.04	11.5	.097	Pulled up from bottom
50	40	15.78	22.84	6.37	933	.12	1.3	.074	In sand
50	50	.50	22.57	6.57	981	6.73	88.6	.329	
50	50	1.00	22.52	6.56	980	6.84	89.4	.330	
50	50	3.00	22.38	6.56	980	6.37	83.0	.332	
50	50	5.00	22.23	6.56	987	5.53	71.5	.334	
50	50	10.00	22.19	6.56	988	6.07	78.2	.335	
50	50	15.00	22.12	6.58	986	5.13	66.8	.325	Bottom
50	50	.50	22.97	6.65	990	6.39	84.8	.416	
50	50	1.00	22.97	6.63	988	6.63	87.1	.416	
50	50	3.00	22.81	6.61	985	6.69	87.0	.417	
50	50	5.00	22.67	6.61	989	6.53	85.6	.417	
50	50	10.00	22.56	6.61	992	6.17	80.1	.414	
50	50	15.00	22.43	6.62	994	6.26	81.3	.399	

Table 7. Field measurements, Montezuma Well—Continued

Grid coordinates, in meters X	Grid coordinates, in meters Y	Depth, in meters	Temperature, in degrees Celsius	pH	Specific conductance, in microsiemens per centimeter	Dissolved oxygen, in milligrams per liter	Saturation of dissolved oxygen, in percent	Oxidation-reduction potential	Remarks
50	50	15.18	22.41	6.62	994	5.95	77.0	0.335	Bottom
50	50	15.42	22.75	6.35	914	.65	8.5	.200	
50	60	.50	23.61	6.58	980	7.42	98.4	.300	
50	60	1.00	23.31	6.57	978	7.52	100.3	.304	
50	60	3.00	22.84	6.57	976	6.97	91.0	.308	
50	60	5.00	22.56	6.56	979	6.15	79.7	.311	
50	60	10.00	22.38	6.57	987	6.08	78.8	.314	
50	60	13.53	22.27	6.58	985	5.42	69.9	.257	
50	70	.50	22.63	6.67	027	7.19	94.1	.263	
50	70	1.00	22.60	6.60	975	6.77	88.8	.276	
50	70	3.00	22.49	6.60	975	6.59	85.4	.282	
50	70	5.00	22.41	6.60	977	6.70	87.2	.287	
50	70	9.62	22.32	6.60	977	5.12	66.7	.219	Soft bottom
50	70	9.62	22.30	6.60	975	5.35	69.2	.235	Bottom in mud
50	80	.50	22.93	6.81	1,005	13.48	177.5	.261	Weeds with scum
50	80	.90	22.90	6.69	987	9.99	130.8	.297	Dense weeds; bottom
50	90	.25	21.46	6.83	1,010	4.59	58.9	.267	Grass, cattails; bottom
53	44	.50	23.64	6.71	986	6.65	90.0	.389	
53	44	1.00	23.23	6.62	981	7.19	95.9	.393	In hole aided by diver
53	44	3.00	23.04	6.61	978	7.30	95.3	.394	
53	44	5.00	22.87	6.60	982	6.90	89.8	.395	
53	44	10.00	22.64	6.60	992	6.36	82.9	.391	
53	44	15.00	22.55	6.60	990	6.38	83.0	.388	
53	44	15.75	22.44	6.61	990	5.89	76.8	.374	
53	44	16.00	23.92	6.34	251	4.18	56.0	.447	
53	44	16.70	23.34	6.36	1,021	4.73	62.7	.368	
53	44	18.00	23.93	6.35	252	4.19	56.1	.444	
53	44	20.00	23.93	6.36	250	4.17	55.8	.445	
53	44	25.00	23.93	6.36	250	4.17	55.9	.445	
53	44	30.00	23.94	6.35	251	4.17	55.8	.444	
53	44	30.60	23.93	6.34	254	4.21	56.4	.443	
55	44	.50	23.57	6.67	982	6.75	90.4	.378	
55	44	1.00	23.34	6.62	980	7.18	95.4	.379	
55	44	3.00	23.04	6.61	977	7.41	97.4	.381	
55	44	5.00	22.78	6.60	982	6.73	87.7	.381	
55	44	10.00	22.60	6.60	991	6.73	87.3	.379	
55	44	15.00	22.47	6.61	990	6.86	88.8	.371	
55	44	16.00	22.90	6.36	451	6.67	87.7	.370	Bottom quicksand
55	44	17.00	23.46	6.34	347	6.19	82.1	.380	
55	44	20.00	23.76	6.34	323	6.15	82.1	.386	

Table 7. Field measurements, Montezuma Well—Continued

Grid coordinates, in meters X	Grid coordinates, in meters Y	Depth, in meters	Temperature, in degrees Celsius	pH	Specific conductance, in microsiemens per centimeter	Dissolved oxygen, in milligrams per liter	Saturation of dissolved oxygen, in percent	Oxidation-reduction potential	Remarks
55	44	23.00	23.88	6.33	247	5.05	67.6	0.398	Bottom
55	55	.50	23.42	6.53	972	6.59	88.1	.356	
55	55	1.00	23.19	6.53	972	6.92	91.1	.356	
55	55	3.00	22.77	6.53	972	6.72	88.0	.357	
55	55	5.00	22.52	6.52	982	5.97	78.3	.358	
55	55	10.00	22.41	6.53	984	6.08	79.5	.356	
55	55	15.00	22.30	6.53	984	5.82	75.4	.352	
55	55	16.00	22.49	6.44	970	5.73	74.3	.356	
60	10	.23	22.38	7.05	996	6.81	84.6	.280	In grass
60	10	.27	22.39	6.60	981	.84	11.2	.111	Solid bottom; smells
60	20	.25	22.01	7.02	1,011	8.83	113.6	.302	
60	20	.50	22.27	6.81	998	7.65	99.1	.306	Weeds and scum
60	20	1.00	22.45	6.76	991	6.95	91.6	.306	
60	20	1.20	22.65	6.71	984	6.73	89.2	.264	
60	20	1.95	22.57	6.70	983	6.22	79.7	.291	
60	20	2.05	22.58	6.70	983	2.22	29.1	.273	Weedy bottom
60	30	.50	22.84	6.71	987	7.01	92.2	.264	
60	30	1.00	22.84	6.71	986	7.03	92.4	.267	
60	30	3.00	22.73	6.62	980	6.94	91.2	.273	
60	30	5.00	22.53	6.59	983	6.17	80.8	.278	
60	30	10.00	22.41	6.59	988	6.36	82.2	.282	
60	30	11.30	22.38	6.58	985	5.35	69.8	.258	Semifirm bottom
60	40	.50	22.46	6.62	983	6.27	82.0	.261	
60	40	1.00	22.49	6.62	983	6.67	87.5	.270	
60	40	3.00	22.45	6.58	984	6.73	87.2	.275	
60	40	5.00	22.38	6.58	987	6.52	84.4	.279	
60	40	10.00	22.30	6.59	988	6.37	82.5	.283	
60	40	15.00	22.28	6.59	989	6.23	80.7	.287	
60	40	15.84	22.29	6.58	991	5.68	73.3	.294	Reasonably firm bottom
60	40	15.9	22.30	6.58	989	6.30	81.2	.299	In bottom
60	40	15.95	22.97	6.37	819	5.14	67.7	.308	In bottom
60	50	1.00	22.74	6.75	991	7.72	101.9	.352	
60	50	4.00	22.51	6.60	986	7.15	93.0	.359	
60	50	7.00	22.29	6.59	995	6.55	85.3	.360	
60	50	10.00	22.23	6.60	995	6.45	84.2	.359	
60	50	13.00	22.21	6.60	995	6.26	81.7	.353	
60	50	15.00	22.30	6.59	997	6.59	86.3	.349	
60	50	15.60	22.30	6.57	1,002	6.48	84.9	.352	
60	50	.50	22.71	6.58	986	6.89	90.3	.335	
60	50	1.00	22.52	6.57	982	5.95	77.4	.337	

Table 7. Field measurements, Montezuma Well—Continued

Grid coordinates, in meters X	Grid coordinates, in meters Y	Depth, in meters	Temperature, in degrees Celsius	pH	Specific conductance, in microsiemens per centimeter	Dissolved oxygen, in milligrams per liter	Saturation of dissolved oxygen, in percent	Oxidation-reduction potential	Remarks
60	50	3.00	22.38	6.57	982	6.42	83.2	0.338	
60	50	5.00	22.27	6.56	987	6.07	78.8	.341	
60	50	10.00	22.19	6.57	988	5.94	76.4	.342	
60	50	15.00	22.15	6.57	988	6.28	80.5	.335	
60	50	15.50	22.12	6.58	987	5.95	76.4	.319	
60	60	.50	23.61	6.58	982	7.49	99.8	.323	
60	60	1.00	23.19	6.57	981	7.40	97.6	.326	
60	60	3.00	22.84	6.57	976	7.30	95.9	.328	
60	60	5.00	22.53	6.57	981	6.14	79.6	.331	
60	60	10.00	22.27	6.57	991	6.79	88.6	.339	
60	60	15.00	22.23	6.53	985	5.23	63.8	.215	
60	60	16.00	22.23	6.56	988	1.43	18.0	.217	
60	70	.50	21.97	6.73	991	7.39	95.2	.295	
60	70	1.00	22.38	6.62	982	6.73	87.9	.304	Open water
60	70	3.00	22.40	6.62	978	6.94	90.9	.308	
60	70	5.00	22.34	6.62	978	6.84	89.1	.311	
60	70	10.00	22.30	6.62	981	6.38	82.6	.314	
60	70	13.85	22.27	6.62	981	6.29	81.0	.303	Semisoft bottom
60	80	.50	22.83	6.67	984	7.64	99.5	.306	
60	80	1.00	22.80	6.63	976	7.37	97.0	.312	Weeds with scum
60	80	3.00	22.56	6.62	976	7.18	93.6	.315	
60	80	4.45	22.41	6.63	978	6.29	81.5	.280	Solid bottom
60	90	.50	22.19	6.86	1,012	9.29	120.9	.292	Weeds; scum
60	90	.71	22.64	6.61	1,013	4.88	61.4	.143	Bottom
70	20	.25	24.51	6.80	964	6.50	87.3	.334	
70	20	.50	23.87	6.75	969	6.60	87.5	.334	Weedy scum
70	20	1.00	23.12	6.57	735	4.50	56.9	.214	Thick weedy bottom
70	20	1.2	22.84	6.53	888	1.03	12.3	.201	On bottom
70	30	.50	22.45	6.65	987	7.05	92.2	.293	
70	30	1.00	22.52	6.65	986	6.95	90.8	.298	
70	30	3.00	22.49	6.59	983	6.86	89.7	.304	
70	30	5.00	22.37	6.58	988	6.57	84.3	.309	
70	30	7.67	22.30	6.60	986	6.51	84.7	.312	Semifirm bottom
70	40	.50	22.56	6.63	985	6.79	88.9	.319	
70	40	1.00	22.52	6.63	984	6.82	89.5	.321	
70	40	3.00	22.42	6.58	985	7.03	91.7	.324	
70	40	5.00	22.34	6.58	988	6.74	87.3	.326	
70	40	10.00	22.30	6.59	986	6.72	87.5	.327	
70	40	14.16	22.29	6.54	972	4.09	52.2	.170	Semisoft bottom
70	40	14.2	22.31	6.51	965	1.32	15.7	.143	In bottom

Table 7. Field measurements, Montezuma Well—Continued

Grid coordinates, in meters X	Grid coordinates, in meters Y	Depth, in meters	Temperature, in degrees Celsius	pH	Specific conductance, in microsiemens per centimeter	Dissolved oxygen, in milligrams per liter	Saturation of dissolved oxygen, in percent	Oxidation-reduction potential	Remarks
70	50	.50	22.77	6.58	982	6.84	90.2	0.336	
70	50	1.00	22.63	6.57	980	6.60	86.4	.338	
70	50	3.00	22.43	6.57	981	6.77	88.0	.339	
70	50	5.00	22.28	6.57	985	5.77	74.9	.341	
70	50	10.00	22.19	6.57	987	5.84	75.5	.341	
70	50	15.00	22.60	6.28	1,034	5.61	72.3	.351	
70	60	.50	23.61	6.60	986	7.04	95.2	.331	
70	60	1.00	23.23	6.57	979	7.54	99.6	.334	
70	60	3.00	22.76	6.57	976	7.09	93.2	.336	
70	60	5.00	22.45	6.58	981	6.51	84.9	.338	
70	60	10.00	22.34	6.57	986	5.77	75.2	.340	
70	60	14.60	22.23	6.58	983	3.75	48.6	.272	
70	70	.25	22.45	6.63	985	6.97	90.6	.284	
70	70	.50	22.52	6.62	981	6.80	88.9	.291	
70	70	1.00	22.56	6.62	979	6.77	89.1	.294	
70	70	3.00	22.45	6.60	979	6.79	88.6	.299	
70	70	5.00	22.41	6.60	978	6.70	86.6	.300	
70	70	10.00	22.34	6.61	982	6.40	82.7	.304	
70	70	12.61	22.30	6.62	982	6.06	78.2	.307	Bottom
70	70	12.61	22.29	6.62	983	5.97	77.0	.309	In mud bottom
80	20	.02	21.69	7.73	1,058	8.40	114.8	.196	Grass, weeds, scum
80	20	.25	22.23	7.42	1,044	9.93	134.3	.210	
80	20	.50	22.52	7.07	944	10.50	136.4	.210	Bottom
80	30	.50	23.12	6.76	985	7.53	99.9	.323	
80	30	1.00	23.12	6.76	987	7.57	100.2	.323	Near edge of weeds
80	30	3.00	23.01	6.65	975	7.77	103.9	.328	
80	30	4.57	22.81	6.62	976	7.98	104.0	.330	Bottom
80	40	.50	22.53	6.63	986	7.14	93.1	.271	
80	40	1.00	22.56	6.62	984	6.98	91.1	.278	Open water
80	40	3.00	22.45	6.59	984	7.04	91.5	.287	
80	40	5.00	22.39	6.59	986	6.90	89.9	.290	
80	40	10.00	22.31	6.60	986	6.56	85.4	.294	
80	40	12.36	22.26	6.60	987	5.96	77.5	.291	Semifirm bottom
80	50	.50	22.77	6.58	982	6.95	91.0	.345	
80	50	1.00	22.64	6.57	979	7.05	92.7	.346	
80	50	3.00	22.43	6.58	980	6.44	84.0	.348	
80	50	5.00	22.31	6.58	980	6.81	88.6	.348	
80	50	10.00	22.19	6.58	983	5.94	76.9	.350	
80	50	14.73	22.13	6.58	984	5.65	72.9	.349	
80	60	.50	23.38	6.58	982	7.00	92.7	.312	
80	60	1.00	23.16	6.58	977	7.82	103.5	.315	

Table 7. Field measurements, Montezuma Well—Continued

Grid coordinates, in meters X	Grid coordinates, in meters Y	Depth, in meters	Temperature, in degrees Celsius	pH	Specific conductance, in microsiemens per centimeter	Dissolved oxygen, in milligrams per liter	Saturation of dissolved oxygen, in percent	Oxidation-reduction potential	Remarks
80	60	3.00	22.80	6.58	974	7.64	100.4	0.318	
80	60	5.00	22.56	6.57	978	6.63	86.3	.321	
80	60	10.00	22.34	6.57	982	6.16	80.0	.324	
80	60	12.00	22.27	6.58	983	6.44	83.1	.325	
80	70	.50	22.71	6.62	982	7.03	92.3	.316	
80	70	1.00	22.64	6.60	979	6.96	91.0	.319	
80	70	3.00	22.56	6.61	979	7.09	92.8	.320	
80	70	5.00	22.45	6.61	980	6.90	89.2	.321	
80	70	7.52	22.41	6.62	981	6.45	84.1	.319	Slightly soft bottom
80	80	.25	21.64	7.14	1,021	10.77	139.1	.323	Used both interleaved weeds and scum
80	80	.48	22.34	7.11	1,029	11.76	161.1	.277	
80	80	.52	21.91	6.93	1,005	10.54	135.4	.327	
80	80	.90	22.51	6.64	979	8.18	107.1	.293	
80	80	1.00	22.00	6.78	994	9.83	125.2	.323	
90	20	.02	22.83	6.88	990	8.38	109.1	.259	Open water
90	20	.25	22.93	6.84	992	7.99	105.2	.261	Very close to outlet
90	20	.50	23.01	6.83	989	7.94	105.0	.263	
90	30	.50	23.23	6.77	987	8.07	107.5	.323	Weeds; no scum
90	30	.90	23.23	6.73	981	8.04	105.2	.252	Bottom
90	40	.50	22.60	6.67	987	7.24	94.8	.308	
90	40	1.00	22.64	6.66	987	7.23	94.2	.310	Edge of weeks; no grass
90	40	3.00	22.52	6.60	982	6.55	84.6	.314	
90	40	3.29	22.41	6.60	982	5.18	67.7	.261	Weedy bottom
90	40	3.29	22.38	6.60	983	5.33	67.8	.248	On bottom
90	50	.50	22.84	6.58	987	7.04	92.3	.346	
90	50	1.00	22.62	6.58	983	7.46	97.7	.348	
90	50	3.00	22.38	6.58	984	6.95	90.5	.349	
90	50	5.00	22.26	6.59	985	6.39	83.6	.350	
90	50	8.00	22.18	6.59	986	6.00	78.7	.350	
90	60	.50	22.64	6.60	986	8.35	108.7	.280	
90	60	1.00	22.64	6.59	985	8.61	113.0	.285	
90	60	3.00	22.45	6.60	980	7.29	94.6	.291	
90	60	5.00	22.34	6.60	980	7.09	91.6	.280	
90	60	5.60	22.30	6.60	982	6.70	87.2	.268	
90	70	.50	22.28	6.70	998	10.54	137.4	.318	Weeds; edge of scum
90	70	1.00	22.41	6.63	979	8.80	113.8	.277	Bottom
100	30	.25	22.27	6.79	982	3.41	42.8	.115	Grass; weeds; scum bottom
100	40	.25	22.16	6.84	1,014	8.27	107.5	.287	In grass
100	40	.50	22.64	6.65	991	4.26	55.8	.237	In bottom