Some notes on the hydrogeology and ground-water quality of the Animas Basin system, southwestern New Mexico

Barry J. Hibbs, Monica M. Lee, John W. Hawley, and John F. Kennedy

2000, pp. 227-234. https://doi.org/10.56577/FFC-51.227

in:

Southwest Passage: A trip through the Phanerozoic, Lawton, T. F.; McMillan, N. J.; McLemore, V. T.; [eds.], New Mexico Geological Society 51 st Annual Fall Field Conference Guidebook, 282 p. https://doi.org/10.56577/FFC-51

This page is intentionally left blank to maintain order of facing pages.

SOME NOTES ON THE HYDROGEOLOGY AND GROUND-WATER QUALITY OF THE ANIMAS BASIN SYSTEM, SOUTHWESTERN NEW MEXICO

BARRY J. HIBBS[1], MONICA M. LEE[1], JOHN W. HAWLEY[2], and JOHN F. KENNEDY[3]

[1]Department of Geological Sciences, California State University–Los Angeles, Los Angeles, CA 90032; [2]Department of Geological Sciences, New Mexico State University, Las Cruces, NM 88003; [3]New Mexico Water Resources Research Institute, New Mexico State University, Las Cruces, NM 88003

Abstract—The Animas basin system comprises an interconnected group of four subbasins (Lordsburg, Lower and Upper Animas, and Cloverdale) with a total surface watershed of about 6340 km^2, and a ground-water flow system area of about 6025 km^2. Very small portions of the system, 35 km^2 and 90 km^2, respectively, extend into Arizona and Mexico. The remaining 6215 km^2 is located in southwestern New Mexico, including parts of Hidalgo, Grant, and Luna counties. Water-bearing strata include consolidated bedrock units in the flanking highlands, and Tertiary and Quaternary basin (bolson) fill units in the central portions of the basin system. Recharge occurs mostly from ephemeral recharge along mountain fronts and from infiltration beneath the stream channel and floodplain of the system's only major axial drainageway, Animas Creek. Ground water flows south–north from the Cloverdale and Upper Animas subbasins, through the Lower Animas subbasin, into the Gila River Valley. Ground water along the regional hydraulic gradient is also captured by irrigation pumping. A smaller component of discharge is by evaporation where depth to groundwater is less than 10 to 12 m. Interior surface drainage collects at Alkali Flats and ground water discharges partly (and almost entirely under pre-development conditions) by subsurface interbasin flow; thus the basin system is classified as a topographically closed and drained basin. Hydrochemical facies in the basin system developed as a result of water-rock and water-soil interactions along flowpaths. Hydrochemical facies vary from calcium-bicarbonate ground waters with total dissolved solids (TDS) less than 250 mg/L in the Cloverdale and Upper Animas subbasins, to sodium-bicarbonate groundwaters with TDS less than 1000 mg/L in the southern part of the Lower Animas subbasin, to sodium-sulfate and sodium-chloride-sulfate ground waters with TDS that sometimes exceeds 1000 mg/L near Alkali Flats in the northern part of the Lower Animas subbasin. Different hydrochemical facies and higher TDS developed as ground water flowed south–north. The primary processes responsible for hydrochemical evolution and salinization include gypsum and halite dissolution, exchange on clay particles of bound sodium for calcium and magnesium in solution, and evaporation where ground water is shallow.

INTRODUCTION

This paper summarizes the results of a hydrogeologic and water-quality study of the Animas basin system, southwestern New Mexico. The study is part of a larger project that was undertaken to characterize binational aquifers in southwestern New Mexico, southeastern Arizona, northwestern Chihuahua, and northeastern Sonora, Mexico (Hawley et al., 2000). The larger study was a continuation of previous binational aquifer studies that were carried out by the authors and their colleagues at the Texas Water Development Board (TWDB), the New Mexico Water Resources Research Institute (NMWRRI), and California State University, Los Angeles (CSULA). Study #1, which was completed in 1997, was centered at the El Paso/Ciudad Juarez/Las Cruces region (Hibbs et al., 1997; Hibbs et al., 1998). Study #3 is located along the Del Rio/Ciudad Acuna to Laredo/Nuevo Laredo segment of the Rio Grande and is still in progress (R. Boghici, personal commun., 2000; Fig. 1). Study #2 (this study) included work on the Mimbres, Hachita-Moscos, Playas and San Basilio, Animas, Gila River basin systems, and San Bernardino basin.

Many of the surface and ground-water resources along the trans-boundary corridor are shared between both nations, yet little binational study of these resources has been undertaken. Solutions to water-related problems can be achieved only when a better understanding of trans-boundary resources is attained. Because of the importance of water quality and quantity to the region, aggregation and analysis of the existing data/information base is vital. Much of the United States/Mexico border region relies primarily on local trans-boundary ground-water resources for all uses. It is necessary to have an adequate understanding of these shared resources to address properly the variety of issues involved in good resource management and problem avoidance at the local, state, national, and international levels. Accordingly, our effort is focused on data assimilation and compilation, assessment of data accuracy and completeness, reconnaissance-level evaluation of the hydrogeology, and recommendations for filling data gaps. This paper summarizes a portion of our findings.

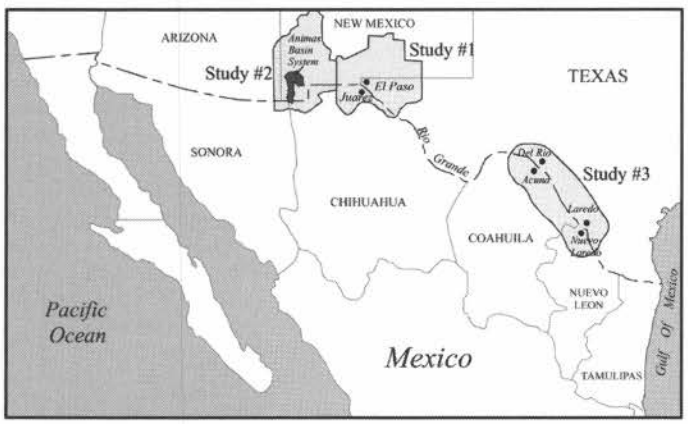

FIGURE 1. U.S./Mexico binational corridor showing the study area discussed in this paper (Study #2) and other binational aquifer study areas.

GEOLOGIC AND HYDROGEOLOGIC CHARACTERISTICS

Location and boundaries

The Animas basin system comprises an interconnected group of four subbasins (Lordsburg, Lower and Upper Animas, and Cloverdale) with a total surface watershed of about 6340 km^2, and a ground-water-flow-system area of about 6025 km^2 (Fig. 2). Very small portions of the system, 35 km^2 and 90 km^2, respectively, extend into Arizona and Mexico. The remaining 6215 km^2 is located in southwestern New Mexico, including parts of Hidalgo, Grant, and Luna counties. The three northern subbasins have a combined surface drainage area of about 5860 km^2.

The Animas basin system is entirely in the Mexican Highland section of the Basin-and-Range physiographic and structural provinces. The Cloverdale, and Upper and Lower Animas components of the basin system are distinct hydrogeologic units, which form a north–south aligned group of intermontane basins that are continuous in a general structural sense. The Lordsburg subbasin has a northwest–southeast structural grain and merges with the Lower Animas subbasin north and west of Lordsburg. The most extensive landforms of the basin system are broad piedmont slopes that extend out from the mountain fronts. These coalescent alluvial-fan surfaces (bajadas) grade to basin-floor areas, which range from narrow alluvial flats along axial drainage ways to broad bolson plains comprising both alluvial flats and playa-lake depressions

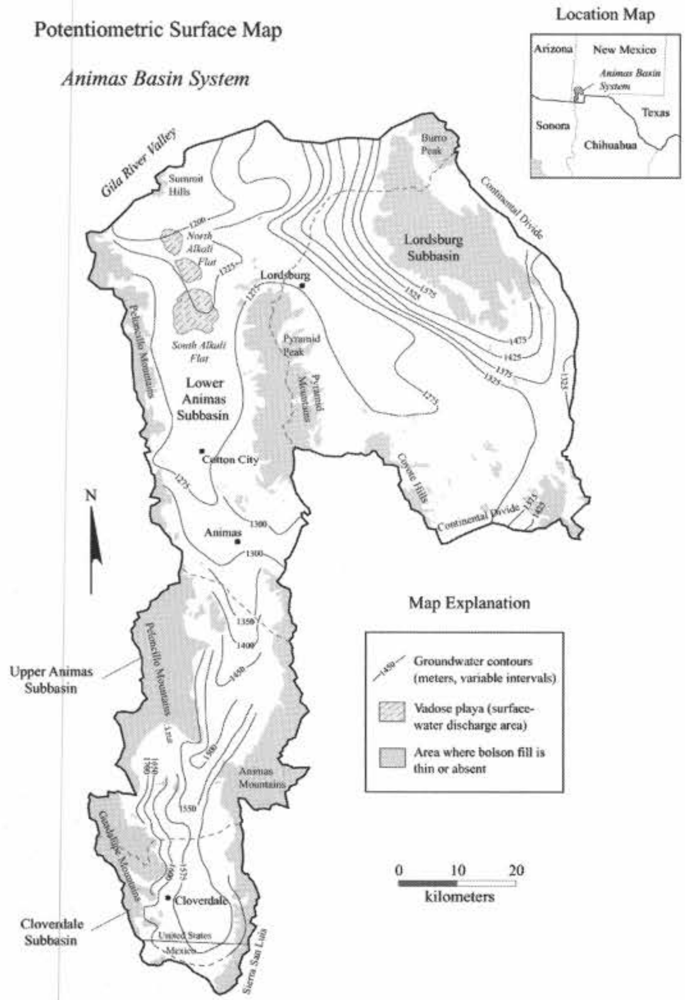

FIGURE 2. Animas basin system potentiometric surface map.

(e.g., Lower Animas subbasin).

The eastern border of the Animas basin system follows the Continental Divide and forms common watershed boundaries (from south to north) with the San Basilio, Playas, Hachita-Moscos, and Mimbres basins. The low-lying San Luis Mountains in the trans-boundary area form most of the eastern border of the Cloverdale subbasin. Continuing northward, the Upper Animas subbasin is bounded on the east by the southern and central parts of the Animas range. The northern section of the Animas Mountains is located north of Whitmire Pass, and forms the southeastern border of the Lower Animas subbasin. The Pyramid Mountains extend northward from South Pyramid Peak to the Lordsburg area and separate the central parts of the Lower Animas and Lordsburg subbasins.

At South Pyramid Peak, the Continental Divide turns abruptly to the east and crosses another topographic and structural saddle between the southern Pyramid uplift and the Brockman Hills (informally named the "Brockman-Pyramid Gap"). This divide segment separates the Lordsburg subbasin from the northern Playas basin to the south. The remaining portion of the southern and the eastern boundary of the Lordsburg subbasin follows the Continental Divide.

The northern border of the basin system follows the surface drainage divide between the northeastern Lower Animas subbasin and the Gila River basin. The western border of the Lower and Animas subbasins follows the crest of the north–south-trending Peloncillo Mountains for about 120 km. The southern segment of the basin system perimeter follows the crest of the Guadalupe Mountains south to near the head of Guadalupe Pass. To the south, the Cloverdale subbasin borders the upper drainage basin of Cajon Bonito in Sonora, Mexico.

Hydraulic components and properties

Maximum depth of water wells in the basin system is approximately 300 m, but most are less than 150 m deep. The zone of saturation is close to the surface in lower parts of the Lordsburg and Lower Animas subbasins (commonly less than 15 to 30 m). On upper to middle piedmont slopes throughout the basin system, however, the potentiometric surface (top of the regional ground-water flow system) may be more than 150 m below the land surface. The regional aquifer system is usually referred to as being "unconfined," but it is probably better classified as semiconfined to confined in many parts of the basin system.

The shallow zones of saturation that are commonly observed in the Upper Animas and Cloverdale subbasins, particularly in the inner valley of Animas Creek, have been identified as "perched" aquifers by Schwennesen (1918) and Reeder (1957). The limited amount of "perched" water historically available for livestock, domestic, and small irrigation agriculture uses occurs in coarse channel gravels that are only present in the inner valleys of Animas Creek and a few major tributaries with intermittent flow regimes. These fluvial deposits generally have high hydraulic conductivity (tens of meters per day) but low storage capacity. The entire "perched" system is restricted to the Upper Animas subbasin. Bedrock constrictions, coupled with the high structural and topographic position of the subbasin (as well as the adjacent Cloverdale subbasin), are the primary factors controlling the marked divergence of the "perched" and "deep" regional aquifer system first documented by Reeder (1957).

Much of the water pumped for irrigation during the past half century has been produced from the upper 150 m of basin fill. Yields of 545 to 2725 m^3/d are common in central basin areas (Trauger and Doty, 1965). Specific information on basin-fill hydraulic properties compiled by Reeder (1957) and O'Brien and Stone (1983) are derived from aquifer tests and well specific-capacity measurements. Highest reported irrigation-well discharge is about 10,000 m^3/d, but most well yields were in the 2725 to 5450 m^3/d range. Calculated transmissivity values range from 273 to 3059 m^2/d with an average value of about 620 m^2/d The specific yield values of 0.11 selected by O'Brien and Stone (1983) for the unconfined portion of the Lower Animas "Valley" aquifer system was based on Reeder's (1957) calculation of average storage coefficient values that range from 0.07 to 0.14.

Surface-water components

Surface flow in the Animas basin system has three components that directly interface with ground-water flow: (1) short reaches of intermittent streams in Upper Animas subbasin, (2) springs, seeps, and wetland (cienega) areas at higher elevations, and (3) ephemeral streams in arroyos and draws.

Major areas of locally intermittent mountain streams occur in the southern Animas and Peloncillo Mountains. Other intermittent flows occur in the larger draws and arroyos in the Animas basin system. The only large axial drainage ways in the basin system are Animas Creek in the Upper Animas subbasin and Lordsburg Draw in the Lordsburg subbasins. Both occasionally contribute storm runoff to the Alkali Flats in the Lake Animas depression. Flood waters commonly move as sheetflows down Lordsburg Draw and the lower Animas-basin floor area north and south of Cotton City. All these draws are ephemeral with underlying vadose-zone thickness ranging from 10 m to more than 30 m.

A few springs and seeps exist in higher mountain valleys and uppermost piedmont areas. These localized discharge points probably support very short reaches of intermittent stream flow in down-valley areas. Most springs and seeps in the upland parts of the basin system are considered to be components of "mountain-front recharge," because at least some of their discharge percolates downwards and laterally through bedrock fractures and ultimately contributes to storage in saturated basin-fill units.

Recharge

Only a small percentage of basin-wide precipitation and surface runoff in the Animas basin system contributes to ground-water recharge. Considering the absence of extensive mountain areas above 1800 m along the eastern, central, and northwestern borders of the basin system, and the widespread cover of desert scrub and semiarid grassland (McCraw 1985), most of the average annual precipitation of 25–30 cm is lost to evapotranspiration. In the southern part of the basin system, however, higher watersheds in the southern Animas and San Luis mountains range from 2000 to 2597 m in elevation. Pine forest vegetation in these places and climate records indicate that annual precipitation may locally range from 38 to 50 cm.

A general approximation of basin-wide recharge is based on the following assumptions: (1) the upper basin system that drains to the broad bolson plains of the Lower Animas subbasin (primarily a discharge zone) has an area of about 4500 km^2; (2) this area receives 1.58×10^9 m^3 of unevenly distributed annual precipitation of about 35 cm; and (3) one percent of this precipitation (1.58×10^7 m^3) contributes to ground-water recharge. This approximation is very close to published estimates (O'Brien and Stone, 1983; Kernodle, 1992) for the entire Animas Valley area.

The mountain-front recharge component varies considerably from place to place. However, it should be a significant contributor to the groundwater reservoir in basins adjacent to the major fault-block uplifts with substantial watershed areas above 1800 m. These areas include higher parts of the Burro Mountains, and most notably, the southern and central Animas Mountains, Sierra San Luis, and the Guadalupe and southern Peloncillo mountains.

The other major source of recharge in the basin-fill aquifer system is water percolating through thinner parts of the vadose zone beneath the stream channel and floodplain of the system's only major axial drainageway, (upper) Animas Creek. The broad piedmont slopes that separate range fronts from axial drainage ways and alluvial flats are not considered to be significant areas of recharge (Hawley et al., 2000). The water table in these areas is commonly very deep, locally exceeding 150 m; the coalescent fan-piedmont deposits are very poorly sorted and partly indurated (including carbonate and zeolite cements), and the vegetative cover of desert scrub and semiarid-zone grasses is very effective in capturing most of the annual precipitation.

Movement and discharge

The shape of the potentiometric surface (water table) and the general direction of ground-water flow (Fig. 2) clearly indicates that the Animas basin system, while topographically closed, fits the drained basin category illustrated by Figure 3 (Schwennesen, 1918; Reeder, 1957). Ground-water flow is generally northward in the "perched" and "deep" aquifers of the Cloverdale and Upper Animas subbasins north of the United States/Mexico border, and it continues through the Lower Animas aquifer system toward the Lake Animas-Alkali Flat depression (Fig. 2). Ground water also flows to this depression from the southeast through the basin-fill aquifer system of the Lordsburg subbasin.

The potentiometric surface is near the basin floor in only one part of the basin system. This area is in the Lower Animas subbasin about 8 km north of Cotton City. The water table profiles and maps in Reeder (1957) show that the potentiometric surface was 4.5–6 m below the surface in that area between 1948 and 1955. The vadose zone thickens in all direction from that part of the basin floor. The slope of the potentiometric surface from this part of the basin is northward, being progressively deeper under the South and North Alkali Flats, and this slope continues past the Summit Hills into the deeply entrenched Gila River Valley north of the Animas basin system. At depths less than 10 m, some ground water almost certainly discharges within the interior of the basin system by physical evaporation and by consumptive use by phreatophytes. Fine-textured sediments in the basin floor favor capillary rise of water that could, in some locations, almost reach land surface. However, a larger component of discharge is by subsurface interbasin flow to the Gila Valley. Reeder (1957), for example, shows the profile of the 1955 water table and documents a significant steepening of gradient beneath the Gila Valley border a short distance north of the Summit Hills. The predevelopment ground-water-flow model of O'Brien and Stone (1983) produces a discharge estimate of about 1.6×10^7 m^3/yr for ground water discharging to the Gila Valley through one or more zones of thick basin fill and/or rock fractures that bypass the Summit horst block in the Lordsburg Mesa area.

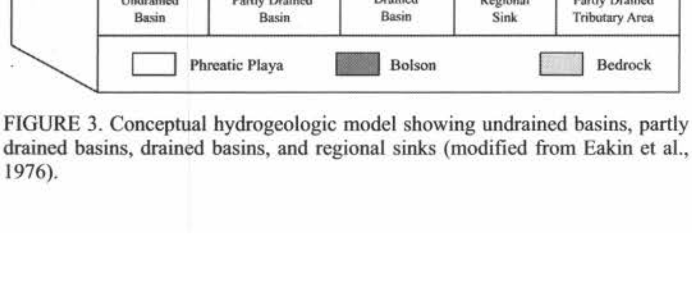

FIGURE 3. Conceptual hydrogeologic model showing undrained basins, partly drained basins, drained basins, and regional sinks (modified from Eakin et al., 1976).

GROUND-WATER QUALITY ASSESSMENT

Scope and data sources

Recognition of the relationships between ground-water quality and position along flowpaths in arid basins provides the basis for performing hydrochemical analysis in the Animas basin system (Mifflin, 1968). Active recharge areas are usually characterized by ground water with fairly low concentrations of dissolved ions, dominantly calcium, magnesium, and bicarbonate. Zones of lateral flow are often characterized by a decrease in the relative concentrations of calcium and magnesium ions and by an increase in sodium (and sometimes potassium) ions by cation exchange. Sulfate and chloride ions often become more important constituents along zones of lateral flow and at discharge areas due to evaporation and dissolution of evaporite minerals (Mifflin, 1968). Thus, considerable insight about aquifer flow regimes and recognition of source rocks are often provided by an assessment of ground-water chemistry at the basin scale. Our goal is therefore to perform an analysis of the ground-water chemistry in the Animas basin system along its full extent, and to use this information to correlate to geologic and hydrogeologic interpretations of flow regimes. Another goal is to assess the potability and irrigation suitability of ground water in the basin system. Water-quality data used in these analyses were collected from the public domain information in the United States and Mexico. These data included STORET data, New Mexico Environmental Department public drinking-water data, U.S. Geological (USGS) ground-water-quality data, and Comision Nacional Del Agua (CNA) ground-water-quality data, contained in Instituto Nacional de Estadistica, Geografia e Informatica (INEGI) water-quality sheets.

General hydrochemistry

Standard hydrochemical constituents are presented graphically as spatial pattern diagrams after the method developed by Stiff (1951). Concentrations of cations are plotted to the left of a vertical axis and anions are plotted to the right of the axis, with all values presented in meq/L. These diagrams allow the determination of "hydrochemical facies" in which the dominant cation/anion pair(s) is shown (e.g., Na-SO_4-Cl facies). Stiff diagrams are placed at the appropriate well location on x-y maps and are coded by total dissolved solids (TDS) concentrations.

The Stiff map indicates that general water quality in the Animas basin system is highly variable (Fig. 4). Ground-water analyses in the Cloverdale subbasin are less than 250 mg/L TDS. Ground waters in the Upper Animas subbasin are similarly dilute, maintaining concentrations

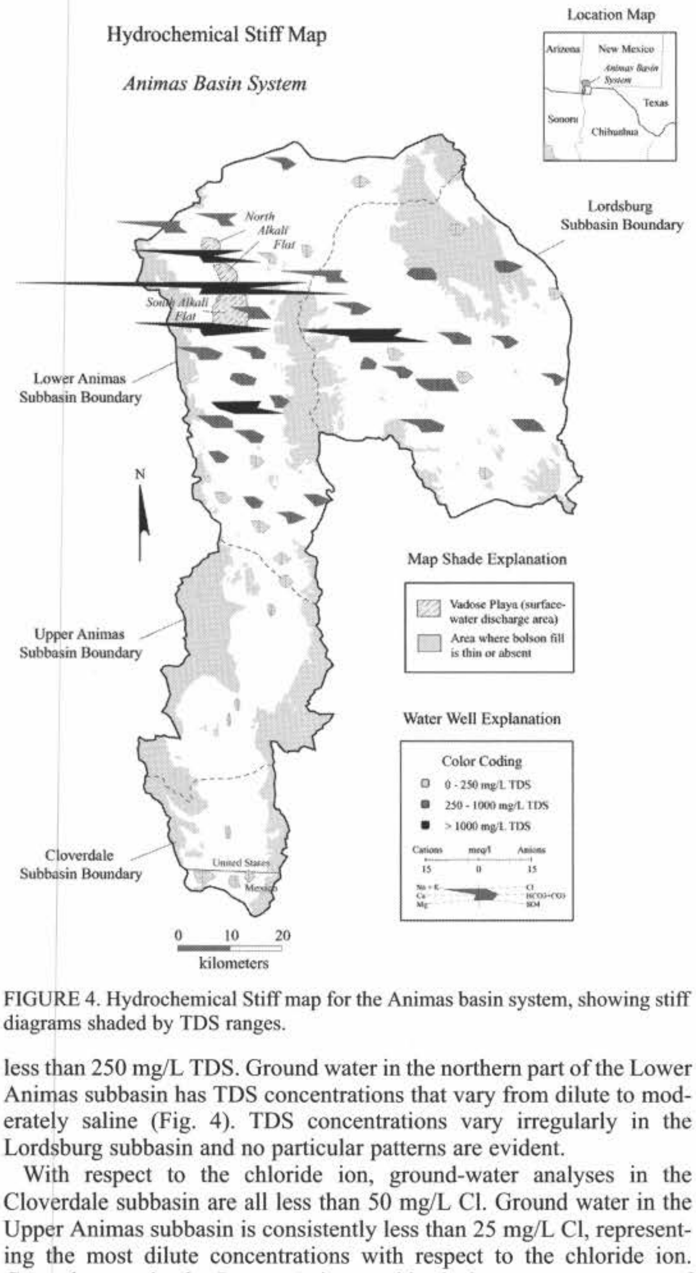

FIGURE 4. Hydrochemical Stiff map for the Animas basin system, showing stiff diagrams shaded by TDS ranges.

less than 250 mg/L TDS. Ground water in the northern part of the Lower Animas subbasin has TDS concentrations that vary from dilute to moderately saline (Fig. 4). TDS concentrations vary irregularly in the Lordsburg subbasin and no particular patterns are evident.

With respect to the chloride ion, ground-water analyses in the Cloverdale subbasin are all less than 50 mg/L Cl. Ground water in the Upper Animas subbasin is consistently less than 25 mg/L Cl, representing the most dilute concentrations with respect to the chloride ion. Ground water in the Lower Animas subbasin has a greater range of chloride concentration, ranging from less than 25 mg/L Cl to greater than 250 mg/L Cl.

Hydrochemical facies in the Cloverdale subbasin are mostly mixed-cation-HCO_3-SO_4 type waters (Fig. 4). The hydrochemical facies in the Animas basin are quite variable, ranging from Ca-HCO_3 type waters in the upper basin that are dilute, to Na-HCO_3 type waters in the middle basin, to Na-Cl-SO_4 waters in the lower basin that have relatively high TDS. The Lordsburg subbasin exhibits even more variability of hydrochemical facies. These include Ca-HCO_3 and Na-HCO_3 type waters that are quite dilute; Na-HCO_3 to Na-HCO_3-SO_4 type waters that have higher TDS; and Na-Cl-SO_4 waters that have the highest concentrations of TDS, sometimes exceeding 1000 mg/L.

Irrigation-water quality

The primary use of ground water in the Animas basin system is irrigated agriculture. O'Brien and Stone (1983) observed that since 1950, the irrigated area (with some shift in location) tends to average from about 4855 to 5665 hectares with ground-water withdrawals averaging about 2.5×10^7 m^3 per year. Almost all of the irrigated-cropland area reported for Hidalgo County of 14,720 hectares is in the Lower Animas subbasin (Hawley et al., 2000). Likewise, most of the irrigated agricultural water use for Hidalgo County of 2.7×10^7 m^3 in 1995 was in this subbasin.

Classification of irrigation-water quality is provided by the classification system of the U.S. Salinity Laboratory (Richards, 1954). This graphical procedure plots sodium absorption ratios (SAR) against specific conductance, and delineates zones that vary from low to very high sodium and salinity hazard. The SAR is defined by equation 1:

$$SAR = \frac{Na}{\sqrt{(Ca + Mg)/2}} \qquad (1)$$

Specific conductance is not available for many of the chemical analyses in the study area. Therefore, specific conductance was estimated by multiplying ground-water TDS by 1.33 (Hem, 1985).

Irrigation-water-quality data in the Animas basin system are grouped into three clusters of data. Data in the Upper Animas subbasin and in the southern half of the Lower Animas subbasin are grouped together as "Animas basin-south" due to the comparable character of irrigation waters in these areas (Fig. 5). Ground-water data in the northern half of the Lower Animas subbasin are identified as "Animas basin-north." Ground-water data in the Lordsburg subbasin are identified as a third distinct cluster of data. Ground-water data in the Cloverdale subbasin are very limited and are not plotted on irrigation water quality plots.

Ground-water samples in Animas basin-south generally have low alkali hazard and medium salinity hazard (Fig. 5). Ground water in Animas basin-north generally varies from low-to-very-high alkali hazard, and from medium-to-very-high salinity hazard. Ground-water samples in the Lordsburg subbasin have mostly low alkali hazard and medium salinity hazard (Fig. 5). A few samples have medium-to-very-high alkali hazard and high-to-very-high salinity hazard in the Lordsburg subbasin. These data indicate that irrigation-water quality is usually good for most varieties of crops in Animas basin-south, fair to poor in Animas basin-north, and good to fair in the Lordsburg subbasin.

Origin of solutes

The Stiff map (Fig. 4) suggests an apparent evolutionary hydrochemical trend as ground-water flows north from the Upper Animas subbasin into the Lower Animas subbasin. To evaluate this hypothesis, the water-quality data are plotted on Piper plots (Piper, 1944). Piper plots express cations as meq/L percentages of total cations on a trilinear diagram. Similarly, anions are plotted by their respective percentages on a separate trilinear diagram. The two points from any specific analysis are then projected onto a central diamond-shaped plot that is parallel to the upper edges of the trilinear diagrams. This method helps to identify hydrochemical mixing trends and evolutionary trends along flowlines.

Ground waters in the Animas Basin system are subdivided into three groups (Fig. 6). Group 1 occupies the Upper Animas subbasin. Downgradient from Group 1, Group 2 occupies the middle and southern portion of the Lower Animas basin. Further downgradient, Group 3 occupies the northern third of the Lower Animas basin above the point where it discharges into the Gila River Valley.

Comparisons of the plots indicates that groundwater evolves from calcium- and bicarbonate-rich water in Group 1, to sodium-, calcium-, bicarbonate-, and sulfate-rich water in Group 2, to sodium-, sulfate-, and chloride-rich water in Group 3. These changes suggest dissolution of calcite in the Upper Animas subbasin (eqn. 2), followed by the exchange of Ca for Na on clay minerals (eqn. 3), and simultaneous dissolution of gypsum (eqn. 4) and influx of dissolved halite from vadose zone profiles (eqn. 5) as ground water moves northward and through the Lower Animas subbasin:

$$CaCO_3 + H_2O + CO_2 = Ca + 2HCO_3 \quad \text{(calcite dissolution)} \qquad (2)$$
$$Na_2\text{-clay} + Ca^{+2} = Ca\text{-clay} + 2Na^+ \quad \text{(cation exchange)} \qquad (3)$$
$$CaSO_4 \cdot 2H_2O = Ca + SO_4 + 2H_2O \quad \text{(gypsum dissolution)} \qquad (4)$$
$$NaCl = Na + Cl \quad \text{(halite dissolution)} \qquad (5)$$

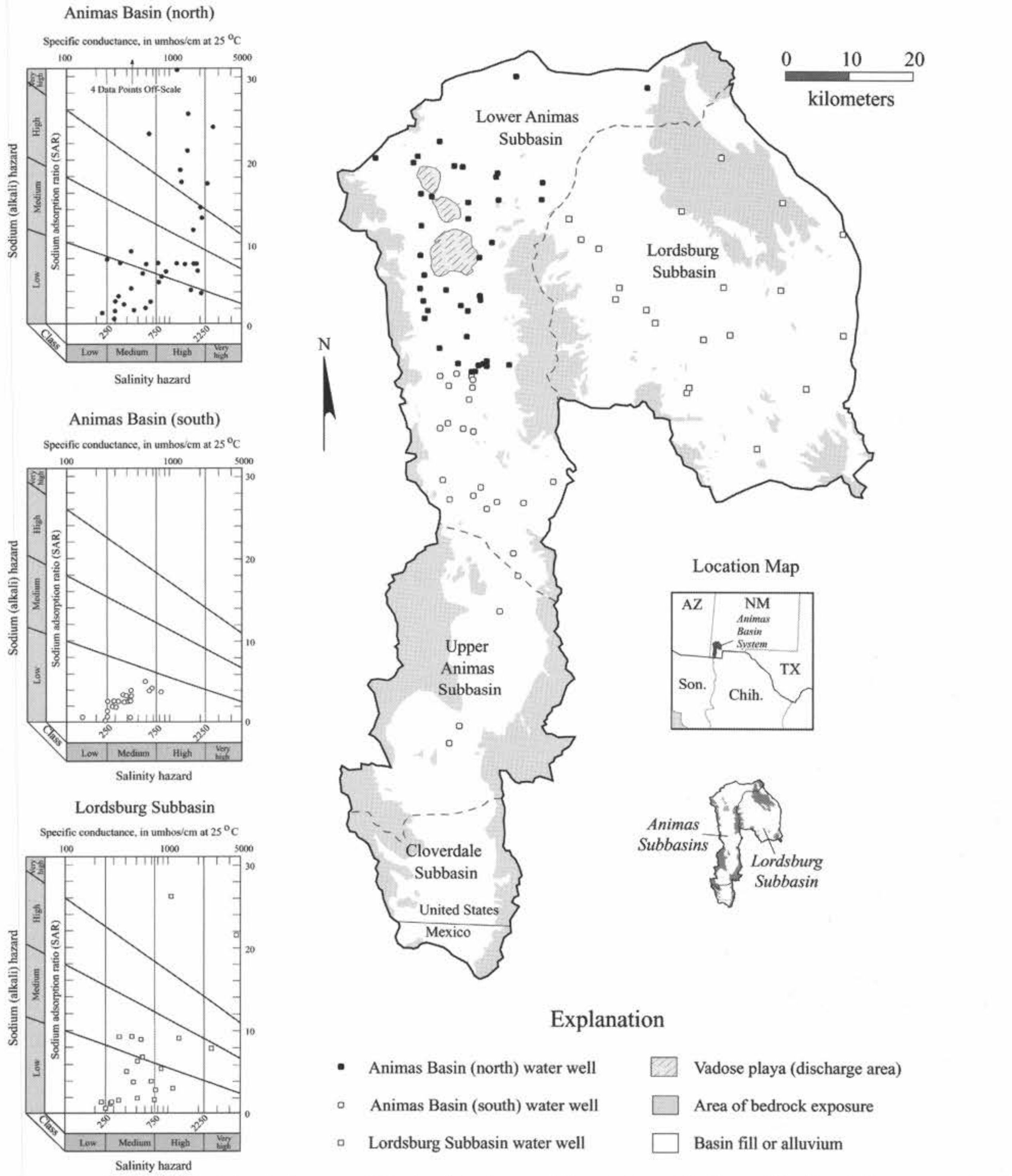

FIGURE 5. Irrigation-water quality plots in the Animas basin system. Well points in the Lower and Upper Animas subbasins are divided into Animas basin-south (circles) and Animas basin-north (dots).

Caliche and calcite cement in basin fill probably account for much of the calcium and bicarbonate in ground waters. Pyroxene, amphibole, feldspar, and other minerals that are less soluble than carbonate rocks and calcite cement are likely sources of smaller amounts of calcium, sodium, and bicarbonate. Clay minerals are important weathering products of these minerals and provide the exchange sites for divalent-monovalent cation exchange.

Gypsum and some halite minerals are present at and near Alkali Flats, which probably accumulated as a result of evaporation of surface water and ground water. Capillary water pulled above the water table by surface tension can be within a few meters of land surface if depth to the water table is shallow (<10 m). There the capillary water can evaporate, leaving behind residual salts that can be redissolved when wetting fronts move downward through the soil profile. Infiltration of runoff along flanking mountain fronts may also dissolve halite in soil profiles and carry salts into the basin fill aquifer.

Saturation indices

Mineral saturation states were computed to determine if a thermodynamic condition exists for dissolution of gypsum, halite, and carbonate

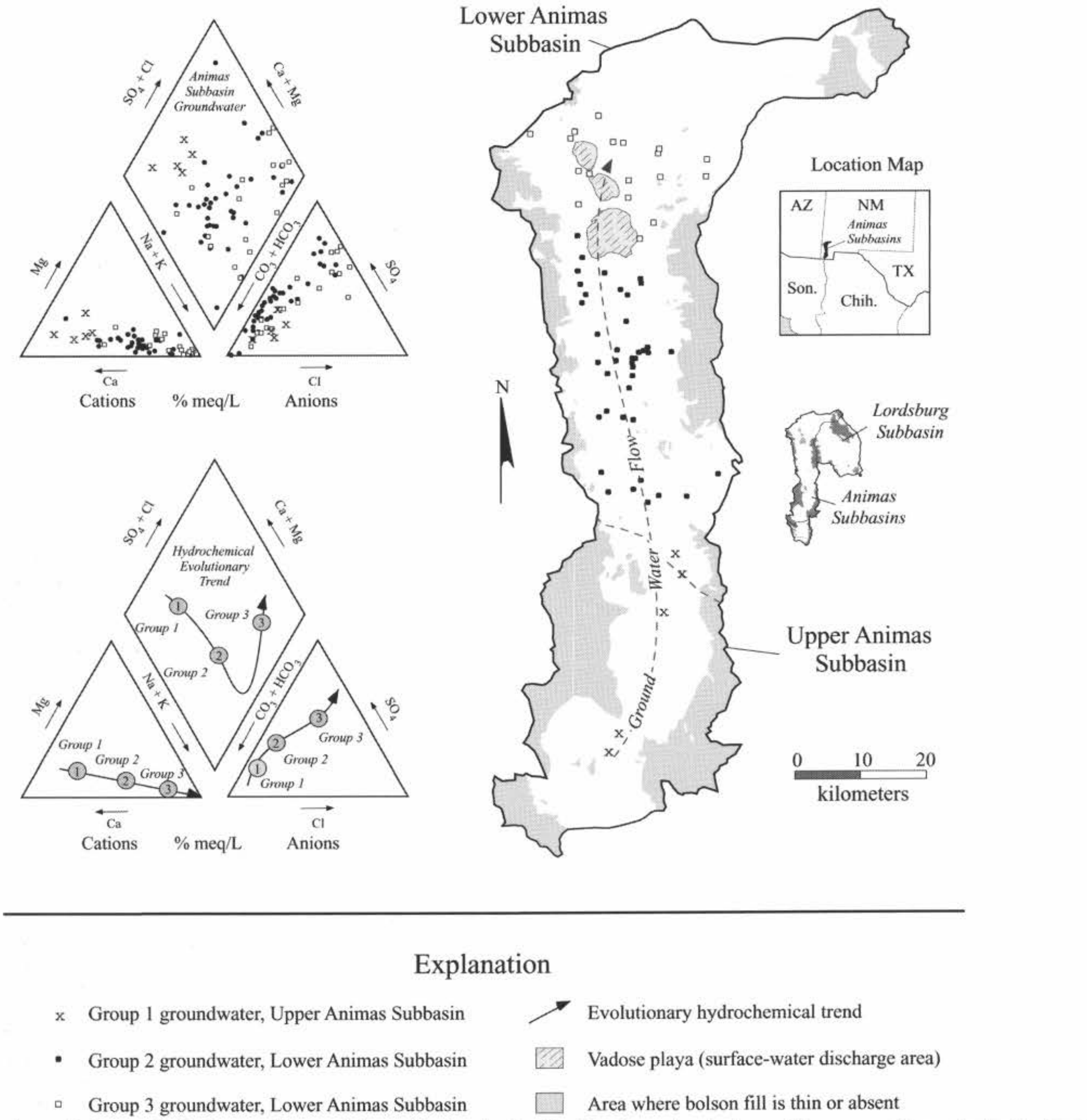

Figure 6. Piper plots and index map for the Upper and Lower Animas subbasins, showing direction of ground-water flow and three groups of groundwater data. Lower Piper plot shows apparent evolutionary trends for the three groups.

rocks and cement in the Animas basin system. The geochemical modeling program PHREEQC (Parkhurst, 1995) was used to compute a saturation index, which represents the degree of equilibrium between water and minerals on the basis of the amount of dissolved ionic species in solution, and the amount that would be present if the water-solute system were at equilibrium between water and minerals at the sample temperature. Equilibrium with respect to a given mineral is indicated by a value of zero. Negative values suggest undersaturation and positive values reflect oversaturation. Saturation indices were computed for 34 ground-water analyses in the Upper and Lower Animas subbasins and for 9 analyses in the Lordsburg subbasin (Fig. 7). The absence of temperature data did not allow us to compute saturation indices for the Cloverdale subbasin.

PHREEQC analyses indicate that ground water is typically at equilibrium with respect to calcite in the Animas and Lordsburg subbasins. Ground water is close to equilibrium with respect to dolomite, although there is a wider range of values for dolomite saturation, especially in the Lordsburg subbasin (Fig. 7). Ground water in the Animas and Lordsburg subbasins is moderately undersaturated with respect to gypsum. Some waters are close to saturation with respect to gypsum in the Animas basin. Ground water in the Animas and Lordsburg subbasins are greatly undersaturated with respect to halite.

DISCUSSION

The previous analysis suggests that several simple reactions and processes control the water chemistry of the Animas basin system:

- Dissolution of carbonate rocks and calcite cement in dilute ground waters.
- Probable dissolution of smaller amounts of pyroxene, amphibole,

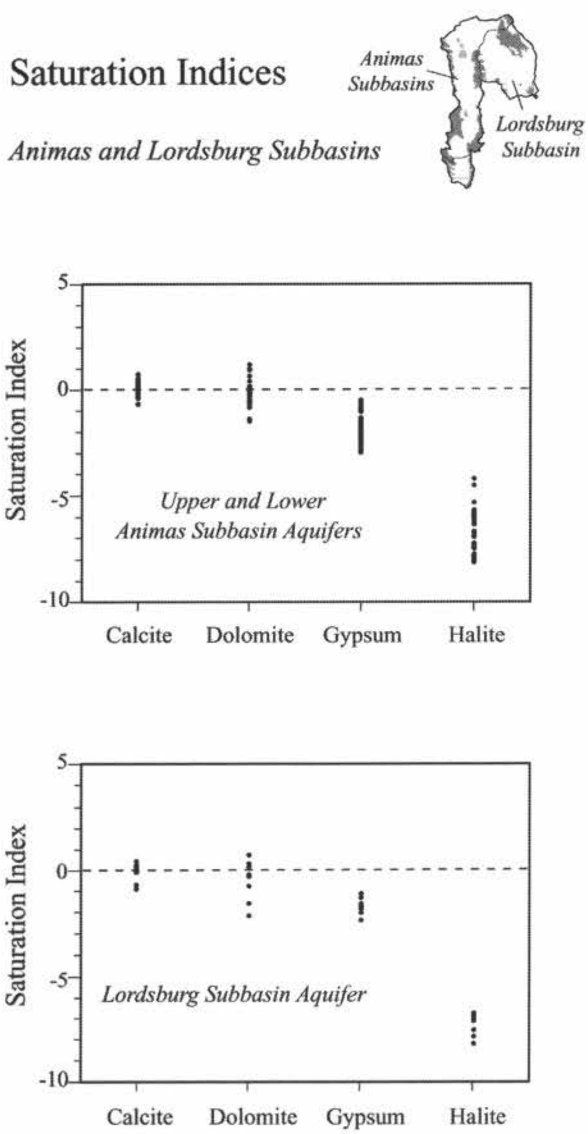

FIGURE 7. Range of saturation indices of calcite, dolomite, gypsum, and halite for the Upper and Lower Animas subbasin aquifers and the Lordsburg subbasin aquifer.

feldspar, and other minerals that are common in volcanic terrains and less soluble than carbonates rocks.

- Dissolution of gypsum, especially near Alkali Flats where ground waters are more saline.
- Dissolution of halite in several parts of the basin, especially near Alkali Flats.
- Cation exchange favoring exchange of Ca for bound Na.

Dissolution of specific minerals is a function of their spatial locations in the basin system. Chloride occurs in rainwater, and precipitates in soils as halite when rainwater evaporates (Hem, 1985; Sami, 1992). The halite can be dissolved by runoff and carried into ground water along arroyos and other recharge areas. Evaporation of surface water, ground water, and soil water by natural discharge and by irrigation recycling further concentrates salts in soils and ground water. Gypsum and halite are present along the basin floor near Alkali Flats, having precipitated near vadose playas where ground water is also very shallow. Gypsum and halite dissolve when meteoric ground waters come into contact with these evaporite minerals. Carbonates are present in the mountains and precipitate as caliche along mountain fronts and at interior locations in the basin.

Dissolution and weathering of these rocks and minerals produce an evolutionary trend from calcium-bicarbonate waters in the southern part of the basin system, to sodium-bicarbonate waters at intermediate locations, to sodium-sulfate-chloride waters at the northern limits of the study area. The modified Chebotarev (1955) sequence is thus exhibited in the basin system:

$$\begin{gathered}\text{Distance along flowpath} \Rightarrow \\ HCO_3 \Rightarrow HCO_3 + SO_4 \Rightarrow SO_4 + HCO_3 \Rightarrow SO_4 + Cl \\ \text{Residence time} \Rightarrow\end{gathered}$$

In this sequence, the first ion in any coupled pair is the dominant chemical species (e.g., HCO_3 is dominant in the couplet, $HCO_3 + SO_4$). While partly a function of longer residence times along flowpaths, the Chebotarev sequence is also a function of contact of ground water with different rock and sediment types. Other rocks, such as volcanic and intrusive igneous rocks that contain pyroxene, amphibole, and feldspars probably contribute smaller amounts of dissolved minerals to ground waters in the basin.

CONCLUSIONS

The findings of this study have important implications for use and development of ground-water resources. The Animas basin system supplies ground water for irrigation and for domestic use by border communities in southwestern New Mexico. Ground water in the southern half of the Animas basin system is usually less than 250 mg/L TDS. Near and extending across Alkali Flats, ground water is usually greater than 500 mg/L TDS, reaching concentrations greater than 1000 mg/L. Analysis of the natural origin of solutes in ground water provides a background for assessing anthropogenic change. Also, recognition of the relationships between ground-water quality and position along flowpaths provides insights about source rocks and characteristics of the aquifer flow regime.

A primary goal of this study was to set upon the task of compiling and organizing the existing information on aquifer properties, aquifer parameters, and chemical quality of the aquifers. In many areas, the data did not allow us to perform more than a reconnaissance-level assessment. The data used to develop the potentiometric surface map (Fig. 2), for example, were composite hydraulic head data, which provided only a 2-dimensional representation of possible 3-dimensional components of flow. Hydrochemical data in time series were also very limited, which did not allow us to evaluate sufficiently any degradation of water quality due to anthropogenic activities.

As an outgrowth of our study, we were able to determine where additional information is needed to refine the conceptual hydrogeologic and hydrochemical models. Of paramount importance is the need to collect more data on geologic units, aquifer compartmentalization, ground-water flow and recharge, and spatial and temporal distribution of hydrochemical facies. A more refined understanding of the aquifers in the basin system will be accommodated by (1) better definition of bedrock-boundary and internal-basin structure; (2) understanding the textural character and geometry of various basin-fill and valley-fill units better; (3) measurement of aquifer properties and hydraulic head at-depth dependent intervals; (4) synthesis and collection of hydrochemical/isotopic information from multi-level monitoring wells; and (5) correlation to borehole and surface geophysical data. The conceptual ground-water flow models refined from these additional data will form the basis for improved, basin-scale and three-dimensional numerical ground-water flow and management models. These models will help to identify other critical data needs and will assist planning efforts.

ACKNOWLEDGMENTS

This project was supported jointly by the U.S. Environmental Protection Agency and the New Mexico Water Resources Research Institute. The views and conclusions in this article are those of the authors and should not be interpreted as representing the official policies and views of the New Mexico State or U.S. Governments. We also wish to thank Rip Langford and Radu Boghici for critical review, suggestions, and improvement of the manuscript.

REFERENCES

Chebotarev, I. I., 1955, Metamorphism of natural waters in the crust of weathering: Geochimica et Cosmochimica Acta, v. 8, p. 22–48, 137–170, 198–212.

Eakin, T. E., Price, D. and Harrill, J. R., 1976, Summary appraisals of the nation's ground-water resources; Great Basin Region: U.S. Geological Survey, Professional Paper 813-G, 37 p.

Hawley, J. F., Hibbs, B. J., Kennedy, J. F., Creel, B., Johnson, M., Remmenga, M., Lee, M. and Dinterman, P., 2000, Trans-international boundary aquifers in southwestern New Mexico: New Mexico Water Resources Research Institute, New Mexico State University, and California State University, Los Angeles; NMWRRI Technical Completion Report, contract no. X-996350-01-3, prepared for the U.S. Environmental Protection Agency, 126 p.

Hem, J. D., 1985, Study and interpretation of the chemical characteristics of natural waters: U.S. Geological Survey Water-supply Paper 2254, 263 p.

Hibbs, B. J., Boghici, R. N., Hayes, M. E., Ashworth, J. B., Hanson, A. T., Samani, Z. A., Kennedy, J. F. and Creel, B. J., 1997, Transboundary aquifers of the El Paso/Ciudad Juarez/Las Cruces region: Texas Water Development Board and New Mexico Water Resources Research Institute; TWDB and NMWRRI Technical Completion Report, contract no. X-996343-01-0 and X-996350-01-0, prepared for the U.S. Environmental Protection Agency, 148 p.

Hibbs, B., Boghici, R., Ashworth, J., Hayes, M., Peckham, D., Guillen, R., Fuentes, O., Laloth, N., Morales, M., Maldonado, A., Creel, B., Kennedy, J., Hanson, A., Samani, Z., Nunez, F., Lemus, R., Moreno, G., Rascon, E., Kuo, R., Waggoner, S., Ito, C., Robinson, J., Valdez, J., Little, D., Rascon, A., Reyes, A., Williams, K., Vaughan, M., Cabra, O., Kelly, T. and King, C., 1998, Transboundary aquifers and binational ground-water data base, City of El Paso/Ciudad Juarez area; Base de datos binacional del acuifero transfronterizo, de Cd. Juarez, Chih./El Paso, Tex.: first binational aquifer report and data base sanctioned by the governments of the United States and Mexico, 47 p. + appendices and CD-ROM. Participating agencies; International Boundary and Water Commission, U.S. Environmental Protection Agency, Texas Water Development Board, New Mexico Water Resources Research Institute, Comision Internacional de Limites y Aguas, Comision Nacional del Agua, Junta Municipal de Agua y Saneamiento de Ciudad Juarez.

Kernodle, J. M., 1992, Summary of U.S. Geological Survey ground-water flow models of basin-fill aquifers in the southwestern alluvial basins region, Colorado, New Mexico, and Texas: U.S. Geological Survey, Open-File Report 90-361, 81 p.

McCraw, D. J., 1985, A phytogeographic history of Larrea in southwestern New Mexico illustrating the expansion of the Chihuahuan Desert [M.A. thesis]: Albuquerque, University of New Mexico, 137 p.

Mifflin, M. D., 1968, Delineation of ground-water flow systems in Nevada: Desert Research Institute, Technical Report Series H-W, no. 4, 111 p.

O'Brien, K. M. and Stone, W. J., 1983, A two-dimensional hydrologic model of the Animas Valley, Hidalgo County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Report 133, 60 p.

Parkhurst, D. L., 1995, User's guide to PHREEQC, a computer program for speciation, reaction-path, advective transport, and inverse geochemical calculations: U.S. Geological Survey, Water-resources Investigations Report 95-4227, 143 p.

Piper, A. M., 1944, A graphic procedure in the geochemical interpretation of water analyses: Transactions of the American Geophysical Union, v. 25, p. 914–923.

Reeder, H. O., 1957, Ground water in Animas Valley, Hidalgo County, New Mexico: New Mexico State Engineer, Technical Report 11, 101 p.

Richards, L. A. (ed.), 1954, Diagnosis and improvement of saline and alkaline soils: U.S. Department of Agriculture, Agricultural Handbook 60, 160 p.

Sami, K., 1992, Recharge mechanisms and geochemical processes in a semi-arid sedimentary basin, Eastern Cape, South Africa: Journal of Hydrology, v. 139, p. 27–48.

Schwennesen, A. T., 1918, Ground water in the Animas Playas, Hachita, and San Luis basins, New Mexico, with analyses of water and soil by R.F. Hare: U.S. Geological Survey, Water-supply Paper 422, 152 p.

Stiff, H. A., Jr., 1951, The interpretation of chemical water analysis by means of patterns: Journal of Petroleum Technology, v. 3, no. 10, p. 15–17.

Trauger, F. D. and Doty, G. C., 1965, Ground water, its occurrence and relation to the economy and geology of southwestern New Mexico: New Mexico Geological Society, Guidebook 16, p. 215–227.