APPENDIX A
BASIC HYDROGEOLOGIC AND GEOHYDROLOGIC COMPONENTS OF THE MESILLA BASIN AQUIFER SYSTEM

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1.0 INTRODUCTION

This report-supplement provides an expanded explanation of the many salient features that could not be covered adequately in the text discussion of hydrogeologic controls on groundwater flow and salinity in Mesilla Basin aquifer systems. Emphasis here is on 1) a background synopsis of major investigations completed prior to 1981, 2) a description of research methods, 3) basic hydrogeologic-framework components that are illustrated in Plates 1 to 9, and 4) related aspects of the groundwater-flow regime. Appendix A--Tables 1 & 2 contains much of the essential base-line information that was used in developing this model, including location code, depth, static-water level, selected chemical analyses of sampled water, hydrostratigraphic correlations, and data sources.

Recent advances in GIS—ARCINFO® methodology and an expanded geological-geophysical-geochemical database, however, now indicate that upgrading and expansion of existing hydrogeologic-framework models are merited. Updating and integration of the provisional (1984-1992) hydrogeologic sections with the new hydrogeologic base map (Plate 1) is definitely needed, if only to provide a consistent framework model of the (hydrologically) interconnected Mesilla—southern Jornada del Muerto basin system. Therefore, while the detail here provides supporting documentation for the interpretations of the geologic and geochemical-geothermal components of the groundwater-flow systems presented in Sections 2 and 3, it also represents the first stage in preparation of a more comprehensive NMWRRI research report on the hydrogeologic framework of aquifer systems in the basin and valley area extending from the Rincon Valley to the El Paso Narrows.

1.1 PREVIOUS WORK (1896-1981)

1.1.1 Early Work

Primary historical sources of background material on the hydrogeologic framework of the southern Basin and Range province (including the Rio Grande rift region) are the pioneering investigations by Hill (1896, 1900), Lee (1907), Meinzer and Hare (1915), Darton (1916), Tolman (1909, 1937) and Bryan (1938). Major early sources of information on the geology and geohydrology of the Mesilla Basin area include reports by Slichter (1905), Richardson (1915), Dunham (1935), and Sayre and Livingston (1945). Slichter's investigation of the Mesilla Valley shallow-aquifer zone, included a definitive study of underflow conditions through El Paso Narrows (Sections 2.7-2.9). Lee (1907) developed the earliest model of ancestral Rio Grande evolution in the New Mexico region; and he emphasized the potential for locating a dam at the Elephant Butte site for irrigation-water storage and flood control.

One of the principal resource documents on the northern Rio Grande basin (Figure 1-1) is the Rio Grande Joint Investigation Report of 1938. This "Regional Planning" document covers the entire upper-river basin from it southern Colorado headwaters area to the Fort Quitman at the southeastern end of Hueco Bolson in Trans-Pecos Texas. Report sections by Kirk Bryan and C.V. Theis, respectively, on the "Geology and groundwater conditions of the Rio Grande depression in Colorado and New Mexico" and "Groundwater in the middle Rio Grande valley" are particularly relevant to the present study (Bryan, 1938; Theis, 1938). Bryan was the first person to recognize that the river-linked series of deep structural basins (his Rio Grande depression), which extend from southern Colorado to Trans-Pecos Texas, are a unified geologic and geohydrologic system. This regional tectonic feature is now designated the Rio Grande rift (Chapin and Seager 1975, Hawley 1978, Keller and Cather 1994). One of Bryan's (1938) lasting contributions to the hydrogeology of the Rio Grande basin was his observation that: " 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)."

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 (*semibolsons*). The Bryan-Tolman conceptual model from a regional hydrogeologic perspective, which incorporates subsequent work in the Basin and Range—Great Basin section (e.g. Mifflin 1988), and in the Trans-Pecos Texas–Chihuahua bolson region (Hibbs et al. 1998), is further discussed in Section 2.4 (Basic Hydrogeologic Concepts).

1.1.2 Studies Between 1945 and 1981

The major advances in science and technology during and immediately after World War II introduced the present era of hydrogeologic-system characterization. Of special note are the developments of modern geophysical-survey, deep-drilling and geochemical-sampling methods that included innovations in borehole geophysics, sample recovery, aqueous geochemistry, and aquifer testing. The resultant breakthroughs in hydrologic, geologic, geophysical, geochemical and soil-geomorphic investigations involved the work of many federal, state, and local institutions, including the USBR, USGS-WRD, USDA-SCS, Texas Water Commission, EPWU, NMOSE, NMBMMR, and NMSU. By 1980 much of the basic hydrogeologic information, that is the foundation for today's aquifer-system models was already available (e.g. Conover 1954, Knowles and Kennedy 1956; Kottlowski 1958, 1960; Leggat et al. 1962; Gile et al. 1966, 1981; Metcalf 1967,1969; Cliett 1969; Hawley 1969; Morrison 1969; Reeves 1969; Hawley and Kottlowski 1969; Hawley et al. 1969; King et al. 1971; Seager et al. 1971, 1975; Harbour 1972; Hawley 1975, 1978; King and Hawley 1975; Lovejoy 1976; Zohdy et al. 1976; Uphoff 1978; Seager and Morgan 1979; Birch 1980; Wilson et al. 1981).

1.2 METHODS

Much of the comprehensive database compiled for this investigation had already been collected for the earlier geohydrologic and hydrogeologic research projects at New Mexico Tech (Hawley 1984, Peterson et al. 1984, and Hawley and Lozinsky 1992). The major published sources of information used in those studies included Leggat and others (1962), King and others (1971), Wilson and others (1981), Wilson and White (1984), and Myers and Orr (1986). In addition, a large amount of unpublished data (primarily drilling, and borehole-sample and geophysical logs) was obtained from files of the USGS-WRD and the NMBMMR.

Hydrogeologic investigations between 1986 and 1992 were a collaborative effort involving the NMBMMR (Hawley and Lozinsky), USGS-WRD (Ken Stevens), NMOSE (Francis West) and EPWU (Tom Cleitt). Emphasis was on compilation and interpretation of subsurface geologic, geophysical and geochemical data. Key sources of borehole data were identified and located on available geologic maps of the Mesilla Basin (scales 1:24,000 and 1:100,000) for use as control points. These sources included borehole geophysical and sample logs, geothermal data, and geochemical analyses. Six new test wells drilled by the USGS-WRD and EPWU provided supplemental information. The Afton, Lanark, La Union, and Noria test wells (MT 1 to 4) were drilled in the basin area west of Mesilla Valley (La Mesa surface). The other two wells (CWF1D and CWF4D) are located in the Canutillo Well Field area on the Rio Grande floodplain west of Vinton, Texas (Nickerson, 1987, 1989; Nickerson and Myers, 1993). Subsurface data were supplemented by detailed seismic reflection profiles made at two sites near the Canutillo Well Field (C.B. Reynolds and Associates, 1986, 1987).

The review of available geochemical, geophysical and geologic-petrologic data and interpretations included making provisional hydrostratigraphic correlations between the six new test borings and 54 other key wells in the basin (Hawley and Lozinsky, 1992, Plates 2-17, Appendix). This large database included water analyses from one or more sampling intervals in most of the key wells (Hawley and Lozinsky 1992, Table 4; Appendix A--Tables 1 and 2).

1.2.1 Drill-Cutting and Thin-Section Analyses

Drill-cuttings from the Afton, Lanark, La Union, and Noria test wells (MT 1 to 4) were initially analyzed with a binocular microscope in order to construct a geologic log for each well and to determine sample intervals for thin section work. No preliminary cutting analysis was performed on samples from the Canutillo wells (CWF1D and CWF4D) because these wells were drilled very late in the study. Color, grain size, and other major characteristics of the sediments were noted on the geologic logs. Cuttings were analyzed in approximate 10 ft (3 m) internals. Geophysical and driller logs aided in the initial examination of the cuttings.

Based on the cutting analysis, samples for thin section study were collected at approximately 100 ft (30 m) intervals from representative sand beds in the Afton, Lanark, La Union, and Noria wells. Samples were also collected from sandy intervals within the CWF1D and CWF4D wells, and from Santa Fe Group outcrops in the area (Nickerson and Myers, 1993). Locations of sampled wells and outcrops are shown on Plate 1. Forty-six thin sections were analyzed using criteria described by Dickinson (1970) in order to determine detrital modes and provenance. Thin-section petrographic data and interpretations are presented in Hawley and Lozinsky (1992,Section III and Appendix A) and they are summarized in Section 2.6.3. Four hundred framework grains per thin section were point counted using a petrographic microscope. Ternary diagrams were constructed based on the point counts and data were also plotted on the geologic-petrographic logs of the Afton, Lanark, La Union, and Noria Test Wells (Hawley and Lozinsky, 1992, Plates 12-15).

1.2.2 Digitizing Geophysical Logs, and Geologic Maps and Sections

Concurrently with the cutting and petrographic analysis, borehole geophysical data from selected key wells were digitized and then plotted onto computer-generated worksheets with a basin cross-section format. The borehole data were plotted to an altitude datum of 4,500 ft (1372 m) above MSL (vertical scale 1 in = 100 ft, 1 cm = 12.2 m). Digitizing of geophysical logs and plotting of cross-section worksheets was done at the USGS-WRD District Office in Albuquerque. Ken Stevens, formerly with that office, developed the computer-generated graphics system utilized in the Hawley and Lozinsky (1992) study for integrating geophysical, geophysical, geologic, and hydrologic data (Plates 2 to 7). During the past 3 years, the entire Mesilla area database, including all available geologic maps and cross-sections, has been upgraded and redigitized where necessary. The vertical scale now used in log plotting is 1 in = 200 ft, 1cm = 12.4 m.

1.2.3 Hydrogeologic Framework and GIS Syntheses

One of the major objectives of the current study has been the creation of a GIS-based physical model of the Mesilla Basin hydrogeology using ARCINFO®. Plate 1 is a map view of the Mesilla Basin hydrostratigraphic framework, which shows the surface-distribution patterns of major bedrock and basin-fill mapping units. It has been compiled during the present (1999-2001) study phase, primarily from baseline geologic and soil-geomorphic mapping (Gile et al., 1981; Seager et al., 1987; Seager, 1995).

Hawley and Lozinsky (1992, Plates 2-11, Table 4) prepared ten preliminary hydrogeologic cross-sections in their original synthesis of a Mesilla Basin model. Six of these sections have been updated and redigitized for incorporation in the present report (Plates 2 to 7); they include selected borehole geophysical and geochemical data, and hydrogeologic (lithofacies, hydrostratigraphic and structural) interpretations. Plates 1, 8 and 9 (with supporting explanations and data in Appendix A - Tables 1 and 2) integrate all available surficial and subsurface information into a 3-D conceptual model of the basin's hydrogeologic framework. The model's base elevation is 1,000 ft (305 m) above mean sea level (asl). Note that our current interpretation of subsurface hydrogeology (Plates 8 and 9) is essentially the same as that of Hawley and Lozinsky (1992).

1.3 HYDRGEOLOGIC FRAMEWORK OF THE MESILLA BASIN

1.3.1 Structural and Bedrock Components

In terms of overall basin and range architecture, the major hydrogeologic-framework components include the bedrock units and tectonic features that form important boundary zones with respect to the basin-fill aquifer system and related aspects of groundwater flow and chemistry. Distribution patterns of major hydrogeologic-framework components are shown on Plate 1. Primary information sources for hydrogeologic-map compilation (scale 1:100,000) are maps and reports by Gile and others (1981,1995), Seager and others (1987), Seager (1995), Woodward and Myers (1997), and Collins and Raney (2000). Heavy vertical to near vertical lines on the hydrogeologic cross sections (Plates 2 to 9) show locations of major fault zones and several volcanic-feeder conduits. Because of the 10X vertical exaggeration on these cross sections, even moderate dips of strata, faults and folds are distorted towards the vertical (e.g., compare Figures 2-8a,b with sections on Plate 3). Structural interpretations are based on a large number of cited geological, geophysical and geothermal-resource investigations, some of which are unpublished (Zohdy, 1969; Zohdy et al., 1976; Ackerman, 1982; Cunniff, 1986; DeAngelo and Keller, 1988; Gross and Icerman, 1983; Reynolds & Assoc., 1986, 1987; Ross and Witcher, 1998; Snyder, 1986; Wen, 1983; Witcher, 1988; Wade and Reiter, 1994; Woodward and Myers, 1997; Keller et al., 1998; Reiter, 2001).

Igneous and sedimentary bedrock units of Oligocene and older age, crop out along the basin margins, and underlie the basin surface at depths ranging up to 3,500 to 4,000 ft. In addition, igneous-intrusive bodies and associated extrusive (volcanic) units within the basin-fill sequence are also significant parts of the hydrogeologic framework in some areas. One of the significant contributions of the present study is that there is now much better definition of the contacts between bedrock boundary units and the basin fill. Compare Plates 8 and 9 with earlier cross-section interpretations (e.g. Wilson et al. 1981, and Hawley, 1984).

Locations of the major basin-boundary faults are shown on Plate 1, and Figures 2-7 and 2-8. The Robledo and East Potrillo faults (*RoF* and *PoF*), respectively, form the northwestern and southwestern boundaries of the "deeper" basin used in recent groundwater-flow models (Peterson et al. 1984; and Frenzel and Kaehler, 1992). Parts of the broad Mesilla Valley fault zone (*MVFz*) are at the western edge of the Tortugas-Doña Ana Mountain structural high. This fault zone marks a much-more poorly defined area of transition between the Mesilla and Jornada del Muerto Basins (Woodward and Myers, 1997); and it has not been used as a numerical-model boundary.

We need to emphasize at this point, however, that there is still much to be learned about the basin's internal structure. Based on recent experience in other parts of the Rio Grande rift, notably the Albuquerque Basin, additional drilling and geophysical studies (including aeromagnetic, gravity and seismic-reflection surveys) should lead to much more precision in the identification of structural-boundary conditions throughout the Mesilla Basin (Keller and Cather, 1994; Hawley et al., 1995; Allen et al., 1998; Connell et al., 1998, Grauch, 1999; Grauch et al., 1999; 2000; Plummer et al., 2000; Sanford et al., 2000; Kucks et al. 2001).

Local bedrock types (Precambrian to middle Tertiary), particularly granitic intrusive rocks, are generally considered to be low-permeability boundary zones that make suitable boundary units in ground-water-flow models (Frenzel and Kaehler, 1990; Kernodle, 1992). However, Paleozoic and Cretaceous carbonate rocks such as those exposed in most of the basin-boundary uplifts (Plate 1) may locally provide conduits for significant amounts of inter-basin groundwater flow. A temperature log in carbonate rocks at the south end of the East Potrillo uplift (Plate 4, borehole 29.1W.6.410; Snyder, 1986) has a distinct isothermic profile segment that indicates significant groundwater circulation at that locality. Similar geothermal and groundwater-flow conditions occur along much of eastern border zone of the Mesilla Valley (Sections 2.8, 2.9, and 3; Gross and Icerman, 1983; Gross, 1988; Ross and Witcher, 1998).

The structural segmentation of the basin into three major subbasins (Northwestern, Southwestern, and Eastern) and a north-south trending, "Mid-Basin uplift" is well illustrated on Figures 2-7 to 2-9, and Plates 1, 8 and 9. A maximum basin-fill thickness exceeding 2,000 ft (610 m) is inferred from borehole data in a large part of the Eastern (La Union-Mesquite) subbasin, but only locally in the Northwestern and Southwestern subbasin, (Plates 1 to 4, 8b-e, 9).

The Eastern (La Union-Mesquite) subbasin (EMSB) is flanked by two of the largest intrabasin fault zones identified in this study (Figures. 2-8, 2-9; Plates 1, 9). The Mesilla fault zone (*MVFz*) to the east is entirely buried by fill of Late Quaternary age, but it is here interpreted as the major boundary feature of the Mesilla "structural basin." In the Las Cruces metropolitan are, the *MVFz* marks the western edge of the bedrock high that 1) includes the partly buried Tortugas-Doña Ana Mountain uplift, and 2) the area of topographic and structural transition between the Mesilla and

Jornada (del Muerto) Basins (Woodward and Myers, 1997). Hawley and Lozinsky (1992) informally named the less well-defined fault zone at the western edge of the Eastern subbasin, the “Mid-basin fault zone” (*MBFz*). It is locally expressed by alignment of volcanic centers and some low scarps on the “West Mesa” surface (Plate 1); but it is most prominently displayed in the subsurface as offsets of distinct stratigraphic-marker units on borehole electric logs (e.g. Plate 4, La Union to Lanark, well sites 27.2.13.331 to 27.1.4.121).

Basin fill thins westward across the *MBFz*; and it is only about 1,500 ft thick above the central part of the Mid-Basin uplift (MdBU) near the Lanark test-well site (Plates1 to 5, 8 b-c, 9 b-c). The best-documented surface expression of the uplift’s western boundary is the (down-to-west) Fitzgerald fault zone (Plates 1, 3, 8c). Estimates of maximum basin-fill thickness in most parts of the Northwestern and Southwestern subbasins are based in the premise that deposits in those areas, even near the East Potrillo and Robledo (western Mesilla Basin-boundary) faults, will not be thicker than the documented fill thickness in parts of the Eastern subbasin that are adjacent to the relatively large, southern Organ and Franklin uplifts.

1.3.2 Basin-Fill Hydrostratigraphic Units and Lithofacies Assemblages

The Mesilla Basin aquifer system comprises three major hydrostratigraphic subdivisions (HSUs) of the Santa Fe Group. These units are ordered in upper to lower (younger to older) stratigraphic sequence (Figures. 2-6, 2-9). The *upper* Santa Fe HSU (USF1, 2) is generally correlative with the Camp Rice Formation, and its’ most productive aquifer zone (*LFA’s 1&2*, Table 3) consists of ancestral Rio Grande channel sand and gravel (HSU-USF2). Piedmont-slope and other basin-margin facies assemblages (*LFA’s 5&6*) in HSU-USF1 generally form aquifer units with moderate potential. However, the lower part of this unit is only saturated in the northeastern basin area near Las Cruces (Hawley and Lozinsky, 1992). The *middle* Santa Fe HSU (MSF1, 2) correlates with much of the Fort Hancock Formation in the Hueco Bolson, which is dominated by fine-grained, alluvial-flat and playa-lake sediments. In the Mesilla Basin, however, the dominant basin-floor facies assemblage (*LFA3*) includes extensive layers of clean fluvial and eolian (?) sand that are interbedded with silty clay. This MSF2 unit is less permeable than the USF2 fluvial facies (*LSF1&2*) due to a greater degree of cementation and the widespread presence of the fine-grained interbeds. HSU-MSF2, however, probably forms the major aquifer zone in the basin, because it is very thick (up to 2,000 ft) and almost entirely saturated. The" medium aquifer" zone of Leggat and others (1962) forms part of this HSU. They originally identified it in deep wells of the EPWU-Cañutillo well field (Figures. 2-8b, 2-9).

The *lower* Santa Fe HSU (LSF) is primarily fine grained and party consolidated throughout much of the basin (*LFA's 3, 9, 10*); and it only forms a significant part of the aquifer system in the lower Mesilla Valley area that extends from near Mesquite to Cañutillo and La Union. Leggat and others (1962) first identified this part of the LSF unit in deepest wells of the EPWU-Cañutillo well field; and they informally named it the "deep aquifer" zone (HSU-LSF 2, Figure 2-9). The major LSF component in the lower Mesilla Valley area is a distinctive eolian-sand facies (*LFA 4*) that intertongue mountainward with piedmont fanglomerates (*LFA's 7, 8)*, and basinward with basin-floor facies assemblages (*LFA's 3, 9*, *10*). The latter facies are here interpreted as fluvial-deltaic and playa-lake deposits (Figure 2-6, Table 2.1). The sand facies is locally as much as 600 ft thick, and its' base ranges from 1,000 to 1,500 feet below the Mesilla Valley floor. This extensive basin-floor to distal piedmont-slope deposit is now interpreted as a buried dune field, with an extent and thickness similar to that of Los Médanos de Samalayuca, a dune complex in north-central Chihuahua that is similar in scale and origin to the Great Sand Dunes of the San Luis Basin in Colorado (Cliett 1969, Hawley 1969, Reeves 1969, Wilson et al. 1981, Schmidt and Marston 1981, Hawley and Lozinsky 1992).

1.3.3 Valley-Fill Hydrostratigraphic Units and Lithofacies Assemblages

The Rio Grande alluvial aquifer (HSU-RA, *LFA's a and b)* underlies the Mesilla Valley floor between Leasburg dam and the El Paso narrows. This hydrostratigraphic unit comprises river-channel and overbank facies ranging in texture from sand and gravel to silt and clay. The base of these fluvial deposits is about 60 to 80 ft below the inner-valley floor, which is locally as much as five miles wide. In many places, the fluvial facies extends laterally for hundreds of feet beyond the valley floor. The basal-channel gravel and sand layer, which is as much as 30 to 40 feet thick, was deposited during the interval of maximum valley incision near the end of the Late Pleistocene ice age (about 15 to 30 thousand years ago; Sections 2.6.7, 2.7.3). The valley-fill HSU extends continuously from Elephant Butte and Caballo reservoirs, through the Rincon and Mesilla Valleys, to the Fort Quitman area of the lower Hueco Bolson.

1.4 LATE CENOZOIC EVOLUTION OF THE HYDROGEOLOGIC SYSTEM

Because the Mesilla Basin is part of an active tectonic zone (Rio Grande rift) that has been evolving for more than 25 million years, the distribution of hydrostratigraphic units and lithofacies assemblages (Plates 8 and 9) must be interpreted in terms of ongoing, but episodic crustal extension and basin subsidence. Regional and local extension and differential displacement, including rotation, of basin and range blocks clearly act as effective controls on basin sedimentation. On the other hand, obvious climate controls on geomorphic processes in the Quaternary stratigraphic record, which locally relate to Quaternary glacial-interglacial cycles (Section 2.8.2), demonstrate that forces other than rift tectonism will also materially influence depositional processes (Gile et al. 1981; Gile, Hawley et al. 1995). On the 25 Ma-time and space scale represented by Santa Fe Group deposits, however, structural deformation and associated igneous activity must be recognized as major controlling factors in terms of the basin-filling process. The *lower* Santa Fe hydrostratigraphic unit (early to middle Miocene) and associated lithofacies (primarily *LFA's 3, 4, 7, 9, 10*) were deposited in a broad, shallow basin that predated major uplift of the flanking mountain blocks (uplifts) bounded by the Mesilla Valley, East Potrillo and East Robledo fault zones (Plates 1, 8, 9). The deepest and most actively subsiding part of this basin appears to have been in the "Southwestern" area east of the East Potrillo uplift (Plates 4 and 8e).

Petrographic studies of drill cuttings, as well as interpretations based on other analyses of samples and driller's logs (Plates 2 to 7) indicate that depositional environments in the *lower* Santa Fe HSU (LSU) contrast markedly with those in younger basin fill (Sections 2.6.5, 2.6.6). During early stages of basin filling, the Mesilla Basin received a major influx of fine- to medium-grained sediments (silt-clay to sand) from adjacent upland source areas that were sites of late Eocene and Oligocene volcanic activity. Since high mountain areas (such as the present Organ-Franklin-Juarez chain) had not yet formed, wedges of coarse-gained piedmont deposits were limited to the extreme basin margins. The most striking lithofacies assemblage (*LSF 4*) in the *lower* Santa Fe HSU comprises thick deposits of clean, fine to medium sand, which are now well documented in the Eastern (La Union-Mesquite) and Southwestern subbasins, including the EPWU—Canutillo well field and several other parts of the Mesilla Valley (Cliett 1969; Wilson et al. 1981; Hawley 1984). These partly indurated beds are as much as 600 ft thick in the La Union-Mesquite subbasin. In the Southwestern subbasin, immediately east of the east Potrillo fault zone, correlative deposits may be 900-1,000 ft thick (Plates 2 to 4, 6, 7, 8b-e, 9a). In the latter area, however, borehole electric and temperature logs indicate that the *lower* Santa Fe section may be finer grained and/or saturated with slightly saline to saline groundwater (see Section 2.9).

Distribution patterns of both piedmont-slope and basin-floor *LFA's* (*1-3, 5-10*) in *middle* and *upper* Santa Fe HSUs (MSF and USF) have also been greatly influenced by differential subsidence of basin fault blocks between the Mesilla Valley fault zone on the east, and the East Robledo and mid-basin faults on the west (Plates 1, 8, 9). As has been previously noted (Sections 2.6.1 and 2.7.1) tectonic subsidence has been most active in areas adjacent to those fault zones particularly in the Eastern (La Union-Mesquite) subbasin.

The *middle* Santa Fe unit was deposited during late Miocene to early Pliocene time when maximum differential movement occurred between the central basin blocks and the Doña Ana-Tortugas, southern Organ, Franklin, Juarez, East Potrillo, Robledo and Mid-Basin uplifts. East of the Rio Grande Valley, both the *middle* and *upper* Santa Fe HSUs (MSF and USF) are dominated by coarse clastic material (fan-piedmont alluvium) derived from the rapidly rising southern Organ and Franklin uplifts (*LFA*'s *5-8*). The developing Robledo and East Potrillo Mountains contributed fan sediments to the Western subbasins during the same interval. *LFA 3* is the major component of the *middle* Santa Fe HSU (MSU2) in the broad central-basin area that extends west from the Mesilla Valley. It is as much as 1,000 ft (305 m) thick in the Eastern (La Union-Mesquite) subbasin (Plates 2, 3, 6, 7, 8b-d, 9a). This sequence of interbedded sand and silt-clay beds also forms the basin's thickest and most extensive aquifer system.

East of the Mesilla Valley fault zone, fan deposits (*LFA's 5* and *7*) prograded westward almost to present location of I-25 during much of the *middle* Santa Fe depositional interval. Similar but smaller alluvial aprons extended basinward from the Robledo and East Potrillo uplifts. Complex intertonguing of piedmont-slope and basin-floor sediments is observed in the *middle* Santa Fe unit beneath the Mesilla Valley (Plate 9a; MSF; *LFA's 2*, *3*, *5*, *7*, and *9*). Analyses of drillers and sample logs show a mixture of alluvial-fan and basin-floor facies derived from local sources. A precursor to the through-going (ancestral) Rio Grande system may have contributed a large volume of fluvial sand and mud to actively subsiding areas, at least in the northern part of the basin, during latest stages of *middle* Santa Fe deposition. Basin-floor aggradation ultimately outpaced basin subsidence and a nearly level, alluvial plain with scattered playa-lake depressions extended across most of the basin area.

The *upper* Santa Fe HSU was deposited during a 2-3 million year interval when large volumes of sediment were washed into the basin by distributaries of the ancestral Rio Grande system, which headed as far north as the San Juan and Sangre de Cristo Mountains of southern Colorado (Southern Rocky Mountain province). This fluvial system discharged at various times into playa-lake plains of the Tularosa Basin and Hueco Bolson (via Fillmore Pass, Figures. 1.1, 1.2), as well as to the Bolson de Los Muertos (Hawley, 1969; Strain, 1971; Hawley, 1975; Gile et al., 1981; Seager, 1981; Seager et al., 1987; Gustavson, 1991).

The final stage of widespread basin aggradation throughout the central and southern New Mexico region (*LFA's 1* and *2*) occurred during eruptions of the Jemez volcanic center that produced the Bandelier Tuff and the Valles caldera 1 to 1.6 million years ago (Goff et al. 1996). At that time braided channels of the ancestral Rio Grande shifted across a broad fluvial plain that included most of the present Mesilla Valley and West Mesa (La Mesa) area (Figure 2.1, Plate 1). Complex intertonguing of ancestral Rio Grande and piedmont-slope *LFAs* (*1-3, 5*) characterize the *upper* Santa Fe HSU (USF) east of the Mesilla Valley fault zone (Plates 8 and 9). At times progradation of alluvial fans from the Organ and Franklin uplifts was very active (*LFA 5*), and the piedmont alluvial apron expanded across the Mesilla Valley fault zone as far west as the present central Mesilla Valley.

The patterns of *upper* Santa Fe Group sedimentation are clearly influenced by both local and regional volcanic and tectonic processes, as well as by early Pleistocene and Pliocene climate cycles (Gile et al. 1981; Mack and Seager 1990, Leeder et al. 1996; Leeder, Mack et al. 1996; Mack et al. 1997). Structural deformation has produced more than 2,000 ft (610 m) of subsidence in the Eastern subbasin since middle Miocene time (past 10 million years). Hundreds of feet of basin subsidence have also occurred along the Mesilla Valley, East Potrillo and East Robledo faults in Plio-Pleistocene time (past 4-5 million years); and this tectonic process clearly influenced the final position of the ancestral Rio Grande and the distribution patterns of *LFA's 1-3* and *5* in the *upper* Santa Fe HSU-USF1, 2 (Figures. 2-7 to 2-9; Plates 8, 9). Differential movement along the major basin-bounding fault zones shown on Plate 1 continued in post-Santa Fe (Quaternary) time and has controlled the position of the inner Mesilla Valley and bordering river terraces from the Selden Canyon to Paso del Norte narrows (Figures 1.2, 2.6, 2.7). Older valley fill units are definitely offset by faults east of the Robledo Mountains (Gile et al., 1981); and the major centers of basaltic volcanism are located on many prominent fault trends, in both basin-boundary and intrabasin positions (Plates 1, 8, 9).

1.5 HYDRAULIC PROPERTIES OF HYDRSTRATIGRAPHIC AND LITHOFACIES UNITS

Irrigation-well specific-capacity data and a few aquifer-performance tests provide the basis for many of the published interpretations of hydraulic properties and sustained production potential of the Mesilla Basin aquifer systems (Wilson et al., 1981; Frenzel and Kaehler, 1992; Wilkins, 1998). Almost all of the large irrigation wells and centers of municipal pumping (Las Cruces and El Paso Metro-areas) are located in the inner Mesilla Valley. Well yields range from a few to more than 3,000 gpm, and average discharge rates of deep irrigation wells in the central part of the valley are about 2,300 gpm (Wilson and White, 1984).

Specific capacities of 10 to 217 gpm/ft are reported for wells completed mainly in the coarse-grained fluvial facies (*LFA's 1* and *2*) of the *upper* Santa Fe Group HSU-USF2 and overlying river-channel deposits of the inner Mesilla Valley (HSU-RA; *LFA's a1, a2*). The average specific capacity reported by Wilson and others (1981) is 69 gpm/ft, and the saturated-fill thickness ranges from 150 and 200 ft. Limited specific-capacity data from 68 wells located in the valley area, which are completed from 200 to 1,600 ft below the water table, show values ranging from 5 to 75 gpm/ft of drawdown, with an average of about 25 gpm/ft (Wilson et al., 1981, Table 2). Wells completed in the 200 to 600-ft depth zone produce primarily from the basal *upper* Santa Fe and *middle* Santa Fe HSUs (*LFA's 2 to 5*); and their specific capacities are usually less than 40 gpm/ft. Wells completed at depths below 600ft commonly penetrate fine-grained and partly indurated basin fill of the *middle* to *lower* Santa Fe HSUs (*LFA's 3-9*); and specific capacities of wells that produce primarily from these units are in the 1 to 10 gpm/ft range.

The well with the highest reported specific capacity (789 gpm/ft) is located at the east edge of the Aden-Afton volcanic field at the Jay Gardner Ranch (26.1W.25.414) and less than 3 miles east of the Afton basalt cones (Plates 1, 3, 8c; Figure 2-8b). A driller's report cited by Wilson and others (1981, p. 294-295) states that this 563-ft well can produce about 30 gpm from a 188-ft zone of saturation (375-ft WT depth) with essentially no drawdown. This particular well, with a measured water temperature of 33º C, is probably producing from a very permeable, intrusive-basalt unit or buried flow sequence, which according to the interpretation illustrated in Plates 3 and 8c, is near the USF2 / MSF2 contact.

Estimated aquifer transmissivities (T) of the upper 1,200 ft of saturated fill are as high as 50,000 ft^2/d at a few localities; but most values range from 10,000 to 40,000 ft^2/d in the central part of the basin (Santa Fe Group and Rio Grande Valley deposits); and the average T for the West Mesa area may be only about 10,000 ft^2/d (Wilson et al. 1981). Based on an aquifer test in the central West Mesa area, an estimated transmissivity of 5,900 ft²/d was calculated for a well screened at selected depth intervals between 710 to 1,210 feet. In the northern part of the West Mesa area, aquifer transmissivity was estimated to be 10,000 ft²/d, with a (confined) storage coefficient of $2x10^{-5}$.

Average horizontal hydraulic conductivities may be as high as 70 ft/d in the uppermost part of the groundwater-flow system; but aquifer tests also show that they decrease markedly with depth. Frenzel and Kaehler (1992, Figure 13) report a "lower to upper quartile" hydraulic-conductivity range of 9 to 43 ft/d in the upper 600 ft of saturated basin fill, with a median value of 22 ft/d. However, this depth zone is probably only representative of the *upper* to uppermost *middle* Santa Fe units (HSU's USF2/MSF2). Horizontal hydraulic conductivities of tested *middle* and *lower* Santa Fe HSUs (MSF2/LSF) in the 600 to 1,600 ft depth interval had a "lower to upper quartile" range of 2 to 14 ft/d, with a median value of 5 ft/d according to Frenzel and Kaehler (1992). Horizontal hydraulic conductivities in conglomeratic piedmont facies of the *lower* Santa Fe HSU (*LFA's 7,8*) rarely exceed 1ft/d; and fine-grained basin-floor units (*LFA's*) not only are much less permeable but also contain saline water.

Vertical hydraulic conductivity values were found to range from about 0.2 ft/d to 3.0 ft/d for the entire thickness of the confining layers at West Mesa aquifer-test sites (Frenzel and Kaehler, 1992). They also estimated that the ratio of horizontal to vertical hydraulic conductivity (anisotropy ratio) for the entire modeled stratigraphic sequence range was about 200; however, they indicate (p. 103) that this estimate is "not considered to be very accurate;" and Kernodle (1992a) suggests that a range in ratios of 200:1 to 1,000:1 may be more appropriate for basin-fill aquifer systems of the Rio Grande rift region (Hawley and Kernodle, 2000).

Estimated aquifer transmissivities of the shallow aquifer system (upper 150 ft of valley and basin fill) of the inner Mesilla Valley area locally exceed 30,000 ft^2/d; but most values range from 10,000 to 20,000 ft^2/d (Wilson et al. 1981, Plate 11). According to Frenzel and Kaehler (1992, Figure 13), a calculated "lower to upper quartile" range in horizontal hydraulic conductivity for the upper 200 ft of the shallow aquifer system is from 43 to 110 ft/d, with a median value of 70 ft/d. These deposits are composed primarily of *LFA's a1, a2, 1 to 3* and HSU'S RA, VA, USF2/MSF2 (Plates 6, 7, 9a).

Specific yield estimates vary from 0.1 to 0.2, assuming unconfined aquifer conditions. This assumption is inappropriate in many parts of the aquifer system, however, because of semiconfined (leaky-confined) to confined conditions. Therefore estimates of groundwater availability, as well as assessment of aquifer-deformation and land-subsidence potential, will require much smaller storage-coefficient values (Land and Armstrong 1985, Kernodle, 1992a, b; Heywood, 1995). Estimates of specific storage used in modeling groundwater flow in confined parts of the Santa Fe Group aquifer system range from $1x10^{-5}$ to $1x10^{-6}$/ft (Kernodle, 1992a, Frenzel and Kaehler, 1992). The storage-coefficient range noted by Wilson and others (1982) is $2x10^{-3}$ to $3x10^{-5}$ (Nickerson and Myers, 1993).

In summary, well specific-capacity data, and transmissivity and hydraulic-conductivity estimates from aquifer testing collectively indicate that the ranges in horizontal hydraulic conductivity (and groundwater-production potential) listed in Tables 2.1 and 2.2 are reasonable values for basin-wide modeling (see Section 1.4). This conclusion is based on the observation (supported by hydrogeologic syntheses in Plates 1 to 9) that the dominant valley-fill and Santa Fe Group lithofacies assemblages (*LFAs*) in the in the upper (0-600ft) and lower (600-1,800ft) intervals tested are *LFA's a, 1,2, &5* and *LFA's 3,4, &7*, respectively.

1.6 GROUNDWATER-FLOW MODELS

Science and technology of the present and recent past are dominated by the exponentially increasing power of computers, and rapid advances in numerical modeling and GIS technology. In the Mesilla Basin and other "Southwest Alluvial Basins," hydrogeologic "ground truth" must be expressed in ways that modelers of groundwater-flow systems can understand and computers can process. The rapid improvements in our understanding of subsurface geophysical and geochemical conditions, geochronology, and the definition of the hydrogeologic units, described herein, 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.

Detailed review of numerical models is beyond the scope of this document; but the reader is referred to the large number of recent reports that provide more information on this topic (e.g. Kernodle, 1992a; Hamilton and Maddock, 1993; West 1996; Balleau 1998; Hibbs 1999; Hibbs et al., 1997, 1998, 2000; Hibbs, Boghici et al. 1998; Sheng et al. 2001). In the Mesilla Basin area, there is an ongoing effort to refine existing basin-scale flow models (e.g. Peterson et al. 1984, Frenzel and Kaehler 1992, Nickerson and Myers 1993, Shomaker and Finch 1996); and modeling of the integrated surface-water and shallow groundwater systems of the EBID has had a high priority in recent years. Complex interrelationships between the chemistry of interconnected surface and shallow-subsurface flow regimes are also receiving increasing emphasis (e.g. Anderholm et al., 1995; Healy, 1986). The Frenzel and Kaehler (1992) report also includes an excellent synthesis of then available information on groundwater chemistry by Scott Anderholm (see Sections 2.9 and 3).

Hawley and Kernodle (2000) emphasize that all numerical flow models must meet the hydrogeologic constraints placed on flow regimes by lithofacies, stratigraphic, and structural-boundary conditions that are either well documented or reasonably inferred. The critique of "U.S. Geological Survey Ground-Water-Flow Models of Basin-Fill Aquifers in the Southwestern Alluvial basins region (Kernodle, 1992a)" relates directly to this concern. "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)." Kernodle (1992a) listed the following general guidelines for flow-model development in "Southwest Alluvial Basins:"

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 ft or to the total depth of the basin fill if less than 4,000 ft. Use at least five model layers, the top layer being 200 ft or less in thickness.
3. Simulate the basin-fill aquifer system as having a horizontal hydraulic conductivity of 20 to 45 ft/d in the open-drainage basins and 2 to 10 ft/d 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 ft/d, and floodplain alluvial deposits as having a hydraulic conductivity of 50 to 70 ft/d.
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.