ground water

Revisiting a Classification Scheme for U.S.-Mexico Alluvial Basin-Fill Aquifers

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Abstract

Intermontane basins in the Trans-Pecos region of westernmost Texas and northern Chihuahua, Mexico, are target areas for disposal of interstate municipal sludge and have been identified as possible disposal sites for low-level radioactive waste. Understanding ground water movement within and between these basins is needed to assess potential contaminant fate and movement. Four associated basin aquifers are evaluated and classified; the Red Light Draw Aquifer, the Northwest Eagle Flat Aquifer, the Southeast Eagle Flat Aquifer, and the El Cuervo Aquifer. Encompassed on all but one side by mountains and local divides, the Red Light Draw Aquifer has the Rio Grande as an outlet for both surface drainage and ground water discharge. The river juxtaposed against its southern edge, the basin is classified as a topographically open, through-flowing basin. The Northwest Eagle Flat Aquifer is classified as a topographically closed and drained basin because surface drainage is to the interior of the basin and ground water discharge occurs by interbasin ground water flow. Mountains and ground water divides encompass this basin aquifer on all sides; yet, depth to ground water in the interior of the basin is commonly >500 feet. Negligible ground water discharge within the basin indicates that ground water discharges from the basin by vertical flow and underflow to a surrounding basin or basins. The most likely mode of discharge is by vertical, cross-formational flow to underlying Permian rocks that are more porous and permeable and subsequent flow along regional flowpaths beneath local ground water divides. The Southeast Eagle Flat Aquifer is classified as a topographically open and drained basin because surface drainage and ground water discharge are to the adjacent Wildhorse Flat area. Opposite the Eagle Flat and Red Light Draw aquifers is the El Cuervo Aquifer of northern Chihuahua, Mexico. The El Cuervo Aquifer has interior drainage to Laguna El Cuervo, which is a phreatic playa that also serves as a focal point of ground water discharge. Our evidence suggests that El Cuervo Aquifer may lose a smaller portion of its discharge by interbasin ground water flow to Indian Hot Springs, near the Rio Grande. Thus, El Cuervo Aquifer is a topographically closed basin that is either partially drained if a component of its ground water discharge reaches Indian Hot Springs or undrained if all its natural ground water discharge is to Laguna El Cuervo.

Introduction

Study Area and Problem Statement

The study area is ~100 miles east of El Paso, Texas (Figure 1), and is part of the southernmost extension of the North American Basin-and-Range physiographic province. The topography of the study area is dominated by long, narrow mountain ranges, intermontane basins (flats and draws), and gently sloping plateaus. Structural development of the region began ~24 million years before present and continues as sporadic Quaternary faulting today (Henry and Price 1985). The climate of the study area is subtropical arid and is characterized by limited precipitation, low humidity, and large and frequent changes in temperature. Summer precipitation occurs as local and scattered summer showers, with moisture originating primarily in the Gulf of Mexico. Winter rainfall is associated with widespread Pacific frontal systems. Mean annual precipitation is ~12 inches. The entire study area is sparsely populated, with only a few small towns and

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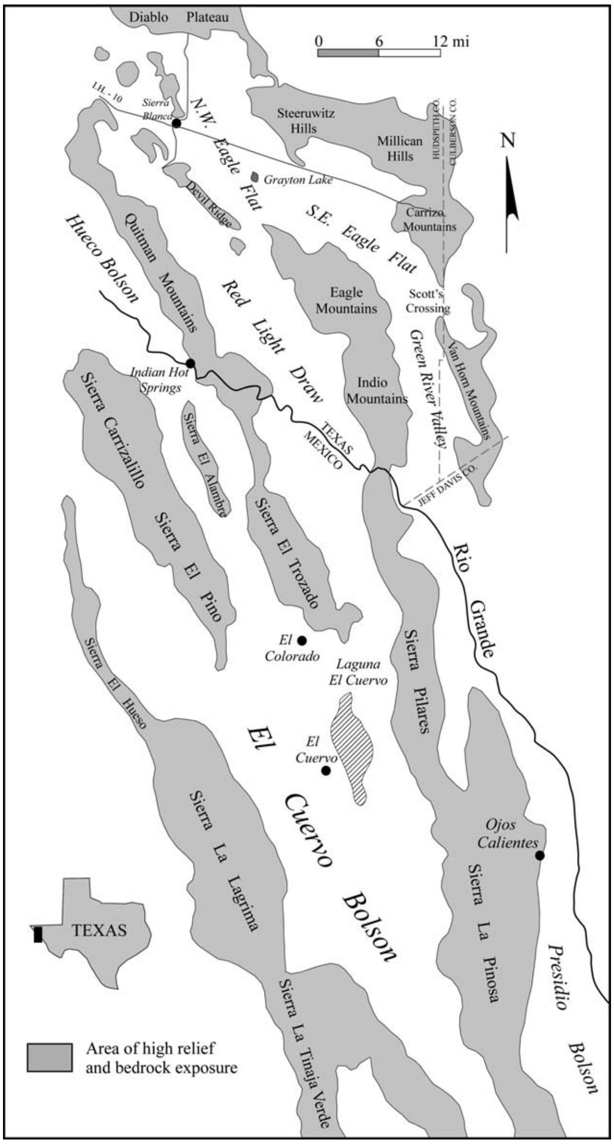

Figure 1. Location of the study area and principal basins in the region.

hamlets and mostly large ranches. A small number of wells satisfy the needs of the local population and livestock. A few springs issue from bedrock formations in the mountains and from basin fill and augment livestock water supplies.

Four basin-fill aquifers are located in the study region: the Red Light Draw, Northwest Eagle Flat, and Southeast Eagle Flat aquifers of Trans-Pecos, Texas; and the El Cuervo Aquifer of northern Chihuahua, Mexico (Figure 1). Low-lying areas of Northwest Eagle Flat have been targeted for disposal of municipal sludge and have been identified as possible repositories for disposal of low-level radioactive waste. Red Light Draw and Southeast Eagle Flat may be hydraulically connected to Northwest Eagle Flat, enhancing the potential for contamination of these other aquifers due to interbasin flow from Northwest Eagle Flat. Some analysts believe there is little chance for contamination of the Northwest Eagle Flat Aquifer directly beneath the basin floor because most recharge occurs at mountain fronts, thus minimizing the potential for contamination of hydraulically connected proximal aquifers by interbasin flow (Darling et al. 1994). Even so, it is important to recognize that the study region has some seismic activity. Faulting could create contamination conduits between land surface and the saturated zone, although such a scenario might be unlikely. This region is also known for strong and prolonged winds and Aeolian deposition. Heavy metals and other contaminants from municipal sludge could be picked up by strong winds and blown to recharge areas at the mountains. Here, the contaminants could be picked up by surface runoff and carried into the saturated zone.

Recent concerns about environmental pollution along the U.S.-Mexico border places a heavy emphasis on issues of potential transboundary ground water flow. Many basin-fill aquifers of this region are complex, three-dimensional ground water flow systems. The sometimes circuitous and irregular patterns of ground water flow, interbasin flow relationships, and regional ground water movement to the Rio Grande underscore a need to understand flow relationships between aquifers before toxic and radioactive wastes are disposed. Many of these aquifers have very deep ground water levels (e.g., 300 to 800 feet), and fluid potential data are only available in the upper part of the saturated zone. This presents an impediment to hydrogeologic interpretations. Despite these limitations, it is often possible to develop reasonable conceptual models of ground water flow and to draw conclusions based on a comprehensive evaluation of multiple types of information, including hydraulic head data, temperature measurements, geochemical and isotopic data, and presence or absence of phreatic or vadose playas. A methodology based on flow systems analysis (Snyder 1962; Maxey 1968; Mifflin 1968, 1988; Winograd and Thordarson 1975; Eakin et al. 1976) is summarized.

Interbasin Relationships and Aquifer Classification

Understanding surface water and ground water movement within and between basins is needed to assess the potential for internal and cross contamination. The terms *closed basin* and *open basin* should refer to surface drainage, whereas the terms *undrained*, *partly drained*, and *drained basins* should be used to refer to intrabasin or interbasin ground water discharge (Snyder 1962; Maxey 1968; Mifflin 1968, 1988; Winograd and Thordarson 1975; Eakin et al. 1976). Such a classification scheme avoids confusion between surface water and ground water movement.

To distinguish between open and closed basins, and drained and undrained basins, it is necessary to define interior types of playas that act as surface water and ground water discharge areas. Playas include (1) phreatic or wet playas and (2) vadose or dry playas. Phreatic playas are ground water discharge areas that are moist near the playa surface (Snyder 1962; Mifflin 1988). Vadose playas are often dry because depth to ground water is too deep for capillary water to reach land surface. Vadose playas are filled periodically with water from surface drainage but not from ground water flow.

On the basis of the presence or absence of these respective types of playas, basins can be classified as (1) topographically closed and undrained basins; (2)

topographically closed and partly drained basins; (3) topographically open or closed drained basins; and (4) topographically open, through-flowing basins (Mifflin 1988) (Figure 2). Topographically closed and undrained basins have interior ground water discharge in the vicinity of a phreatic playa (Figure 2). The phreatic playa also serves as the focal point of surface drainage. Topographically closed and partly drained basins have some ground water discharge to the phreatic playa where surface runoff also collects but some ground water discharges through permeable rock to another basin (Figure 2). A drained basin may be either topographically open or closed and surface discharge is either to an interior vadose playa or to an adjacent basin; however, all its natural ground water discharge is by subsurface interbasin flow through permeable rock (Figure 2). In topographically open and through-flowing basins, surface drainage and ground water discharge are focused at a perennial stream that carries base flow and runoff out of the basin (Figure 2). A through-flowing basin may also be a regional sink for drained and partly drained basins (Mifflin 1988).

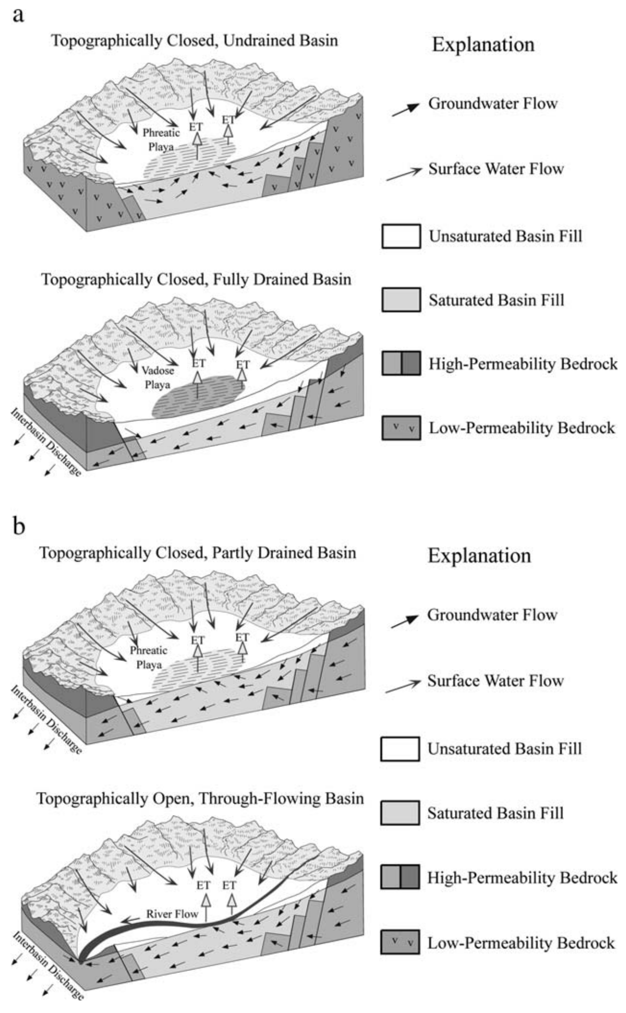

Figure 2. (a) Conceptual hydrogeologic models showing topographically closed and undrained basin and topographically closed and fully drained basin (topographically closed and undrained basin modified from Anderson et al. 1988). (b) Conceptual hydrogeologic models showing topographically closed and partly drained basin and topographically open, through-flowing basin.

Flow Systems Analysis

In drained and partly drained basins, ground water discharges from the basin by subsurface interbasin flow along regional flowpaths (Figure 2). An understanding of basin characteristics and ground water chemistry and temperature helps to define regional vs. local ground water flow systems and therefore if a basin may be drained or partly drained. Local flow systems typically have relatively cool ground water temperatures, low total dissolved solids (TDS), relatively short flowpaths, and boundary controls on ground water flow affected by variations in local lithologies, tectonic features, and topography (Maxey 1968). Regional flow systems are noted for warmer ground water temperatures and generally high TDS, large drainage areas often encompassing two or more topographic basins, and longer flowpaths that are often identified by mature hydrochemical facies (Maxey 1968). While mineralogical assemblages within arid basins are very important for understanding hydrochemical facies and salinity, the occurrence of mature hydrochemical facies (Na-Cl and Na-SO_4-Cl) along regional flowpaths may also result from extended ground water residence time that often leads to water/rock interactions with a variety of different lithologic materials, and precipitation reactions and ion exchange processes that deplete less evolved hydrochemical facies (Ca-HCO_3 and Na-HCO_3) (Chebotarev 1955; Mifflin 1988).

Depth to ground water is an important consideration because an undeveloped basin in an arid region must be drained if the basin has no interior phreatic playa and if depth to ground water is too great to allow discharge by evaporation (e.g., >100 feet). This is true even if the basin aquifer is encompassed on all sides by mountain ranges and local ground water divides. Regional flow systems may carry ground water out of the basin underneath local ground water divides if relatively transmissive strata exist at depth (Mifflin 1988). A regional hydraulic head gradient between the discharging and receiving basin is another condition required. For example, regional flowpaths moving underneath local ground water divides have been documented in the Great Basin (Maxey 1968; Mifflin 1968, 1988; Winograd and Thordarson 1975; Eakin et al. 1976). Numerical models have also simulated movement of regional flowpaths underneath local ground water divides when deeper strata are more permeable than shallow strata (Freeze and Witherspoon 1967).

The availability of very limited and relatively shallow hydraulic head data often provides a two-dimensional representation of the potentiometric surface of arid basins. Ground water may actually flow to depths of thousands of feet beneath land surface before merging along regional flowpaths. The hydrogeologic interpreter is often at risk of misinterpreting basin hydrogeology when relying too much on shallow, two-dimensional hydraulic head data. Flow systems analysis is a method to help avoid inaccurate interpretations.

Flow systems analysis has allowed us to classify a variety of aquifers in the Trans-Pecos and northern Chihuahua region. Classification of the aquifers is provided by an assessment of ground water chemistry, ground water temperature, surface water and ground water relationships within and between basins, and presence or absence of phreatic and vadose playas.

Methods

Methods used to characterize the flow systems included (1) measuring water levels in wells and topographic and geomorphic analysis and (2) acquiring and interpreting water quality and isotopic data.

Water Level Measurements

Composite potentiometric surface maps were made on the basis of water level measurements from all hydrostratigraphic units. There are insufficient data to separately map the regional potentiometric surfaces of each distinct hydrostratigraphic unit or even of separate bedrock and basin-fill aquifer units. Water level measurements made during this study were also supplemented by data from White et al. (1980). Combining historical water level measurements with recent measurements was considered to be acceptable because of the very limited pumping in the area, except for livestock and domestic use at ranch houses. Some old water level measurements could not be repeated because the wells had been destroyed or were inaccessible. In areas where water level measurements were completed and compared to data in White et al. (1980), very little change in the potentiometric surface was observed, usually <3 or 4 feet. An electric probe was used to measure the depth to water relative to the measuring point, usually the top of well casing. Land surface elevations were established by reference to USGS topographic maps and were accurate to ±5 feet. This was considered to be acceptable for regional potentiometric surface mapping.

Water Sampling for Chemical and Isotopical Analyses

Water samples were collected for analysis of radioisotopes, stable isotopes, halides, standard inorganic constituents, and index parameters. Wells were pumped until pH and temperature stabilized. Measurements of pH and temperature were made in flow cells, with electrodes calibrated with buffer solutions that had been equilibrated to sample temperature (Wood 1976). Alkalinity was determined by acid titration of filtered samples to a pH of 3.5 to 3.0. Samples for ionic analysis were filtered through a 0.45-µm in-line filter and collected in separate 500-mL polyethylene bottles. Samples for cation analyses were treated with nitric acid.

Water to be analyzed for tritium (^3H) was filtered through 0.45-µm cartridge filters and sealed in sample bottles without other treatment. Samples collected for analysis of ^3H were stored in 1-L glass bottles. Tritium was determined at the University of Miami Tritium Laboratory on electrolytically enriched water samples by low-level proportional counting; results are reported as tritium units (TU; 1 TU is 1 ^3H atom/10^{18} H atoms), with a typical error of ±0.1 TU. Dissolved inorganic carbon for ^{14}C and $\delta^{13}C$ analysis was collected by direct precipitation using a 30% ammonium hydroxide solution saturated with $SrCl_2$ (Hassan 1982). The $SrCO_3$ slurry was decanted from carboys and later filtered and washed in the laboratory with negligible exposure to the atmosphere. The $SrCO_3$ powder was analyzed by liquid scintillation counting for ^{14}C and mass spectrometry for $\delta^{13}C$ at Beta Analytic Inc., Miami, Florida. ^{14}C is reported as uncorrected percent modern carbon (pmc) activity and $\delta^{13}C$ relative to Peedee belemnite. Samples for analysis of stable isotopes ($\delta^{18}O$ and δ^2H) were collected in 1-L, tightly sealed, high-density polyethylene bottles. Analysis of stable isotopes was performed at the University of Arizona Isotope Geochemistry Laboratory. The δ values are reported relative to standard mean ocean water.

Chemical analyses for cations and silica were performed at the Mineral Studies Laboratory of the Bureau of Economic Geology, the University of Texas at Austin, using inductively coupled plasma-optical emission spectrometry. Chloride, fluoride, sulfate, and nitrate were measured by ion chromatography, and bromide was determined by spectrophotometry. Other published data were used in this analysis (Henry 1979; Fisher and Mullican 1990). These data were collected and analyzed using the same or comparable procedures and laboratories.

Topographically Open, Through-Flowing Basin: Red Light Draw Aquifer

Physiography and Water-Bearing Strata

Red Light Draw is encompassed by the Eagle Mountains and Devil Ridge to the north, the Quitman Mountains to the west, the Indio Mountains to the east, and the Rio Grande to the south (Figure 1). The Eagle Mountains stand at an elevation of 7500 feet above mean sea level (msl), >3000 feet above the floor of Red Light Draw. The floor of Red Light Draw slopes toward the southeast, decreasing over a distance of 30 miles from 4500 feet above msl in the northern reaches of the basin to ~3200 feet above msl along the Rio Grande.

Shallow water-bearing rocks in the Eagle Mountains consist mostly of Tertiary intrusive and extrusive rocks and Cretaceous carbonate and clastic rocks. Some minor Permian carbonate rocks and Precambrian metamorphic rocks are exposed on the Eagle Mountains. Devil Ridge consists mostly of Cretaceous carbonate and clastic rocks. The northern Quitman Range consists of Tertiary volcanic rocks, and the southern Quitman Mountains consist mostly of Cretaceous carbonate and clastic rocks with minor Tertiary volcanics. The Indio Mountains consist of carbonate and clastic rocks of Cretaceous age.

Basin-fill material is Tertiary and Quaternary alluvium, with some mixed volcaniclastic rocks intercalated with the lower basin fill. Basin-fill thickness increases to the south along the draw, from ~500 feet in the northwestern part of the basin to as much as 3500 feet in the southeastern half of the basin. Relatively coarse-textured deposits are found at shallow depths in the upper and middle portions of the Red Light Draw Basin. Along the Rio Grande, the basin fill is often fine textured, commonly of the playa-lacustrine variety.

The Red Light Draw Basin is drained along the axis of the basin, where the draw merges with the Rio Grande floodplain. Surface runoff drains from the highlands to the axis of the basin and eventually to low-lying areas near the Rio Grande.

Major Ion Chemistry and Water Temperature

Wells in the Red Light Draw Aquifer yield water that is an Na-HCO_3 to Na-HCO_3-SO_4 type, with TDS and SO_4 increasing toward the south. Dissolved solids increase from 600 to 800 mg/L in the upper part of the draw to 1200 mg/L in the lower part of the draw. Ground water temperatures are generally between 75°F and 91°F, with most temperatures clustered between 75°F and 82°F.

Recharge Areas, Ground Water Flowpaths, and Discharge Areas

Environmental isotope data suggest that precipitation recharge to the Red Light Draw Aquifer occurs primarily within the upper mountains and to a much lesser extent across the broad alluvial fans. Tritium activities decrease from 0 to 1.3 TU in shallow wells in the upper alluvial fans to background levels in the medial and distal fans, and ^{14}C activities decrease from 50 to <15 pmc (Figures 3 through 5). These sharply lower values appear to indicate a lack of precipitation recharge across alluvial fans, countering the view that runoff from mountain surfaces replenish aquifers in the region by infiltration and recharge at the fans. Old water at the alluvial fans may possibly be attributed to substantial loss of runoff by evapotranspiration and to the influence of widespread, well-developed calcic soils within the basin. These soils form horizons that develop over periods of thousands of years, ranging in thickness from a few inches to as much as 3 feet. The calcic horizons form strata with small vertical permeabilities that may establish barriers to infiltration while providing surfaces for runoff whenever rainfall is heavy enough to generate overland flow.

Ground water is recharged mainly in the Eagle and Quitman mountains and then flows outward beneath the valley floor of Red Light Draw. Flow occurs in both basin fill and fractured bedrock, depending on the thickness of the former. The Rio Grande is the discharge area for ground water in the Red Light Draw Aquifer (Figure 6). In the northern and central areas of Red Light Draw, the depth to ground water ranges from 200 to 500 feet. Within 2 miles north of the Rio Grande, ground water discharges to the surface from wells and springs under artesian conditions.

Aquifer Classification

The Red Light Draw Aquifer is classified as a topographically open and through-flowing basin (Figure 2). Local flow cells that develop on recharge zones in the mountains and mountain fronts converge along the axis of the basin and become part of an intermediate flowpath that moves down the axis of Red Light Draw (Figure 6). The axial flowpath discharges at areas near the Rio Grande. The Rio Grande is the sink for ground water discharge and surface water drainage, thus designating the Red Light Draw Aquifer as topographically open and through flowing.

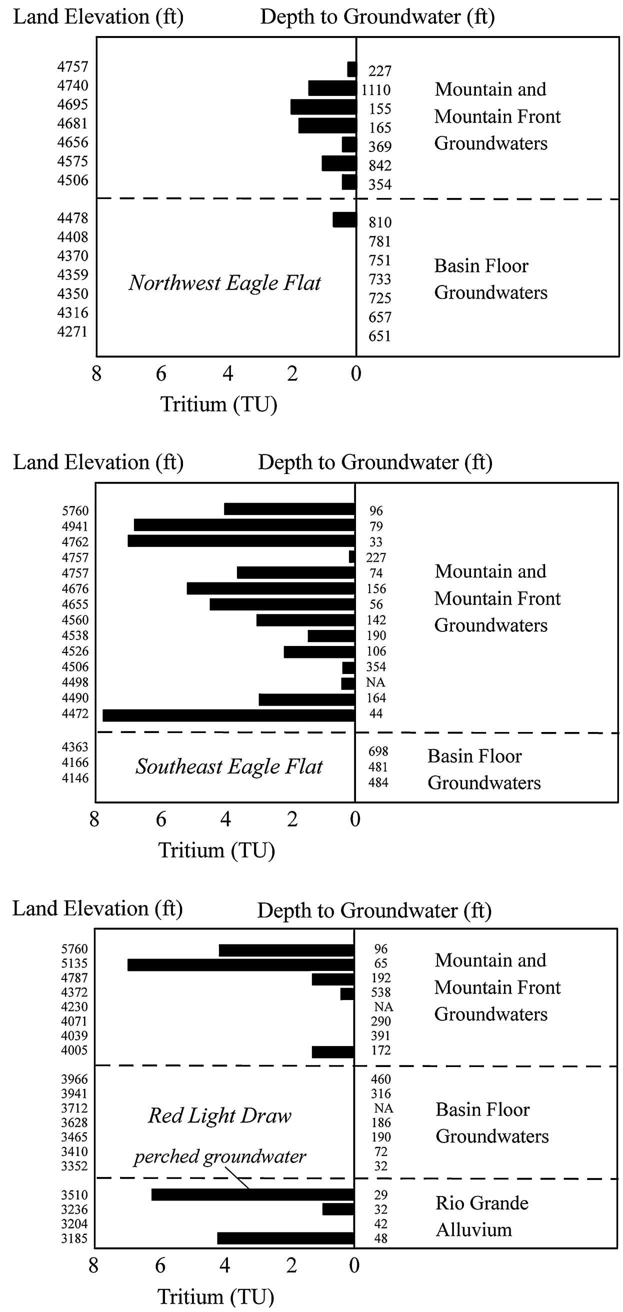

Figure 3. Tritium values (TU) in highland (mountains and mountain fronts) and lowland (basin floor) aquifers in Northwest Eagle Flat, Southeast Eagle Flat, and Red Light Draw. Also shown are surface elevations and depth to ground water. Tritium values indicate that mountains and mountain fronts and areas near the Rio Grande (recent alluvium) are active areas of recharge.

Topographically Open and Closed Drained Basins: Northwest and Southeast Eagle Flat Aquifers

Physiography and Water-Bearing Strata

The Northwest Eagle Flat Basin is surrounded by the Diablo Plateau and Steeruwitz Hills to the north, by Devil Ridge and the Eagle Mountains to the south, and by

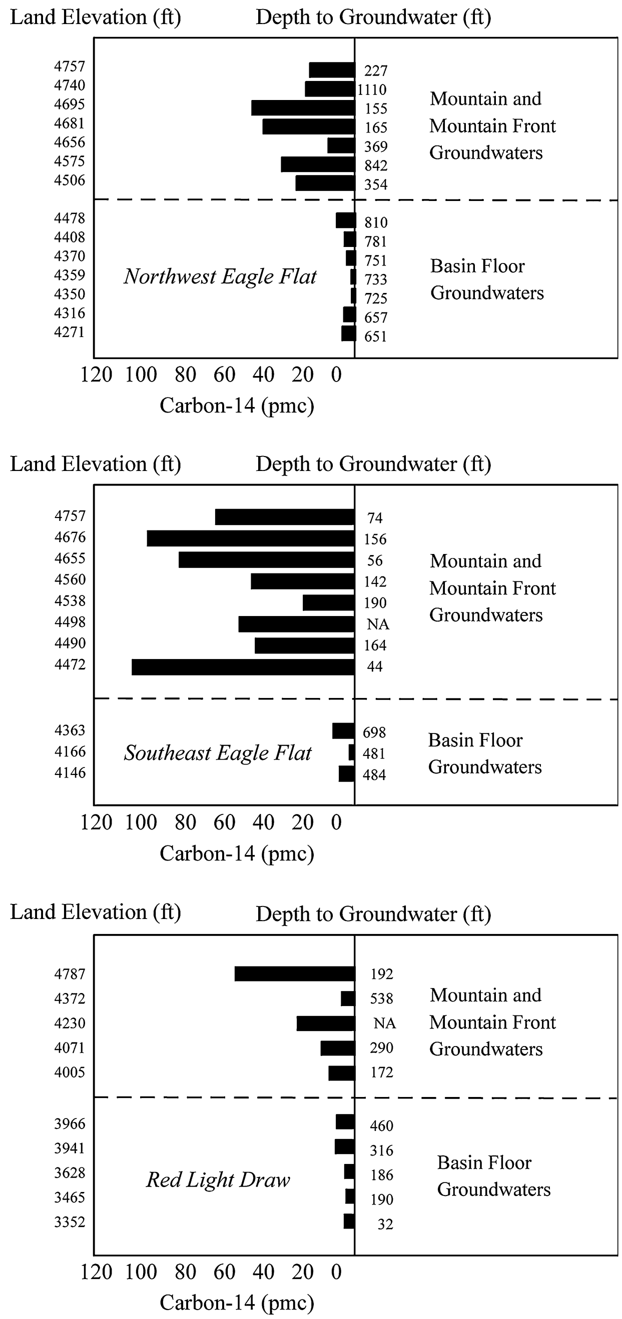

Figure 4. Percentages of modern carbon in highland (mountains and mountain fronts) and lowland (basin floor) aquifers in Northwest Eagle Flat, Southeast Eagle Flat, and Red Light Draw. Also shown are surface elevations and depth to ground water. Percentages of modern carbon suggest that ground water is quite old in flats and draws.

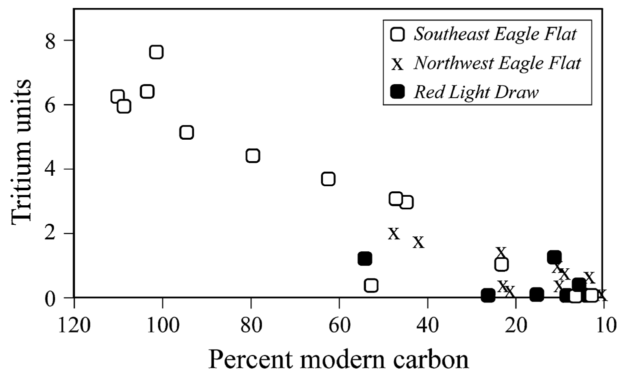

Figure 5. Plot of ^{3}H vs. ^{14}C couplets for water wells in the Southeast Eagle Flat, Northwest Eagle Flat, and Red Light Draw aquifers. The downward sloping trend for Southeast Eagle Flat and Northwest Eagle Flat aquifers indicates mixing between recent recharge water and older ground water.

Southeast Eagle Flat to the east (Figure 1). The floor of Northwest Eagle Flat slopes toward Grayton Lake, a vadose playa that receives surface runoff within the basin. The Southeast Eagle Flat Basin is surrounded by the Millican Hills to the north, the Carrizo Mountains to the east, and the Eagle Mountains and Green River Valley to the south. The floor of Southeast Eagle Flat slopes toward Scott's Crossing where surface drainage moves into the adjacent Wildhorse Flat area.

Water wells in the southern part of the Diablo Plateau derive water mostly from Cretaceous carbonate and clastic rocks. These Cretaceous rocks are underlain by Permian rocks that are highly prolific where they are exposed in the northern Diablo Plateau. Shallow water-bearing rocks in the Millican Hills and Carrizo Mountains consist mostly of Precambrian metamorphic rocks. Basin-fill thickness varies from ~200 to 500 feet in Northwest Eagle Flat to as much as 2000 feet in Southeast Eagle Flat (Gates et al. 1980). Basin fill is mostly Tertiary and Quaternary alluvium, with some mixed volcaniclastic rocks and volcanic flows. Basin fill is usually not saturated in Northwest Eagle Flat because depth to ground water is usually >600 feet along the basin floor. The basin fill is the principal water-bearing strata in Southeast Eagle Flat, however.

Major Ion Chemistry and Water Temperature

Ground water beneath the Northwest Eagle Flat watershed is marked by relatively high TDS and warm temperatures. Ground water is typically of the evolved Na-SO_4-Cl to Na-Cl type, with salinities between 1000 and 4000 mg/L. The highest salinities are associated with deep wells in low-lying areas east of Sierra Blanca. Warm ground water temperatures are associated with higher salinities and deeper water wells. Temperatures of 93°F, for example, were recorded in an 880-foot-deep monitor at Grayton Lake, 10 miles east of Sierra Blanca. Ground water temperatures have been recorded at 100.4°F in deep wells in Northwest Eagle Flat (Hoffer 1978).

Ground water in the northern half of Southeast Eagle Flat is noted for its cool temperatures and low salinities, mostly of the Ca-Mg-HCO_3 type. TDS range from 600 to 1500 mg/L and temperatures from 65.8°F to 71.9°F. Depth to water in most of these wells varies from 50 to 200 feet. Southward of these wells in the Scott's Crossing area, ground water is found at depths as great as 600 feet in thick deposits of basin fill. TDS in these bolson deposits are <400 mg/L, usually of the Na-HCO_3 type. Relatively cool temperatures between 75.2°F and 86°F are found in most of these deeper wells, except at hot wells, where anomalously high temperatures have been recorded at 107.8°F (Figure 6).

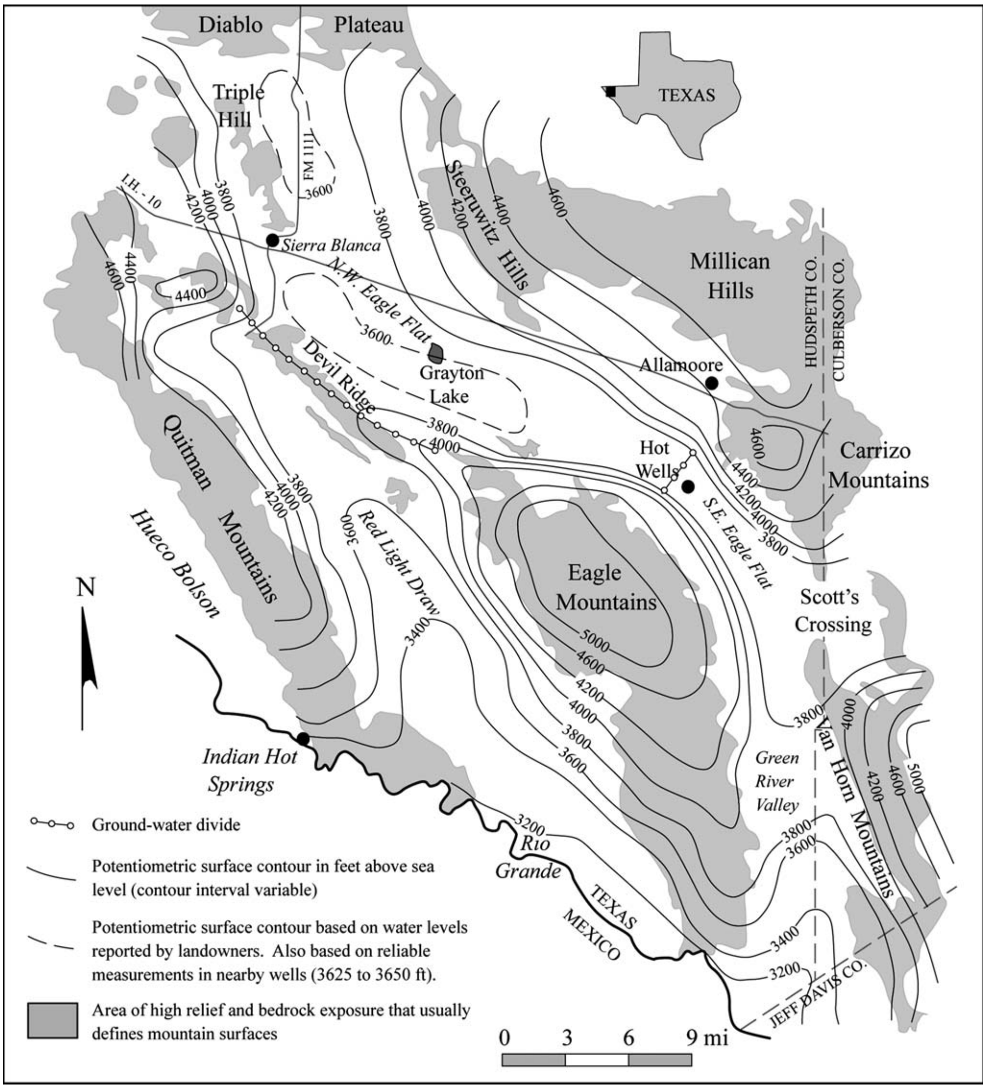

Figure 6. Potentiometric surface map for the Northwest Eagle Flat, Southeast Eagle Flat, and Red Light Draw aquifers (modified from Gates and Smith 1975; Gates et al. 1980; Darling et al. 1994; LBG-Guyton Associates 1998).

Recharge Areas, Ground Water Flowpaths, and Discharge Areas

In the Northwest Eagle Flat watersheds, environmental isotope data suggest that precipitation recharge to the basins occurs primarily within the upper mountains (Darling et al. 1994). Tritium activities decrease from 0.5 to 3 TU in shallow wells in the upper mountains to background levels in the flats and draws, and ^{14}C activities decrease from as much as 60 pmc in the mountains to <10 pmc in the flats, with most of the latter values clustered between 4 and 8 pmc (Figures 3 and 4). These sharply lower values indicate a lack of precipitation recharge across flats and draws. In the northern half of the Southeast Eagle Flat watershed, ^{14}C measurements decrease from levels near or >100 pmc in bedrock exposures in the Millican Hills to 40 to 50 pmc at Allamoore to <5 pmc near Scott's Crossing. Ground water with abundant modern carbon corresponds to ground water with high tritium activities (Figures 3 and 4). Ground water is demonstrably younger when depth to water is between 50 and 250 feet and much older when depth to ground water exceeds 450 feet. Radioisotope data indicate that Southeast Eagle Flat is a more active recharge area than either the Northwest Eagle Flat or the Red Light Draw watersheds (Figure 5). Mixing between recent recharge water and older ground water is indicated by the downward sloping trend in the scatter plot of ^{3}H vs. ^{14}C (Figure 5).

Relatively small amounts of recharge to low-lying areas of Eagle Flat are indicated by considerable depth to ground water. The potentiometric surface in central areas of Northwest and Southeast Eagle Flat varies from 450 to 1000 feet below land surface. Hydraulic gradients in the mountains are as great as 0.066. In the flats and draws, the hydraulic gradients are exceptionally flat (0.0001) and the limited fluid potential data sometimes do not allow important hydrogeologic barriers and boundaries to be distinguished (Figure 6). A local ground water divide separates ground water in Northwest and Southeast Eagle Flat, although head data used to construct the potentiometric surface map are not adequate to determine precisely the location of the ground water divide. A local ground water divide at Devil Ridge also separates the Northwest Eagle Flat Aquifer from the Red Light Draw Aquifer (Hibbs et al. 1995) (Figure 6).

Ground water moving east from the local ground water divide in Southeast Eagle Flat flows eastward through the Scott's Crossing area to Wildhorse Flat via interbasin flow (Gates and Smith 1975). Ground water moving out of the Northwest Eagle Flat Aquifer is more difficult to decipher. Movement of ground water out of Northwest Eagle Flat by interbasin flow is probably the only plausible way for ground water to move out of the basin because well discharge is negligible and because spring and playa discharge areas are entirely absent. Ground water probably travels either by vertical flow underneath the local ground water divide separating Northwest Eagle Flat from Southeast Eagle Flat or by vertical flow beneath the local ground water divide separating Red Light Draw from Northwest Eagle Flat (Hibbs et al. 1995). Ground water in regional flow systems may move underneath local ground water divides when relatively transmissive zones exist at depth (Maxey 1968; Mifflin 1988). Local fluid potential barriers, normally assumed to act as hydraulic boundaries, do not necessarily act as barriers along regional flowpaths (Mifflin 1988). The Northwest Eagle Flat Aquifer is identified as part of a regional flow system on the basis of its warm temperatures, mature hydrochemical facies, higher TDS, and hydrogeologic features. The regional flow system is enveloped by local mountain flow systems and local ground water divides.

A possible conceptual model of ground water flow in Northwest Eagle Flat indicates that ground water may move vertically downward to higher permeability Permian carbonate rocks beneath less permeable Cretaceous rocks (Figure 7). High-permeability rocks act as a sink to ground water flow so long as a hydraulic potential gradient exists between two hydrostratigraphic units. In this conceptual model, ground water moves to the south underneath the local ground water divide at Devil Ridge where the local flow system at the ridge merges with the regional flowpath (Figure 7). Ground water then traverses laterally and back up through Cretaceous rocks beneath the cooler and fresher ground water in the Red Light Draw Aquifer. The regional flowpath conceivably upwells under the Rio Grande and eventually reaches its discharge point at low-lying areas adjacent to the river, a line of lowest fluid potential in the study region. Hydraulic head along the Rio Grande varies from ~3200 to 3150 feet in lower Red Light Draw. The lowest measured hydraulic heads in Cretaceous rocks in Northwest Eagle Flat are ~3620 feet (Figure 6). Well control at the discharge area near the Rio Grande is not adequate at present to trace or fingerprint this water where it presumably upwells in the Rio Grande alluvium.

Aquifer Classification

With interior surface drainage to Grayton Lake and ground water discharge by interbasin ground water flow, the Northwest Eagle Flat Aquifer is defined as a topographically closed and drained basin (Figure 2). The Southeast Eagle Flat Aquifer is classified as a topographically open and drained basin (Figure 2). Surface runoff from the Southeast Eagle Flat Aquifer is to the adjacent Wildhorse Flat Basin. Ground water discharge is also to Wildhorse Flat by subsurface discharge at depth beneath Scott's Crossing (Figure 6). Active, but limited recharge areas along mountain fronts identified by radioisotopes, along with great depth to ground water and negligible ground water pumping provide likely evidence of ground water discharge from these basins by interbasin flow. By deduction, the ground water of Northwest Eagle Flat Aquifer almost certainly moves beneath a local ground water divide because the entire basin is surrounded on all sides by mountain ranges and local divides.

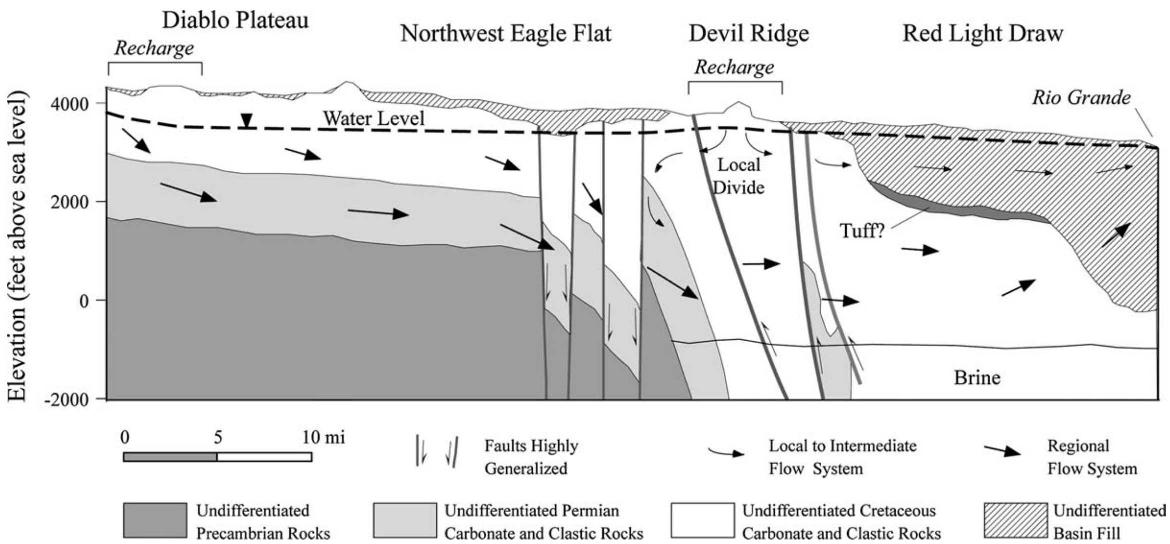

Figure 7. Conceptual hydrogeologic model showing ground water flow along a hypothesized regional flowpath. The regional flowpath is oriented from the Diablo Plateau recharge area, through Northwest Eagle Flat, to discharge areas near the Rio Grande. The regional flowpath moves underneath the local ground water divide at Devil Ridge and shows a tendency for flow to dominate in Permian rocks.

Topographically Closed, Partly Drained (or Undrained?) Basin: El Cuervo Aquifer

Physiography and Water-Bearing Strata

El Cuervo Bolson is surrounded by the Sierra Pilares and Sierra La Pinosa to the east, the Sierra El Hueso and Sierra La Lagrima to the west, and by local ground water divides to the north and south (Figures 1 and 8). The Sierra Pilares and Sierra La Lagrima stand at elevations exceeding 6200 feet above sea level, almost 2650 feet above the floor of El Cuervo Bolson. These prominent ridges are an extension of the Texas lineament. The floor of El Cuervo Bolson slopes gently to Laguna El Cuervo, an interior phreatic playa (Figures 1 and 8).

Most of the exposures in mountains that flank El Cuervo Bolson are Cretaceous carbonate and clastic rocks, although some Tertiary volcanic rocks are found in lesser abundance. Four east-west seismic lines across El Cuervo Bolson indicate approximate basin-fill thickness (W. Haenggi, written communication). All but one seismic line show faulting within the basin. At the northern portion of the basin, just south of El Colorado, the base of the bolson is ~1150 feet below the surface along the axis of the bolson. Toward the southern part of the basin, ~12 miles south 60°, west of El Cuervo (Figure 1), the base of fill is ~2600 feet below land surface just east of the bolson axis, increasing to 4200 feet just west of the Sierra Pilares (W. Haenggi, written communication). Seismic lines show an anticlinal feature in the center of the bolson, between a high angle, east-dipping reverse fault to the east and an east-dipping normal fault to the west (W. Haenggi, written communication). Basin-fill thickness increases to the south and southwest. Most domestic and livestock wells derive water from saturated basin fill and from shallow bedrock units in the highlands.

Major Ion Chemistry and Water Temperature

Except in the vicinity of Laguna El Cuervo, where saline ground water is concentrated about the evaporative discharge area, ground water in the El Cuervo Aquifer

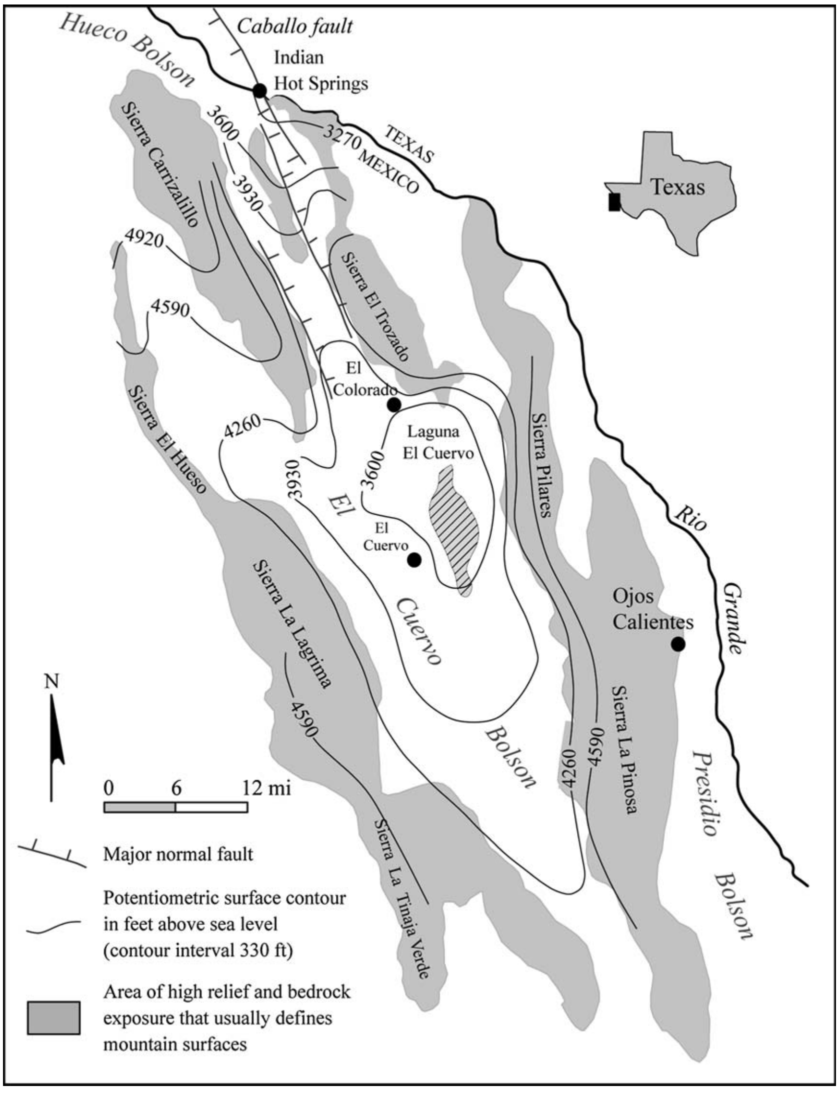

Figure 8. Potentiometric surface map for El Cuervo Aquifer and surrounding region. Within El Cuervo Bolson, map shows ground water flow to discharge areas near the phreatic playa at Laguna El Cuervo. A local ground water divide is mapped between Indian Hot Springs and El Cuervo Bolson. Major normal faults are also mapped between Indian Hot Springs and El Cuervo Bolson.

area is marked by moderately low TDS and generally cool temperatures of 70°F to 79°F. Ground water in the flanking mountains is noted for low salinities, mostly of the Ca-Mg-HCO_3 and Ca-Mg-SO_4 type. A few wells in the mountains have TDS above 1000 mg/L and are mostly of the Na-SO_4-Cl type. An exception is the hot springs at Ojos Calientes on the eastern flank of the basin (Figure 8). This spring issues an Na-Cl-SO_4 water with TDS >2250 mg/L. This spring issues from Cretaceous carbonate rocks at an elevation >300 feet above the Rio Grande.

Ground water in wells screened in livestock and domestic wells in El Cuervo Bolson is marked by two distinct facies; an Na-Mg-SO_4-Cl facies with TDS usually >1000 mg/L toward the northern edge of the basin and an Na-Mg-HCO_3 to Na-Mg-SO_4 facies with TDS usually <1000 mg/L in the middle and southern portions of the basin. Ground water temperature in these wells varies from 72°F to 79°F.

Recharge Areas, Ground Water Flowpaths, and Discharge Areas

The potentiometric surface map indicates that ground water is recharged within the mountains and along mountain fronts and converges at Laguna El Cuervo (Figure 8). Depth to water is as little as 30 feet in wells in the mountains and attains depths as great as 340 feet in wells that flank the mountains. A single spring is present on the valley floor at the hamlet of El Cuervo (Figure 8) and probably is present due to juxtaposition of coarse-textured alluvial fan material against fine-textured basin fill. The existence of the spring implies a permeable connection to a recharge area within the mountains or along mountain fronts.

Local ground water divides are present along mountain ridges, along gaps in the bolson separating Sierra El Hueso from Sierra El Pino, and along gaps separating Sierra El Pino from Sierra El Trozado (Figures 1 and 8). These divides envelop the basin and are integral to the development of the phreatic playa at Laguna El Cuervo.

Aquifer Classification

With interior surface drainage and ground water discharge at Laguna El Cuervo, the El Cuervo Aquifer may be a topographically closed and undrained basin. We postulate that ground water in the El Cuervo Aquifer may also be the source of some of the thermal and moderately saline water that discharges along the Caballo Fault at Indian Hot Springs (Figures 8 and 9). If El Cuervo Aquifer loses a portion of its discharge by interbasin flow to Indian Hot Springs, it is classified as a topographically closed, partly drained basin (Figure 2). In partly drained basins, some of the discharge occurs within the basin (to a phreatic playa), but some ground water flows along permeable pathways to other basins by interbasin flow (Mifflin 1988) (Figure 2). The evidence is evaluated for possible interbasin flow to Indian Hot Springs.

Evidence for Interbasin Ground Water Flow

El Cuervo Bolson and surrounding ridges are oriented in line with a set of northwest trending faults and lineaments that converge on the Caballo Fault at Indian

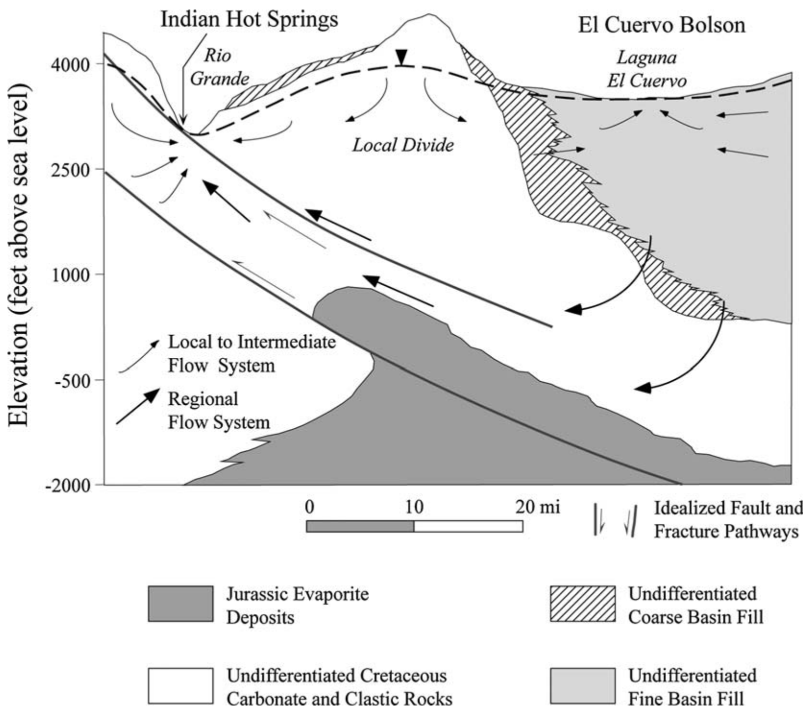

Figure 9. Generalized conceptual hydrogeologic model showing ground water flow along a hypothesized regional flowpath between El Cuervo Bolson and Indian Hot Springs. Ground water recharged to El Cuervo Bolson discharges at Laguna El Cuervo and may discharge partly at Indian Hot Springs along fault and fracture pathways. Ground water along the hypothesized regional flowpath moves underneath the local ground water divide between El Cuervo Bolson and Indian Hot Springs, reacting with evaporite deposits and mixing with more dilute water before discharging at the hot springs.

Hot Springs. These lineaments and faults may act as pathways for movement of ground water reacting with evaporites before discharging at Indian Hot Springs. Hydraulic head at Laguna El Cuervo, the area of lowest fluid potential in the basin, is ~350 feet above Indian Hot Springs. Fault and fracture pathways that converge on Indian Hot Springs and higher fluid potential in the El Cuervo Aquifer provide two conditions necessary for movement of ground water from the El Cuervo Aquifer to Indian Hot Springs (Figure 9).

High-TDS thermal water discharges at Indian Hot Springs. TDS in these Na-SO_4-Cl and Na-Cl water are as great as 7000 mg/L and temperatures are between 81°F and 122°F at the hot springs (von Hippel 1857; Dorfman and Kehle 1974; Reaser et al. 1975; Henry 1979). The molar ratio of Na to Cl (Na/Cl) is close to 1.0 and the Cl/Br ratio is >3000 at Indian Hot Springs. Na/Cl ratios approaching 1.0 are the result of the release of equimolar concentrations of Na and Cl by the dissolution of halite (Drever 1988). High Cl/Br ratios at Indian Hot Springs >3000 provide additional evidence of halite dissolution (Figure 10). Chloride and bromide are conservative anions, and processes other than precipitation or dissolution of salts and/or ground water mixing does not usually modify their concentrations in ground water (Hem 1985). Cl/Br ratios indicate the origin of salinity of ground water as sea water, dissolution of halite, or residual brine from the precipitation of halite (Holser 1979; Darling et al. 1994). The Cl/Br ratio of sea water ranges from 300 to 650 (Holser 1979; Drever 1988) and remains nearly constant during evaporation up to the concentration at which halite precipitates (Darling et al. 1994). Because of its larger size, the bromide ion is excluded from the halite lattice structure, and residual brine is consequently enriched in Br relative to Cl (Cl/Br decreases), while halite is deficient in Br. The Cl/Br ratios of circulating meteoric ground water can increase by several factors as large masses of halite are dissolved.

Indian Hot Springs lie near the edge of a Jurassic evaporite basin that extends southward into Mexico (Henry 1979) (Figure 11). The geochemical signature of water at Indian Hot Springs indicates that ground water comes into contact with halite and gypsum (Henry 1979; Darling et al. 1994) and that water either is not in contact with evaporites long enough to reach saturation or dilute water circulating through nonevaporite rocks mixes with more concentrated water that have been in contact with evaporites for longer periods of time. No large halite deposits are usually found north of the Rio Grande, but they are ubiquitous in the area underlying El Cuervo Bolson. Furthermore, ground water in proximal regions of the Hueco Bolson, Texas portion, do not show an evaporite dissolution signature similar to Indian Hot Springs (Figures 8 and 10). Drilling near the El Cuervo Bolson area indicates that evaporites are hundreds of feet thick and consist of 13% to 80% halite, 5% to 12% gypsum, and 1% to 11% anhydrite (Haenggi 1966). Faulted and diapirically injected gypsum deposits are in contact with carbonate and other rocks in the El Cuervo Bolson study area. Collapse features are evident where more soluble salts have been dissolved out of the evaporite (Haenggi 1966).

Our conceptual model is consistent with the hydrogeologic and hydrochemical conditions that are required for possible interbasin ground water flow to Indian Hot Springs. Moreover, it has been suggested that thermal water is formed at intermediate depths before discharging at Indian Hot Springs (Henry 1979). Others have

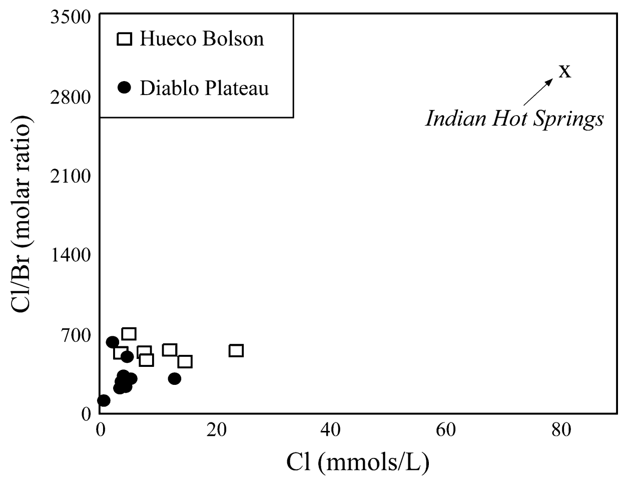

Figure 10. Scatter plot showing Cl/Br molar ratios vs. molar Cl for samples collected from bedrock strata, bolson strata, and Indian Hot Springs. Data show a clearly defined evaporite dissolution signature for Indian Hot Springs and no evidence of evaporite dissolution in ground water from the Hueco Bolson or Diablo Plateau aquifers (source of data, Fisher and Mullican 1990; Darling et al. 1994).

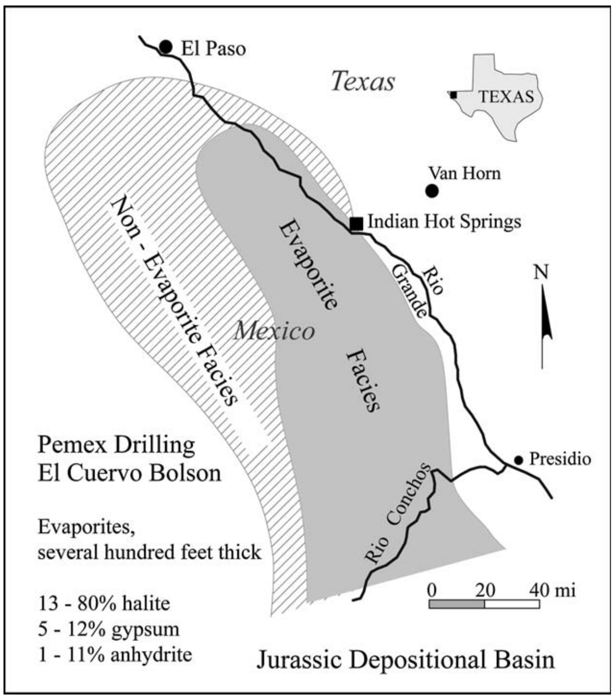

Figure 11. Extent of Jurassic depositional basin including evaporite and nonevaporite rock assemblages. Included in the diagram are thicknesses of evaporite units in El Cuervo Bolson, reported by Pemex for drilling data (modified from DeFord and Haenggi 1971; Henry 1979).

suggested that the water at Indian Hot Springs may be heated by an igneous body at depth (Reaser et al. 1975). We believe the geothermal source could also be related to crustal heat upwelling near the Rio Grande Rift, an area of crustal thinning. El Cuervo Bolson is juxtaposed between the Hueco Bolson and Presidio Bolson (Figure 1) and may represent an extension of the Rio Grande Rift into Texas and Mexico, with associated high heat flow, thermal gradients reaching 150°F/mile, and temperatures measured up to 340°F at a depth of 2.2 miles below land surface (Henry 1979). Heat is conducted strongly through evaporites due to the high thermal conductivity of halite and other evaporite minerals. The thermal conductivities of salts reportedly are the highest of all common rocks and thus act as sinks for heat flow (Walton 1984). Evaporites underlie much of the El Cuervo Bolson and could provide the heat conduction necessary for thermal water at depths (Figure 9). Based on quantitative geothermometry, Henry (1979) suggests depths of flow of between 3300 and 4300 feet to reach reservoir temperatures observed at Indian Hot Springs, a depth consistent with possible movement from El Cuervo Bolson (Figure 9).

Additional evidence of possible hydraulic connections between El Cuervo Bolson and Indian Hot Springs is provided by a plot of stable isotope data (Figures 12 and 13). Hot water of 140°F to 194°F issues from spurting springs at Ojos Calientes on the eastern edge of El Cuervo Bolson (Figure 8). The water is dilute (~2250 mg/L TDS) with respect to Indian Hot Springs water (~7500 mg/L TDS). Ojos Calientes water is probably shifted thermally due to exchange of oxygen with wall rocks where this water is in contact with Cretaceous rocks near the Palo Pegado Fault (Figure 13) (Henry 1979). Overall, the mixing model at Indian Hot Springs is isotopically consistent with (1) mixing with dilute, meteoric water issuing from Red Bull Springs (950 TDS) near the Caballo Fault, along with (2) mixing with thermally shifted water of the type flowing from Ojos Calientes (Figures 12 and 13). The mixing model includes evaporite dissolution along the flowpath toward Indian Hot Springs to produce the evaporite signature shown at the hot springs (Figure 10).

Ground water issues from Ojos Calientes on the eastern margin of El Cuervo Bolson (Figure 8). It is likely that similar hydrothermal processes operate on the mountains flanking the basinward part of the bolson. This water could also be shifted thermally by exchange with wall rocks while moving from mountain recharge into evaporite-bearing rocks beneath El Cuervo Bolson. In this proposed model, the water beneath El Cuervo Bolson

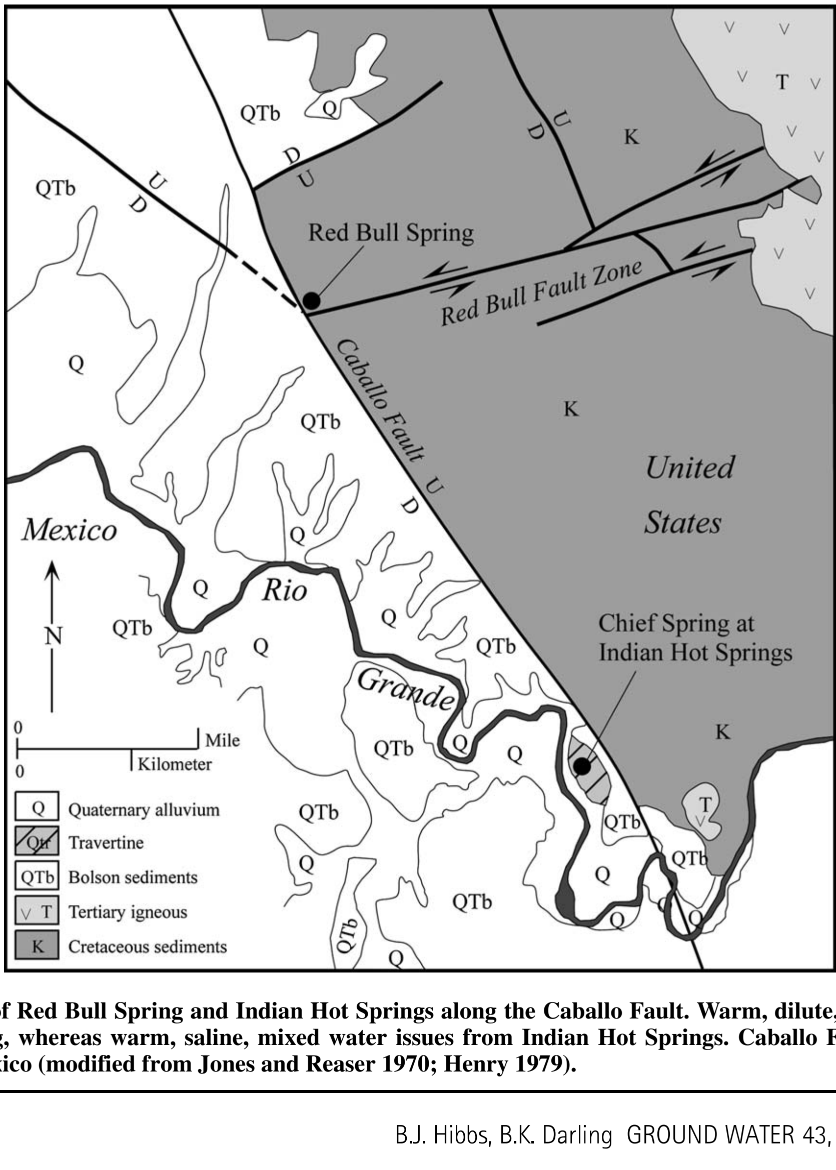

Figure 12. Location of Red Bull Spring and Indian Hot Springs along the Caballo Fault. Warm, dilute, meteoric water issues from Red Bull Spring, whereas warm, saline, mixed water issues from Indian Hot Springs. Caballo Fault trends toward El Cuervo Bolson in Mexico (modified from Jones and Reaser 1970; Henry 1979).

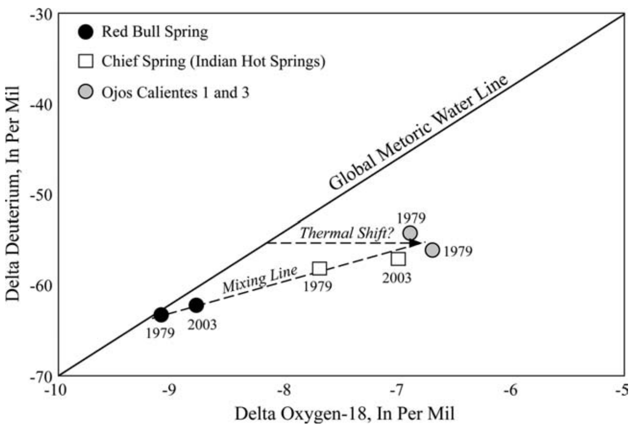

Figure 13. Isotopic composition of water issuing from Red Bull Spring, Indian Hot Springs, and Ojos Calientes, 1979 and 2003. Ojos Calientes water is hot and probably obtains its isotopic signature due to oxygen exchange with wall rocks. Indian Hot Springs water may obtain its isotopic signature by mixing with Red Bull Spring and Ojos Calientes–type water. The shift in the 1979 and 2003 data may be due to drought resulting in more evaporation at spring boxes from reduced discharge rates or by greater evaporation of shallow ground water (local flowpath water that mixes with Red Bull Spring water) prior to recharge (1979 data from Henry 1979).

continues its journey to Indian Hot Springs, reacting with evaporites prior to mixing with dilute water of the type shown at Red Bull Spring (Figures 9, 10, and 13).

The data do not prove that El Cuervo Bolson is a source of flow at Indian Hot Springs and other mixing models are possible. More work with isotopic and environmental tracers, including field sampling in El Cuervo Bolson, are needed to shed additional insights on the source of flow at Indian Hot Springs. Thus, El Cuervo Aquifer is a topographically closed basin that is partially drained if a component of its ground water discharge reaches Indian Hot Springs (Figure 9). If ground water does not move out of El Cuervo Basin by interbasin flow, the aquifer is classified as topographically closed and undrained, with all its natural discharge by evaporation at the phreatic playa at Laguna El Cuervo.

Conclusions

Flow systems analysis is a necessary preliminary step that should precede investigations of the feasibility for waste disposal in these and other basin-fill aquifers. The methodology employed in this study has identified simple hydrogeologic systems that are easy to classify, as well as complicated regional hydrogeologic systems that constrain our ability to define flowpaths and interbasin relationships and flow. Hydrogeologic information is available only for shallow wells tapping the uppermost saturated units in the area. These data are not adequate to define three-dimensional components of flow in the more complicated flow systems.

Despite these limitations, it is possible to derive reasonable inferences about interbasin movement of water based on presence or absence of phreatic playas, depth to ground water, and evidence of recharge along flanking mountains and mountain fronts, usually determined with radioisotopes, potentiometric surface mapping, and flow systems analysis. These data should be supplemented with hydrochemical and temperature data that help to identify regional vs. local and intermediate flow systems. The active intrabasin recharge combined with the lack of a phreatic playa and significant depth to ground water (e.g., >100 feet) in a predevelopment flow system is good evidence of interbasin ground water flow based on fluid mass-balance assumptions. Evaporation of ground water from such depths is negligible and is not a significant component of ground water discharge.

Key to understanding or predicting directions of interbasin ground water flow in topographically closed and drained and partly drained basins requires analysis of possible permeability pathways at depth and identification of potential regional hydraulic head gradients between basins (Mifflin 1988). Emphasis should be placed on defining potentially complex fluid potential cells in these basin aquifers. Analysis of flow systems should take into account possible vertical and underflow components within and between basins and a thorough study of the hydrogeology of adjacent basins to help understand inter- and intrabasin relationships (Mifflin 1968, 1988; Winograd and Thordarson 1975).

Movement of ground water underneath local ground water divides is often an artifact of regional ground water interbasin flow. This type of flow has been observed in aquifers in this study and in studies of the Great Basin. Preparation of potentiometric surface maps with hydraulic head data collected from only the uppermost saturated units (frequently the only well control in arid basins) might erroneously exclude the possibility of ground water movement underneath local ground water divides that are often assumed to be barriers to flow. Insofar as three-dimensional hydraulic head and permeability information is often lacking in arid basins, flow systems analysis will help to develop preliminary conceptual models of ground water movement and the suitability of basins for waste disposal.

Acknowledgments

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Author's Note: The views and conclusions in this article are those of the authors and should not be interpreted as necessarily representing the official policies and views of the U.S. EPA, NSF, or TLLRWDA.

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