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DIGITAL HYDROGEOLOGIC-FRAMEWORK MODEL OF THE SAN FRANCISCO RIVER BASIN, WEST-CENTRAL NEW MEXICO AND EAST-CENTRAL ARIZONA

WRRI Technical Completion Report No. 354

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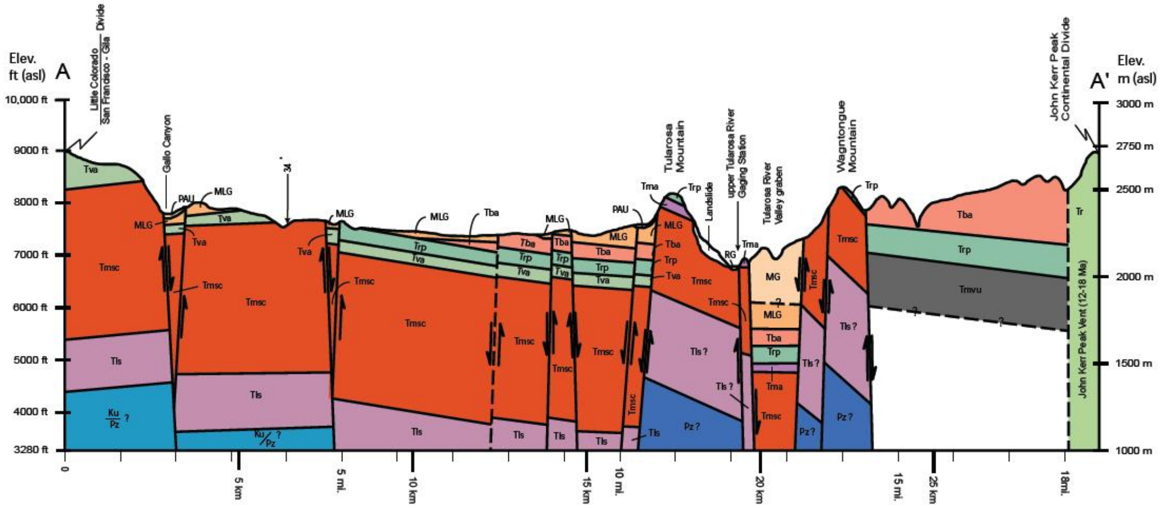

Hydrogeologic Section A-A' - northeastern Reserve graben and upper Tularosa River Valley (see Figure 1-2, page 5).

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By

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This report is especially dedicated to the memory of co-author, esteemed colleague, and mentor, Dr. Bobby J. Creel, who passed away on February 15, 2010.

ABSTRACT

The San Francisco River (**SFR**) is the major Gila River tributary in the upper Gila basin of west-central New Mexico and east-central Arizona (Figure 1-1). This study and related hydrologic-hydrographic investigations are part of ongoing efforts by the New Mexico Interstate Stream Commission (NMISC) to improve geohydrologic models used in management of both surface-water and groundwater resources of the Gila River subdivision of the “Lower Colorado River (Compact administrative) Basin.” The study area includes parts of Catron and Grant Counties in New Mexico as well as most of Greenlee County and a small part of Alpine County, Arizona (Figure 1-1). It comprises not only the **SFR** basin portion of the Gila-San Francisco “ground-water basin” (as declared by the New Mexico State Engineer-NMOSE-6/30/1991), but also the southern edge of the “Lower Colorado Basin” and the western Plains of San Agustín subbasin of the “Rio Grande Basin" east of the Continental Divide. The **SFR** basin is characterized by large topographic relief (3,280-10,760 ft; 1,000-3,279 m), semiarid to humid climatic conditions (including extreme seasonal precipitation events), and complex distribution patterns of basin-fill and bedrock aquifer systems. These factors combine to produce high variability in surface-water/groundwater discharge and availability.

Time and budget constraints did not permit site-specific assessment of aquifer potential; and we could only evaluate the essential elements of the hydrogeologic-framework (stratigraphy-lithology-structure) at a drainage basin and subbasin scale in the New Mexico part of the study area. While primarily based on published hydrogeologic work (Trauger 1972; and Basabilvazo 1997), our study also incorporates a large amount of basic geologic information that has only been available since 1994. As a result, this is the first synoptic integration of a large geologic database specifically designed for characterization of **SFR** basin aquifer systems. Our main achievement has been development of a GIS-based, digital hydrogeologic model using ARC-GIS® and Adobe Illustrator®, respectively, for map and cross-section compilation. From a flow-modeling perspective, hydrogeologic databases and conceptual-framework models have, heretofore, only been available in formats with a wide range of interpretive quality and clarity.

Plate 1 is a plan (map) view of the basin-scale hydrogeologic framework. It schematically illustrates surface-distribution patterns of major bedrock and basin-fill mapping units as well as large-scale tectonic and volcanic features. The map was compiled from a variety of mid-scale GIS sources in New Mexico (1:100,000 to 1:500,000 scale) that were merged with a much less detailed Arizona database (1:500,000 to 1:1,000,000). In addition, unit boundaries and definitions were adjusted in many places to reflect more-detailed quadrangle mapping. The subsurface dimension is illustrated by five schematic cross sections (Plate 2a-e) that were created specifically for this study at a map-scale of 1:100,000, base elevation of mean sea level, and 5x vertical exaggeration. Detailed definitions of hydrostratigraphic mapping units (HSUs) and component lithofacies-assemblages (LFAs) are provided in Tables 3-1 to 3 and 4-1. Table A1 in the Appendix contains selected data from published records of 277 wells and springs in the New Mexico part of the study area, and include preliminary interpretations of the hydrostratigraphy and producing aquifer(s) at each site. Approximate well/spring locations are shown on Plate 3. While all geology-based models tend to be "works in progress," we believe that our digital model and supporting database represents a significant advance over previous work.

Keywords: upper Gila River basin, San Francisco River basin, hydrogeology, GIS, hydrogeologic model

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1.0 INTRODUCTION

1.1 PURPOSE AND SCOPE

The San Francisco River (**SFR**) is the only perennial tributary to the Upper Gila River in the headwaters region of western New Mexico and eastern Arizona (Figure 1-1). The Gila-**SFR** confluence is about 10 miles south of the Clifton-Morenci mining district, the site of the largest open-pit copper mine in North America (EARTH 2009). The 2,790 mi^2 (7,230 km^2) drainage basin is in the Transition Zone physiographic/tectonic province, and includes the Blue River (AZ) and Tularosa River (NM) watersheds and much of the Mogollon-Datil volcanic field. The basic geologic-framework of the region was initially described by G.K. Gilbert (1875); and part of the **SFR** basin is in the first National Forest area protected by the Wilderness Preservation System that Aldo Leopold (1887-1948) helped establish in 1924 (Moore 2008). From a regional, historic, and hydrogeologic perspective, the finite nature of groundwater resources has long been recognized (e.g., Gilbert 1875; Powell 1895; Knechtel 1938; Trauger and Doty 1965; Anderson et al. 1988; Robson and Banta 1995; Hawley et al. 2000; Hawley and Kernodle 2008). Time and budget constraints did not permit site-specific assessment of aquifer potential and we can only evaluate the essential hydrogeologic-framework elements (lithology, stratigraphy, and structure) at a drainage-basin/subbasin scale in this report (cf. Section 4).

The study's primary purpose was to develop a digital hydrogeologic model of **SFR** basin aquifer systems that will provide essential information on hydrologic/hydraulic properties of geologic units to three major user groups: 1) the scientific-technical community (mainly geohydrologists and geochemists) that must create state-of-the-art numerical models of groundwater-flow and hydrochemical systems; 2) governmental agencies charged with water-resource management; and 3) a diverse public sector that has a broad range of concerns, including water supply, protection of water rights, environmental issues, and general "public welfare."

Our basin-scale (conceptual and physical) hydrogeologic model was initially based on fundamental work by Trauger (1972) in Grant County and Basabilvazo (1997) in Catron County, with subsequent incorporation of a large amount of geologic information that has only been available since 1994 (e.g., Cather et al. 1994; Chamberlin et al. 1994; Crews 1994; Houser 1994; Witcher et al. 1994a-c; Ferguson and Enders 2000; Ferguson et al. 2000; Hawley et al. 2000; Ratté 2001, 2008; Mack 2004; and Mack and Stout 2004). A much less detailed characterization of the Blue River subbasin in Arizona is strictly based on review of reconnaissance-level geologic-field investigations by the U.S. Geological Survey, Arizona Geological Survey, and the

University of Arizona (e.g., AZGS-ND; Berry 1976; Houser 1994; Ratté 1982; Ratté et al. 1969, 1984; Wilson et al. 1958). Description of climate, and land use and cover are outside the project scope.

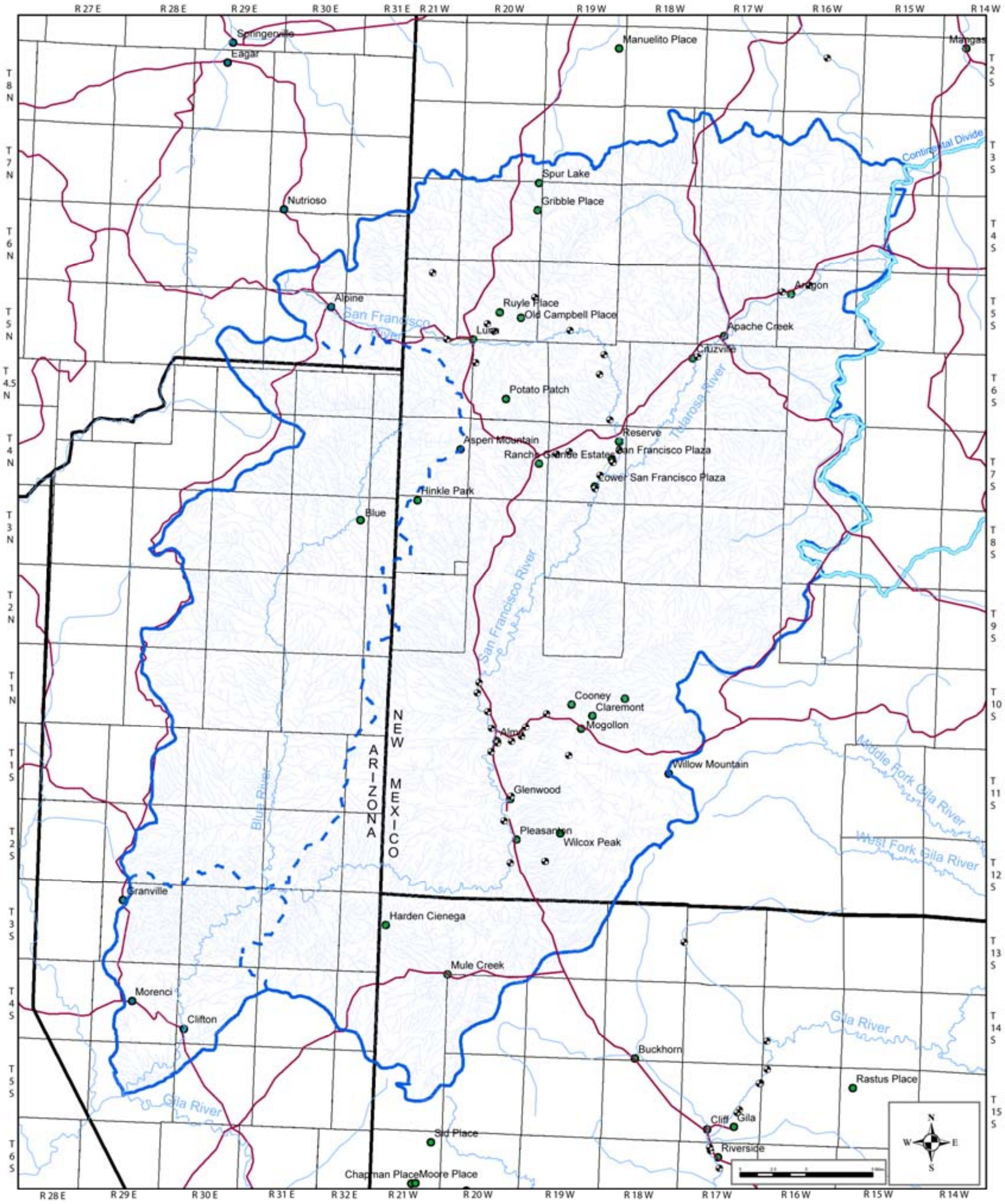

Figure 1-1. Index map of the San Francisco River basin and adjacent parts of New Mexico and Arizona, showing major perennial streams, hydrographic subbasins, and selected localities on a State Land-Survey-grid base.

This study and related concurrent hydrologic-hydrographic investigations were funded by the New Mexico Interstate Stream Commission (NMISC), and are part of an ongoing effort to improve geohydrologic models used in management of both surface-water and groundwater resources of the Gila River subdivision of the "Lower Colorado River (Compact administrative) Basin." The New Mexico Office of the State Engineer (NMOSE) has "declared" shallow "ground-water basins" in the study region for administrative purposes. Borders of these administrative units, however, may not precisely match the surface-watershed and/or groundwater-flow system boundaries described herein. Areas of Catron and Grant Counties covered (Figure 1-1) include not only the **SFR** basin portion of the Gila-San Francisco "groundwater basin" (as declared by the NMOSE-6/30/1991), but also the southern edge of the Little Colorado River ("Lower Colorado") basin and the westernmost "Rio Grande Basin" east of the Continental Divide (western Plains of San Agustín). The "Lower" **SFR** and Blue River subbasins in Arizona (Figure 1-1) include most of Greenlee County and a small area of southern Apache County, and comprise State of Arizona Hydrologic Unit 15040004 (U.S. Geological Survey 1975).

This is the first synoptic integration of hydrogeologic information on the San Francisco River basin in New Mexico and Arizona; and our principal accomplishment has been development of a GIS-based, basin-scale digital model of **SFR** basin hydrogeology using ARC-GIS® and Adobe Illustrator®, respectively, for map and cross-section compilation. From a flow-modeler's perspective, hydrogeologic databases and interpretations have, heretofore, only been available in a variety of formats with a wide range of interpretive quality and clarity. While all geology-based models tend to be "works in progress," we believe that our digital-framework model represents a significant scientific and technological advance over previous work. Plate 1 is a plan view of the basin-region hydrogeologic framework, which shows the surface-distribution patterns of major bedrock and basin-fill mapping units. It was compiled (1:500,000 scale) primarily from cited published geologic map sources during the study phase completed in June 2009. The five schematic hydrogeologic cross-sections (Plate 2a-e) were prepared specifically for this study in order to integrate all available surficial and subsurface information into a 3-D conceptual model of the basin's hydrogeologic framework (horizontal-compilation scale 1:100,000 with 5x vertical exaggeration).

To further facilitate interpretation of published records on individual wells (265) and springs (12) in New Mexico, 277 site locations in Catron and Grant Counties (Basabilvazo 1997, Table 4; Trauger 1972, Table 12) have been incorporated into a preliminary GIS database that characterizes hydrostratigraphy and aquifer zones with more hydrogeologic precision (Appendix Table A1). Approximate well and spring locations are show on Plate 3. While beyond the scope of the present study, creation of state-of-the-art groundwater-flow models will ultimately require much more complete integration of synoptic hydrogeologic interpretations (cf. Plates 1 to 3, Tables 4-1 and A1) with both published and updated well, spring, and streamflow records.

1.2 LOCATION

The San Francisco River (**SFR**) basin is located in west-central New Mexico and east-central Arizona, between 32° 55' and 34° 5' north latitude, and 108° 22.5' and 109° 22.5' west longitude. Major hydrographic features and basin/subbasin boundaries are shown on Figure 1-1. Two-thirds of the 2,791-mi^2 (7,230-km^2) watershed area is in New Mexico (1,865 mi^2; 4,829 km^2) and 927 mi^2 (2,400 km^2) is in Arizona. Principal valley/basin-fill aquifer systems are in and adjacent to the valleys of the **SFR** and its major perennial tributaries, including Tularosa River in New Mexico and Blue River in Arizona (Figure 1-1). More detailed hydrogeologic information (digital map and schematic cross-section format) is presented on Plates 1 and 2a-e. Report emphasis is on deposits in river valleys and structural basins (Gila Group), and older bedrock units (volcanic and sedimentary) with significant aquifer potential.

To facilitate description of aquifer systems on a basin scale, the San Francisco River (**SFR)** basin is subdivided into three informal hydrographic subbasins that are defined in terms of watershed geometry (Figures 1-1, 1-2; Table 1-1): the drainage-basin above the **SFR**-Blue River confluence is designated the Upper **SFR** subbasin; and the downstream watershed area and the tributary Blue River drainage basin comprise, respectively, the Lower **SFR** and Blue River subbasins. Bordering drainage divides include: the **SFR**-Little Colorado River divide to the north, the Continental Divide (with San Agustín closed watershed) to the northeast, the **SFR**-Upper Gila River divide (Mangas to Duncan basin reach) to the east and south, and the Blue River-Upper Gila and Salt River divide to the west. Most of the 2,027-mi^2 (5,249-km^2) Upper **SFR** subbasin is in New Mexico (1,820 mi^2 [4,715 km^2]) with only 206 mi^2 [534 km^2] in Arizona, and includes the watershed of its major eastern tributary, the Tularosa River. Almost the entire 617 mi^2 (1,597 km^2) Blue River watershed is in Arizona, with only 44 mi^2 (115 km^2) in New Mexico. The Lower **SFR** subbasin is entirely in Arizona, and has an area of about 148 mi^2 (383 km^2).

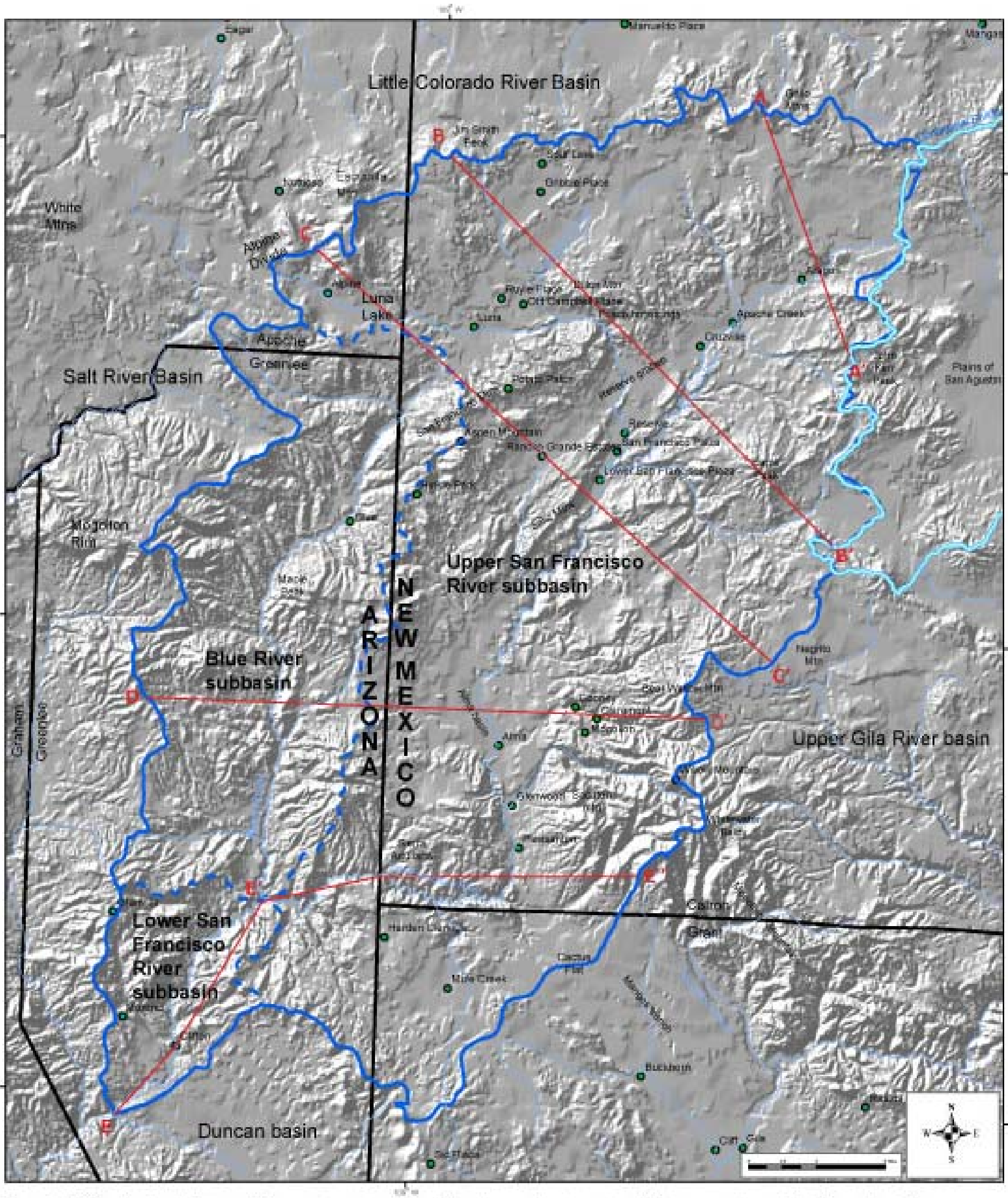

Figure 1-2. Shaded-relief map of the west-central New Mexico and east-central Arizona region of the Transition Zone physiographic province—Datil-Mogollon section, showing locations of the San Francisco River and its hydrologic subbasins, and major highlands (mountains and plateaus) and structural basins of the Mogollon-Datil volcanic field. Primary valley-fill and basin-fill (Gila Group) aquifer systems are located in the Reserve, Alma-Mangas (NM), and Duncan (AZ) structural basins. Shaded relief from latest available U.S. Geological Survey DEM Database.

1.3 PHYSIOGRAPHIC SETTING

The entire study area (Figure 1-2, Table 1-1) is in the southern part of the Datil-Mogollon (D-M) section of the Transition Zone (TZ) province (Peirce 1985; Morrison 1985, 1991; Mack 2004; Pazzaglia and Hawley 2004; Connell et al. 2005). Placement of physiographic-unit (province and section) boundaries is based on recent regional geomorphologic and hydrogeologic research by Hawley and associates at the NM Bureau of Geology (NMBGMR) and the NM Water Resources Research Institute (NMWRRI) (Hawley 2005; Hawley et al. 2000, 2005). The D-M section is adjacent to the Continental and Gila-Colorado River drainage divides, and contains the only continuous (perennial-intermittent) fluvial systems in the study area, the Upper Gila and San Francisco Rivers. The main-stem Gila is ultimately joined by the San Pedro and Salt Rivers, and is tributary to the Colorado River (at Yuma, AZ). The Tularosa River (NM) and the Blue River (AZ) are the primary **SFR** headwater tributaries (Figure 1-1). The most prominent topographic feature in the immediately adjacent part of the Colorado Plateau (Acoma-Zuni section) is the late Miocene, White Mountain volcanic center with a peak elevation at Mount Ord of 11,357 ft (3,462 m). The summit area is one of the two southernmost areas of Pleistocene alpine glaciation in the continental United States (Merrill 1984). Other highlands in the study area that were sites of major Late Pleistocene periglacial activity (Blagbrough 1994a,b) include Escudilla Mountain near Alpine, AZ (max. elev. 10,912 ft; 3,326 m) and peaks of the Mogollon Mountains, NM (max. elev. 10,895 ft; 3,321 m).

The large topographic relief (3,280-10,760 ft; 1,000-3,279 m), semiarid to humid climatic conditions (including extreme seasonal precipitation events), and complex distribution patterns of basin-fill and bedrock aquifer systems combine to produce high variability in surface-water/groundwater discharge and availability (NCDC-ND; Trauger 1972; Gabin and Lesperance 1977; Tysseling et al. 1986; Hanson et al. 1994; Basabilvazo 1997; Waltemeyer 2008). For example, the 1927 to 2008 average mean-daily flow at the gaging station near Glenwood (NM) is 87.55 cfs (2.5 m^3/s), but recorded peak flows include: 17,500 cfs (495 m^3/s) in 1972; 14,000 cfs (395 m^3/s) in 1978; 27,500 cfs (780 m^3/s) in 1983; and 12,900 cfs (365 m^3/s) in 1984.

As the TZ-province name indicates, this highland region encompasses a broad “zone” of structural “transition” between the unextended geologic terrane of the Colorado Plateau province, and the lower-lying, more extended Basin and Range region (Figure 1-2). Typical landforms of the Datil-Mogollon section include the high plateaus and remnant vent complexes of the Middle Cenozoic Mogollon-Datil volcanic field (Ratté 1989; Chapin et al. 2004; Elston 2008), which are cut by deep canyons of the Upper Gila-San Francisco system. The plateau and canyon topography is locally interrupted by narrow structural basins and flanking fault-block uplifts of Late Cenozoic age, including the Reserve and Alma "grabens" (Crews 1994; Houser 1994) and the northern Mangas basin (Mack 2004; "trench" of Trauger 1965). Prominent relict volcanoes of Miocene age also penetrate older (Gila Group) basin-fill sequences in a few places (e.g., Eagle Pk: 9,786 ft; 2,983 m). Highest elevations in the **SFR** basin watershed are in the Mogollon Mountains, with Whitewater Baldy at 10,895 ft (3,321 m), and near the southern end of Escudilla Mountain (AZ) at 10,758 ft (3,279 m). The lowest valley/canyon floor is about 3,280 ft (1,000 m) at the Gila River-**SFR** confluence in the northwestern Duncan Basin (Figure 1-2, Table 1-1).

The perennial-intermittent San Francisco River flows through a series of narrow valleys and canyons (cut in bedrock and indurated basin fill) that alternate with short, broader valley segments, all of which have only a thin (<100 ft; 30 m) cover of unconsolidated alluvium (fluvial-channel, floodplain, and terrace deposits). The same observation applies for the major **SFR** tributary in New Mexico, Tularosa River, but the Blue River (AZ) is essentially confined to bedrock canyons and narrow valleys. In New Mexico, wider valley floors are present near Luna, Cruzville (Tularosa River), Reserve, Alma, and Glenwood, and have been developed for irrigation agriculture in several places (Basabilvazo 1997).

Major intermittent tributaries to the **SF** River above the Tularosa River confluence include Trout Creek and Centerfire Creek, with large watersheds in the northernmost part of the subbasin. The largest Tularosa River tributaries include Apache Creek and "Largo Creek," and Deep Canyon "creek" and Negrito Creek, with their respective headwater areas to the north and southeast of the main stream. Primary downstream **SFR** tributaries in New Mexico include Saliz Canyon "creek" and Pueblo Creek that drain highlands to the west, and Deep Creek, Mineral Creek, Whitewater Creek, and Big and Little Dry Creeks with headwaters in the Mogollon Mountains. Mule Creek enters the "lower canyon" reach, west of Pleasanton, from the south.

Referring to elevation information in Table 1-1, the headwaters of the **SFR** near Alpine Divide (Apache County, AZ) are about 8,556 ft (2,608 m) asl (above mean sea level; and channel elevation at the AZ/NM stateline near Luna is about 7,460 ft (2,274 m)). The Continental Divide (7,350 ft; 2,240 m) east of the Tularosa River headwaters is only about 600 ft (183 m) above the floor of the Plains of San Agustín 12 mi to the southeast (6,746 ft; 2,056 m; Allen 2005). Channel elevation drops almost 1,800 ft (550 m) between the **SFR** Tularosa River confluence (5,650 ft; 1,722 m) and the mouth of Blue River (3,855 ft; 1,175 m). **SFR** channel elevation is about 4,200 ft (1,280 m) in the lower-canyon reach at the NM/AZ state line. Note, however, that the fluvial-geomorphic setting is characterized by high-sinuosity, entrenched meanders, and channel lengths and gradients have yet to be measured with precision in many reaches.

Table 1-1. Major Topographic Features of the San Francisco River Basin

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I. Drainage Divides—Peak/Saddle Elevations in Feet (Meters)

A. Northern (San Francisco-Little Colorado) Divide

Alpine Divide saddle, AZ: 8,556 (2,608)
Escudilla Mountain, AZ: 10,758 (3,279)
Black Peak, NM: 9,010 (2,746)
Jim Smith Peak: 9,278 (2,828)
Fox Mountain: 9,383 (2,860)
Gallo Peak: 9,255 (2,821)
Mangas Mountains: 9,277 (2,828)

B. Northeastern (Continental) Divide

Tularosa River-Plains of San Agustín: 7,350 (2,240)
John Kerr Peak: 8,868 (2,703)
High Point: 9,403 (2,866)

C. East-Central Divide

Eagle Peak (Tularosa Mountains): 9,786 (2,983)
Negrito Mountain (north crater rim): 8,530 (2,600)
Corner Mountain (Mogollon Mountains): 9,938 (3,029)
Bearwallow Mountain (Mogollon Mountains): 9,953 (3,034)
Willow Mountain (Mogollon Mountains): 10,783 (3,287)
Whitewater Baldy (Mogollon Mountains): 10,895 (3,321)
Black Mountain (Mogollon Mountains): 10,643 (3,244)
Sacaton Mountain (Mogollon Mountains): 10,658 (3,249)

D. Southern (San Francisco-Gila River) Divide, NM-AZ

Cactus Flat saddle: 5,288 (1,612)
Tillie Hall Peak: 7,319 (2,231)
Big Lue Mountains, AZ: 7,147 (2,178)

E. Western (San Francisco-Salt River) Divide, AZ

Alpine Divide saddle: 8,556 (2,608)
Blue River-Black (Salt) River Divide: 8,660 (2,640)
Middle Mountain: 8,976 (2,737)
Mogollon Rim (lookout tower) north of Strayhorse: 9,346 (2,849)
Rose Peak: 8,777 (2,675)
Pipestem Mountain: 7,212 (2,198)

Mitchell Peak: 7,950 (2,423)
Enebro Mountain: 7,510 (2,289)

F. Blue Range (Blue-San Francisco) Divide, AZ-NM

Whiterocks Mountain: 8,827 (2,690)
Maple Peak: 8,294 (2,528)

II. Major Stream Systems—Approximate Channel Elevations in Feet (Meters)

A. Main-Stem San Francisco River

Gila River Confluence: 3,280 (1,000)
Gaging Station at Clifton: 3,445 (1,050)
Blue River Confluence: 3,855 (1,175)
AZ-NM Stateline: 4,200 (1,280)
Gaging Station below Pleasanton near Hot Springs —Section E'-E": 4,550 (1,387)
Whitewater Creek Confluence at Glenwood: 4,670 (1,423)
Mineral Creek Confluence at Alma: 4,960 (1,512)
Alma-Little Blue (Graben) Subbasins—Section D-D': 4,920 (1,500)
Upper Alma Subbasin at US-180 Bridge: 4,990 (1,521)
Lower Reserve (Graben) Subbasin below San Francisco Plazas—Section C-C': 5,610 (1710)
Tularosa River Confluence: 5,650 (1,722)
Reserve at NM-12 Bridge: 5,740 (1,750)
The Box (Unit Tma)-Lower End: 6,240 (1,902)
The Box (Unit Tma)-Upper End: 6,440 (1,963)
Near Frisco Hot Springs: 6,500 (1,980)
Luna at US-180 Bridge: 7,010 (2,137)
NM-AZ Stateline above Luna—Section C-C': 7,460 (2,274)
Spillway of Luna Lake, AZ: 7,888 (2,404)
Alpine Divide saddle: 8,556 (2,608)

B. Main-Stem Tularosa River

San Francisco River Confluence: 5,650 (1,722)
Central Reserve (Graben) Subbasin—Section B-B': 6,150 (1,875)
Apache Creek Confluence: 6,400 (1,950)
Gaging Station above Aragon—Section AA': 6,750 (2,057)
Continental Divide-Plains of San Agustín to East: 7,350 (2,240)

C. Main-Stem Blue River

San Francisco River Confluence: 3,855 (1,175)
Little Blue Creek Confluence: 4,410 (1,375)
Little Blue-Alma (Graben) Subbasins—Section D-D': 4,675 (1,425)
Blue, AZ: 5,720 (1,743)
AZ-NM Stateline: 6,400 (1,950)
Gaging Station at US-191: 7,710 (2,350)
Blue River-Black (Salt) River Divide: 8,660 (2,640)

1.4 GEOLOGIC SETTING

Southwestern New Mexico, southeastern Arizona, and adjacent parts of Mexico are in two major geologic provinces with respect to both physiographic and tectonic (structural-geologic) setting. The southern Basin and Range province includes most of the binational region south of the Gila River Valley and west of Silver City; and the Transition Zone (TZ)—Datil-Mogollon (D-M) section to the north includes most of the Upper Gila River basin (Hawley et al. 2000; Mack 2004; Pazzaglia and Hawley 2004; Connell et al. 2005; Mack et al. 2008). Emphasis here is on the D-M section and the Mogollon-Datil (M-D) volcanic field because the entire **SFR** basin is within their borders.

From a regional plate-tectonics perspective, the late Eocene to early Miocene M-D volcanic field is the primary component of the eastern TZ province in terms of both geomorphic expression and deep crustal structure (Chapin et al. 2004; Elston 2008). The TZ overlaps relatively unextended part of the earth's crust beneath the Colorado Plateau, but also includes an arcuate extensional-basin trend (Neogene Reserve-Alma-Glenwood-Mangas graben "system") that merges southward with the Mimbres Basin, a major structural depression in the Basin and Range province (Trauger 1965; Seager 1995; Mack 2004). Valley and canyon reaches of the San Francisco and Tularosa Rivers are deeply entrenched in both bedrock and Gila Group basin fill along this chain of Neogene structural basins between the northern Mangas "trench" (near Pleasanton, Figure 1-2) and the northeastern Reserve graben (near Aragon, cf. Crews 1994, Figure 2). The arcuate structural-basin and erosional-valley/canyon complex also forms the western boundary of the broad topographic high in the central Mogollon-Datil volcanic field that has long been designated the Mogollon Plateau (Elston and Northrop 1976; Crews 1994; Basabilvazo 1997).

The eastern Colorado Plateau, Transition Zone, and contiguous part of the Basin and Range province together form the complex western margin of the Rio Grande rift (Keller and Cather 1994; Mack and Giles 2004), which extends from south-central Colorado to Trans Pecos Texas and northern Chihuahua (Connell et al. 2005). In contrast to the region to its west, the rift is characterized by significant crustal extension, deep basin subsidence, and ongoing basaltic to silicic volcanism. The rift-border area of the TZ in west-central New Mexico also includes the Plains of San Agustín "embayment," which has a structural trend roughly parallel to the northeastern part of the Reserve graben complex of Crews (1994, p. 126-127; cf. Chamberlin et al. 1994; Myers et al. 1994; Ratté 2001; Figure 1-2).

The Mogollon Plateau was the primary eruptive center of late Eocene and Oligocene caldera-type ash-flow tuffs (ignimbrites) that occur throughout the region; and it is the source of a wide range of silicic, intermediate, and basaltic volcanics of Oligocene to Pleistocene age (Ratté et al. 1979, 1984; Elston 2001; Ratté 2001). The Upper Gila River-**SFR** drainage divide (Figure 1-2, Plates 1 and 2c-e) is near the western edge of the Plateau and almost coincides with the northwestern and western "moat/resurgent-dome" boundary zone of the enormous Bursum caldera (about 16 x 25 mi), the best defined caldera in the M-D volcanic field (Rattè et al. 1989). Initial caldera subsidence was associated with explosive eruption of the voluminous and widespread (28.1 Ma, ~1,000 km^3) Bloodgood Canyon Tuff, which was closely followed by emplacement of ring-fracture rhyolites and caldera moat deposits, and ultimate formation of a resurgent dome.

Much of the caldera margin was subsequently buried by the 25-26 Ma, Bearwallow Mountain Andesite, a thick sequence of basaltic andesite to dacite lava flows from several eruptive centers on the Mogollon Plateau. Youngest Bearwallow Mountain flows are locally interbedded with conglomeratic sedimentary rocks of the basal Gila Group basin fill. Pre-caldera rocks of Eocene Age in and adjacent to parts of the M-D volcanic field include andesitic (intermediate) volcanic and associated volcaniclastic rocks with a dense fine-grained matrix (e.g., mudflow deposits). Such lithologic types form negative confining beds that locally mark the base of bedrock zones with any aquifer potential.

The lithostratigraphy and chronostratigraphy in the two hydrologic subdivisions of the San Francisco River basin where the geology setting has been well characterized are summarized in Table 1-2 and Table 1-3 (Upper and Lower **SFR** subbasin, respectively). Emphasis is on lithologic character and age of bedrock and basin-fill (Gila Group) mapping units, and their relationship with hydrostratigraphic units illustrated on Plates 1 and 2a-e, and further described in Section 4 (Table 4-1). The thin (<100 ft, 30 m) alluvial fills of inner valleys of major streams, which form significant shallow aquifers in many places, are described in Sections 3 and 4 (Figure 3-1; Tables 3-1 to 3-3).

TABLE 1-2. Map Unit Lithostratigraphy and Correlation of Cenozoic Rocks in the Upper San Francisco River Subbasin. Adapted from Cather et al. (1994), Chamberlin et al. (1994), Houser (1987; 1994), Ratté (1981; 2001), and Mack (2004)

Overview: With the exception of Pre-Cenozoic (Cretaceous, Paleozoic, and Proterozoic) rocks in the Clifton-Morenci (AZ) area, geologic units exposed in the **SFR** basin comprise Eocene to Pleistocene volcanic rocks, with interlayered volcaniclastic sedimentary rocks, and a thin, discontinuous cover of Quaternary (Pleistocene and Holocene) sediments. The latter deposits include inner-valley fills of the region's major stream valleys. Rocks of Tertiary Age (Pliocene/Miocene/Oligocene/Eocene) are moderately to strongly indurated*, while most Quaternary units are unconsolidated to weakly indurated (except for carbonate- and/or silica-cemented soil horizons and spring deposits). The Upper Cenozoic **Gila Group** (mostly Miocene and Pliocene) forms the fill of the major structural basins (grabens and half-grabens) that now disrupt the continuity of the older bedrock units of the Mogollon volcanic field. Lower and Middle Cenozoic (Eocene-Oligocene) volcanic rocks comprise the **Datil** and **Mogollon Groups** (Cather et al. 1994). Coeval volcaniclastic sedimentary rocks make up the **Spears Group**, which is intercalated with Mogollon/Datil stratigraphic sequence. While not exposed, one other sedimentary-rock unit, the **Baca Formation** of Early Tertiary-Eocene age is only shallowly buried by **Spears Group** volcaniclastic rocks in the Spur Lake area of the northern the **SFR** basin. **Induration denotes irreversible cementation when saturated.*

Miocene to Lower Pleistocene (23-1.5 Ma) Gila Group Basin Fill and Some Intercalated Basaltic and Silicic Volcanic Rocks

Introduction: The **Gila Group** is a complex, variably indurated, basin-fill sequence that postdates most of the activity of the Mogollon-Datil volcanic field; clast content reflects a wide variety of sediment-source environments; and interbedded basaltic and rhyolitic volcanics are locally present, particularly in the basal part. The **Group** is restricted to Neogene structural basins of the Basin and Range physiographic province and adjacent parts of the Transition Zone (Datil-Mogollon section) west of the Rio Grande rift (Drewes et al. 1985; Houser 1994; Ferguson et al. 2000; Ratté 2001). The deep tectonic depressions that formed during several stages of crustal extension were originally sites of segmented (closed-basin) alluvial and lacustrine systems. By Pliocene time (2-5 Ma) drainage was integrated by a through-going ancestral **SFR** that terminated in a large lake in the northern Mangas trench south of the present Cactus Flat divide (Table 1-1, Plate 2e). The present Upper Gila-San Francisco River system was formed by subbasin integration in the early Pleistocene, which marked the end of Gila Group deposition (Hawley et al. 2000; Mack 2004; Connell et al. 2005). Major Gila Group subdivisions in the Upper San Francisco River subbasin include:

Whitewater Mesa beds of Houser (1987, 1994 - Pliocene? and lower Pleistocene) - Alma Basin Map Unit **QTgw**; semi-indurated to well-indurated, mudstone, sandstone, and conglomerate; as much as 165 ft (50 m) thick; high-level remnants of alluvial-fan deposits derived from the Mogollon Mountains. Part of hydrostratigraphic-unit (**HSU**) **PAU.**

Alma beds of Houser (1987, 1994 - uppermost Miocene and Pliocene) - Alma Basin Map Units **Tgau**, **Tgam**, and **Tgal**; semi-indurated to well-indurated, mudstone, sandstone, and conglomerate; as least 655 ft (200 m) thick, fluvial deposits of the ancestral **SFR** system derived from upland and basin areas to the west, north, and northeast. Included in **HSU**s **UG1, and UMG.**

Cradle Mesa lacustrine beds-Houser (1987, 1994 - uppermost Miocene and Pliocene) - Alma Basin Map Unit **Tgc**; semi-indurated to well-indurated, clayey silt and silty clay; diatomaceous deposits of short-lived shallow lakes; at least 65 ft (20 m) thick; Included in **HSU UMG.**

Harve Gulch basalt (~5.6 Ma-latest Miocene, Houser 1987) - Alma Basin Map Unit **Tgh**; olivine tholeiite flows; exposed thickness as much as 115 ft (35 m); Included in **HSU Tb.**

Keller Canyon conglomerate of Houser (1987, 1994 - Miocene) - Alma Basin Map Unit **Tgk**; well-indurated mudstone, sandstone, conglomeratic sandy mudstone, and pebble to boulder conglomerate; includes deposits derived from upland areas beyond present basin boundaries; at least 280 ft (85 m) thick. Included in **HSU**s **UMG and MLG.**

Charlie Moore Mesa basalt (~18.7 Ma - early Miocene, Houser 1994) - Alma Basin Map Unit **Tgcm.** Included in **HSU Tb.**

Little Blue Creek conglomerate of Houser (1994 - Lower Miocene) - Western Alma Basin Map Unit **Tgk**; well-indurated pebble to boulder conglomerate, with some mudstone and sandstone; extends into Blue River subbasin, and derived from upland areas west and north of present Alma basin boundaries; at least 985 ft (300 m) thick. Included in **HSU MLG.**

Dog Gulch Formation (Ratté 1981- Lower Miocene) - Western Mogollon Mountains-eastern Alma Basin (subsurface) Map Unit **Tdg**; well-indurated sandstone and pebble to boulder conglomerate; and piedmont deposits derived from Bursum-caldera and Bearwallow Mountain upland areas; as much as 655 ft (200 m) thick, and locally overlain by a 15.2 Ma basalt flow in Bearwallow Mountain quadrangle. Included in **HSU MLG.**

Upper Eocene to Lower Miocene (35-20 Ma) Pre-Gila Group
Volcanic and Intercalated Volcaniclastic Rocks (Ratté 2001)

Mogollon Group volcanics (29-25 Ma) exposed in the **SFR** basin area comprise both outflow and intracaldera facies of ash-flow tuffs (ignimbrites) and associated (silicic to basaltic) lava flows. The silicic ignimbrites (e.g., Bloodgood Mountain Tuff) are primarily associated with formation of the Bursum and Gila Cliff Dwellings calderas, and are capped in many places by thick basaltic-andesite lava flows (e.g., Bearwallow Mountain Andesite). The group also includes rhyolite domes and flows at scattered igneous-intrusive and eruptive centers. The most extensive hydrostratigraphic-unit correlatives are **HSU**s-**Tba**, **Trp**, and **Tva**, with lesser amounts of units **Trv** and **Ti**; but the only **HSU** with significant aquifer potential is **Tba.**

Datil Group volcanics (35-31 Ma) are primarily represented by thick andesitic lava flows, but locally include some rhyolitic ash-flow tuffs (silicic ignimbrite outflow sheets from early-stage calderas). The major **HSU** correlative is **Tma**, with lesser amounts of units **Tmrp** and **Tmrv**; but the only units with inferred aquifer potential are **Tma** and **Tmrp.**

Spears Group (36-26 Ma) sedimentary rocks include “all of the epiclastic and other volcaniclastic rocks that are interlayered with the volcanic rocks of the Datil and Mogollon Groups, and that overlie the Eocene Baca Formation in the Quemado 30'x 60' quadrangle [Chamberlin et al. 1994]” (Ratté 2001, p. 2). In the Tularosa Mountains 30'x 60' quadrangle, Ratté (2001) has mapped upper and lower (Pueblo Creek) formation-subdivisions of the **Spears Gp**, which are separated by the Datil Gp-Andesite of Dry Leggett Canyon (a **HSU-Tma** correlative). In the NM-AZ Stateline area, near the Tularosa Mountains-Mogollon Mountains-Nutrioso-Clifton quadrangle junction, **Spears** volcaniclastic rocks grade southwestward into units that are mainly volcanic-vent facies and are not differentiated in the Arizona section of the hydrogeologic map (**HSU-Tvu, Plates 1** and **2a-e**). The only correlative **HSU** with significant aquifer potential is **Tmsc.**

Eocene (>35 Ma) Siliciclastic Sedimentary Rocks Predating the Mogollon-Datil Volcanic Field

Baca Formation (Middle Eocene) clastic sedimentary rocks were deposited in basins formed during the late Laramide (Rocky Mountain) stage of compressional tectonism when sediment source areas where located in pre-volcanic bedrock terranes south of the present Colorado Plateau margin (e.g., Mogollon Rim of east-central Arizona). Sandstone, conglomeratic sandstone, and mudstone of fluvial origin make up the bulk of the Formation, with coarser conglomerate marking the axes of former river channels. Well-rounded cobbles and pebbles of quartzite, chert, granitic rocks, and metarhyolite are common in conglomeratic fluvial facies. In the Arizona-New Mexico border area, correlative beds are designated the Eager Formation (Cather et al. 1994). While not exposed in the **SFR** basin, the **Baca (Eagar) Formation** may have some aquifer potential in areas such as the Spur Lake basin, where it is only shallowly buried by the lower **Spears Group**. The only hydrostratigraphic-unit (**HSU**) correlative is **HSU-Tls.**

TABLE 1-3. Map Unit Lithostratigraphy and Correlation in the Lower San Francisco River Subbasin. Adapted from Ferguson and Enders (2000; cf. Heindl and McCullough 1961; Schroder 1996)

Miocene to Lower Pleistocene (22-1.5 Ma) Gila Group Basin Fill and Some Intercalated Basaltic and Silicic Volcanic Rocks—Mostly Combined into Map Unit GU in Arizona, with Hydrostratigraphic Units (HSUs) Schematically Shown in Cross-Section E-E' (Plate 2e)

Introduction: The Clifton-Morenci area is the only part of the Lower **SFR** basin where detailed surface and subsurface mapping of the **Gila Group** has been completed (Ferguson and Enders 2000, Ferguson et al. 2000). Informal formation-rank mapping subdivisions include:

Units of Smuggler Canyon (Pliocene to Pleistocene?) - Map Units **QTgs, QTgg,** and **QTgd**; unconsolidated to weakly indurated, sandstone, conglomerate, mudstone, and boulder gravel; with a separate "granite-clast "and diorite-clast" facies; 0-490 ft (150 m) thick; **units QTgg and QTgd** mapped separately in parts of the Clifton-Morenci area. Included in hydrostratigraphic-units (**HSU**s) **UG1, UMG, GU.**

Units of Buzzard Roost Canyon (Pliocene) - Map Units include **Tgbr-undivided, Tgbr$_{cc}$** (Chase Creek facies), **and Tgbr$_{sf}$** (San Francisco facies); strongly indurated, conglomerate, interbedded with siltstone and sandstone; abundant Paleozoic and Proterozoic clasts in **Tgbr$_{cc}$**, and volcanic clasts dominant in **Tgbr$_{sf}$** ; thickness ranges: undivided unit 0-2,625 ft (800 m), **Tgbr$_{cc}$**, 0-360 ft (110 m), and **Tgbr$_{sf}$** 0-820 ft (250 m). Included in **HSU**s **UMG** and **GU.**

Conglomerate of Midnight Canyon (Miocene) - Map Unit **Tgmc**; strongly indurated, volcaniclastic conglomerate, with clasts up to boulder size and zeolite-cemented silty sand matrix; 0-1,180 ft (360 m) thick; gradational contact with underlying Conglomerate of Bonita Creek-unit **Tbck.** Included in **HSU**s **MLG** and **GU.**

Conglomerate of Bonita Creek (lower Miocene) - Map unit **Tbck**; strongly indurated, volcaniclastic conglomerate, with clasts up to boulder size and zeolite-cemented silty sand matrix; locally interbedded with basaltic andesite flows (upper part of unit **Tb**); 0-490 ft (150 m) thick. Included in **HSU**s **MLG** and **GU;** but not mapped as Gila Group subdivision by Ferguson and Enders (2000).

Upper Eocene to Lower Miocene (35-20 Ma) Volcanic and Intercalated Volcaniclastic Rocks—Pre-Gila Group Tertiary Rocks Combined into Map Unit Tvu in Arizona

Enebro Mountain Formation (lower Miocene-22.3 Ma) - Map Unit **Te, Tet, Ter,** and **Tei**; high-silica rhyolite lava intercalated with non-welded tuff, and locally intruded by hypabyssal rhyolite; 0-1,115 ft (340 m) thick. Not separately mapped in Arizona but included in **HSU-Tv**.

Basaltic conglomerate (lower Miocene) - Map Unit **Tcb**; sandy conglomerate with rounded clasts of basaltic andesite; 0-100 ft (30 m) thick; directly below non-welded tuff member of Enebro Mountain Fm (**Ter** ~22.3 Ma). Not separately mapped in Arizona but included in **HSU Tv.**

Basaltic Andesite-undivided (Oligocene-24.5 to 30 Ma) - Map unit **Tb**; upper lava flows overlie Map Unit **Tbc** (Bloodgood Canyon Tuff) and are correlative with the Bearwallow Andesite in New Mexico; and lower flows are between units **Tbc** (HSU-Tmrp) and the Clifton Tuff (**Tc**), a Cooney Tuff (**HSU-Tmrp**) correlative; 330-3,940 ft (100-1,200 m) thick. Included in **HSU-Tba** in parts of Arizona, but combined with **HSU-Tv** in most places.

Bloodgood Canyon Tuff (Oligocene ~28 Ma) - Map unit **Tbc**; crystal-rich, densely to moderately welded, rhyolite ash-flow tuff; 0-130 ft (40 m) thick. **HSU-Tmrp** correlative, but combined with **HSU-Tv** in Arizona.

Lower Basaltic Andesite (Oligocene ~34 to 28 Ma) - Map unit **Tb**; sequence of basaltic-andesite flows (see unit **Tb** description)**;** 0-490 ft (150 m) thick. **HSU-Tva** correlative, but combined with **HSU-Tv** in Arizona.

Lower Conglomerate (Oligocene <34 Ma) - Map unit **Tcl**; pebbly sandstone and conglomerate between unit **Tb** (**HSU-Tva**) and the Clifton Tuff (**Tc**); 0-50 ft (15 m) thick. Included with **HSU-Tv** in Arizona.

Clifton Tuff (Lower Oligocene to Upper Eocene ~34 Ma) - Map unit **Tc**; crystal-rich, welded rhyolite to rhyodacite ash-flow tuff; 0-360 ft (110 m) thick. **HSU-Tmrp** (Cooney Tuff) correlative, but combined with **HSU-Tv** in Arizona.

Paleocene and Eocene Igneous-Intrusive Rocks (HSU-Tli)

Intrusive breccia-undivided (Eocene) - Map Unit **Tbx**
Porphyry-undivided (Eocene) - Map Unit **Tp**
Younger granite porphyry (Eocene) - Map Unit **Tpgy**
Older granite porphyry-undivided (Eocene) - Map Unit **Tpgo**
Diabase (Eocene) - Map Unit **Td**
Quartz monzonite porphyry (Eocene) - Map Unit **Tpmq**
Monzonite porphyry (Eocene) - Map Unit **Tpm**
Diorite porphyry (Lower Paleocene) - Map Unit **Tpd**

Mesozoic Sedimentary Rocks

Pinkard Formation (Upper Cretaceous) - Map Unit **Kp**; shale interbedded with quartzose sandstone in upper part; 0-1,410 ft (375 m) thick; undivided **HSU-Ku**.

Paleozoic Sedimentary Rocks

Paleozoic, undivided (Cambrian to Pennsylvanian) - Map Unit **Pu**; 245-1,230 ft (75-375 m) thick; undivided **HSU-Pz**.

Tule Springs Formation (Mississippian-Pennsylvanian) - Map Unit **MPt**; limestone; 0-490 ft (150 m) thick; saturated zones with dissolutional (paleokarst) porosity may have some potential as a brackish-groundwater source; part of **HSU-Pzu**.

Modoc Formation (Mississippian) - Map Unit **Mm**; limestone, with some dolostone and calcareous quartzite; 165-330 ft (50-111 m) thick; saturated zones with dissolutional (paleokarst) porosity may have some potential as a brackish-groundwater source; part of **HSU-Pzu**.

Morenci Formation (Devonian) - Map Unit **Dm**; shale over argillaceous limestone; 65-300 ft (20-91 m) thick; upper part of **HSU-Pz**.

Longfellow Formation (Ordovician) - Map Unit **Ol**; limestone, cherty limestone, and dolostone; 165-525 ft (50-160 m) thick; saturated zones with dissolutional (paleokarst) porosity may have some potential as a brackish-groundwater source; middle part of **HSU-Pz**.

Coronado Quartzite (Cambrian) - Map Unit **Cc**; orthoquartzite and feldspathic quartzite; 0-395 ft (120 m) thick; basal part of **HSU-Pz**.

Proterozoic Igneous and Metamorphic Rocks (Undivided HSU-XY)

Granite (Early or Middle Proterozoic) - Map Unit **XYg**
Granodiorite (Early or Middle Proterozoic) - Map Unit **XYgd Ferrodiorite (Early or**
Ferrodiorite (Middle Proterozoic) - Map Unit **XYd**
Pinal Schist (Early Proterozoic) - Map Unit **Xp**

1.5 PREVIOUS WORK RELEVANT TO BASIN HYDROGEOLOGY

Long-term interest in the region’s historical, structural, and economic geology has resulted in a very large body of literature including numerous maps that characterize not only igneous and sedimentary bedrock units of the Mogollon-Datil (M-D) volcanic field but also sedimentary deposits in the structural basins that subsided following the mid-Cenozoic interval of explosive volcanism. Our focus is on the geologic framework of aquifer units in 1) Upper Cenozoic sedimentary basin fill and interlayered volcanic rocks, and 2) subjacent and surrounding bedrock of pre-existing geologic terranes in the New Mexico part of the **SFR** basin. Much of the relevant geologic work published prior to 1990 had already been incorporated in Basabilvazo’s (1997) report on Catron County “ground-water” resources. He (p. 10) recognized, however, that:

> Subdivision of the various Tertiary volcanic rocks on the Mogollon Plateau is hindered by their similar physical appearance and their complex, overlapping stratigraphic and temporal relations. The age and stratigraphic relations of the volcanic rocks of the Mogollon Plateau are not completely known, and hydrologic data are limited.

While hydrologic data are still “limited,” great progress has been made in the area of geochronometry, particularly in determining “absolute” ages of volcanic rocks. New techniques and advances include ^{40}Ar/^{39}Ar, uranium-series, cosmogenic (^{13}Cl)-exposure, and fission-track dating, magneto-stratigraphy, apatite fission-track thermochronology (AFT), and much better geochemical correlation of pyroclastic deposits (Hawley 2005, p. 48). In the **SFR** basin region, the primary methods of rock-age determination comprise $^{40}Ar/^{39}Ar$, fission-track, and magneto-stratigraphic dating. Most important, however, is the fact that even the latest advances in geochronometry must still be well coordinated with geologic mapping efforts in the M-D volcanic field region (e.g., Berry 1976; Chapin and Elston 1978; Ratté et al. 1969, 1989; McIntosh et al. 1991, 1992; Cather et al. 1994; Ratté et al. 1994; Ferguson et al. 2000; Ratté 2001; and Ratté et al. 2006). Detailed geologic quadrangle maps (scale 1:24,000) and smaller scale map compilations (1:100,000-1:500,000) published since the late 1980s reflect these advances, and lithostratigraphic and chronostratigraphic classification systems are now available that greatly facilitate local and regional correlation of map units at a wide range in scales (e.g., Bove 1990; Chamberlin et al. 1994; Crews 1994; Houser 1994; Ferguson and Enders 2000; Ratté 2001, 2008). In short, geologic-map products of the past two decades can be much better interpretative tools for a variety of users than they have been in the past.

Recent review papers, map compilations, and field-trip guidebooks cited here should provide an adequate introduction to the large number of geologic reports and maps that now cover much of the **SFR** basin in New Mexico (e.g., Ratté et al. 1989; Cather et al. 1994; Chamberlin et al. 1994 [2 refs.]; Keller and Cather 1994; Ferguson et al. 2000; Hawley et al. 2000; Ratté 2001; Houser et al. 2002; Mack 2004; Connell et al. 2005; Hawley 2005; Elston 2008; Mack et al. 2008). Reports and/or maps used in compilation of Plates 1 and 2 are specifically cited in Tables 1-2, 1-3, and 4-1. Note, however, that detailed subsurface data and information on aquifer/well production performance are available only in a few parts of the study area (e.g., Trauger 1972; American Groundwater Consultants 1979; Witcher et al. 1994a-c; Ferguson and Enders 2000).

2.0 GIS SYNTHESES

One of the major objectives of the current study has been the creation of a digital, GIS-based physical model of San Francisco River (**SFR**) hydrogeology using ArcGIS® (map compilation) and Adobe Illustrator® (cross-section compilation). Plate 1 is a map view of the basin's hydrostratigraphic framework, which shows the surface-distribution patterns of major bedrock and basin-fill mapping units. The map is compiled from a variety of mid-scale GIS sources in New Mexico (1:100,000 to 1:500,000 scale) that were merged with a less-detailed

Arizona map-database (1:500,000 to 1:1,000,000). Unit boundaries and definitions were adjusted where possible to reflect more-detailed quadrangle mapping (1:24,000 to 1:48,000 scale range). The subsurface dimension is illustrated by five schematic cross sections (Plate 2a-e) that were created specifically for this study at a map-scale of 1:100,000, base elevation of mean sea level, and 5x vertical exaggeration. Because of differences in compilation scales, some features (e.g., faults and thin hydrostratigraphic units) are not consistently shown on Plates 1 and 2a-e. Map-unit definitions, with supporting references, are summarized in Section 4 (Table 4-1).

Hydrogeologic evaluation of 265 well and 12 spring sites in the New Mexico part of the study area was completed by the senior author in the summer of 2009. It utilized both cited published sources, and 1:24,000 to 1:100,000-scale quadrangle maps (including Basabilvazo 1997, Table 4; Trauger 1972, Table 12; Houser 1987; Ratté 1981, 2001; Ratté and Brooks 1981, 1983; Ratté et al. 2006). Approximate locations of the wells and springs are shown on Plate 3; and selected published records with preliminary hydrostratigraphic-unit and aquifer identifications are presented in Appendix Table A1.

3.0 APPLICATION OF BASIC HYDROGEOLOGIC CONCEPTS TO BASIN-SCALE MODELING OF SAN FRANCISCO RIVER BASIN GEOHYDROLOGIC SYSTEMS

3.1 BASIC HYDROGEOLOGIC CONCEPTS

3.1.1 Aquifer Composition

In marked contrast to the large “alluvial-aquifer” systems in the adjacent Basin and Range—Mexican Highland section (Hawley et al. 2000; Kennedy et al. 2000), aquifers in the TZ—Datil-Mogollon section are of much more limited extent and primarily confined to 1) inter-connected fracture zones in middle to lower Cenozoic bedrock and well-consolidated lower parts of the Gila Group basin fill, and 2) thin alluvial fills of major stream valleys. Weakly indurated to unconsolidated sediments that characterize Upper Gila Group deposits in the undissected basins of much of southwestern New Mexico have either been removed by erosion or are now restricted to the vadose zone because of deep valley and canyon entrenchment by the San Francisco River and its major tributaries (Figure 1-2; Plates 1 and 2a-e).

Fractured volcanic rocks (basalts, andesites, and tuffs) of the Mogollon and Datil Groups, and porous sandstone facies of the Spears Group (Tables 1-2, 4-1) that underlie and/or border basin-fill and post-Gila valley-fill deposits have at least local aquifer potential (Plates 1, 2b-d; cf. Heindl 1967; Trauger 1972; Basabilvazo 1997; Finch et al. 2008). Trauger (1972) has also noted that solution-enlarged fractures in carbonate rocks of Paleozoic and Cretaceous Age can be significant groundwater reservoirs in at least a few parts of the northern Mimbres basin to the south. The only part of the **SFR** basin, however, where localized carbonate aquifers might be present is in Paleozoic rocks of the Lower **SFR** subbasin—Clifton-Morenci area (Plates 1 and 2e; Ferguson and Enders 2000). *Special Note:* The large, deformed body of Pennsylvanian limestone that crops out along Trout Creek (NW of Luna—T5S·R21W·S10·120—NMBGMR 2003) is a "float block in the [**Tmsc/Tma**-Plate 1] volcanic terrane (Kues 1994, p. 81; cf. Weber and Willard 1959; Kottlowski 1960)." Kues (1994) also reports that similar exposures of limestone near Alpine Divide, AZ "were interpreted as probable inclusions in andesites [of Dry Leggett Canyon-**Tma**] of the Datil Formation" by Wrucke (1961).

As in adjacent parts of the Basin and Range province, the three major hydrogeologic roles played by bedrock units are forming 1) surface and buried aquifer boundaries, 2) the ultimate source areas for basin- and valley-fill deposits, 3) and locally important upland "terranes" for mountain-block recharge systems. Equally important in terms of groundwater-flow dynamics are 1) boundary structures, such as faults and flexures that separate bedrock uplifts from basin blocks, and 2) a complex variety of intra-basin and basin-margin volcano-tectonic features, including intrusive and extrusive igneous rocks. Subsection 3.2 covers the two most important geologic controls on the groundwater-flow systems in the Transition Zone region: 1) the *hydrostratigraphy* of the various types of sedimentary deposits and interlayered volcanic rocks, 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); however, the concepts used here have been developed specifically for basin-fill aquifer systems of southwestern New Mexico (Hawley and Kernodle 2000; Hawley et al. 2000; Kennedy et al. 2000).

3.1.2 Some Basic Geohydrologic Concepts

Conceptual models of surface-water and groundwater flow in intermontane-basin aquifer systems of the American West have been evolving over the past century (Hawley and Kernodle 2008), with most recent developments in more arid parts of the Basin and Range province (Mifflin 1988). An adaptation of these geohydrologic concepts to the southern New Mexico-"Trans-Pecos Texas" region by Hibbs and Darling (2005) is used here. 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 intra-basin and/or inter-basin movement. *Phreatic playas* (ephemeral-lake plains) are restricted to floors of *closed* basins that are *undrained* or *partly drained.*

The high volcanic plateaus and upland networks of major stream valleys of the TZ—Datil-Mogollon section are major contributors to basin-fill-aquifer recharge in downstream parts of the Basin and Range province, including the Duncan and Safford (structural) Basins (Richter et al. 1983; Drewes et al. 1985; Houser et al. 2002). Surface-water and at least the shallow-groundwater flow systems are well-integrated in the **SFR** basin (Freethey and Anderson 1986; Basabilvazo 1997); and the perennial streams and associated coarse-grained, valley-fill alluvial aquifers commonly function as an integrated hydrologic unit. Numerous warm and hot springs, many near bedrock constrictions at the lower ends of structural basins, however, document deeper groundwater circulating in both bedrock and older Gila Group deposits (Summers 1976, 1979; Mariner et al. 1977; Swanberg 1978, 1983; Witcher 1981, 1988, 1995; Witcher et al. 1982; White and Kues 1992; Goff et al. 2008). Recharge occurs along the losing stretches of perennial and intermittent streams by deep percolation of precipitation-runoff, and by mountain-front and mountain–block recharge mechanisms (cf. Manning and Solomon 2004). Figure 3-1 is a two-dimensional conceptual model of an interconnected fractured bedrock and basin-fill aquifer-recharge system in a Basin and Range hydrogeologic setting (adapted from Feth 1964 by Wasiolek 1995).

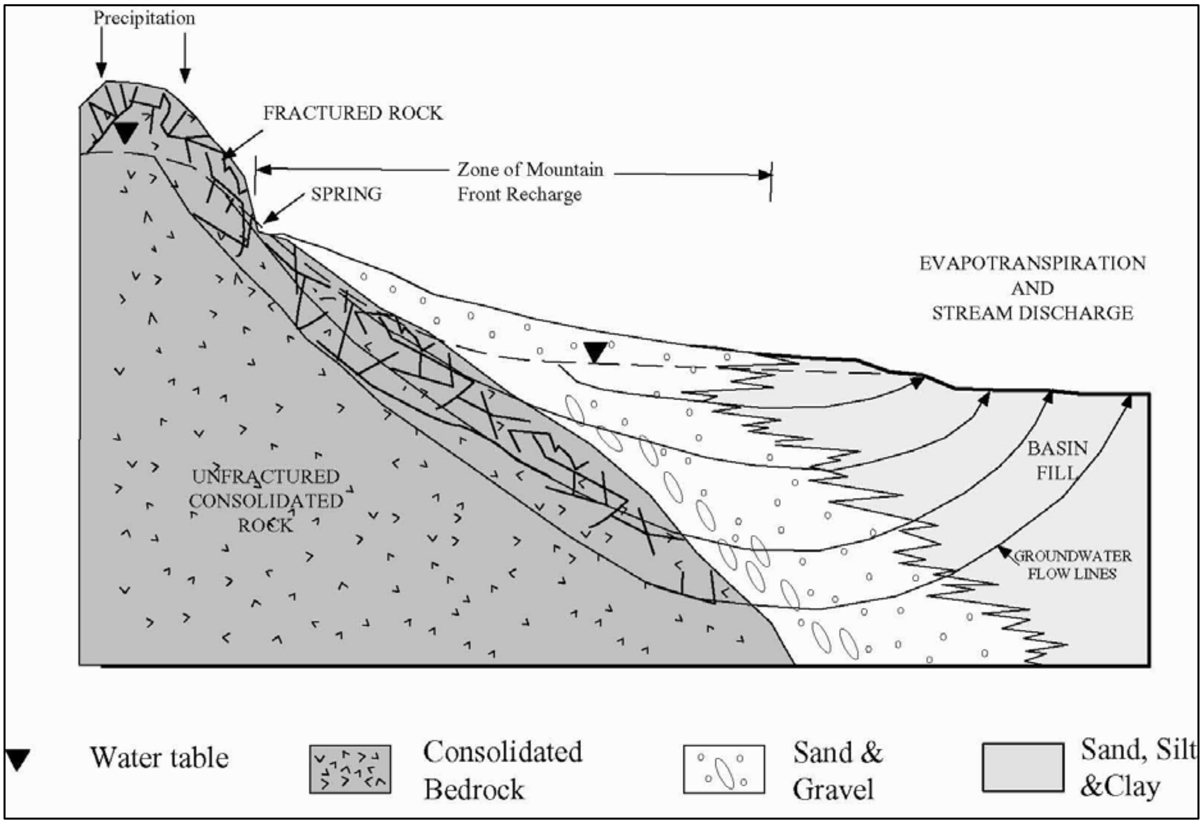

Figure 3-1. Two-dimensional conceptual model of a groundwater recharge system in a Basin and Range hydrogeologic setting (from Wasiolek 1995, modified from Feth 1964).

3.2 HYDROGEOLOGY OF STRUCTURAL BASINS AND MAJOR STREAM VALLEYS

The hydrogeologic framework of basin-fill aquifers in the Rio Grande rift-TZ region, with special emphasis on features related to groundwater-resource management, is described here in terms of three basic conceptual building blocks: lithofacies assemblages (**LFA**s), hydrostratigraphic units (**HSU**s), and bedrock/structural-boundary conditions. A conceptual hydrogeologic model of interconnected shallow valley-fill and deeper basin-fill aquifer systems was initially created to support development of groundwater-flow models in intermontane basins of the Rio Grande rift and adjacent parts “Southwestern Alluvial Basins region” (Robertson 1991; Kernodle 1992; Wilkins 1998; Hawley and Kernodle 2000). However, basic design of the conceptual model is flexible enough to allow it to be modified for use in adjacent basins of the Transition Zone province (Hawley et al. 2000).

This type of model is at best a semi-quantitative description (graphical, numerical, and verbal) of how a given geohydrologic system is influenced by 1) bedrock-boundary conditions, 2) internal-basin structure, 3) basic stratigraphic relationships, and 4) lithofacies and mineralogical composition of a given basin-fill/bedrock stratigraphic section. It provides a mechanism for systematically organizing a large amount of relevant hydrogeologic information of widely varying quality and scale (from very general drillers' observations to detailed bore-hole, geophysical and geochemical data). It is a particularly valuable tool in areas like the **SFR** basin where robust stratigraphic and structural geologic models exist, but detailed geohydrologic information is commonly lacking.

Hydrogeologic-framework elements can be graphically displayed (at appropriate scales) in combined map and cross-section GIS formats so that basic information and inferences on geohydrologic attributes (e.g., hydraulic conductivity, transmissivity, anisotropy, and general spatial distribution patterns) may be transferred to basin-scale, three-dimensional numerical models of groundwater-flow systems. This scheme of data presentation and interpretation, however, is rarely suitable for specific site-scale groundwater investigations. The following discussion summarizes application of framework-model concepts to basin-fill and valley-fill aquifer systems of the southwestern New Mexico region.

3.2.1 Valley/Basin-Fill Lithofacies Assemblages (LFAs)

Lithofacies assemblages (LFAs) are the basic building blocks of the hydrogeologic model (Figure 3-2; Table 3-1), and they are the primary elements of the hydrostratigraphic units (HSUs) discussed below. These sedimentary-facies classes are defined primarily on the basis of grain-size distribution, mineralogy, sedimentary structures, and degree of post-depositional alteration. The secondary basis for definition is according to inferred environments of deposition. LFAs have distinctive geophysical, geochemical and hydrologic attributes; and they provide a mechanism for showing distribution patterns of major aquifers and confining units in hydrogeologic sections. Basin and valley fills are here subdivided into thirteen major LFAs that are ranked in decreasing order of aquifer potential (Tables 3-1 to 3-3; LFAs 1-10, a-c). Figure 3-2 is a schematic illustration of the distribution pattern of major facies assemblages observed in intermontane-basin fills of the southwestern New Mexico region. Lithofacies properties that influence groundwater flow and production potential are summarized in Tables 3-2 and 3-3.

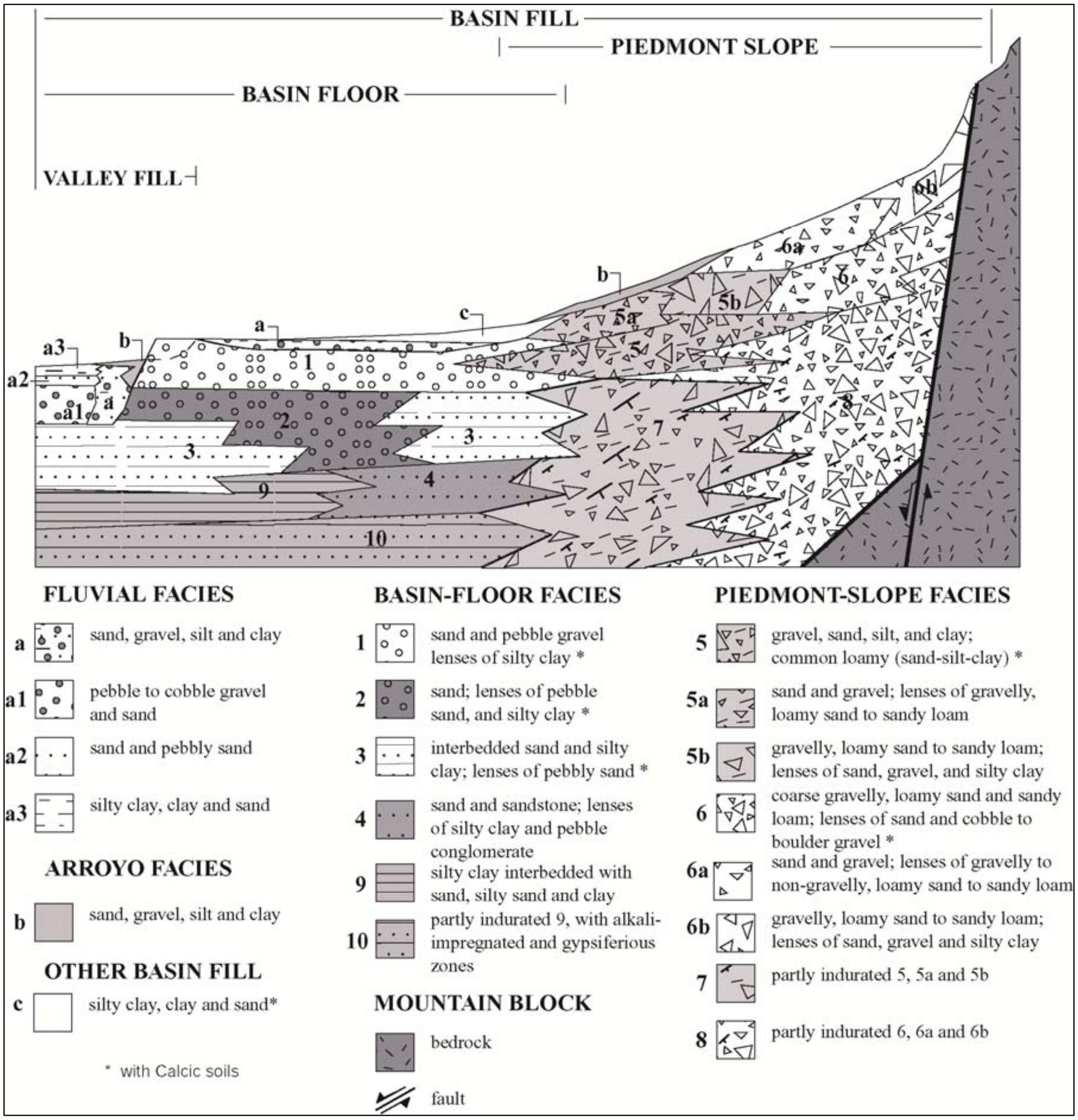

Figure 3-2. Schematic distribution pattern of major lithofacies assemblages (Tables 3-1 to 3-3) in basin and valley fills of the southwestern New Mexico region (from Hawley et al. 2000).

Table 3-1 Summary of depositional settings and dominant textures of major lithofacies assemblages (LFAs) in basin and valley fills of the Southwestern New Region: Gila and Santa Fe Group basin fill (1-10), and post-Gila and Santa Fe river-valley and basin fill (a-c). Adapted from Hawley and Kernoodle (2000), and Hawley et al. (2000)

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 pebbly 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 3-2 Summary of major sedimentary properties that influence the groundwater-production potential of Gila and Santa Fe Group lithofacies assemblages (LFAs 1-10) Modified from Haase and Lozinsky (1992) and Hawley and Kernodle (2000)

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	130 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	>5	Planar	>150	Low	Very low	Very low
10	Low*	>5	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.

[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 medium to coarse-grained beds (as much as 50%)

Table 3-3. Summary of major sedimentary properties that influence the groundwater-production potential of post-Gila and Santa Fe river-valley and basin fill (LFAs a-c). Modified from Hawley and Kernodle (2000)

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]	Horizontal 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	<300	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 (lenticular or discontinuous planar beds).

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

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

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

3.2.2 Valley/Basin-Fill Hydrostratigraphic Units (HSUs)

As a first step in organizing available information on valley/basin-fill stratigraphy and sedimentology, with emphasis on aquifer characteristics, a provisional hydrostratigraphic classification system has been developed (Figure 3-3) that is applicable to most basins of the southeastern Basin and Range province. This is an ongoing process, with progressive system refinement occurring with each new study phase. To date this informal classification scheme has been used with great success in the Albuquerque and Mesilla-Rincon Basins of the Rio Grande rift, and in adjacent parts of southwestern New Mexico (e.g., Hawley and Kernodle 2000, Hawley et al. 2000).

“A hydrostratigraphic unit (Seaber 1988) may represent an entire [litho] stratigraphic unit, a portion of a stratigraphic unit, or a combination of adjacent stratigraphic units with consistent hydraulic properties” (Giles and Pearson 1998, p. 322). Most intermontane-basin fills in the southern New Mexico region are subdivisions of two broad lithostratigraphic categories, the Santa Fe Group in the Rio Grande rift (Keller and Cather 1994) and the Gila Group

("Conglomerate") in Basin and Range, and Datil-Mogollon areas to the west (Trauger 1972; Seager et al. 1982; Drewes et al. 1985; Crews 1984; Houser 1994; Seager 1995; Hawley et al. 2000; Ratté 2001; Mack 2004). The bulk of these deposits are of Neogene Age (Miocene and Pliocene; ~23 to 1.8 Ma). In many previous hydrogeologic studies, clear distinctions have not been made between "bolson fill" or "basin fill" and contiguous (formal or informal) subdivisions of the Santa Fe and Gila Groups. Figure 3-3 is a correlation chart of major hydrostratigraphic units (**HSUs**) and their lithostratigraphic correlatives in the Southwestern New Mexico region. Note that HSUs that comprise basin-floor LFAs have an even Arabic numeral suffix (e.g., UG2), while piedmont-slope (basin-border) LFAs have an odd Arabic numeral suffix (e.g., UG1).

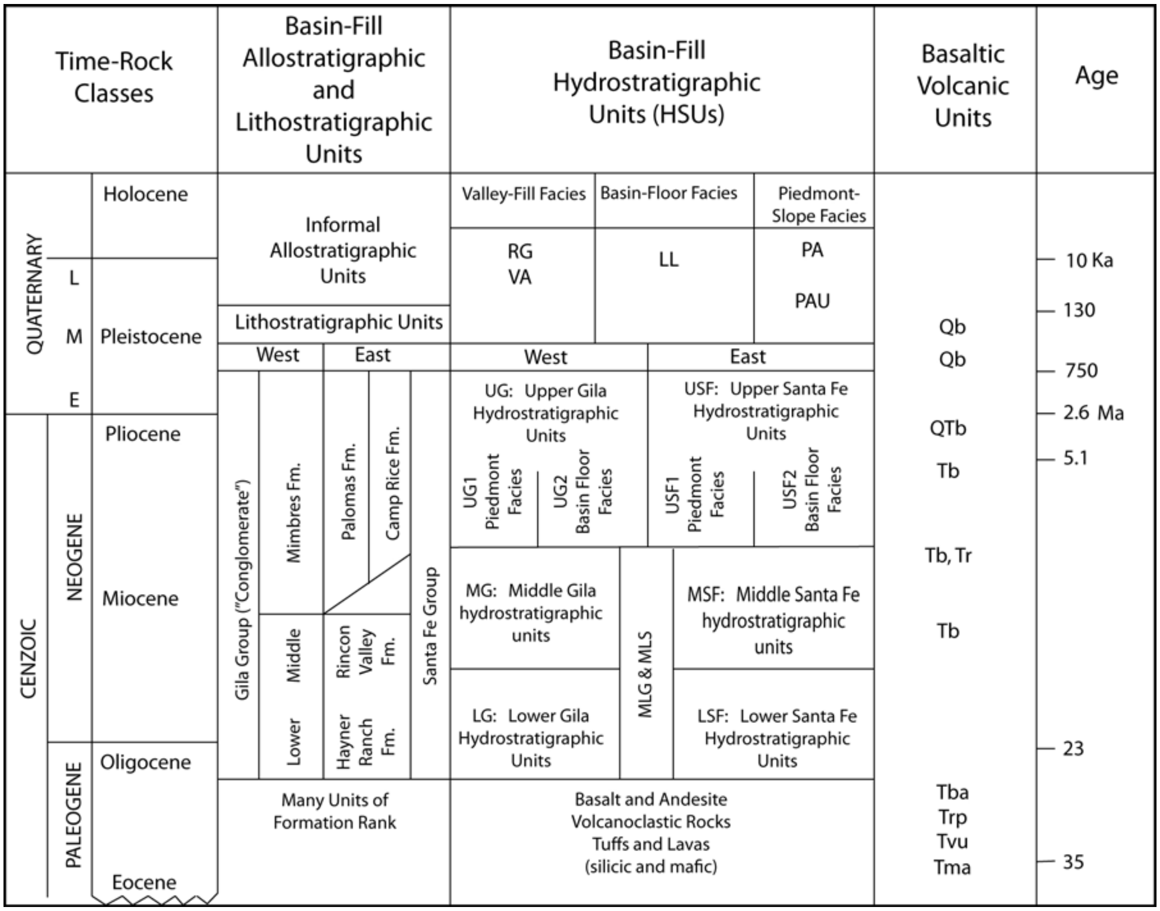

Figure 3-3. General summary and correlation of major chronologic, lithostratigraphic, and hydrostratigraphic units in Upper Cenozoic basin and valley fill, and Middle to Lower Cenozoic bedrock subdivisions in the southwestern New Mexico region. Igneous-rock symbols: Qb–Quaternary basalt, Tb–Tertiary mafic volcanics, and Tv–older Tertiary intermediate and silicic volcanics, and associated plutonic and sedimentary rocks. Modified from Hawley et al. (2000).

Hydrostratigraphic units defined in the **SFR** basin are mappable bodies of basin fill and valley fill that are grouped on the basis of origin and position in both lithostratigraphic and chronostratigraphic sequences. The informal **Upper**, **Middle**, and **Lower Gila** hydrostratigraphic units (e.g., HSUs: **UG1, UMG, MG, MG1,** and **MLG**) comprise the major basin fill that can be characterized in terms of their aquifer potential (non-potential). They roughly correspond to the (formal and informal) upper, middle, and lower lithostratigraphic subdivisions of the Gila Group as currently defined by geologists actively working in the region (e.g., AZGS, NMBGMR, and USGS staff). Dominant lithofacies assemblages in Upper Gila HSUs are LFAs **4-8**, while Middle Gila units are characterized by LFAs **7-9**; and Lower Gila HSUs are primarily well-indurated conglomeratic phases of LFAs **7** and **8**. Fine-grained basin-floor LFAs **3** and **9** (e.g., lake and playa facies) are very uncommon in Gila Group deposits throughout the **SFR** basin.

3.2.3 Structural-Boundary Conditions in Basins and Bordering Bedrock Terranes

Structural-boundary conditions that influence the behavior of both basin-fill and bedrock aquifer systems in the **SFR** basin include 1) the structure and lithostratigraphy of bordering mountain and plateau uplifts, 2) bedrock topography below the basin fill, 3) fault zones and flexures within and at the edges of basins, and 4) igneous (intrusive and extrusive) rocks that penetrate or are interbedded with basin fill (Plates 1 and 2a-e). Volcano-tectonic evolution of the mid-Cenozoic Mogollon-Datil volcanic field and subsequent extensional fault-block subsidence in Neogene basin areas has had a profound effect on the distribution of lithofacies assemblages and the timing and style of emplacement of all major hydrostratigraphic units (Figures. 3-2 and 3-3). Most of the significant bedrock- and structural-boundary features in the area are now well documented by the numerous geologic-quadrangle maps (most with cross sections) that have been completed in **SFR** basin region (e.g., Bove 1990; Ferguson and Enders 2000; Hedlund 1987; Houser 1987; Ratté 1981, 1982; Ratté and Brooks 1981, 1983, 1995; Ratté et al. 1969, 2006; Richter and Lawrence 1981; Richter et al. 1983; Schroder 1996).

4.0 HYDROGEOLOGIC FRAMEWORK OF THE SAN FRANCISCO RIVER BASIN

Emphasis of this section is on the subbasin-scale hydrogeologic-framework components as illustrated by Plate 1 (map), Plate 2a-e (cross-sections), and Table 4-1 (Hydrogeologic unit [**HSU**] definitions). Discussion starts with the large Upper **SFR** subbasin (Subsection 4.1, Table 1-2), excludes the Blue River subbasin, and concludes with a brief commentary on the Lower

SFR subbasin in Arizona (4.2, Table 1-3). A more extended review of effects of Pliocene and Pleistocene river-valley evolution on the hydrogeologic system is presented in Section 5. Since the Upper **SFR** subbasin is the primary geohydrologic unit covered in this study, most of the following discussion is related to the hydrogeology of that subbasin.

4.1 UPPER SAN FRANCISO RIVER SUBBASIN, NEW MEXICO AND ARIZONA

4.1.1 Overview

The Upper San Francisco River (**SFR**) subbasin occupies parts of west-central New Mexico and east-central Arizona above the **SFR**-Blue River confluence, and it includes the watershed of its major perennial-intermittent tributary, the Tularosa River. Subbasin location and general topography are shown in Figure 1-2; and major hydrogeologic-framework components are illustrated on Plates 1 and 2a-e (cross-sections AA', BB', CC', DD', and E'E"). Most of the 2,027 mi^2 drainage basin is in New Mexico, with only 206 mi^2 in Arizona. Principal valley/basin-fill aquifer systems are in and adjacent to the **SFR** and Tularosa River valleys. The latter stream joins the **SFR** about 3 mi south of Reserve (between the villages of San Francisco Plaza and Lower San Francisco Plaza, Figure 1-1). Discussion focuses on two structural-basin complexes, and flanking bedrock highlands: The Reserve graben (Crews 1994; Ratté 2001), and the Alma-Glenwood basin (Ratté 1981; Houser 1987, 1994).

TABLE 4-1. Hydrostratigraphic Unit (HSU) Map-Unit Definitions and Geologic Map-Unit Correlations, San Francisco River (SFR) Basin, New Mexico and Arizona

Introduction: In addition to work by Trauger (1972-Grant County) and Basabilvazo (1997-Catron County), the hydrogeologic framework of the below-listed map-units has been adequately described in only 5 parts of the **SFR** basin: 1) the Alpine Divide area (Wrucke 1961; Witcher et al. 1994a-c), 2) the Reserve subbasin (Crews 1994), 3) the Alma-Glenwood subbasin (Houser 1987,1994; Ratté 1989, 2008), 4) the northern Mangas "subbasin" (Mack 2004; Mack and Stout 2004), and 5) the Clifton-Morenci, AZ area of Greenlee County (Schroder 1996; Ferguson and Enders 2000; Ferguson et al. 2000). The Hydrostratigraphic-Unit (**HSU**)-Lithofacies-Assemblage (**LFA**) classification (Figure 3-2) is adapted from Hawley and Kernodle (2000), and Hawley et al. (2000). Definitions and properties of LFAs are summarized on Tables 3-1 to 3-3.

Post-Gila Group HSUs (Valley-Fill and Piedmont-Slope Deposits, and Basaltic Volcanics)

RG—Channel, floodplain, and low-terrace deposits of major perennial-intermittent streams of the San Francisco River basin (including Blue and Tularosa Rivers); mostly Lithofacies-Assemblage (**LFA**) **a1-a2**; saturated thickness as much as 60 ft (18 m); Holocene and uppermost Pleistocene. Included in NM Statemap unit Qa. Note*: Along with **HSU-UMG**, forms major basin-fill aquifer system in the **SFR** basin area*

VA—Valley-fill alluvium (undivided), deposits of larger ephemeral tributaries to major perennial/intermittent streams (**RG**) and some fluvial-terrace fill; **LFA b**, with many inclusions of unit **RG** (**LFA a**); as much as 60 ft (18 m) thick; primarily in the vadose zone, but basal parts may be seasonally saturated or contain "perched-groundwater" bodies; Holocene and Upper Pleistocene. Included in NM Statemap unit Qa

PA—Piedmont-slope alluvium (undivided), including fan deposits and pediment veneers on slopes graded to base levels commonly independent of existing river-valley system; **LFA**s **b**, **5** and **6**, as much as 100 ft (30 m) thick; primarily in the vadose zone, but basal parts may be seasonally saturated or contain "perched-groundwater" bodies; Holocene to Middle Pleistocene. Includes NM Statemap units Qa and Qp

PAU—High-level remnants of piedmont alluvium most predating earliest stages of river-valley entrenchment (undivided older **PA** and **UG1**), including some landslide deposits; **LFA**s **5** to **6**, usually less than 100 ft (<30 m) thick; primarily in the vadose zone, but basal parts may be seasonally saturated or contain "perched-groundwater" bodies; lower Pleistocene and Upper Pliocene. Includes NM Statemap unit QTp

QTb—Younger basalt flow and vent units of Apache Creek and Gila-Colorado River Divide areas; primarily in the vadose zone, but basal parts may be seasonally saturated; lower Pleistocene and Pliocene. The Apache Creek flow (~1 Ma) caps high (~330 ft, 100 m) strath terraces along lower Apache Creek and the downstream Tularosa River reach, and is inset into middle Gila Gp **HSU-MG** (Luedke and Smith 1978; Ratté 2001). **QTb** remnants in the San Francisco-Little Colorado Divide are mostly north of the **SFR** basin. Includes NM Statemap and USGS quadmap units Qb, QTb, and Tnb

Gila Group HSUs (Neogene Intermontane Basin-Fill and Interbedded Volcanics)

UG1—Upper Gila Gp piedmont-slope alluvial deposits (**LFA**s **5** and **6**), usually <100 ft (<30 m) thick; entirely in the vadose zone; Lower Pleistocene and Pliocene. Includes NM Statemap unit QTp

UMG—Upper and Middle Gila Gp (**UG** and **MG**-undivided): piedmont-slope alluvial and basin-floor (axial-stream) deposits, locally with capping and interbedded basaltic and silicic volcanics (**QTb**, **Tb**, and **Tr**); **LFA**s **4** to **6**, usually <100 ft (<30 m) thick; entirely in the vadose zone; Lower Pleistocene to Upper Miocene. Includes NM Statemap unit QTp. *Note: Primarily piedmont facies **LFAs 5-6 (HSU-UG1)**,with Upper Gila Gp axial-stream facies (mainly **LSF4**) only preserved in Alma subbasin (Houser 1994) and in the Cactus Flat divide area south of Pleasanton (Mack 2004; Mack and Stout 2004)*

MG—Middle Gila Gp (undivided): piedmont-slope and basin-floor deposits, locally with capping and interbedded basaltic and silicic volcanics (**Tb** and **Tr**); **LFA**s **4** to **8**, as much as 3,000 ft (900 m) thick*; most of the unit comprises well-indurated conglomerates, sandstones and mudstones (**LFA**s **7** and **8**) that are cemented with zeolites and some calcite; upper part usually in vadose zone, and the saturated zone forms a significant basin-fill aquifer-system component in many valley areas; Miocene (~6-20 Ma). Included in NM Statemap and USGS quadmap units QTg, Qtgu, and QTgl. **Notes: 1) Maximum thickness of about 3,000 ft penetrated by wells drilled in the lower **SFR** basin below Clifton, AZ (**QTgs/Tgbr**-Ferguson and Enders 2000); and 2) the lithofacies composition and chrono-stratigraphy of this map-unit complex has only been described in detail in the Reserve Graben, the Alma subbasin, and the Clifton-Morenci area (Crews 1994; Houser 1994; Ferguson and Enders 2000)*

MG1—Middle Gila Gp piedmont-slope deposits, primarily **LFA**s **7** and **8**, as much as 1,000 ft (300 m) thick; locally capped with unit **QTb$_1$**; mostly in vadose zone, and much of the saturated part comprises well-indurated conglomeratic sandstone beds (**LFA**s **7** and **8**); Upper Miocene. Includes NM Statemap unit Tfl (Fence Lake Formation of Chamberlin, Cather et al. 1994) and AZGS DGM-1 map unit **Tgbr** (Ferguson and Enders 2000)

Tb—Older basalt flow and vent units capping and interbedded with Middle and Lower Gila Gp **HSU**s; capping units primarily in the vadose zone; interbedded flow and vent units may form significant local aquifers where saturated; Pliocene to middle Miocene (Luedke and Smith 1978). Includes NM Statemap and USGS quadmap units QTb and Tnb

Tr—Rhyolite volcanic and some volcaniclastic rocks that are locally intercalated with Middle and Lower Gila Gp **HSUs**; includes undifferentiated trachytes and andesites in the Arizona White Mountain volcanic field; Miocene (Luedke and Smith 1978). Includes NM Statemap and USGS quadmap units Tnr and Tjr

MLG—Middle and Lower Gila Gp basin (undivided), primarily well-indurated **LFA**s 7 and 8, and some **LFA 9**, as much as 2,000 ft (600 m) thick; capped by and/or interbedded with units **Tb** and **Tr**; basal part locally interbedded with unit **Tba**; saturated below level of floors of major stream valleys; middle Miocene to uppermost Oligocene. Included in NM Statemap unit **QTg**, USGS quadmap unit Tvc (Drewes et al. 1985), and AZGS DGM-1 map units Tgmc and Tbck (Ferguson and Enders 2000; cf. Heindl and McCullough 1961)

Paleogene Bedrock Units (Including Some Locally Significant Aquifer Systems)*

***Tba**—Basaltic andesite to dacitic lava flows and vent units, as much as 600 ft (180 m) thick; upper part locally interbedded with basal unit MLG; uppermost Oligocene. Included in NM Statemap and USGS quadmap unit Tuau (e.g., upper Mogollon Gp-Bearwallow Mountain Andesite of Marvin et al. 1987; Ratté 2001; Chapin et al. 2004)

Trp—Rhyolite pyroclastic rocks mainly from Bursum caldera, with intercalated volcaniclastic sandstone and breccia; as much as 200 ft (60 m) thick; Upper Oligocene. Included in NM Statemap and USGS quadmap units Turp and Tbg (e.g., Mogollon Gp-Bloodgood Canyon Tuff of Elston 1976; Ratté 2001; Chapin et al. 2004)

Tva—andesitic to dacitic lava flows and vent units, with some intercalated volcaniclastic sediments; as much as 1,300 ft (400 m) thick; Oligocene. Included in NM Statemap and USGS quadmap unit Tual (lower Mogollon Gp, Ratté 2001; Chapin et al. 2004)

Trv—Silicic to intermediate-composition lavas. Mainly Rhyolite, dacite and latite domes and flows, with some ash-flow tuffs and andesite flows; Oligocene. Included in NM Statemap and USGS quadmap unit Turf

Tvu—Undivided basaltic to silicic volcanics, with some intercalated volcaniclastic rocks; undifferentiated unit in the Arizona and subsurface parts of cross-sections in New Mexico outside Bursum caldera; Oligocene and uppermost Eocene; primarily **Tba/Trp-Tva/Trv/Tmrp** correlatives. Included in Arizona Statemap unit Tv

***Tbvu**—Undivided silicic to intermediate volcanics, with some intercalated volcaniclastic rocks; undifferentiated subsurface unit in Bursum caldera (cross-sections CC', DD', and E'E"); early Oligocene and late Eocene; primarily **Tva/Trv/Tmrp** correlatives

Ti—Silicic and intermediate intrusive rocks-undivided; mostly Oligocene. Included in NM Statemap and USGS quadmap unit Ti

***Tmsc**—Sedimentary rocks-undivided, mainly volcaniclastic sandstone and conglomerate, with some interbedded andesitic flows (**Tma**) and silicic tuffs; as much as 2,000 ft (600 m) thick; early Oligocene to late Eocene. The upper part (above **Tma**) may be a significant aquifer in the NW part of the study area (north of the **SFR**). Included in NM Statemap and USGS quadmap units Ts, Tos and Tvs (e.g., Spears Gp of Osburn and Chapin 1983; Cather et al. 1994; Chapin et al. 2004)

Tma—Andesitic flow and vent units, and thin silicic tuffs that are interbedded with **Tmsc** (Spears Gp); andesites as much as 600 ft (180 m) thick; early Oligocene to late Eocene. Included in NM Statemap and USGS quadmap unit Tla (includes andesite of Dry Leggett Canyon; Ratté 2001; Chapin et al. 2004)

***Tmrp**—Rhyolite pyroclastic rocks, with intercalated volcaniclastic sandstone and breccia; as much as 700 ft (210 m) thick; early Oligocene to late Eocene. Included in NM Statemap and USGS quadmap unit Tlrp (e.g., Kneeling Nun Tuff and Cooney Tuff of Elston 1976; Ratté 1989, 2001, 2008; and Chapin et al. 2004)

***Tmvu**—Undivided silicic to intermediate volcanics, with some intercalated volcaniclastic rocks; undifferentiated subsurface unit northwest of Bursum caldera (cross-sections BB' and CC'); primarily **Tv/Tmsc-Tma** correlatives

Tlu—Undivided volcanic, and volcaniclastic and siliciclastic sedimentary rocks; undifferentiated subsurface unit on western wall of Bursum caldera (cross-sections DD' and E'E"); Eocene and early Oligocene; primarily **Tmsc-Tma/Tls** correlatives.

***Tls**—Sedimentary rocks, primarily siliciclastic sandstone, conglomerate, and mudstone exposed only in the Little Colorado River basin north of the Gila-Colorado Divide and east of the Continental Divide; as much as 3,000 ft (900 m) thick; Eocene. May be a significant aquifer in the Spur Lake Basin and Dry Leggett Canyon areas. Included in NM Statemap and USGS quadmap unit Tps (e.g., Baca Fm of Cather et al. 1994; Chamberlin; Cather et al. 1994)

Tli—Silicic to mafic intrusive rocks of the Morenci mining district, AZ-undivided; Paleocene and early Eocene. Included in map units Tbx, Tp, Tpgy, Tpgo, Td, Tpm, and Tpd of Ferguson and Enders (2000)

Pre-Cenozoic Bedrock Units in Clifton-Morenci (AZ) Subbasin (intruded by Tli; and include some locally significant carbonate-rock and fractured sandstone aquifer zones*)

***Ku**—Sedimentary rocks-undivided, including quartzitic sandstone, siltstone and shale; Upper Cretaceous. Included in AZ Statemap unit Ks

***Pzu**—Sedimentary rocks-undivided, mainly limestone, with some shale and quartzitic sandstone; Pennsylvanian and Mississippian. Included in AZ Statemap units Pz and MPt (Ferguson and Enders 2000)

***Pz**— Sedimentary rocks-undivided, mainly dolomitic limestone, with some shale and quartzitic sandstone; mainly Upper Cambrian to Mississippian. Included in AZ Statemap unit MЄ

XY—Crystalline intrusive and metasedimentary rocks-undivided, including granite, diorite, and schist; Proterozoic. Included in AZ Statemap units XYg and Xms

4.1.2 Major Structural and Bedrock Components

4.1.2a. Reserve Graben Area. The upper (northern) part of the subbasin has three major geomorphic and structural-geologic components (best illustrated by Plates 2a to 2c). Note especially, however, that the cross-section 5x vertical exaggeration distorts all structural features with any significant dip. The northeast-trending Reserve graben complex (Crews 1994), including valley and canyon reaches of the Tularosa River and a short **SFR** valley segment below Reserve, is flanked to the southeast by the Mogollon Plateau (Eagle-Tularosa Mountains area; Section 1.4; Plate 1), and to the north and northwest by high-level structural basins and the San Francisco-Dillon fault-block uplifts. In the latter area, the cliff-forming Andesite of Dry Leggett Canyon (Table 1-2, cf. Ratté 2001; **HSU-Tma** ,Table 4-1) separates upper and lower reaches of the **SFR** in "The Box" canyon area below Frisco Hot Springs (SW of Dillon Mtn-Plate 2b, Table 1-1). **HSU-Tma** also separates 'upper" and "lower" parts of the thick Spears Group volcaniclastic sequence (**HSU-Tmsc**; Table 1-2); and the combined **Tma**/ lower **Tmsc HSU**s appear to form a significant "aquitard" zone. On the other hand, saturated sandstones of the upper **Tmsc** unit are here interpreted to have at least local aquifer potential.

Centerfire Creek heading in the Centerfire Bog area (shallowly underlain by **HSU-Tma**) is a large tributary that joins the upper **SFR** above Frisco Hot Spring, and its upper drainage basin includes the high-level Spur Lake Basin (elev. ~7,400 ft; 2,250 m). There, basin structure appears to be continuous with that of the Colorado Plateau—Acoma Zuni section to the north (Plate 2b), and it is the only part of Upper **SFR** subbasin where Lower Cenozoic (Eocene), pre-volcanic sedimentary rocks (**HSU-Tls**) are near the surface. This unit is a Baca-Eagar Formation correlative (Table 1-2, cf. Chamberlin et al. 1994), which is a known source of public and stock water supplies in the Quemado area (Basabilvazo 1997, p. 35-36). It therefore deserves further study as a potential small, but significant groundwater resource. By far the most important control point for our conceptual model of subsurface lithostratigraphy of the northwestern **SFR** basin is the 4,050-ft (1,234-m) deep, Alpine 1 Federal geothermal-core hole located at Alpine Divide (8,556 ft; 2,608 m elev.; Table 1-1). The well site is at the northwest end of Section CC' (Plate 2c), and subsurface stratigraphy and geothermal conditions were described in detail by Witcher and others (1994a-c). Key stratigraphic information from the corehole is plotted at endpoint C of Plate 2c.

A related topic that deserves special attention concerns the improper identification (usually by non-geologists) of Lower and Middle Cenozoic sedimentary rocks as Upper Cenozoic basin and valley fill, usually within a geohydrologic context. An example of this practice is in Freethey and Anderson (1986, Sheet 3) that otherwise provides a good regional summary of "predevelopment hydrologic conditions." Part of the problem results from the fact that older Cenozoic sedimentary "rocks" (e.g., upper **HSU-Tmsc**) are commonly poorly consolidated in comparison with overlying (M-D) volcanic rocks, and contrast even more strikingly with well-indurated lower Gila Group "basin fill" (cf. Crews 1994). Even on general geologic-map compilations, broad valley-floor areas that actually have a very thin alluvial cover on poorly consolidated “Paleogene bedrock units (Figure 3-3)” are too commonly labeled “Qal” (Quaternary Alluvium). We therefore strongly recommend that cross sections and/or fence diagrams should be the rule rather than the exception in all hydrogeologic and geohydrologic field studies, even at a reconnaissance level. As previous noted (Section 3.2), 3-D hydrogeologic models are invariably “works in process,” but they can be easily updated as more-robust subsurface information becomes available.

4.1.2b. Alma-Glenwood Basin Area (Ratté 1981; Houser 1987, 1994). The southern part of the Lower **SFR** subbasin also has three major geomorphic and structural-geologic components (best illustrated by Plates 2d to 2e). The complex north-trending Alma basin (graben), named the Glenwood basin by some, is flanked on the east by the northern Mogollon Mountains (western edge of the Bursum Caldera) and to the west by high-level tablelands of the **SFR**-Blue River divide area and the Sierra Aguilada (intermediate) volcanic center (Houser 1994; Mack and Ratté 2008). The high Mogollon Mountains and Plateau (peaks as high as 10,895 ft; 3,321 m) are the source area for several large intermittent to perennial streams, including Mineral Creek and Whitewater Creek that join the **SFR** near Alma and at Glenwood, respectively.

The eastern part of Section DD' (Plate 2d) schematically illustrates the complex hydrogeologic character of the western “moat” and “resurgent-dome” components of the Bursum caldera. Note again, however, that the cross-section 5x vertical exaggeration distorts all structural features with any significant dip. To the north (SE end of Plate 2c) these features are buried by a thick cover of the post-caldera Bearwallow Mountain Andesite (25-26 Ma-Ratté 2001; **HSU-Tba,** Table 1-4). The east-tilted, half-graben structure (typical of most basins along the arcuate Alma-Reserve basin trend-Plate 1, cf. Crews 1994) is schematically portrayed in the central part of Section DD' (Plate 2d). Of special significance is the geologic inference that **HSU-Tba** has been down-faulted more than 3,000 ft (914 m) below its nearest exposure on the Bursum caldera “wall” immediately adjacent to the eastern basin-boundary, Mogollon fault “system” (further discussed in Subsection 4.3). The bedrock sequence at the western edge of the Alma extends beneath the **SFR**-Blue River divide area of Arizona, where the D-M volcanic sequence has not been differentiated (**HSU-Tvu**, Table 4-1).

Section E'E" (Plate 2e) crosses the southern end of the arcuate Reserve—Alma-Glenwood basin trend (Mack 2004; Mack and Ratté 2008) near the Cactus Flat “saddle” (Figure 1-2). The latter feature is a small tableland remnant that includes the low point of the drainage divide between the southern **SFR** and Upper Gila River basins (elev. 5,288 ft; 1,612 m; Table 1-1). The south to southeast trending series of structural basins south of the divide, which was originally named the Mangas “trench” by Trauger (1965), is now designated the Mangas basin (Mack 2004; Mack and Stout 2004). The eastern part of Section E'E" (Plates 1 and 2e) illustrates the hydrogeologic framework of the southwestern edge of the Bursum caldera complex in the west-central part of the Mogollon Mountains. The western part of the section follows the east-west) trend of the **SFR** “lower canyon” reach, which is characterized by deeply entrenched meanders cut in andesitic to dacitic lava flows of the Mogollon Group (Table 1-2) and extends to the **SFR**-Blue River confluence west of the NM-AZ state line (Table 1-1). Hydrogeologic aspects of the Late Cenozoic geomorphic evolution of the basin and river-valley/canyon system, including the shift from *closed* basin-floor aggradation to an *open-drainage* fluvial environment, is the subject of Section 5.

4.1.3 Gila Group Basin Fill

As has been previously noted, thick Gila Group basin-fill deposits are restricted to the few deep, fault-block (half-graben and full-graben) basins of the Reserve graben complex and the Alma (Glenwood) basin. Structural framework and bedrock-boundary characteristics of the basin were described in Subsection 4.1.2. Major lithostratigraphic, hydrostratigraphic and lithofacies components of the basin-fill sequence are schematically shown in Sections AA' to E'E" (Plate 2a-2e). Emphasis here is on the subbasin-scale distribution patterns of Gila Group hydrogeologic units (**HSUs**) and their lithofacies assemblage (**LFA**) components as defined and illustrated in Figure 3-2, and Tables 3-1, 3-2 and 4-1. Because stratigraphic sequence and lithofacies composition are quite similar, the upper **SFR** subbasin is covered in a single discussion section that combines observations on basin-fill hydrogeology in both the Reserve and Alma-Glenwood structural basins. Furthermore, with the exception of the Alpine Divide area (Witcher 1994a-c) deep well-log records are unavailable in this subbasin, so hydrogeologic interpretations are strictly based on the high-quality geologic field studies of the many well-exposed Gila Group stratigraphic sections present in the **SFR** valley and canyon area.

We have selected the Alma-Glenwood area (Plate 2d) to illustrate the essential hydrostratigraphic and lithofacies characteristics of the basin-fill sequence, because 1) representative Upper, Middle, and Lower Gila **HSUs** are all well exposed, 2) these units have been mapped in detail (Ratté 1981; Houser 1987, 1994), and 3) geochronology is well documented by radiometric ages of capping and interbedded basalt flows. This stratigraphic information is summarized in detail in Table 1-2, where it is correlated with the subbasin-scale, map (and cross-section)-unit descriptions in Table 4-1.

The most striking hydrogeologic characteristic of the potentially saturated part of the Gila Group in the Upper **SFR** subbasin is its well-indurated, mudstone-sandstone-conglomerate composition (primarily LFAs 7 and 8 Figure 3-2, Tables 3-1, 3-2, 4-1). Inferred horizontal hydraulic conductivities (K_h) are low (Table 3-2); and even highly fractured zones tend to be well-cemented with calcitic, zeolitic, and silicic materials. Weakly indurated to unconsolidated fluvial-facies assemblages (LFAs 1-3), for example HSU-UG2 (Figure 3-3), so common in the Mimbres Basin (Hanson et al. 1994; Hawley et al. 2000), is only preserved in the southern Alma basin and Cactus Divide area (Mack and Stout 2004), where it is entirely in the vadose zone (Subsection 4.3).

4.1.4 Post-Gila Group Valley Fill

The only post-Gila Group hydrostratigraphic units mapped in any detail in this report are 1) coarse-grained channel, floodplain, and low-terrace deposits of the San Francisco and Tularosa Rivers (**HSU-RG**) and 2) thin alluvial deposits in lowland areas adjacent to the **SFR** floodplain, or on the floors and lower side slopes of larger tributary stream valleys (**HSU-VA**). General lithofacies-assemblage (**LFA**) characteristics of these units are illustrated and summarized in Figure 3-2 and Tables 3-1 and 3-3 (e.g., **LFA**s a1-3, and b). In the many places where river deposits are too narrow to delineate at the basemap scale, they are either combined with **HSU-VA** or simply identified by the blue-line map symbol for the **SFR** itself. Information reported by Trauger (1972) and Basabilvazo (1997), as well as observed by Hawley throughout the region (1963 to present), indicates that saturated thickness of both **RG** and **VA HSU**s never exceeds 100 ft (30 m).

Saturated valley-fill deposits of the inner **SFR** Valley and the valleys of its major perennial to intermittent tributaries constitute the primary aquifer unit in the lowland parts of the basin system (Basabilvazo 1997). To our knowledge, the hydraulic properties of a typical coarse-grained river-channel deposit have never been quantitatively documented in the Upper **SFR** subbasin. However, hydraulic properties of a comparable river-channel/floodplain cross section have been reported by Trauger (1972, p. 64) on a reach of the Gila River near the Grant-Hidalgo County line and a gaging station. The aquifer there comprises very coarse-grained river-channel deposits (**HSU-RG**, **LFA**s-**a1** and **2**) that are about 100 ft (30 m) thick and 230 ft (70 m) wide. The hydraulic gradient is 0.0028 (15 ft/mi), and the estimated horizontal hydraulic conductivity of the gravel and sand aquifer is about 300 ft/d (90 m/d). Calculated underflow discharge across the entire inner-valley cross-section (area of 23,000 ft^2; 2,100 m^2), with alluvium inset in lowpermeability bedrock units, is about 19,000 ft^3/d (530 m^3/d; 0.43 ac-ft/d) or about 160 ac-ft/yr (1.95×10^5 m^3/yr). Comparable very high conductivity and gradient values are also recorded in the upper Mimbres River and upper Animas Creek valleys in nearby *Southwest Alluvial Basins* (Wilkins 1998; Hawley, et al. 2000).

4.2 LOWER SAN FRANCISCO RIVER SUBBASIN, ARIZONA

The lower reach of the San Francisco River extends between its respective confluences with the Blue River and the main-stem Gila River, and is entirely in east-central Arizona. The mouth of the **SFR** (elev. ~3,330 ft; 1,000 m) is about 10 (river) miles downstream from the Clifton Gaging Station (US-191 Bridge) and 40 mi below the Blue River confluence. The Lower **SFR** subbasin is located between 32° 55'and 33° 15' north latitude, and 109° 10' and 109° 22.5' west longitude, and has an area of about 148 mi^2 (383 km^2). Major topographic features, streams, place names, and public-land survey grids (AZ and NM) are shown on Figures 1-1 and 1-2.

In contrast to other parts of the **SFR** basin, there are no perennial tributaries, and principal valley-fill and Gila Group basin-fill aquifers are restricted to the river valley and to the northwestern part of the Duncan (structural) basin south of the Clifton-Morenci mining district (Richter et al. 1983; Ferguson and Enders 2000; Ferguson et al. 2000). The Freeport-McMoRan Copper and Gold Co. (formerly Phelps Dodge Corp) Morenci property has been mined since 1872 (Lindgren 1905) and is North America's largest copper mine. Today the mine produces more than 800 million pounds of copper a year (EARTH 2009, p. 73). Detailed hydrogeologic characterization of the Lower **SFR** basin is beyond the scope of this study, but the recent detailed characterization of both the bedrock and basin-fill geology of the area (Schroder 1996; Ferguson and Enders 2000; Ferguson et al. 2000) has allowed us to compile a large amount of lithostratigraphic and chronostratigraphic information that is directly applicable to ongoing and future hydrogeologic/geohydrologic studies throughout the **SFR** Basin. Of special significance is the fact that this is the only part of the study area where adequately logged water and mineral-exploration wells have been drilled through the entire Gila Group (locally as much as 3,000 ft; 900 m thick).

5.0 EFFECTS OF RIVER-VALLEY EVOLUTION ON THE HYDROGEOLOGIC SYSTEM

One of the distinguishing features of the San Francisco River basin is the deeply entrenched network of valleys and canyons that have been cut by the **SFR** and its major tributaries in Latest Cenozoic time (Plates 2a to 2e). Upper Gila Group deposits, which form major aquifers in much-less dissected downstream basins, are almost entirely in the vadose zone in the **SFR** basin. In fact, the Gila Group is a significant aquifer-system component only in the lower Duncan basin between Clifton and the **SFR**-Upper Gila confluence (Ferguson and Enders 2000; Richard et al. 2007). The hydrogeologic significance of the valley/canyon entrenchment process relates to the fact that deep valley and canyon incision during the past two to five million years has created a regional *sink* for groundwater *draining* from much of the basin-fill/bedrock aquifer sequence between the inner valley/canyon floors and the watershed divides that form the high-altitude eastern, northern, and much of western basin boundaries (Figure 1-2, Table 1-1, Plates 1 and 2a-e).

Detailed geologic mapping in the Cliff-Buckhorn area of the Mangas structural basin south of the Cactus Flat divide documents the final phases of basin aggradation and formation of an integrated Upper Gila fluvial system in Pliocene to Early Pleistocene time (Leopoldt 1981; Finnell 1987). In the latest Miocene and during much of the Pliocene (Figure 3-3), the northern Mangas basin was topographically *closed* and either *undrained* or *partly drained* in terms of groundwater discharge (Section 3.1.2). The basin-floor area at that time served as the “terminal-sink” for both the ancestral “upper” Gila and San Francisco fluvial systems (Leopoldt 1981; Mack 2004; Mack and Stout 2004); and it was first occupied by ephemeral saline-alkaline lakes and finally by shallow freshwater lakes and marshes (Lake Buckhorn; Mack and Ratté 2008). Basin-floor aggradation culminated in latest Pliocene or earliest Pleistocene time (~2 Ma); and uppermost Gila Group deposits are locally preserved about 700 ft (215 m) above the present Gila Valley floor near Cliff (Finnell 1987). According to Leopoldt (1981), this lacustrine/cienega system ultimately drained (spilled?) southwestward through the Middle Gila Box near Redrock into the Virden section of the deep Duncan (structural) basin upstream from the present **SFR**-Gila confluence (Richard et al. 2007). Contemporaneous or subsequent spillout from the Duncan Basin to the Safford Basin through a “gap” in the volcanic highlands separating these structural basins completed integration of the Upper Gila fluvial system (Houser et al. 2002); and the complex process of deep valley and canyon incision was initiated.

Recent field studies by Mack and Stout (2004; Mack and Ratté 2008), both north and south of the Cactus Flat divide (Figure 1-2; 5,288 ft; 1,612 m-Table 1-1), have located a thick sequence of ancestral **SFR** deposits that grade southward into Lake Buckhorn sediments. The uppermost fluvial deposits are about 750 ft (230 m) above the modern river-valley floor at the upper end of the "lower **SFR** canyon" reach, which is about 2 miles downstream from the gaging station at San Francisco (Lower Frisco Hot Springs, Figure 1-1, Plate 2e). High-level remnants of these axial-river deposits can be traced northward as far as the northeastern Alma basin (Houser 1987, 1994; Mack 2004-Figure 6). As in the case of the integration of the Upper Gila River in the Mangas-Duncan basin reach, there is still considerable uncertainty about the factors involved in the diversion of the ancestral "upper" **SFR** into the Blue River basin across the present "lower canyon" area between the Duck Creek basin (to the south) and Sierra Aguilada (Figure 1-1, Plates 1 and 2e). Regional- to local-scale tectonic processes and multi-scale climate change definitely played a significant role in development of an integrated Upper Gila-**SFR** fluvial system (Menges and Pearthree 1983; Machette et al. 1998; Pazzaglia and Hawley 2004; Mack 2004; Connell et al. 2005). One plausible integration mechanism involves late Pliocene-early Pleistocene alluvial aggradation of the Cactus Flat area by progradation of the large fans that head in the Big and Little Dry Creek basins in the Sacaton Mountain area of the Mogollon Mountains (Figure 1-1, Plate 2e). This constructional process could have ultimately blocked the south-flowing ancestral **SFR** and diverted it into its present "lower canyon" reach. The latest Pliocene-earliest Pleistocene timing of this possible "spill-out" may or may not closely coincide with the integration of Upper Gila River west of the Mangas basin. Whatever the cause(s) of river-system integration, its fluvial-geomorphic impact on the entire **SFR** basin was profound. Effects include relatively rapid valley and canyon entrenchment and drainage of a large quantity of groundwater from as much as 750 ft (230 m) of basin-fill and bedrock aquifers during the past two million years.

Adding to the complexity of river-valley evolution is the fact that the time-period being considered marks the onset of worldwide glacial/interglacial and pluvial/interpluvial climate fluctuations (Connell et al. 2005; Hawley 2005). In addition, active extensional tectonism is very well documented along the fault zone that separates the Mogollon Mountains block from eastern Mangas trench-Alma (Glenwood) basin block. High-level "pediment-terrace" deposits of the Late Pliocene to Early Pleistocene "upper" Gila Group are offset about 360 ft (110 m) along the Mogollon fault zone (Leopoldt 1981). This zone separates the central Mangas structural basin from the Mogollon Mountain block to the northeast (Ratté and Gaskill 1975). The youngest documented offset along an intra-basin fault in the area is a 10 ft (3 m) displacement of the youngest Middle Pleistocene “pediment-terrace” surface that is about 300 ft (90 m) above the Gila River base level near Cliff.

6.0 SUMMARY

The San Francisco River (**SFR**) is the only perennial tributary to the upper Gila River in the headwaters region of western New Mexico and eastern Arizona (Figure 1-1). The Gila-**SFR** confluence is about 10 miles south of the Clifton-Morenci mining district, the site of the largest open-pit copper mine in North America (EARTH 2009). The 2,790 mi^2 (7,230 km^2) drainage basin is in the Datil-Mogollon section of the Transition Zone physiographic/tectonic province, and includes the Blue River (AZ) and Tularosa River (NM) watersheds and much of the Mogollon-Datil volcanic field. The basic geologic-framework of the region was first described by G.K. Gilbert (1875); and part of the **SFR** basin is in the first National Forest area protected by the Wilderness Preservation System that Aldo Leopold (1887-1948) helped establish in 1924 (Moore 2008).

The **SFR** basin is characterized by large topographic relief (3,280-10,760 ft; 1,000-3,279 m), semiarid to humid climatic conditions (including extreme seasonal precipitation events), and complex distribution patterns of basin-fill and bedrock aquifer systems. These factors combine to produce high variability in surface-water/groundwater discharge and availability. For example, the 1927 to 2008 average mean-daily flow at the gaging station near Glenwood (NM) is 87.55 cfs (2.5 m^3/s), but recorded peak flows include: 17,500 cfs (495 m^3/s) in 1972; 14,000 cfs (395 m^3/s) in 1978; 27,500 cfs (780 m^3/s) in 1983; and 12,900 cfs (365 m^3/s) in 1984 .

The study’s primary purpose was to develop a digital hydrogeologic-framework model of **SFR**-basin aquifer systems that will provide essential information on the water-bearing and water-transmitting properties of basin-fill and bedrock units to three major user groups: 1) the scientific-technical community who are developing numerical models of groundwater-flow and hydrochemical systems; 2) governmental agencies charged with water-resource management; and 3) a diverse public who have a broad range of concerns, including water supply, protection of water rights, environmental issues, and general “public welfare.” Work was initially funded by the New Mexico Interstate Stream Commission, and is part of an ongoing effort to improve geohydrologic models used in management of both surface-water and groundwater resources of the Gila River subdivision of the “Lower Colorado River (Compact administrative) Basin.” The parts of Catron and Grant Counties covered include not only the **SFR** basin portion of the Gila-San Francisco “ground-water basin” (as declared by the NMOSE-6/30/1991), but also the southern edge of the “Lower Colorado Basin” and the westernmost part of “Rio Grande Basin" east of the Continental Divide (Plains of San Agustín). The combined “lower” **SFR** and Blue River subbasins in Arizona occupy most of Greenlee County and a small part of Apache County near Alpine.

Time and budget constraints did not permit site-specific assessment of aquifer potential in this study; and we could only evaluate the essential elements of the hydrogeologic-framework (stratigraphy-lithology-structure) at a drainage basin and subbasin scale. Our hydrogeologic model was initially based on published work by Trauger (1972) in Grant County and Basabilvazo (1997) in Catron County, with subsequent incorporation of a large amount of geologic information that has only been available since 1994 (e.g., Cather et al. 1994; Chamberlin et al. 1994; Crews 1994; Houser 1994; Witcher et al. 1994a-c; Ferguson and Enders 2000: Ferguson et al. 2000; Hawley et al. 2000; Elston 2001; Ratté 2001, 2008; Chapin et al. 2004; Mack 2004; Mack and Stout 2004).

This is the first synoptic integration of geologic information for aquifer-system characterization in the **SFR** basin; and our principal achievement has been development of a GIS-based, digital hydrogeologic model using ARC-GIS® and Adobe Illustrator®, respectively, for map and cross-section compilation. From a flow-modeling perspective, hydrogeologic databases and conceptual-framework models have, heretofore, only been available in a variety of formats with a wide range of interpretive quality and clarity. While all geology-based models tend to be “works in progress,” we believe that our digital model and supporting database represents a significant advance over previous work.

Plate 1 (CD-ROM) shows the surface-distribution patterns of major bedrock and basin-fill hydrostratigraphic mapping units as well as large-scale tectonic and volcanic features. The map is compiled from a variety of mid-scale GIS sources in New Mexico (1:100,000 to 1:500,000 scale) that were merged with a less-detailed Arizona map-database (1:500,000 to 1:1,000,000). In addition, unit boundaries and definitions were adjusted in many places to reflect more-detailed quadrangle mapping. The subsurface dimension is illustrated by five schematic cross sections (Plate 2a-e, CD-ROM) that were created specifically for this study at a map-scale of 1:100,000, base elevation of mean sea level, and 5x vertical exaggeration. Hydrogeologic evaluation of 277 well and spring sites in the New Mexico part of the study area, utilizing cited published sources as well as 1:24,000-scale quadrangle maps, was completed by the senior author in the summer of 2009. Well and spring locations are shown on Plate 3, and selected published records with preliminary hydrostratigraphic-unit and aquifer identifications are presented in Appendix Table A1 (CD-ROM).

7.0 REFERENCES

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