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CONCEPTUAL MODEL OF THE BOLSON-FILL AQUIFER, SOLEDAD CANYON AREA, DOÑA ANA COUNTY, NEW MEXICO

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ABSTRACT.—A conceptual model of the bolson-fill aquifer in the Soledad Canyon area was developed to synthesize existing information, to promote a better understanding of the flow system, and to provide a framework for development of a numerical ground-water-flow model. Hydraulic properties of the aquifer are expected to be highly variable because of the heterogeneity of bolson-fill sediments and tectonic activity. Water-transmitting properties of the bolson-fill deposits have been affected by debris flows, calcium carbonate cementation, and faulting. Mountain-front recharge was assumed to be the primary recharge mechanism in the study area. Mountain-front recharge rates estimated using empirical, regression, and chloride-balance methods probably represent a reasonable range of volumetric recharge rates in the Soledad Canyon area. Significant discharge from the bolson-fill aquifer is limited to Soledad Canyon production wells. Ground-water withdrawal from nearby Post Headquarters wells apparently has not affected ground-water storage in the Soledad Canyon area, and it appears unlikely that alluvial deposits that contain springs are hydraulically connected to the bolson-fill aquifer. Ground-water quality in the study area becomes poorer toward the center of the basin and with increasing depth. The freshwater part of the aquifer is estimated to be approximately 16 km wide and more than 610 m thick in the study area. The conceptual model developed for the Soledad Canyon area assumes a narrow transition zone between fresh and saline water that can be approximated by a stationary, sharp interface.

INTRODUCTION

The Tularosa Basin and Hueco Bolson of south-central New Mexico (Fig. 1) are within a large structural basin that contains important aquifers. The occurrence of freshwater (dissolved-solids concentration less than 1000 mg/L) in the Tularosa Basin and Hueco Bolson is limited to the margins of the basin, primarily near the mouths of larger mountain canyons, where ground water is recharged along the flanks of the bordering mountains. Ground-water quality in the basin generally becomes poorer toward the center of the basin and with increasing depth.

White Sands Missile Range (WSMR) obtains potable water from alluvial-fan and basin-fill deposits in the Tularosa Basin along the eastern flanks of the San Andres, San Augustin, and Organ Mountains. In the past, ground-water withdrawals from the Post Headquarters well field (Fig. 2) have resulted in declining ground-water levels, increases in dissolved-solids concentrations, and encroachment of saline water (Risser, 1988; Kernodle, 1992). Between 1987 and 1993, WSMR installed water-supply and observation wells in the Soledad Canyon area under a Memorandum of Understanding with the neighboring Fort Bliss Military Reservation. The Soledad Canyon well field is located on Fort Bliss property approximately 12 km south of the WSMR Post Headquarters area (Fig. 2). The Soledad Canyon well field was developed to meet an increasing ground-water demand and to diminish the possibility of lateral encroachment and vertical upconing of saline water by decreasing the volume of water withdrawn from the Post Headquarters well field. Since its development, the Soledad Canyon well field has been increasingly relied upon for providing potable water to WSMR.

A conceptual model of the bolson-fill aquifer in the Soledad Canyon area was developed to help understand the flow system and to provide a framework for development of a numerical ground-water-flow model. The numerical model can be used to evaluate the effect of existing Soledad Canyon wells and possible future development on water quantity and quality in the aquifer.

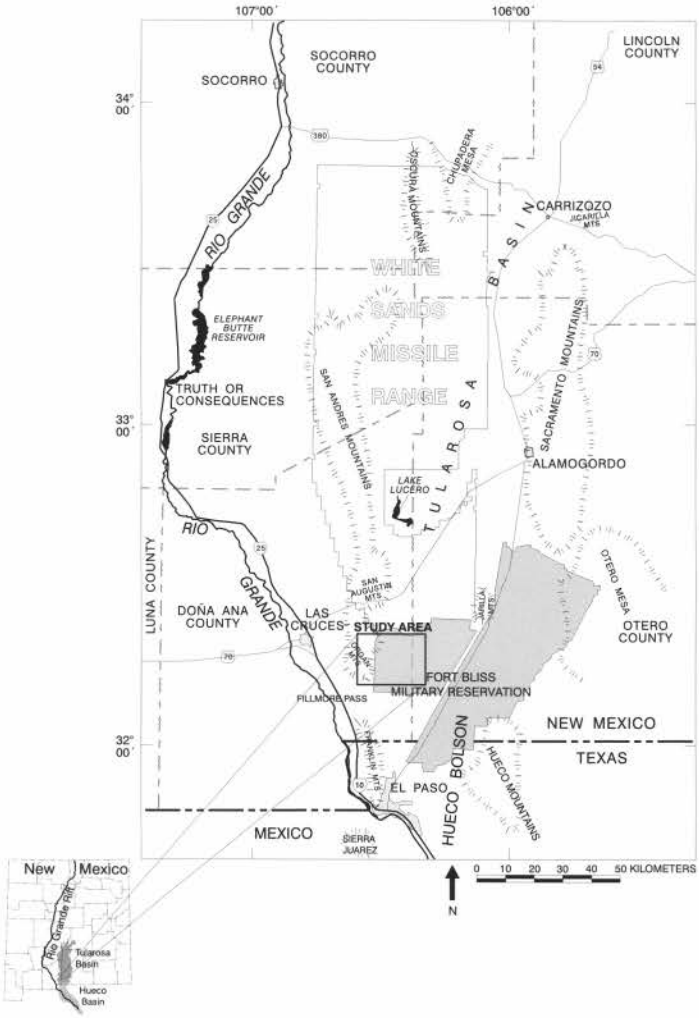

FIGURE 1. Location of the study area.

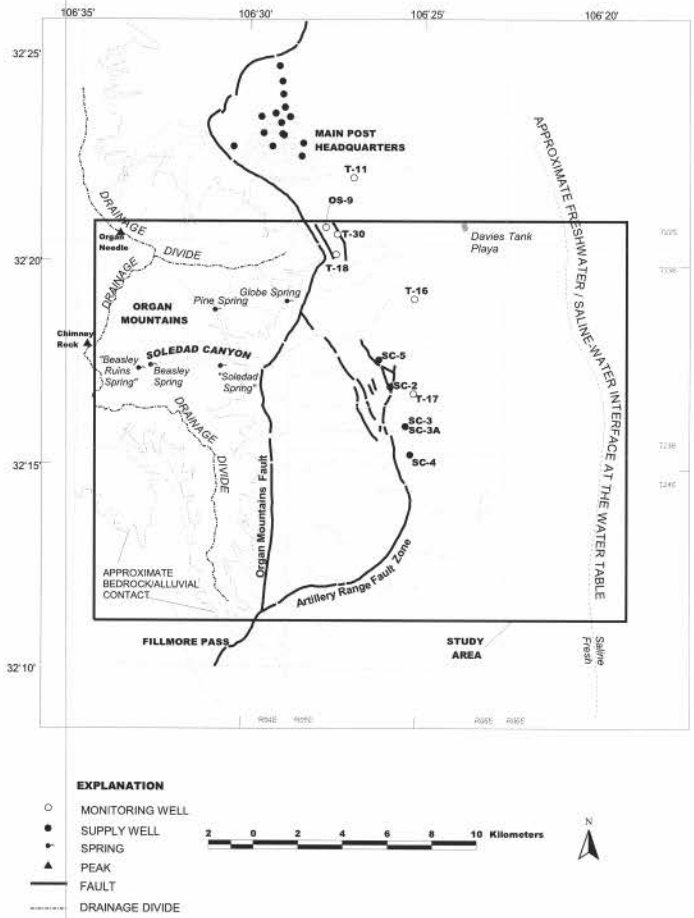

FIGURE 2. Location of physiographic, geologic, and hydrologic features and selected wells and springs.

DESCRIPTION OF STUDY AREA

The freshwater part of the aquifer in the Soledad Canyon area is a lens-shaped body underlain by saline water and bounded laterally by less permeable rocks of the Organ Mountains on the west and by saline water on the east. The study area corresponds to the freshwater part of the basin within the Soledad Canyon reentrant (Fig. 2) and includes portions of the Organ Mountains and Tularosa Basin (Fig. 1). The study area is separated from the Post Headquarters reentrant to the north and is bounded by the Organ Mountains on the west, a freshwater/saline-water interface on the east (Wilson and Myers, 1981), and Fillmore Pass on the south. For some analyses, it was necessary to include data for wells near but outside the study area boundary shown in Figure 2.

Physiography and Climate

The Tularosa Basin and Hueco Bolson are within a large structural basin containing as much as 3048 m of bolson fill (Risser, 1988; Orr and Risser, 1992). The basin is bounded on the west by the Oscura, San Andres, San Augustin, Organ, and Franklin Mountains and Sierra Juarez and on the east by the Jicarilla, Sacramento, and Hueco Mountains and Otero Mesa. Chupadera Mesa forms the northern terminus of the basin (Fig. 1). Although separately named, the Tularosa Basin and the Hueco Bolson are the northern and southern parts of one rift basin. The southern terminus of the Tularosa Basin is generally delineated by the presence of a gentle topographic divide near the New Mexico-Texas State line (Kernodle, 1992).

The Tularosa Basin is a high desert area, averaging about 1219 m in altitude. To the west, the Organ Mountains rise more than 1.5 km from the basin floor to their 2747-m summit (Seager, 1981) of Organ Needle (Fig. 2). Soledad Canyon, climbing from an altitude of 1463 m near its mouth to approximately 1890 m near Chimney Rock (Fig. 2), drains most of the central part of the Organ Mountains. The mouth of Soledad Canyon is mantled by a large alluvial fan that receives drainage from the main portion of the canyon; the fan is part of an apron of coalesced alluvial fans and rock pediments along the base of the Organ Mountains that lead to the basin floor. Fault scarps cutting both fans and pediments on the eastern flank of the uplift are locally more than 45 m high (Seager, 1981).

In the study area, the Tularosa Basin is characterized by low average humidity (38%) and rainfall (25-38 cm/yr). Average minimum and maximum annual temperatures are 8°C and 26°C, respectively. Summer temperatures are high, averaging 35°C, with frequent readings over 38°C. Winter temperatures generally are mild, but nighttime temperatures occasionally are below freezing (Basabilvazo et al., 1994; R.G. Myers, WSMR, personal commun., 2000). Vegetation in the study area includes mesquite, creosote bush, yucca, and several varieties of cactus and grasses in the lower altitudes and oak, juniper, and piñon in the canyons at higher altitudes (Seager, 1981; U.S. Department of the Army, White Sands Missile Range, and U.S. Geological Survey, n.d.).

Geologic Setting

Soledad Canyon is a reentrant of bolson-fill deposits of Tertiary and Quaternary age into igneous, metamorphic, and sedimentary rocks of Precambrian to Tertiary age in the Organ Mountains (Fig. 3). The present basin-and-range configuration of the Organ Mountains and adjacent Tularosa Basin developed in response to late Tertiary crustal extension associated with the Rio Grande rift.

During the initial period (Oligocene) of Rio Grande rift extension, volcanic rocks of the Organ cauldron buried deposits and structures previously formed in the study area during the Laramide orogeny. The volcanic rocks of the Organ cauldron, as well as the Precambrian core of the large Laramide uplift, were subsequently intruded by the source of the volcanism, the Organ batholith (Mack and others, 1998). Bedrock in the Organ Mountains adjacent to the study area is predominantly Precambrian granite and the Tertiary Organ Needle quartz-monzonite phase of the Organ batholith (Seager, 1981; Seager et al., 1987).

Block faulting during the first major stage of crustal extension in the southern Rio Grande Rift (early to middle Miocene) probably did not displace the Organ batholith; current basins and ranges formed during a second stage of rift-related extension that started in latest Miocene time and is continuing today (Seager, 1981; Mack et al., 1998). Repeated movement on the Organ Mountains fault and Artillery Range fault zone (Figs. 2-3) has raised the

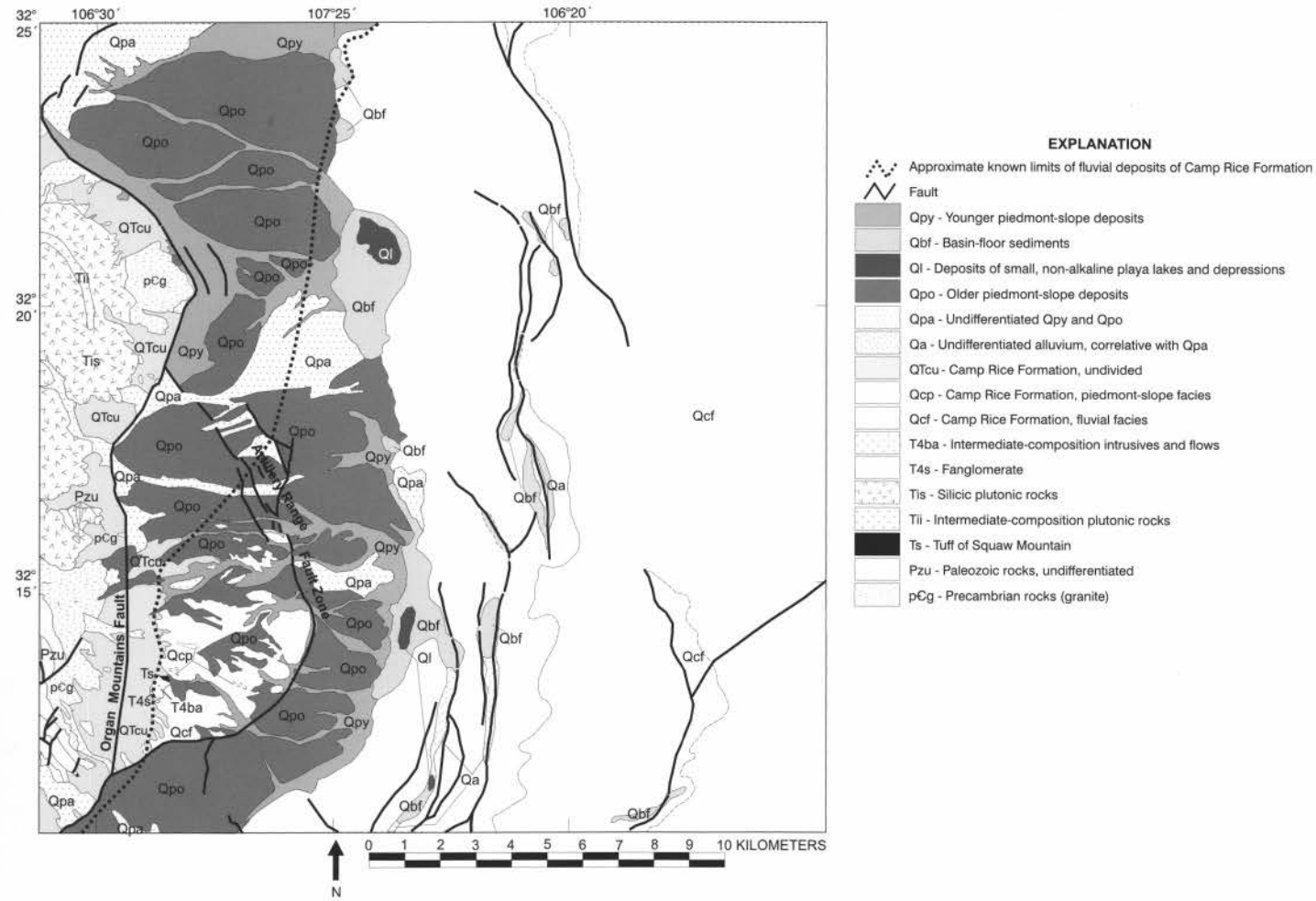

FIGURE 3. Geologic map of portions of the study area and adjacent areas (modified from Seager et al., 1987).

modern fault-block range, downdropped the western part of the Tularosa Basin, and allowed great thicknesses of bolson-fill sediments to accumulate. A belt of short faults, related to the range-boundary faults, parallels the mountain front in the eastern part of the study area (Seager, 1981; Seager et al., 1987) (Fig. 3).

Seager (1981) recognized three general subdivisions of bolson-fill deposits in the study area. The Camp Rice Formation of the Santa Fe Group, the oldest of the three, is the sedimentary record of the second major stage of rift-related extension (Mack et al., 1998). In the Soledad Canyon area, the oldest (Pliocene to early Pleistocene) Camp Rice Formation deposits (QTcc, Fig. 4) compose a basal piedmont-slope facies that consists primarily of fanglomerate and conglomerate derived from adjacent mountains and deposited as alluvial fans and debris flows. This basal part of the Camp Rice Formation, mapped together with other piedmont-slope deposits in Figure 3, probably also contains closed-basin deposits, including lacustrine clay and evaporites (Orr and Risser, 1992). Deposits making up the basal part of the Camp Rice Formation locally interfinger with fluvial deposits (Qcf) that are part of a large fan delta deposited by the ancestral Rio Grande as it flowed into the southern Tularosa Basin through Fillmore Pass (Fig. 2). The Camp Rice fluvial facies interfingers with the overlying piedmont-slope facies (Qcp), which consists of fan deposits grading to gravelly silt, loam, or clay (Seager, 1981; Seager et al., 1987). Although lacustrine deposits within the Camp Rice Formation were not mapped in the study area, Seager (1981) presented a schematic depicting a large lake coexisting with the fluvial Camp Rice facies. Camp Rice deposits may be as much as 300 m thick locally (Orr and Risser, 1992).

Continued uplift of the eastern side of the Organ and Franklin Mountains probably forced the ancestral Rio Grande to abandon its course through the present-day Fillmore Pass region and move westward into the Mesilla Basin, leading to the present closed-basin conditions in the Tularosa Basin (Seager, 1981). The second general subdivision of Quaternary bolson-fill deposits (late Pleistocene) is composed of several generations of alluvial-fan and pediment deposits (Qpo) graded to closed-basin floors that post-date river valley incision in the study area. The third and youngest general subdivision of bolson-fill deposits is made up of modern arroyo-channel, canyon-fill, and alluvial-fan deposits (Qpy). In addition to these youngest piedmont-slope deposits, fine-grained basin-floor (Qbf) and playa-lake (Ql) sediments are exposed in the study area (Seager, 1981; Seager et al., 1987) (Fig. 3).

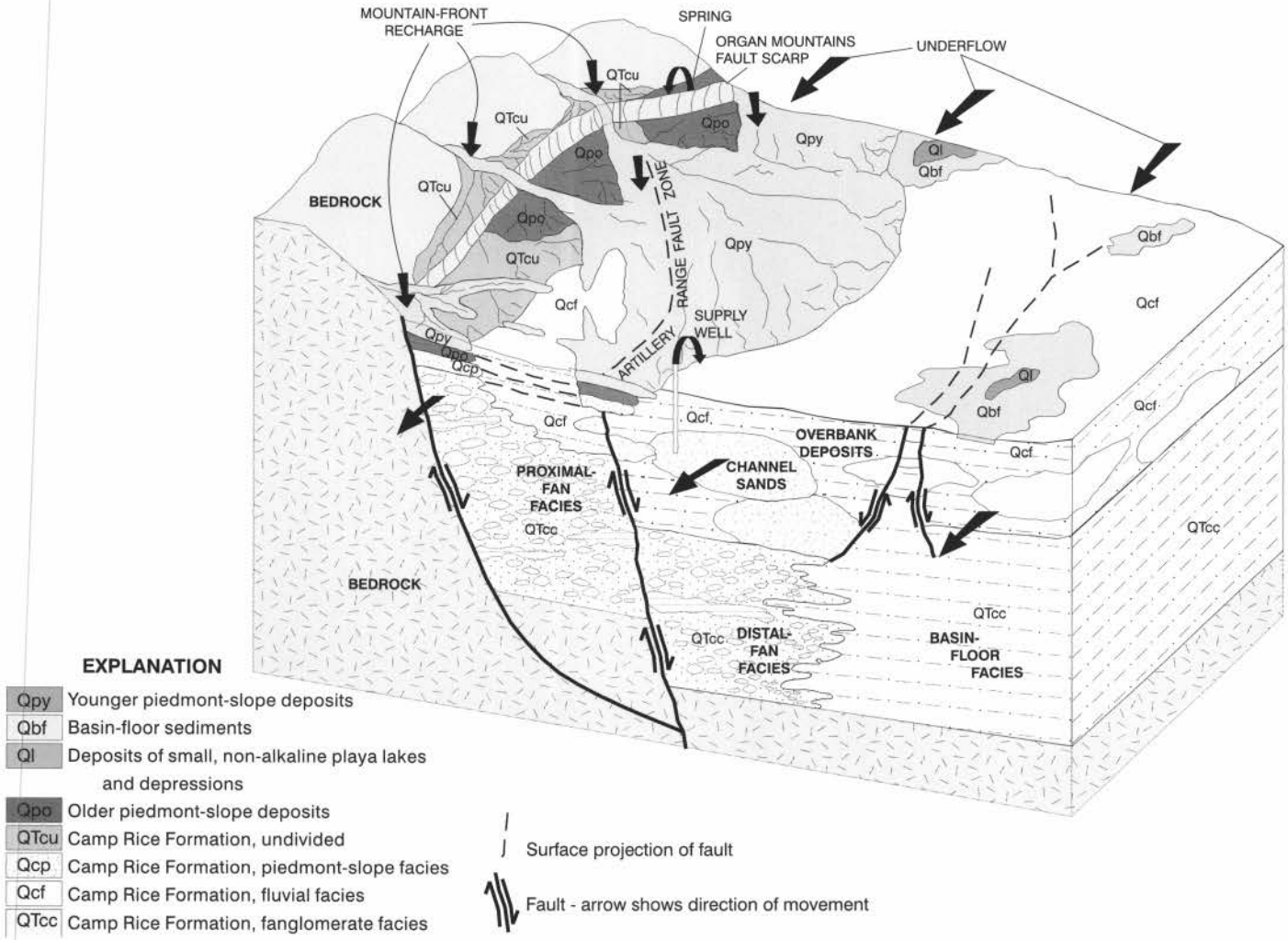

FIGURE 4. Schematic diagram illustrating the conceptual model of the hydrogeologic system (surficial geology based on Seager et al., 1987).

Hydrologic Setting

The Tularosa Basin is a closed surface-water drainage system, separated from the Hueco Bolson (a through-flowing basin) by a surface divide near the New Mexico-Texas State line. Most of the surface-water runoff from the mountains bordering the Tularosa Basin infiltrates before reaching the axis of the basin. Sustained surface-water flow during periods of intense precipitation may reach depressions and playas on the basin floor, forming ephemeral lakes that eventually evaporate and develop into alkali flats (Basabilvazo et al., 1994).

The Tularosa Basin and Hueco Bolson, although topographically separated, form one ground-water basin (Orr and Risser, 1992). The general direction of ground-water flow in the Tularosa Basin and Hueco Bolson is from north to south. In the study area, flow components are easterly and southeasterly near mountainous recharge areas (Knowles and Kennedy, 1958; McLean, 1970; Wilson and Myers, 1981; Orr and Risser, 1992).

CONCEPTUAL MODEL OF THE BOLSON-FILL AQUIFER

A conceptual model of the bolson-fill aquifer in the Soledad Canyon area was developed to synthesize existing information, to promote a better understanding of the flow system, and to provide a framework for development of a numerical ground-water-flow model. Conceptualization of hydrogeologic properties, recharge and discharge characteristics, and location and extent of freshwater are described in the following sections.

Hydrogeology of the Bolson-fill Aquifer

The schematic geologic block diagram shown in Figure 4 illustrates the author's conceptualization of the hydrogeologic flow system in the Soledad Canyon area. The unconfined aquifer, consisting of bolson-fill sediments described in the previous section, is bounded on the west and beneath by less permeable igneous, metamorphic, and sedimentary bedrock. Piedmont-slope

TABLE 1. Transmissivity (T) estimates for selected wells in the study area.

Well identifier (Fig. 2)	T (m^2/day)	Method of estimating T	Data source
SC-2	234	Pumping test - drawdown	U.S. Army Corp of Engineers (1988)
SC-2	252	Pumping test - recovery	U.S. Army Corp of Engineers (1988)
SC-3	308	Pumping test - recovery	U.S. Army Corp of Engineers (1988)
SC-3	312	Pumping test - drawdown	U.S. Army Corp of Engineers (1988)
SC-3A	247	Pumping test - recovery	U.S. Army Corp of Engineers (1988)
SC-3A	298	Pumping test	U.S. Army Corp of Engineers (1988)
SC-3A	312	Pumping test - drawdown	U.S. Army Corp of Engineers (1988)
OS-9	10	Pumping test	Herrick (1955)
T-11	169	Pumping test - recovery	Doty (1968)
T-11	179	Pumping test - drawdown	Doty (1968)
T-11	158	Aquifer test (unspecified type)	Kelly (1973)
T-16	468	Aquifer test (unspecified type)	Kelly (1973)
T-16	236	Specific capacity	Lyford (1970)
T-16	467	Pumping test	Lyford (1970)
T-16	445	Pumping test - recovery	Lyford (1970)
T-17	204	Aquifer test (unspecified type)	Kelly (1973)
T-17	204	Pumping test - drawdown	Lyford (1970)
T-17	125	Specific capacity	Lyford (1970)
T-17	221	Pumping test - recovery	Lyford (1970)
T-18	24	Aquifer test (unspecified type)	Kelly (1973)
T-18	14	Pumping test - drawdown	Lyford (1970)
T-18	17	Pumping test - recovery	Lyford (1970)

deposits upslope from the Organ Mountains fault scarp (QTcu, Fig. 4) are conceptualized as a thin veneer of sediments overlying bedrock and are not considered to be part of the aquifer. On the basis of previously published contours of the altitude of the top of consolidated bedrock in the study area (McLean, 1970, fig. 5), the bolson-fill sediments may be as much as 1845 m thick on the downthrown side of the Organ Mountains fault in the study area.

As illustrated in Figure 4, concurrent faulting and deposition of the sediments described in the previous section could have resulted in complex lithology. Hydraulic properties in the study area are expected to be highly variable because of the heterogeneity of bolson-fill sediments and tectonic activity. In general, sediments derived from adjacent uplifted areas become finer grained and better sorted with distance from the source area. Although this general trend probably is reflected in the progression from piedmont-slope and proximal-fan facies of the Camp Rice Formation near the Organ Mountains fault to distal-fan and basin-floor facies, water-transmitting properties of these deposits also have been affected by debris flows, cementation, and faulting. Coarser deposits near the mountain front, containing clasts as large as 6.1 m in diameter (Seager, 1981), may be among the least transmissive because of very poor sorting, interbedded fine-grained debris-flow sediments, and cementation with calcium carbonate. Evidence of recent (1991) and past debris flows on the east flank of the Organ Mountains was presented by Seager (1981), Heckman and Mueller (1998), and Stone (1998). Alluvial-fan deposits that are well cemented with calcium carbonate have been documented in the study area (Seager, 1981; Seager et al., 1987; R.G. Myers, personal commun., 2000).

The effect of the numerous faults (Fig. 3) on the hydraulic properties of bolson-fill sediments in the study area is not well understood. On the basis of large water yields from wells located near fault zones in the Post Headquarters area, Kelly and Hearne (1976) concluded that fault zones are areas of high permeability. However, evidence of lower permeability in fault zones was presented by Lyford (1970). His analysis of pumping test data for well T-18, located in close proximity to faults in the northwestern part of the study area (Fig. 2), indicated that this fault zone acts as a flow barrier.

Transmissivity estimates for selected wells in the study area are presented in Table 1. Transmissivity estimates for wells located in the same part of the study area (Fig. 2) generally are in agreement, with the exception of estimates made using the specific-capacity method. The transmissivity distribution indicates that the aquifer is more transmissive in the vicinity of the Artillery Range fault zone near the Soledad Canyon supply wells (wells SC-2, SC-3, SC-3A, and T-17) than near the two short faults (Fig. 2) in the northern part of the study area (wells OS-9 and T-18). Although the presence of faults could be responsible for these transmissivity variations, the Soledad Canyon supply

wells may simply be completed within more productive sands and gravels of the Camp Rice fluvial facies.

Previously published lithologic logs (Wilson and Myers, 1981) and those examined for this study indicate that the bolson-fill aquifer near the Soledad Canyon supply wells is contained within alternating and interfingering lenses of clay, silt, sand, and gravel. This lithology is consistent with the conceptual model of the Camp Rice fluvial facies (Fig. 4). No extensive sand or clay layers were identified from the Soledad Canyon-area lithologic logs examined for this study. Wilson and Myers (1981, p. 6) drew a similar conclusion based on their analysis of lithologic and geophysical logs from boreholes in the Soledad Canyon area, stating "no continuous, individual units of sand or clay can be traced between test wells." Although bedding is visible in some outcrops, widespread and continuous sedimentary layers apparently are not present in the subsurface because of the nature of the depositional environments and displacement on the Artillery Range fault zone and the belt of faults in the eastern part of the study area.

Recharge

Potential sources of recharge to the bolson-fill aquifer in the Soledad Canyon area include direct infiltration of areal precipitation, mountain-front recharge, and infiltration of effluent from a wastewater-treatment facility. Because of the high rate of evaporation in the study area (238 cm/yr; New Mexico Climate Center, 2001), recharge from areal precipitation over most of the study area is assumed to be negligible. The primary recharge mechanism is assumed to be mountain-front recharge, a term used in this study to describe infiltration of streamflow resulting from snowmelt runoff and precipitation in the Organ Mountains. As shown schematically in Figure 4, mountain-front recharge infiltrates modern arroyo-channel, canyon-fill, and alluvial-fan deposits.

Mountain-front Recharge

For this study, mountain-front recharge was estimated using three methods. The first method was based on the results of an infiltration study in the Post Headquarters area, where infiltration was determined to be approximately 3% of precipitation (Ballance and Basler, 1967, 1969). Using this empirical method, mountain-front recharge was calculated as

$$R_{mf} = 0.03\ P\ A$$

where R_{mf} is the annual volumetric rate of mountain-front recharge, in units of length^3/year; P is annual precipitation depth, in units of length/year; and A is drainage area, in units of length^2.

A second method uses a regression equation developed to estimate streamflow at mountain fronts based on regional relations of basin and climatic characteristics (Waltemeyer, 1994, 2001). In this method, streamflow is calculated as

$$Q = 1.70 \times 10^{-4}\ A^{1.35}\ P^{1.65},$$

where Q is streamflow, in cubic feet per second; A is drainage area, in square miles; and P is precipitation depth, in inches. All runoff is assumed to infiltrate, and R_{mf} is equated to Q using unit conversions.

Finally, recharge was estimated by calculating a chloride mass balance on the Soledad Canyon watershed using the relation

$$R_{mf} = P\ A\ (C_p / C_r),$$

where P is annual precipitation depth, in units of length/year; A is drainage area, in units of length^2; C_p is the chloride concentration in bulk precipitation, in mg/L; and C_r is the chloride concentration in mountain-front recharge, in mg/L. The chloride-balance method, including critical assumptions and sources of error, was discussed in detail by Anderholm (2001).

Watershed boundaries constructed with GIS methods were used to determine a drainage area of 62 km^2 contributing to the Soledad Canyon reentrant (Fig. 2). Maps of normalized mean annual precipitation for 1931-60 (U.S. Department of Commerce, n.d.) and spatially gridded annual precipitation for 1961-90 (Daly et al., 1994, 1997) were used to estimate a long-term average annual precipitation of 40.6 cm/yr for the Soledad Canyon drainage area. Previously reported estimates of C_p for New Mexico and southwestern Texas range from 0.35 to 0.41 mg/L (Anderholm, 2001). Both values were used to bracket a range of R_{mf} values using the chloride-balance method. A chloride concentration of 10 mg/L in samples collected near the water table in wells T-11 and T-30 (Fig. 2) is considered representative of the concentration in mountain-front recharge; therefore, 10 mg/L was used for C_r for calculations using both the minimum (C_p = 0.35 mg/L) and maximum (C_p = 0.41 mg/L) bulk precipitation concentrations.

Mountain-front recharge estimated for this study is presented in Table 2. The estimates, ranging from approximately 76-106 ha-m/yr, probably represent a reasonable range of volumetric recharge rates for the Soledad Canyon watershed. Because an assumption of the regression method is infiltration of all runoff, mountain-front recharge calculated using this method (106 ha-m/yr) probably represents the upper end of the range of reasonable recharge rates.

Mountain-front recharge estimated for this study is greater than the recharge amount estimated by Risser (1988), but similar to that estimated by Wilson and Myers (1981) for the Soledad Canyon area. Risser (1988) used physical characteristics of the Soledad Canyon watershed to calculate an estimated annual runoff of 62 ha-m. He assumed that all runoff infiltrates to the water table. Wilson and Myers (1981) estimated aquifer recharge from the Soledad Canyon watershed as approximately 92 ha-m/yr by assuming that 3% of an estimated annual 33 cm/yr of precipitation distributed over an area of 93 km^2 recharges the aquifer. The actual amount of mountain-front recharge varies spatially with characteristics of the alluvial-fan deposits and both spatially and temporally with precipitation patterns.

The degree to which intermittent streamflow infiltrates arroyo-channel, canyon-fill, and alluvial-fan deposits is probably affected by the degree of cementation by calcium carbonate precipitates, or

TABLE 2. Comparison of annual mountain-front recharge volumes (hectare-meters/year) estimated using empirical, regression, and chloride-balance methods.

Empirical method	Regression method	Chloride-balance method	
		Maximum (C_p = 0.41 mg/L)	Minimum (C_p = 0.35 mg/L)
75.28	106.29	102.69	87.66

caliche. Caliche is common in pediment deposits in the study area (Seager, 1981; Seager et al., 1987; R.G. Myers, personal commun., 2001). Knowles and Kennedy (1958) also noted abundant caliche in the Hueco Bolson and stated that most recharge occurs where caliche deposits are absent or fractured. A lack of caliche in arroyos (R.G. Myers, personal commun., 2001) probably enhances recharge to sediments near arroyos in the study area.

Mountain-front recharge probably is affected considerably by precipitation. Risser (1988) found that water in the arroyos contributed a significant amount of recharge water to the Post Headquarters area well field during periods of heavy rainfall. Two major precipitation events occurred in 1978 and 1980, after which water levels rose nearly 2.5 m/yr in some wells west of the Post Headquarters well field (Risser, 1988).

Wastewater-treatment Effluent Recharge

Prior to 1986, effluent from a wastewater-treatment plant was discharged into an unlined channel about 5 km southeast of the Post Headquarters (Risser, 1988). In 1986, Davies Tank Playa (Fig. 2) became the new location for wastewater discharge. Infiltration of wastewater-treatment effluent discharged into the playa by the wastewater-treatment plant is a potential source of recharge to the aquifer in the study area. Evaporation from standing water in the playa reduces the amount of effluent available to recharge the aquifer.

An evaporation-corrected wastewater recharge rate was estimated by subtracting the average rate of evaporation in the study area from the rate of wastewater discharge. The average rate of evaporation in the study area was assumed to be equivalent to the mean value of 238 cm/yr for 1959-95 at New Mexico State University (New Mexico Climate Center, 2001). Recent estimates of the amount of wastewater discharged into the playa range from approximately 416 to 757 million L/yr (J.E. Harris, WSMR, personal commun., 2000, 2001). The playa bottom is approximately 80 ha in area, and the wetted area ranges seasonally from 8 to 10 ha (J.E. Harris, personal commun., 2001). The rate of wastewater discharge was calculated using the average discharge volume for 2000-01 (586.5 million L/yr) and an estimated wetted playa bottom area of 8 ha. The volume of wastewater available to recharge the aquifer, calculated as the evaporation-corrected wastewater recharge rate multiplied by the estimated wetted playa-bottom area, is approximately 40 ha-m/yr.

The percentage of the volume of wastewater available to recharge the aquifer that infiltrates to the water table is unknown. Risser (1988) stated that water-level measurements in the vicinity of playa lakes about 6.4 km east of the Post Headquarters show little recharge from infiltration because seepage is hindered by clayey playa beds. At Davies Tank, however, the lack of physical evidence of salt accumulation on the playa bottom, combined with the presence of enlarged desiccation features (R.G. Myers, personal commun., 2001), indicates a permeable playa bottom and good recharge potential. For this study, 60-90% of the estimated 40 ha-m/yr is estimated to actually recharge the aquifer. Therefore, wastewater-treatment effluent recharge is estimated to range from 24 to 36 ha-m/yr.

Discharge

Possible outlets for ground water in the bolson-fill aquifer in the Soledad Canyon area include supply wells, spring discharge, and evapotranspiration. Locations of supply wells in the study area are shown in Figure 2. Four water-supply wells were installed in Soledad Canyon (SC-2, SC-3, SC-4, and SC-5), but only SC-2 and SC-3 have been used for this purpose. Monthly pumpage volumes are available from April 1991, when production from SC-2 and SC-3 began, to December 1999. Annual pumpage volumes for SC-2 and SC-3 combined, calculated by summation of monthly volumes by water year, vary from 34 to 82 ha-m/yr.

Prior to development of the Soledad Canyon well field, ground-water withdrawal from Post Headquarters wells could have affected ground-water storage in the Soledad Canyon area. The effect of ground-water withdrawal from the Post Headquarters well field on water resources in the study area was evaluated by mapping the measured changes in water levels during the period prior to development of the Soledad Canyon well field (Fig. 5). Withdrawal of water from the Post Headquarters well field apparently has not caused water levels to decrease uniformly in the Soledad Canyon area. Water levels in some observation wells south of the Post Headquarters well field rose by as much as 3 m during 1982-90, whereas water levels in other wells declined

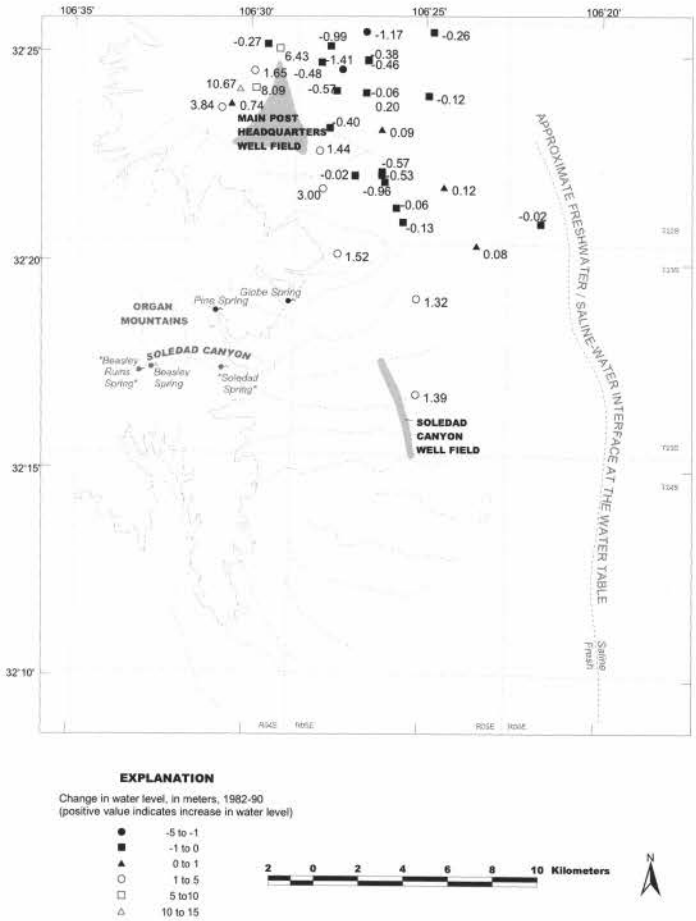

FIGURE 5. Water-level change in boreholes and test wells, in meters, 1982-90.

by as much as 1.52 m. Maps showing the changes in measured water levels for 1949-72 (Kelly and Hearne, 1976) and 1978-82 (Risser, 1988) also indicate that pumpage from the Post Headquarters well field has had negligible effects on water levels in the Soledad Canyon area. Therefore, it is concluded that withdrawal of ground water from Post Headquarters wells has not depleted ground water in storage in the Soledad Canyon area.

Springs in the study area are located within bedrock and piedmont-slope deposits upslope from the Organ Mountains fault scarp (Fig. 2). Very few data are available for springs in the study area: only one spring discharge measurement is available. Globe Spring, located within piedmont-slope deposits, flowed at a rate of 87 L/min in April 1945 (White and Kues, 1992) but is now dry. Qualitative observations indicate that flow at Pine Spring, also located within piedmont-slope deposits, is seasonal, but that Beasley Spring perennially issues from bedrock above the alluvial contact in Soledad Canyon (R.G. Myers, personal commun., 2000). A dry spring box located among ruins near Beasley Spring ("Beasley Ruins Spring," Fig. 2) indicates that a second spring once issued from bedrock in Soledad Canyon to provide water to former inhabitants. A third, unnamed spring in Soledad Canyon ("Soledad Spring," Fig. 2) also is located within bedrock. Soledad Spring was observed to be flowing in late March/early February 2000 (S. Offut, Fort Bliss Military Reservation, personal commun., 2000); flow was minimal in April 2001.

The source of water to springs located within alluvial deposits is uncertain. Determining whether these springs are contact springs that issue from the fractured bedrock because of contact with alluvial materials of lower hydraulic conductivity or whether the springs are sourced solely by ground water within the alluvial deposits is not possible with available data. On the basis of the conceptualization of the hydrogeology shown in Figure 4, it appears unlikely that springs flowing from alluvial deposits above the Organ Mountains fault are hydraulically connected to bolson-fill deposits. Therefore, spring flow is not a mechanism for discharge from the bolson-fill aquifer in the Soledad Canyon area.

Evapotranspiration also is not a significant mechanism for discharge from the bolson-fill aquifer in the Soledad Canyon area. Evapotranspiration probably occurs upslope from the Organ Mountains fault, where piedmont-slope deposits are thought to be thin, and the water table probably is close to land surface. On the downthrown side of the Organ Mountains fault, however, water levels are deep (approximately 40 to 105 m below land surface), and the aquifer is not subject to evapotranspiration losses.

Ground-water Quality

Water quality in the study area becomes poorer toward the center of the Tularosa Basin and with increasing depth. In the eastern part of the study area, dissolved-solids concentrations are as large as 16,800 mg/L near the water table (data on file with the U.S. Geological Survey, Albuquerque, New Mexico). Dissolved-solids concentrations are as large as 33,000 mg/L approximately 500 m below land surface (Lyford, 1970). Because of possible upconing and lateral encroachment of saline water into the well field, the location and extent of saline water in the study area are of interest.

Previously published water-quality and electric-log data (Knowles and Kennedy, 1958; McLean, 1970; Wilson and Myers, 1981; and Orr and Risser, 1992) and mapped contours representing the altitude of the top of consolidated bedrock and the freshwater/saline-water interface (McLean, 1970; Wilson and Myers, 1981) were supplemented with additional water-quality and electric-log data (on file with the U.S. Geological Survey) to estimate the geometry of the freshwater/saline-water interface for this study. The altitude of the interface estimated for each well was based on (1) the altitude of consolidated bedrock, (2) the altitude of the apparent transition on electric logs between fresh and saline water, or (3) a dissolved-solids concentration of 3,000 mg/L. The dissolved-solids concentration used to approximate the depth of the freshwater/saline-water interface corresponds to the division between slightly saline and moderately saline water defined by Tibbals (1990).

The estimated position of the freshwater/saline-water interface is shown in Figure 6. The part of the aquifer containing freshwater, approximately 16 km wide and more than 610 m thick in the study area, generally parallels the surface contact of the bedrock and bolson-fill deposits. The lens of potable water is underlain by saline water and is bounded laterally by the less permeable rocks of the Organ Mountains on the west and by saline water on the east. The freshwater lens extends northward into the Tularosa Basin and southward into the Hueco Bolson.

A transition zone of varying density probably exists between fresh and saline water at depth and toward the center of the

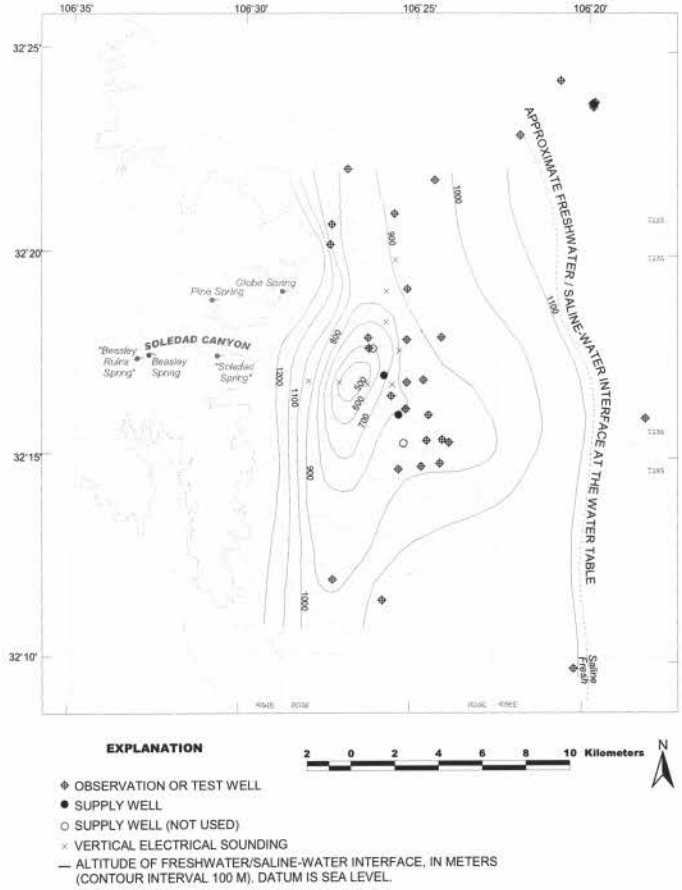

FIGURE 6. Estimated altitude of the freshwater/saline-water interface.

Tularosa Basin in the study area. Fresh and saline water probably mix across a zone of diffusion, the width of which is controlled by dispersive characteristics of the aquifer. If the zone is narrow, the boundary between fresh and saline water can be conceptualized as a stationary, sharp interface. The nature of the interface, however, cannot be well characterized with available data. The conceptual model developed for the Soledad Canyon area assumes a narrow transition zone that can be approximated by an idealized sharp interface.

SUMMARY

Conceptualization of hydrogeologic properties, recharge and discharge characteristics, and location and extent of freshwater provides a better understanding of the Soledad Canyon bolson-fill aquifer and a framework for development of a numerical ground-water-flow model. The hydraulic properties of the bolson-fill aquifer in the study area are highly variable because of the heterogeneity of bolson-fill sediments and tectonic activity. Interfingering piedmont-slope, alluvial-fan, fluvial, and basin-floor deposits probably have a wide range of hydraulic properties. Coarser deposits near the mountain front may be among the least transmissive because of very poor sorting, interbedded, fine-grained debris-flow sediments, and calcium carbonate cementation. Continuous sand or clay layers are not apparent in the subsurface because of the nature of the depositional environments and displacement on the Artillery Range fault zone and the belt of faults in the eastern part of the study area. The effect of numerous faults on hydraulic properties of bolson-fill sediments is not well understood. Although the distribution of transmissivity within the aquifer indicates that the aquifer is more transmissive in the vicinity of the Artillery Range fault zone near the Soledad Canyon supply wells than near the two faults in the northwestern part of the study area, supply wells may simply be located within more productive sands and gravels of the Camp Rice fluvial facies.

Although mountain-front recharge is the most significant form of recharge to the bolson-fill aquifer in the Soledad Canyon area, effluent from a wastewater-treatment facility also is an important recharge source. Mountain-front recharge, used in this study to describe infiltration of streamflow resulting from snowmelt runoff and precipitation in the Organ Mountains, was estimated using empirical, regression, and chloride-balance methods. The estimated rates, ranging from approximately 76 to 106 ha-m/yr, probably represent a reasonable range of volumetric recharge rates for the study area. The actual amount of mountain-front recharge varies spatially with characteristics of the alluvial-fan deposits and spatially and temporally with precipitation patterns. The volume of recharge resulting from wastewater-treatment effluent discharged into Davies Tank Playa was calculated to be approximately 40 ha-m/yr. Because characteristics of the playa bottom into which the effluent is discharged indicate good recharge potential, 60-90% of the estimated 40 ha-m/yr is estimated to actually recharge the aquifer. Wastewater-treatment effluent recharge therefore is estimated to range from 24 to 36 ha-m/yr.

Supply wells, spring discharge, and evapotranspiration were taken into account as possible forms of discharge from the bolson-fill aquifer. Monthly pumpage volumes for Soledad Canyon supply wells, available for April 1991 to December 1999, were used to calculate annual pumpage volumes that vary from 34 to 82 ha-m/yr. Because ground-water withdrawal from the Post Headquarters well field apparently has not caused water levels to decrease uniformly in the Soledad Canyon area, it is concluded that pumpage from Post Headquarters wells has not affected ground-water storage in the Soledad Canyon area.

From the available data, determining the source of water to springs within alluvial deposits is not possible. However, the conceptualization of the hydrogeologic system indicates that springs issuing from alluvial deposits above the Organ Mountains fault are not hydraulically connected to bolson-fill deposits. Therefore, spring flow is not a mechanism for discharge from the bolson-fill aquifer in the Soledad Canyon area. Evapotranspiration also is not a significant mechanism for discharge from the bolson-fill aquifer in the Soledad Canyon area because water levels are deep on the downthrown side of the Organ Mountains fault.

Because of possible lateral encroachment of saline water into the well field, the location and extent of saline water in the study area are of interest. The altitude of the freshwater/saline-water interface was determined using lithologic descriptions, electric logs, and water-quality data for wells in the study area. The altitude of the interface estimated for each well was based on (1) the altitude of consolidated bedrock, (2) the altitude of the apparent transition on electric logs between fresh and saline water, or (3) a dissolved-solids concentration representative of the division between slightly saline and moderately saline water. The estimated position of the freshwater/saline-water interface defines a freshwater geometry approximately 16 km wide and more than 610 m thick in the study area. Unfortunately, the nature of this interface cannot be adequately characterized with available data. The conceptual model developed for the Soledad Canyon area therefore assumes a narrow transition zone that can be approximated by a stationary, sharp interface.

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