CHAPTER 3 - OVERVIEW

GENERAL GEOGRAPHIC SETTING

Introduction

The area encompassed by this study lies primarily in New Mexico between north latitude 33°45'00" and 31°20'00" and west longitude 106°58'12" and 109°03'00". The general location is shown in Figure 3-1 and covers an area of about 31,600 km^2 (12,000 mi^2) in New Mexico. Principal transboundary aquifer systems in the region include the Mimbres Basin, Hachita-Moscos Basin, Playas Basin, Animas Basin, and the San Bernardino Basin (Figure 3-1). The San Simon Basin is also part of a transboundary aquifer system; however, the far eastern portion of this basin is only partially in New Mexico. It merges southward with the San Bernardino Basin, which extends into Mexico along the Arizona-Sonora boundary. Major aquifer systems in the Mimbres and Hachita-Moscos basins cross the International Boundary and extend into the state of Chihuahua. The Gila Basin in New Mexico is a through flowing system that drains into Arizona and does not contribute significantly to transboundary aquifers within southwestern New Mexico. This major contributor to the Colorado River system comprises the upper Gila Basin within the Gila-San Francisco watershed.

Because of the inherent complexity of intermountane-basin aquifers and groundwater-flow systems, and the prevailing arid to semiarid climatic conditions, large variability in groundwater quantity and quality is to be expected in the study region. From this regional geohydrologic perspective, moreover, the very finite nature of groundwater resources has always been recognized (Meinzer and Hare 1915, Darton 1916, Schwennesen 1918, Trauger and Doty 1965, Wilkins 1986, Anderson et al. 1993, Robson and Banta 1995, DGGTN nd-c,e). It is beyond the scope of this project to delineate specific places where quantity and/or quality conditions dictate that groundwater resources may or may not be available for future development, particularily in the context of current economic and environmental concerns. Groundwater availability, however, will be addressed from the broader perspective of individual basins (introduced below) and their subbasin components.

This report divides the study area into six separate aquifer systems, which is done to simplify the discussion of significant transboundary aquifers. We chose to use the term "system" to acknowledge the complexity of groundwater flow in the region. The primary systems within the study area are the Mimbres Basin (Chapter 4), the Hachita-Moscos Basin (Chapter 5), the Playas Basin (Chapter 6), and the Animas Basin (Chapter 7). The Gila Basin system is also included in this study (Chapter 8), even though it does not contribute to a transboundary aquifer system within our study area. However, this basin has a significant watershed in New Mexico, and it serves as a regional sink for some transboundary aquifers west of the Continental Divide. The discussion of the Gila Basin is limited mainly to the Gila River Valley and the valley of Sapillo Creek, which is the main Gila tributary contiguous to the Mimbres Basin. The San Bernardino Basin is a significant transboundary aquifer in its own right, however, the majority of the basin is outside New Mexico, and it will receive less attention (Chapter 9).

The New Mexico Office of the State Engineer has defined most groundwater basins in the area for administrative purposes. These "declared basins" include the San Simon, Virden, Gila River, Animas, Lordsburg, Playas, and Mimbres basins. Administrative basins in contiguous parts of Arizona, Sonora, and Chihuahua are also recognized where deemed appropriate. Borders of these administrative units, however, do not necessarily match the geohydrologic boundaries of the surface-watershed or groundwater-flow systems that are the subject of this investigation.

The compilation of geographic and hydrogeologic information on transboundary aquifers of the study region (described above and introduced in this chapter) is synthesized on Plate 1. This information will be discussed in much more detail in the following sections and in chapters (4 to 9) dealing with individual components of the six basin complexes or "basin systems" of the study area (Mimbres, Hachita-Moscos, Playas, Animas, Gila, and San Bernadino).

The Mimbres Basin aquifer system is developed extensively and satisfies the municipal, industrial, and agricultural water demands in the Deming and Columbus, New Mexico, and Palomas, Chihuahua areas. The locally common name of "Palomas" is used instead of the official name of General Rodrigo M. Quevedo that is listed on more recent maps of Mexico. The same community is also referred to as Puerto Palomas and "Las Polomas" on some maps. The Hachita-Moscos Basin aquifer system has little development and primarily satisfies the water needs of local ranchers. In the 1950s, the Playas Valley supported many agricultural enterprises; in recent years the primary user of Playas Valley groundwater has been the Phelps Dodge Smelter. The current downturn in copper production, however, indicates that mine-mill consumption faces a significant decline in, at least, the near future. The Animas Valley aquifer system is the location of much of the current agricultural activity and groundwater exploitation.

Physiographic Setting

Most of the study area lies within the Mexican Highland section of the Basin and Range province (Fenneman 1931, Hawley 1986) and only the northern (upper Gila and Mimbres River Basins) are located in the Datil-Mogollon section of the Transition-Zone province (Hawley 1969, 1975, 1986, Morrison 1991). The surface drainage system of the region is distinguished by numerous *closed* topographic basins and the Continental Divide, which crosses the study area from northeast to southwest. Divide elevations range from 3,051 m (10,011 ft) in the Black Range, at the head of the Mimbres River watershed, to about 1,359 m (4,460 ft) near the point where Interstate Highway I-10 crosses the broad "Antelope Plains" area between Deming and Lordsburg.

The Continental Divide separates surface waters flowing to the Gulf of Mexico and Gulf of California in only a few places. In most of the Basin and Range-Mexican Highland region, surface water flows toward closed depressions on the extensive floors of the *closed* intermontane basins (*bolsons*) that characterize this part of the Basin and Range province. These depressions probably have not spilled to the valleys of the Rio Grande, Gila or Yaqui fluvial systems for several hundred thousand to more than one million years.

Datil-Mogollon Section of the Transition Zone Province

The northeastern part of the study area includes the southern portion of the Datil-Mogollon section of the Transition Zone (TZ) province (Peirce 1985, Hawley 1986, Morrison 1991). This area marks the transition of unextended geologic "terrane" of the Colorado Plateau province, and the lower-lying, more extended Basin and Range area. Typical landforms of the Datil-Mogollon section include the high plateaus of the Middle Cenozoic Mogollon-Datil volcanic field (Elston 1984, Ratté et al. 1984), which are cut by deep canyons of the upper Gila-San Francisco River system. The plateau and canyon topography is locally interrupted by narrow structural basins and flanking fault-block uplifts. The highest peaks are in the Mogollon Mountains, with Whitewater Baldy at 3,320 m (10,892 ft), and the Black Range, with both Reeds and Hillsboro peaks at 3,051 m (10,011 ft), and lowest valley and canyon floors are in the 1,600 to 1,900 m (5,250 to 6,250 ft) range. The Datil-Mogollon section contains the only perennial fluvial systems in the study area, namely the Gila and San Francisco rivers, which are tributary to the Colorado River (at Yuma, AZ), and the headwaters reach of the Mimbres River.

Mexican Highland Section of the Basin and Range (B&R) Province

The dominant landforms of Basin and Range-Mexico Highland section (Bolson subsection of Hawley 1969, 1975, 1986) are gently sloping to nearly level alluvial and lacustrine plains of the extensive intermontane basins that characterize the study area. Basin (*bolson*) floors merge mountainward with broad piedmont slopes (primarily "bajadas" formed by coalescing alluvial fans) that flank isolated mountain highlands and other upland areas with "hilly" (<300m) local relief. Some basins have floors containing ephemeral-lake plains (playas) and no surface outlets. Others contain axial drainageways which occasionally discharge to lower external areas (semibolsons, Tolman 1909).

Bedrock-cored uplands occupy less than 20% of the Basin and Range area, and they typically rise abruptly from the piedmont alluvial plains. Most basins and ranges are tilted, fault-bounded blocks of extended parts of the Earth's crust. Differential subsidence and uplift of crustal blocks over the past 25 million years (Ma) has produced the present topography of north-south and northwest-southeast trending basins and ranges.

The major mountain ranges in the Mexican Highland part of the study area are: the Big Burro Mountains, with Burro Peak at 2,449 m (8,035 ft); the Cooke's Range, with Cooke's Peak at 2,563 m (8,408 ft); the Big Hatchet Mountains, with Big Hatchet Peak at 2,573 m (8,441 ft), and the Animas Mountains, with Animas Peak at 2,600 m (8,532 ft).

Basin system index map

Index	*Basin System*	*Chapter*
1	Mimbres Basin	4
2	Hachita- Moscos Basin	5
3	Playas- San Basilio Basin	6
4	Animas Basin	7
5	Gila Basin	8
6	San Bernardino	9

Explanation

Primary Highway	Boundary between the Datil-Mogollon subprovince and the Basin and Range Province
Secondary Highway	Pluvial Lakes/Playas (see Table 3-4)
County Line	
State Line	
International Boundary	
Perennial Streams	
Intermittent Streams	
Surface Drainage Basin Divides	
Surface Drainage Subbasin Divides	
Continental Divide	

Pluvial Lakes

- Animas (LA)
- Cloverdale (LCl)
- Cochise (LCo)
- Goodsight (LG)
- Hachita (LH)
- Palomas (LPa)
- Playas (LPl)
- San Agustin (LSA)

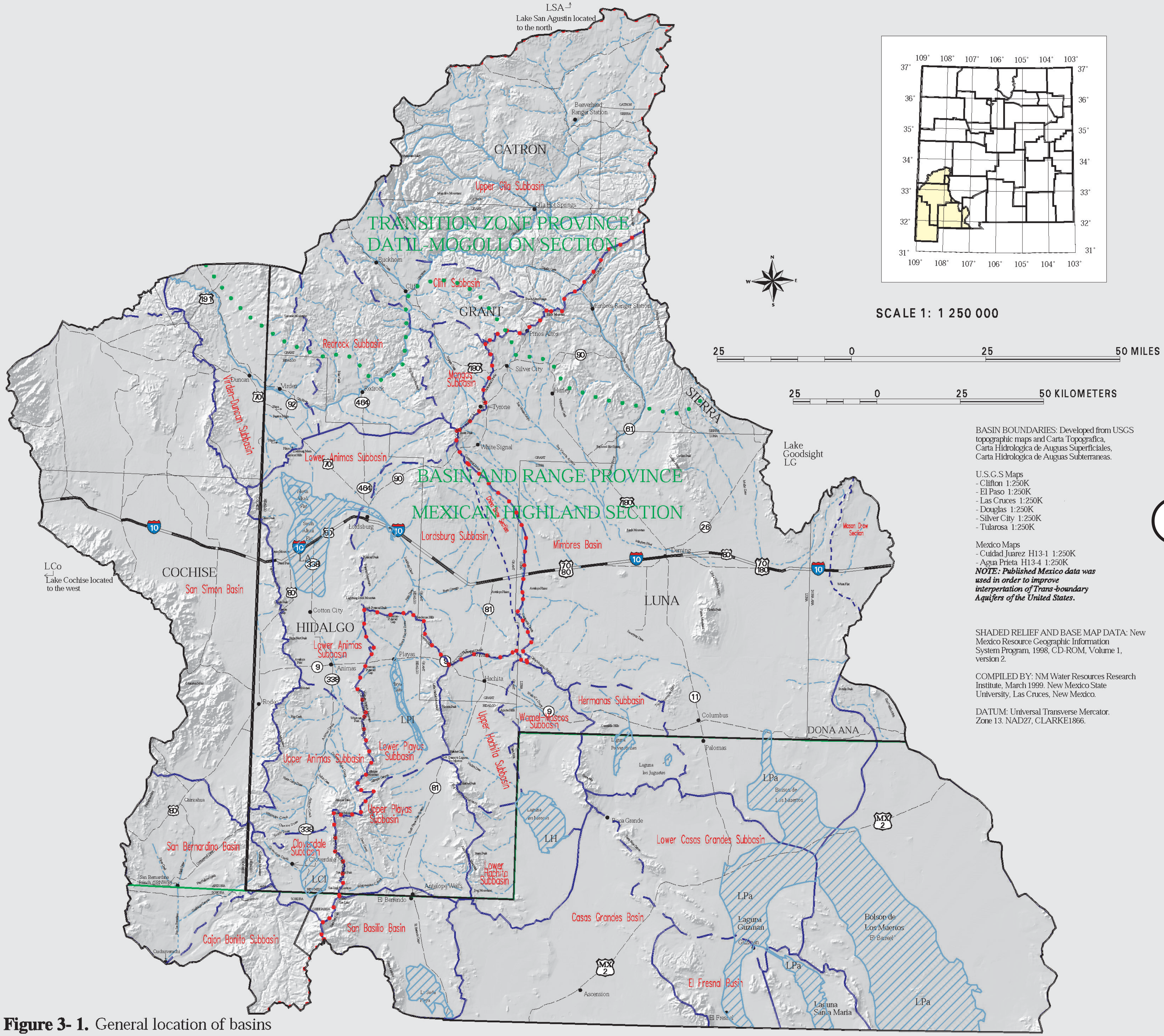


Figure 3- 1. General location of basins

BASIN BOUNDARIES: Developed from USGS topographic maps and Carta Topografica, Carta Hidrologica de Auguas Superficiales, Carta Hidrologica de Auguas Subterraneas.

U.S.G.S Maps
- Clifton 1:250K
- El Paso 1:250K
- Las Cruces 1:250K
- Douglas 1:250K
- Silver City 1:250K
- Tularosa 1:250K

Mexico Maps
- Cuidad Juarez H13-1 1:250K
- Agua Prieta H13-4 1:250K

NOTE: Published Mexico data was used in order to improve interpertation of Trans-boundary Aquifers of the United States.

SHADED RELIEF AND BASE MAP DATA: New Mexico Resource Geographic Information System Program, 1998, CD-ROM, Volume 1, version 2.

COMPILED BY: NM Water Resources Research Institute, March 1999. New Mexico State University, Las Cruces, New Mexico.

DATUM: Universal Transverse Mercator. Zone 13. NAD27, CLARKE1866.

The thick basin (or *bolson*) fills of the Mexican Highland section comprise the major aquifer systems of the transboundary region. Figure 3-2 illustrates the relationship between the mountain ranges and the aquifer system found in the thick basin fill. For example, the ultimate outlet for both surface and subsurface flow in the Mimbres Basin system (Chapter 4) is the vast complex of alkali flats in northwestern Chihuahua that includes the Bolson de los Muertos areas (Figure 3-1) that was flooded by "pluvial" Lake Palomas in Late Pleistocene time (Hawley 1969, 1975; Morrison 1969, 1991; Reeves 1969).

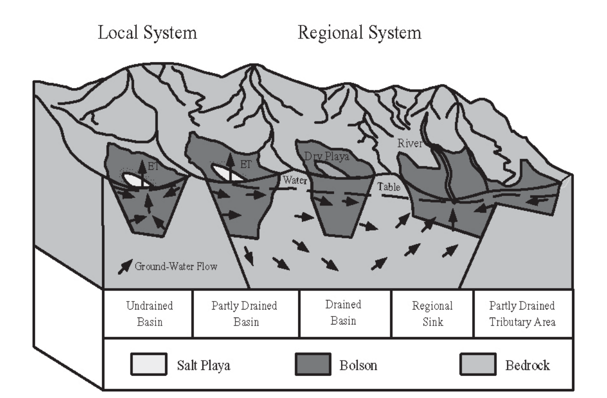


Figure 3-2. Conceptual hydrogeologic model showing undrained basins, partly drained basins, drained basins, and regional sinks (modified from Eakin et al. 1976).

Climate

The study area is typical of the arid southwest, with mostly clear skies and limited rainfall and humidity. Average annual precipitation varies from less than 25.4 cm (10 in) per year in low lying basins to as much as 76.2 cm (30 in) per year at higher elevations. Annual rainfall at the Deming, New Mexico station (elevation 1,321 m; 4,332 ft) averaged 23.4 cm (9.22 in) over the 1948-1995 period. The average for Lordsburg (elevation 1,295 m; 4,250 ft) for the same period was 28.1 cm (11.06 in). White Signal (elevation 1,850 m; 6,070 ft), New Mexico, which is just a few miles southwest of Silver City, had an average of 37.8 cm (14.89 in) for the period 1949-1994. In the upper reach of the Mimbres River at the Mimbres Ranger Station (elevation 1,904 m; 6,247 ft) the average was 43.3 cm (17.05 in) for the period 1948-1995 (Chart 3-1 thru 3-4) (USDC 1999). Nearly half of the annual precipitation is from thunderstorms that occur from July through September.

The average monthly minimum and maximum air temperature for Deming and Mimbres Ranger Station is presented in Charts 3-5 and 3-6. At Deming the average high summer (June, July, and August) temperatures typically are above 32° C (90° F) with average lows about 16° C (61° F). Winter (December, January, and February) average low temperatures are usually about -4° C (25° F) and average highs about 14° C (58° F). At the Mimbres Ranger Station, the average high summer temperatures are about 29° C (85° F) and average summer lows are about 10° C (50°). Average winter high temperatures are about 12° C (53° F) and average winter low temperatures are about -7° C (20° F). Large diurnal changes in temperature of about 17 ° C (30° F) are common.

Additional climatic information for the Mimbres, Hachita-Moscos, Playas-San Basilio, Animas, Gila, and San Bernadino basin systems is provided in individual Chapters 4 to 9.

BASIC HYDROGEOLOGIC CONCEPTS

Aquifer Composition

In both the Mexican Highland section and the Datil-Mogollon sections, groundwater occurs primarily in the poorly consolidated sediments that have accumulated in structural basins between mountain ranges (Figure 3-2). Intermontane basin fills of Late Cenozoic age form the primary aquifers of the study area. The basins themselves are commonly referred to as "alluvial basins" (Stone et al. 1979, Wilkins 1986, 1998), although their fills are not entirely of alluvial origin (i.e., stream deposits) since they also include a variety of lacustrine, eolian and colluvial sediments. However, the major aquifer units are, in fact, deposits of "running water," and therefore are appropriately classified as alluvium. Fractured volcanic rocks (basalts, adesites, and tuffs) that immediately underlie or are interlayered with the basin fill also form productive aquifers in some areas.

Solution-enlarged fractures in carbonate rocks of Paleozoic and Cretaceous Age are significant groundwater reservoirs in only a few places (Trauger 1972, Brady et al. 1984, Hanson et al. 1994). Unlike some parts of the Basin and Range province (e.g., eastern Nevada andTtrans-Pecos Texas), there are no extensive bodies of carbonate rock that provide conduits for interbasin groundwater flow (Maxey 1968, Winograd and Thordarson 1975, Mifflin 1968, 1988; Bedinger et al. 1984, 1989, Hibbs et al. 1998). However, the occurrence of groundwater in most consolidated rocks

Chart 3-1. Total annual precipitation Deming, New Mexico, 1948 - 1995.

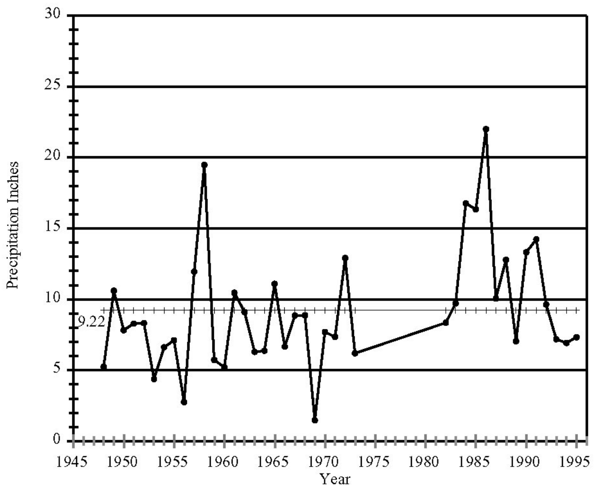


Chart 3-2. Total annual precipitation Lordsburg, New Mexico, 1948 - 1995.

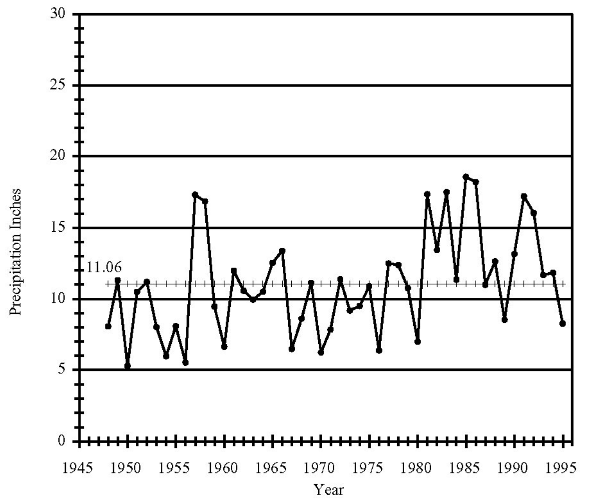


Chart 3-4. Total annual precipitation Mimbres Ranger Station, New Mexico, 1948 - 1995.

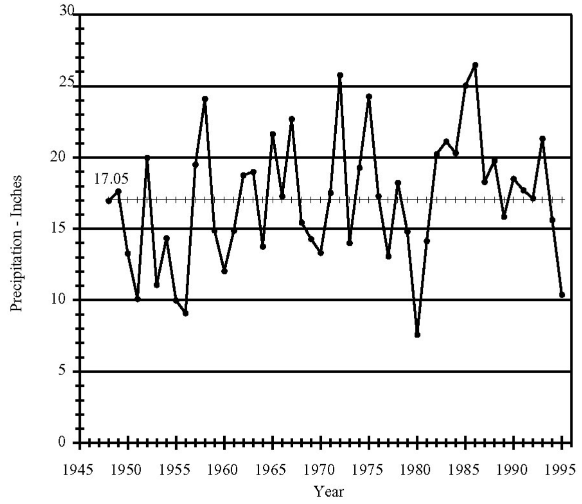


Chart 3-4. Total annual precipitation White Signal, New Mexico, 1949 - 1995.

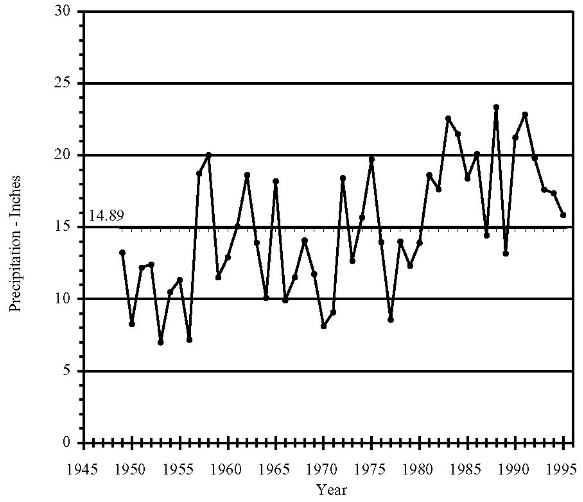


Chart 3-5. Average monthly minimum and maximum air temperature Deming, New Mexico, 1961 - 1982.

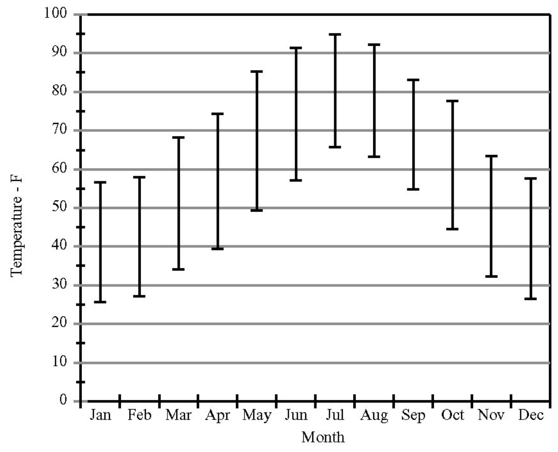
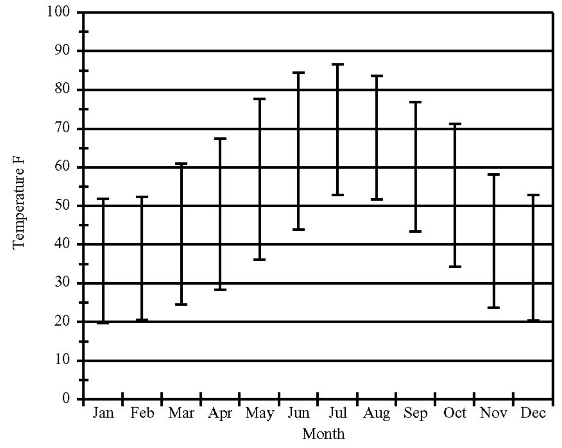


Chart 3-6. Average monthly minimum and maximum air temperature, Mimbres Ranger Station, New Mexico, 1956 - 1996.



of the region is limited to water-filled fracture zones of very low yield. Such zones occur in a wide variety of *bedrock* units including sedimentary, volcanic, intrusive igneous, and metamorphic types (Plate 1).

The two major roles played by bedrock units are (1) in the formation of surface and buried basin boundaries and (2) as ultimate source areas for most of the transported sediment that form the basin fill. Boundary structures such as faults and flexures that separate bedrock uplifts from basin blocks are part of a group of tectonic and volcanic features (including intrusive and extrusive igneous units) that also play a major role in groundwater-flow dynamics.

Subsequent sections of this chapter will deal with the two most important geologic controls on the groundwater-flow system in any basin-fill aquifer setting, namely (1) the *hydrostratigraphy* of the various types of sedimentary deposits and interlayered volcanics, and (2) the *lithofacies* composition of sedimentary components in terms of texture, mineralogy, and degree of consolidation and cementation. Hydrostratigraphic and lithofacies categories are widely used in hydrogeologic models (Seaber 1988, Anderson 1989); however, the concepts used here have been developed specifically for basin fills of the Rio Grande rift region (Hawley 1969, King et al. 1971, Peterson et al. 1984, Hawley and Lozinsky 1992, Hawley et al. 1995, Connell et al. 1998).

Basic Flow-Model Concepts

The conceptual model of surface-water and groundwater flow in the intermontane-basin aquifer systems of the study area is based on early work in the Basin and Range province by Darton (1916), Meinzer (1923), Tolman (1937) and Bryan (1938), with subsequent development by Maxey (1968), Mifflin (1968, 1988), Winograd and Thordarson (1975), and Eakin and others (1976). The adaption of these hydrogeologic concepts to the southern New Mexico-“Trans-Pecos Texas” region by Hibbs and others (1998) is used here (Figure 3-2). The terms *closed* and *open* refer solely to the surface flow into, through and from intermontane basins, whereas the terms *undrained*, *partly drained*, and *drained* designate classes of groundwater flow involving intrabasin and or interbasin movement. *Phreatic playas* (ephemeral-lake plains) are restricted to floors of *closed* basins that are *undrained* or *partly drained*; and *vadose playas* occur in both *closed* and *open, drained* basins (Figure 3-2). *Note that the proper Spanish term for playa is el barrial (Ordóñez 1936, Hawley 1969), which is misspelled “barreal” on many local maps.*

Surface Flow

Most surface flow in the Mexican Highland section is to *closed* basins, some of which are crossed by the international border. There are many areas where ephemeral surface drainage is either from the United States side into Mexico or vise versa. Most of the northern part of the region is in the topographically open watershed of the Gila River Basin. Portions of the Gila, upper Mimbres, and lower Animas River flow are diverted for agricultural purposes and lost directly to evapotranspiration. The Playas, Hachita-Moscos, and Animas basins are *closed*, and surface flow is to ephemeral-lake plains that were sites of “pluvial” lakes during the last “Ice Age” (10-25 ka). The Animas and Mimbres River watersheds included large networks of ephemeral streams that discharge to both *vadose* and *phraetic* playas (*barriales* and alkali flats or salinas). The Rio Casas Grandes is the only major perennial to intermittent fluvial network in the region that discharges to a *closed* and *undrained* depression (Blasquez 1959).

Groundwater Flow

The end-member classes of basin-flow systems are *undrained* and *drained* (Hibbs et al. 1998). The former class denotes areas where groundwater-flow is completely internal to a given basin and the ultimate zone of discharge is to a “wet” or *phreatic playa* area on the bolson floor. The term *drained*, on the other hand, refers to interbasin flow regimes where subsurface discharge is to some type of regional *sink*. Playas are also present in the *drained* class of bolsons, but the zone of (basin-fill) saturation is commonly well below the basin floor. Ephemeral precipitation-runoff events are the source of playa-lake flooding, and these landforms are therefore designated “dry” or *vadose playas*. 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 groundwater-flow regime (Maxey 1968, Eakin et al. 1976, Mifflin 1968, 1988).

Subsurface geologic conditions, relating primarily to the very irregular buried bedrock topography within basin parts of the study area, will receive much more attention in Chapters 4 to 9. Buried inter-basin and intra-basin ridges, fault zones, and igneous bodies that intrude or are interlayered with basin-fills affect both local and regional groundwater-flow systems. Few intermontane basins or bolsons are truly *undrained* in terms of groundwater discharge, whether or not they are *closed* or *open* in terms of surface flow. Groundwater discharge in the region occurs 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 *phreatic playas* and cienegas (valley-floor-wetlands).

Groundwater recharge occurs along the losing stretches of perennial and intermittent streams, deep percolation of precipitation, and by mountain front recharge. Figure 3-3 is a two-dimensional conceptual model of an interconnected fractured bedrock and basin-fill aquifer-recharge system in a Basin and Range hydrogeologic setting (Anderholm 1994, Anderholm 1998, Wasiolek 1995). The upland networks of major stream valleys of the Datil-Mogollon section, and the Sierra Madre Occidental region of northwestern Mexico are the major surface contributors to the recharge of basin-fill aquifers in the Mexican Highland section. The only other important recharge contributors to these groundwater reservoirs are the few high and massive mountain ranges that form isolated highlands. Significant contributors to aquifers in the Hachita-Moscos, Playas and San Basilio, Animas (Animas and Lordsburg subbasins), San Simon, and San Bernadino Basin systems include parts of the Big Burro, Big Hatchet, Animas-San Luis, Peloncillo-Guadalupe, and Chiricahua-Pedrogosa ranges. Smaller amounts of recharge to the Mimbres Basin system are contributed by precipitation-runoff from the Cooke’s Range and the Florida Mountains.

Overview of the Regional Groundwater Flow System

Except for the Gila River Basin, all of the alluvial-basin systems of the Mexican Highland section described in this report extend across the International Boundary into the Republic of Mexico. As has already been noted, surface-water drainage divides, including the Continental Divide, do not necessarily mark subsurface-flow boundaries. Individual physiographic and hydrogeologic components (e.g., mountains, hills, and intermontane lowlands) will be identified by local geographic names that, for the most part, have already been used in official technical reports.

The *open* and *drained* San Bernadino Basin at the southwestern edge of the region has an area of about 1,000 km^2 (387 mi^2) in Cochise County, Arizona and includes part of the headwaters of the Rio Yaqui system, which flows directly to the Gulf of California. The far eastern portion (about 90 km^2, 35 mi^2) of this basin occurs in New Mexico. The southern end of the San Bernadino Basin is in the northeastern corner of Sonora, Mexico and has an area

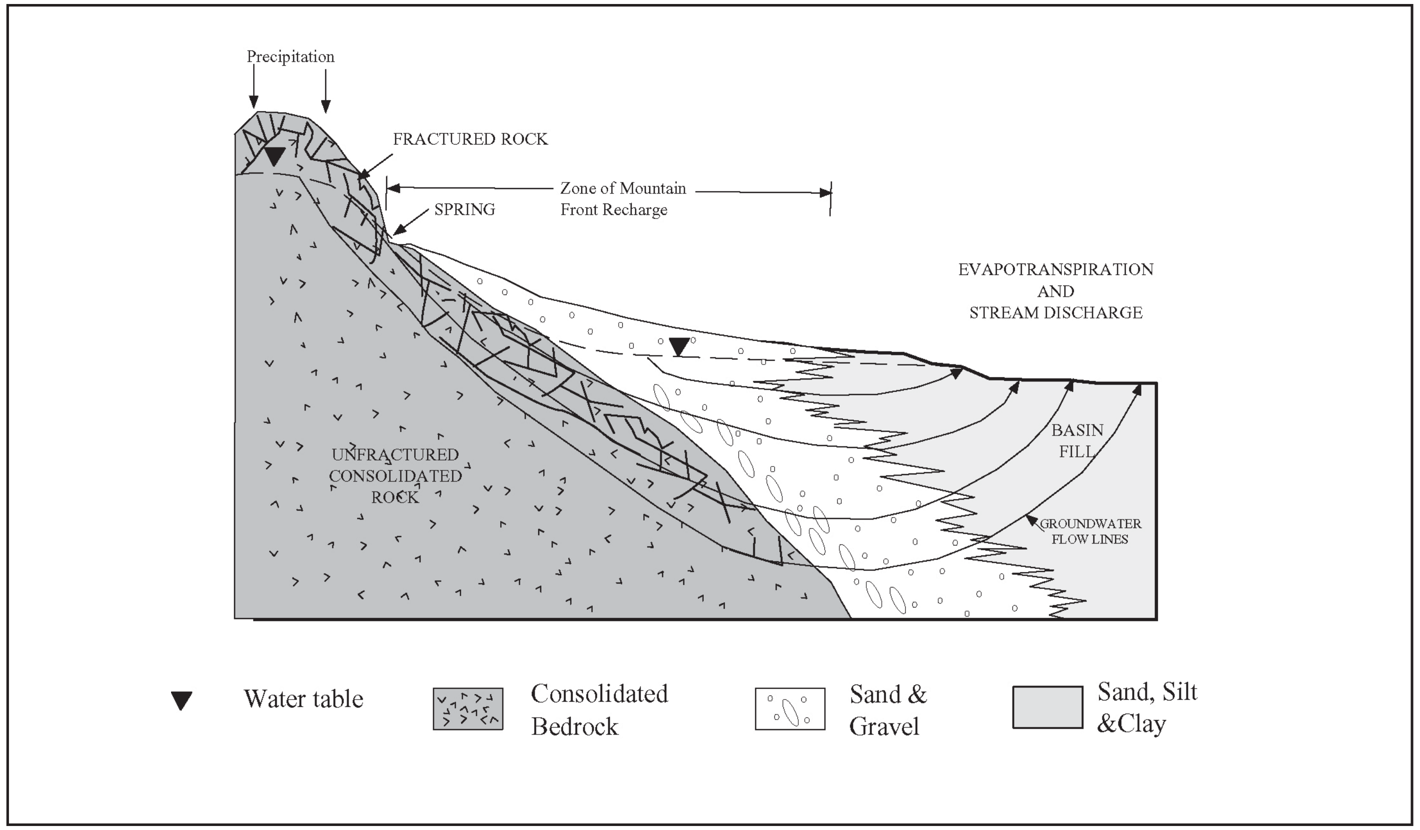


Figure 3-3. Two-dimensional conceptual model of a groundwater recharge system in a Basin and Range hydrogeologic setting (from Wasiolek 1995, modified from Feth 1964, and Mifflin 1968)

of about 490 km^2 (190 mi^2). A very small portion (about 100 km^2, 39 mi^2) of the Animas Basin system straddles the International Boundary and the Sonora-Chihuahua border in the Cloverdale (San Luis) Subbasin area. The *partly drained* Animas system extends northward toward Lordsburg, New Mexico and has an area of about 6,200 km^2 (2,390 mi^2). A small part (30 km^2, 12 mi^2) of the western Animas Basin extends into Arizona. Just across the Continental Divide to the east are the *partly drained* basins of the Playas, Basilio, and Hachita-Moscos systems, which have an area of about 2,100 km^2 (810 mi^2) in Chihuahua, Mexico. Some of the subsurface discharge from these *closed* surface-water basins (bolsons or bolsones) drains to a regional *sink* formed by the Rio Casa Grandes near Ascencíon, Mexico. This river and its associated groundwater-flow system, in turn, discharge into the *undrained* Laguna Guzman-Santa Maria *phreatic playa* complex in northern Chihuahua.

The largest basin in this study is the *open* and *drained* Mimbres Basin system, which is east of the Continental Divide. It is located between the Rio Grande and Mesilla Basin to the east, and the Animas and Playas, and Hachita-Moscos Basin systems on the west (Figure 3-1). The Mimbres Basin system has an area of 11,300 km^2 (4,360 mi^2) in New Mexico and extends into northwestern Chihuahua (area of at least 1,900 km^2; 730 mi^2). It merges southward with the extensive alkali flats (phreatic playas) of the *closed* and *undrained* Bolson de los Muertos–Salinas la Union region. The *open* and *drained* Upper Mimbres Basin system in the northeasternmost part of the study area includes the watershed of its only perennial stream, the Mimbres River.

The position of topographic divides on both the land surface and the potentiometeric surface (water table) maps were used to distinguish individual groundwater flow systems (Figure 3-4). As noted above, most groundwater-flow directions are strongly influenced by intra-basin and bedrock-boundaries of a lithologic and structural nature. The conceptual model of local and regional flow systems (Figure 3-2) illustrates the possible paths that groundwater may follow depending on intra-basin and bedrock-boundary restrictions. Boundary conditions effectively restrict most of the groundwater flow to a given *closed* basin system. However, there is evidence that groundwater does flow between some *closed* basins in the study area (Schwennessen 1918, Doty 1960, Trauger and Herrick 1962).

Figure 3-4 shows the general local-regional groundwater flow system for southwestern New Mexico, and it is based in part on a map created by Brady and others (1984). Additional water-level control provided by the USGS allowed for modifications and updates to previous work. The arrows indicate the direction of groundwater flow from areas of recharge to areas of discharge. This figure also illustrates the subsurface connection between some basins in the region and their transboundary nature. The general direction of groundwater flow in basin-boundary areas is also shown.

Groundwater flow in the Animas and Playas basin systems is northward away from the international border. Groundwater flow in the Mimbres Basin system, Hachita-Moscos Basin system, and the San Bernardino Basin is southward toward the international border. The Playas Basin system is complex, with groundwater-flow in the southern area partly draining to the Hachita-Moscos Basin, whereas the northern (lower) part of the basin may have a groundwater-discharge component to the Lower Animas Subbasin. Groundwater and surface water flow in the Gila Basin system is toward the west and southwest into Arizona. The Gila Basin contributes no groundwater or surface water to the transboundary systems in southwestern New Mexico.

Each basin system has *drained* and *partly drained* subbasins that contribute groundwater to regional *sink* basins. The Cloverdale Subbasin, of the Animas Basin system, is a *partly drained* basin that spills northward into the main Animas Basin. The Lordsburg Subbasin is a *drained* basin that spills westward to the Lower Animas Subbasin. The Lower Animas playa complex is the surface expression of the partly *drained* Animas Basin system; however, the regional sink for groundwater flow is the Gila River Basin (Figure 3-4). The groundwater flow in the Gila Basin system can best be described as a *drained* tributary area, with a regional *sink* basin further to the west in Arizona. As noted above, the Upper Playas Subbasin drains to the north into a *partly drained* regional sink at Playas Lake as well as to the Hachita-Moscos Basin system, while the latter unit drains into a regional sink in Mexico formed by the Rio Casas Grandes and Laguna Guzman. The perennial reaches of the Mimbres River and the San Vicente Arroyo are in the *open* and *drained* tributary areas of the Mimbres Basin system. The rest of the basin ultimately drains southward toward a regional *sink* in the Bolson de Los Muertos area of Mexico.

GEOLOGIC SETTING

Introduction

Southwestern New Mexico, southeastern Arizona, and adjacent parts of Mexico comprise two major geologic provinces with respect to both geomorphologic and structural framework. The southern Basin and Range province extends into the states of Chihuahua and Sonora, and includes most of the region south of the Gila River Valley and the Upper Mimbres Subbasin. The Datil-Mogollon section to the north is dominated by the large Mogollon-Datil volcanic field and is part of a "Transition Zone" province between the moderately extended Basin and Range region and the relatively unextended area of the earth's crust (to the north) that forms the Colorado Plateau province. These structural provinces are on the western margin of the Rio Grande rift (Keller and Cather 1994), an area of relatively large crustal extension, major basin subsidence and basaltic to silicic volcanism that extends south from central Colorado to "Trans Pecos Texas" and northern Chihuahua. The eastern Mimbres Basin system is transitional with the Rio Grande rift.

Long-term interest in the region's historical, structural, and economic geology has resulted in a large body of literature including numerous maps that delineate not only pre-Neogene igneous and sedimentary bedrock units but also basin-fills of Late Cenozoic structural basins (King et al. 1971, Trauger 1972, Gile et al. 1981, Rattè and Gaskill 1975, Rattè et al. 1984, Elston 1984, Seager et al. 1982, 1987, Drewes et al. 1985, Seager 1995, and du Bray and Pallister 1999).

The emphasis of this section is on the geologic framework of aquifer units that comprise intermontane-basin and valley fills of the southwestern New Mexico region. Coverage of geologic history predating Late Cenozoic (past 25 Ma) deposition of the basin-fill aquifer systems is limited to events and features that directly influence transboundary groundwater-flow systems and their geochemical properties. Reference here is simply made to several excellent review papers on the regional geologic setting and history that will provide a good introduction to the vast number of reports and maps that cover the area (Clemons 1998, Chapin and Cather 1994, Clemons and Mack 1988, Mack and Clemons 1988, Mack et al. 1998, Sawyer and Pallister 1989, Seager and Mack 1986, Seager and Morgan 1979, Seager et al. 1984, 1997).

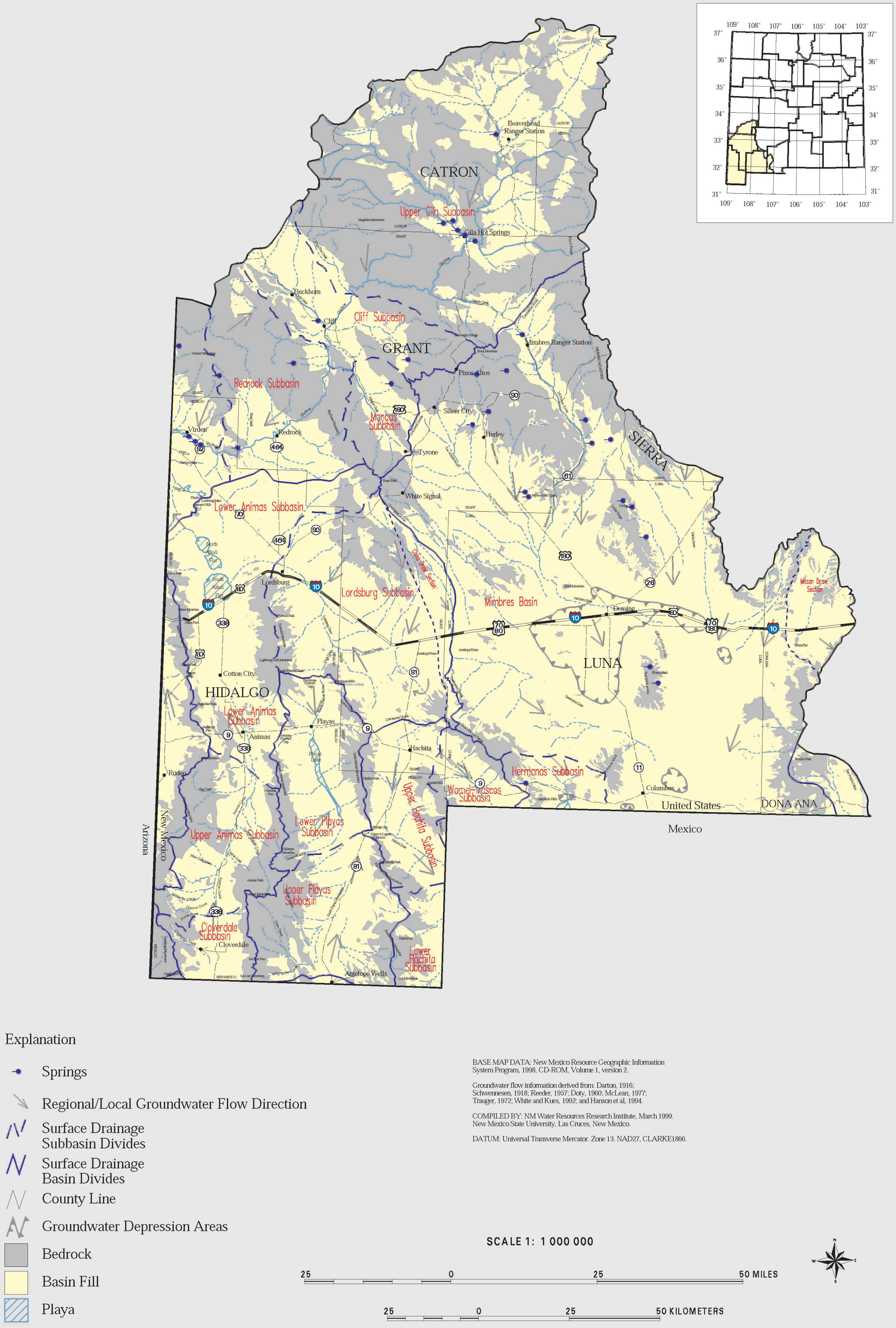
Datil-Mogollon Section

The Datil-Mogollon section, which includes the mountain headwaters of the Gila and Mimbres rivers, is primarily a complex of (1) Middle Tertiary calderas that were sources of very extensive and thick (silicic) ash-flow tuff sheets, and (2) large basaltic andesite volcanos that form local sources of widespread, but relatively thin lava flows (Rattè et al. 1979, McIntosh et al. 1991). Much of the Mogollon-Datil volcanic field is underlain by early Tertiary volcanic and associated sedimentary rocks of andesitic (intermediate) composition. The sequence includes widespread volcaniclastic mudflow deposits, with a dense fine-grained matrix, that commonly mark the base of bedrock zones with any aquifer potential.

Mexican Highland Section

The extended geologic terrane that includes much of the Mexican Highland section is located between the Tertiary Chiricahua uplift and caldera complex (du Bray and Pallister 1999), and the Quaternary West Potrillo basalt field (Seager 1989, 1995). It is characterized by tilted fault-block ranges that rise abruptly from broad structural basins (locally called *bolsons*). These depressions are partly filled with the thick sequences of basin-fill deposits that form the aquifer systems described below. The structural framework of the Basin and Range province has precursors that date back as much as 2 billion years. Plate-boundary interactions were mostly convergent in and adjacent to this region (primarily to the south and west) until the early Oligocene (30 to 35 Ma). Major orogenic intervals of the past 500 Ma include the Late Paleozoic Ouachita and ancestral Rocky Mountain orogenies, and the Late Cretaceous and early Tertiary Cordilleran and Laramide orogenies. The northwest-southeast and north-south trending structural grain exhibited in ranges and basins throughout the region reflects these early orogenic processes. The northwest trending basement-cored uplifts and associated tectonic features of Laramide (primarily early Tertiary) age, which are well preserved in the Burro and Florida mountains, are representative of structures that have had a major influence on the extensional processes and landforms of the Late Cenozoic.

Thick sequences of carbonate and clastic sedimentary rocks characterize much of the Paleozoic and Mesozoic (Late Jurassic and Cretaceous) stratigraphic section exposed in many ranges and underlying most basin areas (at quite variable depths). Magmatism and associated volcanic and plutonic activity of late Mesozoic through Middle Cenozoic time produced large volcanic fields,



BASE MAP DATA: New Mexico Resource Geographic Information System Program, 1998, CD-ROM, Volume 1, version 2.

Groundwater flow information derived from: Darton, 1916; Schwennesen, 1918; Reeder, 1957; Doty, 1960; McLean, 1977; Trauger, 1972; White and Kues, 1992; and Hanson et al, 1994.

COMPILED BY: NM Water Resources Research Institute, March 1999.
New Mexico State University, Las Cruces, New Mexico.

DATUM: Universal Transverse Mercator. Zone 13. NAD27, CLARKE1866.

Figure 3- 4. Groundwater flow in the region

major igneous intrusions (plutons), and rich mineral deposits, including the large porphyry-copper ore bodies that have been or are being exploited in the Cananea (Sonora), Bisbee, Tyrone and Santa Rita mining districts.

The final episodes of Middle Tertiary volcanism occurred during a long period of transition from the convergent plate-margin style of tectonics to crustal extension throughout the region. The possible mechanisms for this shift in deformation style are well illustrated in a recent paper by Stewart (1998), and they relate to changing boundary conditions and direction of motion of subducting plates and transform faults along the western continental margin (Engebretson et al. 1985, Bohannan and Parsons 1995, Severinghaus and Atwater 1990).

Overview of Late Cenozoic Geologic History of the Mexican Highland Section

The Mexican Highland section occupies most of southeastern Arizona, southern and central New Mexico, western trans-Pecos Texas, and Chihuahua, Mexico (Figure 3-1). Basin areas below about 1,524 m (5,000 ft) form the bulk of the Chihuahua Desert region (Schmidt 1973, 1986, McCraw 1985, Betancourt et al. 1990). Broad intermontane basins occupy 60 to 80% of the area, and the intervening complex range blocks include a wide variety of rock units of Precambrian, Paleozoic, Late Mesozoic, and Cenozoic age. Continental clastic, volcanic, and plutonic units of Tertiary age are widespread. Physiographic concepts and terminology used herein are based on Fenneman's (1931) classification as modified by Hawley (1969, 1975, 1986).

As already noted, the terms *open* and *closed* are used here to describe only surface flow, while groundwater flow is described with the terms *drained*, *undrained*, and *partly drained*. *Closed* basins include parts of the Animas, Playas, San Basilio, and Hachita-Moscos basin systems. The Gila River and San Simon Creek basins are *open* and are tributary to the Colorado system, while the *open* and *drained* Rio San Bernardino Basin discharges to the Gulf of California via the Rio Yaqui.

Intermontane basins of the Mexican Highland section between the Rio Grande Rift and the Peloncillo Range along the New Mexico-Arizona border are characterized by very large *closed* depressions (*bolsons*). Only the western and northern border zones have deep valleys and well integrated fluvial systems. The Continental Divide in southwestern New Mexico follows the highest profiles of a series of surface-drainage divides that separate a number of *closed* basins. Broad piedmont-alluvial plains grading to basin floors with local playa-lake depressions are the dominant landscape features (Figure 3-1). As described in more detail below, basins with large *playas* (Animas, Cloverdale, Los Moscos, Playas, Los Muertos, and Goodsight) were sites of permanent lakes during major glacial-pluvial intervals of Pleistocene time (Table 3-1). The largest pluvial lake in the region, Lake Palomas (Reeves 1969), is located in the Bolson de los Muertos area of north-central Chihuahua (Figure 3-1). This complex of deep structural basins includes the distal parts of the Casas Grande, Santa Maria and Carmen fluvial systems that originate in the Sierra Madre Occidental, as well as the Mimbres Basin of New Mexico. The Bolson de Los Muertos was also the *sink* for part of the ancestral upper Rio Grande in Pliocene to Pleistocene time (Hawley et al. 1976, Gile et al. 1981).

This brief description of the study area emphasizes:

1. Evolution of Neogene (Miocene and Pliocene) tilted fault-block basins and ranges in the Mexican Highland Section;
2. Progressive erosion of emerging mountain uplifts, and contemporaneous basin-filling that continues to the present;
3. Stratigraphy of basin-fill deposits, and contrasting environments of piedmont-slope and basin-floor deposition;
4. Plio-Pleistocene development of precursors of the region's major fluvial systems (Gila, Casas Grandes, Mimbres, and ancestral Rio Grande);
5. Pleistocene dissection of basin-fill in upper piedmont areas and along valleys of major through-going fluvial systems;
6. Continued aggradation of central basin (bolson) plains, where surface drainage is not integrated with through-going streams;
7. Middle to Late Quaternary record of major pluvial-lakes in closed basins and episodic cutting and filling of major stream valleys, both related to cyclic glacial-interglacial climate shifts on a 100 Ka time scale, which affect the entire continent and adjacent oceanic basins.

Table 3-1. Selected data on Late Quaternary lakes in southeastern Arizona, southern New Mexico, Chihuahua

Lake Name	**Location**		**Late Wisconsin Pluvial Lake Features**						**Remarks**
	North Latitude	West Longitude	Lake Area km² (mi²)	Maximum Lake Elevation m (ft)	Basin Floor Elevation m (ft)	Sill Elevation m (ft)	Overflow?	Pre-Late Wisconsin Lake Elevation m (ft)	Lake Named by: Major Sources of information: Playa Name(s) and elevations:
Animas (LA)	32 15'	108 45'	388L (150)	1,279* (4,195)	1,259L (4,130)	1,292L (4,240)	No **	Yes	Schwennesen (1918) Fleischhauer and Stone (1982) Alkali Flats - 1,259 m
Cloverdale (LCl)	31 30'	108 45'	104ME (40)	1,578M* (5,177)	1,561M (5,120)	1,578M (5,176)	No **	Yes	Schwennesen (1918) Krider (1998)
Cochise (LCa)	32 15'	110 00'	310L (120)	1,274L* (4,180)	1,260L (4,135)	1,298L (4,260)	No	Yes 1,290L (4,230)	Meinzer and Kelton (1913) Long (1966), Schreiber (1978), Waters (1989) Wilcox Playa - 1,260m
Goodsight (LG)	32 30'	107 30'	39L (15)	1,372LM* (4,500)	1,358LM (4,456)	1,375LM (4,510)	No **	Yes	Hawley (1965) Clemons (1979)
Hachita (LH)	31 30'	108 00'	150M (58)	1,262M* (4,140)	1,250ME (4,100)	1,262 -1,273M (4,140 - 4,177)	? (to J) **	Yes?	Schwennesen (1918) Brand (1937), Hawley (1969), Morrison (1969), Axtell (1978), Miller (1981) Laguna de los Moscos - 1,250 m
Palomas (LPa)	31 00'	107 00'	7,770L (3,000)	1,225LE (4,018)	1,175M (3,856)	1,250M (4,100)	No**	Yes	Reeves (1969) El Barreal - 1,175-1,180 m Laguna Guzman - 1,185-1,190 m Laguna Santa Maria - 1,175-1,180 m Salinas de Union - 1,175 m
Playas (LPl)	31 45'	108 30'	65M (25)	1,311LME (4,300)	1,303M (4,275)	1,314M (4,312)	?	Yes? (to G)**	Schwennesen (1918) Axtell (1978)
San Agustin (LSA)	34 00'	108 00'	780L (300)	2,115L* (6,940)	2,065L (6,775)	2,158M (7,078)	No**	Yes 2,135L (7,005)	Powers (1939) Weber (1980), Stearns (1962), Markgraf and others (1984), Phillips and others (1992) San Agustin Playa - 2,065 m C-N Playa 0 2,101 m

Note that drainage-basin areas (ground- and surface-water) are still not well documented in many lake basins

L - Data from cited literature. See remarks, Willams and Bedinger (1984), and Hawley (1993).

M - Estimates from maps and aerial photographs, 1:24,000 to 1:100,000 scales

E - Estimates not well documented, need field verification

* - Well-defined shoreline features mark high stands

** - Groundwater outflow important discharge mechanism

The major geologic features of the area formed in response to Late Neogene crustal extension. Basins are a linked-series of elongated troughs bounded by normal faults forming zones of down-thrown blocks (grabens) adjacent to uplifted blocks (horsts). The uplifted blocks, locally rise a thousand meters above the basin floors due to vertical fault displacement. The grabens formed between the horsts commonly comprise a complex set of subbasins. Most basins are asymmetrical (half grabens), trending generally north to south, and the structural relief and direction of fault-block tilting commonly shifts across *accommodation zones* (Chapters 6 and 7) along many basin trends (Faulds and Varga 1998, Stewart 1998).

As noted in the preceding section, a large variety of rock types and structures form the hydrogeologic framework of the study area's intensely deformed mountain blocks. They include, from oldest to youngest, Precambrian igneous and metamorphic rocks that are faulted and fractured; Paleozoic (especially Pennsylvanian and Permian) carbonate and clastic rocks that are folded, fractured and locally karstified; Mesozoic (mostly Cretaceous) rocks that are also structurally deformed and weakly karstified; and Tertiary and Quaternary volcanic rocks and local igneous-intrusive units that are jointed and fractured.

Basin fills of Late Cenozoic age are derived from erosion of rocks from flanking highlands, and are interbedded in some places with volcanic flows. Semiconsolidated to unconsolidated sediments that occur in both mountain and basin settings include Upper Oligocene to Lower Pleistocene basin and valley fill, and Middle to Late Quaternary alluvium, lacustrine deposits, and eolian sediments (Plate 1). The Upper Cenozoic basin-fill sediments consist largely of sand and gravel bodies interstratified with silt and clay, and loamy mixtures of all these textural classes. Interbedded volcanics are shown in some geologic logs, especially in the lower more consolidated basinfill (Drewes et al. 1985, Clemons 1986, Doty 1960, Hanson et al. 1994, O'Brien and Stone 1982b, Reeder 1957, Seager 1983, 1995, and Trauger 1972).

The depositional record for approximately the past 25 Ma in the study region is summarized on Plate 1 and Figure 3-5, (with supplementary stratigraphic and geomorphic information in Tables 3-3, 3-4, and 3-5). Most of this region is in the Mexican Highland section except where it extends northward a short distance into the Datil-Mogollon section.

Gila and Santa Fe Group Basin Fill

The southwestern Datil-Mogollon section and contiguous parts of the Mexican Highlands form the extended type area of the "Gila Conglomerate" as originally defined by Gilbert (1875). This lithostratigraphic unit has been raised to group status and subdivided into formations that range in age from Late Oligocene to Middle Pleistocene. It comprises the bulk of the fill in most basins of the Datil-Mogollon and Mexican Highland sections located west of the Rio Grande drainage basin (Heindl 1962, 1963, Krieger et al. 1973, Elston et al. 1976). The Santa Fe Group is the equivalent basin-fill unit in basins of the Rio Grande rift and is exposed at the eastern edge of the study area (Hawley 1969, King et al. 1971, Seager et al. 1982, Seager 1995). Although commonly used to describe relatively coarse-grained piedmont facies of basin-fills in the area, both the "Gila" and "Santa Fe" lithostratigraphic concepts have been expanded to include all facies in a basin-fill environment ranging from clay-rich lake beds and eolian sands to alluvial-fan and river gravels.

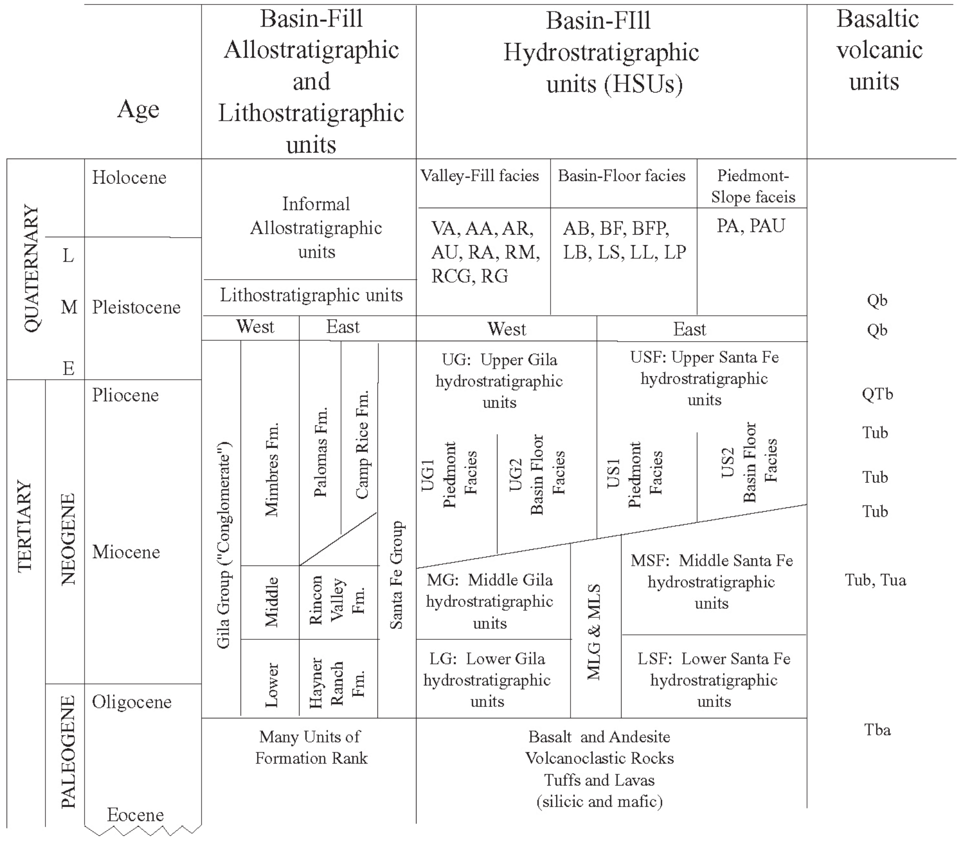


Figure 3-5. General summary and correlation of lithostratigraphic and hydrostratigraphic units in Upper Cenozoic Basin Fill of the southwestern New Mexico region

The time-transgressive top of the Gila and Santa Fe groups is here defined by the youngest basin fill that predates incision of the Gila River, Rio San Bernardino, and Rio Grande Valley systems. The Late Pliocene to early Pleistocene age (>750 ka) of these deposits is established by radiometric dating of interbedded or capping volcanics (including lava flows and ash lenses), and local fossil vertebrate faunas. A common distinguishing feature of Upper Gila and Santa Fe stratigraphic sequences is the widespread occurrence of well-developed horizons of soil-carbonate accumulations (morphogenetic stages III-V, Gile et al. 1966, 1981, Machette 1985) in both buried and relict-surface positions.

Bolson surfaces have continued to aggrade in many parts of the region where Middle to Late Quaternary valley entrenchment has not occurred. Thickness of post Gila-Santa Fe basin fill, however, is usually less than 60 m (200 ft), and much of this material is unsaturated. Following guidelines in the North American Stratigraphic Code (NACOSN 1983) and current mapping criteria for similar deposits in adjacent Rio Grande rift basins (Gile et al. 1981, Seager et al. 1982, Seager and Clemons 1988, and Seager 1995), Middle and Late Quaternary basin fill (and correlative valley-fill deposts) have been informally subdivided into *allostratigraphic* (unconformity-bounded) map-unit classes (Figure 3-5).

At present, "Gila Group," "Formation," and "Conglomerate" designations are all being used in various parts of the study area (Trauger 1972, Rattè et al. 1984, Drewes et al. 1985, Hanson et al. 1994). However, confusion still exists on proper age assignments for various subdivisions of the unit and some workers in Arizona have advocated abandonment of the term "Gila" (Heindl 1962, Krieger et al. 1973). Oldest radiometric dates near the base of the Gila Group are as old as latest Oligocene (~ 25 Ma), and vertebrate faunas in the upper part of the unit are of Hemphillian and Blancan (Late Miocene and Pliocene) land-mammal provincial age (Lindsay 1984, Lindsay et al. 1984, Galusha et al.1984, Tomida 1985). Radiometric ages of basalts and volcanic ash beds in the Upper Gila Group and recent work on magneto-stratigraphic correlation support the biostratigraphic age determinations (Leopoldt 1981, Izett and Wilcox 1982, Brooks and Rattè 1985, McIntosh et al. 1991 and above-cited papers). The present pre-Quaternary correlation for the bulk of the Upper Gila Group contrasts markedly with the large body of published information on the age of the unit, which equates a Upper Gila (Blancan provincial) age (>1.5 or 1.9 Ma) with the early-glacial part of the Pleistocene (<1 Ma).

The Santa Fe Group is much better defined than the Gila Group, particularly in terms of its hydrogeologic properties resulting from much detailed characterization of deposits in adjacent basins of the Rio Grande rift structural province (Peterson et al. 1984, Seager et al. 1987, Hawley and Lozinsky 1992, Mack et al. 1997). This report represents the first attempt in extending hydrostratigraphic and lithofacies concepts used in the Palomas, Jornada and Mesilla basins to the "alluvial basins" west of the Rio Grande rift.

Topographically Closed Basins of the Mexican Highlands West of the Rio Grande Rift

Fills of internally drained structural basins (bolsons) form the bulk of the Quaternary/Pliocene depositional record in the area south and west, respectively, of the upper Gila River and Rio Grande valleys (Figure 3-1). Except for through-going streams in the shallowly entrenched draws of the San Simon, San Bernardino, and southern Sulphur Springs valleys, surface discharge and some groundwater flow is to *sinks* presently occupied by playa-lake plains.

Recently published large-area geologic maps and cross sections by Seager (1995), Seager and others (1982), and Drewes and others (1985) give a general, but reasonably accurate overview of Late Cenozoic basin-fill units. They also serve as comprehensive indexes of detailed mapping in the area. A good regional characterization of basin-fill distribution is provided by the new state geologic map (scale 1:500,000, Anderson et al. 1997). All facies of Middle Miocene to Middle Pleistocene basin-fill are included in the Gila "Conglomerate" by Drewes and others (1985); while Seager and others (1982) limit their Gila "Group" map unit to basin-fill of Miocene age in most areas. Clemons (1982, 1984) proposed "trial" use of the term "Mimbres formation" to designate Upper Gila Group basin-fills of Pliocene to Middle Pleistocene age in the Mimbres River Basin, and possibly in areas to the west. With respect to both facies composition and general age, the Mimbres Formation correlates with the Camp Rice Formation of the Santa Fe Group in the southern Rio Grande rift region to the east (Seager 1995, Seager et al. 1987). Older Gila Group deposits of Seager and others (1982, 1987) correlate generally with the Rincon Valley and Hayner Ranch formations of the Middle and Lower Santa Fe Group.

Alluvial deposits are by far the largest component of the basin fill, and coalescent-fan piedmonts (bajadas) and basin-floor alluvial plains form extensive constructional surfaces of Quaternary age. Widespread surficial eolian deposits are also shown on most maps of the region, but the thickness of these sandy to loamy sediments is not well documented in subsurface data. Thick lacustrine sequences occur in basin-floor facies assemblages of the Lower Animas subbasins and Mimbres Basin systems (Blandford and Wilson 1987, O'Brien and Stone 1984, Seager 1995). Closure of lake basins has been produced by three basic mechanisms, all of which are commonly active in any given basin. Local structural subsidence of a basin segment relative to adjacent range and basin blocks is the ultimate formative process; but closure is usually enhanced by a combination of (1) alluvial damming of basin-floor segments (e.g., by progradation of alluvial fans), and (2) local deflation of former lake plains with resultant playa "lows" and downwind "highs" of eolian deposits.

An important, but areally limited part of the alluvial depositional record includes gravelly veneers on proximal piedmont slopes, which cap rock pediments as well as erosion surfaces cut on older basin-fills. These erosion-surface veneers are usually less than 30 m thick, and commonly extend up valleys and canyons of adjacent ranges as stepped sequences of piedmont-terrace deposits.

Other important Quaternary/Pliocene units include: (1) extensive basalt flows of the San Bernardino (Geronimo), Animas, Potrillo and Palomas volcanic fields (Lynch 1978, Kempton and Dungan 1989, Seager 1989, 1995, Seager et al. 1984, 1987), and (2) cave fills of Late Quaternary age that usually contain significant paleoenvironmental and archaeological records (Van Devender and Worthington 1978, Betancourt et al. 1990, Harris 1985, Connin et al. 1998). The basalt fields are discussed further in chapters on the Mimbres, Animas, and San Bernardino basins.

Neotectonic features include Mid- to Late-Quaternary fault scarps mapped in the Mimbres, Hachita, Animas, Virden-Duncan, and San Simon structural basins by Machette and others (1986, 1998), and Scarborough and others (1986), but much of the area between the Hachita and Animas basins appears to have been tectonically stable since the Late Miocene or early Pliocene. During the course of the present study, however, many more scarps cutting young basin-fill deposits and Plio-Pleistocene basalt flows were observed on the newly available sets of air photos and the space imagery that cover the region both in the United States and Mexico. General location of these semilinear features are shown on Plate 1.

Pluvial Lake Basins

The southwestern Mexican Highland area includes six of the Late Quaternary "pluvial" lakes listed in Table 3-1 (Animas, Cloverdale, Cochise, Goodsight, Hachita, Palomas and Playas; Figure 3-1: LA, LCl, LCo, LG, LH, LPa, LPl, LSA). The area contains the largest (Palomas, 7,770 km^2) and three of the smaller lakes of the region (Playas, Cloverdale, and Hachita - 50 to 150 km^2). Lakes Palomas and Hachita (including Los Moscos playa), located in northwestern Chihuahua, expanded a short distance across the International Boundary during their very highest stages. The small area inundated by Lake Cloverdale (~ 95 km^2, elevation ~ 1,577 m) occupies parts of New Mexico, Chihuahua, and Sonora at the south end of Animas Basin system (Krider 1998).

Following Meinzer's pioneering work in Sulphur Springs Valley (Meinzer and Kelton 1913) and other basins in the region, the early hydrogeologic studies by Schwennessen (1918) furnished much of the basic information on pluvial lakes Animas, Cloverdale, and Playas. Mapping of deposits in the ancient Lake Hachita basin is primarily based on reconnaissance work by Hawley (1969) and Morrison (1969), and observations on hydrogeology by Trauger and Herrick (1962).

Detailed research on lake and playa deposits has only been done in the Animas and Sulphur Springs valleys (Lakes Cloverdale, Animas and Cochise), but pluvial Lakes Hachita and Playas have received very little attention since the early studies by Schwennesen (1918). Reconnaissance investigations on pluvial Lake Palomas and the major contributing drainage basins of Rio Casas Grandes, Santa Maria, and Carmen in Chihuahua are described by Reeves (1969), Morrison (1969) and Hawley (1969). These large fluvial systems head in subhumid to semiarid highlands in or adjacent to the Sierra Madre Occidental (Schmidt 1973, 1986), and only about 20% of the Lake Palomas watershed is in the United States.

Detailed topographic maps and aerial photographs (1:24,000 and 1:50,000 scale) of the lakes Cloverdale, Hachita, and Playas drainage basins have only recently become available. Thus, for the first time, reasonably accurate mapping of lake deposits and measurement of watershed area-altitude parameters is possible. Except for the Animas Basin system, much of the current information on these lakes (Table 3-1) still needs to be field checked and will be subject to some revisions.

Local alluvial damming of valley floors appears to have played a major role in closure of the present Playas and Los Moscos depressions, and episodic throughflow from Lake Playas to Lake Palomas via the lower Hachita (Laguna Los Moscos) and Casa Grandes valleys possibly occurred during the Mid- to Late-Quaternary time (Table 3-1). Recent shifts in sites of basin-floor aggradation at the confluence of Upper Playas and Hachita basins (Figure 3-1) clearly indicate that surface flow from the Upper Playas Subbasin can alternately discharge into the Playas Lake and Laguna los Moscos depressions. Furthermore, distributaries of the Rio Casas Grandes in the Ascencion-Los Moscos area may have been able to contribute to or receive discharge from Lake Hachita depending on subtle shifts in basin floor aggradation during the Late Pleistocene.

Fleischhauer and Stone's (1982) and Krider's (1998) investigations of surficial lake and alluvial deposits, and associated geomorphic surfaces and soils in the Lake Animas and Lake Cloverdale basins (Figure 3-1) are the only detailed studies of shoreline chronologies in the region. Subsurface work to date has only dealt with basin-fill geohydrology (Reeder 1957, O'Brien and Stone 1983), and the potentially good stratigraphic and paleo-environmental record still needs to be investigated. These studies are discussed in more detail in Chapter 7.

One of the most striking features of the Quaternary depositional record is the fluvial fan complex constructed by distributaries of the lower Mimbres River during Late Pleistocene to Mid-Holocene time (Plate 1). This bifurcating system of low sand and gravel ridges and intervening clay flats covers more than 1,200 km^2 (463 m^2) of the lower Mimbres basin floor both east and west of the Florida Mountains (Love and Seager 1996, Mack et al. 1997). From its apex about 15 km (9 mi) west northwest of Deming (elevation ~ 1,380 m, 4,527 ft), the fan complex extends southeast about 70 km (44 mi) to its terminus along the International Boundary east of Columbus and Palomas (Figure 3-1). The thickness of fan deposits and their age range have not yet been determined; however, they may be locally as thick as 90 m (300 ft). The fan's sand and gravel channel facies forms much of the shallow basin-fill aquifer in the Deming area. Fluvial deposits of Wisconsin age at the distal part of the fan near the International Boundary grade to high-level deltaic and lacustine sediments of Lake Palomas at elevations in the 1,200 to 1,225 m (3,937 to 4,020 ft) range (La Mota and Camel Mountain shorelines of Reeves 1969). Unpublished water-well records show that extensive clay-rich sequences as much as 100 m (330 ft) thick underlie the Upper (?) Pleistocene sand and gravel unit at the lower end of the Mimbres Basin (T.N. Blandford, personal communication 1986, Blandford and Wilson 1987). Additional information on the lower Mimbres River system is presented in Chapter 4.

Pluvial lakes, and other geomorphic and paleoecologic indicators of Late Pleistocene environmental conditions that differed markedly from those of the historic and recent prehistoric period, are particularly important in the context of the study area's geohydrology. These features demonstrate that long intervals of the Pleistocene, particularly during the last glacial (Wisconsin) stage about 10,000 to 40,000 years ago, were significantly wetter and cooler than the present. While documented paleoenvironmental conditions varied greatly throughout the region (from the basin floors of the present Chihuahua Desert to the high plateaus and ranges of the Datil-Mogollon and Mexican Highlands sections), it is clear that evapotranspiration was suppressed and precipitation-runoff-recharge was enhanced during glacial-pluvial intervals (Waters 1985, 1989, Betancourt et al. 1990, Hawley 1993, Blagbrough 1994, Krider 1998, Connin et al. 1998). Emphasis through this report, particularly in *closed* basin systems that contained large pluvial lakes (Chapters 4, 5, 6,and 7), is on the fact that groundwater-flow regimes observed today have a major storage component inherited from thousands to tens of thousands of years ago.

THE CONCEPTUAL MODEL OF THE REGIONAL HYDROGEOLOGIC SYSTEM

Introduction

The conceptual hydrogeologic model of an inter-connected surface-water, shallow valley-fill/basin-fill and deep-basin aquifer system presented in this report was initially developed for use in groundwater flow models of the Mesilla and Albuquerque basins (Peterson et al. 1984, Hawley and Lozinsky 1992, Hawley and Haase 1992, Frenzel and Kaehler 1992, Thorn et al. 1993, Hawley et al. 1995, Kernodle et al. 1995, Kernodle 1996). However, original model design was flexible enough to allow it to be modified for use in other basins of the Rio Grande and adjacent parts of the southeastern Basin and Range province. This model is simply a qualitative description (graphical, numerical, and verbal) of how the geohydrologic system is influenced by (1) bedrock-boundary conditions, (2) internal-basin structure and (3) the textural character, mineralogical composition and geometry of various basin-fill and valley-fill stratigraphic units. Its basic elements, which are briefly described below, can be graphically displayed in a combined map and cross-section format so

Table 3-2. Post Gila and Santa Fe Group hydrostratigraphic units

Late Quaternary fluvial hydrostratigraphic units: deposits of major streams with perennial or intermittent flow regimes

RG - Channel, floodplain and low terrace deposits of the Gila River; up to 30 m saturated thickness; mostly lithofacies assemblages *a1* and *a2*

RCG - Channel, floodplain and low terrace deposits of the Rio Casas Grandes

RCGf - Channel, floodplain and low terrace deposits of the Rio Casas Grandes, fine-grained facies

RCGd - Rio Casas Grandes Delta

RSB - Channel, floodplain and low terrace deposits of the Rio San Bernardino

RMr - Channel, floodplain and low terrace deposits of the Upper Mimbres River, fluvial facies; up to 10 m saturated thickness; mostly lithofacies assemblage *a2*

RM - Channel, floodplain and low terrace deposits of the Lower Mimbres River

RMF - Fluvial-fan deposits of the ancestral and modern Mimbres River, undivided; up to 20 m thick and primarily in vadose zone; lithofacies assemblage *a*

RMFc - Fluvial-fan deposits of the Mimbres River, course-grained facies; mostly lithofacies assemblage *a2*

RMFf - Fluvial-fan deposits of the Mimbres River, fine-grained facies; mostly lithofacies assemblage *a3*; includes extensive gypsiferous and alkali impregnated sediments in the Florida sub-basin

RA - Channel, floodplain and low terrace deposits of the lower Animas River; up to15 m thick, and primarily in the vadose zone, lithofacies assemblage *a*

RAc - Channel floodplain and low terrace deposits of the upper Animas River; up to15 m thick, partly saturated, mostly lithofacies assemblages *a1* and *a2*

RAf - Basin-floor and fluvial fan deposits of the ancestral and modern Animas River, undivided; up to 30m thick, mostly lithofacies assemblages *a2* and *a3* map units; includes increasing proportion of gypsiferous and alkali impregnated sediments in lowermost part of Animas Valley

CA - Cienega (relict wet meadow) deposits of ancestral Animas River floodplain; up to 15 m thick and partly saturated; mostly marls, organic layers and facies assemblages *a1*and *a2*

TA - Quaternary, terrace deposits of Upper Gila River

Quaternary basin-floor hydrostratigraphic units

BF - Undivided alluvial flat deposits, including fills of small "playa"depressions; as much as 30 m thick and primarily in vadose zone; mostly lithofacies assemblage *c*; gradational to or intertonguing with map units BFY, BFO, BFU, RMF and RAF

BFs - BF with major component of alkali impregnated or gypsiferous sediments

BFP - Playa-lake deposits in local depressions on basin-floor alluvial plains (unit BF); as much as 5 m thick and entirely in vadose zone, fine-grained with thin sandy layers

BFY - Alluvial flat deposits, including fills of small "playa" depressions; as much as 10 m thick and entirely in the vadose zone; mostly lithofacies assemblage *c*

BFO - Alluvial flat, channel and floodplain deposits of ancestral Mimbres and Animas fluvial systems, and local "playa" depression fills; as much as 20 m thick and partly in vadose zone; mostly lithofacies assemblage *c*, with local areas of gypsiferous sediments

LB - Beach ridge deposits, undivided, marking highest stands of Lakes Animas, Cloverdale and Playas in late Wisconsin and early Holocene time; mostly pebble gravel and sand, with lesser amounts of silt and clay; up to 10 m thick and entirely in the vadose zone

LS - Sandy shoreline deposits, with major component of inter-beach ridge lacustrine and eolian sediments; mostly pebbley sand and sand-silt-clay mixtures; up to 10 m thick and mostly in vadose zone

LP - Playa lake and lake plain sediments, undivided, deposited 1) during highstands of Lakes Animas, Cloverdale, Playas, Palomas, and Goodsight; and 2) on ephemeral (playa) lake plains during intervals of lake desication; mostly fine-grained sediments (silt - clay) with some sand and pebbley sand deposits

LPS - LP with major component of alkali impregnated and gypsiferous sediments

LL - Lacustrine plain sediments, deposits like LP and LS units that may include pre-Wisconsin lacustrine and cienega sediments and BFO correlatives

BFU - Early to middle Quaternary, alluvial flat, channel and floodplain deposits of ancestral fluvial systems, and local playa depression fills; with unmapped inclusions of unit BF in upper part; as much as 40 m thick, and partly in vadose zone; mostly lithofacies assemblages c and 3; gradational to and intertonguing laterally with units PA and PAU; and transitional with HSUs UG2 and UG1

Major piedmont-slope and valley-fill hydrostratigraphic units

PA and PAU - Quarternary, undivided piedmont depostis that are transitional to upper part of HSUs US1 and UG1

PA - Quaternary, Younger (PAY) and older (PAY) piedmont-slope deposits, undivided, stippled where up to 3 meters of upper Quaternary eolian cover is present

PAY - Quaternary, Younger piedmont-slope deposits

PAO - Quaternary, Older piedmont-slope deposits

AA and AR - Late Quaternary, arroyo-channel deposits, facies *b*

AB - Late Quaternary, unchannelled alluvial deposits of axial basin floodways, facies *b* and *c*

VA - Middle to Late Quaternary, undivided deposits of major ephemeral streams in valleys tributary to the Rio Grande, Gila, Mimbres and Animas fluvial systems, facies *b*

Table 3-3. Gila and Santa Fe Group hydrostratigraphic units

Gila Group

UGL - Quaternary and Tertiary, Upper Gila hydrostratigraphic unit, sandy, fluvial and eolian sediments (with partially indurated calcic paleosols) of the Lordsburg Mesa, like the San Vicente Mimbres confluence and near Deming; up to 3 meters thick and entirely in the vadose zone

UG - Quaternary and Tertiary, Upper Gila hydrostratigraphic unit, undivided basin-floor to medial piedmont slope deposits and equivalent Mimbres Formation

UG2 - Quaternary and Tertiary, Upper Gila hydrostratigraphic unit, undifferentiated fine to medium grained basin-floor deposits; including those of ancestral Mimbres and Rio Santa Barbara systems

UG2r - Quaternary and Tertiary, Upper Gila hydrostratigraphic unit, ancestral Gila River channel and floodplain deposits including local inset and high terrace fills (mostly in vadose zone)

UG2s - Quaternary and Tertiary, Upper Gila hydrostratigraphic unit, gypsiferous basin-floor facies

UG1 - Quaternary and Tertiary, Upper Gila hydrostratigraphic unit, piedmont slope facies, undifferentiated (mostly medial to distal)

UG1c - Quaternary and Tertiary, Upper Gila hydrostratigraphic unit, course-grained piedmont facies (mostly proximal)

MG - Upper Tertiary, Middle Gila hydrostratigraphic unit, undivided (includes MG1 and MG2)

MG2 - Upper Tertiary, Middle Gila hydrostratigraphic unit, basin-floor facies undivided, mostly pebbley sandstones and mudstones

MG1 - Upper Tertiary, Middle Gila hydrostratigraphic unit, mostly conglomerate piedmont facies

LG - Upper Tertiary, Lower Gila hydrostratigraphic unit

Santa Fe Group

USL - Quaternary and Tertiary, Upper Santa Fe hydrostratigraphic unit, sandy, fluvial and eolian sediments (with partially indurated clacic paleosols) of the La Mesa area; up to three meters thick and entirely in the vadose zone, stippled where up to 3 meters of upper Quaternary eolian cover is present

US2 - Quaternary and Tertiary, Upper Santa Fe hydrostratigraphic unit, basin-floor facies, undivided, includes upper Camp Rice Formation subdivisions, stippled where up to 3 meters of upper Quaternary eolian cover is present

US2r - Quaternary and Tertiary, Upper Santa Fe hydrostratigraphic unit, fluvial basin-floor facies, includes Camp Rice Formation, stippled where up to 3 meters of upper Quaternary eolian cover is present

US1 - Quaternary and Tertiary, Upper Santa Fe hydrostratigraphic unit, undivided piedmont facies (mostly medial to distal), includes Camp Rice Formation, stippled where up to 3 meters of upper Quaternary eolian cover is present

US1c - Quaternary and Tertiary, Upper Santa Fe hydrostratigraphic unit, course-grained piedmont facies (mostly proximal), includes Camp Rice Formation

MSF - Upper Tertiary, Middle Santa Fe hydrostratigraphic unit, including Rincon Valley Formation

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 groundwater-flow systems.

The hydrogeologic framework of trans-international boundary aquifers, with special emphasis features on related environmental concerns, is described here in terms of three basic conceptual building blocks:

1. Hydrostratigraphic units are mappable bodies of basin-fill and valley-fill deposits grouped on the basis of origin and position in both lithostratigraphic and chronostratigraphic sequences (Plate 1, Tables 3-2, 3-3).
2. Lithofacies subdivisions are the basic building blocks of the model (Table 3-4). In this study, basin and valley fills are subdivided into thirteen major lithofacies (*1* to *10* and *a* to *c*). These mappable sedimentary bodies are defined primarily on the basis of grain-size distribution, mineralogy, sedimentary structures and degree of post-depositional alteration. They have distinctive geophysical, geochemical and hydrologic attributes.
3. Structural and bedrock features include basin-boundary mountain uplifts, bedrock units beneath the basin-fill, fault zones and flexures within and at the edges of the basin that influence aquifer composition, and behavior, and igneous-intrusive and extrusive rocks that penetrate or are interbedded with basin deposits (Plate 1, Tables 3-2 and 3-3).

Maps, schematic cross-sections, and supporting well-log interpretations (cited literature) are the key to the region's complex hydrogeologic framework and constitute the major body of basic and interpretative information used in preparation of this report (Plate 1).

Hydrostratigraphic Units

Hydrostratigraphic units are the major integrative components of the model and comprise bodies of basin and valley fill that can be mapped at scales of 1:24,000 to 1:500,000. These informal mapping units are defined in terms of (a) relative stratigraphic position, (b) distinctive combinations of lithologic character (lithofacies, described below) such as grain-size distribution, mineralogy and sedimentary structures, (c) depositional environments and diagenetic features, and (d) general age of deposition (Tables 3-2 and 3-3). Genetic classes include ancestral-river and present river-valley fills, basin-floor and piedmont alluvial deposits, and lacustrine and eolian sediments. The general attributes of ten major and five

Table 3-4. Summary of Gila and Santa Fe Group (*1-10*) and Post-Gila and Santa Fe (*a,b,c*) lithofacies depositional settings and dominant texture in southwestern New Mexico (modified from Hawley and Haase 1992, Table III-2)

Lithofacies	**Dominant 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 to clay
5	Distal to medial piedmont-slope, alluvial fan	Gravel, sand, silt, and clay; common loamy (sand-silt-clay)
5a	Distal to 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 to sandy loam
5b	Distal to medial piedmont-slope, alluvial-fan; associated with small steep watersheds; debris-flow sheet-flood, and distributary-channel	Gravelly, loamy sand to sandy loam; lenses of sand, gravel, and silty clay
6	Proximal to 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 to non-gravelly, loamy sand to sandy loam
6b	Like *5b*	Gravelly, loamy sand to 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 gypsiferous and alkali-impregnated zones
a	River-valley, fluvial	Sand, gravel, silt and clay
a1	Basal channel	Pebble to 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 to lacustrine plain	Silty clay, clay and sand (like *3,5,* and *9*)

Table 3-5. Summary of properties that influence groundwater production potential of Gila and Santa Fe Group lithofacies (modified from Haase and Lozinsky 1992) [>, greater than; <, less than]

Lithofacies	Ratio of sand plus gravel to silt plus clay[1]	Bedding thickness (meters)	Bedding configuration[2]	Bedding continuity (meters)[3]	Bedding connectivity [4]	Hydraulic conductivity (K)[5]	Groundwater production potential
1	High	> 1.5	Elongate to planar	> 300	High	High	High
2	High to moderate	> 1.5	Elongate to planar	> 300	High to moderate	High to moderate	High to moderate
3	Moderate	> 1.5	Planar	150 to 300	Moderate to high	Moderate	Moderate
4	Moderate to low*	> 1.5	Planar to elongate	30 to 150	Moderate to high	Moderate	Moderate
5	Moderate to high	0.3 to 1.5	Elongate to lobate	30 to 150	Moderate	Moderate to low	Moderate to low
5a	High to moderate	0.3 to 1.5	Elongate to lobate	30 to 150	Moderate	Moderate	Moderate
5b	Moderate	0.3 to 1.5	Lobate	30 to 150	Moderate to low	Moderate to low	Moderate to low
6	Moderate to low	0.3 to 1.5	Lobate to elongate	30 to 150	Moderate to low	Moderate to low	Low to moderate
6a	Moderate	0.3 to 1.5	Lobate to elongate	30 to 150	Moderate	Moderate to low	Moderate to low
6b	Moderate to low	0.3 to 1.5	Lobate	< 30	Low to moderate	Low to moderate	Low
7	Moderate *	0.3 to 1.5	Elongate to lobate	30 to 150	Moderate	Low	Low
8	Moderate to low *	> 1.5	Lobate	< 30	Low to moderate	Low	Low
9	Low	> 3.0	Planar	> 150	Low	Very low	Very low
10	Low*	> 3.0	Planar	> 150	Low	Very low	Very low

[1] High >2; moderate 0.5-2; low < 0.5

[2] Elongate (length to width ratios > 5); planar (length to width ratios 1-5); lobate (asymmetrical or incomplete 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, VI).

[5] High 10 to 30 m/day; moderate, 1 to 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 3-6. Summary of properties that influence groundwater production potential of Post Gila and Santa Fe Group lithofacies [>, greater than; <, less than]

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

[1] High >2; moderate 0.5-2; low < 0.5

[2] Elongate (length to width ratios > 5); planar (length to width ratios 1-5); lobate (asymmetrical or incomplete 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, VI).

[5] High 10 to 30 m/day; moderate, 1 to 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%)

minor map-unit classes into which the area's basin and valley fills have been subdivided are summarized in Table 3-4 and on Plate 1.

Correlation of major hydrostratigraphic and lithostratigraphic units is summarized on Figure 3-5. The Upper (UG, US), Middle (MG, MSF), and Lower (LG, LSF) Gila and Santa Fe hydrostratigraphic units comprise the major basin-fill aquifer zones, and they correspond roughly to the (informal) Upper, Middle and Lower rock-stratigraphic subdivisions of the Gila and Santa Fe Groups used in local and regional geologic mapping (e.g., Trauger 1972, Clemons 1998, Drewes et al. 1985, Seager et al. 1982 1987, Seager 1995). The other major hydrostratigraphic units (RG, RM, RA, RCG, RSB) comprise channel and floodplain deposits of the Gila and Mimbres rivers and Animas Creek in the United States, and the Rio Casas Grandes and San Bernardino in Mexico. These inner river-valley fills of Late Quaternary age (<25 ka) form the upper part of the region's major shallow-aquifer system. Lake and playa deposits, fills of major arroyo valleys, and surficial piedmont-slope alluvium are primarily in the unsaturated (vadose) zone. However, they may form important groundwater discharge and recharge sites and are represented by map units LL, BF, AA, AB, AP, AR, VA, and PA. Historical phreatic conditions exist, or have recently existed, in a few playa remnants of large pluvial lakes of Late Quaternary age (map units LP and LPS). Notable examples are "alkali flats" in the lower Animas, Playas, Hachita (Laguna Los Moscos), Mimbres (El Barreal), and Casa Grandes (Laguna Guzman) basins. The lower reaches of the Mimbres and Casas Grandes systems also include extensive fluvial-fan and fan-delta deposits (RMF, RCGF, RCGD). Distribution of hydrostratigraphic units throughout the study region is shown on Plate 1 and Figures 4-2, 5-2, 6-2, 7-2, 8-2, and 9-2 (1:500,000 scale).

Lithofacies Assemblages

Introduction

Lithofacies assemblages summarized in Table 3-4, and schematically illustrated on Figure 3-6 and Plate 1 cross-sections, are the basic building blocks of the model. These units are mappable bodies defined primarily in terms of grain-size characteristics (gravel, sand, silt, clay, or mixtures thereof), mineral composition, degree of cementation, geometry of bodies of a given textural class, subsurface distribution patterns, and inferred environments of deposition. Proper identification of lithofacies assemblages obviously depends on the availability of good quality geologic information, including site-specific subsurface information (e.g., borehole sample and geophysical logs, drilling records, and other hydrological and geochemical data) as well as the professional experience of the investigators.

Lithofacies units have distinctive characteristics both in terms of geophysical and geochemical properties and in hydrologic behavior (Haase and Lozinsky 1992, Hawley and Lozinsky 1992, Hawley 1996, Whitworth 1995, Connell et al. 1998). In this study, deposits have been divided into thirteen major lithofacies assemblages (*1* to *10*, *a* to *c*) that are used in combination with hydrostratigraphic unit classes to provide a schematic 3-D view of subsurface conditions in the study region (Plate 1). *Note that these assemblages and their subdivisions are usually simply referred to as facies.*

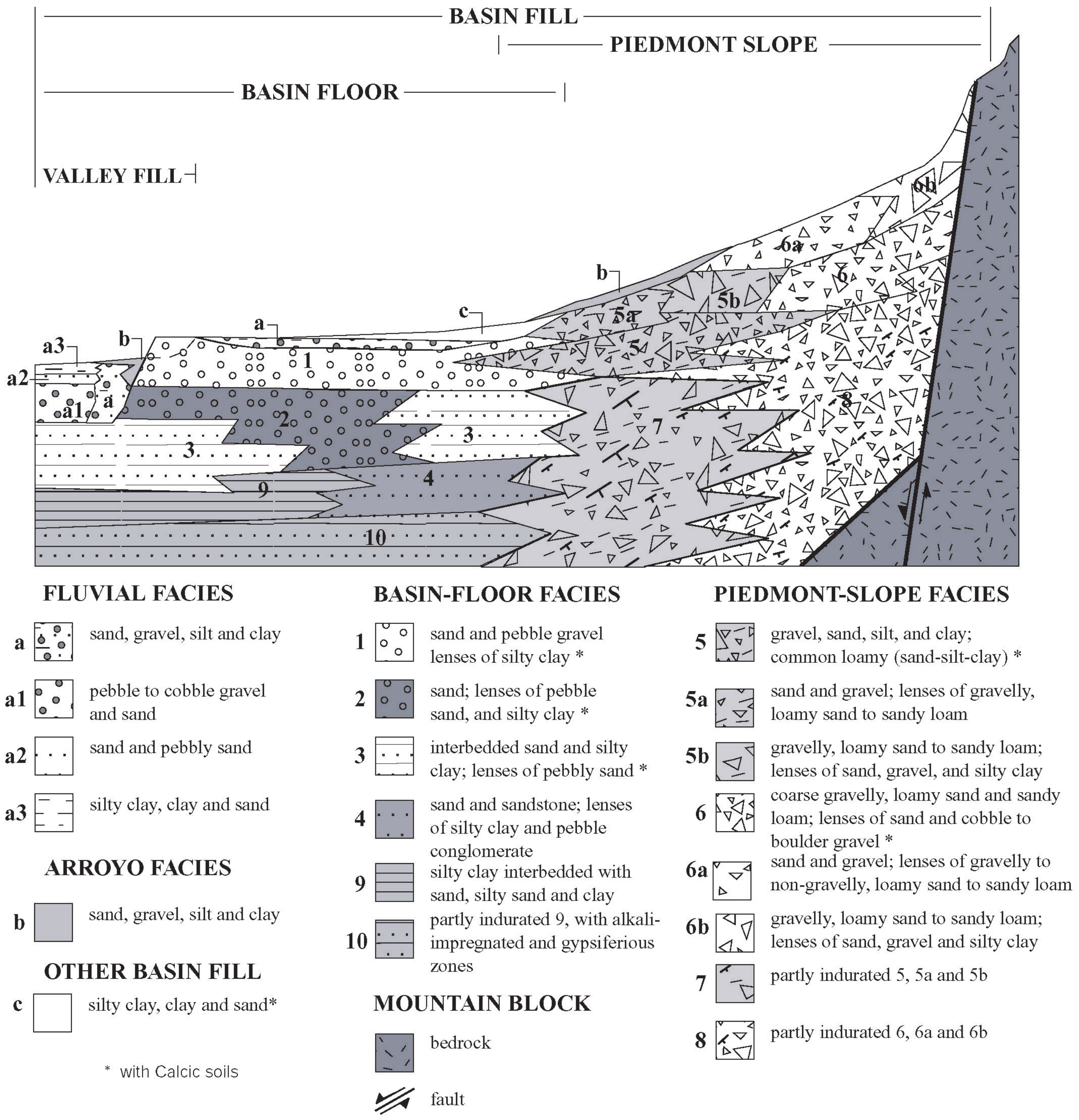


Figure 3-6. Hypothetical distribution pattern of lithofacies in fault-block basins such as the Albuquerque Basin. Modified from Hawley and others (1995). See Tables 3-7 and 3-8 and text for more detailed unit descriptions and explanations of facies distribution patterns in various hydrostratigraphic units.

Basin-Fill Facies Subdivisions

Basin-fill lithofacies assemblages *1*, *2*, *3*, *5* and *6* are primarily unconsolidated. Facies *1* to *3* are restricted to basin floors and facies *5* and *6* are associated respectively with distal to proximal parts of piedmont slopes (Plate 1). Any thin zones of induration (irreversible cementation) that may be present are not continuous, and they are commonly associated with surface and buried horizons of soil-carbonate accumulation (calcisols–Gile et al. 1981, Machette 1985, Mack et al. 1993). Clean, uncemented sand and gravel bodies are major constituents of facies *1* and *2*; and much of the coarse-clast assemblage in these fluvial deposits is derived from source areas upstream from basin-floor depocenters. Note that coarse-grained (sand and gravel-dominated) facies *1* is equivalent to lithofacies Ib of previous studies (Hawley et al. 1995). Clay and sandstone zones, respectively, form a significant part of facies *3* and *4,* but both units are broadly lenticular to tabular and contain extensive, well-connected layers of permeable sand. Facies assemblage *4* consists mainly of thick eolian and fluvial sand layers that are partially indurated (common calcite cement in outcrop).

Lithofacies assemblages *5* and *6* are characterized, respectively, by lenticular bodies of gravelly sand and sandy gravel that are bounded by poorly sorted zones of gravel, sand, silt and clay (loamy gravels to gravelly loams). These assemblages form the dominant distal to medial (unit *5*) and medial to proximal (unit *6*) facies components of piedmont alluvial aprons (usually formed by coalescent alluvial fans). Fans expanding out from the mouths of large upland drainage basins (e.g., in Animas, Burro and Chiricahua mountains) include extensive (distributary) networks of coarse-grained stream-channel fills (clean, gravelly sand), which form a large part of subfacies *5a* and *6a*. In marked contrast, small high-gradient fans derived from small-steep mountain-front watersheds contain a high proportion of the debris-flow and sheet-flood materials, which are dominated by the poorly sorted (loamy) mixtures of fine and coarse-grained sediments that are typical of subfacies *5b* and *6b*. Figure 3-3 illustrates a model of mountain-front recharge that is associated with these facies.

Lithofacies assemblages *7* and *8* are, respectively, partly to well-indurated equivalents of facies *5* and *6*. Lithofacies *9* and *10* comprise thick sequences of fine-grained basin-floor sediments, with disconnected (lenticular) bodies of sand and sandstone, that include alluvial-flat, fluvial-deltaic and lacustrine sediments. Facies *9* is primarily non-indurated and has a minor evaporite constituent, while facies *10* contains up to 50 % mudstone, siltstone and shale, and local evaporite zones (primarily sodium and calcium sulphate deposits).

Coarse-grained (gravel and sand) channel deposits of the ancestral Animas, Mimbres, Gila, Rio Grande, and Rio Casas Grandes fluvial systems (lithofacies *1* and *2*) are the major components of the Upper Gila (UG2) and Santa Fe (US2) hydrostratigraphic units. Sandy to interbedded coarse-and fine-grained deposits of ancient fluvial systems (facies *1* to *3*) locally form important aquifers and potential enhanced-recharge zones. Buried tributary channel fills (subunits *5a* and *6a*) deposited on extensive piedmont slopes graded to ancestral-river systems also form other major facies assemblages that have good aquifer performance and recharge potential in some areas.

River-Valley-Fill Subdivisions

At the northern edge of the study area, the deeply entrenched Gila River Valley has developed since Early Pleistocene time (past 1 Ma). Valley incision has resulted in local removal or drainage of Gila Group deposits and older bedrock units. The succession of inset fills that occupy the present Gila Valley system include fluvial-channel and floodplain deposits (facies *a*) and arroyo-channel and fan alluvium (facies *b*). Both active channel floodplain and abandoned valley-fill (terrace) deposits are represented. These facies assemblages are the basic building blocks of hydrostratigraphic units RG, TA, and VA. Subfacies *a1* (gravelly) and *a2* (sandy) comprise, the coarse-to-medium-grained channel deposits of the Gila River (RG) and are typical of the shallow-aquifer system beneath modern river-valley floors (also units RCG, RM, RA). These subfacies are also major components of the river-terrace (TA) fills that flank the inner Gila Valley between Duncan-Virden and the Gila Cliff reaches. (Note they are equivalent to subfacies Iv of Hawley et al. 1995.) Silt-clay-rich subfacies *a3* is also an important local component of inner-valley (RG) fills, particularly beneath the modern floodplain outside of active channel areas. Lithofacies *b* is an undivided complex of textural and clast-type classes associated with the high-gradient, ephemeral depositional environments of tributary arroyo systems (washes) that are graded to present (RG) and former (TA) river-valley floors. Facies *b* is a general correlative of subfacies *Vv* of Hawley and Haase (1992), and it is the product of the same alluvial, hyperconcentrated-flood-flow and mass-wasting processes that produced piedmont lithofacies *5* and *6*.

Facies *a* and *b* are also the basic building blocks of hydrostratigraphic units RM and RA, located, respectively, in the valleys of the upper Mimbres River and Animas Creek, as well as in mapped segments of the lower Rio Casas Grandes (RCG). The distal distributary channels (including fan deltas) of all three of these fluvial systems (RCGF, RCGD, RMF and RAF) are complexes of facies assemblages *a1*, *a3* and *c*. Facies *c* is primarily a fine to medium-grained assemblage of interbedded silty clays and sands, grading to silty to sandy clays with local evaporite zones (cf. facies *3*, *9*, *10*) and eolian sediments (cf. facies *4*). This facies is associated with alluvial flat, wet meadow (cienega), playa and paleolake environments of deposition.

Intra-Basin and Bedrock-Boundary Structural Components

Intra-basin and bedrock-boundary structures are major components of the model and include (1) basin-bounding mountain uplifts and bedrock units beneath the basin-fill, (2) fault zones within and at the edges of the basin that influence fill thickness and composition, and (3) the igneous intrusive and extrusive (volcanic) rocks that locally penetrate or overlap basin-fill deposits. Regional tectonic and more local structural controls on lithofacies distribution patterns and subbasin "segmentation" are illustrated on Plate 1, and they are described in more detail in sections on individual basins in subsequent parts of this report. Emphasis is placed on how geologic structure influences both internal-aquifer characteristics and unit-boundary conditions that enhance or restrict groundwater flow. For example, idealized basin-boundary recharge conditions along the subsurface part of a mountain front fault zone are illustrated on Figure 3-3 (from Wasiolek 1995).

Discussion

Since introduction of this methodology for organizing data on the hydrogeologic properties of basin and valley fills in a Rio Grande rift tectonic setting (Petersen et al. 1984, Hawley and Lozinsky 1992, Hawley and Haase 1992, Hawley et al. 1995), the conceptual model briefly described above has proved to be a valuable tool for classifying and interpreting a very large and quite varied data base. Such variability is evident with respect to both spatial distribution and general quality of basic data, the latter ranging from *hard* to *anecdotal*. The model simply provides a template for characterizing and graphically presenting the large amount of available hydrogeologic information on texture, mineralogy, diagenesis, depositional environments, age, and general aquifer properties of basin and valley fills. The end results of the data collection-analysis-synthesis process are the hydrogeologic and geohydrologic inferences presented on Plate 1, Figures 4-2a, b, 5-2, 6-2, 7-2 and 9-2, and Tables 3-5 to 3-9. Without constant feedback, this process can be quite subjective, primarily because it requires reasonably correct identification of both genetic and chronologic units in sedimentary sequences that may not be exposed anywhere except in boreholes. Textural and mineralogic classification based on modern sample and wireline logging techniques can be very accurate, but proper recognition of depositional environments, age and diagenetic processes normally require considerable field experience in mapping areas with a similar geologic history and well-exposed *control* sections of basin and valley fills. Therefore caution should be used when employing these methods.

Fortunately, in the southeastern Basin and Range region, there are many well-studied areas where combined surface geologic and subsurface geohydrologic evaluations of available data bases have already been made (cf. Frenzel and Kaehler 1992, Hawley and Lozinsky 1992, Kernodle 1992a, Thorn et al. 1993, Haneberg 1995a, Kernodle et al. 1995, Hawley 1996, Allen et al. 1998, Connell et al. 1998, Smith and Kuhle 1998). For example, the Tesuque Formation of the Espanola Basin (Hearne 1980, McAda and Wasiolek 1988, Lazarus and Drakos 1995) serves as an excellent analog for facies *5* to *8* and hydrostratigraphic units US1, UGI, MS1 and MG1.

Detmer's (1995) detailed field investigation of aquifer-permeability in the Albuquerque metropolitan area relates primarily to facies *1*, *2*, *5a*, *a* and *b* (Table 3-4) and hydrostratigraphic units US1, US2, RG, PA and VA. Similar, more intensive permeability measurements at one site in the Belen Basin by Davis and others (1993) and Lohman and others (1991) provide an excellent characterization of basin-fills representative of facies *3* and hydrostratigraphic units US2, UG2, MG2, and MSF2. Recent petrographic work on the Sierra Ladrones and Zia formations of the northwestern Albuquerque Basin (Mozley and Davis 1996, Beckner and Mozley 1998) describes the hydrologic properties of facies assemblages *2* to *4* in relation to evolution of permeability distribution over geologic time caused by diagenetic processes in paleogroundwater-flow systems. Groundwater-flow (and quality) in lithofacies *2* to *4* in Santa Fe Group aquifers of the Mesilla and Hueco bolsons is particularly well characterized (Wilson et al. 1981, Frenzell and Kaehler 1992, Cliett and Hawley 1996, Hibbs et al. 1998).

Studies of ancestral and modern river-channel facies units (*1*, *2* [US2], *a1*, and *a2* [RG]) are also very important because they are typical of medium to coarse-grained fluvial deposits worldwide (cf. Anderson 1989). Fine-grained basin-floor facies *9* and *10* (hydrostratigraphic units MG, LG, MSF and LSF) are usually easy to identify in the subsurface. Moreover, these important confining units never form aquifers.

Structural elements of the model, both intra-basin and bedrock-boundary components, always pose special problems in terms of groundwater flow and recharge conditions. Fault zones being investigated by co-workers in central and southern New Mexico have proved to be particularly important features that normally act as barriers to groundwater flow both along basin boundaries and in intra-basin areas (Haneberg 1995b, Mozley and Goodwin 1995a, 1995b, Sigda 1995, Woodward and Myers 1997). Finally, stress-dependent changes in hydraulic conductivity of Santa Fe Group sediments over time (historic and geologic) related to changes in hydrostatic and overburden pressures are being investigated by a number of workers in the region (e.g., Haneberg 1995a, Haneberg et al. 1998, Heywood *in progress*; Kernodle 1992b).

WATER QUALITY

Regional Water Quality

The complex and highly variable lithologies and rock types in the study region create a variety of hydrochemical facies that contribute to the irregular distribution of salinity in the aquifers. Groundwater varies from very dilute to moderately saline and hydrochemical facies vary from calcium-magnesium-bicarbonate to sodium-chloride-sulfate type waters. Irrigation water quality is generally acceptable, with many groundwaters characterized by medium salinity hazard and low alkali hazard. Some groundwaters have marginal water quality for domestic, livestock, and irrigation purposes. Nitrate in groundwater seldom exceeds the USEPA drinking water standard of 10 mg/L NO_3-N.

The evolutionary hydrochemical trends that are evident in most of the basins in the study area include the development of dilute, calcium-magnesium-bicarbonate groundwaters in the mountains that evolve to dilute, sodium-bicarbonate groundwaters in alluvial fans. Groundwater continues to evolve to slightly saline, sodium-bicarbonate-sulfate type waters in many basins; the sulfate concentrations in groundwater becoming greater than the bicarbonate concentrations, as groundwater moves further downgradient. The chloride ion is the dominant anion in a few groundwaters at the end of their flowpath. The modified Chebotarev (1955) sequence is thus exhibited:

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

While partly a function of evolution along flowpaths, the Chebotarev sequence is also a function of contact of groundwaters with different rock and sediment types, combined with evaporative discharge processes. These reactions and processes include: (1) dissolution of calcite, dolomite, and other mineral assemblages in the bedrock highlands to produce calcium-bicarbonate rich groundwaters; (2) exchange of bound sodium for calcium and magnesium in solution due to monovalent-divalent cation exchange on clay particles in alluvial fill; (3) addition of calcium and sulfate from dissolution of gypsum, along with monovalent-divalent cation exchange as groundwaters move into playa sediments that contain gypsum; (4) dissolution of halite that has precipitated in soils due to evaporation, with the resulting addition of sodium and chloride to groundwaters as rainwater infiltrates through soil profiles near mountain fronts and playas; and (5) evaporation of groundwaters near phreatic playas that concentrates sodium, sulfate, and chloride in solution. With respect to the potability of groundwaters and irrigation suitability, the basic water quality findings are described as follows.

Mimbres Basin

Groundwater in the northern half of the Mimbres Basin is usually less than 500 mg/L TDS (total dissolved solids). Near and extending across the U.S./Mexico border, groundwater is usually greater than 500 mg/L TDS, reaching concentrations greater than 1,000 mg/L in the southernmost part of the Mimbres Basin. Groundwater has low alkali hazard and medium salinity hazard for irrigation purposes in most groundwaters in the northern part of the basin. Salinity risks increase to high hazard, and alkali hazard is low to very high in the southern Mimbres Basin. Nearly all of the water quality analyses are well below 5 mg/L NO_3-N.

Hachita-Moscos Basin

Water quality data are limited in the Hachita-Moscos Basin. The available data indicate that most groundwater samples in the northern Moscos Basin and Hachita Basin are less than 500 mg/L TDS. In the southern Moscos Basin, groundwater often exceeds 500 mg/L TDS and several samples are greater than 1,000 mg/L TDS. Groundwater has low alkali hazard and medium salinity hazard for irrigation purposes in most groundwaters in the Hachita Basin and northern Moscos Basin. About half the samples in the southern Moscos Basin have medium to very high alkali hazard and high salinity hazard. The other samples have low alkali hazard and medium salinity hazard. Nearly all of the water quality analyses are well below 5 mg/L NO_3-N.

Playas and San BasilioBasin

Groundwaters in the Upper Playas Subbasin are less than 500 mg/L TDS. The southern half of the Lower Playas Subbasin is also characterized by groundwater with salinities less than 500 mg/L TDS. Groundwater salinities in the northern half of the Lower Playas Subbasin often vary from 500 to 1,000 mg/L TDS. Groundwater has low alkali hazard and low-to-medium salinity hazard for irrigation in the Upper Playas Subbasin. Nearly all of the groundwater samples in the Lower Playas Subbasin have low-to-medium alkali hazard and medium salinity hazard. Most groundwater samples have less than 1 mg/L NO_3-N.

Animas Basin

Groundwater in the southern part of the Animas Basin is usually less than 250 mg/L TDS. Groundwater is usually greater than 250 mg/L TDS in the northern part of the Animas Basin, reaching concentrations greater than 1,000 mg/L in several areas. Groundwater has low alkali hazard and low to medium salinity hazard in the southern part of the Animas Basin. Groundwater in the northern part of the basin has highly variable salinity and alkali hazard; most samples exhibiting medium-to-high salinity hazard and low-to-high alkali hazard. Most of the water quality analyses for this basin are below 5 mg/L NO_3-N.

San Bernardino Basin

Groundwaters in the San Bernardino Basin are less than 1000 mg/L TDS. Several clusters of samples at the international border, near the axis of the basin, are less than 250 mg/L TDS. The data in Mexico are too limited to evaluate relationships of salinity to spatial locations in the basin. Groundwater has low alkali hazard and low-to-medium salinity hazard in the Mexican portion of the San Bernardino Basin. Most groundwater samples in the U.S. part of the San Bernardino Basin have low alkali hazard and medium salinity hazard. Nitrate data are very limited in the San Bernardino Basin. The very limited data indicate levels all less than 2.0 mg/L NO_3-N, both in the U.S. and Mexico.

Susceptibility to Contamination

The natural sensitivity assessment consisted of developing a GIS layer for each of the seven DRASTIC parameters (depth to water, net recharge, aquifer media, soil media, topography, impact of the vadose zone, and hydraulic conductivity). These layers were combined to create a natural sensitivity (NATSEN) map.

Depth-to-Water Table (D)

Depth-to-water refers to the depth from the land surface to the surface of the saturated zone in an unconfined aquifer or to the top of the confined aquifer. Above the water table, the pore spaces are partially filled with water and air. The water table may be present in any type of media and be either a permanent feature or seasonal. The depth-to-water is important primarily because it determines the distance and time which a contaminant must travel before reaching the aquifer. The data for the depth-to-water parameter were derived from the USGS Ground Water Site Inventory Database (GWSI).

To develop the depth-to-water contour coverage, the GWSI depth-to-water values were plotted and contours drawn to reflect the depth-to-water range. The contour map was then converted to a polygon coverage that represented the depth-to-water range. The range value was then multiplied by the weight to derive a depth-to-water index. The higher the index value the greater the influence this parameter has on aquifer susceptibility. The weight of 5 was chosen to indicate the importance of this parameter to the leaching process. The depth-to-water table interval range, and the DRASTIC rating, weight, and resulting index are listed in Table 3-7.

Table 3-7. Depth-to-water table parameter rating (Dr), weight (Dw), and index (D)

Range[1]	Rating[1]	Weight[2]	Index (D)	Percent of area
0-3	10	5	50	0.28%
3-6	9	5	45	3.10%
6-9	7	5	35	0.25%
9-12	5	5	25	3.79%
12-15	3	5	15	0.41%
15-30	2	5	10	4.73%
30+	1	5	5	87.40%

[1] Modified for local conditions from Aller et al. 1985, Table 4.
[2] From Aller et al. 1985, Table 3.

Net Recharge (R)

The primary source of groundwater is precipitation and seepage from losing streams that infiltrate through the unsaturated zone to the water table. The average annual precipitation ranges from less than 0.254 m (10 in) in low areas to as much as 0.762 m (30 in) at higher elevations. Net recharge indicates the amount of water per unit area of land that penetrates the ground surface and reaches the water table. The study area is an arid region where evapotranspiration exceeds precipitation. Therefore, the only significant potential effective recharge to the aquifer is through deep percolation of mountain-front runoff and infiltration from losing-water bodies such as the Rio Mimbres and Gila River.

Hanson and others (1994) use estimates of mountain-front recharge to show the relative distribution of recharge for the Mimbres Basin. The available estimates of average net recharge, at best, for the region are less than 1.2 mm (<0.5 in) per year (Darton 1916), however, there is virtually no information on actual rates of recharge for basins within the region (Hanson et al. 1994). To develop a GIS coverage for net recharge, a surface geology map (Plate 1) was modified to show areas of bedrock versus non-bedrock. The bedrock within the region is primarily crystalline and oftentimes is moderately to highly fractured (Trauger 1972). These fractures act as a conduit for groundwater flow into the regional aquifer system. The areas of bedrock (mountainous areas) generally receive larger amounts of precipitation and therefore an assumption is made that these areas have a higher rate of net recharge than the areas of non-bedrock. Table 3-8 lists the ranges for net recharge.

Table 3-8. Net recharge parameter rating (Rr), weight (Rw), and index (R)

Media[1]	Range (mm)[2]	Rating (Rr)[2]	Weight (Rw)[3]	Index (R)	Percent of Area
Basin-fill	0-5	1	4	4	62.5%
Bedrock	5-10	3	4	12	37.5%

[1] Based on modification of geology map (Plate 1).
[2] Modified for local conditions from Aller et al. 1985, Table 5.
[3] From Aller et al. 1985, Table 3.

Aquifer Media (A)

The aquifer media refers to the consolidated or unconsolidated material that serves as an aquifer. The major aquifer systems in the study area are made up of the saturated portion of the basin fill and valley fill. The bedrock also serves as an aquifer, however, the amount of water available, found mostly in fractures, from bedrock wells is limited (Trauger 1972). The GIS coverage for aquifer media uses a surface geology map (Plate 1) to delineate areas of aquifer material that have similar hydrogeologic characteristics. The characteristics can best be described as media composition, particle size, permeability, porosity, density, and so on. These areas of similar aquifer material are also called "lithofacies." The lithofacies described above were used to depict the aquifer media parameter. The parameter represents the effectiveness of the lithofacies as an aquifer. The higher the number, the greater the ability of the lithofacies to hold and transmit water. These units were assigned the DRASTIC ratings and weight listed in Table 3-9.

Table 3-9. Aquifer media parameter rating (Ar), weight (Aw) and index (A)

Facies Range[1]	Rating (Ar)[2]	Weight (Aw)[2]	Index (A)	Percent of Area
Bedrock	1	3	3	39.7%
1, 6a, 6b, a1, c	8	3	24	3.6%
2, 7, 8, a2	7	3	21	10.4%
3, 4	6	3	18	1.6%
5, 5a, 5b, 6, a, b	9	3	27	39.6%
9, 10, a3	4	3	12	5.1%

[1] Based on lithofacies descriptions discussed above.
[2] From Aller et al. 1985, Table 3.3

Soil Media (S)

A soil's susceptibility to potential contamination is affected largely by the type and amount of clay present, the shrink/swell potential (controlling the development of macropores and other secondary permeability features), and the soil's grain size. Moreover, soils of arid regions often have indurated calcic horizons, also known as caliche (Machette 1985). The DRASTIC index includes soil ratings appropriate for the pollution potential associated with development of secondary permeability.

The soils data were acquired from the USDA Natural Resource and Conservation Service in digital form (USDA SCS 1994). The data included the STATSGO and attribute database files that contained information concerning soil characteristics (USDA SCS 1994). Based on the soil characteristics of the map unit, values were assigned as specified by the DRASTIC model (Aller et al. 1985, p. 8-9). The selection of a value for the parameter was based on the most restrictive soil zone that occurred in the profile. The DRASTIC values for the parameter were then attached to the database. Table 3-10 contains the soil media and DRASTIC rating, weight and resulting index.

Table 3-10. Soil media parameter rating (Sr), weight (Sw) and index (S)

Soil Media[1]	Rating (Sr)[1]	Weight (Sw)[2]	Index (S)	Percent of Area
Bedrock, cemented	1	5	5	83.20%
Clay	2	5	10	9.40%
Clay Loam	3	5	15	3.20%
Sandy Clay	4	5	20	3.10%
Silty Clay Loam	5	5	25	0.03%
Gravel	10	5	50	1.10%

[1] Modified for local conditions from Aller et al. 1985, Table 7.
[2] From Aller et al. 1985, Table 3.

Topography (T)

The topography coverage was derived from USGS Digital Elevation Model (DEM) files. A DEM consists of an array of elevations for ground positions that are usually at regularly spaced intervals. The 1-degree DEM provides coverage in 1- by 1-degree blocks and is available for all of the contiguous United States, Hawaii, and most of Alaska. The basic elevation model is produced by the Defense Mapping Agency (DMA) using cartographic and photographic sources.

The 1-degree DEM consists of a regular array of elevations referenced horizontally on the geographic coordinate (latitude/longitude) system of the World Geodetic System 1984 Datum. Elevation data located on the degree lines (all four sides) correspond to the same profiles on adjoining DEM blocks. Elevations are in meters relative to mean sea level. Spacing of the elevations along and between each profile is at 3 arc-seconds with 1,201 elevations per profile.

The DEMs for the 1:250,000 scale Clifton, Douglas, El Paso, Las Cruces, Silver City, and Tularosa quads were acquired. These were imported into ARC/INFO using the function 'demlattice.' The six lattices were then merged into one large lattice that was then clipped by a coverage of the study area. The lattice coverage was then used to derive a polygon coverage that represented the slope (or topography) for the study area. The 'latticepoly' command used a lookup table to assign codes to the range in slope. This code was then used to attach a DRASTIC parameters database to the coverage. The actual slope is an indication of the ability of the terrain to either gather or shed water. A steep slope sheds water more rapidly than a gentle slope. A gentle slope allows for water to penetrate into the subsurface. The topography rating, weight, and index are listed in Table 3-11.

Table 3-11. Topography parameter rating (Tr), weight (Tw), and index (T)

Range (% Slope)	Rating (Tr)	Weight (Tw)[1]	Index (T)	Percent of Area
0-2	10	3	30	34.7%
2-6	9	3	27	9.1%
6-12	5	3	15	1.7%
12-18	3	3	9	0.5%
18+	1	3	3	54.0%

[1] From Aller et al. 1985, Table 3.

Impact of the Vadose Zone Media (I)

The vadose zone media refers to the unsaturated zone of consolidated or unconsolidated material above the water table. The type of vadose zone media determines the attenuation characteristics of the material below the typical soil horizon and above the water table (Aller et al. 1985). The vadose media acts as a zone of biodegradation, neutralization, mechanical filtration, chemical reaction, volatilization, and dispersion. The GIS coverage showing the impact of the vadose zone media uses a surface geology map (Plate 1), modified to show lithofacies characteristics. The vadose zone media ratings, weights and index are listed in Table 3-12.

Table 3-12. Vadose zone media parameter rating (Ir), weight (Iw) and index (I)

Facies Range[1]	Rating (Ir)[2]	Weight (Iw)[2]	Index (I)	Percent of Area
Bedrock, *2*	5	4	20	39.2%
1, 7, 8, a2	6	4	24	10.1%
4, 5, 5a, 5b, 6, a, b	8	4	32	40.8%
6a, 6b, a1, c	7	4	28	4.7%
9, 10	3	4	12	1.9%
a3	1	4	4	3.2%

[1] Based on lithofacies descriptions and modification of Plate 1.
[2] Modified for local conditions from Aller et al. 1985, Table 9.
[3] From Aller et al. 1985, Table 3.

Hydraulic Conductivity of the Aquifer (C)

The hydraulic conductivity refers to the ability of the aquifer media to transmit water, which controls the rate at which groundwater will flow under a given hydraulic gradient. This GIS coverage was derived from a modification of a surface geology map (Plate 1), and is based on hydraulic characteristics of the lithofacies. The hydraulic conductivity ratings, weights and index are listed in Table 3-13.

Table 3-13. Hydraulic conductivity of the aquifer parameter rating (Cr), weight (Cw), and index (C).

Facies Range[1]	Rating (Cr)[2]	Weight (Cw)[2]	Index (C)	Percent of Area
Bedrock, 9, 10	1	2	2	39.8%
1, 2, a, a1	4	2	8	1.5%
3, 4, 5, 5a, 5b, 6, 6a, a2, a3, b	3	2	6	47.7%
6b, 7, 8, b	2	2	4	11.0%

[1] Based on lithofacies descriptions and modification of Plate 1.
[2] From Aller et al. 1985, Table 3.

By combining the seven DRASTIC parameters a natural sensitivity (NATSEN) index was developed. These values were grouped into three categories: *low* - indicating the groundwater aquifer is very well protected and contamination risk from nonpoint sources is low; *moderate* - the groundwater aquifer is somewhat protected, but more than one of the parameters are conducive to contamination; *high* - the groundwater aquifer is much more susceptible to contamination due to a number of hydrologic conditions. Table 3-14 presents the areal extent of each of the three natural sensitivity categories. Figure 3-7 presents the NATSEN coverage in map form.

Table 3-14. Areal extent of the natural sensitivity classes in the region

Natural Sensitivity Index	Class	Areal extent (km^2)	Percent of Area
3	High	190	0.6%
2	Moderate	17,010	53.8%
1	Low	14,400	45.6%
Total		31,600	100.0%

Findings

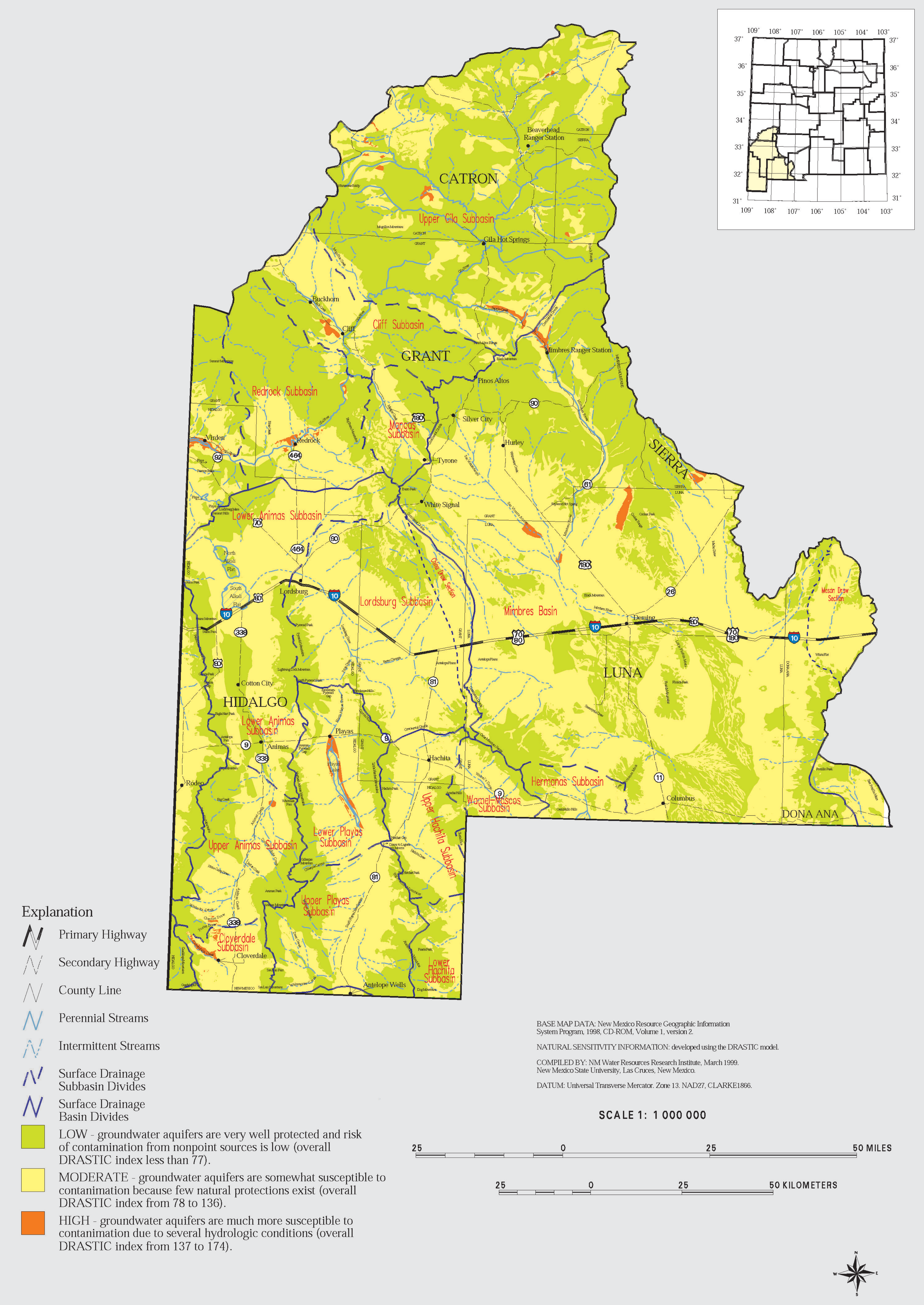
The results indicate that the technique and data provide reliable **regional-scale** indications of groundwater aquifer sensitivity to contamination from surface sources. Because the STATSGO data are generalized, which may combine as many as 21 individual SSURGO soil map units, this restricts the use of the assessment. It may serve as a guide that can indicate areas where more detailed assessments should be undertaken. In the same light, it can also serve to indicate areas where no further assessment need be undertaken.

The High Natural Sensitivity Class (red) areas on Figure 3-7 should be analyzed in greater detail. Some Moderate areas (yellow) adjacent to perennial streams likewise warrant analysis. The areas listed below (currently classified as moderate) are near perennial streams, where the composition of the valley fill and shallow water table would suggest a higher classification value. However, lack of detail in STATSGO data results in a lower value.

1. Perennial reach of the lower Gila River system between Virden and Redrock;
2. Perennial reach of the middle Gila River system above Cliff;
3. Perennial reach of the upper Mimbres River system from near the Mimbres Ranger Station to the Grant and Luna county line; and
4. Ephemeral reach of the lower Mimbres River above Deming.

The results of the DRASTIC model have not been extensively field-checked. However, during the water well verification stage (Chapter 2, Figure 2-1) of this project, the field team made observations in the Virden Valley, Upper Playas Subbasin, Upper and Lower Mimbres subbasins. The field team noted that the groundwater levels near streams were less than three meters in the Upper Mimbres Subbasin and Virden Valley. It also was noted that groundwater was greater than fifty meters from the land surface in the Lower Mimbres Subbasin (near Deming) and the Upper Playas Subbasin.

The primary focus of the susceptibility to contamination analysis was to look at the contamination potential of the region. The DRASTIC map does not show areas that are contaminated, only areas that have a relative potential for contamination from human activities. The model does not take into account the hydrochemical characteristics of the aquifer material or the location of possible human activities that may contribute to aquifer contamination. The DRASTIC model was designed by Aller et al. (1985) to function as a systematic tool for identifying areas that had a higher potential for contamination, however, the model often fails to accurately predict groundwater contamination (Barbash and Resek 1996). This is a significant limitation to the DRASTIC model. However, this model is highly effective in pointing out areas that require further study (Figure 3-7). Please note that the model evaluates parameters that effect transport of water at a small scale (1:500,000). The model does not attempt to investigate aquifer sensitivity at a large scale (< 1:100,000) and more importantly, does not attempt to investigate the influence of human activity on the groundwater aquifer system. The authors recognize that a detailed study of the relationship between human activity and the aquifer system would require the addition of geochemical data. Afseth (1995) combined data from the Conterminous United States Mineral Assessment Program, the National Uranium Resource Evaluation, the Center for Inter-American Resource Investigation, and Mineral Resource Data System to develop a method to quantify the environmental status of the region. Such a method would be an important component in a detailed study of the relationship between human activity and the quality/quantity of groundwater aquifers in southwestern New Mexico.



BASE MAP DATA: New Mexico Resource Geographic Information System Program, 1998, CD-ROM, Volume 1, version 2.

NATURAL SENSITIVITY INFORMATION: developed using the DRASTIC model.

COMPILED BY: NM Water Resources Research Institute, March 1999. New Mexico State University, Las Cruces, New Mexico.

DATUM: Universal Transverse Mercator. Zone 13. NAD27, CLARKE1866.

Figure 3- 7. Natural sensitivity of groundwater aquifers to contamination from nonpoint sources