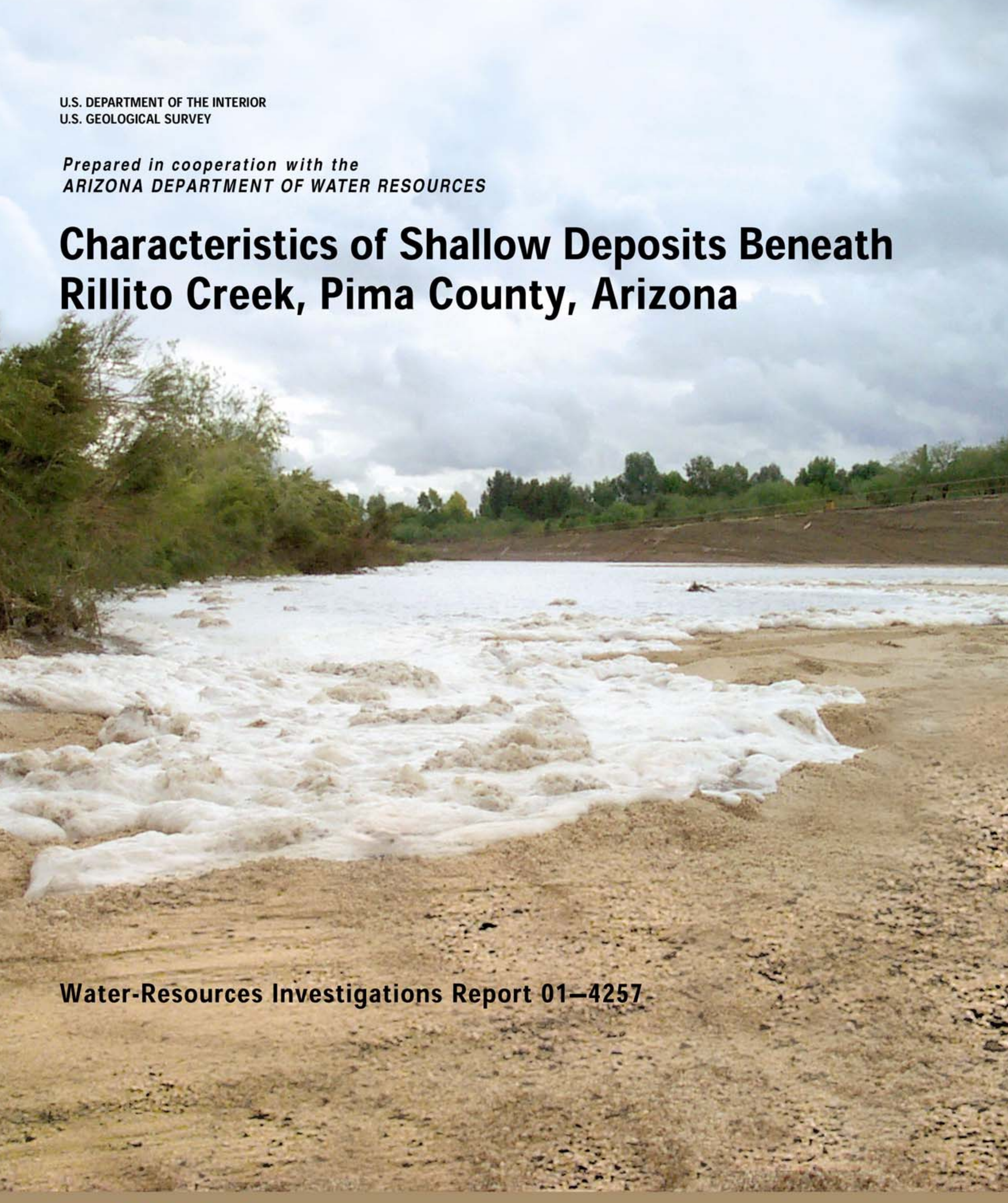
U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Prepared in cooperation with the
ARIZONA DEPARTMENT OF WATER RESOURCES

Characteristics of Shallow Deposits Beneath Rillito Creek, Pima County, Arizona



Water-Resources Investigations Report 01–4257

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By John P. Hoffmann, Marcella A. Ripich, *and* Kevin M. Ellett

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Tucson, Arizona
February 2002

U.S. DEPARTMENT OF THE INTERIOR
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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
acre	4,047	square meter
square foot (ft^2)	0.09290	square meter
square mile (mi^2)	2.590	square kilometer
	Volume	
gallon (gal)	0.003785	cubic meter
million gallons (Mgal)	3,785	cubic meter
acre-foot (acre-ft)	1,233	cubic meter
	Pressure	
bar	1,020	centimeter
	Hydraulic conductivity	
foot per day	0.3048	meter per day

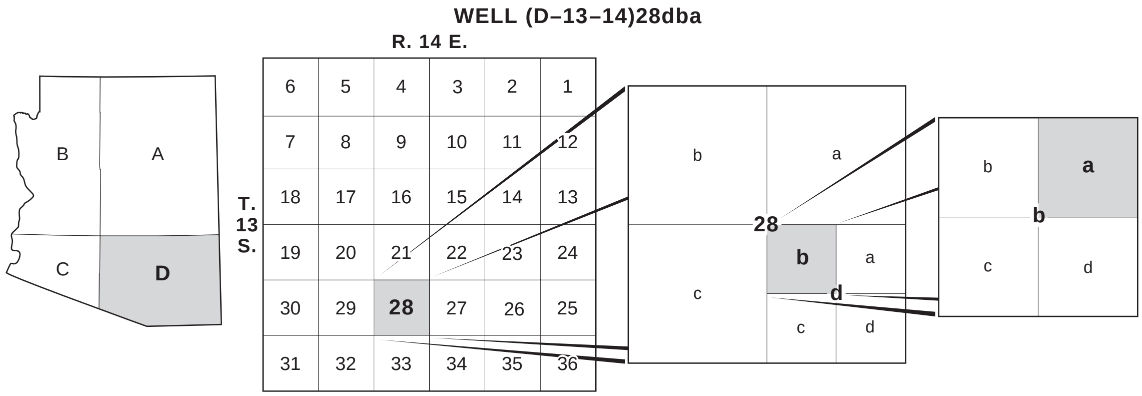
ABBREVIATED GEOPHYSICAL TERMS

Ampere is the International System (S.I.) unit of electric current measured as one coulomb per second or one volt per ohm. Ohm is the International System unit of electrical resistance equal to that of a conductor in which a current of one ampere is produced by a potential of one volt across its terminals. Ohm meter (Ω•m) is a unit of resistivity, also written as ohm meter squared per meter ($\Omega \bullet m^2/m$), and is the resistance of a meter cube to the flow of current between opposite faces. Gamma is a unit of magnetic field equal to one nanotesla, the preferred International System name (1 gamma=10^{-5} gauss=10^{-9} tesla). Hertz is a unit of frequency equal to one cycle per second. Kilohertz is a unit of frequency equal to 1,000 hertz.

VERTICAL DATUM

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

WELL-NUMBERING AND NAMING SYSTEM



Quadrant D, Township 13 South, Range 14 East, section 28, 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 the 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 (D–13–14)28dba designates the well as being in the NE1/4, NW1/4, SE1/4, section 28, Township 13 South, and Range 14 East.

Characteristics of Shallow Deposits Beneath Rillito Creek, Pima County, Arizona

By John P. Hoffmann, Marcella A. Ripich, *and* Kevin M. Ellett

Abstract

Characteristics of the stream-channel and basin-fill deposits beneath a 12-mile reach of Rillito Creek, Pima County, Arizona, were obtained to describe the geohydrologic system. The findings presented here are part of a larger project to improve the understanding of recharge processes beneath ephemeral streams.

The stream-channel deposits, which range in thickness from 15 to 40 feet, generally are sandy gravels or gravelly sands. On average, the stream-channel deposits are 44 percent gravel, 51 percent sand, 2 percent silt, and 3 percent clay. The underlying basin-fill deposits also are sandy gravels or gravelly sands but have, on average, a larger component of silt and clay than the stream-channel deposits—about 9 percent silt and 6 percent clay.

Porosity values for the stream-channel and basin-fill deposits are similar: about 31 and 34 percent on average, respectively. Volumetric moisture content and percent saturation, however, generally were lower in the stream-channel deposits than in the basin-fill deposits. Moisture content in the stream-channel deposits ranged from 2 to 40 percent and averaged about 18 percent, whereas moisture content in the basin-fill deposits ranged from 7 to 47 percent and averaged about 24 percent. Saturation in the stream-channel deposits ranged from 9 to 100 percent and averaged about 58 percent; saturation in the basin-fill deposits ranged from 30 to 100 percent and averaged about 69 percent. Porosity and moisture content correlate with silt and clay content. Cumulative thickness of water in the 100- to 125-foot thick unsaturated zone obtained by integrating the moisture content over depth, ranged from 17.2 to 40.4 feet.

Matric potential for saturation levels at the time of sample collection generally was less than -1 bar for deposits that were less than 35 percent saturated. Matric potential generally was greater than -0.1 bar for deposits that were more than 65 percent saturated. Moisture-retention curves are a function of the physical properties, such as porosity and grain size, of the sediments. The shapes and van Genuchten fitting parameters of moisture-retention curves for the stream-channel deposits are different from those of the basin-fill deposits. For instance, the fitting parameter, α, for stream-channel deposits ranged from 4.56 to 1,220 bar^{-1} and averaged 220 bar^{-1}, whereas α for basin-fill deposits ranged from 4.22 to 67.9 bar^{-1} and averaged 22.8 bar^{-1}. The residual water content for the basin-fill deposits is greater than that for the stream-channel deposits. Relative hydraulic conductivity of the stream-channel deposits is less than relative hydraulic conductivity of the basin-fill deposits at the same matric potential. Unsaturated hydraulic conductivity for moisture conditions that existed at the time of sample collection typically was more than two orders of magnitude less than saturated hydraulic conductivity.

Saturated vertical hydraulic conductivity of the stream-channel deposits is about an order of magnitude greater than that of the basin-fill deposits. The equivalent hydraulic conductivity of stream-channel deposits ranges from 2 to 7.3 feet per day, and averages about 4 feet per day, whereas the equivalent hydraulic conductivity of the basin-fill deposits ranges from 0.06 to 1.5 feet per day and

averages 0.61 foot per day. The equivalent vertical hydraulic conductivity of the entire unsaturated zone cored is 0.75 foot per day. Assuming no vertical to horizontal anisotropy, the equivalent horizontal hydraulic conductivity generally is about two to three times that of the equivalent vertical hydraulic conductivity. The difference between average equivalent vertical and horizontal hydraulic conductivity values results from the differences in methods used to calculate the respective values.

Electrical methods were useful in discriminating between stream-channel deposits and basin-fill deposits. In general, electrical conductivity of the stream-channel deposits was less than 30 millimhos per meter and averaged 27 millimhos per meter. The conductivity of the basin-fill deposits was greater than that of the stream-channel deposits and averaged 44 millimhos per meter. The greater conductivity probably is related to factors such as greater moisture content and fraction of fine sediments in the basin-fill deposits. Apparent resistivity measured with two-dimensional resistivity soundings generally decreased with depth. The resistivity values from the near-surface measurements represent dry stream-channel deposits and averaged 303 ohm meters. The resistivity values for basin-fill deposits generally were less than 140 ohm meters and less than 100 ohm meters when saturated.

Seismic-velocity values for the recent alluvium (stream-channel and terrace deposits) ranged from 1,150 to 2,200 feet per second, whereas values for basin-fill deposits ranged from 2,000 to 11,650 feet per second. The average seismic velocity for the stream-channel deposits (1,300 feet per second) was less than that for the terrace deposits (1,600 feet per second). Saturated basin-fill deposits had an average velocity of 7,800 feet per second, whereas unsaturated basin-fill deposits had an average velocity of 2,750 feet per second.

INTRODUCTION

The Tucson area in Pima County, Arizona, is experiencing an overdraft of its ground-water supply because of an increase in population and ground-water usage (Ralph Marra, hydrologist, Tucson Water, written commun., 1999). Overdraft has led to water-level declines of more than 200 ft in the Tucson Basin. This condition has led to concerns about land subsidence and a degradation of water quality. The amount of overdraft, estimated to be about 165,000 acre-ft/yr in 1995, is difficult to determine because recharge in arid and semiarid environments cannot easily be quantified. The current overdraft condition in the region has increased public and governmental awareness of the need for water-management options, such as artificial recharge. Rillito Creek, an ephemeral stream in northern Tucson (**fig. 1**), has been proposed as a site for an in-channel recharge facility.

The predominant type of recharge to alluvial basins in southern Arizona results from infiltration and percolation of streamflow (Davidson, 1973; Hanson and Benedict, 1994). Although infiltration of streamflow is known to occur in ephemeral stream channels in the Southwest, the processes that control the spatial distribution and volume of infiltration that recharges the underlying aquifers are poorly understood. Determination of the properties of deposits underlying an ephemeral stream channel can help to improve the understanding of processes that control recharge.

Improved estimates of recharge along Rillito Creek are needed to reduce uncertainties in ground-water flow models that currently are being developed for the Tucson Basin. A regional flow model is being developed by the Arizona Department of Water Resources (ADWR), and a finely discretized nested model within the regional model is being developed by the U.S. Geological Survey (USGS). The nested model will be developed using detailed geohydrologic data gathered during this study and will be designed to evaluate the potential for artificial recharge in the Rillito Creek channel. Characterizing the physical properties and geometry of the channel and underlying sediments is necessary to accurately represent the geohydrologic system in the nested model. This study was done by the USGS in cooperation with the ADWR.

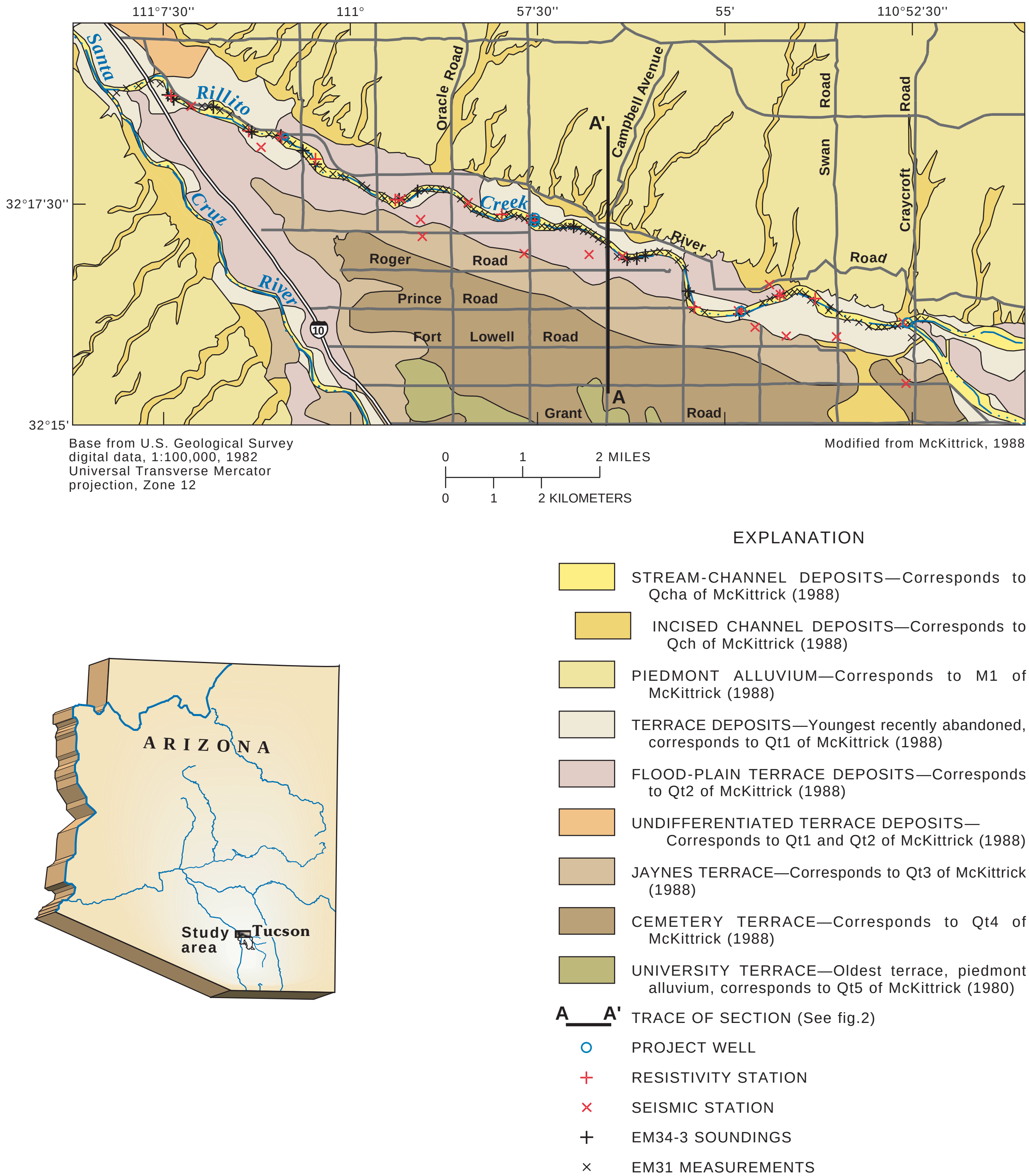


Figure 1. Location of Rillito Creek, Pima County, Arizona, and geologic and geophysical data-collection sites.

Purpose and Scope

This report presents information that describes the physical properties of the shallow subsurface deposits along a 12-mile reach of Rillito Creek. Data used in this study include well logs from 63 existing wells, information gathered from the drilling and coring of 5 new boreholes within the creek channel, and the results of borehole and surface geophysical surveys. Data collected for this study delineate the recent alluvium and underlying sediments to depths of about 150 ft within about 1 mi of the creek and describe the vertical and lateral distribution of flow-related properties within these deposits.

Previous Investigations

Several geological maps of the Tucson area have been published (Smith, 1938; Pashley, 1966; Davidson, 1973; Anderson, 1987; McKittrick, 1988; Klawon and others, 1999; Pearthree and Biggs, 1999). The stratigraphic framework of the Tucson Basin was described by Davidson (1973) and Anderson (1987). Smith (1938) used geomorphological distinctions to map the surface geology. Pashley (1966) also used geomorphological distinctions to map the terrace deposits that overlie the older basin-fill deposits as he reinterpreted Smith's (1938) terraces and described the erosional and depositional history of Rillito Creek. McKittrick (1988) used geomorphologically based criteria to map the surface geology within the Tucson metropolitan area. The most recent surface-geology maps (Klawon and others, 1999; and Pearthree and Biggs, 1999) are similar to those of McKittrick, although some minor modifications were made.

One of the earliest geohydrologic investigations of the area (Maddox, 1960) used well-log data to determine the subsurface stratigraphy of the Tucson Basin with emphasis on the thickness of the unconsolidated basin-fill deposits. Stream-channel and flood-plain deposits were described as "inner-valley fill" (Maddox, 1960, p. 32), and most of these deposits were noted to be north of Rillito Creek and out of the study area. Davidson (1973) examined the geohydrology and water resources of the Tucson Basin. He did not examine the stream-channel deposits within and adjacent to Rillito Creek, except to note that the terrace and stream alluvia are composed of coarse gravel, gravelly sand, silty gravel, and sandy silt. No report to date has been published that emphasizes the physical properties and geometry of shallow alluvium beneath Rillito Creek.

Acknowledgments

Kathy Jacobs and Denise Wieland of the ADWR facilitated much of the fieldwork for this study. Susan Wittemore of the Pima County Real Estate Division was instrumental in obtaining access to many of the field sites.

DESCRIPTION OF THE STUDY AREA

The study area is in and adjacent to Rillito Creek in the northern part of the Tucson metropolitan area (**fig. 1**). The climate of the study area is semiarid, and annual rainfall averages about 12 in. Rillito Creek is an ephemeral stream that drains an area of more than 900 mi^2. It originates at the confluence of the Pantano and Tanque Verde Washes in the eastern part of the study area and flows northwestward to its confluence with the Santa Cruz River (fig. 1, pl. 1–3). The altitude of the creek ranges from 2,500 ft above sea level at the Pantano and Tanque Verde Wash confluence to 2,155 ft at its confluence with the Santa Cruz River. The creek flows only in response to summer thunderstorms, winter storms, and snowmelt from the Santa Catalina Mountains to the north and the Rincon Mountains to the east. Storm-related flows can persist from a few hours to a few days. Depth to ground water in the study area ranges from a few feet near the Pantano and Tanque Verde Washes to about 140 ft near the Santa Cruz River. Regional ground-water flow direction in the Tucson Basin generally is to the northwest.

Urban growth has led to the development of land close to the banks of Rillito Creek and to the installation of utility lines within the creek. Flooding in 1983 caused significant property damage in and adjacent to the creek (Pearthree and Baker, 1987). This damage has prompted local agencies to stabilize the banks along the entire length of the creek and to install grade-control structures on the downstream side of every bridge and at selected sites between bridges.

Hydrogeologic Setting

Rillito Creek is in southern Arizona in the Basin and Range physiographic province. The region is characterized by broad, northwestward-trending basins bounded by steep, linear, fault-block mountain ranges (Fenneman, 1931). The mountains comprise granitic, metamorphic, sedimentary, and volcanic rocks of Precambrian to Tertiary age (Anderson, 1987).

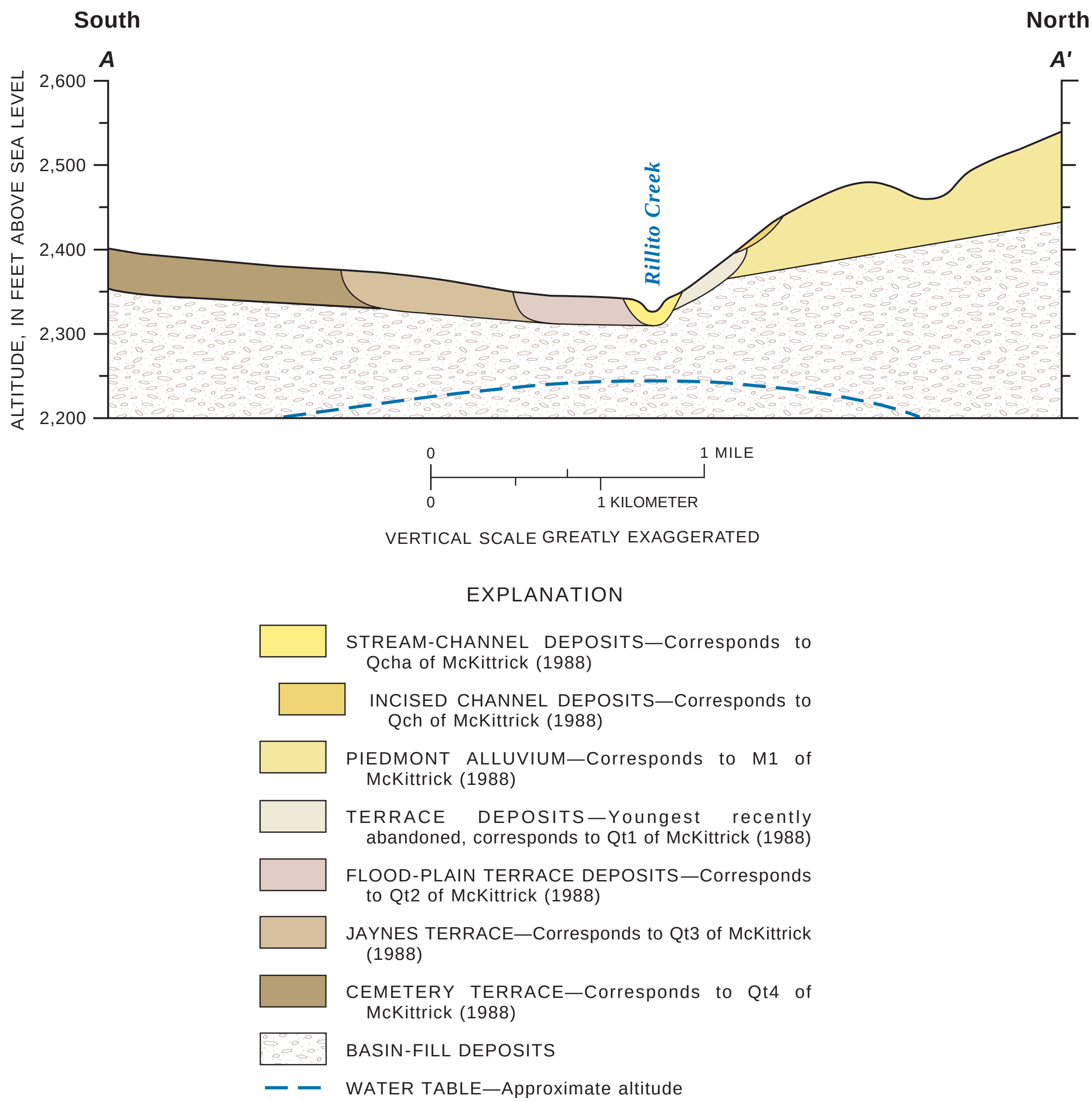


Figure 2. Generalized geologic section across Rillito Creek showing the relation of recent alluvium to the underlying basin-fill deposits.

The basin formed as a result of Cenozoic crustal extension and contains several thousand feet of basin-fill deposits that overlie the bedrock complex.

The principal geologic units of the basin-fill deposits include, in descending order, the Fort Lowell Formation, the Tinaja beds (informal usage), and the Pantano Formation. Grain sizes of these deposits generally decrease with increasing distance from the basin margins. A veneer (typically less than 50 ft) of recent alluvium overlies the basin-fill deposits.

The Fort Lowell Formation consists of unconsolidated to poorly consolidated interbedded gravel, sand, sandy silt, and clayey silt. Thickness of this unit ranges from about 100 to 350 ft in the study area (Anderson, 1987). In most parts of the study area the Fort Lowell Formation extends above the water table and is, therefore, only partly saturated. Where saturated, the Fort Lowell Formation and the underlying Tinaja beds and Pantano Formation form the primary aquifer in the Tucson Basin (Davidson, 1973).

The Tinaja beds are saturated throughout the study area. They are classified into upper, middle, and lower beds (Anderson, 1987). The upper beds consist of unconsolidated to poorly consolidated clayey silt, sandy silt, sand, and gravel (Davidson, 1973). Thickness of the upper Tinaja beds ranges from about 100 to more than 400 ft in the study area. The middle Tinaja beds consist primarily of gypsiferous and anhydritic clayey silt and mudstone; the lower Tinaja beds consist mainly of silty gravel and conglomerate.

The Pantano Formation consists of conglomerate, sandstone, mudstone, and gypsiferous mudstone. Depth of the Pantano Formation exceeded the depth of this investigation.

The recent alluvium includes modern stream-channel and older terrace deposits that are dominated by gravel and coarse sand (Davidson, 1973). The recent alluvium occurs above the water level in the study area and, owing to a typically coarse-grained texture, functions as an efficient infiltration medium for surface runoff.

Depositional History of Recent Alluvium near Rillito Creek

At the end of basin-fill deposition, Rillito Creek was about 1.25 mi south of its present position. The terraces surrounding Rillito Creek that were mapped by Smith (1938) and Pashley (1966) record three fluvial episodes of erosion and deposition (**fig. 2**). During the first cycle of erosion and deposition, the creek carved the University terrace and deposited the sediments that now form the Cemetery terrace (**fig. 1**). During the second cycle, the creek occupied a more northerly flood plain, which is represented by the Jaynes terrace. The most recent cycle of erosion and deposition resulted in the present flood plain, which is north of the Jaynes terrace. The northward erosion by Rillito Creek has resulted in a steep erosional scarp along the north bank, which is higher now than at any other time (Pashley, 1966). The areal distribution of terraces (McKittrick, 1988) is shown in plates 1–3. Qt1 and Qt2 (McKittrick, 1988) correspond to the recent flood plains of Pashley (1966) and Smith (1938). Strata Qt3, Qt4, and Qt5 correspond to the Jaynes, Cemetery, and University terraces, respectively.

METHODS OF INVESTIGATION

The methods used to meet the objectives of this study included (1) the evaluation of existing well-log data from within the study area, (2) the drilling and coring of five boreholes, (3) borehole geophysical surveys, and (4) surface geophysical surveys. These data have been integrated to provide information that will be used to develop the conceptual model of the study area.

***Evaluation of Existing Data*.—**Existing data used in this study include geologic logs from 63 wells within the study area (pl. 1–3). Data from these wells were prioritized on the basis of geologic detail and well location and combined with data from borehole drilling, coring, and geophysical surveys to construct a stratigraphic framework of the study area.

***Borehole Drilling*.—**In March and April 1999, five boreholes were drilled at four sites in the active channel of Rillito Creek (fig. 1, pl. 1–3, and **table 12** in the section entitled “Basic Data” at the back of the report). All boreholes were installed using the ODEX air-hammer method, which is also known as the under-reamer method (Driscoll, 1986; Hammermeister and others, 1986). Drilling depths ranged from 54 to 173 ft. The ODEX method minimizes washouts, cave-ins, and the disturbance of the unsaturated material near the borehole. This method also allows for the collection of high-quality cuttings and cores. Hole diameters ranged from 7.5 to 9 in. Site selection was based on the need for information in areas not covered by pre-existing well logs.

At each hole, cuttings were collected every foot, when possible, and selected cuttings were analyzed for particle-size distribution. Cuttings were selected on the basis of observed changes in texture. Cores from both stream-channel and basin-fill deposits were collected at each borehole. From depths of 0 to 22 ft, 2-foot-long cores were collected at 5-foot intervals using a 4-inch-diameter piston core barrel. Cores were collected every 10 ft for the next 20 ft, and every 20 ft to final depth. In order to preserve the integrity of each core sample, cores were collected according to procedures developed by Hammermeister and others (1986). In summary, this procedure requires that each of the four, 6-inch core-barrel sleeve liners be capped, taped, plastic wrapped, and immediately placed in a heat-sealable aluminum pouch. When possible, a sample from inside the cutting edge of the core barrel (a shoe sample) also was collected and preserved in an aluminum pouch. A total of 10–12 cores were collected at each borehole using this method.

The cores and cuttings were analyzed at the USGS Hydrologic Research Laboratory in Sacramento, California. Analyses presented in this report include physical properties (bulk density, particle density, porosity, volumetric water content, and percent saturation), saturated hydraulic conductivity, matric potential, and particle-size distribution. Selected cores also were subsampled for measurement of moisture retention data. All analyses were performed in accordance with standards developed by the American Society for Testing and Materials (ASTM) or other approved technical procedures. Bulk density (ρ_b) was determined by oven drying samples at 105^o C. Particle density (ρ_p) was measured using a Micrometrics Accupyc 1330 helium pycnometer. Porosity (ϕ) was calculated according to

$$\phi = 1 - (\rho_b / \rho_p) . \qquad (1)$$

Volumetric water content was calculated as the difference between the initial sample weight and the weight of the sample after oven drying. Percent saturation was calculated as the quotient of the volumetric water content divided by porosity. Saturated hydraulic conductivity was measured in accordance with ASTM D5084 (American Society for Testing and Materials, 1990). Matric potential was measured by using the heat dissipation method described by Campbell and Gee (1986). Heat dissipation probes were saturated prior to their installation into the core. Owing to capillary forces, water from the saturated ceramic probe drains into the soil matrix until equilibrium is reached. Accuracy of the matric-potential measurement is +/-0.1 bar (Campbell and Gee, 1986). In addition, the high air-entry value of the ceramic material limits the resolution of the measurement at the extreme wet end (from 0 to -0.1 bar). Matric potentials are, therefore, reported to the nearest 0.1 bar; and, for full saturation, matric potential values are reported as "greater than -0.1 bar." Matric potentials also were determined on the basis of sediment saturation and moisture retention data. Unsaturated hydraulic conductivity of sediments at saturation levels, at time of sample collection, was calculated using these matric potentials.

A combination of sieve analysis and hydrometer analysis determined particle-size distribution of the cores and cuttings. Gravel- and sand-sized fractions on a mass basis were determined by sieve analysis in accordance with ASTM procedure C136 (American Society for Testing and Materials, 1996). Silt and clay-sized fractions were determined by using hydrometer analysis in accordance with the procedure developed by Gee and Bauder (1979) outlined in Klute (1986). Classification of textural size fractions is in accordance with the U.S. Department of Agricultural system (U.S. Department of Agriculture, 1975). In this system, sand-sized particles range from 0.05 mm to 2 mm, silt-sized particles range from 0.002 to 0.05 mm, and clay-sized particles are less than 0.002 mm. All particles greater than 2 mm in diameter are considered to be gravel-sized particles. Sediment texture of the cores and cuttings was classified using the nomenclature developed by Folk (1954).

***Borehole Geophysical Surveys*.—**All boreholes drilled for the study were logged using geophysical electromagnetic-induction (EM) and natural gamma-ray tools. Data were collected at 0.1 ft intervals from within open boreholes after the ODEX casing was removed. The electromagnetic instruments measure apparent electrical conductivity (the ability of a material to transmit the flow of an electrical current) of the subsurface materials and are especially useful in distinguishing the electrically conductive silt and clay from sand and gravel. The EM logs began at a depth of about 5 ft below land surface because of the length of the borehole-logging tool. Natural gamma logs measure the gamma radiation. Gamma radiation typically is high in fine-grained sediments, such as clays, that have high potassium contents.

***Surface Geophysical Surveys*.**—The surface-geophysical data were collected at sites that could be correlated and verified with lithologic information from borehole well logs. Surveys also were done in areas where few data were available; these surveys were used to infer lithologic information. Latitude and longitude were determined for each site using the global-positioning satellite system and a Precision Lightweight GPS Receiver. Altitude was determined using orthophotoquads with 2-ft contour intervals.

Surface EM methods were used to help determine the vertical and horizontal extent of the fine- and coarse-grained sediments. The electrical conductivity of the stream-channel deposits can be a function of grain size and moisture content. Conductivity values for dry alluvium in the arid Southwest commonly are less than 10 mmhos/m. Values for saturated sand and gravel typically range from 20 to 50 mmhos/m; those of saturated clay and silt commonly are about 100 mmhos/m or greater. Saturated alluvial deposits typically have conductivity values that range from 50 to 100 mmhos/m, which indicate a mixture of clay, silt, sand, and gravel. Data were collected with an EM34-3 instrument from 22 soundings within the creek channel (**fig. 1** and pl. 1–3). Electromagnetic data also were collected along a profile parallel to and along the length of the creek at about 625-foot intervals using an EM31 instrument.

Depth of investigation for the EM data ranges from about 10 to 200 ft and is a function of transmission frequency, coil spacing, and dipole type (table 1). Although depth of investigation for the electromagnetic-induction instruments extends to about 200 ft, depth of the material contributing to the signal differs for each dipole type. For example, the material at a depth of about 0.4 times the coil spacing provides the maximum contribution to the signal for the vertical dipole (the near-surface material contributes little to the signal). Conversely, for the horizontal dipole, the contribution from near-surface material is large and drops off monotonically with depth (McNeill, 1980).

Direct-current (DC) electrical-resistivity surveys were done to aid in delineating the horizontal and vertical extents of the stream-channel deposits. The DC resistivity method uses two-dimensional (2-D) resistivity soundings to image the electrical properties of the subsurface materials. The resistivity method measures the resistance of subsurface materials to the flow of an electrical current. Because resistivity is the inverse of electrical conductivity, these data provide a valuable comparison to electrical conductivity measurements. Because water is a conductor of electricity, resistivity decreases with increasing water content. Water content generally can be an indication of particle size because fine-grained materials tend to have greater water content than coarse materials. The resistivity of different materials varies widely and can be used to delineate rock types. In this study, electrical resistivity was used to distinguish the generally coarse-grained deposits from the finer grained deposits. Alluvium resistivity can range from 10 to 800 ohm meters (Ω•m; Loke, 1999); silt and clay layers and lenses are the least resistive, and sand and gravel layers are the most resistive.

Resistivity measurements were made by transmitting an electrical current into the subsurface through two current electrodes. Two potential electrodes were inserted in the ground colinear with the current electrodes, and a voltage was measured between them. For this study, 2-D electrical resistivity surveys were done with 28 electrodes along 13 profiles within the creek. Data were collected at each profile using three array types: Wenner, Schlumberger, and dipole-dipole. The Wenner array is most sensitive to vertical variations in resistivity; the dipole-dipole array is most sensitive to lateral variations in resistivity. The Schlumberger array has intermediate sensitivity for both horizontal and vertical variations in resistivity. Depths of investigation for the profiles ranged from about 70 to 130 ft depending on array geometry. Each array was oriented approximately parallel to the channel of the creek. Because the Wenner array is sensitive to vertical changes in resistivity and the signal-to-noise ratio for the Wenner array was the highest of the three array types, results from the Wenner array are discussed in this report. Data were inversely modeled to identify the electrical resistivity of the subsurface materials using RES2D (Loke, 1999).Vertical-electrical one-dimensional (1-D) soundings centered on the Wenner arrays also were analyzed using RESIX^{PLUS} modeling software (Interpex Limited, 1992).

Seismic-refraction surveys were used to estimate the thickness of the stream-channel and terrace deposits that overlie the basin-fill deposits. Sediments tend to be more compacted with increasing depth and, therefore, tend to transmit pressure waves at increasingly higher velocity. The velocity contrast between layers produces a refracted pressure wave that is detected by a line of geophones installed at land surface. The primary objective of the seismic surveys was to delineate the contact between the recent alluvium and the older, more compacted, basin-fill sediments.

Table 1. Depths of investigation using EM31 and EM34-3 instruments at various frequencies, coil spacings, and dipole types

[Data from McNeill, 1980]

Electromagnetic-induction instrument	Frequency, in hertz	Coil spacing, in feet	Maximum depth of investigation, in feet	
			Vertical dipole	Horizontal dipole
EM31	9,800	12.0	19.7	9.8
EM34-3	6,400	32.8	49.2	24.6
EM34-3	1,600	65.6	98.4	49.2
EM34-3	400	131.2	196.9	98.4

Seismic data were collected along 24 survey lines, 12 of which were in the stream channel and 12 on the adjacent terraces. All survey lines were oriented north and south. Two energy sources were used to produce the pressure-wave signal. For shallow investigations (upper 100 ft), a 6-pound sledge hammer was used as the signal source; explosive charges were used for deeper investigations (to depths of about 250 ft). Geophone spacings of between 5 and 10 ft were used. Seismic-line locations were surveyed using a GPS receiver. A 48-channel digital seismograph was used to record the data from the refraction surveys. Data were analyzed to determine the thickness of the recent alluvium and seismic velocity of recent alluvium and basin-fill deposits using the SIP software package (Rimrock Geophysics Inc., 1995).

CHARACTERISTICS OF SHALLOW DEPOSITS BENEATH RILLITO CREEK

The storage and flow of water through the unsaturated deposits beneath Rillito Creek are functions of the physical and hydraulic properties of the deposits. Three geologic units were penetrated during the drilling of the five boreholes: the stream-channel deposits of the recent alluvium, and the Fort Lowell Formation and Tinaja beds of the basin-fill deposits. Stream-channel deposits at the five boreholes range in thickness from 15 to 36 ft (pl. 1–3). The basin-fill deposits were not completely penetrated by any of the boreholes. Geophysical properties were measured at boreholes and in adjacent areas to infer continuity, thickness, and physical and hydraulic properties of subsurface deposits.

Particle-Size Distribution and Physical and Hydraulic Properties

Particle-size distribution.—Particle-size distribution analysis presents statistical proportions of varying particle sizes. The results of this analysis can be used to define sediment texture and identify particle-size relations that influence physical and hydraulic properties. Stream-channel deposits are characterized generally as sandy gravels or gravelly sands on the basis of nomenclature described by Folk (1954). Average gravel, sand, silt, and clay contents in each deposit were calculated as weighted averages:

$$\bar{x} = \sum_{i=1}^{n} \frac{x d_i}{d} , \qquad (2)$$

where

$\bar{x}$ = average component of gravel, sand, silt, or clay, in percent;

x = component of gravel, sand, silt, or clay in cuttings sample, in percent (see section entitled "**Basic Data**" at the back of the report);

d_i = thickness represented by the cuttings, in feet; and

d = total thickness of unit, in feet; unit represents either the stream-channel deposit, the basin-fill deposits, or their combined thickness.

On average, the stream-channel deposits are 44 percent gravel, 51 percent sand, 2 percent silt, and 3 percent clay (**table 2**). There is a wide range, however, in the percentage of gravel and sand components. Results of particle-size analyses of the cuttings are listed in **tables 13** and **14** in the section entitled "Basic Data" at the back of the report.

The basin-fill deposits also are sandy gravels or gravelly sands, but have on average a larger component of silt and clay than the stream-channel deposits—about 9 percent silt and 6 percent clay (table 2). Although most basin-fill deposits in the boreholes were sandy gravels or gravely sands, a layer of predominantly fine-grained sediments characterized as sandy mud or muddy sand was found at a depth of about 40 to 100 ft below land surface in borehole (D-13-13)16add.

Particle-size analyses of the cores generally were in agreement with those of the cuttings (tables 13 and 14, in the section entitled "Basic Data" at the back of the report), although some differences exist.

Table 2. Summary of particle-size analyses of stream-channel and basin-fill deposits at five boreholes drilled in Rillito Creek, Pima County, Arizona

[Particle-size analyses were done on drill cuttings. Averages are weighted by the total thickness of deposits sampled (see equation 2). The number of samples analyzed and averaged is listed with the borehole location. See section entitled "**Basic Data**" at the back of the report for detailed particle-size analyses of drill cuttings. mm, millimeter; >, greater than; <, less than; NA, not applicable]

Borehole name	Particle-size data from drill cuttings							
	Gravel (>2 mm)		Sand (0.05–2 mm)		Silt (0.002–0.05 mm)		Clay (<0.002 mm)	
	Average, in percent	Range, in percent	Average, in percent	Range, in percent	Average, in percent	Range, in percent	Average, in percent	Range, in percent
Stream-channel deposits								
(D-13-13)16add (15 samples)	51.5	8–77	44.6	21–85	0.9	0–4	3.1	2–6
(D-13-14)19bcbn (13 samples)	45.4	18–65	49.9	33–77	1.3	0–6	3.5	2–5
(D-13-14)19bcbs (9 samples)	32.6	19–60	63.1	33–78	.9	0–3	3.5	2–5
(D-13-14)28dba (11 samples)	50.0	9–67	42.0	22–65	3.6	0–12	4.4	1–15
(D-13-14)26daa (6 samples)	42.5	6–62	53.7	11–87	1.5	0–3	2.3	1–4
Arithmetic average of weighted averages	44.4	NA	50.7	NA	1.6	NA	3.4	NA
Basin-fill deposits								
(D-13-13)16add (15 samples)	34.8	0–86	31.0	11–90	21.4	4–63	12.8	4–42
(D-13-14)19bcbn (13 samples)	35.5	7–72	55.6	21–81	5.5	1–14	4.1	1–9
(D-13-14)19bcbs (9 samples)	26.1	8–74	61.4	24–76	7.3	1–13	5.2	1–9
(D-13-14)28dba (11 samples)	28.2	7–63	59.0	18–75	7.5	1–17	5.2	2–8
(D-13-14)26daa (6 samples)	63.9	30–82	29.6	13–56	3.7	1–8	2.8	1–6
Arithmetic average of weighted averages	37.7	NA	47.3	NA	9.1	NA	6.0	NA
Arithmetic average without (D-13-13)16add (for basin-fill deposits only)	38.5	NA	51.4	NA	6.0	NA	4.3	NA

These differences may be related to several factors, including (1) the pulverizing of coarser-grained material resulting in an under-representation of the coarse fraction and an over-representation of the fine fraction, (2) inadequate removal of cuttings during drilling typically resulting in an under-representation of the coarse fraction, (3) subsequent purging of the borehole typically resulting in an over-representation of the coarse fraction, (4) loss of fine material at the surface where the drilling fluid (air) is separated from the cuttings, (5) sample size (cores were 6 inches long and 4 inches wide; cuttings were collected over a 1-foot interval of the borehole, which had a diameter of 7.5 to 9 inches), and (6) selecting a nonrepresentative split of cuttings for particle-size analysis.

Physical and hydraulic properties of the unsaturated zone sediments.—Moisture in the unsaturated zone results from the infiltration and percolation of surface flows. Flow of water through the unsaturated zone is a function of the physical and hydraulic properties and antecedent conditions of the sediments in the unsaturated zone, and of hydraulic driving forces such as gravity and matric pressure.

Porosity and volumetric moisture content of cores collected from the unsaturated zone beneath Rillito Creek varied (**table 3**). Porosity of the stream-channel deposits (about 31 percent) was similar to that of the basin-fill deposits (about 34 percent; table 3). Moisture content was lower in the stream-channel deposits than in the basin-fill deposits. Moisture content of the stream-channel deposits ranged from 2 to 40 percent and averaged about 18 percent; in the basin-fill deposits it ranged from 7 to 47 percent and averaged about 24 percent (table 3). Saturation, which is the volumetric water content divided by porosity, ranged from 9 to 100 percent and averaged about 58 percent in the stream-channel deposits. In the basin-fill deposits, saturation ranged from 30 to 100 percent and averaged about 69 percent.

Moisture content correlated positively with silt and clay content (**fig. 3**). Moisture content can vary temporally and reflects conditions at the time of core collection. In this study, cores were collected in late March 1999. The most recent flow in Rillito Creek before core collection was in November 1998 (Tadayon and others, 2000). The flow in November 1998 lasted for about 2 days and was small (average flow was less than 30 ft^3/s). Prior to November 1998, the most recent flows having a duration exceeding 1 day occurred as a result of summer monsoonal storms in 1998; therefore, moisture content and percent saturation probably reflect slow drainage.

Cumulative thickness of water in the unsaturated zone was obtained by integrating the moisture content over depth from the land surface. At time of core collection, cumulative water content ranged from 17.2 to 40.4 ft of water (**fig. 4**). Thickness of the unsaturated zone, at time of core collection, varied from about 100 ft at borehole (D-13-14)19bcbs to about 125 ft at borehole (D-13-13)16add (**table 12**, see section entitled “Basic Data” at the back of the report).

Matric potential, defined as the pressure head of water in the unsaturated zone, generally was close to zero for the cores collected from both stream-channel and basin-fill deposits. Although most cores had a matric potential of -0.4 to more than -0.1 bar (**table 16**, see section entitled “Basic Data” in the back of the report), the lowest potentials measured were -4.0 and -3.9 bars. These values were for cores collected close to the land surface that had moisture contents of about 5 percent. Excluding data from these cores, matric potential of the stream-channel deposits generally was greater than -0.1 bar, whereas that of unsaturated basin-fill sediments generally ranged from about -0.1 to -1.0 bar.

For unsaturated sediments, water content decreases as matric potential becomes increasingly negative. The moisture-retention curve (MRC) describes the relation between water content and matric potential under equilibrium conditions (**fig. 5**). The MRC has a nonlinear relation that is influenced by the distribution of pore space, which is affected by sedimentary texture and structure. The slope of the MRC defines the specific moisture capacity (change in moisture content due to a change in matric potential). A commonly used algebraic expression for relating water content to matric potential was proposed by van Genuchten (1980):

$$\Theta = (1 + (\alpha|h|)^n)^{-\left(1 - \frac{1}{n}\right)} , \qquad (3)$$

where

Θ = dimensionless water content; water content minus residual water content, divided by the saturated water content minus residual water content;

α = van Genuchten fitting parameter, in 1/bar

h = matric potential, in bars; and

n = van Genuchten fitting parameter (dimensionless).

Table 3. Summary of data for selected physical properties of unsaturated stream-channel and basin-fill deposits at five boreholes drilled in Rillito Creek, Pima County, Arizona

[Cores were analyzed for moisture content; porosity was calculated using equation 1; saturation was calculated by dividing moisture content by porosity. Averages were weighted by the total thickness of deposits sampled using equation 2. See section entitled "**Basic Data**" at the back of the report for detailed analysis of physical properties. NA, not applicable]

Borehole name (number of samples)	Volumetric moisture content, in percent		Porosity, in percent		Saturation, in percent	
	Average	Range	Average	Range	Average	Range
Stream-channel deposits						
(D-13-13)16add (6)	20	2–29	27	20–33	73	9–97
(D-13-14)19bcbn (5)	14	10–19	26	23–41	52	23–81
(D-13-14)19bcbs (5)	15	5–18	37	34–42	39	15–51
(D-13-14)28dba (5)	25	12–40	35	22–52	72	41–100
(D-13-14)26daa (2)	15	5–26	32	28–36	52	12–91
Arithmetic average of weighted averages	17.8	NA	31.4	NA	57.6	NA
Basin-fill deposits						
(D-13-13)16add (5)	41	34–46	42	33–52	98	88–100
(D-13-14)19bcbn (5)	19	13–25	30	23–37	64	34–98
(D-13-14)19bcbs (6)	24	14–47	34	25–49	72	35–95
(D-13-14)28dba (7)	12	7–20	29	21–36	43	30–60
(D-13-14)26daa (0)	Did not core basin-fill deposits					
Arithmetic average of weighted averages	24.0	NA	33.8	NA	69.3	NA

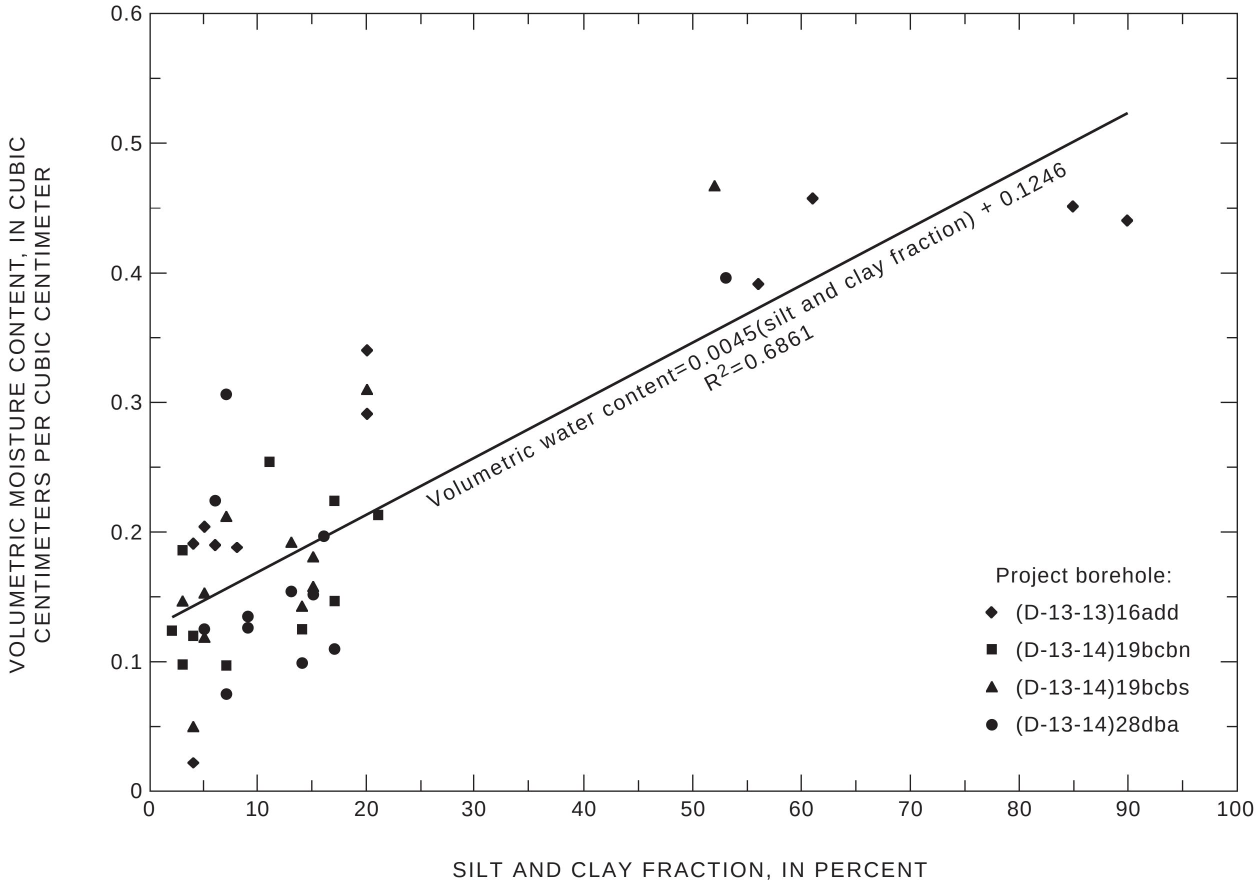


Figure 3. Relation of volumetric moisture content to silt and clay content for cores collected from boreholes drilled along Rillito Creek, Pima County, Arizona.

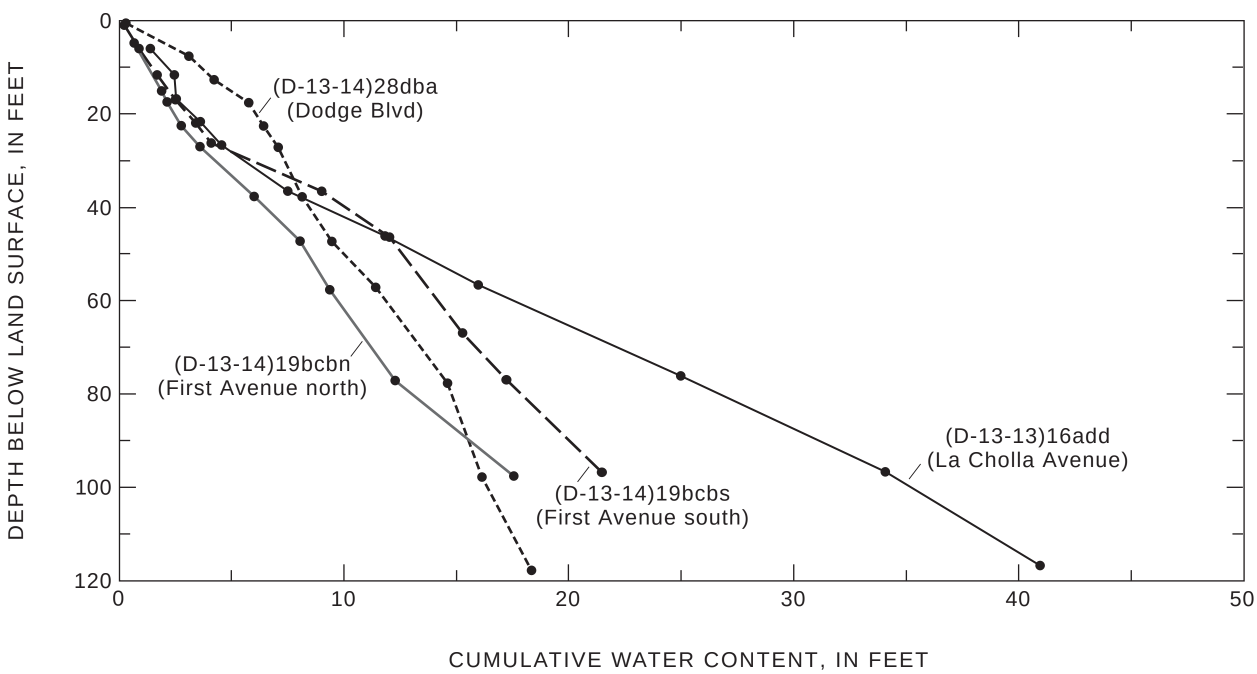


Figure 4. Cumulative moisture content in the unsaturated zone, March–April 1999, Rillito Creek, Pima County, Arizona.

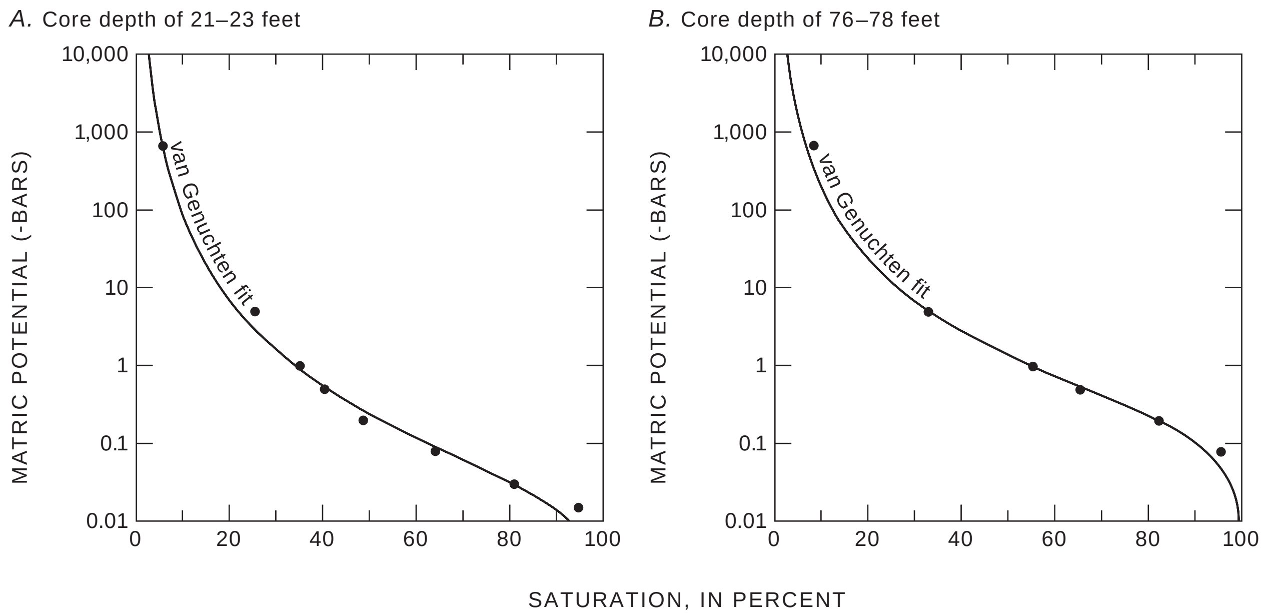


Figure 5. Typical moisture retention data and curves for stream-channel and basin-fill deposits, Rillito Creek, Pima County, Arizona. Data shown are from cores collected from borehole (D-13-13)16add. *A*, stream-channel deposit. *B*, basin-fill deposit.

The residual water content (RWC) is defined as the amount of water remaining in the sediment after increasing negative pressures result in discontinuous water films, which allows water to move only by vapor diffusion. The hydraulic conductivity for liquid flow is considered to be zero at the RWC. In this study, the RWC is defined as the amount of water remaining in the sediment at -663 bars (the highest negative pressures used in MRC calculations). The RWC tends to increase with increasing percentage of fine-grained sediments (**fig. 6**). Accordingly, the RWC for the basin-fill sediments is greater than that for the stream-channel deposits (**table 4**). The MRCs for stream-channel and basin-fill deposits tend to have different van Genuchten fitting parameters. For example, α ranged from 4.56 to 1,220 bar^{-1} and averaged 220 bar^{-1} for stream-channel deposits and ranged from 4.22 to 67.9 bar^{-1} and averaged 22.8 bar^{-1} for basin-fill deposits (table 4). Fitting parameters and RWC values for each core analyzed are listed in **table 17** in the section entitled “Basic Data” at the back of the report. The MRC data can be used to calculate the specific yield of an aquifer by subtracting the RWC from the saturated water content, which is assumed to be equivalent to porosity. The average specific yield for both the stream-channel and basin-fill deposits is about 0.30 (table 4). This calculation reflects a maximum specific yield because residual moisture content defined in this study requires a pressure of -663 bars.

Unsaturated hydraulic conductivity is less than saturated hydraulic conductivity and can vary by orders of magnitude as a function of matric potential. The van Genuchten fitting parameters and matric potential can be used to calculate a relative hydraulic conductivity (van Genuchten, 1980) by:

$$Kr(h) = [1 + (\alpha|h|)^n]^{\frac{-m}{2}} \left[1 - \left(1 - [[1 + (\alpha|h|)^n]^{-m}]^{\frac{1}{m}}\right)^m\right]^2 \quad , \qquad (4)$$

where *Kr(h)* is relative hydraulic conductivity of the sediment for a given matric potential and m is 1-1/n (Mualem, 1976). *Kr(h)* curves for each core are shown in **figure 7** for matric potentials ranging from -9.8E-7 bar (representing conditions near saturation) to -650 bars (representing conditions near RWC).

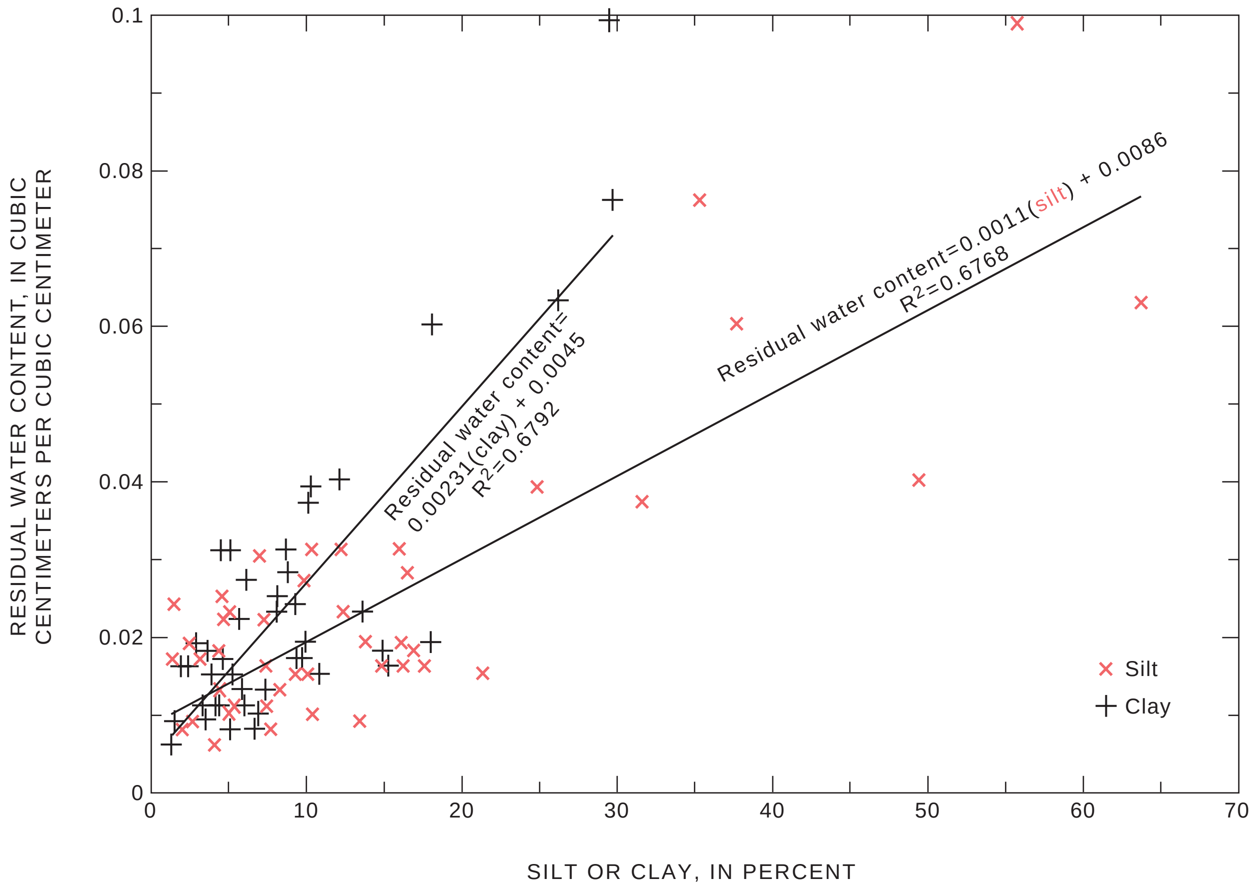


Figure 6. Residual water content as a function of clay and silt fraction for cores collected from boreholes drilled along Rillito Creek, Pima County, Arizona.

Table 4. Summary of data for selected hydraulic properties of stream-channel and basin-fill deposits in the unsaturated zone, Rillito Creek, Pima County, Arizona

[α, van Genuchten fitting parameter in per bar; *n*, van Genuchten fitting parameter, dimensionless; RWC, residual water content in cubic centimeters per cubic centimeter; average saturated water content is equivalent to average porosity, in percent (Table 3); average specific yield is calculated by subtracting average residual water content from saturated water content]

Unsaturated-zone parameter						Average saturated water content[1]	Average specific yield
α		n		RWC, in percent			
Average	Range	Average	Range	Average	Range		
Stream-channel deposits							
220	4.56–1,220	1.272	1.206–1.377	1.7	0.6–7.6	31.4	0.30
Basin-fill deposits							
22.8	4.22–67.9	1.331	1.199–1.528	2.8	.9–9.9	33.6	.31

[1] Average saturated water content assumed to be equivalent to average porosity (table 3).

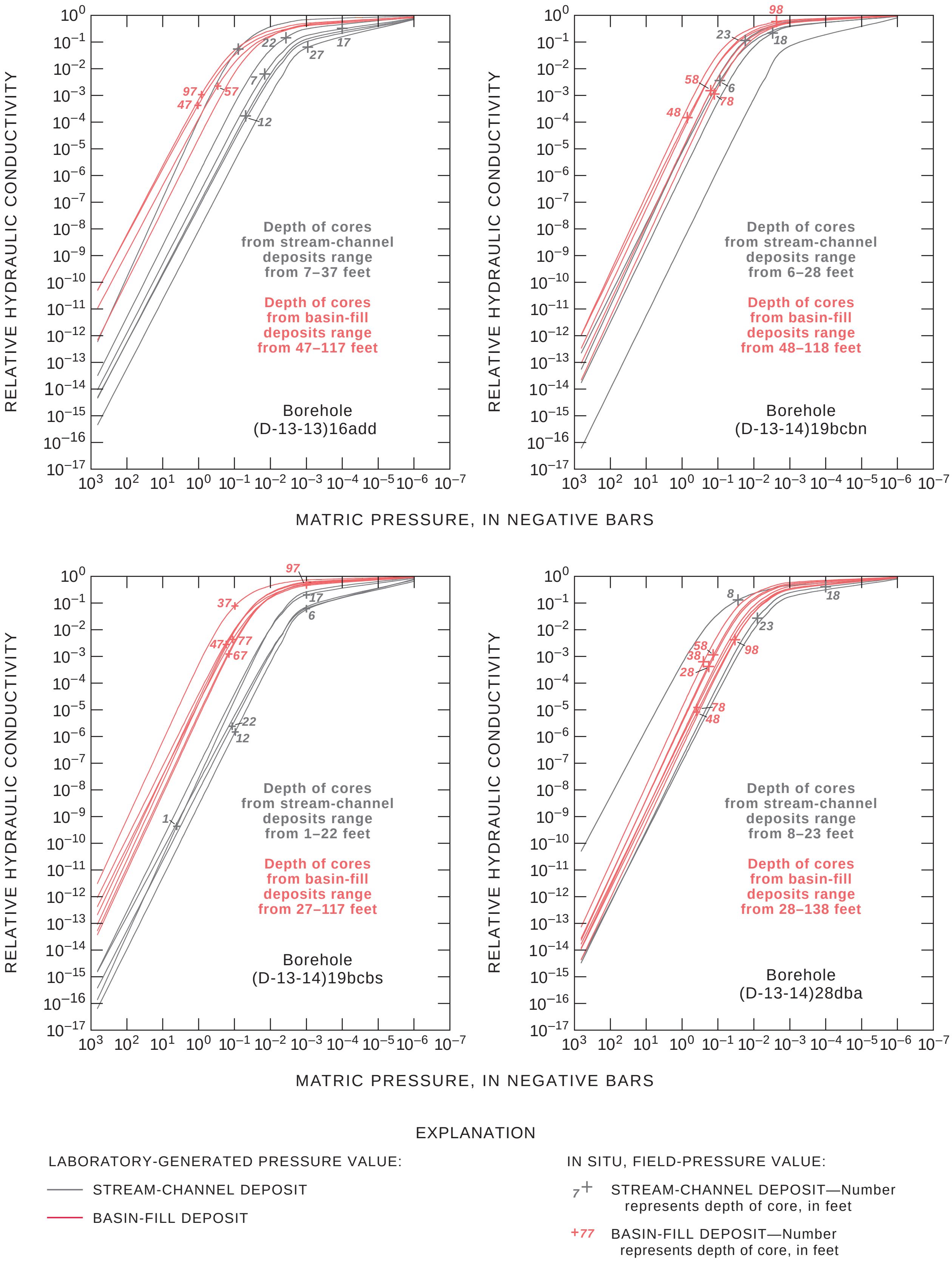


Figure 7. Relative hydraulic conductivity as a function of matric potential for cores collected from boreholes drilled along Rillito Creek, Pima County, Arizona.

Kr(h) values range over 10 orders of magnitude for this range in matric potential. Stream-channel deposits generally have smaller *Kr(h)* values than do basin-fill deposits at the same negative matric potential (fig. 7), probably because the stream-channel deposits are coarser grained and enable water to drain more readily. Matric potentials at the time of sample collection are shown in figure 7. These were calculated by solving for *h* in equation 3 using the saturation data for the time of sample collection and the van Genuchten fitting parameters determined from the moisture retention curves (**table 17**, see section entitled “Basic Data” at the back of the report).

Relative hydraulic conductivity values for matric potentials existing at the time of core collection (**table 16**, see section entitled “Basic Data” at the back of the report) are shown in table 5. If the saturated hydraulic conductivity (K_{sat}) of the sediment is known, the unsaturated hydraulic conductivity (K_{unsat}) can be calculated as the product of the *Kr(h)* and K_{sat}. Saturated hydraulic conductivity values from **table 15** (see section entitled “Basic Data” at the back of the report) are used to calculate the K_{unsat} of cores at the time of collection (table 5). Unsaturated hydraulic conductivity for moisture conditions that existed at the time of sample collection typically was more than two orders of magnitude less than saturated hydraulic conductivity.

Table 5. Saturated hydraulic conductivity, relative hydraulic conductivity, and unsaturated hydraulic conductivity for cores collected along Rillito Creek, Pima County, Arizona

[Data for saturated hydraulic conductivity (K_{sat}) are in feet per day from table 15 in the section entitled “Basic Data” in the back of the report for the corresponding depth interval; data for hydraulic conductivity [*Kr*(*h*)] are from equation (3) using matric potentials (*h*) of the cores at time of collection (table 16 in section entitled “Basic Data” at the back of the report); unsaturated hydraulic conductivity (K_{unsat}) is the product of saturated hydraulic conductivity and relative hydraulic conductivity. SC, stream-channel; BF, basin-fill]

Type of deposit	Depth interval, in feet	K_{sat}[1]	*Kr*(*h*)	K_{unsat}
Borehole (D-13-13)16add				
SC	6–8	7.04	6.8E-04	4.8E-03
SC	11–13	7.13	5.6E-04	4.0E-03
SC	16–18	3.24	1.1E-14	3.3E-14
SC	21–23	1.11	1.7E-02	1.9E-02
SC	26–28	2.67	6.0E-02	1.6E-01
SC	36–38	8.06	6.6E-02	5.3E-01
BF	46–48	.43	8.8E-03	3.8E-03
BF	56–58	.10	5.7E-02	5.7E-03
BF	96–98	.04	1.1E-03[2]	4.0E-05
BF	116–118	.11	1.0	1.1E-01
Borehole (D-13-14)28dba				
SC	7–9	7.94	1.4E-03	1.1E-02
SC	17–19	6.81	3.3E-02	2.3E-01
SC	22–24	6.89	1.7E-05	1.2E-04
BF	27–29	.54	5.5E-05	2.9E-05
BF	37–39	1.94	5.8E-06	1.1E-05
BF	47–49	2.30	9.9E-06	2.3E-05
BF	57–59	1.64	1.5E-03	2.4E-03
BF	77–79	.25	4.9E-04	1.2E-02
BF	97–99	.80	3.4E-07	2.7E-07
Borehole (D-13-14)19bcbs				
SC	0–2	6.67	2.7E-08	1.8E-07
SC	5–7	7.38	2.7E-08	2.0E-07
SC	11–13	7.33	1.5E-05	1.1E-04
SC	16–18	2.15	4.6E-06	1.0E-05
SC	21–23	2.09	3.9E-05	8.2E-05
BF	26–28	1.86	1.1E-05	2.0E-05
BF	36–38	.06	1.4E-01	8.3E-03
BF	46–48	.07	2.8E-03[2]	2.0E-04
BF	66–68	1.02	2.6E-04	2.7E-04
BF	76–78	2.50	2.5E-04	6.2E-04
BF	96–98	3.43	2.5E-02	8.7E-02
Borehole (D-13-14)19bcbn				
SC	5–7	4.76	2.3E-08	1.1E-07
SC	17–19	8.24	3.01E-06	2.5E-05
SC	22–24	4.66	7.2E-05	3.4E-04
BF	27–29	2.15	1.2E-02	2.5E-02
BF	47–49	.89	1.1E-03	1.0E-03
BF	57–59	2.22	7.4E-06	1.6E-05
BF	77–79	1.43	4.7E-05	6.7E-05
BF	97–99	5.35	7.5E-02	4.0E-01

[1]For boreholes (D-13-13)16add and (D-13-14)28dba saturated hydraulic conductivity is an average of the two measurements made on cores (table 15).
[2]Based on matric potential determined from heat-dissipation probe method (table 16).

Saturated hydraulic conductivity.— K_{sat} of each sample was determined parallel to the main axis of the core; therefore, K_{sat} represents a vertical saturated hydraulic conductivity (K_z). The K_z of the stream-channel cores ranged from 1.1 to 8.2 ft/d, about an order of magnitude greater than that of basin-fill cores (table 6). The hydraulic conductivity of any medium typically is inversely related to grain size because fine-grained sediments have larger surface areas, which increase the resistance to fluid flow through the medium. K_z for deposits beneath Rillito Creek show this inverse correlation (**fig. 8**). Layering and (or) degree of compaction also influence the hydraulic conductivity of a detrital medium. Layering and (or) compaction perhaps are less pronounced in the stream-channel deposits as the stream-channel deposit cores have a greater K_z than basin-fill deposit cores given similar sand, silt, and clay contents (fig. 8).

Assuming the coring process did not significantly disturb the structure or increase the degree of compaction of sediments and that K_{sat} of cores is representative of the K_{sat} of adjacent sediments, K_{sat} of the core probably is representative of the K_{sat} of sediments beneath Rillito Creek. The degree to which sediment structure has been disturbed by coring is difficult to determine. Increased sediment compaction from coring appears to be minimal because measured bulk density values are in the expected range for these sediments (pl. 1–3).

Table 6. Summary of saturated vertical hydraulic conductivity data for stream-channel and basin-fill deposits at four boreholes drilled along Rillito Creek, Pima County, Arizona

[Data are from core analyses. Equivalent saturated hydraulic conductivity in the vertical direction is calculated as the harmonic mean of hydraulic conductivity values (equation 5). Equivalent saturated hydraulic conductivity in the horizontal direction is calculated as the arithmetic mean of hydraulic conductivity values (equation 6; Freeze and Cherry, 1979). See section entitled "**Basic Data**" at the back of the report for detailed analysis of saturated hydraulic conductivity]

	Stream-channel deposits				Basin-fill deposits				Undifferentiated (combined stream-channel and basin-fill deposits)	
Borehole name	Number of cores	Range of saturated vertical-hydraulic conductivity (K_z), in feet per day	Equivalent saturated hydraulic conductivity (vertical) ($\hat{K}_z$), in feet per day	Equivalent saturated hydraulic conductivity (horizontal) ($\hat{K}_h$), in feet per day	Number of cores	Range of saturated hydraulic conductivity (K_z), in feet per day	Equivalent saturated hydraulic conductivity (vertical) ($\hat{K}_z$), in feet per day	Equivalent saturated hydraulic conductivity (horizontal) ($\hat{K}_h$), in feet per day	Equivalent saturated hydraulic conductivity (vertical) ($\hat{K}_z$), in feet per day	Equivalent saturated hydraulic conductivity (horizontal) ($\hat{K}_h$), in feet per day
(D-13-13)16add	6	1.1–1.8	3.4	5.4	4	0.04–0.43	0.06	0.11	0.08	1.8
(D-13-14)19bcbn	5	1.1–8.2	2.0	3.3	5	.89–5.3	1.5	2.6	1.9	2.7
(D-13-14)19bcbs	5	2.1–7.4	3.4	4.8	7	.06–3.4	.18	1.1	.21	1.7
(D-13-14)28dba	6	6.8–7.9	7.3	6.2	7	.25–2.3	.69	1.3	.82	2.2
Arithmetic average			4.0	4.9			.61	1.3	.75	2.1

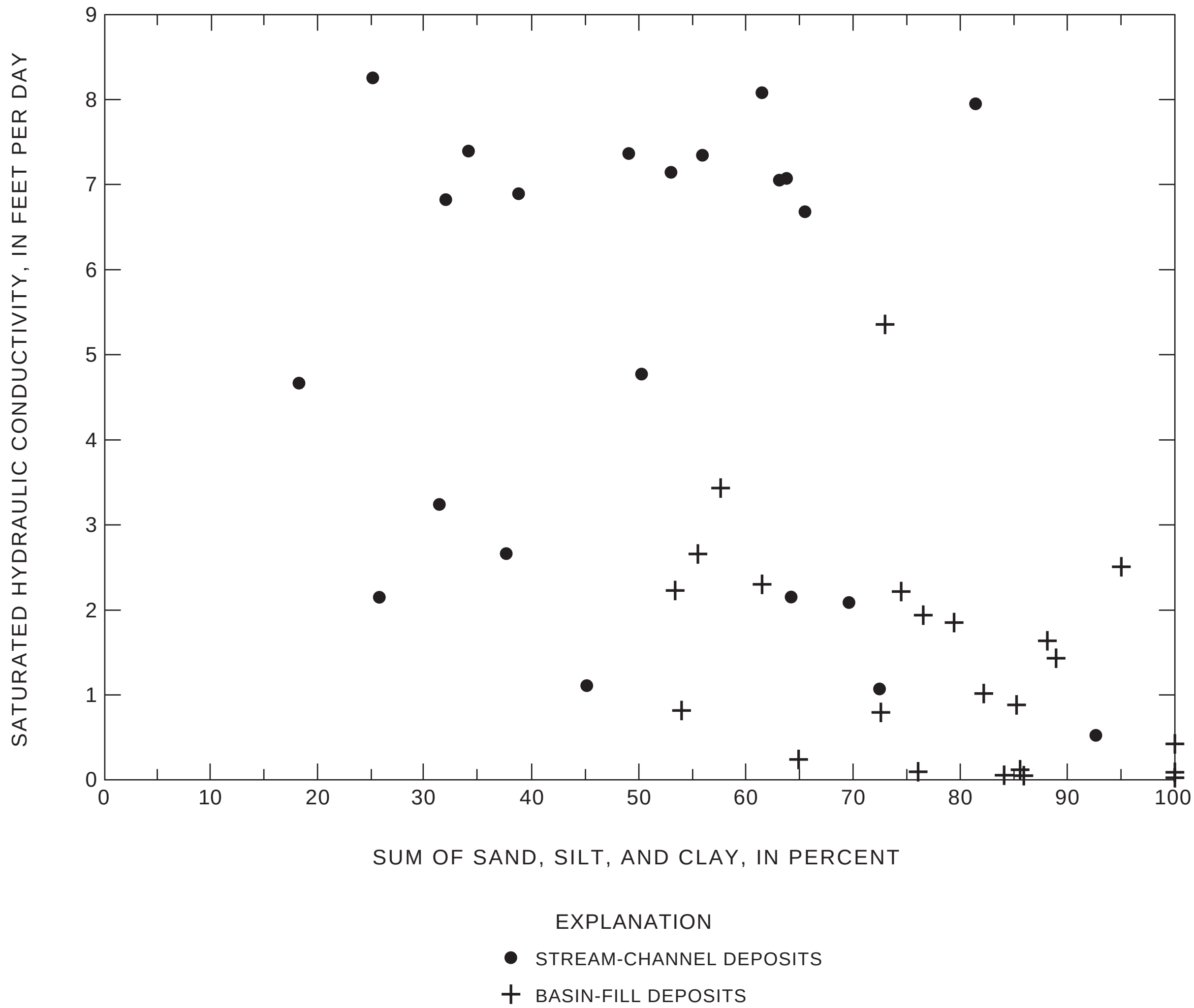


Figure 8. Relation of saturated hydraulic conductivity to sand, silt, and clay content for cores collected from boreholes drilled along Rillito Creek, Pima County, Arizona.

For heterogeneous media, such as the deposits beneath Rillito Creek, hydraulic conductivity varies spatially. The equivalent hydraulic conductivity depends on the direction of flow. For saturated vertical flow, the equivalent saturated vertical hydraulic conductivity ($\hat{K}_z$) for a layered system is calculated as the harmonic mean of the hydraulic conductivity values of the individual layers as:

$$\hat{K}_z = \frac{d}{\sum_{i=1}^{n} \frac{d_i}{K_i}} \tag{5}$$

where

$\hat{K}_z$ = equivalent saturated vertical hydraulic conductivity, in feet per day;

d = total thickness of unit, in feet; unit represents either the stream-channel deposits, the basin-fill deposits, or their combined thickness;

d_i = thickness the core represents, in feet, (in this study, it is the thickness between cores analyzed);

K_i = measured saturated vertical hydraulic conductivity, in feet per day; and

n = number of layers

(Freeze and Cherry, 1979, p. 34, equation 2.31). For horizontal flow, the equivalent saturated hydraulic conductivity ($\hat{K}_h$) for a layered system is calculated as the arithmetic mean:

$$\hat{K}_h = \sum_{i=1}^{n} \frac{K_i d_i}{d} \qquad (6)$$

where

$\hat{K}_h$ = equivalent saturated horizontal hydraulic conductivity, in feet per day;

K_i = measured saturated vertical hydraulic conductivity, in feet per day;

d_i = thickness the core represents, in feet, (in this study, it is the thickness between cores analyzed);

d = total thickness of unit, in feet; unit represents either the stream-channel deposits, the basin-fill deposits, or their combined thickness; and

n = number of layers,

(Freeze and Cherry, 1979, p. 34, equation 2.32). For heterogeneous media, the harmonic mean is always smaller than the arithmetic mean.

Saturated conditions may not exist even during sustained streamflow if the capacity of the subsurface sediments to transmit water is greater than the supply of water. Saturated conditions will exist only after sustained periods of streamflow infiltration at a rate that enables water to fully saturate the underlying sediments. Equation 4 is invalid until saturated conditions exist. Once saturated hydraulic connection is achieved between the stream and the water table, the system behaves as though the stream were perennial (Cooley and Westphal, 1974; Peterson and Wilson, 1987). During the time from the onset of streamflow until full saturation, the unsaturated hydraulic conductivity, which is calculated as the product of the relative hydraulic conductivity (equation 4) and K_{sat}, needs to be considered. Since the relative hydraulic conductivity decreases rapidly with decreasing water content (or matric potential; **fig. 7**), the difference between the hydraulic conductivity of the stream-channel deposits and that of the basin-fill deposits will be larger in partially saturated conditions than when both deposits are fully saturated. $\hat{K}_z$ values for the stream-channel deposits are greater than those for the basin-fill deposits (**table 6**). $\hat{K}_z$ of stream-channel deposits ranges from 2.0 to 7.3 ft/d and averages 4.0 ft/d, whereas $\hat{K}_z$ of the basin-fill deposits ranges from 0.06 to 1.5 ft/d and averages 0.61 ft/d. $\hat{K}_z$ ranges from 0.08 to 1.9 ft/d and averages 0.75 ft/d for the unsaturated zone cored in the study area. For comparison of $\hat{K}_z$ of the stream-channel deposits to $\hat{K}_z$ of the basin-fill deposits, it is necessary to assume saturated conditions exist.

$\hat{K}_h$ of the stream-channel deposits is about four times greater than $\hat{K}_h$ of the basin-fill deposits (table 6). The calculation of $\hat{K}_h$ assumes no horizontal to vertical anisotropy within layers (hydraulic conductivity is the same in the horizontal direction as it is in the vertical direction) and, therefore, uses the saturated-hydraulic conductivity data from the cores. Although layers are assumed to be isotropic, $\hat{K}_h$ is somewhat greater than $\hat{K}_z$ for similar units (table 6). In addition, if anisotropy within layers exists, hydraulic conductivity is probably greater in the horizontal direction than in the vertical direction because of the predominant horizontal layering of streambed sediments.

Geophysical Properties

The geophysical measurements described below are a reflection of the interaction between the static physical properties of the underlying deposits and the dynamic hydrologic properties that are related to rainfall, runoff, infiltration, and drainage.

Borehole geophysical surveys.— Borehole electrical conductivity was useful in differentiating between the stream-channel deposits and basin-fill deposits. In general, electrical conductivity of the stream-channel deposits was less than 30 mmhos/m and averaged 27 mmhos/m (**table 7**, pl. 1–3). Conductivity of the basin-fill deposits was greater than that of the stream-channel deposits and averaged 44 mmhos/m (table 7, pl. 1–3). The greater conductivity probably is related to greater moisture content and percentages of fine-grained sediments in the basin-fill deposits (**fig. 9**). Because natural gamma counts were about the same in the stream-channel and basin-fill deposits (table 7, pl. 1–3), they were not useful in differentiating between the two units.

Table 7. Summary of borehole geophysical data for stream-channel and basin-fill deposits, Rillito Creek, Pima County, Arizona

Borehole name	Average electrical conductivity, in millimhos per meter		Average natural gamma radiation, in counts per second	
	Stream-channel deposits	Basin-fill deposits	Stream-channel deposits	Basin-fill deposits
(D-13-13)16add	26	75[1, 2]	102	103
(D-13-14)19bcbn	22	33	102	96
(D-13-14)19bcbs	23	31	105	97
(D-13-14)28dba	38	41	106	102
(D-13-14)26daa	24	41	89	95
Average	27	44	101	99

[1]Average electrical conductivity for fine-grained layer from about 43 to 100 feet below land surface is 115 millimhos per meter (pl. 3).

[2]Average electrical conductivity for basin-fill deposits beneath the silt and clay is 43 millimhos per meter (pl. 3).

Surface electromagnetic data.— Measurements of apparent electrical conductivity, using an EM31 instrument (coil spacing of 12 ft), were collected twice—once in June 1999 and again in August 1999—along the dry riverbed at an interval of about 625 ft. Resultant data indicate that the apparent electrical conductivity of the shallow stream-channel deposits ranges from about 3 to 47 millimhos/m and averages 12 mmhos/m (table 8 and fig. 10). The eastern (upstream) two-thirds of the creek generally has the smallest conductivity values, which average about 10 mmhos/m. The greatest values were measured in the western (downstream) third of the creek. This difference probably is related to an increased percentage of finer grained sediments, which also have greater moisture contents, in this area. The survey in June 1999 was done during dry conditions; the most recent flow in the creek had been about 9 months earlier. The survey in August 1999 was done within 2 weeks after flow. Conductivity of the shallow sediments in August 1999 averaged about 6 percent greater than the conductivity in June 1999. The increase probably is related to increased moisture content.

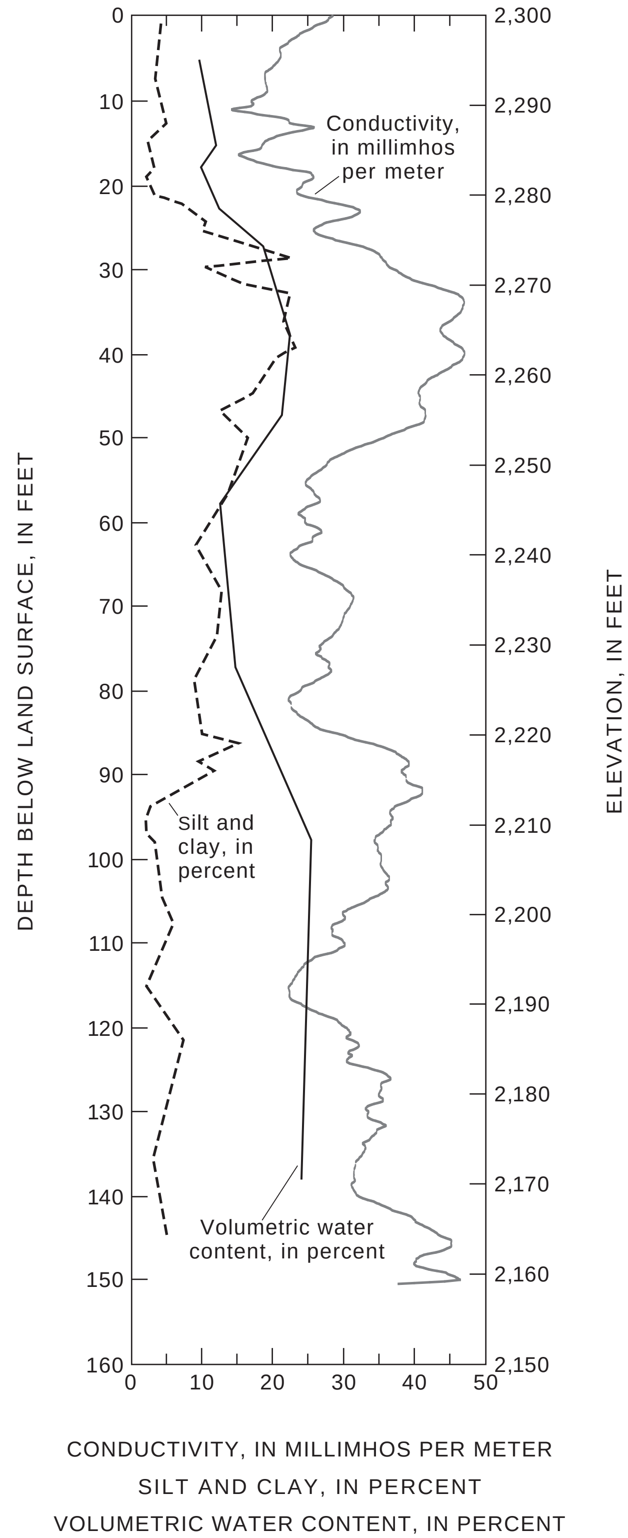


Figure 9. Example of borehole electrical-conductivity log and correlation with silt and clay content determined from cuttings, and volumetric moisture content determined from cores at borehole (D-13-14)19bcbn, Rillito Creek, Pima County, Arizona.

Table 8. Average, minimum, and maximum apparent electrical conductivity for various coil spacings and orientations, June and August 1999, Rillito Creek, Pima County, Arizona

Apparent electrical conductivity, in millimhos per meter	June 1999		August 1999		June 1999					
	EM31 coil spacing, in feet				EM34-3 coil spacing, in feet					
	12.0				32.8		65.6		131.2	
	Vertical dipole	Horizontal dipole	Vertical dipole	Horizontal dipole	Vertical dipole	Horizontal dipole	Vertical dipole	Horizontal dipole	Vertical dipole	Horizontal dipole
	Stream-channel deposits								Basin-fill deposits	
Average	12.8	10.4	13.4	10.8	11.5	11.5	14.4	13.8	31.8	30.6
Minimum	6.1	3.1	7.2	4.2	8.0	6.5	4.5	8.5	20.0	24.0
Maximum	47.3	43	39.9	43.3	18.7	24.0	31.3	23.3	47.0	42.5

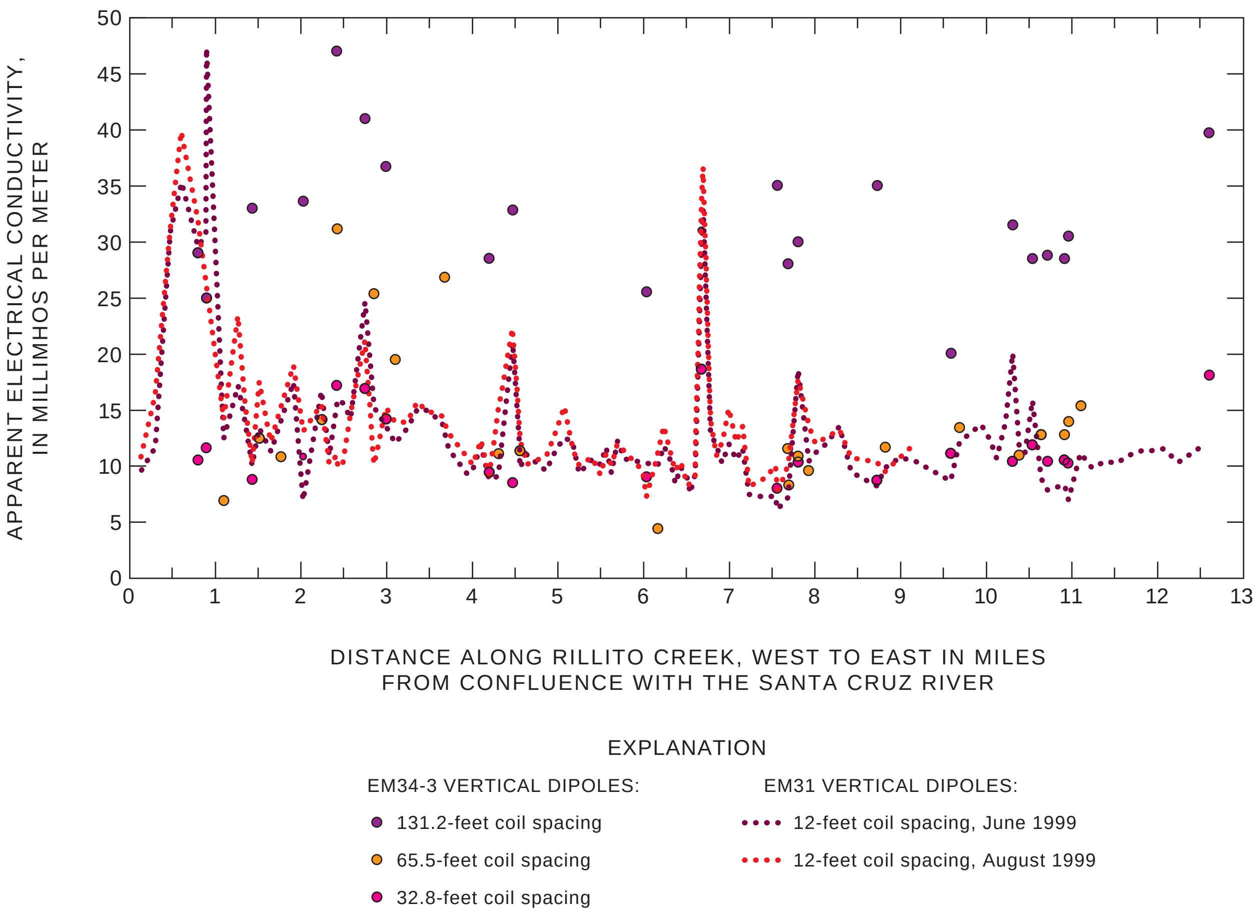


Figure 10. Apparent electrical conductivity determined from surface electromagnetic surveys for vertical dipoles of various coil spacings, Rillito Creek, Pima County, Arizona.

Data from 22 electromagnetic depth soundings collected within the creek channel in June 1999 using an EM34-3 instrument generally indicate an increase in conductivity with increased coil spacing (**table 8**, **fig. 10**). The average conductivity values are about 12, 14, and 32 mmhos/m for the vertical dipoles of 32.8-, 65.6, and 131.2-foot coil spacings, respectively. The increased conductivity with increased coil spacing indicates an increase in conductivity with increasing depth. In general, the properties of the stream-channel deposits contribute the most to the apparent electrical conductivity for the 12-, 32.8- and 65.6-foot coil spacings; the properties of the basin-fill deposits contributed the most to the conductivity for the deeper-looking 131.2-foot coil spacing. The stream-channel deposits have an average apparent electrical conductivity between 10.4 and 14.4 mmhos/m. The basin-fill deposits have an average apparent electrical conductivity between 30.6 and 31.8 mmhos/m. The apparent conductivity values determined from surface methods generally were less than those determined from borehole logs. The difference between the surface and borehole results probably arises because the surface measurements are affected by the low-conductivity near-surface conditions, whereas the borehole logs measure conditions from 5 ft below land surface over the depth interval spanned by the instrument.

Direct-current (DC) electrical-resistivity.— DC electrical resistivity surveys were used to identify the resistivity of stream-channel and basin-fill deposits. DC methods are useful because the generally drier, coarser grained stream-channel deposits are more resistive to induced electrical currents than are the basin-fill deposits. Depth of investigation for Wenner array surveys are about half the current-electrode spacing, which in this study varied from 16.4 to 147.6 ft. Values of apparent resistivity were averaged along the 2-D array for each depth (table 9). With the exception of survey R1, resistivity decreased with increased depth at all survey sites (table 9), which indicated that fine-grained fractions and water contents increased with increased depth. The three uppermost depths of investigation were mostly within stream-channel deposits and had resistivity values generally greater than 140 Ω•m. The shallowest measurements (8.2 ft) represent dry stream-channel deposits and averaged 303 Ω•m (table 9). The measurements at 16.4 and 24.6 ft averaged 177 Ω•m and 145 Ω•m, respectively, and represent mostly stream-channel deposits. At some sites, however, basin-fill deposits may be shallower than 24.6 or 16.4 ft (R13, for example; pl. 1). Measurements from 32.8 ft and below represent predominantly basin-fill deposits and average 75 to 124 Ω•m. In contrast to resistivity values from surveys R2–R13, resistivity values from R1 increased with depth from 70 to 163 Ω•m. These values suggest an abundance of fine-grained sediments in the stream-channel deposits and a coarsening of sediments with depth.

Table 9. Average apparent electrical resistivity for various electrode spacings and depths along two-dimensional Wenner arrays at all survey locations, Rillito Creek, Pima County, Arizona

[Depths are estimated as half the electrode spacing. Resistivity survey sites are shown in **figure 1** and plates 1-3. Values are in ohm meters]

Electrode spacing, in feet	Depth, in feet	Resistivity survey site (resistivity in ohm meters)													Average resist-ivity, in ohm meters	Average resis-tivity[1], in ohm meters
		R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13		
16.4	8.2	70	274	214	249	404	273	378	173	155	231	622	276	618	303	322
32.8	16.4	94	157	164	169	290	193	261	148	115	176	203	188	137	177	183
49.2	24.6	122	146	142	142	225	170	199	138	107	140	137	152	65	145	147
65.6	32.8	140	131	120	118	178	146	158	127	107	112	110	121	45	124	123
82.0	41.0	151	115	98	98	146	125	129	117	92	90	92	100	36	107	103
98.4	49.2	156	101	81	82	125	110	114	109	92	73	82	87	33	96	91
114.8	57.4	159	90	69	73	112	99	109	101	80	60	74	78	33	87	82
131.2	65.6	161	82	57	58	104	89	98	95	68	56	68	72	34	80	73
147.6	73.8	163	74	50	35	99	82	90	87	na	56	55	69	36	75	67

[1] Average calculated without results from resistivity survey site R1.

Apparent resistivity of the shallow (8.2 ft) stream-channel deposits reflect the heterogeneity of the shallow stream-channel deposits. For instance, resistivity values are greatest at survey sites R5, R7, R11, and R13 (generally >400 Ω•m; table 9). At these sites fine sediments could have been removed and transported downstream; alternatively, coarse sediments could have been deposited in these locations. Shallow sediments with resistivity values less than 200 Ω•m at survey sites R1, R8, and R9 (**table 9**) indicate areas where fine-grained sediments could have accumulated. These interpretations are supported by the correlation between resistivity and particle-size distribution in the shallow sediments at boreholes near the survey sites.

The smallest value of apparent resistivity measured was at the upstream-most survey, R13, where the depth to water generally is less than 15 ft and where the clay-rich Tinaja beds are close to the land surface. Resistivity of these saturated basin-fill deposits generally is less than 50 Ω•m (table 9).

Apparent resistivity values centered beneath the middle of each survey line were used to construct 1-D layered-resistivity models (pl. 1–3). The 1-D models predict layer resistivity values on the basis of electrode spacing and apparent resistivity values. The 1-D models are useful in approximating the contact between the stream-channel deposits and basin-fill deposits. The uppermost layer in most of the 1-D models has a greater resistivity than the lower layers (table 10, pl. 1–3). Excluding model results from R1, resistivity values for the uppermost layer range from 165 to 1,549 Ω•m and average 577 Ω•m. This uppermost model layer probably represents unsaturated stream-channel deposits, the thicknesses of which range from about 5 to 61 ft and average 29 ft. The lower model layers, which have resistivity values that range from 32 to 184 Ω•m and average 81 Ω•m, probably represent variably saturated basin-fill deposits.

Seismic-refraction surveys.—Seismic-refraction surveys determined the velocity of a compressional wave traveling through the recent alluvium and basin-fill deposits and the thickness of the recent alluvium. On the basis of seismic model interpretations, velocity values for recent alluvium are less than those for basin-fill deposits. Values for recent alluvium ranged from 1,150 to 2,200 ft/s; values for basin-fill deposits ranged from 2,000 to 11,650 ft/s (table 11, pl. 1–3).

Table 10. Resistivity and thickness of one-dimensional model layers, Rillito Creek, Pima County, Arizona

[Resistivity survey sites are shown in **figure 1** and plates 1–3, one-dimensional models in plates 1–3. NA, not applicable]

Model Layer number	Resistivity survey site														
	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	Average	Average[1]
Layer resistivity, in ohm meters															
1	30	732	224	228	351	282	467	165	213	189	1,512	1,018	1,549	535	577
2	184	147	34	13	85	74	81	63	88	46	140	175	32	89	81
3	NA	38	NA	NA	NA	NA	NA	NA	NA	NA	20	55	NA	28	29
Layer thickness, in feet															
1	8	10	46	57	35	35	30	61	19	35	10	5	12	28	29
2	NA	71	NA	NA	NA	NA	NA	NA	NA	NA	73	49	NA	65	

[1] Average calculated without results from Resistivity survey site R1

Table 11. Average, minimum, and maximum seismic velocity values for recent alluvium and basin-fill deposits beneath and adjacent to Rillito Creek, Pima County, Arizona

[Recent alluvium includes stream-channel deposits and terrace deposits. Undifferentiated basin-fill includes unsaturated and saturated deposits. Average seismic velocity is in feet per second and is rounded to the nearest 50 feet per second]

Seismic velocity	Recent alluvium			Basin-fill		
	Stream-channel deposits	Terrace Deposits	Undifferentiated recent alluvium	Unsaturated	Saturated	Undifferentiated basin-fill
Average	1,300	1,600	1,450	2,750	7,800	3,950
Minimum	1,150	1,200	1,150	2,000	4,900	2,000
Maximum	1,550	2,200	2,200	4,650	11,650	11,650

The average velocity values for the recent alluvium (stream-channel and terrace deposits) and undifferentiated basin-fill deposits (saturated and unsaturated) are 1,450 ft/s and 3,950 ft/s, respectively. Stream-channel deposits (average of 1,300 ft/s) have smaller velocity values than the terrace deposits (average of 1,600 ft/s). No spatial trend is evident in the velocity values for the recent alluvium (fig. 11). Saturated basin-fill deposits have greater velocity values than unsaturated basin-fill deposits. Values for saturated basin fill averaged 7,800 ft/s and ranged from 4,900 to 11,650 ft/s, whereas values for unsaturated basin-fill deposits averaged 2,750 ft/s and ranged from 2,000 to 4,650 ft/s (**table 11**; pl. 1–3). The greatest velocity values determined (10,100 and 11,100 ft/s) were for the saturated upper Tinaja beds of the basin-fill deposits (seismic sections 21 and 22 in pl. 1). The high velocity suggests partly consolidated sediments. Thickness of the stream-channel deposits ranged from 10 to 30 ft and averaged 24 ft (**fig. 12**) on the basis of the low-velocity model-layer interpretations. Thickness of terrace deposits ranged from 10 to 30 ft and averaged 20 ft.

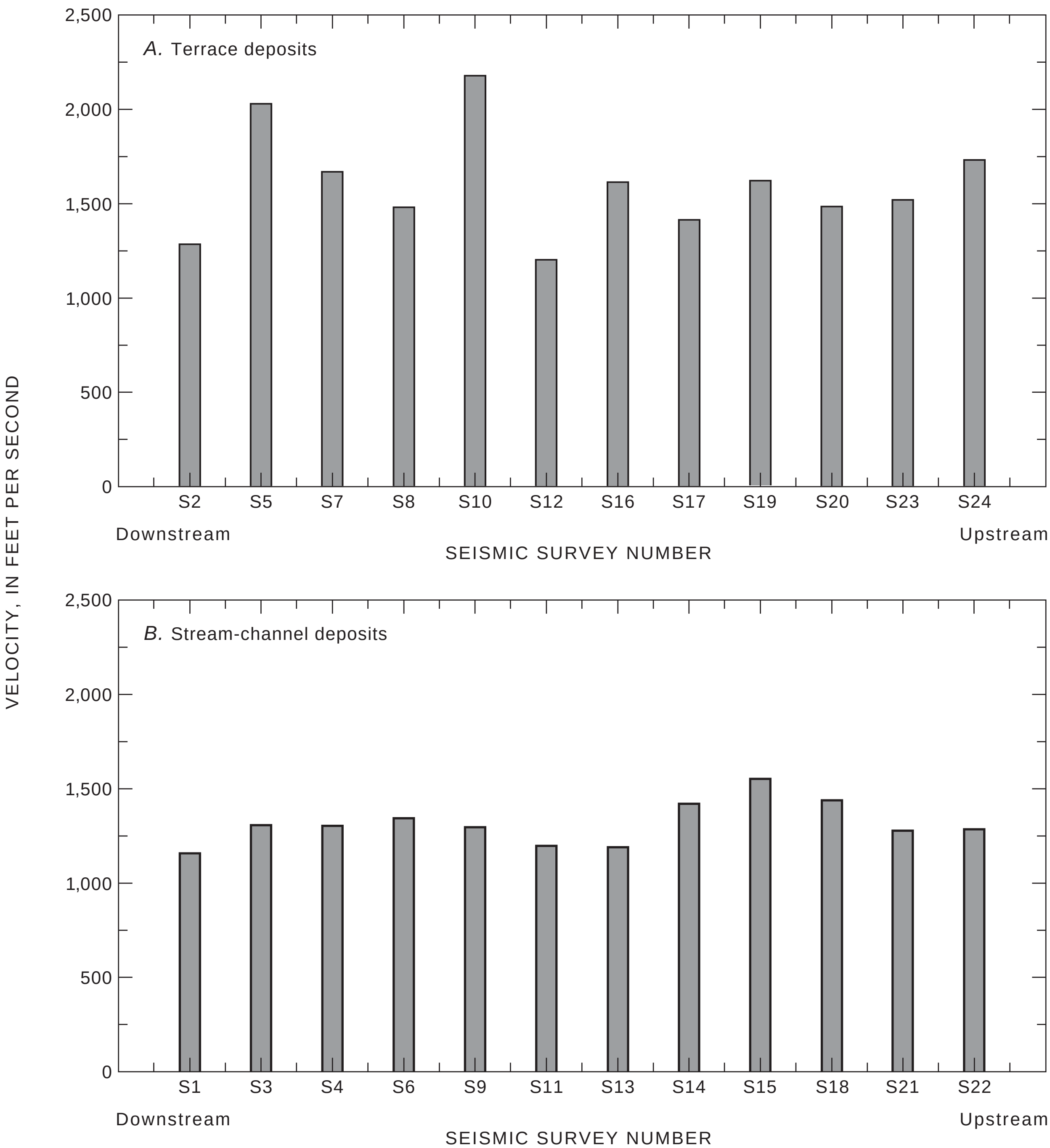


Figure 11. Seismic velocity values for low-velocity layer in seismic model interpretations, Rillito Creek, Pima County, Arizona. Layer represents recent alluvium (pl. 1–3). *A*, Velocity values for terrace deposits. *B*, Velocity values for stream-channel deposits.

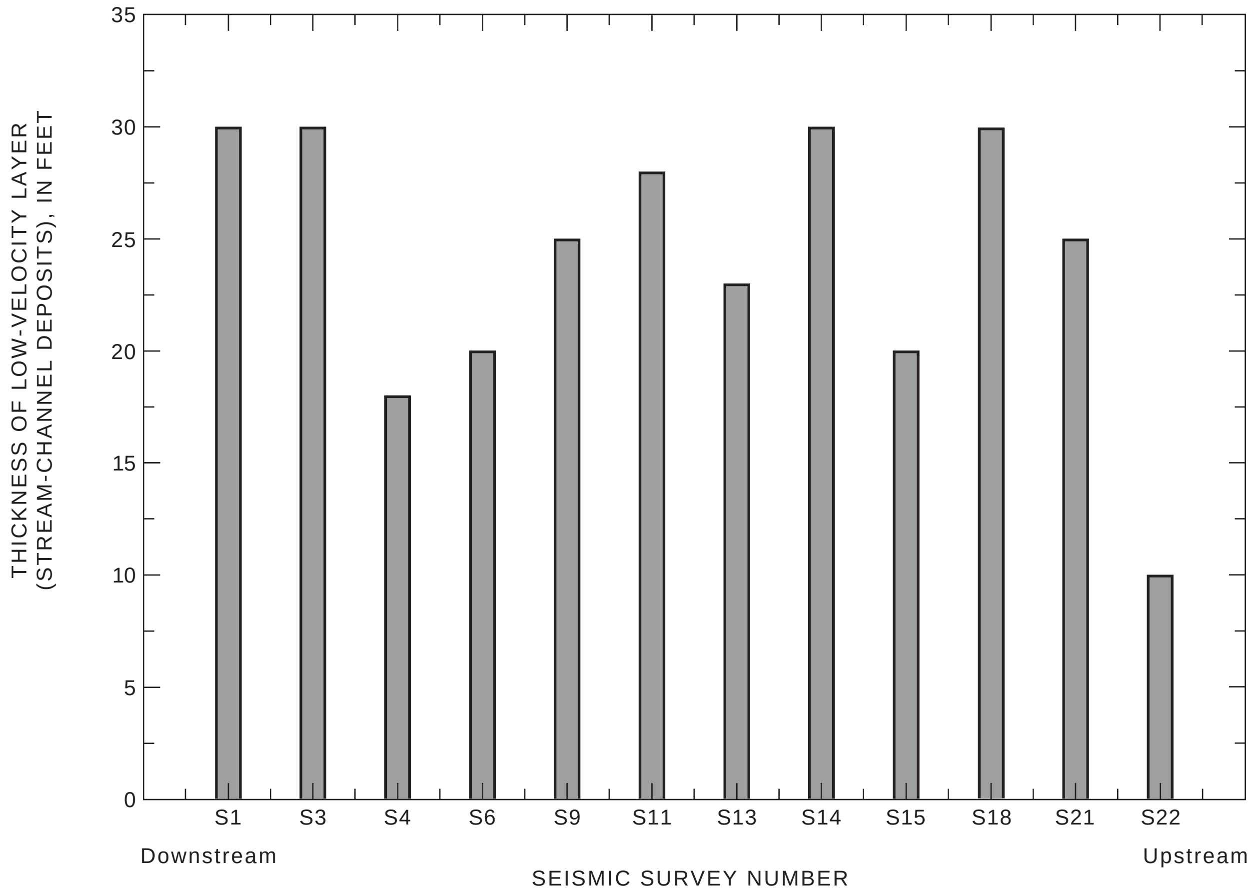


Figure 12. Thickness of low-velocity layer in seismic model interpretations, Rillito Creek, Pima County, Arizona. Low-velocity layer represents stream-channel deposits (pl. 1–3).

SUMMARY AND CONCLUSIONS

As part of a larger project to better understand ground-water recharge along Rillito Creek, the USGS gathered data to describe the shallow sediments beneath the creek. These data were used to improve the understanding of the properties and geometry of the shallow sediments into which streamflow infiltrates and percolates. These data will be used by the USGS and ADWR in the construction of a conceptual geohydrologic model of the study area. The conceptual model will be used to develop a numerical ground-water model to examine various recharge scenarios.

Data used in this study included well logs from 63 existing wells, information gathered from the drilling and coring of 5 boreholes within the creek channel, and borehole and surface geophysical surveys. Data collected for this study emphasized the recent alluvium and underlying sediments to depths of about 150 ft within about 1 mi of Rillito Creek.

The stream-channel deposits, which range in thickness from 15 to 40 ft, generally are sandy gravels or gravelly sands. On average, the deposits are 44 percent gravel, 51 percent sand, 2 percent silt, and 3 percent clay. The underlying basin-fill deposits also are sandy gravels or gravelly sands, but have, on average, a larger component of silt and clay (about 9 percent silt, and 6 percent clay) than the stream-channel deposits.

Porosity generally correlated well with the fraction of fine-grained sediments and generally was about 34 percent in the stream-channel deposits and basin-fill deposits. Volumetric moisture content and percent saturation, however, were less in the stream-channel deposits than in the basin-fill deposits. Moisture content, which also correlated well with the fraction of fine-grained sediments, averaged about 18 percent in the stream-channel deposits and about 24 percent in the basin-fill deposits. Saturation averaged about 54 percent in the stream-channel deposits and about 67 percent in the basin-fill deposits. Cumulative water thickness in the approximately 100- to 125-foot-thick unsaturated zone ranged from 17.2 to 40.4 ft under the conditions that existed at the time of sampling.

The unsaturated hydraulic conductivity of the deposits beneath Rillito Creek varied by several orders of magnitude as a function of matric potential. Relative hydraulic conductivity of the stream-channel deposits was less than that of the basin-fill deposits for a given matric pressure, probably because the coarser grained stream-channel deposits drain more readily than the finer grained basin-fill deposits. For matric pressures measured at time of sample collection, the unsaturated hydraulic conductivity of the deposits beneath Rillito Creek generally was more than two orders of magnitude less than the saturated hydraulic conductivity.

The saturated hydraulic conductivity of the deposits beneath Rillito Creek is related inversely to grain size because particles of finer grained sediments have a larger surface area, which increases the resistance of fluid flow through the medium. Structure, such as layering and (or) degree of compaction, however, also plays a role in the equivalent hydraulic conductivity of the medium. This role is evident as the stream-channel deposits tend to have a greater hydraulic conductivity than basin-fill deposits that have similar sand, silt, and clay content. Saturated vertical hydraulic conductivity of the stream-channel deposits is greater than that of the basin-fill deposits. Values for stream-channel deposits ranged from 2.0 to 7.3 ft/d and averaged 4.0 ft/d, whereas values for basin-fill deposits ranged from 0.06 to 1.5 ft/d and averaged 0.61 ft/d. Saturated vertical-hydraulic conductivity ranged from 0.08 to 1.9 ft/d and averaged 0.75 ft/d for the unsaturated zone in the study area. Although the deposits are assumed to be locally isotropic, layers having differing hydraulic conductivity create an effective anisotropy at larger scale. Average saturated horizontal-hydraulic conductivity is about twice that of the vertical-hydraulic conductivity.

Electrical conductivity was useful in differentiating the generally coarse-grained stream-channel deposits from the basin-fill deposits. Conductivity was less than 30 mmhos/m and averaged 27 mmhos/m for the stream-channel deposits; values for basin-fill deposits averaged 44 mmhos/m. The greater conductivity for the basin-fill deposits probably is related to higher moisture content and fraction of fine sediments. Electrical resistivity measured by 2-D resistivity soundings generally decreased with increased depth. The resistivity values from the near-surface measurements represent dry stream-channel deposits and averaged 303 Ω•m. The resistivity values for basin-fill deposits generally were less than 150 Ω•m and were less than 100 Ω•m for saturated deposits.

Seismic-velocity values for the recent alluvium ranged from 1,150 to 2,200 ft/s; values for basin-fill deposits ranged from 2,000 to 11,650 ft/s. Stream-channel deposits, with an average velocity value of 1,300 ft/s, had lower velocity values than the terrace deposits, which averaged 1,600 ft/s. Saturated basin-fill deposits had velocity values that averaged 7,800 ft/s, whereas values for unsaturated basin-fill deposits averaged 2,750 ft/s.

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BASIC DATA

Table 12. Borehole location and drilling summary, Rillito Creek, Pima County, Arizona

Borehole name	Location information			Drilling information		
	Northing, in meters	Easting, in meters	Altitude, in feet above mean sea level	Total depth, in feet below land surface	Drill-bit diameter, in inches	Depth to water table, in feet below land surface, June 1999
(D-13-13)16add	3573989	498575	2,245	172.5	7.5	125.14
(D-13-14)19bcbn	3572277	503845	2,312	157.1	7.5	99.65
(D-13-14)19bcbs	3572209	503829	2,309	137	7.5	98.02
(D-13-14)28dba	3570294	508188	2,375	158	7.5	126.42
(D-13-14)26daa	3570047	511696	2,425	56	9	10.82

Table 13. Particle-size analyses of core samples from boreholes, Rillito Creek, Pima County, Arizona

[NA, not applicable; SC, stream-channel; BF, basin-fill; <, less than; mm, millimeters; >, greater than; ---, dashes indicate no data]

		Sample particle-size distribution, in percent				Gravel particle-size distribution, in percent				<2-mm particle-size distribution, in percent		
Type of deposit	Depth to top of core, in feet	Gravel	Sand	Silt	Clay	> 19.0 mm	9.5–19.0 mm	4.75–9.5 mm	2.0–4.75 mm	Sand 0.05-2.0 mm	Silt 0.002-0.05 mm	Clay < 0.002 mm
(D-13-13)16add												
SC	6.5	37	56	3	5	9	4	7	17	89	4	7
SC	11.5	47	48	1	5	10	8	9	19	90	1	9
SC	17.0	69	27	1	3	25	12	12	20	87	3	10
SC	22.0	55	40	1	4	16	10	11	18	88	2	10
SC	27.0	62	34	2	2	27	10	10	16	92	4	4
SC	37.0	39	42	13	7	3	6	7	22	68	21	11
BF	46.5	0	15	56	29	0	0	0	0	15	56	29
BF	57.0	0	44	38	18	0	0	0	0	44	38	18
BF	76.5	0	39	49	12	0	0	0	0	39	49	12
BF	97.0	0	10	64	26	0	0	0	0	10	64	26
BF	117.0	24	57	13	7	NA	NA	NA	NA	75	16	9
BF	136.5	10	81	7	3	0	1	2	8	89	7	3
(D-13-14)28dba												
SC	1.0	36	55	4	4	6	6	8	16	86	7	7
SC	8.0	18	29	29	24	5	0	1	12	35	35	30
SC	13.0	51	43	2	4	20	6	9	15	88	4	8
SC	18.0	68	25	2	5	16	11	14	27	78	7	15
SC	23.0	61	33	4	1	27	12	9	12	87	10	3
BF	27.5	7	77	14	2	0	0	1	6	84	15	2
BF	38.0	23	62	12	2	7	2	4	10	81	16	3
BF	47.5	38	53	8	1	17	8	6	8	85	13	1
BF	57.5	12	72	14	2	0	0	2	9	82	16	2
BF	78.0	35	52	11	1	3	6	8	18	81	17	2
BF	98.0	27	65	3	4	7	7	4	10	90	5	6
BF	118.0	47	36	7	10	6	11	10	19	68	14	18
BF	138.0	46	44	3	7	5	7	12	21	82	5	14

Table 13. Particle-size analysis of core samples from boreholes, Rillito Creek, Pima County, Arizona—Continued

		Sample particle-size distribution, in percent				Gravel particle-size distribution, in percent				<2-mm particle size, in percent			Sand particle-size distribution, in percent[1]				
Type of deposit	Depth, in feet	Gravel	Sand	Silt	Clay	>19.0 mm	9.5–19.0 mm	4.75–9.5 mm	2.0–4.75 mm	Sand 0.05–2.0	Silt 0.002–0.05	Clay < 0.002	1.0–2.0 mm	0.05–1 mm	0.25–0.5 mm	0.106–0.25 mm	0.053–0.106 mm
(D-13-14)19bcbn																	
SC	5.5	50	42	2	5	6	7	15	22	85	5	11	27	30	19	15	9
SC	6.0	23	56	11	10	8	1	2	11	72	15	13	6	8	17	44	24
SC	15.5	28	68	2	2	8	5	4	10	94	2	3	20	38	31	9	2
SC	16.0	40	58	0	3	1	3	8	28	96	0	5	59	27	9	3	1
SC	17.5	65	32	0	3	0	20	21	24	91	1	8	35	31	22	9	3
SC	18.0	75	22	2	1	12	25	21	18	86	8	6	36	29	19	11	5
SC	22.5	84	13	1	2	47	19	10	8	83	6	11	28	27	23	15	7
SC	23.0	82	16	1	1	40	16	14	12	86	7	7	39	28	17	10	5
SC	27.5	74	23	1	2	20	14	13	28	88	5	7	44	24	17	12	4
BF	28.0	0	93	3	4	16	4	6	10	93	3	4	17	39	30	11	3
BF	37.5	0	67	22	11	12	11	11	23	67	22	11	34	24	18	15	10
BF	38.0	0	65	25	10	10	15	14	14	65	25	10	23	25	22	17	13
BF	47.5	0	84	12	4	0	0	3	11	84	12	4	18	35	28	13	6
BF	48.0	15	64	14	7	0	1	3	11	76	16	8	24	26	23	17	10
BF	57.5	36	52	9	3	7	7	8	15	82	14	4	18	33	28	14	8
BF	58.0	25	60	11	3	0	2	6	18	81	15	5	19	34	26	13	7
BF	77.5	11	72	13	4	0	0	2	8	81	14	5	16	24	32	20	9
BF	78.0	14	74	8	3	0	1	3	11	86	10	4	28	32	21	13	6
BF	97.5	31	55	9	5	2	5	8	15	79	13	7	24	21	24	19	12
BF	98.0	27	62	7	4	3	4	7	14	84	10	6	23	24	26	18	9
BF	137.5	27	57	9	7	1	5	7	14	78	12	9	17	22	26	23	13
BF	138.0	44	47	6	3	18	8	8	11	85	10	5	24	31	22	15	8
(D-13-14)19bcbs																	
SC	0.5	34	62	3	1	0	5	7	23	95	4	1	48	31	14	5	2
SC	5.5	75	20	1	4	13	8	20	34	81	4	15	59	18	10	9	4
SC	6.0	66	28	0	5	8	6	13	39	83	1	15	57	23	9	7	4
SC	11.5	44	53	0	3	2	8	10	24	95	0	5	34	38	21	5	2
SC	12.0	57	40	1	2	5	16	12	24	93	2	5	40	36	18	5	2
SC	16.5	59	37	2	2	11	13	14	21	90	6	4	34	37	19	7	3
SC	17.0	36	60	1	4	7	6	5	18	93	1	6	33	32	24	9	3
SC	21.5	61	35	2	2	19	12	12	18	89	5	6	26	44	18	8	4
SC	22.0	30	55	11	4	8	2	6	15	79	15	6	25	33	22	13	7
BF	26.5	21	65	12	2	0	2	4	14	82	15	3	24	33	25	13	6
BF	27.0	24	60	13	3	1	3	6	15	80	17	4	21	29	27	15	7
BF	36.5	0	58	31	10	0	0	0	0	58	32	10	3	5	9	44	39
BF	37.0	14	34	42	10	0	0	4	10	40	48	12	4	4	4	22	66
BF	46.5	16	64	13	7	0	0	1	15	77	15	8	25	28	22	16	9
BF	47.0	9	69	15	8	0	0	1	8	76	16	8	23	27	23	17	10

Table 13. Particle-size analysis of core samples from boreholes, Rillito Creek, Pima County, Arizona—Continued

Type of deposit	Depth, in feet	Sample particle-size distribution, in percent: Gravel	Sand	Silt	Clay	Gravel particle-size distribution, in percent: >19.0 mm	9.5–19.0 mm	4.75–9.5 mm	2.0–4.75 mm	<2-mm particle size, in percent: Sand 0.05–2.0	Silt 0.002–0.05	Clay < 0.002	Sand particle-size distribution, in percent[1]: 1.0–2.0 mm	0.05–1 mm	0.25–0.5 mm	0.106–0.25 mm	0.053–0.106 mm
BF	66.5	23	66	7	4	7	2	3	11	86	9	5	20	34	26	14	7
BF	67.0	18	67	10	5	0	2	3	12	82	12	6	---	---	---	---	---
BF	76.5	14	69	10	7	0	0	3	12	80	12	8	19	25	26	19	10
BF	77.0	5	82	10	3	0	1	3	14	86	10	3	28	31	23	12	6
BF	96.5	33	59	4	4	1	8	9	15	89	5	5	31	30	22	12	5
BF	97.0	42	50	4	3	2	6	11	23	87	7	6	---	---	---	---	---
BF	136.5	14	78	4	4	1	2	3	8	91	5	5	---	---	---	---	---
BF	137.0	27	64	5	4	8	2	4	13	87	7	5	23	28	24	17	9
(D-13-14)26daa																	
SC	.5	36	60	2	1	1	3	8	24	94	4	2	32	37	27	2	2
SC	8.0	50	49	1	0	7	4	8	32	97	3	0	69	21	6	2	1
SC	13.0	67	27	2	4	33	8	8	19	84	5	11	47	26	14	8	5

1 Sand fraction distribution was not calculated for cores from boreholes (D-13-13)16add and (D-13-14)28dba.

Table 14. Particle-size analyses of cuttings samples from boreholes, Rillito Creek, Pima County, Arizona

[SC, stream-channel; BF, basin-fill; <, less than; mm, millimeter; >, greater than]

		Sample particle-size distribution, in percent				Gravel particle-size distribution, in percent				<2-mm particle-size distribution, in percent			Sand particle-size distribution, in percent				
Type of deposit	Depth, in feet	Gravel	Sand	Silt	Clay	>19.0 mm	9.5–19.0 mm	4.75–9.5 mm	2.0–4.75 mm	Sand 0.05–2.0	Silt 0.05–0.002	Clay <0.002	1.0–2.0 mm	0.50–1.0 mm	0.25–0.50 mm	0.106–0.25 mm	0.053–0.106 mm
(D-13-13)16add																	
SC	1.0	13	79	4	5	0	0	1	11	91	4	5	39	30	20	8	3
SC	2.0	8	85	0	6	0	0	0	8	93	0	7	46	34	10	5	3
SC	3.0	39	56	2	4	0	0	3	36	91	4	6	51	25	12	7	4
SC	5.0	36	58	1	4	0	2	6	29	92	2	7	41	45	10	2	2
SC	9.0	39	57	0	4	0	6	8	25	93	0	7	55	32	10	2	1
SC	10.0	64	32	1	3	1	20	21	22	88	3	9	47	33	11	5	3
SC	13.0	77	21	0	2	0	18	29	30	90	1	9	65	21	7	4	2
SC	14.0	58	37	1	4	0	3	16	39	89	2	9	65	23	5	4	2
SC	15.0	28	67	0	5	0	0	2	27	93	0	7	60	33	5	1	1
SC	19.0	68	30	0	3	0	18	23	27	91	1	8	70	23	3	2	2
SC	23.0	44	55	0	3	0	5	14	25	97	0	6	80	19	0	0	0
SC	25.0	45	52	1	2	0	0	11	34	95	1	4	69	23	4	3	1
SC	28.0	57	40	1	2	0	2	18	37	94	1	4	66	31	2	1	1
SC	29.0	66	30	1	2	0	18	36	13	90	3	7	30	50	15	3	2
SC	35.0	69	29	1	2	0	18	23	27	92	3	5	78	15	3	2	2
BF	42.0	25	56	10	9	0	6	5	14	75	13	12	33	27	18	13	8
BF	45.0	5	51	27	17	0	1	1	3	54	28	18	10	24	29	22	14
BF	48.0	3	35	36	27	0	0	0	3	36	37	27	12	21	26	21	20
BF	52.0	4	31	35	30	0	0	0	4	32	37	31	12	23	29	19	17
BF	55.0	4	11	45	40	0	0	0	4	11	47	42	2	9	18	28	44
BF	63.0	0	36	43	21	0	0	0	0	36	43	21	0	2	15	43	40
BF	68.0	0	48	34	18	0	0	0	0	48	34	18	1	4	19	46	31
BF	75.0	0	31	49	20	0	0	0	0	31	49	20	1	3	17	37	42
BF	78.0	0	36	41	23	0	0	0	0	36	41	23	1	5	17	38	38
BF	81.0	0	39	40	20	0	0	0	0	39	40	21	1	5	17	40	36
BF	85.0	0	28	51	21	0	0	0	0	28	51	21	0	3	14	42	41
BF	87.0	0	15	61	25	0	0	0	0	15	61	25	1	6	11	27	54
BF	93.0	5	10	59	25	0	1	3	2	11	63	27	7	8	8	21	56
BF	99.0	2	13	51	33	0	1	1	1	14	52	34	7	15	21	24	34
BF	100.0	28	50	14	8	0	4	9	15	69	19	12	10	18	35	26	11
BF	101.0	23	63	8	6	0	5	8	9	82	10	8	10	17	37	30	7
BF	107.0	48	38	9	5	0	12	17	19	73	17	10	31	20	20	18	11
BF	115.0	62	31	4	3	0	20	16	26	81	11	9	42	30	13	9	6
BF	118.0	63	30	4	4	0	8	15	39	81	10	10	56	23	12	6	3
BF	121.0	56	38	2	3	0	1	13	42	88	4	8	66	15	10	6	3

Table 14. Particle-size analysis of cuttings samples from boreholes, Rillito Creek, Pima County, Arizona—Continued

		Sample particle-size distribution, in percent				Gravel particle-size distribution, in percent				<2-mm particle-size distribution, in percent			Sand particle-size distribution, in percent				
Type of deposit	Depth, in feet	Gravel	Sand	Silt	Clay	>19.0 mm	9.5–19.0 mm	4.75–9.5 mm	2.0–4.75 mm	Sand 0.05–2.0	Silt 0.05–0.002	Clay <0.002	1.0–2.0 mm	0.50–1.0 mm	0.25–0.50 mm	0.106–0.25 mm	0.053–0.106 mm
(D-13-13)16add—Continued																	
BF	123.0	88	9	2	1	0	17	33	38	73	16	12	64	8	10	11	7
BF	126.0	19	59	14	8	0	2	2	15	73	17	10	35	26	16	14	9
BF	128.0	44	49	4	3	0	0	4	40	88	7	5	76	15	3	3	3
BF	131.0	41	54	3	2	0	3	14	25	91	5	4	48	41	8	2	2
BF	135.0	25	67	3	4	0	3	9	13	90	4	6	23	46	25	4	2
BF	141.0	51	35	8	5	5	21	12	14	73	16	11	23	22	23	21	11
BF	144.0	81	12	4	3	1	31	30	20	66	19	15	31	15	18	22	14
BF	148.0	83	13	2	2	0	18	30	35	75	12	13	68	15	6	6	5
BF	160.0	86	9	3	2	1	41	30	14	64	21	16	37	20	16	15	12
(D-13-14)26daa																	
SC	3.0	6	87	3	4	0	0	0	5	93	3	4	19	38	32	9	2
SC	5.0	40	58	1	2	0	0	8	31	96	1	3	47	35	14	3	1
SC	6.0	48	49	1	2	0	2	15	32	94	2	4	45	26	18	9	2
SC	9.0	84	14	0	1	1	10	38	35	92	1	6	75	17	4	3	2
SC	11.0	88	11	0	1	0	8	38	42	91	2	8	81	13	3	2	1
SC	14.0	62	36	0	1	1	6	17	38	95	1	3	76	20	3	1	1
BF	16.0	46	47	4	4	0	7	13	25	86	7	7	31	32	21	12	5
BF	19.0	78	20	1	1	4	16	22	36	92	2	5	73	16	6	3	2
BF	21.0	48	43	4	5	4	18	11	15	83	8	10	35	33	18	9	4
BF	24.0	49	46	3	3	0	11	12	26	90	5	5	52	27	12	6	3
BF	27.0	67	24	4	4	1	23	18	26	74	13	13	50	24	12	10	6
BF	30.0	42	46	8	4	2	3	9	28	78	14	7	49	25	12	9	6
BF	33.0	65	25	7	4	1	13	21	31	70	19	11	34	21	18	17	10
BF	35.0	78	18	2	1	1	15	27	35	83	10	6	66	16	8	6	4
BF	38.0	54	41	2	2	3	8	10	33	91	4	5	66	19	9	4	2
BF	41.0	76	19	3	2	3	14	27	32	78	14	8	42	20	18	13	7
BF	43.0	75	21	3	1	0	22	23	30	81	13	6	58	16	11	9	6
BF	46.0	68	22	6	3	3	17	23	25	70	19	11	30	21	21	18	10
BF	50.0	82	13	3	2	5	32	26	20	72	18	10	39	23	16	13	9
BF	52.0	71	21	5	3	2	23	21	25	71	18	11	39	18	18	16	10
BF	54.0	70	26	2	2	3	17	20	29	87	6	7	66	17	9	6	3
BF	56.0	30	56	8	6	2	0	4	24	80	11	9	51	23	12	9	5
(D-13-14)28dba																	
SC	2.0	39	57	1	2	0	6	10	23	94	2	4	43	33	17	5	2
SC	3.0	39	58	0	4	1	12	11	15	95	0	6	53	33	12	2	1
SC	4.0	48	49	0	3	1	16	14	17	94	1	5	23	18	30	27	2

Table 14. Particle-size analysis of cuttings samples from boreholes, Rillito Creek, Pima County, Arizona—Continued

		Sample particle-size distribution, in percent				Gravel particle-size distribution, in percent				<2-mm particle-size distribution, in percent			Sand particle-size distribution, in percent				
Type of deposit	Depth, in feet	Gravel	Sand	Silt	Clay	>19.0 mm	9.5–19.0 mm	4.75–9.5 mm	2.0–4.75 mm	Sand 0.05–2.0	Silt 0.05–0.002	Clay <0.002	1.0–2.0 mm	0.50–1.0 mm	0.25–0.50 mm	0.106–0.25 mm	0.053–0.106 mm
(D-13-14)28dba—Continued																	
SC	5.0	9	65	11	15	2	3	2	3	72	12	16	4	9	45	39	4
SC	9.0	20	56	12	11	0	4	5	12	71	15	14	5	2	21	58	13
SC	11.0	23	55	11	10	0	2	5	16	72	15	13	9	4	18	55	14
SC	14.0	67	30	1	2	0	19	22	26	92	3	5	67	25	2	4	2
SC	15.0	75	22	2	1	1	23	22	30	88	6	5	65	21	4	6	4
SC	16.0	79	18	1	1	3	23	24	30	86	7	7	64	17	4	10	5
SC	19.0	40	54	2	3	0	11	11	19	90	4	6	29	49	15	4	2
SC	25.0	65	28	4	3	2	13	28	22	81	11	7	35	25	20	13	7
BF	26.0	10	73	11	5	2	3	2	4	82	12	6	15	25	32	21	7
BF	32.0	7	67	17	8	0	0	1	6	73	19	9	14	27	31	17	12
BF	39.0	11	67	14	8	0	1	2	8	75	16	9	20	32	24	13	12
BF	45.0	15	71	8	5	0	1	3	11	84	10	6	22	32	26	14	6
BF	50.0	11	75	8	6	0	1	3	8	84	9	6	29	34	20	11	5
BF	61.0	18	70	7	6	0	0	5	12	85	8	7	22	32	25	14	6
BF	71.0	22	63	10	5	0	4	5	12	80	13	7	27	31	22	13	7
BF	81.0	22	62	10	6	0	2	6	14	79	13	8	22	28	24	16	9
BF	91.0	36	55	6	4	1	7	11	17	85	9	6	41	26	15	11	6
BF	101.0	22	70	4	5	1	3	5	14	89	5	6	31	33	23	10	3
BF	111.0	23	63	6	8	0	4	8	10	81	8	11	23	26	26	17	7
BF	121.0	37	54	5	5	0	1	12	23	85	7	8	31	23	23	16	7
BF	126.0	46	45	4	4	0	3	17	27	84	8	8	35	25	21	12	6
BF	127.0	40	52	4	4	0	3	11	26	86	7	7	39	25	19	11	5
BF	132.0	54	38	4	4	0	5	21	28	83	9	8	35	21	21	16	7
BF	139.0	79	18	1	2	1	17	24	37	87	6	7	62	14	10	9	5
BF	140.0	39	47	7	6	1	9	14	15	78	11	11	23	22	24	21	11
BF	147.0	63	30	3	3	0	19	23	22	82	9	9	34	30	18	11	6
BF	156.0	56	39	2	3	1	18	15	22	88	4	7	47	37	9	4	3
(D-13-14)19bcbn																	
SC	0.0	43	47	6	4	2	7	12	22	83	11	6	41	29	14	8	7
SC	2.0	48	45	3	3	2	9	13	24	87	6	7	45	32	12	7	4
SC	4.0	44	49	3	4	0	14	11	19	88	6	6	43	31	16	7	3
SC	7.0	57	39	1	4	0	6	20	31	90	1	9	45	29	19	5	2
SC	8.0	44	50	2	4	0	8	15	22	89	3	8	33	31	29	5	2
SC	10.0	18	77	0	5	0	0	1	17	94	0	6	33	43	21	3	1
SC	11.0	32	63	1	4	0	2	12	18	93	1	6	40	44	14	1	1
SC	19.0	54	43	0	3	0	0	14	40	93	0	7	52	27	14	5	2
SC	24.0	47	48	1	4	0	1	17	30	91	2	7	45	28	18	7	3

Table 14. Particle-size analysis of cuttings samples from boreholes, Rillito Creek, Pima County, Arizona—Continued

		Sample particle-size distribution, in percent				Gravel particle-size distribution, in percent				<2-mm particle-size distribution, in percent			Sand particle-size distribution, in percent				
Type of deposit	Depth, in feet	Gravel	Sand	Silt	Clay	>19.0 mm	9.5–19.0 mm	4.75–9.5 mm	2.0–4.75 mm	Sand 0.05–2.0	Silt 0.05–0.002	Clay <0.002	1.0–2.0 mm	0.50–1.0 mm	0.25–0.50 mm	0.106–0.25 mm	0.053–0.106 mm
(D-13-14)19bcbn—Continued																	
SC	26.0	65	33	0	2	0	3	24	38	94	0	6	66	25	5	2	1
SC	29.0	40	57	0	3	0	0	5	35	96	0	6	50	38	11	1	0
SC	30.0	57	41	0	2	0	1	21	35	96	0	5	53	34	12	1	1
BF	32.0	52	45	1	3	0	8	17	27	93	1	5	55	30	10	2	1
BF	33.0	45	48	4	4	0	2	9	33	87	7	6	51	32	10	4	3
BF	35.0	33	57	5	5	0	0	9	23	84	8	8	28	31	24	12	5
BF	36.0	22	68	5	5	0	0	5	16	87	6	7	41	30	16	8	4
BF	39.0	19	59	14	9	0	0	5	14	72	17	11	15	22	28	23	11
BF	40.0	33	57	5	5	0	0	9	23	84	8	8	28	31	24	12	5
BF	42.0	25	59	9	7	2	4	5	14	79	13	9	19	27	30	18	7
BF	43.0	20	58	13	9	0	2	4	14	72	16	12	21	25	25	19	10
BF	46.0	13	65	12	9	0	1	2	10	75	14	10	24	24	24	18	10
BF	49.0	7	69	14	9	0	0	2	6	75	15	10	18	23	27	20	11
BF	50.0	8	71	12	9	0	0	1	7	78	13	10	25	28	24	15	8
BF	53.0	12	70	11	7	0	1	2	9	80	12	8	24	27	24	17	9
BF	54.0	26	57	11	6	0	4	6	16	77	15	8	21	24	25	19	11
BF	56.0	17	70	7	6	0	0	4	13	85	8	7	29	33	22	11	5
BF	59.0	12	72	10	7	0	0	3	9	81	11	8	17	26	29	19	8
BF	65.0	9	77	9	5	0	0	1	7	85	10	6	18	29	27	19	7
BF	71.0	16	75	6	3	0	0	1	15	89	7	4	28	31	25	12	4
BF	76.0	8	79	8	5	0	1	2	6	86	9	5	25	27	25	17	6
BF	81.0	11	76	7	5	0	0	1	10	86	8	6	19	30	28	17	6
BF	86.0	10	81	6	3	0	0	0	10	90	6	4	31	34	21	10	4
BF	92.0	17	73	6	4	0	5	5	7	88	7	5	18	29	30	18	5
BF	93.0	30	55	10	5	2	9	5	13	78	14	8	20	24	26	20	11
BF	95.0	48	43	5	4	2	15	15	15	82	10	8	24	24	26	19	8
BF	96.0	23	65	7	5	0	3	6	15	85	9	6	26	29	25	14	6
BF	100.0	62	35	1	2	3	7	19	33	93	3	4	65	21	8	4	2
BF	101.0	72	26	1	1	0	9	28	35	92	3	5	77	16	3	2	2
BF	103.0	77	21	1	1	0	8	29	40	91	5	5	78	16	2	2	2
BF	104.0	66	30	2	1	0	16	21	29	90	6	4	64	26	4	3	3
BF	110.0	69	27	2	2	1	6	28	33	86	7	6	40	35	15	5	4
BF	113.0	57	37	3	3	0	16	14	27	86	8	6	40	33	16	7	5
BF	120.0	48	50	1	2	0	6	12	31	96	1	3	59	31	7	2	1
BF	126.0	42	51	4	4	0	11	8	23	87	7	6	26	33	26	11	5
BF	139.0	71	26	1	2	0	18	25	28	89	5	6	55	24	11	6	4
BF	149.0	49	45	3	3	0	3	14	32	89	6	5	56	30	7	3	3

Table 14. Particle-size analysis of cuttings samples from boreholes, Rillito Creek, Pima County, Arizona—Continued

		Sample particle-size distribution, in percent				Gravel particle-size distribution, in percent				<2-mm particle-size distribution, in percent			Sand particle-size distribution, in percent				
Type of deposit	Depth, in feet	Gravel	Sand	Silt	Clay	>19.0 mm	9.5–19.0 mm	4.75–9.5 mm	2.0–4.75 mm	Sand 0.05–2.0	Silt 0.05–0.002	Clay <0.002	1.0–2.0 mm	0.50–1.0 mm	0.25–0.50 mm	0.106–0.25 mm	0.053–0.106 mm
								(D-13-14)19bcbs									
SC	2.0	27	71	0	3	0	0	6	20	97	0	3	36	29	26	8	1
SC	3.0	31	67	0	2	0	4	7	20	97	0	4	38	32	24	6	1
SC	4.0	33	64	0	3	0	2	5	26	95	1	4	53	28	14	5	1
SC	8.0	60	33	2	5	0	10	20	30	82	5	13	36	26	20	12	6
SC	9.0	52	42	1	5	0	4	16	33	88	3	10	50	24	15	9	4
SC	10.0	24	73	0	4	0	2	5	16	96	0	5	31	33	30	6	1
SC	13.0	30	62	3	5	0	4	6	21	89	4	7	28	32	27	10	3
SC	15.0	24	74	0	2	0	0	6	17	97	0	3	46	42	11	1	0
SC	20.0	19	78	0	3	0	0	3	16	96	0	4	44	45	10	1	0
BF	23.0	9	70	13	9	0	1	2	6	76	14	10	15	24	30	20	10
BF	24.0	8	71	12	9	0	2	1	5	77	13	10	15	26	28	22	9
BF	29.0	9	76	9	6	0	1	2	7	83	10	7	12	32	30	19	7
BF	34.0	9	76	9	6	0	0	2	7	84	10	7	14	35	31	14	6
BF	38.0	41	40	13	6	1	11	14	15	68	22	10	22	25	23	18	12
BF	41.0	31	52	10	7	0	5	10	16	76	14	10	23	30	26	14	7
BF	42.0	34	48	9	9	0	2	8	24	73	14	13	23	28	24	16	9
BF	49.0	16	67	11	6	0	1	2	13	80	13	7	17	23	32	21	8
BF	56.0	14	70	11	5	0	1	2	11	81	13	6	24	30	21	16	9
BF	63.0	8	80	8	4	0	1	1	5	87	9	5	13	29	35	17	6
BF	69.0	20	68	8	5	0	3	4	13	85	9	6	25	29	24	16	6
BF	75.0	17	69	9	5	0	1	4	12	83	11	6	23	33	25	14	6
BF	81.0	16	75	5	4	0	1	2	14	89	6	4	31	29	23	13	4
BF	89.0	22	68	4	5	0	1	8	13	88	6	7	25	25	25	19	6
BF	90.0	35	56	4	4	0	11	12	13	87	7	7	22	29	26	17	6
BF	92.0	23	68	4	5	0	2	5	16	88	6	6	28	30	29	10	4
BF	95.0	24	68	4	4	2	2	4	14	89	6	6	32	34	25	6	3
BF	100.0	52	40	5	3	1	14	15	21	83	10	7	29	26	25	13	8
BF	104.0	16	73	6	5	0	1	2	14	87	7	6	20	30	32	13	5
BF	105.0	46	46	5	3	0	7	17	22	85	9	6	33	30	21	11	6
BF	113.0	49	45	3	3	0	8	16	26	88	6	6	30	37	22	7	3
BF	116.0	74	24	1	1	0	12	25	37	92	4	4	63	18	10	5	3
BF	121.0	38	55	4	3	0	5	11	22	88	7	5	22	33	29	11	4
BF	129.0	20	69	6	5	0	1	5	14	86	7	6	18	29	31	16	6

Table 15. Saturated vertical hydraulic conductivity of core samples, Rillito Creek, Pima County, Arizona

[SC, stream-channel; BF, basin-fill]

Type of deposit	Depth to top of core, in feet	Saturated hydraulic conductivity, in feet per day[1]	Type of deposit	Depth to top of core, in feet	Saturated hydraulic conductivity, in feet per day
(D-13-13)16add			**(D-13-14)28dba—Continued**		
SC	6.5	6.91	BF	47.5	2.25
SC	6.5	7.18	BF	47.5	2.35
SC	11.5	7.37	BF	57.5	1.68
SC	11.5	6.89	BF	57.5	1.60
SC	17.0	3.36	BF	78.0	.24
SC	17.0	3.12	BF	78.0	.25
SC	22.0	.95	BF	98.0	.81
SC	22.0	1.28	BF	98.0	.79
SC	27.0	2.15	BF	118.0	.56
SC	27.0	3.18	BF	118.0	.63
SC	37.0	7.99	BF	138.0	.89
SC	37.0	8.14	BF	138.0	.76
BF	46.5	.44	**(D-13-14)19bcbn**		
BF	46.5	.42	SC	5.5	4.76
BF	57.0	.08	SC	18.0	8.24
BF	57.0	.12	SC	23.0	4.66
BF	76.5	[2]6.16	SC	27.5	2.15
BF	76.5	[2]6.26	BF	38.0	[2]7.00
BF	97.0	.02	BF	47.5	.89
BF	97.0	.05	BF	58.0	2.22
BF	117.0	.11	BF	77.5	1.43
BF	117.0	.10	BF	98.0	5.35
(D-13-14)28dba			BF	138.0	2.66
SC	1.0	5.92	**(D-13-14)19bcbs**		
SC	1.0	8.20	SC	1.0	6.67
SC	8.0	6.93	SC	6.0	7.38
SC	8.0	8.94	SC	11.5	7.33
SC	13.0	6.97	SC	17.0	2.15
SC	13.0	7.74	SC	22.0	2.09
SC	18.0	6.81	BF	26.5	1.86
SC	18.0	6.81	BF	37.0	.06
SC	23.0	6.62	BF	46.5	.07
SC	23.0	7.15	BF	67.0	1.02
BF	27.5	.53	BF	77.0	2.50
BF	27.5	.54	BF	97.0	3.43
BF	38.0	2.12	BF	136.5	.13
BF	38.0	1.75			

[1]Two measurements were made on each core from (D-13-13)16add and (D-13-14)28dba. The average of these two values is used in calculations for table 5 and is listed in table 6.

[2]Data suspect owing to core-sleeve flow and were not used in table 5.

Table 16. Physical properties and matric potential of core samples, Rillito Creek, Pima County, Arizona

[SC, stream-channel; BF, basin-fill; matric potentials are reported for cores collected above the water table; >, greater than; dashes indicate no data]

Type of deposit	Depth to top of core, in feet	Bulk density, in grams per cubic centimeter	Particle density, in grams per cubic centimeter	Porosity, in cubic centimeters per cubic centimeter	Volumetric moisture content, in cubic centimeters per cubic centimeter	Saturation, in percent	Matric potential, in bars: From heat dissipation probes[1]	Matric potential, in bars: From field saturation and van Genuchten parameters[2]
(D-13-13)16add								
SC	6.5	1.92	2.64	0.27	0.19	68	>-0.1	-0.04
SC	12.0	1.92	2.65	.27	.19	70	>-.1	-.03
SC	17.0	2.00	2.64	.24	.02	9	>-.1	-480
SC	22.0	2.00	2.65	.24	.20	84	>-.1	-.02
SC	27.0	2.13	2.65	.20	.19	97	>-.1	-.001
SC	37.0	1.77	2.63	.33	.29	89	>-.1	-.07
BF	46.5	1.28	2.65	.52	.45	88	-1.0	-.24
BF	57.0	1.57	2.64	.41	.39	96	-.3	-.04
BF	76.5	1.45	2.70	.45	.46	100	>-.1	0
BF	97.0	1.52	2.64	---	.44	---	-.8	---
BF	117.0	1.76	2.65	.33	.34	100	>-.1	0
BF	[3]136.5	---	---	---	---			
(D-13-14)26daa								
SC	1.0	1.68	2.64	0.36	0.05	12	-3.9	---
SC	7.5	1.89	2.63	.28	.26	91	>-.1	---
SC	[3]12.5	1.79	2.65	.32				
(D-13-14)28dba								
SC	1.0	1.83	2.65	0.31	0.13	41	-0.2	-0.19
SC	8.0	1.27	2.65	.52	.40	76	>-.1	-.66
SC	13.0	2.07	2.65	.22	.22	100	>-.1	0
SC	18.0	1.77	2.65	.33	.31	92	>-.1	-.005
SC	23.0	1.85	2.64	.30	.12	42	>-.1	-.18
BF	27.5	1.68	2.63	.36	.15	42	-.2	-.37
BF	38.0	1.76	2.63	.33	.10	30	-.3	-1.3
BF	47.5	1.75	2.67	.34	.14	39	-.4	-.36
BF	57.5	1.77	2.64	.33	.20	60	-.1	-.12
BF	78.0	1.95	2.65	.26	.15	58	-.4	-.10
BF	98.0	1.82	2.64	.31	.07	24	>-.1	-1.06
BF	118.0	2.07	2.65	.22	.11	51	-.1	-.15
BF	[3]138.0	2.09	2.64	.21				

Table 16. Physical properties and matric potential of core samples, Rillito Creek, Pima County, Arizona—Continued

Type of deposit	Depth to top of core, in feet	Bulk density, in grams per cubic centimeter	Particle density, in grams per cubic centimeter	Porosity, in cubic centimeters per cubic centimeter	Volumetric moisture content, in cubic centimeters per cubic centimeter	Saturation, in percent	Matric potential, in bars: From heat dissipation probes[1]	Matric potential, in bars: From field saturation and van Genuchten parameters[2]
(D-13-14)19bcbn								
SC	5.5	1.56	2.66	0.41	0.10	23	>-0.1	-8.70
SC	15.5	1.68	2.65	.37	.12	33	>-.1	-.05
SC	18.0	1.86	2.65	.30	.10	33	--	-.70
SC	23.0	1.87	2.65	.29	.12	42	>-.1	-.47
SC	27.5	2.04	2.65	.23	.19	81	>-.1	-.003
BF	38.0	2.04	2.65	.23	.22	98	-.3	-.03
BF	47.5	1.78	2.64	.33	.21	65	-.7	-.31
BF	58.0	1.65	2.64	.37	.13	34	-.2	-1.08
BF	77.5	1.66	2.64	.37	.15	40	-.1	-.39
BF	98.0	1.91	2.64	.28	.25	92	>-.1	-.06
BF	[3]138.0	1.96	2.64	.26				
(D-13-14)19bcbs								
SC	1.0	1.76	2.65	0.34	0.05	15	-4.0	-0.98
SC	6.0	1.65	2.65	.38	.12	32	>-.1	-.86
SC	11.5	1.71	2.65	.35	.15	42	>-.1	-.04
SC	17.0	1.54	2.64	.42	.15	37	>-.1	-.22
SC	22.0	1.71	2.64	.35	.18	51	-.1	-.04
BF	26.5	1.57	2.63	.40	.14	35	>-.1	-1.3
BF	27.0	1.35	2.66	.49	.47	95	>-.1	-.06
BF	46.5	1.90	2.64	---	---	---	-.2	---
BF	67.0	1.81	2.64	.31	.16	50	-.1	-.25
BF	77.0	1.74	2.64	.34	.19	57	-.1	-.36
BF	97.0	1.97	2.64	.25	.21	83	>-.1	-.04
BF	[3]136.5	1.98	2.64	.25				

[1] Matric potential determined using heat dissipation probes on core sleeve adjacent to core sleeve for which physical properties were determined.

[2] Estimated by solving for *h* in equation 3 on the basis of percent saturation (this table), and van Genuchten parameters (table 17). These matric potentials are used to estimate relative hydraulic conductivity (equation 4 and table 17).

[3]Core sample collected below water table.

Table 17. Data for van Genuchten parameters used to fit moisture retention curves and residual water content for core samples, Rillito Creek, Pima County, Arizona

[Sum of squares is equal to the sum of the squares of the difference between moisture-retention curve and laboratory data. SC, stream-channel; BF, basin-fill; RWC, residual water content, in percent; ft, feet; cm^3/cm, cubic centimeter per centimeter]

Type of deposit	Depth interval (ft)	van Genuchten fitting parameters α (1/bar)	n (dimensionless)	m (1-1/*n*)	RWC, in percent	Sum of squares
(D-13-13)16add						
SC	6–8	108.398	1.239	0.193	1.3	0.005
SC	11–13	154.824	1.230	.187	1.7	.002
SC	16–18	175.970	1.212	.175	1.7	.004
SC	21–23	51.696	1.275	.216	1.9	.006
SC	26–28	362.345	1.235	.190	1.1	.002
SC	36–38	8.652	1.385	.278	1.5	.008
BF	46–48	4.771	1.199	.166	9.9	.011
BF	56–58	8.265	1.214	.176	6.0	.005
BF	76–78	5.873	1.327	.246	4.0	.001
BF	96–98	4.216	1.229	.187	6.3	.009
BF	116–118	16.369	1.275	.215	2.8	.001
BF	136–138	29.704	1.528	.346	1.1	.019
(D-13-14)28dba						
SC	0–2	71.987	1.337	0.252	1.0	0.004
SC	7–9	4.555	1.212	.175	7.6	.010
SC	12–14	55.933	1.239	.193	2.5	.004
SC	17–19	128.258	1.256	.204	1.6	.001
SC	22–24	101.925	1.295	.228	1.0	.001
BF	27–29	31.576	1.350	.259	1.6	.002
BF	37–39	19.191	1.373	.272	1.9	.003
BF	47–49	62.657	1.301	.232	.9	.006
BF	57–59	29.136	1.369	.269	1.6	.003
BF	77–79	52.386	1.305	.234	1.6	.002
BF	97–99	67.878	1.333	.250	2.2	.006
BF	117–119	35.875	1.384	.277	1.9	.011
BF	137–139	46.299	1.338	.253	2.3	.007

Type of deposit	Depth interval (feet)	van Genuchten fitting parameters α (1/bar)	n (dimensionless)	m (1-1/*n*)	RWC, in percent	Sum of squares
(D-13-14)19bcbn						
SC	5–7	25.800	1.272	0.214	2.4	0.001
SC	15–17	1,220.202	1.271	.213	.9	.002
SC	17–19	49.197	1.312	.238	1.3	.003
SC	22–24	22.293	1.365	.267	.8	.004
SC	27–29	440.077	1.295	.228	1.0	.004
BF	37–39	6.005	1.272	.214	3.9	.001
BF	47–49	12.049	1.301	.231	3.1	.002
BF	57–59	22.235	1.339	.253	1.7	.002
BF	77–79	31.415	1.361	.265	1.5	.004
BF	97–99	8.500	1.355	.262	2.7	.012
BF	137–139	13.114	1.351	.260	3.1	.021
(D-13-14)19bcbs						
SC	0–2	156.951	1.377	0.274	0.6	0.002
SC	5–7	292.539	1.206	.171	1.8	.003
SC	11–13	490.571	1.281	.220	.8	.002
SC	16–18	136.740	1.291	.226	1.1	.006
SC	21–23	343.163	1.249	.199	1.1	.002
BF	26–28	15.919	1.345	.257	1.8	.002
BF	36–38	5.348	1.372	.271	3.7	.008
BF	46–48	14.023	1.282	.220	3.1	.001
BF	66–68	26.448	1.359	.264	1.5	.001
BF	76–78	18.766	1.283	.221	2.3	.001
BF	96–98	24.714	1.351	.260	2.2	.017
BF	136–138	17.461	1.375	.273	2.2	.020

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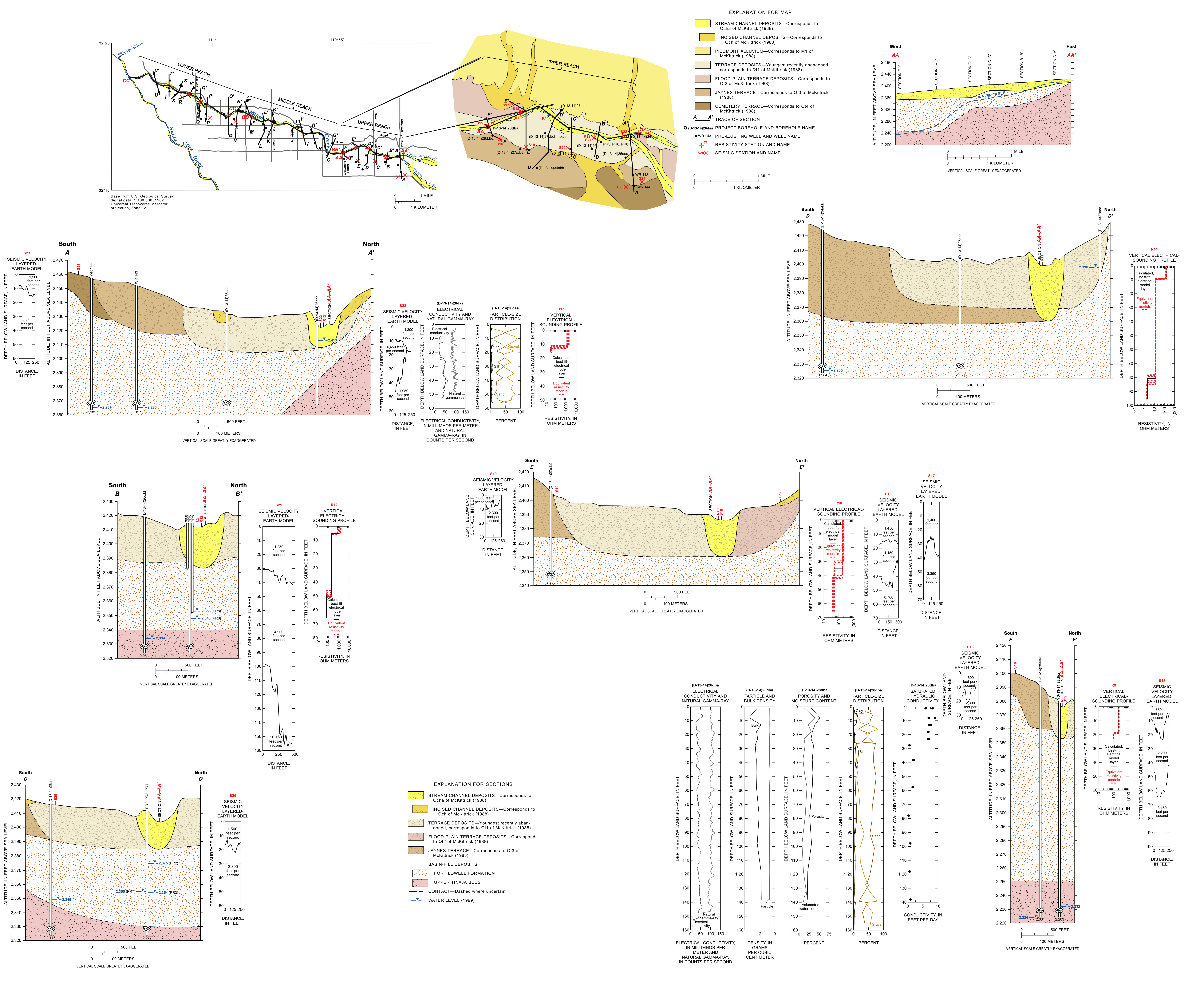

GENERALIZED SURFACE GEOLOGY; LOCATIONS OF SEISMIC SURVEYS, ELECTROMAGNETIC SOUNDINGS, AND RESISITIVITY ARRAYS; HYDROLOGIC SECTIONS; INTERPRETED VELOCITY AND RESISTIVITY LAYERS; AND BOREHOLE LOGS IN THE UPPER REACH OF RILLITO CREEK

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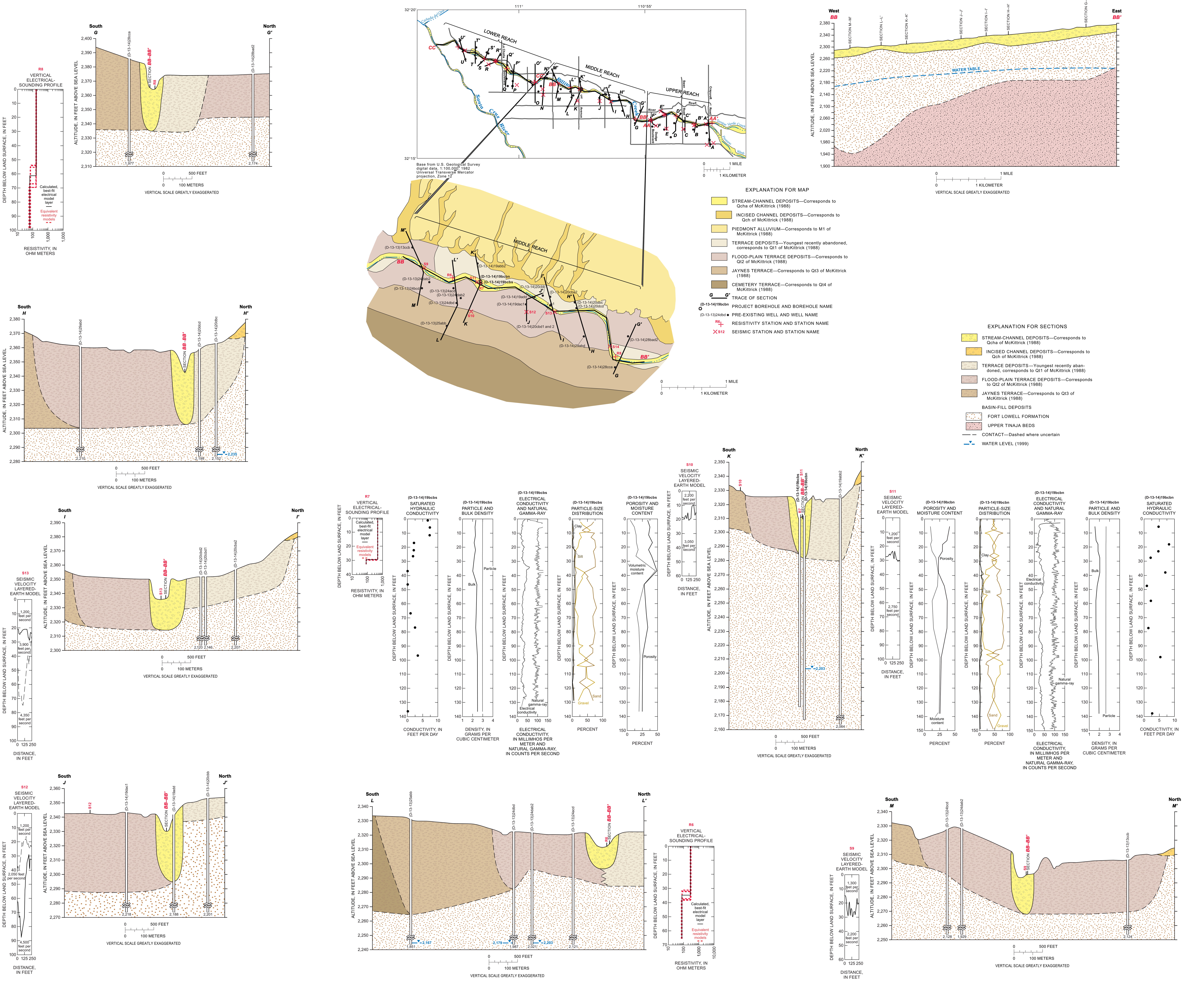

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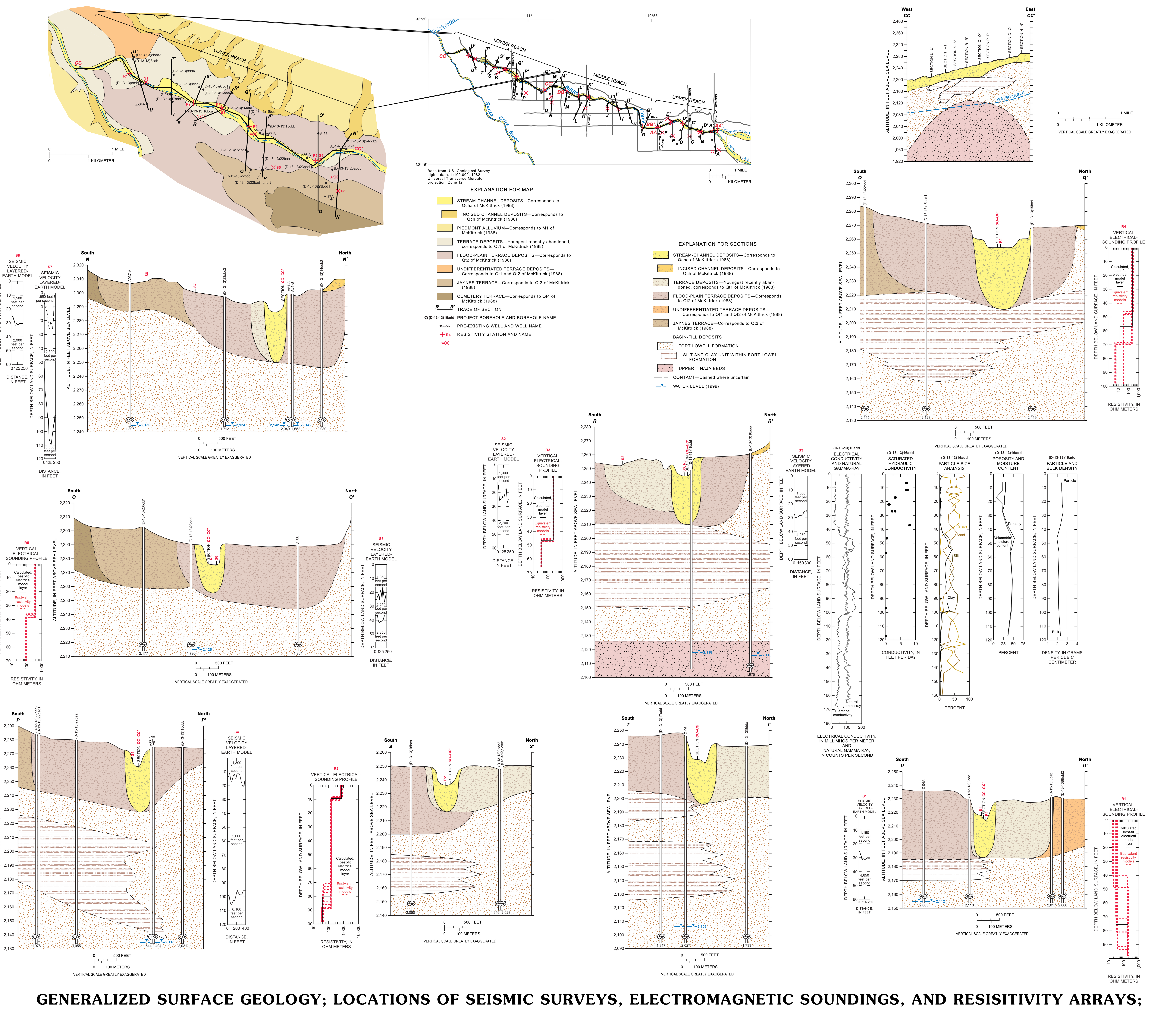

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