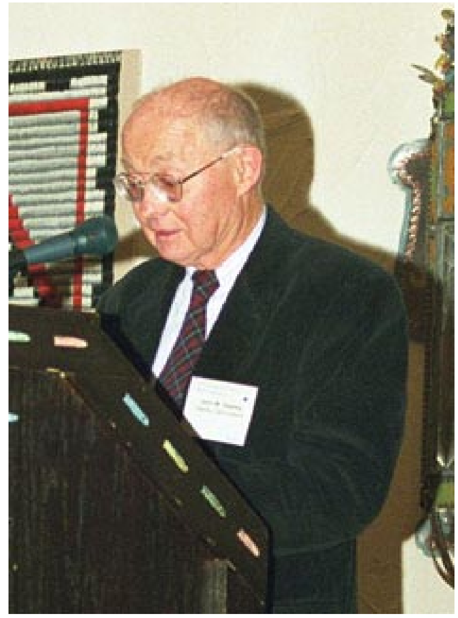

Overview of the Hydrogeology and Geohydrology of the Northern Rio Grande Basin - Colorado, New Mexico, and Texas

John Hawley *has a Ph.D. in geology from the University of Illinois (1962), and has spent most of his 40-year professional career working on a variety of problems relating to the exploitation of natural resources and disposal of hazardous wastes in fragile desert environments. He was first employed by the U.S. Soil Conservation Service in Las Cruces and Lubbock, and between 1977 and 1997 headed the environmental geology program of the Office of State Geologist at New Mexico Tech, Bureau of Mines and Mineral Resources Division. John was awarded emeritus status from the NMTech Board of Regents on his retirement in 1997, and he now works part-time as a consultant and NMWRRI specialist on the hydrogeologic framework of Rio Grande Basin and other parts of the International Boundary region.*

Overview of the Hydrogeology and Geohydrology of the Northern Rio Grande Basin - Colorado, New Mexico, and Texas

Mike Kernodle *joined the U.S. Geological Survey in 1973 after serving with the State of Tennessee as a geologist for 5 years. He retired from the Survey in 1998, and now works as a part-time consultant and serves as a technical advisor to the Middle Rio Grande Water Assembly. Mike has over 25 years of experience in groundwater-flow modeling, with the last 18 years in New Mexico, and 14 years experience in hydrologic applications of geographic information systems. While in New Mexico, he has authored or co-authored 30 reports, atlases, and papers.*

INTRODUCTION

This brief overview of the hydrogeology and geohydrology of basin-fill aquifers in the northern Rio Grande Basin covers a large region that extends from the San Luis "Valley" of south-central Colorado to the Hueco Bolson southeast of El Paso and Ciudad Juarez (Figure 1). This is the general area covered by the Rio Grande Joint Investigation of 1938 (Natural Resources Committee 1938). Emphasis here is on three basin-fill aquifer systems that are representative of the most productive groundwater reservoirs in this part of the United States: The Alamosa subbasin of the San Luis "Valley," the central part of the Albuquerque Basin, and the southern Mesilla Basin between Las Cruces and El Paso. The complex geohydrologic system that exists in the region must be understood both in the context of events leading to enactment of the Rio Grande Compact, and to all subsequent issues relating to management of groundwater as well as surface-water resources.

A very important part of the Rio Grande Joint Investigation Report was the chapter by Kirk Bryan (1938) on the "Geology and ground-water conditions of the Rio Grande depression in

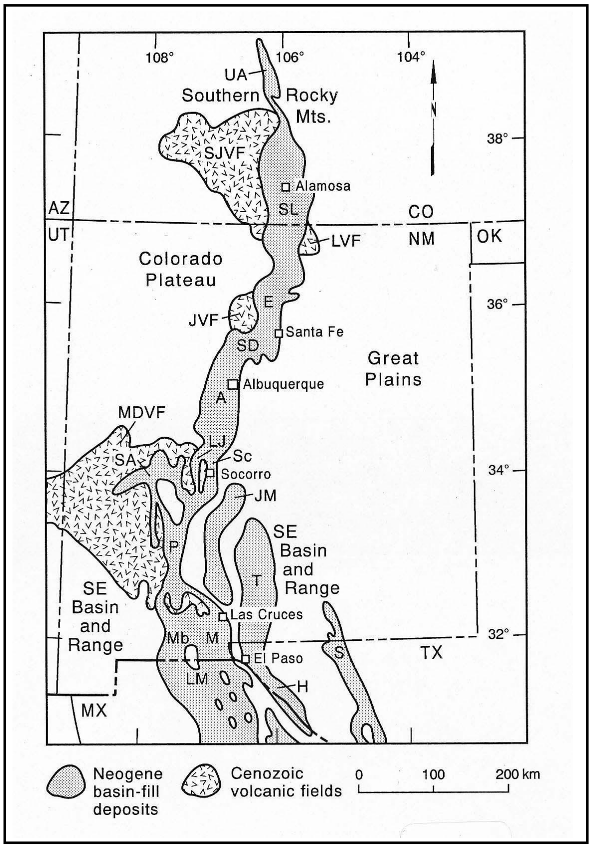

Figure 1. Index map showing major basins of the Rio Grande rift and contiguous volcanic fields. Modified from Keller and Cather (1994). Basins abbreviations from north to south: Upper Arkansas (UA), San Luis (SL), Española (E), Santo Domingo (SD), Albuquerque (A), Socorro (Sc), La Jencia (la), San Augustin (SA), Jornada del Muerto (JM), Palomas (P), Tularosa (T), Mimbres (Mb), Mesilla (M), Los Muertos (LM), Hueco (H), and Salt (S). Cenozoic volcanic fields: San Juan (SJVF), Latir (LVF), Jemez (JVF), and Mogollon-Datil (MDVF).

Colorado and New Mexico." Bryan was the first person to recognize the hydrogeologic importance of a series of deep structural basins that are the defining components of the Rio Grande rift (RGR) tectonic province (Hawley, 1978; Chapin and Cather, 1994). This area includes parts of the Southern Rocky Mountain, and Basin and Range physiographic provinces (Hawley 1986). From a hydrogeologic standpoint, Bryan's (1938) important contributions include his observations that:

1. The main body of sedimentary deposits of the Rio Grande depression, from the north end of the San Luis valley to and beyond El Paso, is considered to be the same general age and to belong to the Santa Fe formation (p. 205).

2. In general, the basins appear to have been elongated into ovals and to be divisible into two major types ... basins with a through-flowing river and basins with enclosed drainage (p. 205).

3. [Rio Grande depression basins] differ from other basins [in the Basin and Range province] principally in being strung like beads on a string along the line of the Rio Grande (p. 221).

Bryan's (1938) observations reflect not only his own work in the northern Rio Grande basin starting in 1909, but also the ongoing studies of his students (e.g., Bryan and McCann 1937, 1938; Denny 1940; Stearns 1953; Upson 1939; and Wright 1946) as well as previous hydrogeologic work in the region by Lee (1907); Siebenthal (1910); Meinzer (1911); Meinzer and Hare (1915); and Darton (1916). Reports by Lee (1907) and Siebenthal (1910), respectively, on water resources of the Rio Grande and San Luis "Valleys" cover much of the region described in this paper. Lee also presented an early conceptual model of the evolution of the Rio Grande fluvial system, and he emphasized the potential for building a large dam at the Elephant Butte site for irrigation water storage. Based on observations in Mexico and the American Southwest, Tolman (1909, 1937) also made a major contribution in better definition of the fundamental hydrogeologic distinction between depositional systems in aggrading intermontane basins with topographic closure (*bolsons*) and those that are open in terms of both surface and subsurface flow (*semi-bolsons*).

Figures 2 and 3 illustrate the basic conceptual models, which were initially developed by Bryan (1938) and Tolman (1937), for hydrogeologic systems and hydraulic regimes in groundwater reservoirs that occur in Upper Cenozoic basin (*bolson*) fills of western North America. Figure 2 is adapted from Bryan (1938, Figures 51 and 52), and it clearly demonstrates that a basic understanding of the integrated groundwater and surface-water flow system in basins of the "Rio Grande depression" already existed at the time (1937-1939) of final acceptance of Rio Grande Compact provisions.

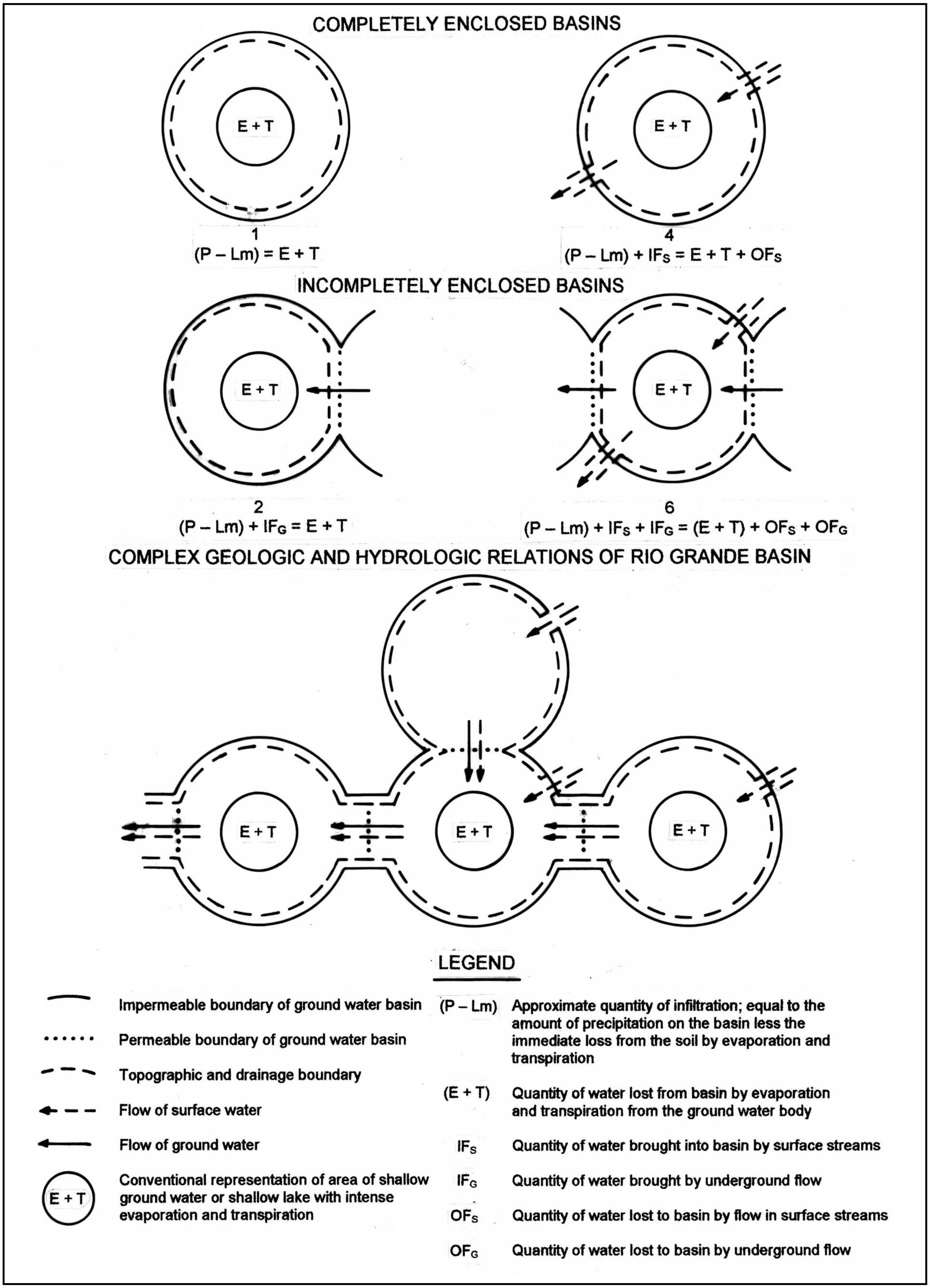

Figure 2. Kirk Bryan's conceptual models of hydraulic regimes in groundwater reservoirs of the "Rio Grande depression." Modified from Bryan (1938, Figures 51 and 52).

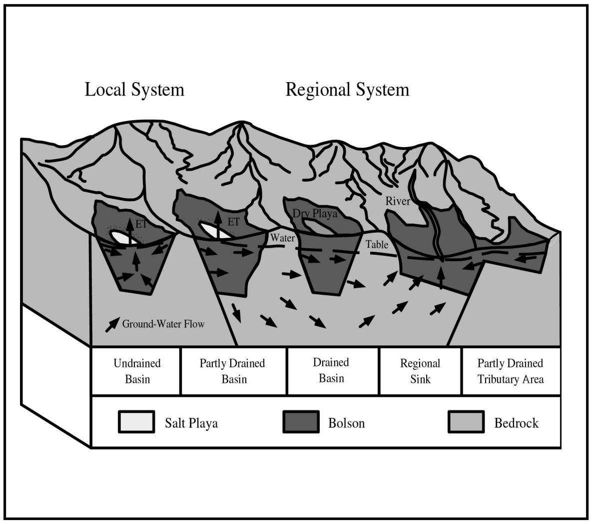

Figure 3. Conceptual hydrogeologic model showing *undrained* basins, *partly drained* basins, *drained* basins, and regional sinks (modified from Eakin et al. 1976; Hibbs et al. 1998). *Phreatic playas* are restricted to *undrained* and *partly drained* basins; and *vadose* conditions exist in "dry playa" areas.

Figure 3 illustrates the Bryan-Tolman conceptual model in a more general hydrogeologic sense for the entire Basin and Range province, and it incorporates subsequent work in the Great Basin section (e.g., Mifflin 1968, 1988; Eakin et al. 1976), and in the Trans-Pecos Texas and Chihuahua bolson region (Hibbs et al. 1998). The topographic terms *closed* and *open* are here used only in reference to the surface flow into, through, and from intermontane basins, whereas the terms *undrained*, *partly drained*, and *drained* designate classes of groundwater flow involving intrabasin and/or interbasin movement. *Phreatic* and *vadose*, respectively, indicate saturated and unsaturated subsurface conditions. *Phreatic playas* (with springs and seeps) are restricted to floors of *closed* basins (*bolsons*) that are *undrained* or *partly drained*, and *vadose playas* occur in both *closed* and *open*, *drained* basins. In the Rio Grande rift study region, as well as in most other desert basins of western North America, the intermediate basin class referred to as *partly drained* is probably the major groundwater-flow regime. Few intermontane basins (*bolsons* and *semibolsons*) are truly *undrained* in terms of groundwater discharge, whether or not they are *closed* or *open* in terms of surface flow.

Under predevelopment conditions, groundwater discharge in the region occurred mainly through subsurface leakage from one basin system into another, discharge into the gaining reaches of perennial or intermittent streams, discharge from springs, or by evapotranspiration from *phreatic playas* and cienegas (valley-floor wetlands). Most recharge to basin-fill aquifers occurs by two mechanisms, (1) "mountain front," where some precipitation falling on bedrock highlands contributes to the groundwater reservoir along basin margins (Figure 4); and (2) "tributary," where the reservoir is replenished and along losing reaches of larger intrabasin streams (Hearne and Dewey 1988; Anderholm 1994; Kernodle 1992; Wasiolek 1995). The upland networks of major stream valleys in the Sangre de Cristo, San Juan, and Jemez Mountains of southern Colorado and northern New Mexico are the primary source areas for recharge of basin-fill aquifers in the RGR region. Secondary contributors to these groundwater reservoirs are the few high and massive mountain ranges that form isolated highlands bordering individual basin units. Recharge estimates in this paper are based on the assumption that (1) less than 5% of average annual precipitation contributes to recharge, and (2) this contribution is distributed very unevenly over higher watersheds and in major stream valleys.

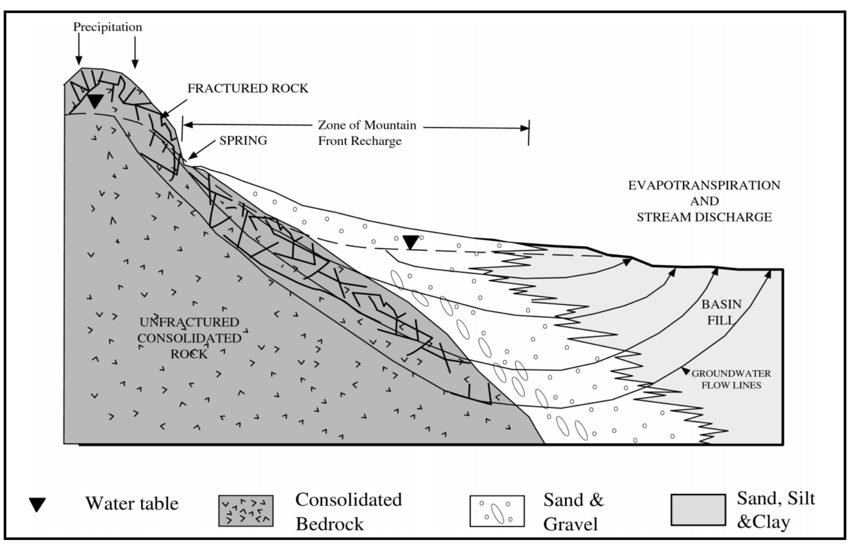

Figure 4. Two-dimensional conceptual model of a groundwater recharge system in a Basin and Range by hydrogeologic setting (from Wasiolek 1995, modified from Feth 1964, and Mifflin 1968).

DEVELOPMENT OF HYDROGEOLOGIC AND GEOHYDROLOGIC CONCEPTS SINCE 1945

The major scientific and technological breakthroughs during and immediately after World War II introduced a new era of hydrogeologic system characterization that continues today. These breakthroughs included development of modern geophysical-survey and deep drilling methods, and advances in geochemistry. Characterization of basin-fill aquifers in the San Luis Basin by Powell (1958) and Emery and others (1971) is representative of work in that area prior to 1975. Hydrogeologic mapping and related hydrologic and geologic investigations in basins of north-central RGR and central New Mexico is exemplified by the work of Bjorklund and Maxwell (1961), Titus (1961), Theis and Conover (1962), Spiegel (1962), Spiegel and Baldwin (1963), Griggs (1964), Cushman (1965), Weir (1965), Lambert, (1968), and Kelley (1977). Concurrent studies in the southern part of the region by the U.S. Geological Survey, Texas Water Commission, City of El Paso, U.S. Soil Conservation Service, and New Mexico State University combined detailed mapping and innovations in subsurface methods using borehole geophysics, standard sample logging, and aquifer geochemistry (e.g., Knowles and Kennedy 1958; Leggat et al. 1962; Cliett 1969; Hawley et al. 1969; King et al. 1971; Wilson et al. 1981).

Recent and future hydrogeologic mapping has been and will be characterized by the increased availability of high quality geophysical and geochemical data, and deep borehole sample and core logs. This era is dominated by the opportunities generated by the exponentially increasing power of computers, and evolution of numerical modeling and GIS technology. In the Rio Grande Basin region, as elsewhere, the bridge between the early 20th Century conceptual world and the present will continue to be *hydrogeologic ground truth*. Both surface and underground views of geohydrologic systems must now be expressed in units that modelers of groundwater-flow systems can understand and computers can process. Rapid improvements in the understanding of subsurface geophysical and geochemical systems, lithofacies assemblages, structural boundary conditions, and definition of hydrostratigraphic units (Seaber 1988) now allow modelers to join forces effectively with hydrogeologists, geophysicists and geochemists in meeting the incredible water-resource challenges that face Third Millennium society in this and other arid and semiarid regions.

Current investigations that directly relate to hydrogeologic characterization and groundwater-flow model development in the northern Rio Grande Basin are illustrated in the following sections. Recommended publications include: Balleau (1999), Bartolino (1999), Bedinger and others (1989), Hawley (1993), Haneberg (1995, 1998), Heywood (1995), Hansen and Gorbach (1997), Hibbs (1999), Hibbs and others (1997, 1998), Slate (1998), Lewis and West (1995), Tiedeman and others (1998), and West (1996).

CONCEPTUAL HYDROGEOLOGIC-FRAMEWORK MODEL

The hydrogeologic framework of basin-fill aquifers in the RGR region, with special emphasis on features related to environmental concerns, is described here in terms of three basic conceptual building blocks: lithofacies assemblages (LFAs), hydrostratigraphic units (HSUs), and structural-boundary conditions. A conceptual hydrogeologic model of an interconnected shallow valley-fill/basin-fill and deep-basin aquifer system was initially developed for use in groundwater-flow models of the Mesilla and Albuquerque basins (Peterson et al. 1984; Kernodle 1992, 1996, 1998; Hawley and Lozinsky 1992; Frenzel and Kaehler 1992; Hawley and Haase 1992; Thorn et al. 1993; Hawley et al. 1995; Kernodle et al. 1995). However, basic design of the conceptual model is flexible enough to allow it to be modified for use in other basins of the Rio Grande rift and adjacent parts of the southeastern Basin and Range province (Hawley et al. 2000).

The model is simply a qualitative description (graphical, numerical, and verbal) of how a given geohydrologic system is influenced by (1) bedrock-boundary conditions, (2) internal-basin structure, and (3) the lithofacies and mineralogical composition of various basin-fill stratigraphic units. It provides a mechanism for systematically organizing a large amount of relevant hydrogeologic information of widely varying quality and scale (from very general drillers observations to detailed bore-hole, geophysical and geochemical data). Model elements can then be graphically displayed in a combined map and cross-section GIS format so that basic information and inferences on geohydrologic attributes (e.g., hydraulic conductivity, transmissivity, anisotropy, and general spatial distribution patterns) may be transferred to basin-scale, three-dimensional numerical models of groundwater-flow systems. As emphasized by McCord and Stephens (1999), this scheme of data presentation and interpretation is generally not designed for groundwater-flow models at a site-specific scale.

Lithofacies Assemblages

Lithofacies assemblages (LFAs) are the basic building blocks of the hydrogeologic model (Figure 5, Table 1), and they are the primary components 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, and they are grouped according to inferred environments of deposition. LFAs have distinctive geophysical, geochemical and hydrologic attributes, and they provide a mechanism for showing distribution patterns of major aquifers and confining units in hydrogeologic cross sections. Basin and valley fills are here subdivided into thirteen major assemblages that are ranked in decreasing order of aquifer potential (Tables 1 to 3; LFAs ***1-10***, ***a-c***). Figure 5 is a schematic illustration of the distribution pattern LFAs observed in the Rio Grande rift and southeastern Basin and Range Region. Lithofacies properties that influence groundwater flow and production potential in this region are summarized in Tables 2 and 3. Note that *Roman numeral* notations (I-X) originally used in previous hydrogeologic framework models (Hawley et al. 1995) have been changed to *Arabic* style in order to facilitate the development of alpha-numeric attribute codes that can be used in both conceptual and numerical models of basin-fill aquifer systems.

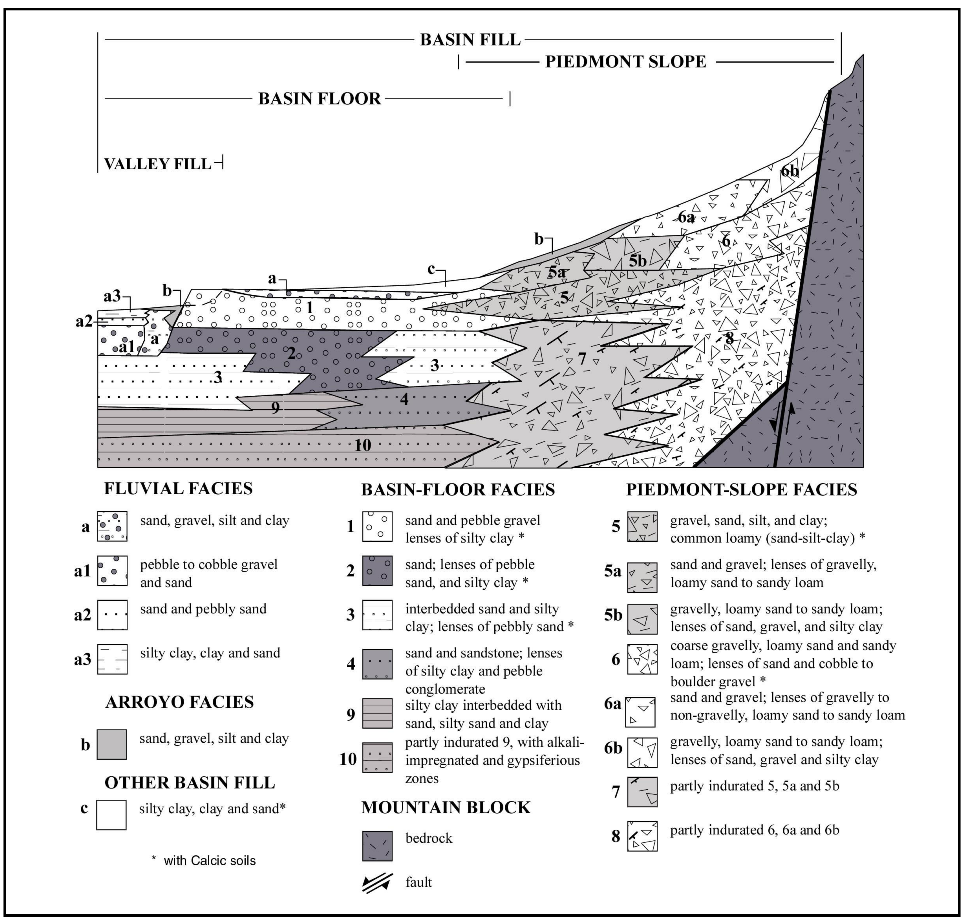

Figure 5. Schematic distribution pattern of major lithofacies assemblages (Tables 1-3) in basin-fill deposits of the Rio Grande rift region (from Hawley et al. 2000).

Table 1. Summary of lithofacies-assemblage depositional settings and dominant textures for Santa Fe Group (***1-10***) and Post-Santa Fe (***a,b,c***) basin and valley fills (modified from Hawley and Haase 1992, Table III-2)

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

Table 2. Summary of properties that influence groundwater production potential of Santa Fe Group lithofacies assemblages (modified from Haase and Lozinsky 1992) [>, greater than; <, less than]

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

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

Table 3. Summary of properties that influence groundwater production potential of Post - Santa Fe Group lithofacies assemblages [>, greater than; <, less than]

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

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

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

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

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

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

Hydrostratigraphic Units

Most intermontane-basin fills in the New Mexico region have been subdivided into two major lithostratigraphic units (Figure 6), the Santa Fe Group in Rio Grande rift basins (e.g., Hawley 1978; Chapin and Cather 1994) and the Gila Group in basins of the Mexican Highland and Datil-Mogollon sections to the west (Hawley et al. 2000). In addition, a clear distinction has rarely been made between deposits simply classed as "bolson" or "basin" fill and contiguous (formal and informal) subdivisions of the Santa Fe and Gila groups. As a first step in organizing available information on basin fill stratigraphy that has a close relationship with aquifer characteristics, a provisional hydrostratigraphic classification system (Seaber 1988) has been developed. It follows guidelines used successfully in the Albuquerque and Mesilla basins (Hawley and Lozinsky 1992; Hawley et al. 1995) and in adjacent "Southwest Alluvial Basins" as defined by Wilkins (1986, 1998).

Hydrostratigraphic units defined in the RGR region 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 Santa Fe*** hydrostratigraphic units (HSUs: ***USF, MSF, LSF***) comprise the major basin-fill aquifer zones, and they correspond roughly to the (formal and informal) upper, middle, and lower lithostratigraphic subdivisions of the Santa Fe Groups used in local and regional geologic mapping (Figure 6). Dominant lithofacies assemblages in the ***upper Santa Fe*** HSU are *LFAs* ***1-3, 5 and 6***. The ***middle Santa Fe*** HSU is characterized by *LFAs* ***3, 4, 7-9***, and the ***lower Santa Fe*** commonly comprises *LFAs* ***9, 7-10***. Basin-floor facies assemblages ***3*** and ***9*** are commonly present throughout the Santa Fe Group section in closed-basin (bolson) areas.

The other major hydrostratigraphic units comprise channel and floodplain deposits of the Rio Grande (***RG***) and its major tributaries such as the Rio Chama and Rio Puerco. These valley fills of Late Quaternary age form the upper part of the region's most productive shallow-aquifer system (*LFA**a***). Surficial lake and playa deposits, fills of larger arroyo valleys, and piedmont-slope alluvium are primarily in the *vadose* zone. However, they locally form important ground-water discharge and recharge sites. Historical *phreatic* conditions exist, or have recently existed, in a few playa remnants of large pluvial lakes of Late Quaternary age (Hawley 1993). Notable examples are "gypsum or alkali flats" in the Tularosa, Jornada del Muerto and Los Muertos basins, which are contiguous to, but outside the area discussed in this paper.

Bedrock and Structural Boundary Components

Structural and bedrock features that influence aquifer composition and behavior include basin-boundary mountain uplifts, bedrock units beneath the basin-fill, fault zones and flexures within and at the edges of basins, and igneous-intrusive and extrusive rocks that penetrate or are interbedded with basin fill. Tectonic evolution of the fault-block basins and ranges of the study area (many with a half-graben structure and accommodation-zone terminations) has had a profound effect on the distribution of lithofacies assemblages and the timing and style of emplacement of all major hydrostratigraphic units (Figs. 5 and 6). Discussion of this topic is beyond the scope of this paper, however, the reader is referred to pertinent reviews in Collins and Raney (1991), Keller and Cather (1994), Hawley and others (1995), Bauer and others (1995), Goff and others (1996), Mack and others (1997, 1998), Faulds and Varga (1998), Haneberg (1998), and Pazzaglia and Lucas (1999).

HYDROGEOLOGIC FRAMEWORK OF REPRESENTATIVE RGR BASINS

Figures 7, 8, and 9 are schematic hydrogeologic cross-sections that illustrate the basic structural framework and distribution patterns of major hydrostratigraphic units, respectively, in the central parts of the San Luis, Albuquerque, and Mesilla basins of the Rio Grande rift structural province. In addition to parts of the Española Basin near Los Alamos and the Hueco Bolson near El Paso (Purtymun 1995; Cliett and Hawley 1996), these are the only areas where high-quality borehole geophysical and sample logs, and a variety of other geophysical and geochemical survey data are available. It is important to note that much of this information is related to deep-

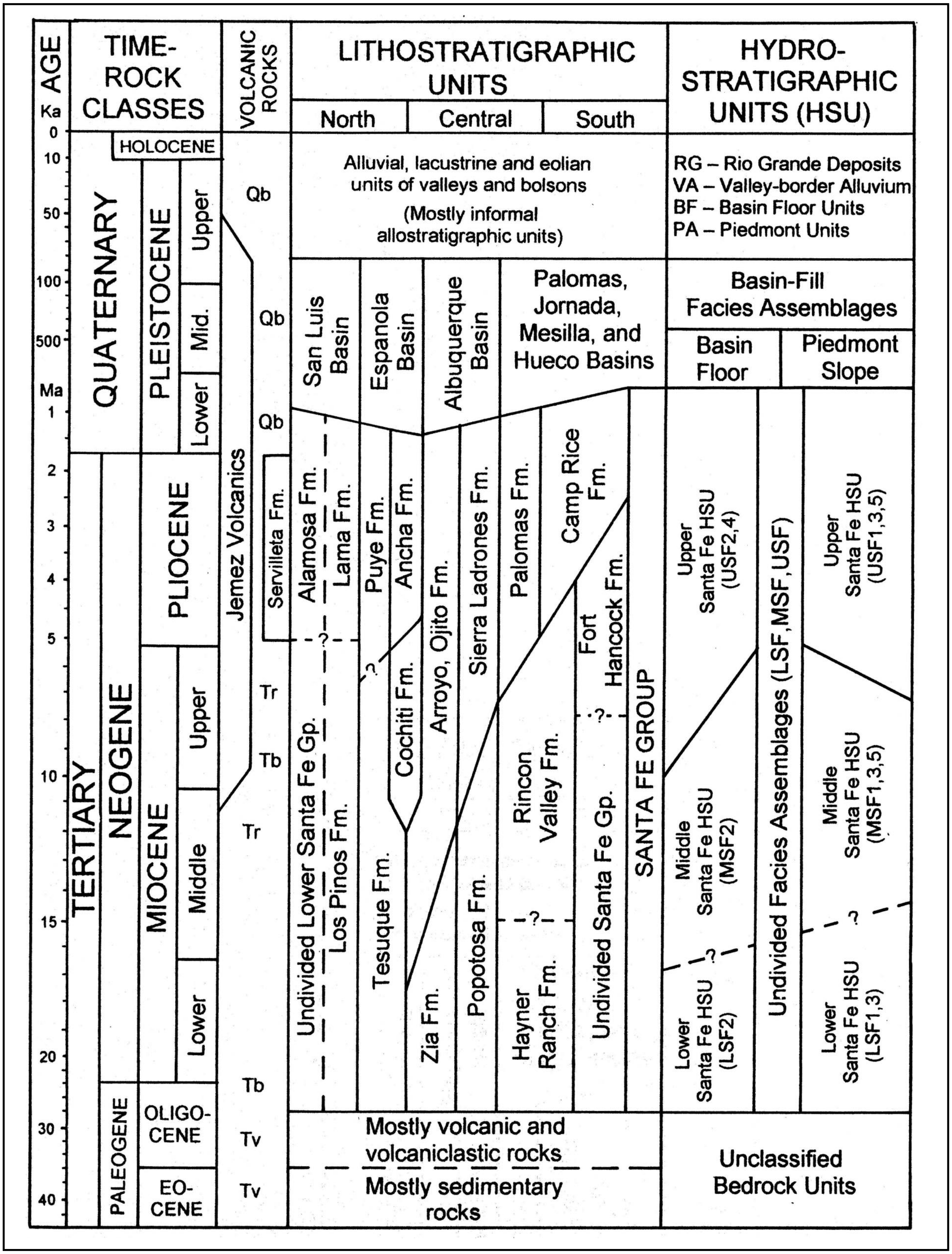

Figure 6. Regional summary and correlation of major lithostratigraphic and basin-fill hydrostratigraphic units (HSUs) in the Rio Grande rift region. Volcanic-rock symbols: Qb-Quaternary basalt; Tb and Tr- Tertiary mafic and silicic volcanics, respectively; Tv-primarily intermediate and silicic volcanics.

basin exploration for hydrocarbon and geothermal resources. Geologic mapping and geochronologic studies throughout the RGR region demonstrate the continuity and correlation of major lithostratigraphic and informal hydrostratigraphic units (Figure 6) that were originally recognized by Kirk Bryan (cf. Hawley 1978; Chapin and Cather 1994).

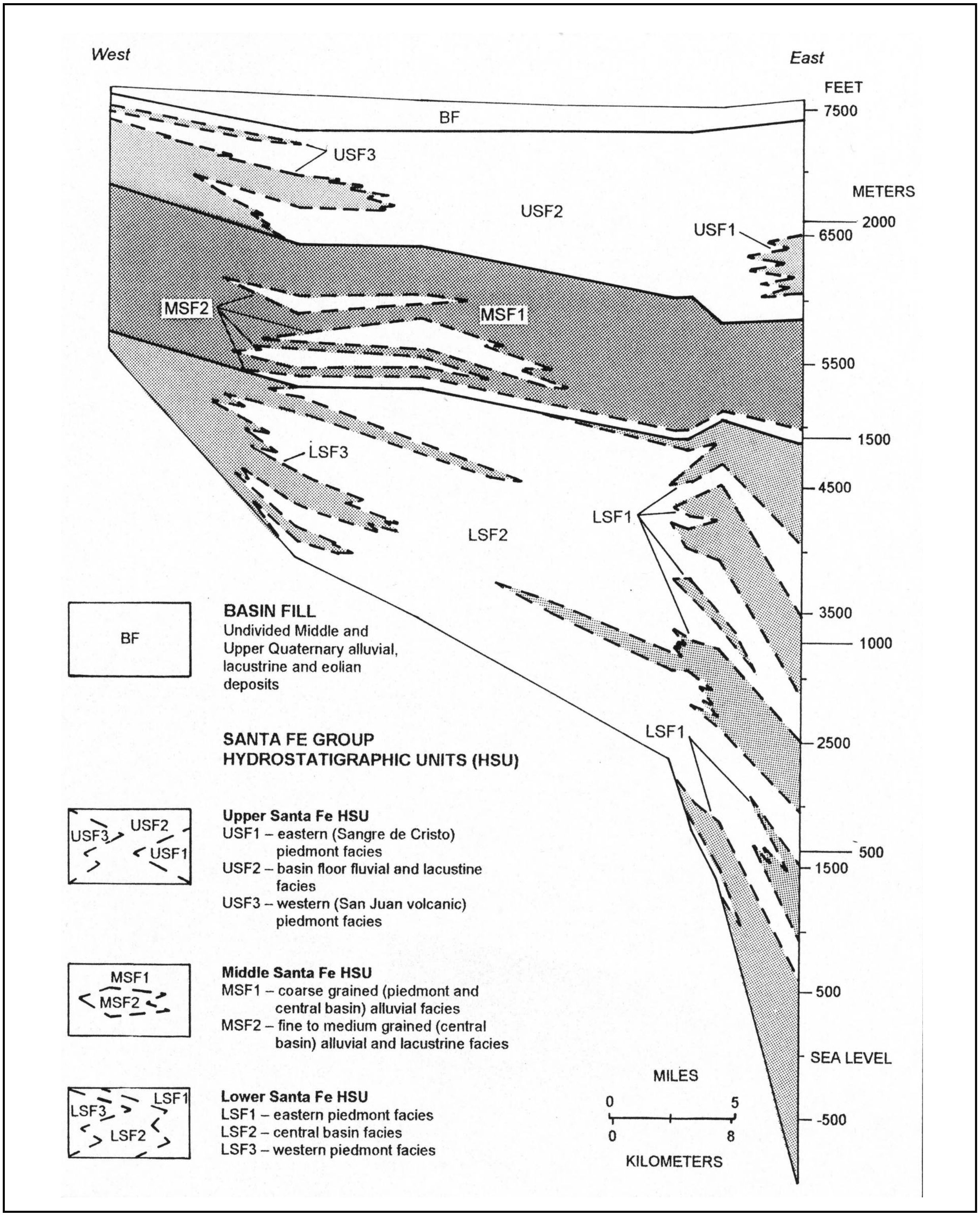

Figure 7. Schematic hydrogeologic cross section of the Alamosa subbasin of the San Luis structural basin near the Alamosa-Saguache County Line. Modified from Brister and Gries (1994, Figure 3). The base of the section is the top of an ash-flow tuff unit of late Oligocene age.

Figure 7 is a hydrogeologic section, adapted from Brister and Gries, 1994, that documents the half-graben structure and relatively narrow width of the Alamosa subbasin of the San Luis Valley in the area west of Great Sand Dunes National Monument. It is the only RGR basin discussed in this paper that is both topographically *closed* and internally *drained* (cf. Figures 2 and 3). Brister and Gries (1994) include the Alamosa Formation of Siebenthal (1910) in their Upper Santa Fe Group lithostratigraphic unit, and their "Lower" Santa Fe Group correlates with the Santa Fe Formation of previous workers (Powell 1958; Emery et al. 1971). In this paper the gravelly upper part of the "lower" Santa Fe section is informally defined as the ***middle Santa Fe*** HSU, which comprises two major facies groups, piedmont slope (**MSF1** and **3**) and basin floor (**MSF2**). Note that the Hearne and Dewey (1988) model of the San Luis Basin only covers the upper 3,200 feet of saturated basin fill, and it, therefore, is primarily restricted to the ***upper*** and ***middle Santa Fe*** HSUs.

The Brister-Gries study utilized information from cross-basin seismic-survey lines as well as sample and geophysical logs from deep boreholes. As shown in Figure 7, the Santa Fe Group is locally as much as 9,500 ft. thick near the eastern edge of the half-graben (hanging-wall) block. This study also demonstrates that Santa Fe Group basin fill is relatively thin in the western half of the Alamosa subbasin, and that most basin deposits heretofore correlated with the Santa Fe Group by hydrogeologists are actually Lower to Middle Cenozoic sedimentary and volcanic rocks that predate RGR development. This suggests that model estimates of "Santa Fe Formation" hydraulic conductivity made by Hearne and Dewey (1988) may be much too high in large parts of the western Alamosa subbasin (cf. Table 4).

The east-central part of the Albuquerque Basin includes the deepest known segment of the RGR structural depression. Basin fill in the area near Isleta Pueblo locally exceeds 14,500 ft. (Lozinsky 1994; Hawley et al. 1995, Fig. 3). Figure 8 is a schematic hydrogeologic section of

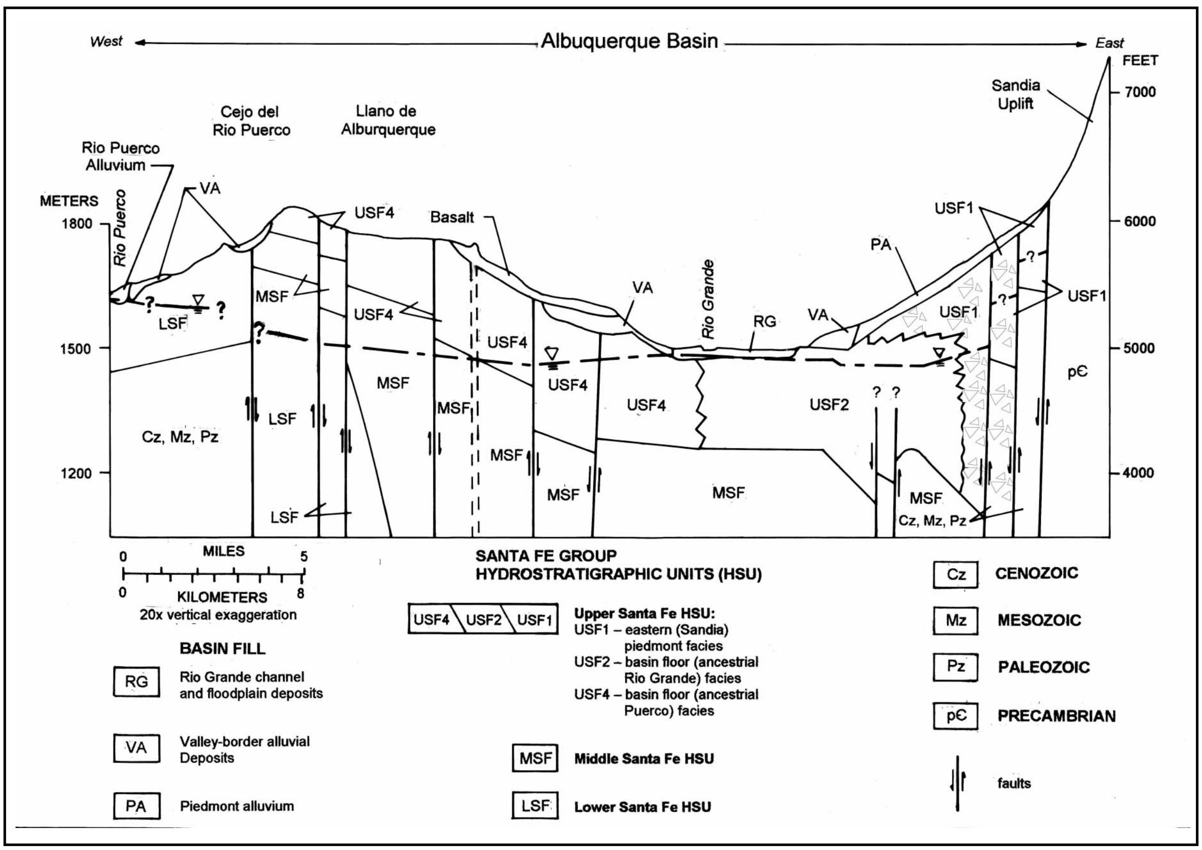

Figure 8. Schematic hydrogeologic cross section of the northern Albuquerque Basin about 3 miles south of the Bernalillo-Sandoval County Line. Modified from Hawley and others (1995, Fig. 4).

the central basin area between Albuquerque and Rio Rancho. Its base is at mean sea level, which is about 3,200 feet below the active layers of the groundwater-flow model discussed in the concluding section of this report. As in the Alamosa subbasin, the major aquifer system utilized in the Albuquerque-Rio Rancho metropolitan area comprises the ***upper*** and ***middle Santa Fe*** Hydrostratigraphic Units (HSUs: ***USF*** and ***MSF***) as originally defined in Hawley and Haase (1992) and Hawley and others (1995). However, the Albuquerque Basin is typical of all RGR basins in New Mexico in that the Rio Grande Valley system is (1) deeply entrenched and (2) contains a hydrologically very significant inner valley fill of Late Quaternary River deposits (HSU-***RG***). The major aquifer is the ancestral Rio Grande (fluvial) facies in the ***upper*** and *upper part of the* ***middle Santa Fe*** HSUs (primary LFAs ***1-3***). The trough in the water table, schematically shown beneath the Llano de Alburquerque on Figure 8, is here interpreted as a feature bounded by major fault zones that restrict groundwater inflow from adjacent parts of the Rio Grande and Rio Puerco Valleys.

The Middle Rio Grande Basin between Cochiti Dam and Elephant Butte Reservoir is the major area of ongoing geologic, geophysical, hydrologic, and hydrogeochemical investigations in the entire RGR region (Haneberg 1995, 1998; Hansen and Gorbach 1997; Slate 1998; Bartolino 1999; Pazzaglia and Lucas 1999). There will clearly be some revisions in the conceptual hydrogeologic models of this complex basin system as the result of this work. Basic model interpretations (Hawley et al. 1995, and Kernodle et al. 1995), however, still appear to be validated by current investigations.

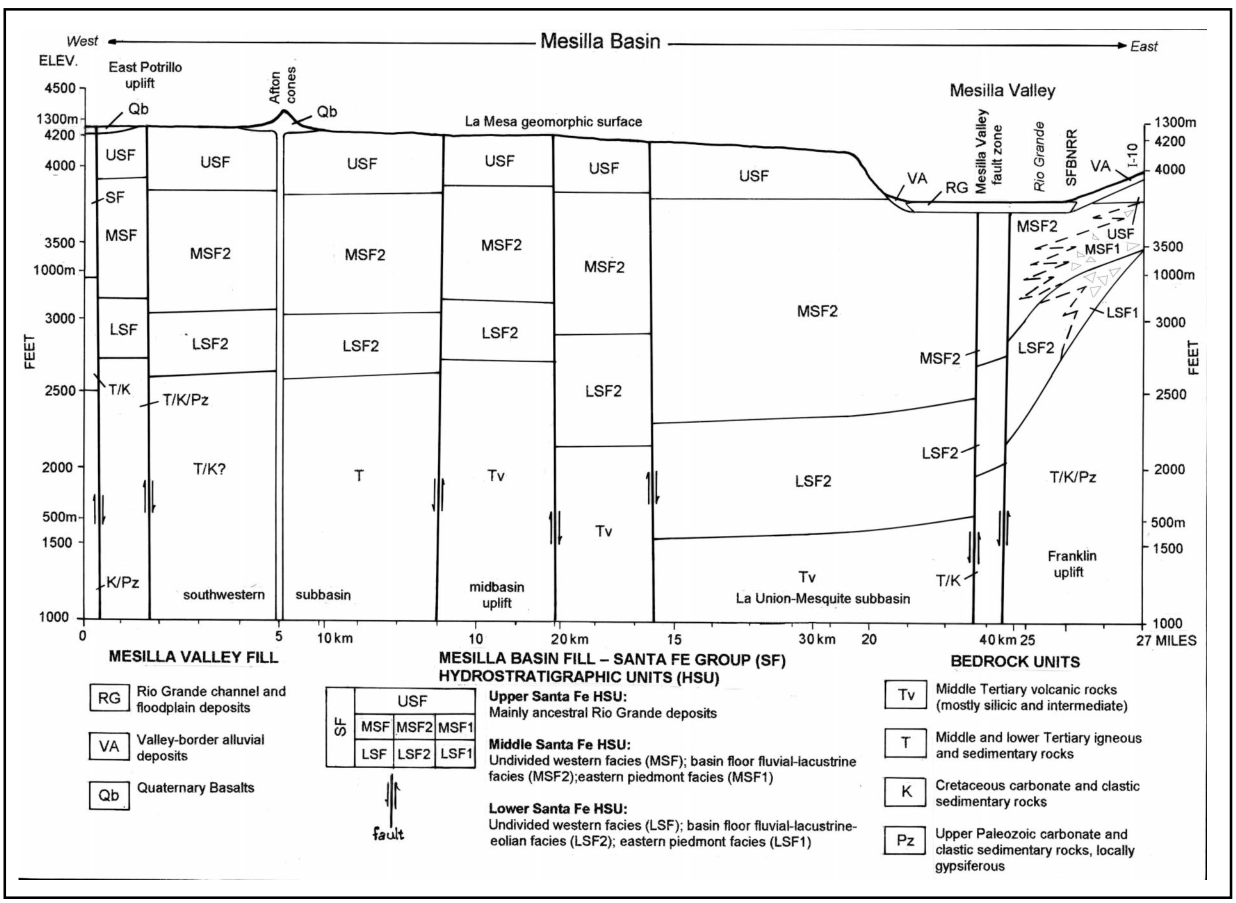

Figure 9. Schematic hydrogeologic cross section of the central Mesilla Basin (Bolson) near the 32nd Parallel in Dona Aña County, New Mexico and northwestern El Paso County, Texas. Modified from Hawley and Lozinsky (1992, Plate 16C).

Figure 9 is a schematic hydrogeologic cross-section of the south-central Mesilla Basin, which is approximately aligned along the 32nd Parallel. The section is based on (1) geologic mapping, primarily by Seager and others (1987), and (2) subsurface geophysical, hydrogeologic, and water-quality information collected by Hawley and Lozinsky (1992). Major contributors to the hydrogeologic interpretations shown in Figure 9 include Leggat and others (1962), Cliett (1969), Hawley and others (1969), King and others (1971), Gile and others (1981), Wilson and others (1981), Peterson and others (1984), Seager and others (1987), and Ken Stevens (USGS-WRD unpublished).

The distinctive feature of the rift-basin-fill sequence in the Mesilla Basin is that it is relatively thin in comparison to the Albuquerque and San Luis basins, with a saturated thickness of no more than 3,000 ft. As in basin areas to the north and the Hueco Bolson to the southeast, the most productive and thickest aquifers are ancestral Rio Grande fluvial deposits (LFAs ***1*** and ***2***) of the ***upper Santa Fe*** HSU (***USF2***). However, these units are only saturated in the northeastern part of the basin near Las Cruces (Hawley and Lozinsky 1992). In the southern and western part of the basin the ***upper Santa Fe*** HSU is entirely in the vadose zone, and the most productive aquifers comprise the ***middle*** and ***lower Santa Fe*** HSUs (***MSF2/LSF2****: LFAs* ***3*** and ***4***). A particularly productive aquifer is the "deep aquifer"of Leggat and others (1962), which underlies the southern Mesilla Valley in the Anthony-Canutillo area (HSU ***LSF 2***, Figure 9). This unit includes a distinctive eolian sand facies (*LFA* ***4***) that intertongues mountainward with piedmont fanglomerates (*LFAs* ***7-8)***, and basinward with basin-floor facies assemblages *LFAs* (***3, 9*** and ***10***?). The latter facies are here interpreted as fluvial-deltaic-playa/lake deposits (Table 1, Figure 5).

GROUNDWATER FLOW MODELS

Introduction

Groundwater-flow models are a numerical way (just one) to merge hydrogeology and geohydrology to produce a link between cause, process, and effect. The intention is an attempt to predict the future or to test the validity of the conceptual model of the groundwater system. In so doing, the usual approach is to replicate as closely as possible every internal condition and outside influence that can affect groundwater flow levels (heads). Even so, the title of Knoikow and Bredehoeft's 1992 article says it all: "Groundwater models cannot be validated." Modeling is an ever-evolving and ever-learning iterative process as more knowledge of the system is gained and incorporated. Improvements in science and technology will always be necessary for proper utilization of this new knowledge base.

Models of groundwater flow in the Rio Grande Basin aquifer system first need to be examined in terms of the hydrogeologic constraints placed on flow regimes by structural-boundary, lithofacies, and hydrostratigraphic conditions that are either well documented or reasonably inferred (Table 4). Kernodle's (1992) critique of "U.S. Geological Survey Ground-Water-Flow Models of Basin-Fill Aquifers in the Southwestern Alluvial basins region" sets the tone for this paper. "As a rule identifiable geologic features that affect groundwater-flow paths, including geologic structure and lithology of beds, need to be represented in the model (p.65)"; and major categories of geohydrologic boundaries in alluvial basins include: "1) internal boundaries that alter flow paths, including small-permeability beds, fissure-flow volcanics and faults; 2) recharge boundaries, primarily around the perimeter of basins (mountain-front recharge), and along the channels of intermittent streams, arroyos, and washes (tributary recharge); [and] 3) recharge and discharge boundaries associated with semipermanent surface-water systems in the flood plains of major streams ... (p. 66)". Finally, "although two-dimensional models may successfully reproduce selected responses of the aquifer, they fail to accurately mimic the function of the system (p. 59)". In comparison ... three-dimensional models more accurately portray the flow system in basin-fill [aquifers] by simulating the vertical component of flow. However, the worth of the model is still a function of the accuracy of the hydrologist's concept of the workings of the aquifer system (p. 59)."

Table 4.--Summary of modeled aquifer properties for documented U.S. Geological Survey three-dimensional groundwater-flow models in the Rio Grande basin region of Colorado, New Mexico and West Texas (modified from Kernodle, 1992)

Basin	San Luis[1]	Española[2]	Albuquerque[3]	Mesilla[4]	Hueco[5]
Layers in model	7	22	11	5	2
Total depth (ft.) in model	3,200	4,000±	1,730	3,450	3,000±
Thickness of top layer (ft)	0-150	300±	20	200±	200
Horizontal hydraulic conductivity					
Alluvium	NA	NA	40	70/140	20
Santa Fe Group		1.0		3-22	17/134
Upper	25-450		10-70		
Middle/Lower	30-40		2-10		
Simulated fines	10	NA	0.5	NA	NA
Anisotropy ratio	670/2,300	330	200	200	0.0035-33,000
Specific yield	0.20	0.15	0.15	0.20	0.1-0.3
Specific storage (storage coefficient)	$5X10^{-6}$	$2X10^{-6}$	$2X10^{-6}$	$1X10^{-6}$	($1X10^{-4}$ to $4X10^{-4}$)
Boundaries					
River, canals, and drains	L	C,L	L	R	L
Other	MRF, ET	MFR	MFR, ET	MFR, ET	MFR
Primary properties altered during calibration	Q	Q	NA	K, VK, R	VK, S
Major sources of water to wells	ET	S	S, R	R, S	S

1. Hearne and Dewey, 1988 **2.** Hearne, 1988 **3.** Kernodle, 1998; Kernodle et al., 1995 **4.** Frenzel and Kaehler, 1992 **5.** Meyer, 1976
Abbreviations: NA, not applicable; **L,** head-dependent flux (leaky); **C,** specified-head cell (constant head); **R,** head-dependent flux (w/flow-routing river and drains); **ET,** evaportranspiration (or salvaged ET); **MRF,** mountain-front and tributary recharge; **Q,** groundwater withdrawal amount and location; **K,** horizontal hydraulic conductivity; **B,** boundary conditions; **VK,** vertical conductivity; **I,** irrigation-return flow; **S,** aquifer storage (specific yield and/or specific storage)

Geohydrologic Setting

The "string of pearls", the string of groundwater basins in the Northern Rio Grande Basin, primarily are interconnected by surface waters of the Rio Grande and not so much by groundwater underflow. Estimates of groundwater rates of downstream interbasin flow are generally in the range of 10 to 20 cubic feet per second (Kernodle and Scott 1986; Kernodle et al. 1987; McAda and Wasiolek 1988).

Typically, each basin has an upper and lower constriction consisting of low hydraulic conductivity prebasin-fill deposits, or has a structural barrier such as the La Bajada-Pajarito fault complex which partially separates the Albuquerque Basin from the Santa Fe/Española basin to the north. Another example is the Franklin - Sierra Juarez uplift between the Hueco Bolson and the Mesilla Basin. All of the basins discharge groundwater, to some degree, to the next one downstream. In most instances the constrictions or structural obstacles cause an upward discharge of old and, frequently, reduced-quality water. Examples include La Cienega (valley-floor wetland) and lower Santa Fe River areas in the Santa Fe/Española Basin, the La Joya to San Acacia reach in the Albuquerque Basin, and the lower reaches of the Mesilla Valley above the El Paso narrows.

As previously mentioned, a major source of recharge to the basins is mountain-front and tributary recharge. Another major source of recharge is the Rio Grande, the string that connects the "pearls." A less significant source of recharge is from adjacent basins that do not contain segments of the Rio Grande Valley system. For example, a significant amount of underflow comes from the San Juan Mountains into the Alamosa subbasin of the San Luis Valley (Hearne and Dewey, 1988); and modest amounts of underflow occur from the Colorado Plateau to the Albuquerque Basin (Frenzel and Lyford 1982; Kernodle and Scott 1986), and from the Jornada del Muerto Basin to the Mesilla Basin (Frenzel and Kaehler 1992). It is important to note that other basins not covered in this discussion also have interconnections (Figure 1). For example, the San Agustin Basin contributes to the Socorro

Basin (Kernodle et al. 1987) and the Tularosa Basin contributes underflow to the Hueco Bolson (Bedinger et al. 1989; Hibbs et al. 1997).

Even before 20th-Century exploitation of major groundwater resources, every intra-basin source of water plus a portion of flow in the Rio Grande went to evaporation from open water or to transpiration. Each basin along the "string of pearls" with the possible exception of the Alamosa and Sunshine Valley subbasins of the San Luis Basin, caused a diminished flow in the river except during periodic local flood events. After groundwater development began, more water was lost from the surface-water system (a gain to groundwater) and less was lost to evapotranspiration. No efforts have yet been made to augment other sources of recharge to the basins' aquifers.

Models – Past, Present, and Future

The earliest model of a northern Rio Grande Basin was the one by Reeder and others (1967) of a portion of the Albuquerque Basin. It was based on some still valid concepts and others that are obsolete; but they made it work with a hand-cranked calculator. Over the following years, many government-financed and private models were completed of this and other basins in the rift. Each progressive step took advantage of technological improvements in computing power and collective improvements in the overall understanding of Rio Grande rift-basin flow systems.

The SWAB RASA (Southwest Alluvial Basins Regional Aquifer-Systems Analysis program–Wilkins 1986; 1998) addressed the geohydrology of 22 basin-fill aquifers in the Rio Grande rift and adjacent parts of the southeastern Basin and Range province in New Mexico, western Texas, and southern Colorado. As part of that study, four models were commissioned to explore the practical and economic feasibility of different approaches to modeling rift basins.

A model of the Alamosa subbasin of the "Valley" tested a superposition approach (Hearne and Dewey 1988) as well as a two-dimensional vertical cross-section model to determine the necessary depth of simulation of the subsequent areal three-dimensional model. A model of the "Albuquerque-Belen Basins" (Kernodle and Scott 1986; Kernodle et al. 1987) tested the feasibility of using a deep (200 feet) constant hear boundary throughout the 2- to 5-mile wide flood plain to represent the Rio Grande. A third model was contracted to the New Mexico Bureau of Mines and Mineral Resources (O'Brien and Stone 1983) to use flow-net analysis to guide transmissivity estimates for a two-dimensional model. The fourth SWAB model to be formally documented was of the Mesilla Basin (Frenzel and Kaehler 1992). That model aspired to include every hydrologic detail of even the remotest importance.

An early objective of the SWAB RASA was to construct a groundwater-flow model of the entire rift system. As the study progressed, it became very clear that the "string of pearls" could not be simulated from a groundwater perspective. Hence, a different approach was taken: to evaluate all existing public-domain (e.g., USGS or government contract) models in an attempt to analyze the assets, flaws, common attributes, and various calibration approaches (Kernodle 1992). Altogether, 14 models were evaluated, with selected information on five of them included in Table 4. The critique resulted in a set of nine guidelines that were tested in new models for a basin with an already existing model (Albuquerque) and for joined basins (San Agustin-Socorro), which had not previously been modeled. A third model of the Palomas-Engle Basin was left incomplete. Each model was allocated approximately three weeks for completion. The experimental model of the Albuquerque Basin was, statistically, an improvement over its predecessor even though the first took years to complete and the other, only weeks. Still, both are seriously outdated in their portrayal of the current understanding of the hydrogeologic framework of the basin.

The nine guidelines (Kernodle 1992) are listed below, but, be aware that technological improvements and recent data acquisition have expanded the envelope on some of them (cf. Tables 2-4):

1. Perform a literature search to determine basin geometry, geologic structure, and lithology.
2. Use a three-dimensional model to simulate the aquifer to a depth of approximately 4,000 feet or to the total depth of the basin fill if less than 4,000 feet. Use at least five model layers, the top layer being 200 feet or less in thickness.
3. Simulate the basin-fill aquifer system as having a horizontal hydraulic conductivity of 20 to 45 feet per day in the open-drainage

basins and 2 to 10 feet per day in the closed drainage basins, except where field data indicate otherwise. Simulate fine-grained playa or lake deposits as having a hydraulic conductivity of 0.25 to 10 feet per day and flood-plain alluvial deposits as having a hydraulic conductivity of 50 to 70 feet per day.

4. Do not vary horizontal hydraulic conductivity as a function of depth unless specific lithologies are being simulated. Compaction of the aquifer and increases in temperature with depth need not be simulated as affecting the apparent hydraulic conductivity (or flow paths), except where these specific problems are being addressed. The two factors have opposite, and potentially offsetting, effects.
5. Use a horizontal to vertical hydraulic-conductivity ratio of from 200:1 to 1,000:1 except where geologic features such as faults, clay sequences, or steeply dipping beds exist.
6. Simulate aquifer specific storage to be in the range of 2 x 10^{-6} to 5 X 10^{-6} per foot, and specific yield in the range of 0.10 to 0.20.
7. Include rivers and drains, if present, in the simulations as head-dependent-flux boundaries, preferably with flow routing to allow the location of the boundary to change with time.
8. Include estimated mountain-front and tributary recharge, evapotranspiration, and net irrigation flux.
9. Include historical groundwater withdrawals.

To this list we might add that short- and long-term climatic changes can have significant impacts on all water resources (Hawley 1993; Hawley et al. 2000). The region has experienced a prolonged drought from the early 1950s until the late 1970s. The following two decades were very abnormally wet. During those two decades the population and dependence on groundwater has grown enormously. The laissez faire attitude of the 1950s must, and will, be replaced by a pro-active approach to overall water resources management.

We have learned a lot about the geology and hydrology of the Rio Grande Rift during the last decade. But, we cannot take too much pride in our recent accomplishments or our modeling prowess. We are busy building the knowledge base, but the solid foundation was laid many years ago by true pioneers in science.

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