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THE HYDROGEOLOGIC FRAMEWORK OF BASIN-FILL AQUIFERS AND ASSOCIATED GROUND-WATER-FLOW SYSTEMS IN SOUTHWESTERN NEW MEXICO—AN OVERVIEW

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Abstract—Ongoing cooperation between the governments of the United States and the Republic of Mexico, particularly projects involving the U.S. Environmental Protection Agency, requires that major aquifer systems with transboundary components be adequately characterized in terms of their hydrogeologic framework, ground-water-flow regimes and water-quality conditions. As part of this program, the New Mexico Water Resources Research Institute and cooperating institutions have developed Geographic Information System (GIS) coverages (ARC/INFO® format) that integrate large amounts of available surface and subsurface information on basin-fill aquifers in the International Boundary region between Trans-Pecos Texas and southeastern Arizona. Emphasis of this overview is on major GIS elements relating to aquifer composition and general ground-water-flow regimes in four intermontane basin systems of southwestern New Mexico and northwestern Chihuahua: Mimbres, Hachita-Moscos, Playas, and Animas. The ARC/INFO® format allows 3-D presentation of hydrogeological information and related interpretations that can be used in numerical ground-water-flow models. The hydrogeologic framework and hydraulic properties of basin and valley fills are categorized on the basis of (1) hydrostratigraphic unit (HSU) and lithofacies assemblage (LFA) composition and (2) the nature of basin-boundary and intra-basin bedrock and structural controls. Major aquifers are formed by medium– coarse-grained fluvial-facies assemblages deposited by the ancestral Mimbres and Animas fluvial systems. These poorly consolidated HSUs and LFAs are informal subdivisions of the (Pliocene–Quaternary) upper Gila Group and overlying basin-floor deposits. Typical horizontal hydraulic conductivities range from 1 to 10 m/day, and unit thicknesses are as much as 150 m. Laterally equivalent piedmont-slope facies and underlying middle and lower Gila Group HSUs have much lower aquifer potential because of finer matrix texture and greater degree of consolidation and cementation. Whereas all of the basin systems in the study area have surface-flow components that discharge to subbasins with topographic closure and ephemeral lakes (playas), the ground-water-flow regime in most subbasins has an underflow-discharge component that drains to terminal sinks in lower contiguous basins or river-valley areas. Historically, transboundary ground-water flow from the United States to Mexico has been documented in a few areas, but at a very low rate ($<10.5 \times 10^6$ m^3/yr).

INTRODUCTION

The New Mexico Water Resources Research Institute (NMWRRI) and cooperating organizations recently completed an intensive review of available information on Trans-International Boundary Aquifers in southwestern New Mexico for the U.S. Environmental Protection Agency (USEPA). This 2-yr project involved compilation, analysis, and synthesis of geographic, hydrogeologic, geohydrologic, and hydrogeochemical information in a large region (Fig. 1) extending from the upper Gila River basin on the north to the lower Rio Casas Grandes basin in northern Chihuahua, and westward from the eastern edge of Mimbres River basin to the San Bernardino basin of southeastern Arizona and northeastern Sonora (Hawley et al., 2000). The study was a continuation of joint efforts by the governments of the United States and Mexico to identify all major transboundary aquifers, to better characterize ground-water flow and quality conditions, and to develop adequate Geographic Information System (GIS) coverages (Hibbs et al., 1998a, b). Highlights of these recent NMWRRI-USEPA investigations in areas visited during the 51st New Mexico Geological Society Field Conference are briefly covered here and in a companion paper by Hibbs et al. (this volume). Emphasis in this paper is on GIS development with respect to (1) the hydrogeologic framework of basin-fill aquifers and (2) ground-water flow regimes in the four major basin systems: Mimbres, Hachita-Moscos, Playas, and Animas. Ground water in these systems discharges to closed-topographic depressions and stream valleys in the southwestern New Mexico region west of the Rio Grande rift (Fig. 1). The companion paper in the guidebook by Hibbs et al. reviews ground-water quality and hydrogeologic interrelationships in the Animas basin system.

The hydrogeology of basin-fill aquifers in most of the region has never been investigated at more than a reconnaissance level (e.g., Trauger and Doty, 1965; Wilkins, 1986, 1998). Hydrogeologic-framework and ground-water-flow characteristics of major aquifer systems are only well documented in widely spaced areas of irrigation agriculture and near the few centers of urban population and mineral-processing activity (Reeder, 1957; Doty, 1960; Trauger, 1972; Hawkins and Stephens, 1983; O'Brien and Stone, 1983, 1984; Hanson et al. 1994). Preliminary numerical models of ground-water flow in the basin-fill aquifer system have been developed for the Mimbres basin (system) and the Lower Animas subbasin (Hanson et al., 1994; Hawkins, 1981; O'Brien and Stone, 1983). These models are two dimensional, however, and they are poorly suited for accurate characterization of the well-documented vertical changes in aquifer conditions such as head distribution and decreasing permeability with depth (Kernodle, 1992a). The provisional three-dimensional hydrogeologic models of basin-fill aquifers developed as part of this NMWRRI-USEPA study (ARC/INFO® GIS format) are an initial step toward creation of numerical models that more accurately portray the essential elements of the ground-water-flow system (Hawley et al., 2000).

Physiographic setting

Most of the study area (Fig. 1) is in the Mexican Highland section of the Basin-and-Range physiographic province (Hawley, 1986). Three basin systems: Mimbres, Hachita-Moscos, and Playas, are east of the Continental Divide, and the Animas-Cloverdale system is to the west. Elevations range from 2600 m at Animas Peak to less than 1200 m at the lower end of the Mimbres basin system. The northern and highest part of the study area is in the Datil-Mogollon section of the Transition Zone province (Fig. 1). As the province name implies, large-scale geomorphic and structural features mark a broad zone of transition between the Colorado Plateau of west-central New Mexico and east-central Arizona, and the Basin-and-Range province (Hawley, 1986; Morrison, 1991). The latter region has an extended crustal structure characterized by broad and deep fault-block depressions. Elevations of the highest peaks in the Datil-Mogollon section exceed 3000 m and much of this area of high plateaus with deep canyons is above 1800 m. The section includes most of the perennial to intermittent reaches of the upper Mimbres River system and its high-mountain tributaries in the Black and Piños Altos ranges adjacent to the Continental Divide.

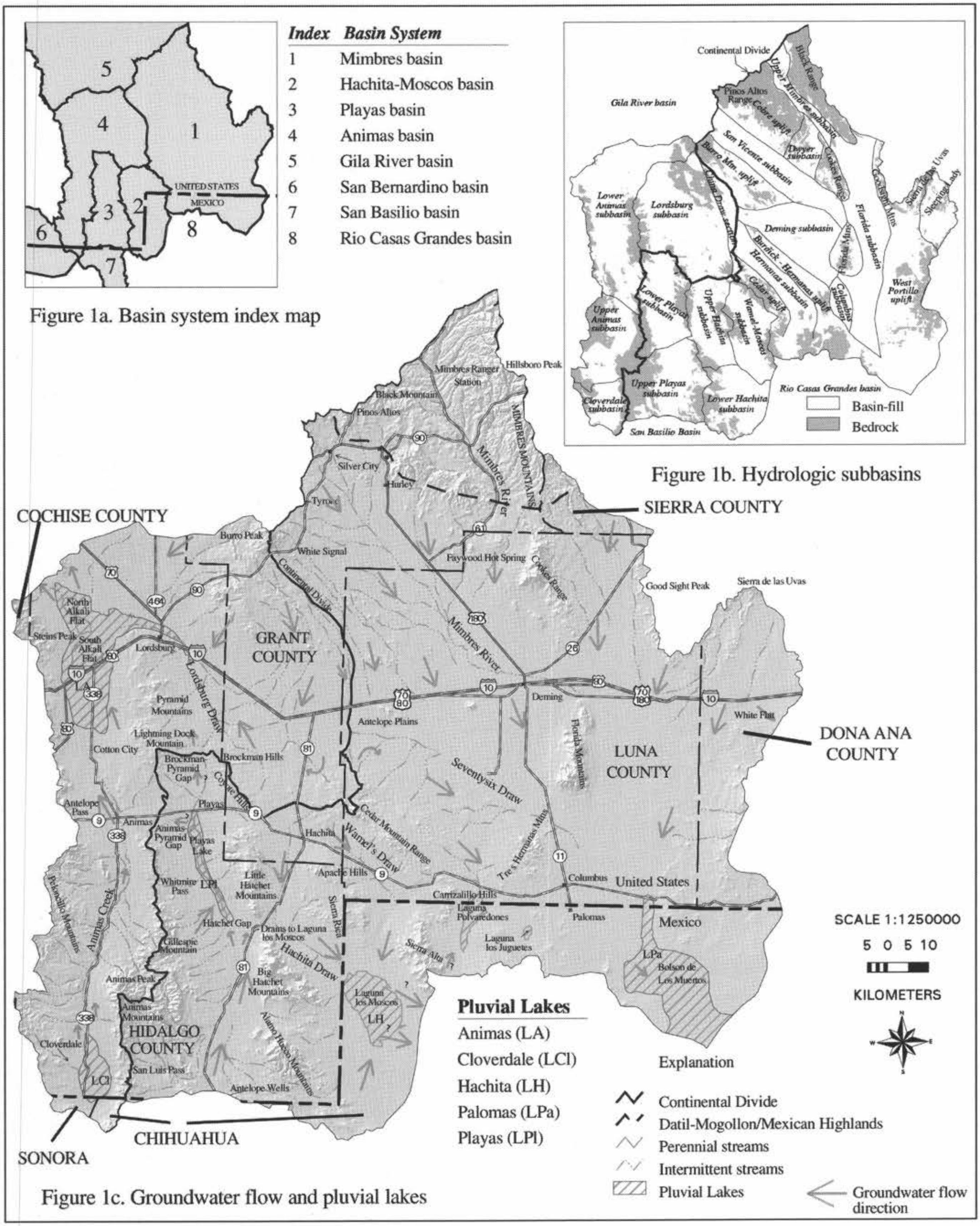

FIGURE 1. Location of the study area in southwestern New Mexico. The locations of the following basin systems are shown on Figure **1a**: (1) Mimbres, (2) Hachita-Moscos, (3) Playas, (4) Animas, (5) Gila River, (6) San Bernardino, (7) San Basilio, and (8) Rio Cases Grandes. Each basin system is comprised of numerous subbasin units (Fig. **1b**). The following pluvial lakes are listed on Figure **1c**: Animas (LA), Cloverdale (LCl), Hachita (LH), Palomas (LPa), and Playas (LPl).

The more-permeable fill components of the deep structural basins that form about 75% of the Mexican Highland section comprise the major aquifers described in this paper. There are two classes of intermontane basins: (1) topographically closed basins with piedmont and basin-floor alluvial surfaces grading to central playa (ephemeral-lake) depressions are designated bolsons, and (2) open basins with piedmont slopes grading to axial streams that discharge to lower-lying areas are referred to as semibolsons (Hill 1900; Tolman, 1909; Hawley, 1969). In this paper, the terms open and closed refer solely to surface-flow regimes. All stream systems are ephemeral except in the upper valley of the Mimbres River and Animas Creek, and in short canyon reaches in the highest parts of the Animas, Peloncillo-Guadalupe, and Big Burro ranges (Fig. 1).

Land use, landcover, and climate

The study area includes a wide variety of land-use/landcover categories, with conifer forests present at the highest elevations and grassland to desert scrub prevalent in drier, lower-elevation areas (Hawley et al., 2000). Lowlands contain a mix of irrigated farmland, rangeland and alkali-flats. The major urban areas include Deming, Lordsburg, Silver City, and Hurley, with a number of smaller rural communities scattered throughout the area. The Silver City-Hurley area has been one of the largest metallic-mineral producing centers of the region for more than a century.

Climatic conditions are typical of the arid to semiarid Southwest, with mostly clear skies and limited rainfall and humidity (Hawley et al., 2000). Average annual precipitation varies from less than 25.4 cm per yr in low-lying basins to as much as 76.2 cm per yr at higher elevations in the mountains. Annual rainfall at Deming (elevation 1321 m) averaged 23.4 cm between 1948 and 1995. In the upper reaches of the Mimbres River (elevation 1904 m), the average was 43.3 cm for the same period. Nearly half of the annual precipitation is from convective thunderstorms that occur sporadically from July to October. In the lower elevation areas, the average high summer (June, July, and August) temperatures typically are above 32ºC. Winter (December, January, and February) average low temperatures are usually about -4ºC. At higher elevation areas, average high summer temperatures are about 29ºC and winter low temperatures are about -7ºC. Large diurnal changes in temperature of about 17ºC are common. Average class A pan evaporation typically is about 250–260 cm on basin floors.

BASIC CONCEPTS OF BASIN HYDROGEOLOGY

Introduction

In both the Mexican Highland and Datil-Mogollon sections, ground water primarily occurs in the poorly consolidated sediments that have accumulated in structural basins between mountain ranges. These intermontane basins (bolsons, semibolsons) are commonly referred to as "alluvial basins" (Wilkins, 1986, 1998; Kernodle, 1992a). Their fills are not entirely of alluvial origin (i.e., stream deposits), because they include lesser amounts of lacustrine, eolian, and colluvial sediments (Gile et al., 1981; Seager et al., 1982, 1987; Drewes et al., 1985; Seager, 1995; Mack et al., 1997; Hawley et al., 2000). Fractured volcanic rocks (basalts, andesites, and tuffs), which immediately underlie or are interlayered with the basin fill, also form productive aquifers in some places (Trauger, 1972; Blandford and Wilson, 1987); but the occurrence of ground water in most consolidated rocks of the region is limited to water-filled fracture zones of typically very low yield. Such zones occur in a wide variety of fractured bedrock units including sedimentary, volcanic, intrusive-igneous, and metamorphic types. Bedrock uplands are the ultimate source areas for the basin fill and bedrock terranes usually form effective boundaries for basin-fill aquifer systems. Unlike some parts of the Basin-and-Range province (e.g., southern Nevada and Trans-Pecos Texas), there are no extensive bodies of carbonate rock that provide conduits for interbasin ground-water flow (Maxey, 1968; Hibbs et al., 1998a). Both interbasin and intrabasin boundary structures, such as faults and flexures, are also part of a group of tectonic and volcanic features that play a major role in ground-water-flow dynamics.

Each of the four basin systems described in this paper is characterized by one or more distinct ground-water-flow regimes, and only two (Mimbres and Hachita-Moscos) have significant transboundary aquifer components that extend into Mexico (Fig. 1). The Gila river basin, which heads in the high plateaus of the Mogollon-Datil volcanic field, is at the northern edge of the study area. The basin includes a series of deep canyons and valleys that are cut well below most of the aquifers of the intermontane basins to the south. The Duncan-Virden segment of the Gila river valley acts as the regional sink for nearly all pre-development (pre-1900) ground water flow in the northern Animas basin system. Regional ground water sinks for the southern Mimbres and Hachita-Moscos basin systems (Fig. 1) are formed by the Bolson de los Muertos and Rio Casas Grandes valley (Reeves, 1969; Hawley, 1969, 1975, 1993; Hanson et al., 1994).

Conceptual model of ground-water flow in basin-fill aquifers

The conceptual model of surface-water and ground-water flow in the intermontane-basin aquifer systems of the study area (Fig. 2) is based on previous work in the Basin-and-Range province (Maxey, 1968; Eakin et al., 1976; Mifflin, 1988; Hibbs et al., 1998a). As already noted, the terms <u>closed</u> and <u>open</u> refer only to the surface flow into, through, and from intermontane basins, whereas the terms <u>undrained</u>, <u>partly drained</u>, and <u>drained</u> designate classes of ground-water flow involving intrabasin and/or interbasin movement. <u>Phreatic</u> and <u>vadose</u> indicate saturated and unsaturated subsurface conditions, respectively. <u>Phreatic playas</u> (with springs and seeps) are restricted to floors of <u>closed</u> basins (<u>bolsons</u>) that are <u>undrained</u> or <u>partly drained</u>, and <u>vadose playas</u> occur in both <u>closed</u> and <u>open</u>, <u>drained</u> basins. In the transboundary study region, as well as in most other desert basins of western North America, the intermediate basin class referred to as partly drained is probably the major ground-water-flow regime. Few intermontane basins (<u>bolsons</u> and <u>semibolsons</u>) are truly <u>undrained</u> in terms of ground-water discharge, whether or not they are <u>closed</u> or <u>open</u> in terms of surface flow.

Under pre-development conditions, ground-water discharge in the region occurred mainly through subsurface leakage from one basin system into another, discharge into the gaining reaches of perennial or intermittent streams, discharge from springs, or by evapotranspiration from <u>phreatic playas</u> and cienegas (valley-floor wetlands). Most recharge to basin-fill aquifers occurs by two mechanisms: (1) "mountain front," where some precipitation falling on bedrock highlands contributes to the ground-water reservoir along basin margins; and (2) "tributary," where the reservoir is replenished along losing reaches of larger intra-basin streams (Anderholm, 1994; Hanson et al., 1994; Kernodle, 1992a; Wasiolek, 1995). The upland networks of major stream valleys in the highlands of the Datil-Mogollon section and the Sierra Madre

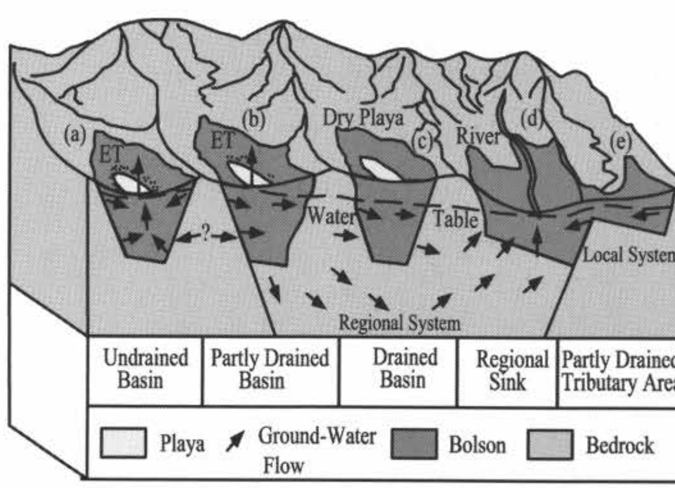

FIGURE 2. Conceptual hydrogeologic model showing undrained basins (a), partly drained basins (b), drained basins (c), regional sinks (d), and partly drained tributary area (e) (modified from Eakin et al., 1976). Phreatic playas are restricted to undrained and partly drained basins; and vadose conditions exist in "dry playa" areas. "ET" indicates areas of high evapotranspiration.

Occidental region of northwestern Mexico are the primary source areas for recharge of basin-fill aquifers in the Mexican Highland section (Hawley et al., 2000). Secondary contributors to these ground-water reservoirs are the few high and massive mountain ranges that form isolated highlands within individual basin systems. Recharge estimates in this report are based on the assumptions that (1) only 1 to 2% of average annual precipitation contributes to recharge, and (2) this contribution is distributed very unevenly over higher watersheds and in major stream valleys.

Conceptual hydrogeologic-framework model

The hydrogeologic framework of basin-fill aquifers in the study area (Hawley et al., 2000), with special emphasis on features related to environmental concerns, is described here in terms of three basic conceptual building blocks: Hydrostratigraphic units (HSUs), lithofacies assemblages (LFAs), and structural-boundary conditions. A conceptual hydrogeologic model of an interconnected shallow valley-fill/basin-fill and deep-basin aquifer system was initially developed for use in ground-water-flow models of the Mesilla and Albuquerque basins (Peterson et al., 1984; Kernodle, 1992a; Hawley and Lozinsky, 1992; Frenzel and Kaehler, 1992; Hawley and Haase, 1992; Thorn et al., 1993; Hawley et al. 1995; Kernodle et al. 1995); however, basic design of the conceptual model is flexible enough to allow it to be modified for use in other basins of the Rio Grande rift and adjacent parts of the southeastern Basin-and-Range province. This model is simply a qualitative description (graphical, numerical, and verbal) of how a given geohydrologic system is influenced by (1) bedrock-boundary conditions, (2) internal-basin structure, and (3) the lithofacies and mineralogical composition of various basin-fill stratigraphic units. It provides a mechanism for systematically organizing a large amount of relevant hydrogeologic information of widely varying quality and scale (from very general drillers' observations to detailed bore-hole, geophysical and geochemical data). Model elements can be graphically displayed in a combined map and cross-section GIS format so that basic information and inferences on geohydrologic attributes (e.g., hydraulic conductivity, transmissivity, anisotropy, and general spatial-distribution patterns) may be transferred to basin-scale, three-dimensional numerical models of ground-water-flow systems. As emphasized by McCord and Stephens (1999), this scale of data presentation and interpretation is not designed for site-specific ground-water investigations.

Hydrostratigraphic units

Most basin fill in southwestern New Mexico has been subdivided into two major lithostratigraphic units, the Santa Fe Group in Rio Grande rift basins (e.g., Seager et al, 1982, 1987) and the Gila Group [Gila conglomerate of Gilbert, 1875] in basins of the Mexican Highland and Datil-Mogollon sections to the west (e.g. Trauger, 1972; Drewes et al., 1985). In addition, a clear distinction has rarely been made between deposits simply classed as "bolson" or "basin" fill and contiguous (formal and informal) subdivisions of the Gila Groups (e.g., Hanson et al, 1994; Seager, 1995; and Clemons, 1998). As a first step in organizing available information on basin-fill stratigraphy that has a close relationship with aquifer characteristics, a provisional hydrostratigraphic classification system has been developed following guidelines used successfully in Albuquerque and Mesilla basins of the Rio Grande rift (Hawley et al., 1995).

Hydrostratigraphic units defined in this study area by Hawley et al. (2000) are mappable bodies of basin fill and valley fill that are grouped on the basis of origin and position in both lithostratigraphic and chronostratigraphic sequences. The informal ***upper***, ***middle***, and ***lower Gila*** and ***Santa Fe*** hydrostratigraphic units (HSUs) comprise the major basin-fill aquifer zones, and they correspond roughly to the (formal and informal) upper, middle and lower lithostratigraphic subdivisions of the Gila and Santa Fe groups used in local and regional geologic mapping (Table 1, Fig. 3). Santa Fe units are mapped only along the eastern edge of the Mimbres basin system in an area that is transitional to the Rio Grande rift structural province. The other major hydrostratigraphic units comprise channel and floodplain deposits of the Mimbres River and Animas Creek in the United States, and the Casas Grandes fluvial system in Mexico. These valley fills of Late Quaternary age (<130 ka) form the upper part of the region's most productive shallow-aquifer system. Surficial lake and playa deposits, fills of larger arroyo valleys, and piedmont-slope alluvium are primarily in the *vadose* zone. However, they locally form important ground-water discharge and recharge sites. Historical *phreatic* conditions exist, or have recently existed, in a few playa remnants of large pluvial lakes of Late Quaternary age. Notable examples are "alkali flats" in the lower Animas, Playas, Hachita (Laguna Los Moscos), Mimbres, Bolson de las Muertos, and Casas Grandes (Laguna Guzman) basins (Fig. 1). The lower reaches of the Animas, Mimbres and Casas Grandes systems include extensive fluvial-fan and fan-delta deposits (Fleischhauer and Stone, 1982; Love and Seager, 1996; Mack et al. 1997). The latter grade to playa-lake-plain complexes that are remnants of pluvial lakes Animas and Palomas.

TABLE 1. Major hydrostratigraphic units and their relationship to lithofacies assemblages (see Tables 2–4)

VALLEY-FILL HYDROSTRATIGRAPHIC UNITS—MIDDLE & LATE QUATERNARY	
Channel, overbank, & low-terrace deposits of perennial streams (late Quaternary)	
RA	Upper Animas Creek fluvial unit; mostly LFA ***a***, with minor Cienega sediments (HSU: CA, LFA ***c***)
RM	Mimbres River fluvial unit; mostly LFAs ***a1*** & ***a2***
RGC	Rio Casas Grandes fluvial unit; mostly LFAs ***a1*** & ***a2***
Deposits of major ephemeral streams along basin axes	
AA	Arroyo channel complexes (late Quaternary); LFA ***b***
AR	Channel complexes of large arroyos tributary to major fluvial systems (late Quaternary), mostly LFA ***b*** with some LFA ***a*** components
AU	Arroyo channel complexes—undivided (mostly mid-Pleistocene); mostly LFA ***b***
Deposits of major ephemeral streams or piedmont slopes & river-valley borders	
VA	Arroyo channel complexes (late Quaternary), LFA ***b***
BASIN-FLOOR HYDROSTRATIGRAPHIC UNITS—MIDDLE & LATE QUATERNARY	
Fluvial-fan, shallow channel, & overbank deposits of perennial to intermittent streams	
RAF	Animas Creek fluvial-fan & fan-delta unit; LFAs ***a*** & ***c***
RMF	Mimbres River fluvial-fan & fan-delta unit; LFAs ***a*** & ***c***
RCGF	Rio Casas Grandes fluvial-fan unit; mostly LFA ***a***
RCGD	Rio Casas Grandes fan-delta unit; LFAs ***a*** & ***c***
Deposits of major ephemeral streams in axial-basin sites	
AB	Unchannelled floodway deposits (narrow); LFAs ***b*** & ***c***
BF	Alluvial-flat deposits (broad); mostly LFA ***c***
BFP	Unit BF, with small vadose-playa-fill components; LFA ***c***
Lacustrine sediments (mostly late Quaternary)	
LB	Relict beach-ridge deposits (mostly coarse grained) of pluvial lakes
LS	Relict shoreline deposits (mostly medium grained) of pluvial lakes
LL	Relict lake-plain deposits; undivided, with LS & LP inclusions
LP	Playa & relict lake-plain complex; LFA ***c***
PIEDMONT-SLOPE HYDROSTRATIGRAPHIC UNITS—MIDDLE & LATE QUATERNARY	
PA	Alluvial fan deposits & pediment veneers ; mostly LFAs ***b***, ***5***, & ***6***
PAU	Piedmont-slope alluvium-undivided; like unit PA (mostly middle Pleistocene).
GILA GROUP BASIN FILL—MOSTLY NEOGENE	
Upper Gila hydrostratigraphic units (late Miocene to early Pleistocene)	
UG	Basin-floor & piedmont-slope deposits, undivided
UG1	Piedmont-slope deposits; mostly LFAs ***5*** & ***6***
UG2	Basin-floor deposits; mostly LFAs ***1–3***, with some LFA ***9***
Middle Gila Hydrostratigraphic Unit (middle–late Miocene)	
MG	Basin-floor & piedmont deposits, undivided; mostly LFAs ***3***, ***4***, ***7–10***
Lower Gila hydrostratigraphic unit (late Oligocene–middle Miocene)	
LG	Basin-floor & piedmont deposits, undivided; mostly LFAs ***4***, ***7–10***

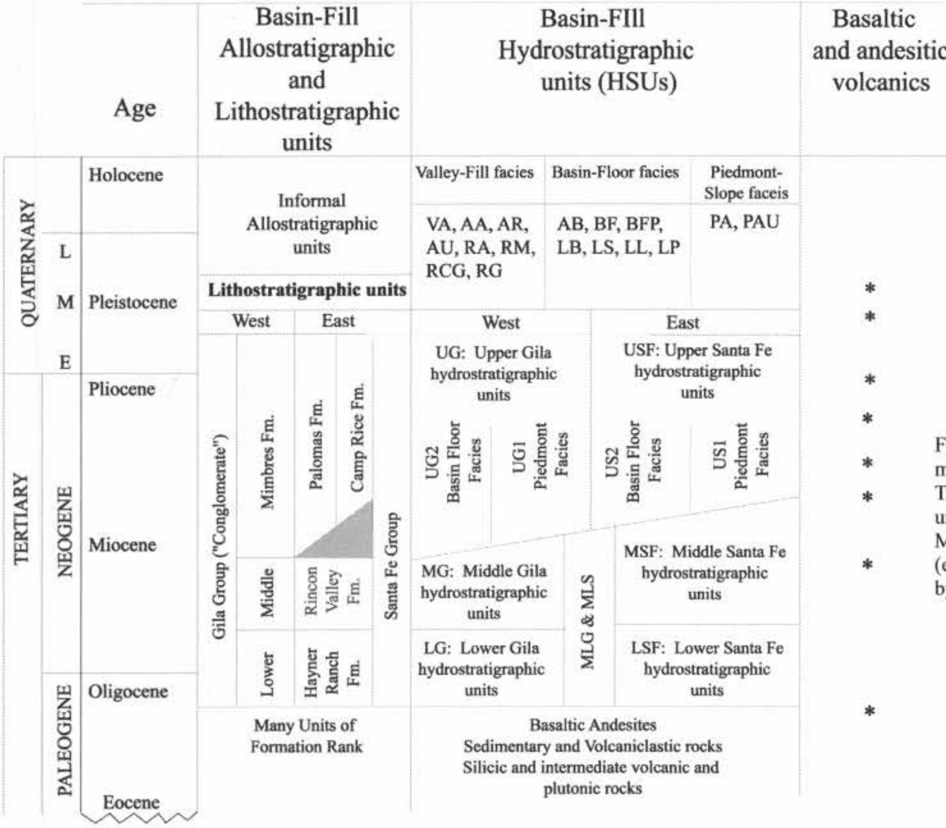

FIGURE 3. Provisional stratigraphic correlations of major basin and valley fills of late Cenozoic age (see Table 1), and relationships with contiguous bedrock units (Oligocene–Quaternary) in the southwestern New Mexico region. Approximate position of mafic volcanics (extrusive and intrusive) in basin-fill sequence indicated by asterisk.

Lithofacies assemblages

Lithofacies assemblages (LFAs) are the basic building blocks of the model (Table 2). These sedimentary facies classes are defined primarily on the basis of grain-size distribution, mineralogy, sedimentary structures, and degree of post-depositional alteration; they are grouped according to inferred environments of deposition. LFAs have distinctive geophysical, geochemical, and hydrologic attributes, and they provide a mechanism for showing distribution patterns of major aquifers and confining units in hydrogeologic cross-sections. In this study, basin and valley fills are subdivided into 13 major assemblages that are ranked in decreasing order of aquifer potential (Tables 2 to 4; LFAs ***1–10***, ***a-c***). Figure 4 is a schematic illustration of the distribution pattern LFAs observed in the Rio Grande rift and southwestern New Mexico Basin-and-Range region. Table 1 lists inferred interrelationships between major HSUs and LFAs. Lithofacies properties that influence groundwater flow and production potential in this region are summarized in Tables 3 and 4. Note that *Roman numeral* notation (I–X) originally used in previous hydrogeologic framework models (Hawley et al., 1995) has been changed to *Arabic* style in order to facilitate the development of alpha-numeric attribute codes that can be used in both conceptual and numerical models of basin-fill aquifer systems.

Bedrock and structural boundary components

Structural and bedrock features that influence aquifer composition and behavior include basin-boundary mountain uplifts, bedrock units beneath the basin-fill, fault zones and flexures within and at the edges of basins, and igneous intrusive and extrusive rocks that penetrate or are interbedded with basin fill. Tectonic evolution of the fault-block basins, many with a half-graben structure and accommodation-zone terminations, and ranges of the study area has had a profound effect on the distribution of lithofacies assemblages and the timing and style of emplacement of all major hydrostratigraphic units (Figs. 3, 4). Discussion of this topic is beyond the scope of this paper, and the reader is referred to particularly pertinent reviews by Seager and Morgan (1979), Mack and Seager (1990), Smith (1994), Mack et al. (1997), Faulds and Varga (1998), and Hawley et al. (2000).

Hydraulic properties of major hydrogeologic units

The most productive part of the basin-fill aquifer system is formed by (1) unconsolidated to partly indurated deposits of the ***upper*** and ***middle Gila*** HSUs, and (2) overlying basin and valley fills deposited by the Animas, Mimbres, and Gila fluvial systems (Hawley et al., 2000). The total saturated thickness of these units rarely exceeds 150 m. Limiting assumptions used in this study for preliminary estimates of available water stored in the basin-fill aquifer systems include: (1) aquifer is unconfined, (2) estimated average thickness is 100 m, (3) specific yield is 0.1, and (4) water is potable quality (<1,000 mg/L TDS). Irrigation-well specific-capacity data and a few pumping tests from the Animas, Playas, and Mimbres basin systems provide the basis for many of the published interpretations of aquifer performance and hydraulic properties (Reeder, 1957; Doty, 1960; Trauger, 1972; Hanson et al., 1994; Wilkins, 1998).

Maximum discharge ranges for most irrigation wells are from 1090 to 5450 m^3/d (cubic meters per day). Calculated aquifer transmissivities are as high as 4650 m^2/d (square meters per day) at a few localities, but most values are in the 200–2000 m^2/d range. Typical ranges in horizontal conductivity for the upper, more productive parts of the aquifer system are from 1 to 10 m/d. Specific yield estimates vary from 0.1 to 0.2, assuming unconfined aquifer conditions. Because semiconfined to confined conditions prevail in many parts of the aquifer system, estimates of ground-water availability (as well as assessment of aquifer-deformation and land-subsidence potential) may require much smaller storage coefficient values (Kernodle, 1992a, b; Haneberg and Friesen, 1995).

Highest average specific capacities (232–304 $m^3/d/m$) are reported for wells completed mainly in the coarse-grained fluvial facies (LFAs ***1*** and ***2***) of ***upper Gila*** HSUs and overlying deposits of the ancestral Mimbres and Animas fluvial systems (e.g., HSUs, RMF, and RAF; LFAs ***a1*** and ***a2***). Saturated thickness of these units is about 100 m. Wells completed in the 100–200-m zone usually penetrate partly indurated basin-fill of the ***middle Gila*** HSU, as well as the basal part of ***upper Gila*** deposits (LFAs ***3–5***, ***7***). Their specific capacities are typically in the 143–214 $m^3/d/m$ range. Wells completed at depths between 200 and 300 m commonly penetrate partly indurated to well-consolidated deposits of the

TABLE 2. Summary of inferred depositionsl settings and processes, and dominant textural classes of lithofacies assemblages in Gila-Santa Fe (*1–10*) and post-Gila-Santa Fe (*a–c*) hydrostratigraphic units (modified from Hawley and Haase, 1992, Table III-2).

Lithofacies	Inferred depositional settings and process	Dominant textural classes
1	Basin-floor fluvial plain	Sand and pebble gravel lenses of silty clay
2	Basin-floor fluvial, locally eolian	Sand; lenses of pebble sand, and silty clay
3	Basin-floor, fluvial-overbank, fluvial-deltaic and playa-lake; eolian	Interbedded sand and silty clay; lenses of pebbly sand
4	Eolian, basin-floor alluvial	Sand and sandstone; lenses of silty sand–clay
5	Distal–medial piedmont-slope, alluvial fan	Gravel, sand, silt, and clay; common loamy (sand-silt-clay)
5a	Distal–medial piedmont-slope, alluvial fan; associated with large watersheds; alluvial-fan distributary-channel primary, sheet-flood and debris-flow secondary	Sand and gravel; lenses of gravelly, loamy sand–sandy loam
5b	Distal–medial piedmont-slope, alluvial-fan; associated with small steep watersheds; debris-flow, sheet-flood, and distributary-channel	Gravelly, loamy sand–sandy loam; lenses of sand, gravel, and silty clay
6	Proximal–medial piedmont-slope, alluvial fan	Coarse gravelly, loamy sand and sandy loam; lenses of sand and cobble to boulder gravel
6a	Like *5a*	Sand and gravel; lenses of gravelly–non-gravelly, loamy sand–sandy loam
6b	Like *5b*	Gravelly, loamy sand–sandy loam; lenses of sand, gravel, and silty clay
7	Like *5*	Partly indurated *5*
8	Like *6*	Partly indurated *6*
9	Basin-floor—alluvial flat playa lake, and fluvial-lacustrine; distal-piedmont alluvial	Silty clay interbedded with sand, silty sand and clay
10	Like *9*, with evaporite processes (paleophreatic)	Partly indurated *9*, with gypsiferious and alkali-impregnated zones
a	River-valley and basin-floor fluvial	Sand, gravel, silt and clay
a1	Basal channel	Pebble–cobble gravel and sand (like *1*)
a2	Braided plain channel	Sand and pebbly sand (like *2*)
a3	Overbank meander-belt oxbow	Silty clay, clay, and sand (like *3*)
b	Arroyo channel and valley-border alluvial-fan	Sand, gravel, silt, and clay (like *5*)
c	Basin floor alluvial flat, cienega, playa, and fluvial-fan–lacustrine plain	Silty clay, clay and sand (like *3*, *5*, and *9*)

middle and ***lower Gila*** units (LFAs ***3–5***, ***7–9***), and average specific capacities range from 125 to 161 m^3/d. Specific capacities of wells drilled below 200 m are usually much less than 90 $m^3/d/m$. Horizontal hydraulic conductivities in conglomeratic sandstones and mudstones of the ***lower Gila*** HSU (LFAs ***7***, ***8***) rarely exceed 0.3 m/d. The available published information for these units indicate that vertical hydraulic conductivities are significant, on the order of several hundred to several thousand times, less than horizontal conductivities (Kernodle, 1992a).

OVERVIEW OF GROUND-WATER FLOW IN BASIN-FILL AQUIFER SYSTEMS

Of the four basin systems discussed, the Mimbres and Hachita-Moscos systems are the only ones with important transboundary aquifers and ground-water-flow components (Fig. 1). All predevelopment (pre-1900) discharge was southward into Mexico (Darton, 1916; Schwennesen, 1918). The estimated upper limit of annual transboundary ground-water movement through these basin-fill aquifer systems during the past century is about 10.5 x 10^6 m^3. The hydrogeologic framework and ground-water-flow regimes in these basin systems (Hawley et al., 2000) are briefly summarized below.

Mimbres basin system

The largest and most complex basin system described in this paper is the *open* and *drained* Mimbres system (Fig. 1). The upper Mimbres,

TABLE 3. Summary of lithofacies properties that influence ground-water flow in Gila Group hydrostratigraphic units.

Lithofacies	Ratio of sand plus gravel–silt plus clay[1]	Bedding thickness (meters)	Bedding configuration[2]	Bedding continuity (meters)[3]	Bedding connectivity[4]	Hydraulic conductivity (K)[5]	Ground water production potential
1	High	>1.5	Elongate–planar	>300	High	High	High
2	High–moderate	>1.5	Elongate–planar	>300	High–moderate	High–moderate	High–moderate
3	Moderate	>1.5	Planar	150–300	Moderate–high	Moderate	Moderate
4	Moderate–low*	>1.5	Planar–elongate	30–150	Moderate–high	Moderate	Moderate
5	Moderate–high	0.3–1.5	Elongate–lobate	30–150	Moderate	Moderate–low	Moderate–low
5a	High–moderate	0.3–1.5	Elongate–lobate	30–150	Moderate	Moderate	Moderate
5b	Moderate	0.3–1.5	Lobate	30–150	Moderate–low	Moderate–low	Moderate–low
6	Moderate–low	0.3–1.5	Lobate–elongate	30–150	Moderate–low	Moderate–low	Low–moderate
6a	Moderate	0.3–1.5	Lobate–elongate	30–150	Moderate	Moderate–low	Moderate–low
6b	Moderate–low	0.3–1.5	Lobate	<30	Low–moderate	Low–moderate	Low
7	Moderate*	0.3–1.5	Elongate–lobate	30–150	Moderate–low	Low	Low
8	Moderate–low*	>1.5	Lobate	<30	Low–moderate	Low	Low
9	Low	>0.3	Planar	>150	Low	Very low	Very low
10	Low*	>0.3	Planar	>150	Low	Very low	Very low

[1] High >2; moderate 0.5–2; low <0.5

[2] Elongate (length–width ratios >5); planar (length–width ratios 1–5); lobate (asymmetrical or discontinuous planar beds).

[3] Measure of the lateral extent of an individual bed of given thickness and configuration.

[4] Estimate of the ease with which groundwater can flow between individual beds within a particular lithofacies. Generally, high sand + gravel/silt + clay ratios, thick beds, and high bedding continuity favor high bedding connectivity. All other parameters being held equal, the greater the bedding connectivity, the greater the groundwater production potential of a sedimentary unit (Hawley and Haase 1992, p. VI).

[5] High, 10–30 m/day; moderate, 1–10 m/day; low, <1 m/day; very low, <0.1 m/day.

* Significant amounts of cementation of coarse-grained beds (as much as 30%)

TABLE 4. Summary of lithofacies properties that influence ground-water flow in of post-Gila Group basin and valley fills.

Lithofacies	Ratio of sand plus gravel–silt plus clay[1]	Bedding thickness (meters)	Bedding configuration[2]	Bedding continuity (meters)[3]	Bedding connectivity[4]	Hydraulic conductivity (K)[5]	Ground water production potential
a	High	>1.5	Elongate–planar	>300	High	High	High
a1	High–moderate	>1.5	Elongate–planar	>300	High–moderate	High–moderate	High–moderate
a2	Moderate>	>1.5	Planar	150–300	Moderate–high	Moderate	Moderate
a3	Moderate	>1.5	Planar–elongate	30–150	Moderate–high	Moderate	Moderate
b	Moderate–low	0.3–1.5	Elongate–lobate	<100	Moderate	Moderate–low	Moderate–low
c	Low–moderate	0.3–1.5	Elongate–lobate	30–150	Low	Low	Low

[1] High >2; moderate 0.5-2; low <0.5.
[2] Elongate (length–width ratios >5); planar (length–width ratios 1-5); lobate (asymmetrical or discontinuous planar beds).
[3] Measure of the lateral extent of an individual bed of given thickness and configuration.
[4] Estimate of the ease with which ground water can flow between individual beds within a particular lithofacies. Generally, high sand + gravel/silt + clay ratios, thick beds, and high bedding continuity favor high bedding connectivity. All other parameters being held equal, the greater the bedding connectivity, the greater the ground-water production potential of a sedimentary unit (Hawley and Haase 1992, p. VI).
[5] High, 10–30 m/day; moderate, 1–10 m/day; low, <1 m/day; very low, <0.1 m/day.
*Significant amounts of cementation of coarse-grained beds (as much as 30%).

Dwyer, San Vicente, Deming, Hermanas, and Florida subbasins form the major structural lows; the Cookes Range, Florida uplift, and Tres Hermanas Mountains are the largest intra-basin ranges (Darton, 1916; Trauger, 1972; Seager et al., 1982, Drewes et al., 1985; Hanson et al., 1994; Seager, 1995; Clemons, 1998). The Mimbres basin complex covers about 11,300 km^2 of New Mexico and about 2,000 km^2 of Chihuahua (Hawley et al., 2000). Low, volcanic upland areas separate most of the basin system from the Palomas and Mesilla basins of the Rio Grande rift structural province to the east. Much of the system's western and northern boundary is along the Continental Divide, and includes the crests of Sierra Alta, the Cedar Mountain Range, and the southern Burro uplift (Fig. 1). The Upper Mimbres subbasin is located in the southeastern Datil-Mogollon section and includes the only perennial reach of the Mimbres River. About 85% of the basin system is in the Mexican Highland section and includes the only major transboundary aquifer unit in the study area (Hawley et al., 2000). Older channel and fluvial-fan deposits of the ancestral Mimbres River extend to the Mexican border in the Deming and Florida subbasins. These deposits cover much of the basin-floor area between Deming and the Columbus-Palomas border community and they constitute the largest alluvial aquifer in the study area (Darton, 1916; Seager, 1995; Love and Seager, 1996; Mack et al., 1997).

Maximum fill thicknesses in the deepest structural subbasins (San Vicente, Deming, Hermanas, and Florida) are in the 600–1525-m range (Birch, 1980; Heywood, 1992, unpublished; Klein, 1995; Seager, 1995; Clemons, 1998)). As emphasized throughout this paper, productive aquifer zones are usually restricted to the upper 300 m of the basin-fill sequence (HSUs: UG2/MG; LFAs 1-3, a). Intervening structural highs form not only "insular" (Cookes, Florida, Tres Hermanas) mountain ranges and hilly uplands, but also buried bedrock highs or "sills." These

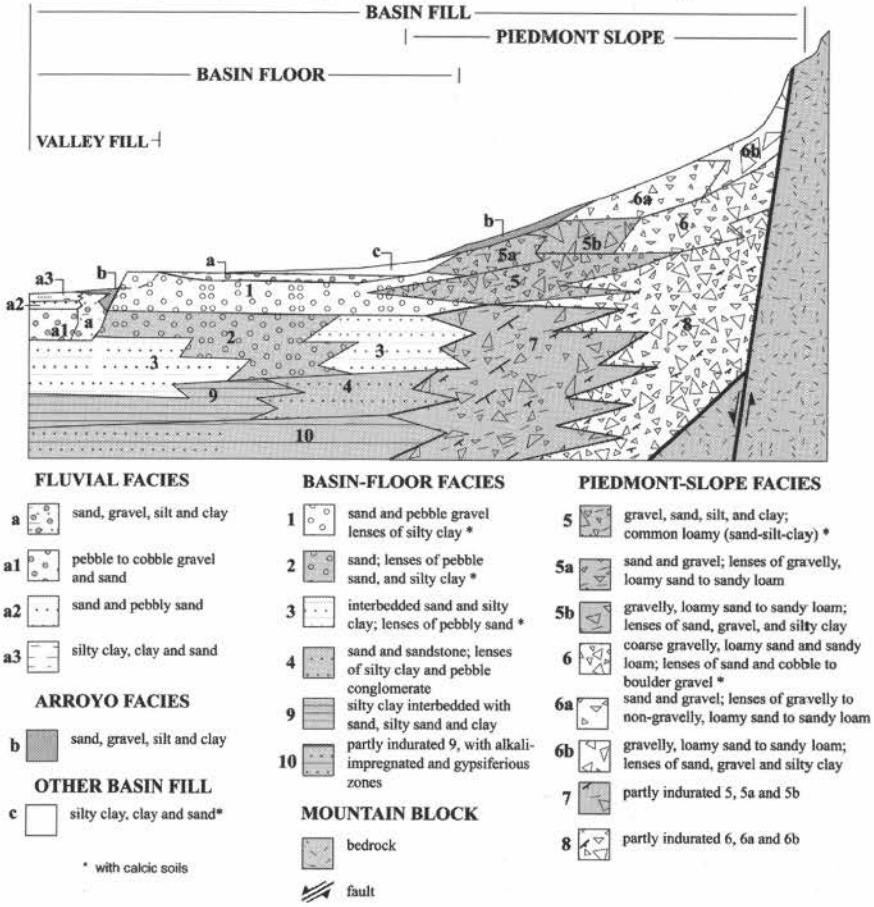

FIGURE 4. Schematic distribution pattern of major lithofacies components of hydrostratigraphic units (see Table 1) in intermontane basins of the Mexican Highland Section.

geohydrologic constrictions have a relatively thin cover of saturated basin fill and restrict southward ground-water flow between subbasins (Hawley et al., 2000). A very "optimistic" estimate of potable ground water stored in the unconfined part of the aquifer system is no more than 38 x 10^9 m^3. This estimate may be much too high, because at many localities most of the upper 100 m of the basin-fill aquifer is fine grained, and semiconfined to confined conditions prevail (Hanson et al., 1994; Haneberg and Friesen, 1995). In addition, much of the water stored in thicker aquifer zones may be very old (thousands to tens of thousands of years) and of poor quality, and it is not effectively recharged under Holocene climatic conditions. Published estimates suggest that 1–2% of average annual precipitation, primarily concentrated in high mountain areas in the northern part of the basin system, contributes to ground-water recharge (Hanson et al., 1994). Total annual recharge could be as high as about 74 x 10^6 m^3, with the mountain-front component estimated at about 66 x 10^6 m^3.

Ground water in the Mimbres basin system generally moves from the northern highlands adjacent to the Continental Divide to the interior (San Vicente, Deming and Florida) subbasins flanking the Cookes Range and Florida Mountains (Fig. 1). It then flows southward toward the Hermanas-Columbus (Palomas)-West Portillo segment of the International Boundary zone (Blandford and Wilson, 1987). Estimated predevelopment (pre-1900) flow into Mexico was about 8 x 10^6 m^3 annually (Hanson et al., 1994). Much of this flow has been intercepted by irrigation wells in the Deming, Hermanas, and Columbus-Palomas areas during the past century. The regional sink for ground water crossing the New Mexico-Chihuahua border is the complex of _vadose_ and _phreatic playas_ on the floor of Bolson de los Muertos at the south end of the Columbus and Florida subbasins of the Mimbres system (Hawley et al., 2000). This area has an elevation of about 1175 m and includes the eastern basin of pluvial Lake Palomas (Reeves, 1969). The lake had a maximum highstand area of about 7770 km^2 recorded by relict shoreline features at an elevation of about 1225 m (Hawley 1969, 1993).

Hachita-Moscos basin system

The _closed_ and _partly drained_ Hachita-Moscos basin system includes a small, but important trans-boundary aquifer component. The system has an area of about 2700 km^2, with about 1100 km^2 in Chihuahua (Fig. 1). The system includes three half-graben complexes that are designated the Upper Hachita, Wamel-Moscos and Lower Hachita subbasins by Hawley et al. (2000). Early reconnaissance of hydrogeologic conditions was done by Schwennesen (1918) and Trauger and Herrick (1962). Bordering mountain ranges effectively separate the Hachita-Moscos system from the Mimbres and Playas basin systems except at Hatchet Gap between the Big and Little Hatchet ranges (Fig. 1). In this area there is a small amount of surface and subsurface inflow from the Upper Playas subbasin to the southwest. Ephemeral axial streams (Hachita and Wamel's Draws) carry surface runoff from highland areas and converge in a large _closed_ depression in Chihuahua that is occupied by the ephemeral-lake plain of Laguna los Moscos. During Late Quaternary pluvial stages, this depression was episodically flooded by Lake Hachita (Schwennesen, 1918). Maximum lake surface area was about 150 km^2 based on highest relict-shoreline elevations at 1262 m (Hawley, 1993).

Geophysical surveys (Birch, 1980; Klein, 1995; Heywood, 1992) indicate that maximum fill thicknesses in the subbasins range from about 600 to 1525 m. The primary aquifer system comprises basin-floor and piedmont-slope deposits of the **_upper_** and **_middle Gila_** HSUs (UG1,2 and MG) that are unconsolidated to partly indurated. These units are no more than 200 m thick, and LFAs *1–5* are the major aquifer components. Available ground water of potable quality in storage is probably significantly less than the maximum volume of 6 x 10^9 m^3 estimated by Hawley et al. (2000). Their estimated annual recharge to Hachita-Moscos basin fill aquifers is about 6 x 10^6 m^3. This amount includes a small annual underflow component (less than 10,000 m^3 that "spills" from the Upper Playas subbasin into the Upper Hachita subbasin through Hatchet Gap (Schwennesen, 1918; Hawley et al., 2000).

Ground-water flow generally mimics surface topography and moves eastward along basin axial trends toward Laguna los Moscos. Early geohydrologic observations indicate that this _playa_ has both _phreatic_ and _vadose_ flow components (Schwennesen, 1918; Trauger and Herrick, 1962). More recent work also suggests that there is a partial underflow (drainage) connection between Laguna Los Moscos and the Lower Valley of Rio Casas Grandes, which is located only 10 km to the east across a very low topographic divide (Hawley et al., 2000). A preliminary estimate of potential annual ground-water flow across the combined Hachita and Wamel-Moscos International Boundary segments is no more than 2.5 x 10^6 m^3.

Playas basin system

The _partly closed, partly drained_ Playas basin system (Fig. 1) has an area of about 2400 km^2 (Schwennesen, 1918; Doty, 1960). It is bordered on the south by a "no-flow" drainage divide with the San Basilio basin of northwestern Chihuahua (Hawley et al., 2000). The Continental Divide, which follows the crest of the Animas Mountains, forms the western and northern boundary of the Playas basin system. Its eastern border with the Hachita-Moscos system follows the crest of the Dog, Alamo Hueco, and Big and Little Hatchet uplifts. The Upper (southern) Playas subbasin is an _open_ and _drained_ geohydrologic unit that primarily discharges northward to the _closed_ and _partly drained_ Lower Playas subbasin, but as already noted, a small amount of flood runoff and ground-water underflow "spills" through Hatchet Gap into the Upper Hachita subbasin. The Lower Playas subbasin includes a large ephemeral-lake plain (_phreatic-vadose playa_ complex) now periodically flooded by Playas Lake. During the Late Quaternary this depression was episodically flooded by pluvial Lake Playas (Schwennesen, 1918; Van Devender and Worthington, 1978), which had a maximum surface area of about 65 km^2 based on the elevation of the highest shoreline features at about 1311 m (Hawley, 1993).

Maximum basin-fill thickness is estimated to be at least 600 m (Birch, 1980; Klein, 1995), but the primary aquifer system comprises basin-floor and piedmont-slope deposits of the **_upper_** and **_middle Gila_** HSUs (UG2, UG1, and MG). These units are unconsolidated to partly indurated (mainly LFAs **_1-5_**) and no more than 300 m thick. A very optimistic estimate of available potable ground water stored in the unconfined part of the saturated zone is no more than 6 x 10^9 m^3, and estimated annual recharge to the Playas basin aquifer system is about 7 x 10^6 m^3. The major recharge sources in both the Playas and Animas-Cloverdale systems are the high Sierra San Luis and Animas mountain ranges that border the Upper Playas subbasin on the west (Hawley et al., 2000).

A provisional estimate (Hawley et al., 2000) of annual northward flow from the Upper to Lower Playas subbasins in the **_upper_** and **_middle Gila_** basin-fill aquifer system is about 5.48 x 10^6 m^3. Most of this flow was discharged by evaporation and transpiration in the southern Playas Lake depression in predevelopment time (pre-1945). However, previous investigations suggest that a very small amount of underflow also could have "leaked" from the Lower Playas area into aquifers of the northern Animas Basin system via conduits beneath the Continental Divide northwest and north(?) of Playas Lake (Fig. 1; Schwennesen, 1918; Reeder, 1957; Doty, 1960).

Animas basin system

The Animas basin system (Fig. 1) is an interconnected group of four structural and geohydrologic subbasins with a watershed area of about 6340 km^2 (Schwennesen, 1918; Reeder, 1957; Hawley et al., 2000). The Continental Divide, including the crests of the San Luis and Animas ranges, forms the entire eastern boundary of the system. Its western border with the San Bernardino and San Simon basins (mainly in Arizona) is formed by the Peloncillo-Guadalupe range. The _closed_ and _partly drained_ Cloverdale (or San Luis) subbasin, at the south end of the Animas basin system, extends into Mexico and straddles the intersection of the borders of New Mexico, Chihuahua, and Sonora (Krider, 1998; Vincent and Krider, 1998). This subbasin, with a total area of 480 km^2, has a small transboundary aquifer component (<100 km^2). It includes a large _phreatic-vadose playa_ complex, as well as a "perched-aquifer" zone in a shallow _closed_ depression. The latter area was episodically flooded by pluvial Lake Cloverdale during both the Wisconsin

Glacial Stage and wetter intervals of the Holocene (Schwennesen, 1918; Krider, 1998). The maximum lake area was about 104 km^2 based on the elevation of highest shoreline features at about 1577 m (Hawley, 1993).

The only perennial to intermittent streams in the Animas basin system are in the southern part of the *open* and *drained* Upper Animas subbasin, which is separated from the Cloverdale subbasin by a low topographic divide (Krider, 1998). This fluvial system occupies the valley of Animas Creek and its major headwater tributaries (Schwennesen, 1918; Reeder, 1957; Vincent and Krider, 1998). The Upper Animas subbasin opens northward into the *closed* and *drained* Lower Animas subbasin, which includes the important Animas-Cotton City area of irrigation agriculture west of the central Mimbres basin system. Dominant surficial units are widespread fluvial-deltaic deposits of ancestral Animas Creek and an extensive middle–late Pleistocene basalt flow west of Animas (Schwennesen, 1918; Reeder, 1957; Fleischhauer and Stone, 1982; O'Brien and Stone, 1983, 1984; Drewes et al., 1985; Machette et al., 1986). The northern part of the Lower Animas subbasin includes extensive dune fields and a large ephemeral-lake plain with alkali flats that forms a *vadose playa* complex. During late Quaternary pluvial intervals, the basin floor area below elevations ranging from 1270 to 1279 m was episodically flooded by Lake Animas (Schwennesen, 1918). At its deepest (latest Pleistocene) stage the lake had a surface area of about 390 km^2 (Fleischhauer and Stone, 1982; Hawley, 1993).

The *open* and *drained* Lordsburg subbasin, which heads in the Burro Mountain-Continental Divide area (Fig. 1) joins the Lower Animas subbasin at the eastern edge of the South Alkali Flat depression. The major axial streams in this subbasin are ephemeral Lordsburg Draw and Burro Cienega, its largest tributary. A shallow basin-fill aquifer with an area of about 315 km^2 at the eastern edge of the Lordsburg subbasin (China Draw section) contributes some underflow discharge to the western Mimbres basin system across the Continental Divide.

Maximum basin-fill thickness is estimated to be about 600 m (Birch, 1980; O'Brien and Stone, 1984; Klein, 1995). The primary aquifer consists of coarse-grained basin-floor facies assemblages deposited by the ancestral Animas Creek and Lordsburg Draw fluvial systems. Major hydrostratigraphic units include ***upper*** and ***middle***(?) ***Gila*** fluvial facies (HSUs: USF 2 and MSF; LFAs *1-3*), and post-Gila Group stream and fan-delta deposits of middle and late Pleistocene age (HSU: RAF; LFAs ***a***, ***c***). Maximum thickness of productive aquifer zones may locally exceed 200 m, but most ground-water production in the Animas-Cotton City-Lordsburg irrigation area is from the upper 150 m of saturated basin fill. A very optimistic estimate of available ground water of potable quality stored in the unconfined part of the saturated zone is no more than 1.2×10^{10} m^3. Estimated annual recharge to the Lower Animas subbasin aquifer system is about 1.58×10^7 m^3. The major recharge sources are from the high ranges that flank the Upper Animas subbasin (Reeder, 1957; Hawkins, 1981; O'Brien and Stone, 1983).

A very small component of ground-water flow from the thin "perched" aquifer zone in the Lake Cloverdale area may leak southwestward into the Sonora part of the adjacent San Bernardino basin; however, most ground water in the Cloverdale subbasin discharges as underflow into "perched" and "deep" aquifers of the Upper Animas subbasin beneath the valleys of Animas Creek and its major tributaries. Underflow then moves northward toward agricultural and urban pumping centers in the Lower Animas subbasin. Under predevelopment conditions a large volume of ground water moved beyond the local cienegas and the Alkali Flat (*vadose playa*) area and discharged as underflow to the Duncan-Virden Valley segment of the Gila River basin aquifer system (Schwennesen, 1918; Reeder, 1957). O'Brien and Stone (1983) estimate that the pre-development outflow from the Lower Animas subbasin to this area was as much as 16×10^6 m^3/yr. Prior to ground-water pumpage in the Lower Playas subbasin, a small amount of underflow probably leaked into the Lower Animas subbasin through conduits in the structural gap between the Animas and Pyramid uplifts (Schwennesen, 1918; Reeder, 1957; Doty, 1960).

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