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# SIMULATION OF GROUNDWATER FLOW IN THE SOUTHERN JORNADA DEL MUERTO BASIN, DOÑA ANA COUNTY, NEW MEXICO

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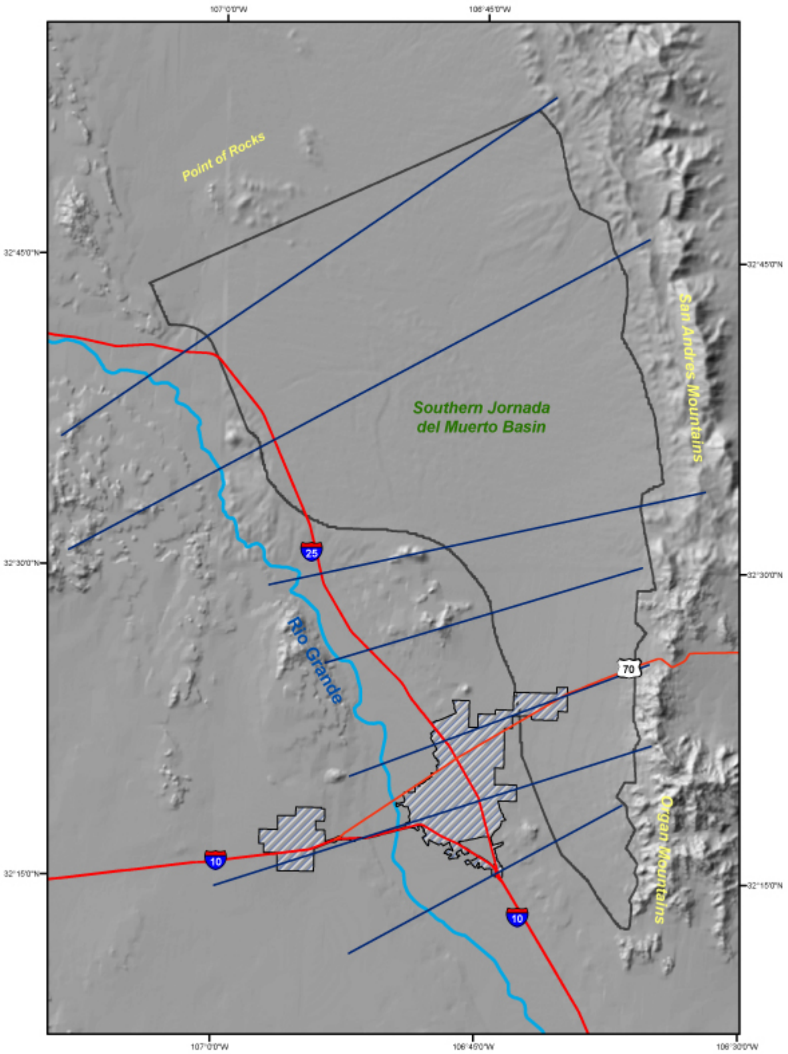

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By

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TECHNICAL COMPLETION REPORT

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# DISCLAIMER

Cover Map: study area

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# ABSTRACT

The Lower Rio Grande Water Users Organization (LRGWUO) is working to develop a unified groundwater flow model for the Lower Rio Grande Project deliverables. To meet their goal, a three-layer conceptual model of the southern Jornada del Muerto Basin is developed in the current work. The flow model is developed with grid properties and parameter distributions consistent with the groundwater flow model for administration and management in the Lower Rio Grande Basin (OSE-2007 flow model) prepared by S.S. Papadopulos and Associates (2007) for the Rincon-Mesilla Basins. Field data that includes layer elevations, aquifer properties, boundary stresses, and initial piezometric heads were delineated in ArcGIS. MODFLOW (2000) numerical code is used for solving the governing differential equations with Groundwater Vistas (Version 5) used as the graphical user interface for performing model simulation and calibration. The model has 180 rows, 105 columns, and three layers with a uniform grid resolution of 402.336 m (one quarter of a mile). The model is rotated 24˚ in counter clock direction to maintain consistency with the OSE-2007 flow model. The model is simulated under transient conditions from 1968 to 2007 with two seasons per irrigation year. Pumping from domestic and municipal wells, inter-basin flows through specified boundaries, and recharge from the mountain upfronts forms the major stress components of the study area. Recharge to the basin from the upland areas behind the model boundary was estimated based on the calibration statistics and basin specific characteristics. Aquifer properties of model layer 1 were identified as the most sensitive parameters. Water table elevations in the 72 analytical wells were considered during calibration. The simulation results were interpreted in terms of volumetric budget and water table elevation contours for selected stress periods. A significant decrease in the water table during simulation was observed in southern and southeastern parts of the basin. However, the water table in the northeastern and central parts of the basin is increasing with time. The kriged surface of water table elevations predicted that the groundwater gradient slopes predominantly east to west and is flattening at a decreasing rate during the simulation period.

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# 1. INTRODUCTION

## 1.1 STUDY AREA

The southern Jornada del Muerto (SJDM) Basin is situated primarily in Doña Ana County in southern New Mexico. Figure 1.1 delineates the study area, which is bounded by the San Andres Mountains to the east and the Organ Mountains to the southeast. A chain of mountains formed by the Tortugas uplift, the Goat Mountains, the San Diego Mountains, the Doña Ana Mountains, Rincon Hills, and the Caballo Mountains characterizes the western boundary of the study area. The study area was located between Townships (TS) 16 S to 24 S and Ranges (R) 02 W to 03 E. The northern boundary of the study area was limited to the Point of Rocks (POR) region, an uplift near the Doña Ana and Sierra County border due to the absence of hydrogeology to the north of POR. The aerial extent of the study area is 576 mi$^2$ (1,490 km$^2$) . The ground surface elevation ranged from 4,015 ft (1224 m) above sea level (a.s.l.) on the relatively level plains of the basin to 9,295 ft (2,833 m) a.s.l. on the high crest of the San Andres Mountains.

High temperatures characterize the climate of the region in the summer and mild temperatures in winter. Figures 1.2 and 1.3 show average monthly temperatures and average monthly precipitation from 1961-90. Most of the precipitation is monsoon driven, falling during July, August, and September. The average annual precipitation in this region is about 9.72 in (246.88 mm) (http://jornada-www.nmsu.edu/index.php, 7/13/08). Higher altitudes generally have cooler temperatures and receive additional rainfall. Recharge to the Jornada comes primarily from precipitation and infiltration of mountain runoff through major arroyos. The mean annual wind speed of the region is 6.04 mi/hr (2.7 m/s) and the prevailing wind direction is west to southwest (Hupy 2004).

Groundwater pumping was not significant in the SJDM Basin except in the southern areas near Las Cruces. Pumping of groundwater from municipal and multi-utility wells was done for the needs of Las Cruces; whereas small magnitudes of pumping were observed from a number of domestic and livestock wells distributed uniformly across the study area. As a part of the Chihuahua Desert, the Jornada Basin has a typical arid environment with the main vegetation being grass and shrubs. Irrigation was negligible in this area except in a few places where people were raising pasture to feed cattle.

The City of Las Cruces (CLC) and other municipal areas in the Lower Rio Grande (LRG) administrative region have been growing quite rapidly in recent years. The SJDM Basin is a potential groundwater source for the domestic needs of Las Cruces. The CLC municipal wells and other wells have been tapping groundwater from the southern Jornada Basin for city needs. The groundwater flow modeling of the southern Jornada Basin is required for a better understanding of the regional hydrogeology of the basin and to allow for the prediction of groundwater fluctuations under induced stress conditions. The groundwater flow model for the southern Jornada Basin is developed by orienting the model and considering the grid and boundary parameters consistent with the OSE–2007 flow model developed for the Mesilla and Rincon Basins by S.S. Papadopulos and Associates, Inc.

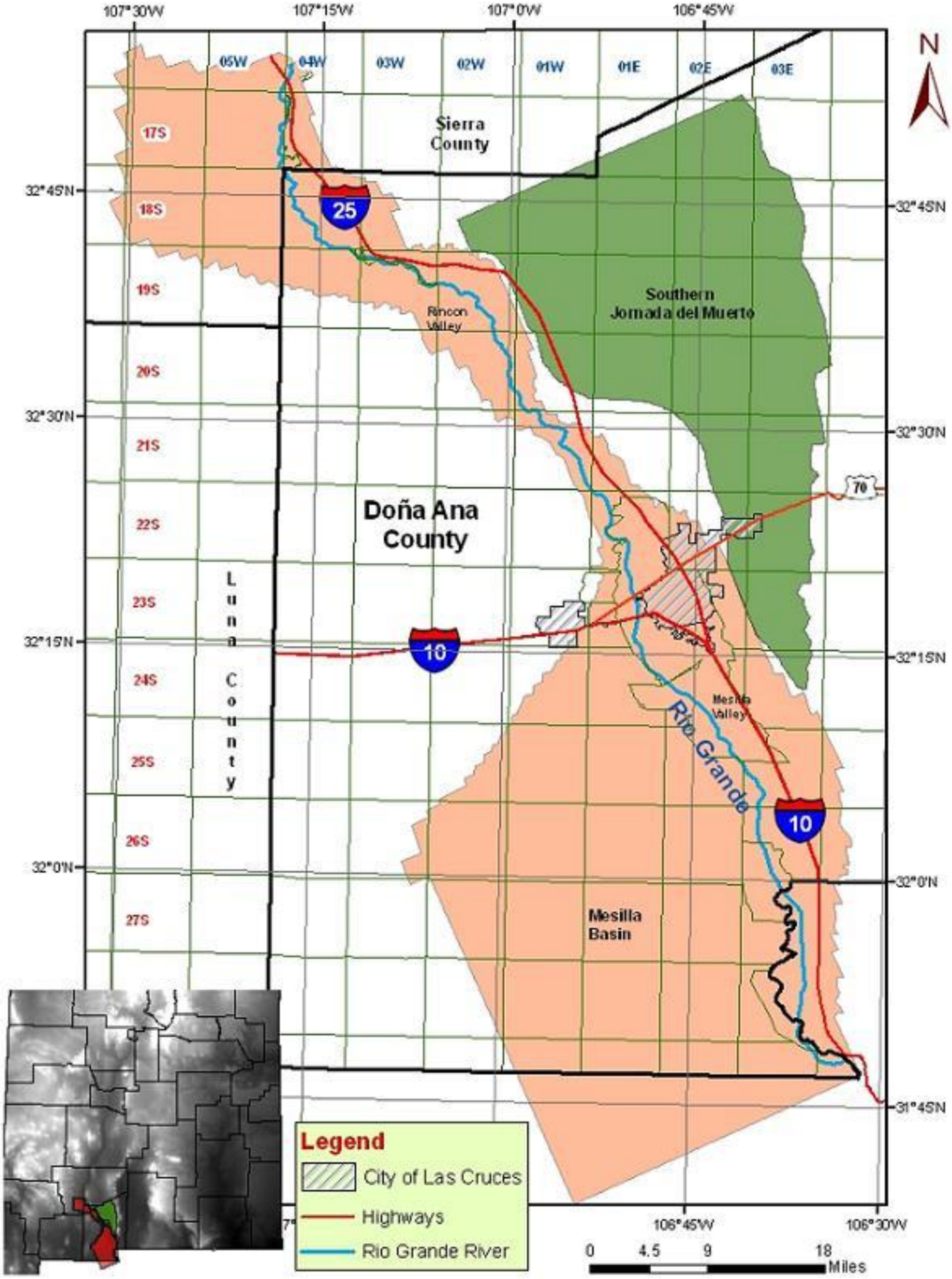


**Figure 1.1** Map of study area and the adjacent groundwater basins

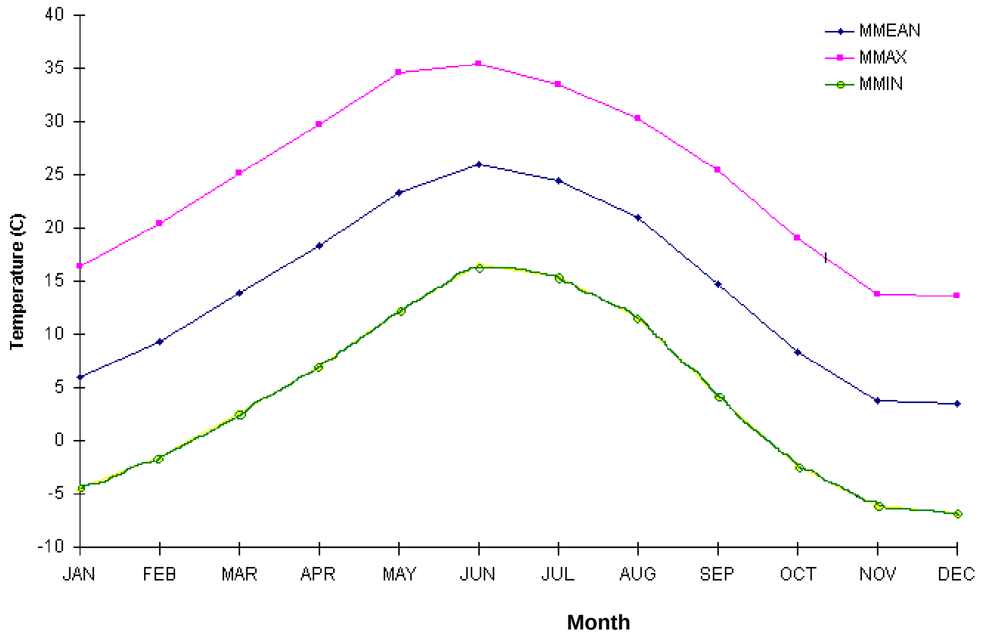


**Figure 1.2** Average monthly temperatures from 1961-90 (source: http://jornada-www.nmsu.edu/index.php)

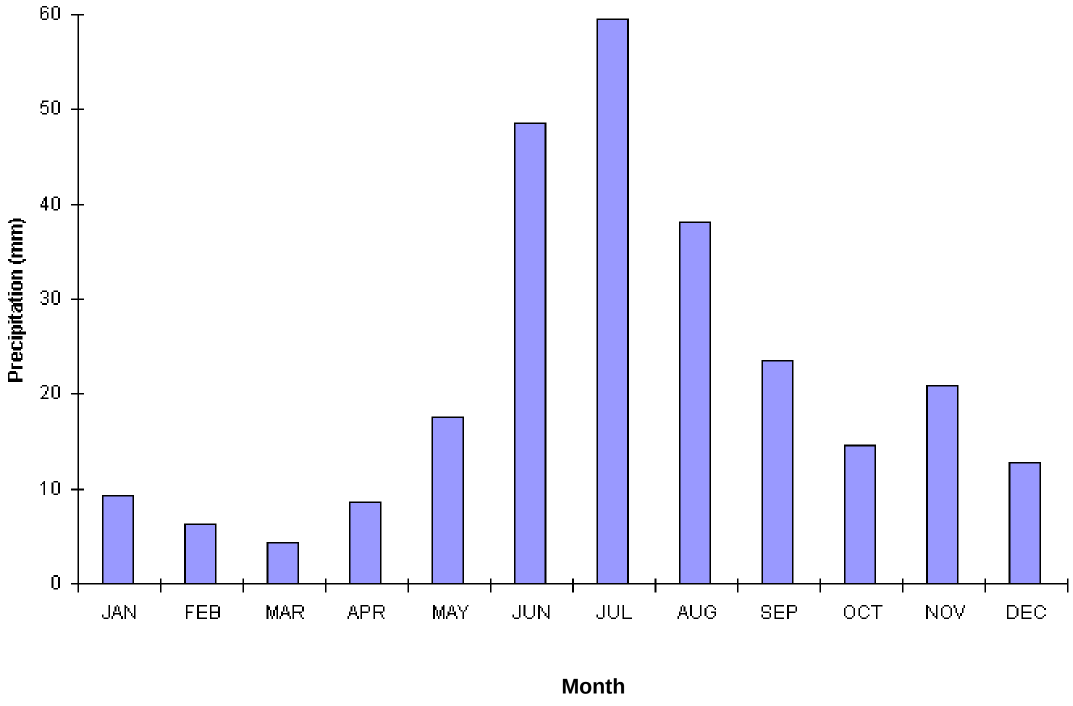


**Figure 1.3** Average monthly precipitation from 1961-90 (source: http://jornada-www.nmsu.edu/index.php)

## 1.2 WELL NUMBERING SYSTEM

The well numbering system in New Mexico is based on the Bureau of Land Management's township and range subdivision. The state of New Mexico is divided into four quadrants. The two quadrants running north to south are represented as townships divided by New Mexico's principle Meridian. The other two quadrants are divided by a baseline running east to west and are designated as ranges. A township of 36 square miles is subdivided into 36 one square mile sections. Sections are divided into quarter sections of four 160-acre tracts. These quarter sections are designated 1, 2, 3 and 4 for the northwest, northeast, southwest, and southeast corners, respectively. Each quarter section is divided into four 40-acre tracts, and then divided into four 10-acre tracts. Both the 40-acre and 10-acre tracts are designated as 1, 2, 3 and 4 for the northwest, northeast, southwest, and southeast corners. This well numbering system is depicted in Figure 1.4 for the well 23S.01E.24.341. A zero has assigned for a particular part of a location if the given well is not within the proximity of a particular section or tract (King et al., 1971).

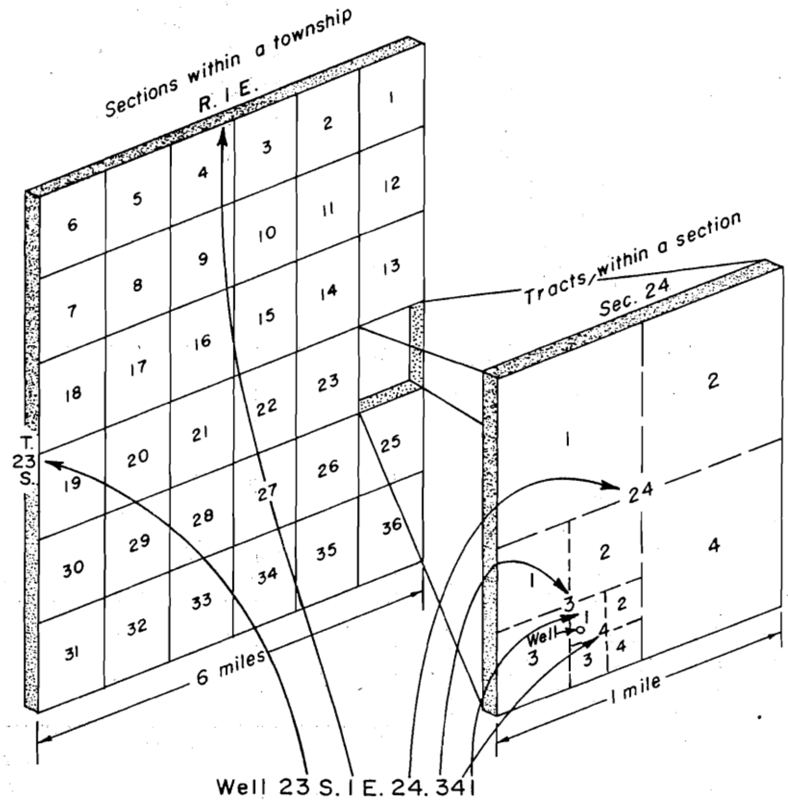


**Figure 1.4** Well numbering system in New Mexico (Wilson et al., 1981)

## 1.3 OBJECTIVES OF PRESENT STUDY

The objectives of the present work are as follows:

1) Analyze the hydrogeology of the SJDM Basin developed by Hawley and Kennedy, 2004

2) Incorporate the recently developed hydrogeology, pumping, and meteorological data into the model that was not included in the existing models

3) Modify and alter the model boundaries of the Jornada Basin (delineated in previous modeling studies) in order to be compatible with the adjacent groundwater basins

4) Effectively characterize the elevation profiles of hydrostratigraphic units and water levels by hand contouring the elevation data that take into account the presence of geological faults and divides

5) Develop the conceptual model of the SJDM Basin in ArcGIS, and estimate the continuous surface of aquifer and geological characters using geostatistical techniques

6) Create a numerical flow model of the SJDM Basin with recently available pumping data inconsistent with the OSE-2007 flow model for later integration of the two models

7) Compare the empirical estimates of mountain front recharge for the SJDM Basin and select the final method based on calibration statistics

8) Simulate the model from 1968 to 2007 on a seasonal basis for later integration with the OSE-2007 flow model

9) Estimate the flows entering and leaving the SJDM Basin in terms of various stress components for selected irrigation years

10) Analyze the spatial and temporal variation of the groundwater profile in the SJDM Basin to induced stresses

11) Evaluate the existing and future effects within the SJDM Basin on groundwater storage, gradient, and underflows to the adjacent basins

# 2. LITERATURE REVIEW

## 2.1 HYDROGEOLOGY

The SJDM structural basin is in the Rio Grande rift (RGr) tectonic province (Figure 2.1) and the southeastern Basin and Range physiographic province (Connell et al. 2005). The basin is a fault-bounded graben with a westward tilt, and was produced by continental rifting that began in the Oligocene Epoch as early as 30 million years (Ma) ago (Mack 2004). It is bordered on the east by the San Andres-Organ Mountain range; and the Doña Ana Mountains form much of basin’s western and southwestern boundary. Except for a discontinuous layer (less that 30 ft) of Quaternary alluvial, eolian, and playa-lake sediments, all Upper Cenozoic deposits in RGr basins are assigned to the Santa Fe Group lithostratigraphic unit (Mack 2004).

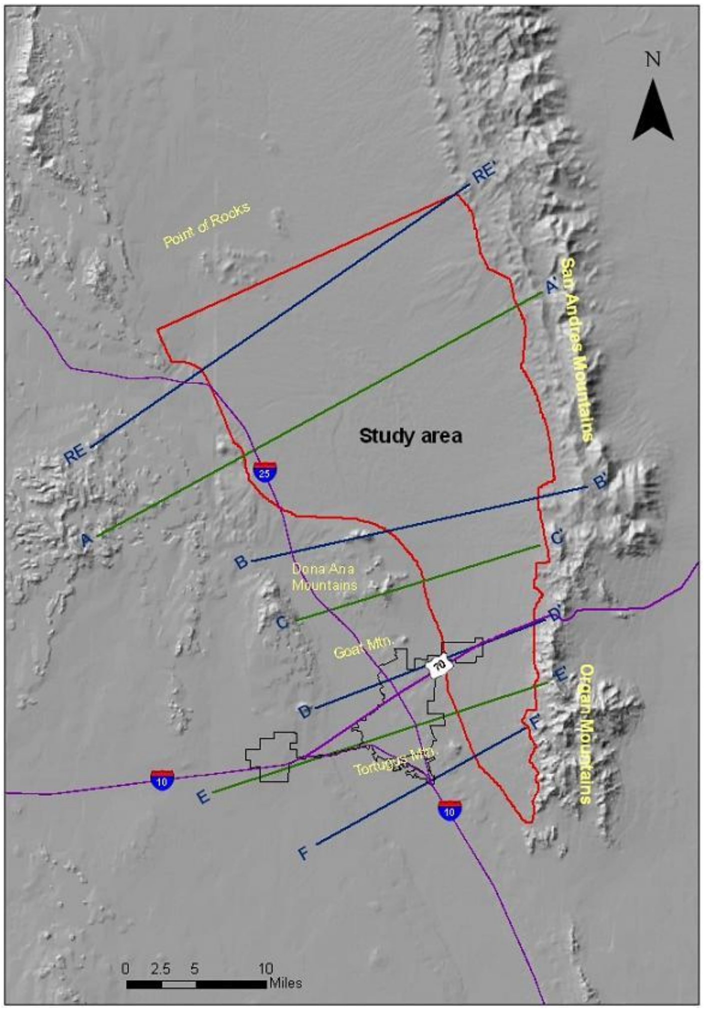


**Figure 2.1** Index map of the study area with hydro-geologic cross sections

The Doña Ana Mountains and a partly buried bedrock high that extends southward to Tortugas Mountain (east of Las Cruces) separate the SJDM and northern Mesilla Basins (Figures 2.1 to 2.7; King et al. 1971, Gile et al. 1981, Wilson et al. 1981, Seager et al. 1987, Woodward and Myers 1997, and Hawley and Kennedy 2004). A similar structural high also extends northwestward from the Doña Ana Mountains to the Rincon Hills (southwest of Point of Rocks, Figure 2.1) and is exposed in the Tonuco uplift (Figure 2.2). The Jornada fault zone, separates the Doña Ana uplift and partly buried structural-high extensions from the deepest parts of the SJDM Basin, and is the most prominent and continuous fault zone in the study area (Figures 2.2 to 2.5).

The structural high (horst) that separates the southern SJDM and northeastern Mesilla Basins south of the Doña Ana Mountains is shallowly buried by unsaturated Upper Santa Fe alluvium in most places. There are, however, several saddles in the buried bedrock ridge where basal parts of these deposits are saturated (e.g. Figure 2.7; Woodward and Myers 1997). Moreover, the general elevation of the structural high is close to the altitude of the water table at the southern end of the Jornada Basin, where predevelopment-heads were significantly higher than those in the adjacent part of the Mesilla Valley (King et al. 1971, Wilson et al. 1981). Therefore, small quantities of inter-basin groundwater flow could have occurred, the amounts depending on buried-channel dimensions, and basin-fill hydraulic conductivity and gradient (Hawley and Kennedy 2004).

As previously noted, the Santa Fe Group (SFG) comprises almost all the alluvial-basin fill of the SJDM, and includes some basaltic-andesite volcanic rocks in its basal part (Seager et al. 1987, Hawley and Kennedy 2004). SFG basin fill in the study area has approximately the same thickness range as correlative deposits in the central Mesilla Basin (maximum saturated thickness of 3,000 to 3,500 ft), but it is much finer grained. Basin-fill thickness and width decrease from the north to south in the southernmost Jornada Basin (Seager et al.1987). Geologic mapping and geophysical exploration indicate that the SFG is at least 3,500 ft thick east of the Tonuco uplift (Figure 2.2, Seager et al. 1971), and as much as 2,500 ft thick between the Doña Ana Mountains and at the NASA site area adjacent to the San Andres Mountains (Figures 2.3 and 2.4, Maciejewski and Miller 1998). Based on water-level measurements reported by King et al. (1971) and Wilson et al. (1981), predevelopment groundwater movement in SJDM was primarily northwestward toward the Rincon Valley along the deepest part of the structural basin adjacent of the Jornada fault zone; and a secondary outflow component discharged to the northeastern Mesilla Valley area through gaps in the bedrock high between the Doña Ana and Tortugas uplifts (Figures 1.1 and 2.1).

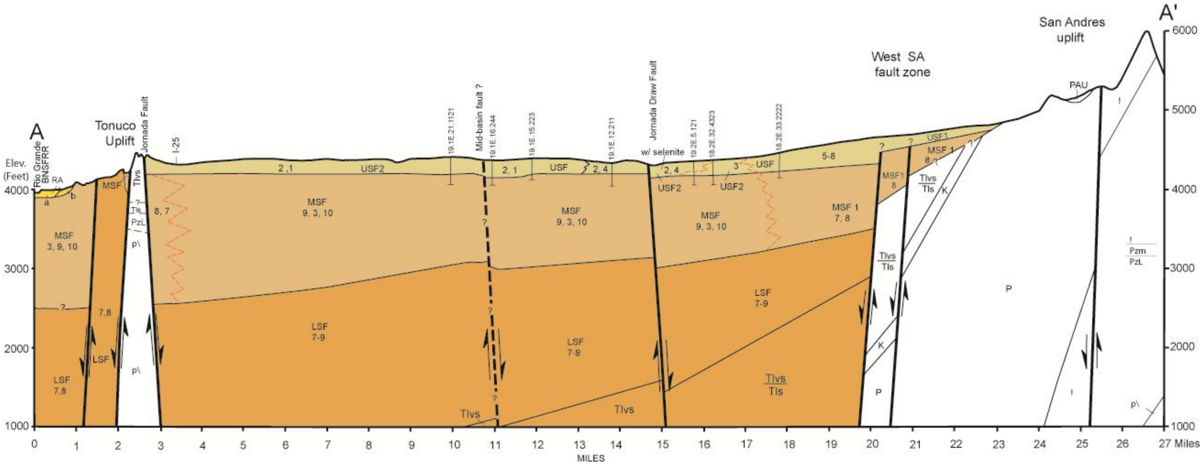


**Figure 2.2** Schematic hydrogeologic cross section A-A' (Hawley and Kennedy 2004)

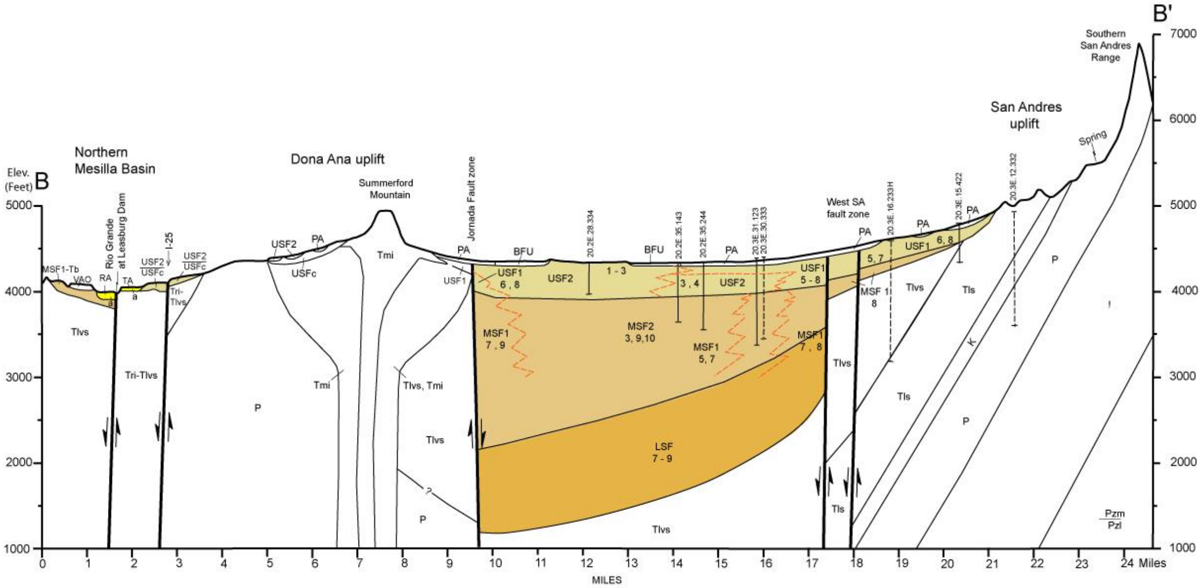


**Figure 2.3** Schematic hydrogeologic cross section B-B' (Hawley and Kennedy 2004)

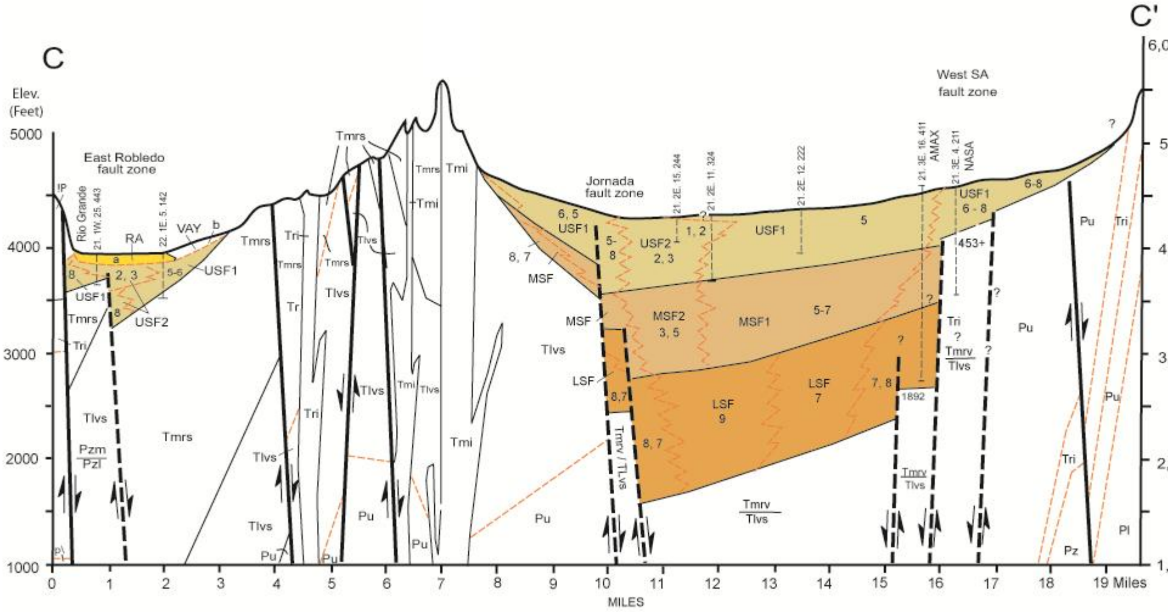


**Figure 2.4** Schematic hydrogeologic cross section C-C’ (Hawley and Kennedy 2004)

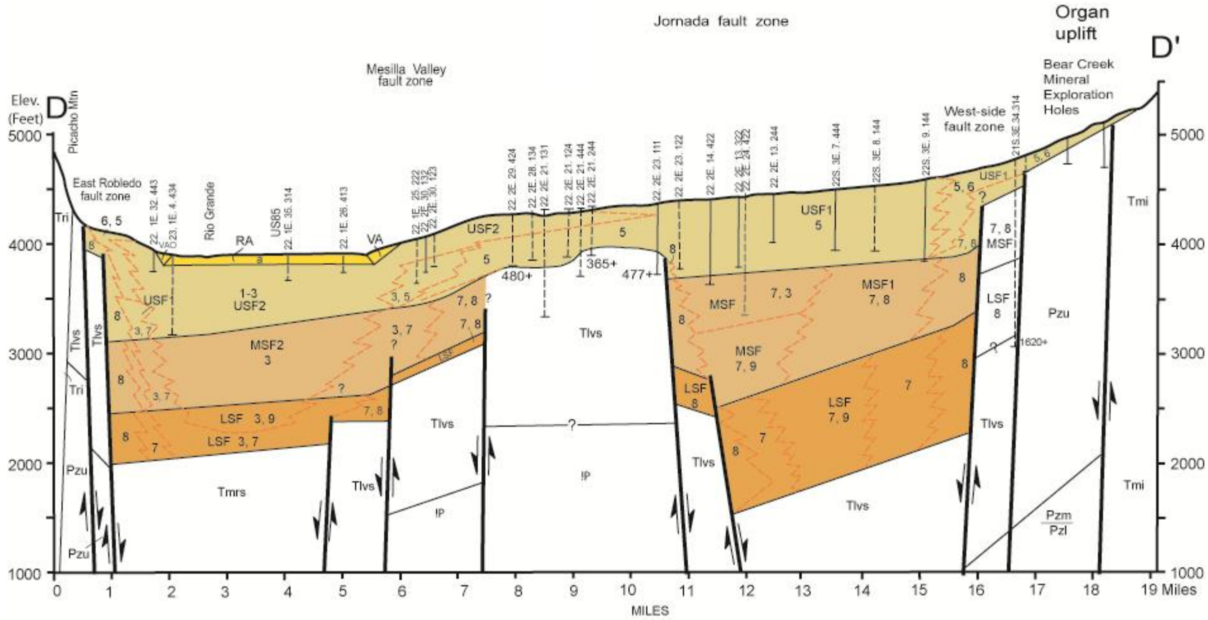


**Figure 2.5** Schematic hydrogeologic cross section D-D’ (Hawley and Kennedy 2004)

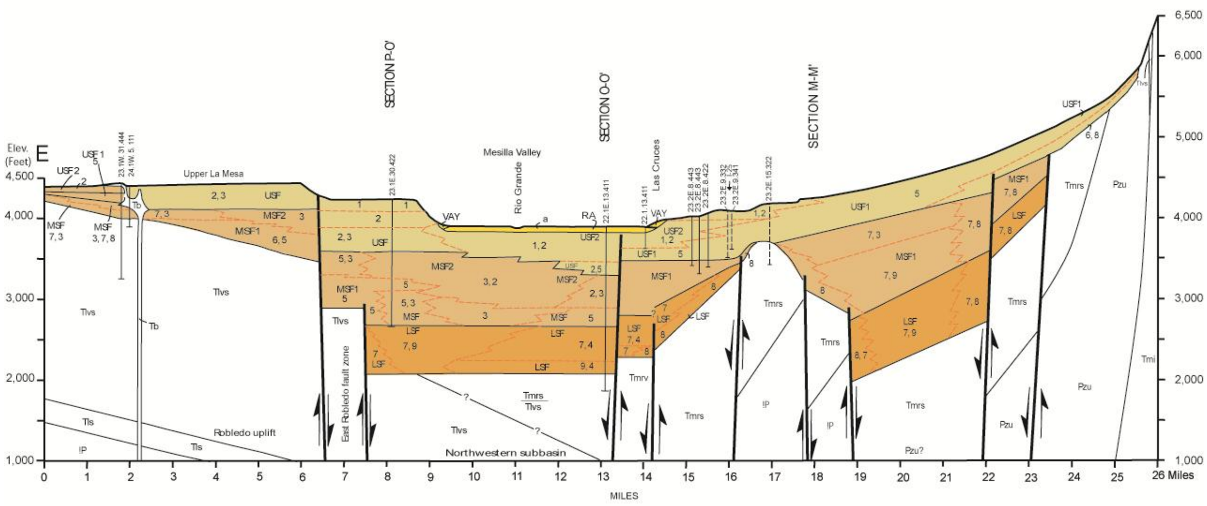


**Figure 2.6** Schematic hydrogeologic cross section E-E’ (Hawley and Kennedy 2004)

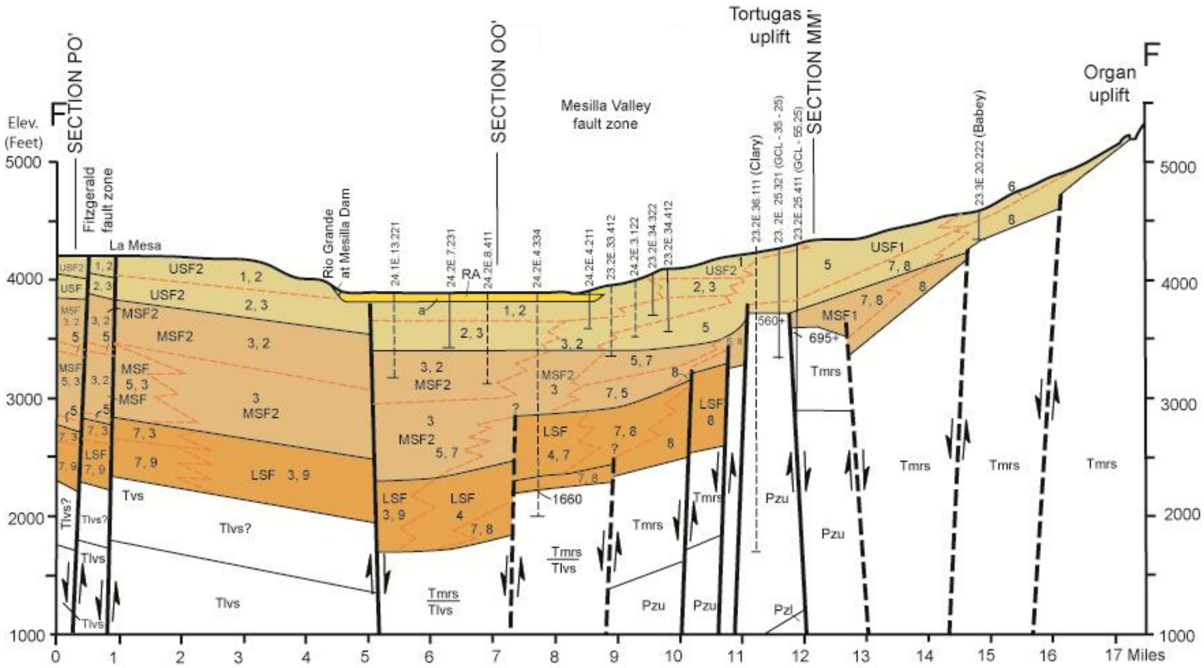


**Figure 2.7** Schematic hydrogeologic cross section F-F’ (Hawley and Kennedy 2004)

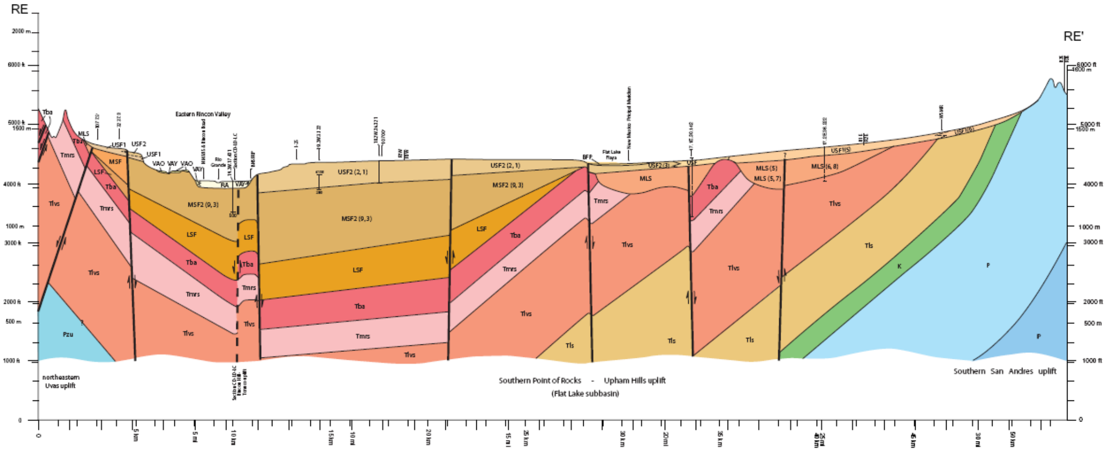


**Figure 2.8** Schematic hydrogeologic cross section RE-RE’ (Hawley and Kennedy 2004)

Hawley and Kennedy (2004) have subdivided the Santa Fe Group into informal Lower, Middle, and Upper hydrostratigraphic units (HSUs) based on lithologic character, depositional environment, and age. Lithologic (lithofacies) subdivisions of individual HSUs are more specifically defined in terms of hydraulic properties for geohydrologic modeling at a basin scale (see below). The Lower Santa Fe (LSF) HSU is an approximate correlative of the Hayner Ranch Formation (10-25 Ma age range). The unit is as much as 2000 ft thick, and consists primarily of partly indurated, fine- to coarse-grained, alluvial fill (Seager and Hawley 1973, Seager et al. 1971, 1987). It is not a significant aquifer, however, except possibly in basal parts where intercalated basaltic andesites are present.

The Middle Santa Fe (MSF) HSU generally correlates with the Rincon Valley Formation that was deposited when Rio Grande rift-basin subsidence was most active (about 4 to 10 Ma). The unit is as much as 2,000 ft thick in half-graben footwall sub-basins adjacent to the Jornada fault zone (Seager et al. 1987). Fine-grained, partly gypsiferous basin-floor sediments (playa-lake lithofacies) are the dominant MSF component in the northern part of the study area; and the only significant aquifer zone is in the uppermost 200 ft where eolian and fluvial sand beds are locally occur in interbedded sand/clay sequences (Figures 2.2, 2.3 and 2.8; Seager et al. 1971, 1987, Wilson et al. 1981, Hawley and Kennedy 2004). In the southern part of the study area, however, coarser-grained piedmont-alluvial facies are a major MSF constituents; and significant aquifer zones are present in upper parts of the HSU east of the Doña Ana uplift and adjacent to the US-70 corridor (Figures 2.4 to 2.6; King et al. 1971, Wilson et al. 1981, Seager et al. 1987, Hawley and Kennedy 2004).

The Upper Santa Fe (USF) HSU is an approximate correlative of the Lower Pleistocene Camp Rice Formation (2.6-0.8 Ma). The unit is characterized by medium- to coarse-grained basin-floor deposits of the ancestral Rio Grande fluvial system, and is as much as 600 ft thick in the southern part of the SJDM Basin (Figures 2.3 to 2.5; Seager et al. 1987, Hawley and Kennedy 2004, Connell et al. 2005, Mack et al. 2006). Uppermost USF beds in much of the basin include an indurated zone of soil-carbonate accumulation (pedogenic-calcrete, caliche) that is as much as 6 ft thick (Gile et al. 1981). During latest stages of basin-floor aggradation in the early Pleistocene, westward shift of the ancestral Rio Grande system coupled with continued movement of the Jornada fault resulted in topographic closure of the SJDM. The large ephemeral lake (playa) that flooded parts of the basin-floor following basin closure has been named Lake Jornada by Gile (2002). Because of large amounts of gypsum in both San Andres Range source-rocks and piedmont-slope runoff/sediment delivery systems, fine- to medium-grained USF lithofacies assemblages are commonly cemented with gypsiferous evaporites (mostly *selenite*) beneath much of the former lake-plain area. The vadose zone is about 300 ft thick in most of the SJDM; and HSU-USF forms a significant aquifer only in its thickest sections east and southeast of the Doña Ana uplift. In the northern part of the study area (east of the Rincon Valley, Figure 1.1), however, Upper Santa Fe deposits are less than 300 ft thick and mostly unsaturated (Figures 2.2 and 2.8; Hawley and Kennedy 2004).

For better definition of aquifer properties, SFG HSUs are further subdivided into various combinations of ten principal lithofacies assemblages (LFAs), each of which is distinguished by environment of deposition, and textural and other lithologic characteristics with definable ranges in hydraulic properties (Hawley and Kernodle 2000). Schematic hydrogeologic cross sections of the study area (Figure 2.1) are shown in Figures 2.2 through 2.8. Hawley and Kennedy (2004) derived horizontal hydraulic conductivity ($K_h$) ranges based on inferred lithofacies composition of the HSUs delineated in these sections. Their estimates of the groundwater production potential of each lithofacies assemblage were based on: (1) the ratio of sand plus gravel to silt plus clay, (2) bedding thickness, (3) bedding configuration (e.g., whether elongate, planar, or lobate), (4) bedding continuity, and (5) hydraulic conductivity (Hawley and Kennedy 2004, Table3-2).

Shomaker and Finch (1996) assigned hydraulic conductivity values ranging from 0.1 to 40 ft/day for their layers 1 and 2. Leakance across the bedding is believed to be significant, at least in sediments of the Santa Fe Group. Ratios of horizontal and vertical hydraulic conductivity were evaluated in model calibration. The estimated transmissivity of the upper 1,000 ft of saturated thickness in the southern end of SJDM ranges from 5,000 to 15,000 ft2/day (Wilson et al. 1981). The NMOSE also conducted one pumping test near the Organ Mountains, and transmissivity was estimated at about 7,000 $ft^2$/day (Rao 1988). Rao (1988) further assigned transmissivity values by subdividing the southern Jornada and Mesilla Valley into twelve zones.

A storage coefficient of 0.1 was used in the single layer model of southern Jornada Basin (Rao 1988). Hawley and Kennedy (2004) have reported the specific yield ranging from 0.1 to 0.2. Shomaker and Finch (1996) used a value of 0.15 for specific yield in their three layer model. Specific storage ranges from $10^{-5}$ to $10^{-6}$ and storage coefficients range from $2x10^{-3}$ to $3x10^{-5}$ per ft of thickness (Hawley and Kennedy 2004). Groundwater throughout the SJDM Basin generally replenishes through leaky confined conditions except for the upper section of the saturated zone where it is unconfined. Groundwater movement from the southern Jornada generally flows to the northwest. Gradients in the water table along the mountain front decrease toward the basin center (Wilson et al. 1981). Groundwater discharges northwestward into Rincon Valley between the Tonuco uplift (San Diego Mountain) and the Rincon Hills (western part of Figure 2.8; King et al. 1971). A small component of predevelopment discharge (estimated at less than 850 ac-ft/yr) also spilled as underflow to the northern Mesilla Valley through a shallow gap (gaps?) in the buried structural high between the Doña Ana and Tortugas uplifts (Hawley and Kennedy 2004).

Major producing wells in the study area tap groundwater from the lower USF and upper MSF HSUs (Wilson et al. 1981, Hawley and Kennedy 2004). Wells west of the NASA site near the base of the San Andres Mountains, and those near the US 70 corridor yield 500 to 1,500 gallons per minute (gpm) and 100 to 1,000 gpm, respectively (Figures 2.3 to 2.5; Doty 1963, King et al. 1971; Wilson et al. 1981). Wells in the area between the Doña Ana uplift and Point of Rocks, where HSU-USF is less than 300 ft thick, only produce from thin sand bed in the lowermost and uppermost parts of HSU's USF and MSF, respectively (Figures 2.2 and 2.8). Sustained yields rarely, if ever, exceed 10 gpm and water quality is marginal at best. This observation also applies to the central Jornada Basin, area north of the Point of Rocks, where SFG basin fill is thin or absent (Figure 2.1).

A surface-water/groundwater divide near the US-70 corridor (T. 22 S., R. 2-3 E.) indicates that predevelopment groundwater flow in that area was both northward into the south-central part of the SJDM and westward into the northern Mesilla Valley. To the south, the southernmost Jornada structural basin and the east-central Mesilla Basin are part of a single (linked) surface-water and groundwater flow system (Figures 2.6 and 2.7). Isaacks Lake in T. 21 S., R. 2 E., about 5-mi north of US 70, is the largest playa-lake depression (about 1 $mi^2$) in the closed (internally drained) part of the SJDM Basin, and it episodically fills with summer-storm runoff from adjacent basin slopes (Gile et al. 1981). East of Point of Rocks at the extreme north end of the SJDM study area, the south flowing Jornada Draw discharges to Flat Lake, another large playa (Figure 2.8; Hawley and Kennedy 2004). The floors of both these ephemeral lake plains are 250 to 300 ft above the regional water table; and almost all of the water lost from flooded surfaces is due to evaporation rather than seepage (Shomaker and Finch 1996).

Precipitation on the adjacent mountain ranges (as much as 14 in/year) is the principal source of recharge to the groundwater in the SJDM Basin according to King and others (1971). Rao (1988), on the other hand, estimated that average recharge to the groundwater body included 5% of the precipitation on the basin "floor" at an average of 9 in/year (Rao 1988). The mountain front recharge area for this aquifer system extends southward from Bear Canyon in the southern San Andres Range to the Fillmore Canyon area of the central Organ Mountains. All recharge is assumed to enter the USF-HSU except for deep- circulating geothermal water, which enters the lower part of the SFG and underlying Paleozoic carbonate rocks in the East Mesa geothermal field (Witcher et al. 2004). Gross (1988) and GCL (1995) estimate the geothermal flow as 1240 and 500 gpm, respectively (Shomaker and Finch 1996).

## 2.2 MODELING STUDIES

Very few groundwater flow models have been developed for the Jornada del Muerto Basin. But the southern Jornada has been a focus of several modelers in the past as it is the most productive and heavily utilized part of the entire basin.

Rao (1988) modeled the southern Jornada Basin to observe the effects of any groundwater pumping near the horst between Goat Mountain and the Tortugas uplift, southeast of Las Cruces. Because of narrow horst, it was difficult to calculate the drawdown between the Jornada and the Mesilla Basins. The purpose of the study was to assign different transmissivities to the groundwater movement from the Jornada to the Mesilla Basin. A single layer model was developed using the Digital Model of Groundwater Flow Package (Version 2.0) from the Modular Three Dimensional Finite Difference Groundwater Flow Model (MODFLOW). The study area extends from TS 18 S to 25 S and R 01 W to 04 E. This model includes some parts of the Mesilla and Rincon Valleys. The model had 24 columns and 35 rows with a cell size of 1 mile by 1 mile with a grid refinement near the horst. The storage coefficient was assumed to be 0.1. The study area was divided into twelve zones based on previous research and pumping tests were assigned transmissivities. Transmissivity values ranged from 500 to 30,000 $ft^2$/day and the reported permeability was lower in the northern part of the Jornada compared to the southern part. Transmissivity near the horst was assigned as100 $ft^2$/day.

King and others (1996) developed a groundwater model for the proposed Spaceport in the central region of the Jornada Basin. This model was prepared for the New Mexico Economic Development Commission (NMEDC). The purpose of that study was to evaluate the water supply requirements for the next 50 years and also to study the effect of groundwater pumping on nearby wells. The proposed Spaceport requires 2,000 to 4,000 ac-ft/year of water for the next 50 years. The study area was located in the TS 12 S to 18 S and R 03 W to 04 E. A two dimensional model was created using MODFLOW. A uniform grid with 39 rows by 38 columns and of cell size 1 mile by 1 mile was considered. The model assumptions were 1) single layer with confined aquifer and variable transmissivity, 2) Rio Grande at Rincon acts as a constant head boundary, 3) uniform areal recharge in addition to the mountain front recharge, and 4) vertical flow in the aquifer is negligible. The storage coefficient and transmissivity were assigned as 0.01 and variable thickness of aquifer multiplied by saturated hydraulic conductivity, respectively. Fifteen monitoring wells were considered within the study area for the steady state analysis, but most of the wells were located in the central, eastern, and western parts of the basin. During steady state calibration, the authors changed three parameters: uniform areal recharge, mountain front recharge, and hydraulic conductivity. In the transient analysis, the authors had suggested two different options for water supply. The first was to develop a well field within the Spaceport location. The second one was to use the L7 ranch well located to the north of Spaceport that has a higher quality of water. The authors estimated the drawdowns for three well field locations with pumping rates of 1,000 to 4,000 ac-ft/year with a duration from 5 to 50 years. The model results indicated that pumping could be done at a rate of 2,000 ac-ft/year at all three wells without any effect on neighboring wells. The authors also performed a sensitivity analysis to estimate transmissivity of the aquifer. Results showed that the transmissivity values range from 6,000 to 11,000 $ft^2$/day.

In 1996, Shomaker and Finch revised the 1990 single layer model into a three dimensional model for the southern Jornada Basin. The purpose of the model was to estimate the water budget using MODFLOW to evaluate the drawdown effects of pumping wells LRG-430-S -39 and LRG-430-S -30. The study area was located in the TS 16 S to 25 S and the R 02 W to 03 E. A three layer model was described as a rectangular grid with 20 rows, 33 columns and the cell dimensions ranging from 1 mile by 1 mile to 2 miles by 2.5 miles at the well locations. Layer 1 was simulated as unconfined, layer 2 as type 3 aquifer (confined, but changes to unconfined based on available head), and layer 3 as a confined aquifer. Hydraulic conductivity values for layer 1 and 2 ranged from 0.1 ft/day to 40 ft/day while the transmissivity for layer 3 ranged between 1 $ft^2$/day (at the mountain front) and 3,000 $ft^2$/day (in most parts of basin fill). The ratio of vertical conductivity to horizontal conductivity was assumed as 0.005. A specific yield of 0.15 was used for layer 1, a storage coefficient of $10^{-6}$ multiplied by layer thickness was considered for layer 2 (if it was confined, otherwise 0.15) and same for the layer 3 were assigned. Layer 1 thickness was assumed as100 to 160 ft or less near the bedrock boundaries, and the thickness of layer 2 thickness was 1,260 ft. Geothermal flow was estimated during the calibration as 59 ac-ft/year, which enters into the layer 3 located in the East Mesa geothermal field (Shomaker and Finch 1996). Some arbitral values were assigned for groundwater inflow below POR to the northern boundary, mountain front, and natural discharge to the Mesilla Basin and were estimated during the calibration along with the aquifer properties.

The model was simulated for a steady state for the pre-1962 period, and for the transient condition for the period from 1962 through 1994. Predictive drawdowns under induced pumping were estimated for the next 100 years. From the volumetric budget, it was estimated that 100 million ac-ft of water was available in the entire basin, out of which 41 million ac-ft of water was present in the beds of high hydraulic conductivity. Using the three layer model and the above conditions, the authors conducted the analysis and found that the saturated thickness of the aquifer would be productive if the existing water rights continue for 100 years. The authors had estimated the recharge as 3,800 ac-ft/yr along the eastern boundary of the Jornada Basin. It was reported that 18 wells were associated with water rights that would not produce full amounts of water after 40 years. They predicted that this number would increase to 20 if pumping of LRG-430-S-29 and LRG-430-S-30 wells were considered.

In 1995, Geoscience Consultants Limited prepared a single layer model for the Jornada Basin but it is not included in this report. In 2007, S.S. Papadopulos and Associates Inc. developed a comprehensive model of the Lower Rio Grande Administrative Basin that includes the Mesilla and Rincon Basins. The irrigation year was divided into two seasons: irrigation and non-irrigation seasons. The model was developed with 5 layers, 388 rows, and 164 columns. The model was simulated under transient conditions for the period 1940 to 2004. To simulate the model, the authors used MODFLOW Version 2000, ArcGIS 9.2 and Groundwater Modeling Software (GMS). They specified the connections to Jornada Basin at Mesilla (buried horst) and at Rincon. The authors considered the general head boundaries at Rincon Arroyo but not at the Mesilla-Jornada connection probably because the inflow from the Jornada was not significant compared to the other flows within the Mesilla. The simulation results were presented in the form of water budgets, hydrographs, and the Rio Grande depletions for various stress periods.

# 3. MODEL DESIGN

## 3.1 OVERVIEW

ArcGIS 9.2 was used to delineate the conceptual model of the study area from the 10 m digital elevation model (DEM) and the surface hydrogeology map of the region (Hawley and Kennedy 2004). Spatial analyst and geostatistical analyst tools in ArcGIS were used to generate the continuous surface of layer elevations and hydraulic characteristics from their measured values along the cross sections. The initial water table profile was estimated from the hand-drawn contours of piezometric heads for the 1968 irrigation year and the water table elevations measured in those 51 monitoring/production wells that are consistent with hand-drawn contour values (King et al. 1971; Wilson et al. 1981; Shomaker and Finch 1996). Pumping from wells, mountain front recharge, head dependent fluxes, and evaporation from surface water bodies were identified as model stress components and were accordingly represented as model dependent boundary components. All GIS files used in this report have State Plane New Mexico Central FIPS 3002 projected coordinate system with North American Datum (1983).

## 3.2 CONCEPTUAL MODEL

Surface topography of the region was characterized from the 10 m DEM obtained from the New Mexico Water Resources Research Institute (NMWRRI). Surface analysis using spatial analyst tools in ArcGIS was performed on the DEM to identify the hydrogeologic boundaries of the model. As the hydrogeology of the region to the north of the POR has not been explained in the literature, the northern boundary of the model is limited to the POR region. The model is bounded by the San Andres Mountains and the north end of the Organ Mountains in the east. The isolated Goat, Tortugas, and Doña Ana Mountains define the western boundary of study area. The basin is separated from the adjacent Mesilla Basin by the continuous Jornada fault uplift. In order to be consistent with the OSE-2007 flow model, the model boundary was adjusted near the horst. The flow model is made up of three layers based on the hydrostratigraphic subdivisions of the Santa Fe Group (Hawley and Kennedy 2004). The study area is located between TS 17S to 24S and R 02W to 03E with an aerial extent of 576 mi$^2$ (1,490 km$^2$). The digitized map of the study area with the available cross sections (Hawley and Kennedy 2004) is represented in Figure 3.1.

### 3.2.1 Modeling the continuous surface

Groundwater flow models require the input parameters to be represented at each and every grid cell location. However, the parameters such as layer elevations, aquifer properties, and initial water levels are measured at sparse locations due to time and money constraints. Therefore, an accurate estimate of the continuous surface for parameter values from their measurements at random locations is vital in generating a numerical model that closely resembles field conditions. The geostatistical analyst tool in ArcGIS is a powerful technique that is capable of producing the prediction surface, and also some measure on the capability of these predictions. Different kriging interpolation techniques were tried depending on the distribution of data for generating the continuous surface. Different theoretical semi-variograms were fitted to the data in order to choose the best one for interpolation based on cross validation statistics.

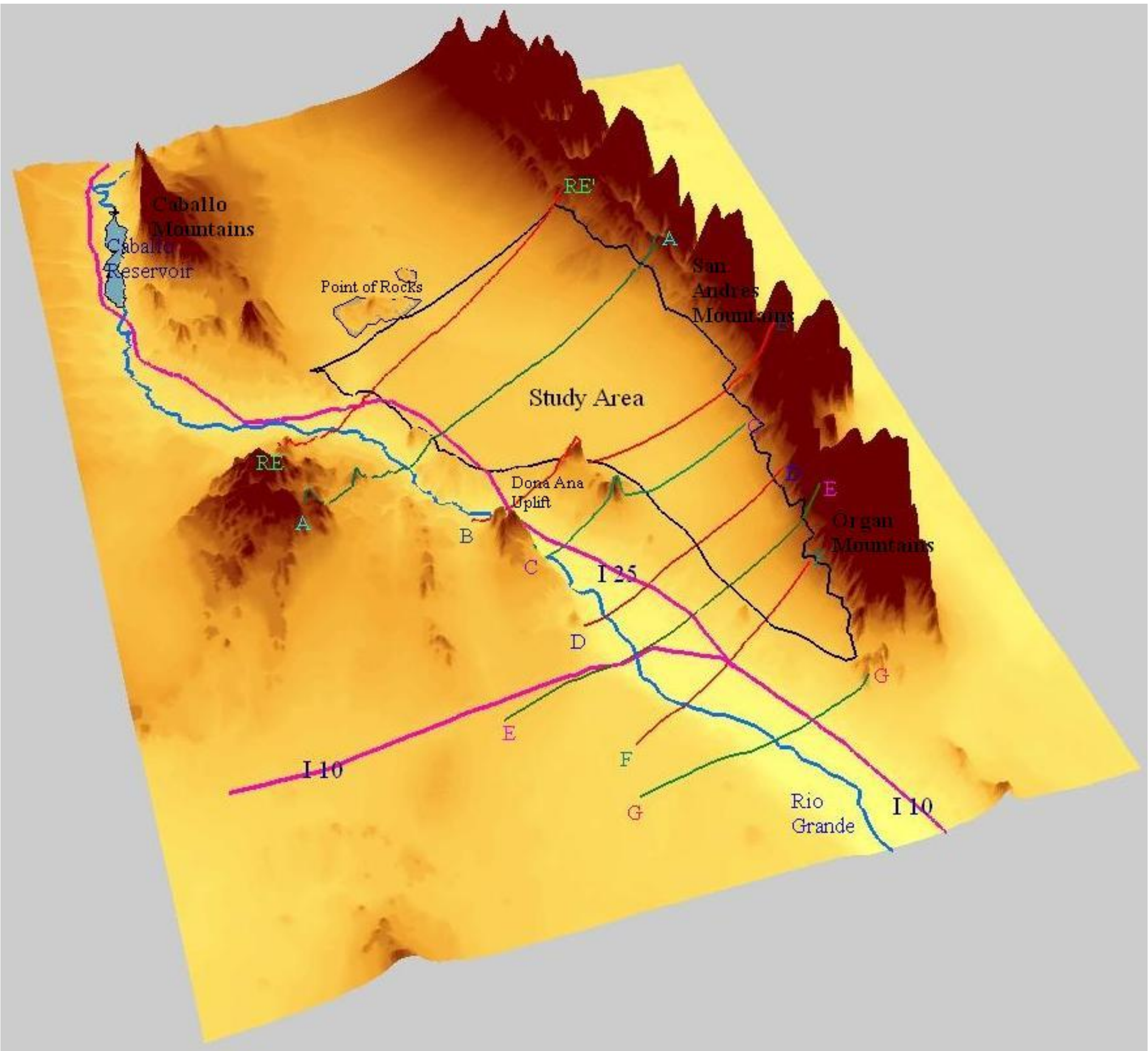


**Figure 3.1** Three dimensional representation of the study area

### 3.2.2 Layer elevations

The vertical extent of the model was composed of three hydrostratigraphic units of the Santa Fe Group deposits. Layer 1 defined the USF, consisting of ancestral Rio Grande channel sand and gravel deposits, which was the most productive aquifer zone. Layer 2 defined the MSF unit, with extensive layers of clean fluvial and eolian sand interbedded with silty clay and formed the major aquifer zone in the basin. Layer 3 defined the LSF unit, consisting of fine grained, basin-floor sediments, and does not form a significant part of the aquifer system (Hawley and Kennedy 2004).

As the presence of geological faults and divides changes layer elevations and groundwater levels on either side, the geostatistical analyst tool was not used to krig elevation surfaces. Elevation contours were drawn at 20 ft intervals in the western part of the basin and at 100 ft intervals elsewhere by Dr. John Hawley. Layer elevation surface from these hand contoured map was prepared by keeping in mind the presence of geological faults. Water table elevation contours represented by Wilson and others (1981) was used in generating the water table profile across the study area. The surface profile of ground and water table elevations are represented in Figure 3.2. Layer thickness was obtained by subtracting the bottom elevation from the top elevation (water table elevation for layer 1) of that layer and is shown in Figure 3.3.

### 3.2.3 Hydraulic conductivity

Hydraulic conductivity ranges based on the lithofacies assemblage were prepared by Hawley and Kennedy for the study area. Hydraulic conductivity values in the study area ranged from moderate (3 to 30 ft/day) to very low (less than 0.a ft/day). The parameter values along the cross sections were assigned using the weighted mean based on the dominant lithofacies. Estimates of hydraulic conductivity values, derived from the pumping tests as reported by Wilson and others (1981), were also used in generating the hydraulic conductivity surface for the model layers. Transmissivity values as used by the numerical flow model were calculated as the product of hydraulic conductivity and the saturated thickness of the aquifer. The spatial variation of hydraulic conductivity in the three model layers is represented in Figure 3.4. The kriged hydraulic conductivity values slightly differ from the published data between cross sections A-A' and B-B'. In case of any discrepancies, the published values of hydraulic conductivity were used in simulation.

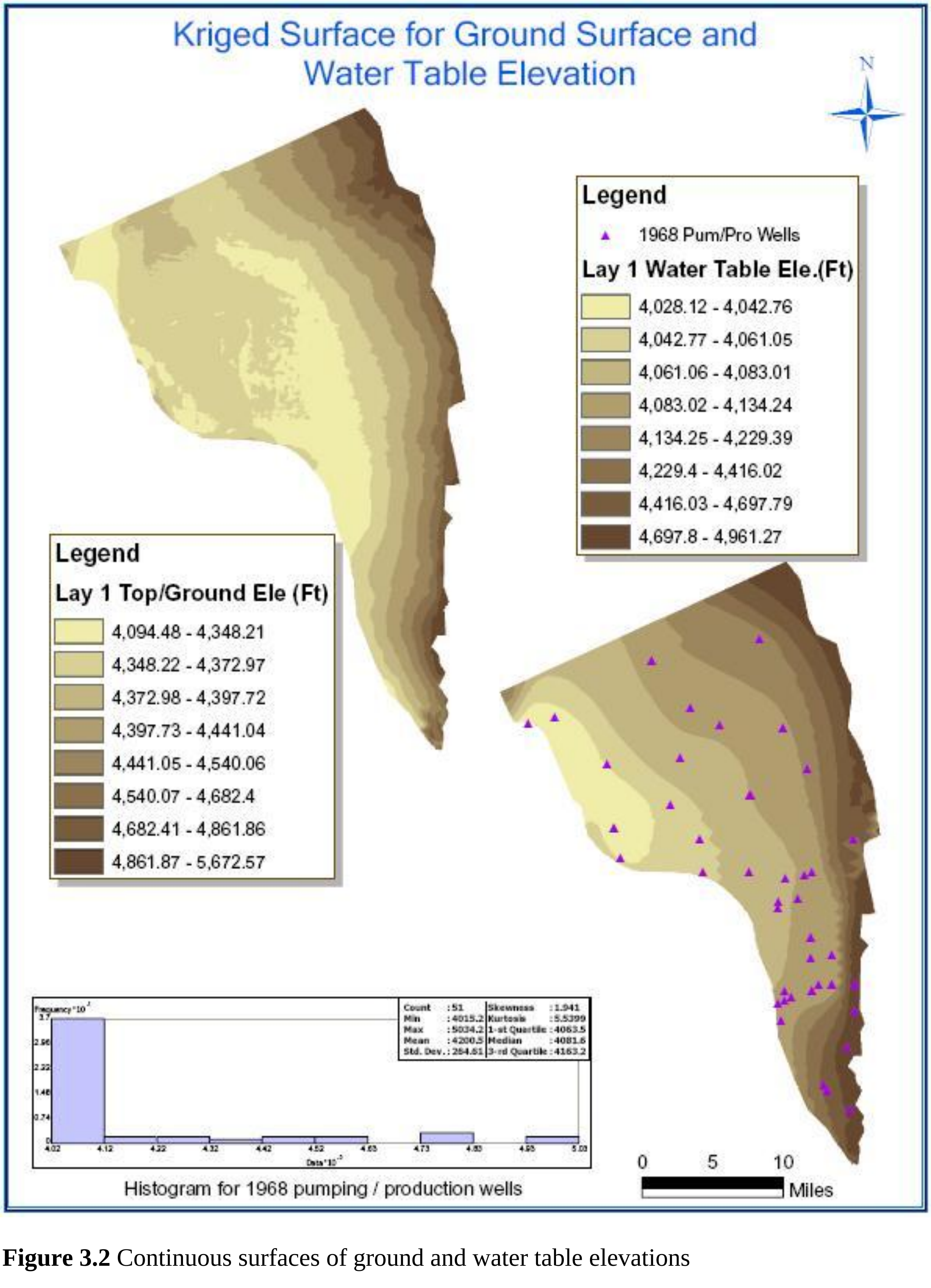


**Figure 3.2** Continuous surfaces of ground and water table elevations

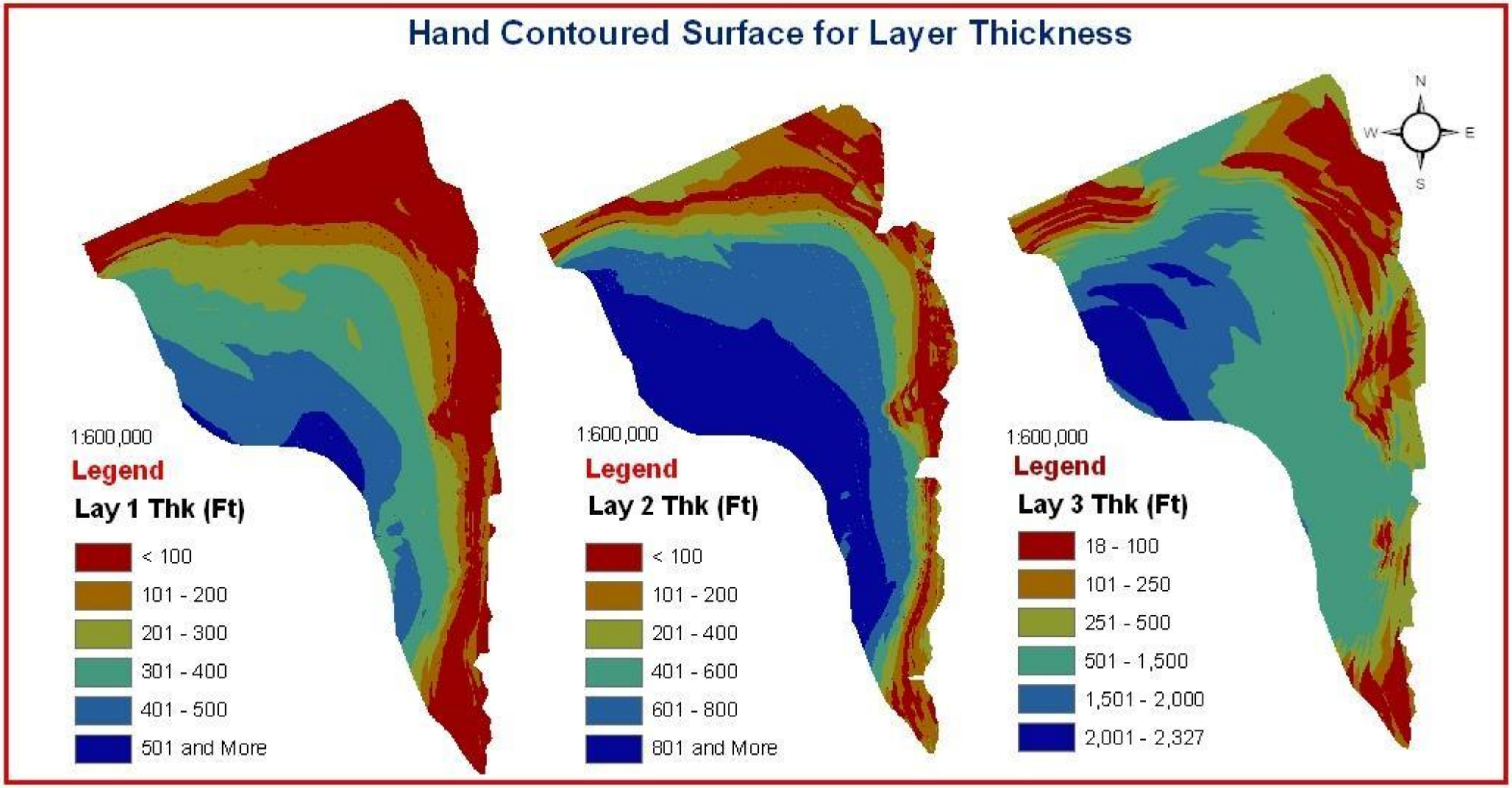


**Figure 3.3** Continuous surface of model layers thickness (derived from hand-drawn contours)

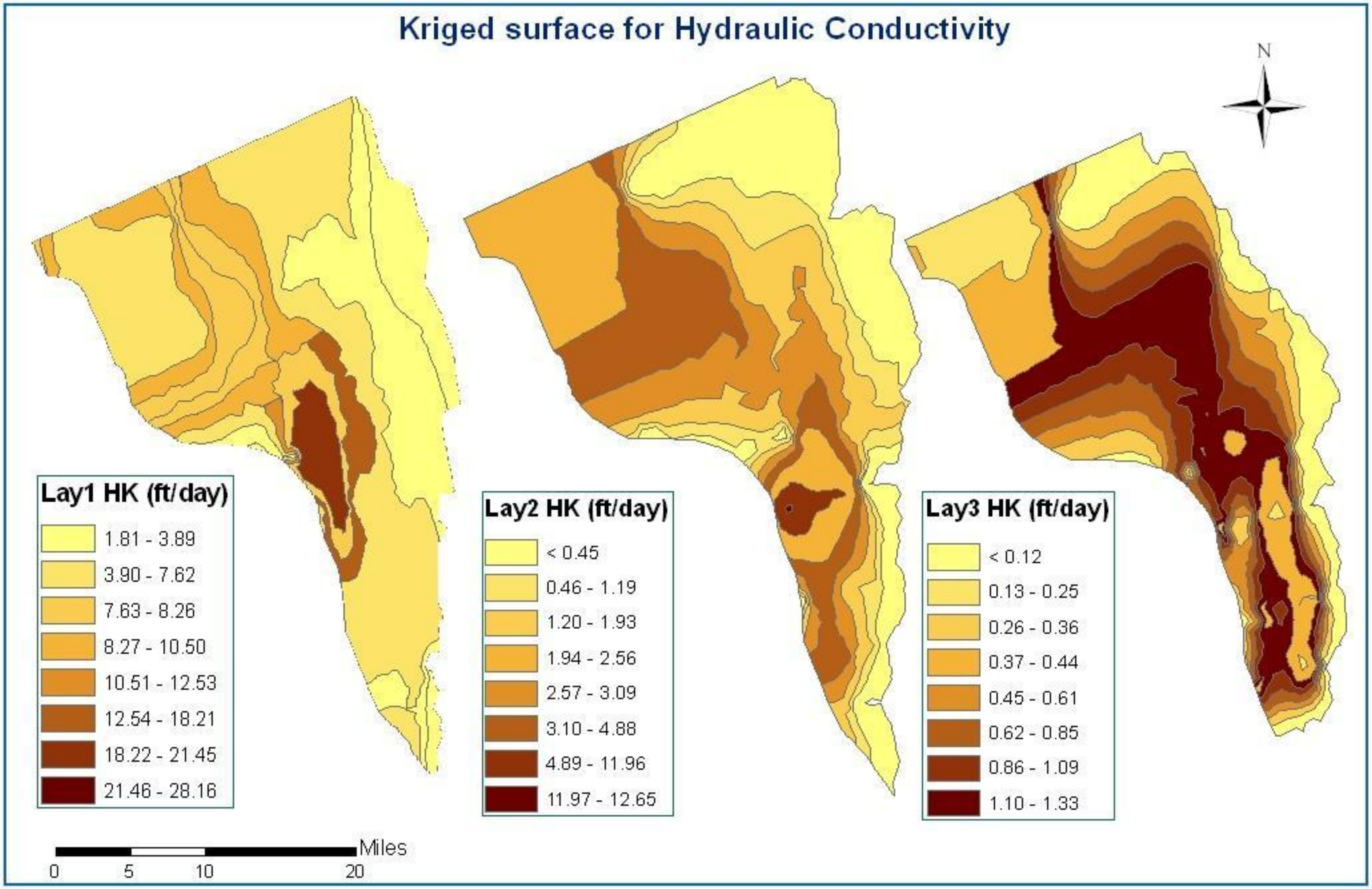


**Figure 3.4** Spatial distribution of layer hydraulic conductivity values

### 3.2.4 Storage characteristics

Layer 1 contains the water table, hence represented as an unconfined aquifer with specific yield estimates varying from 0.1 to 0.2. An average value of 0.15 seemed to be appropriate for the initial run and was adjusted during calibration. Layers 2 and 3 were designated as confined aquifers with specific storage ranging from $1\text{x}10^{-5}$ to $1\text{x}10^{-6}$ /ft (Kernodle 1992; Frenzel and Kaehler 1992). An average value of $5.5\text{x}10^{-6}$ /ft was used as the final specific storage in the numerical flow model. As layers 2 and 3 were not stressed significantly during the simulation, the same value of specific storage was used throughout the simulation period. The spatial variation of specific storage for model layer 1 is represented in Figure 3.5.

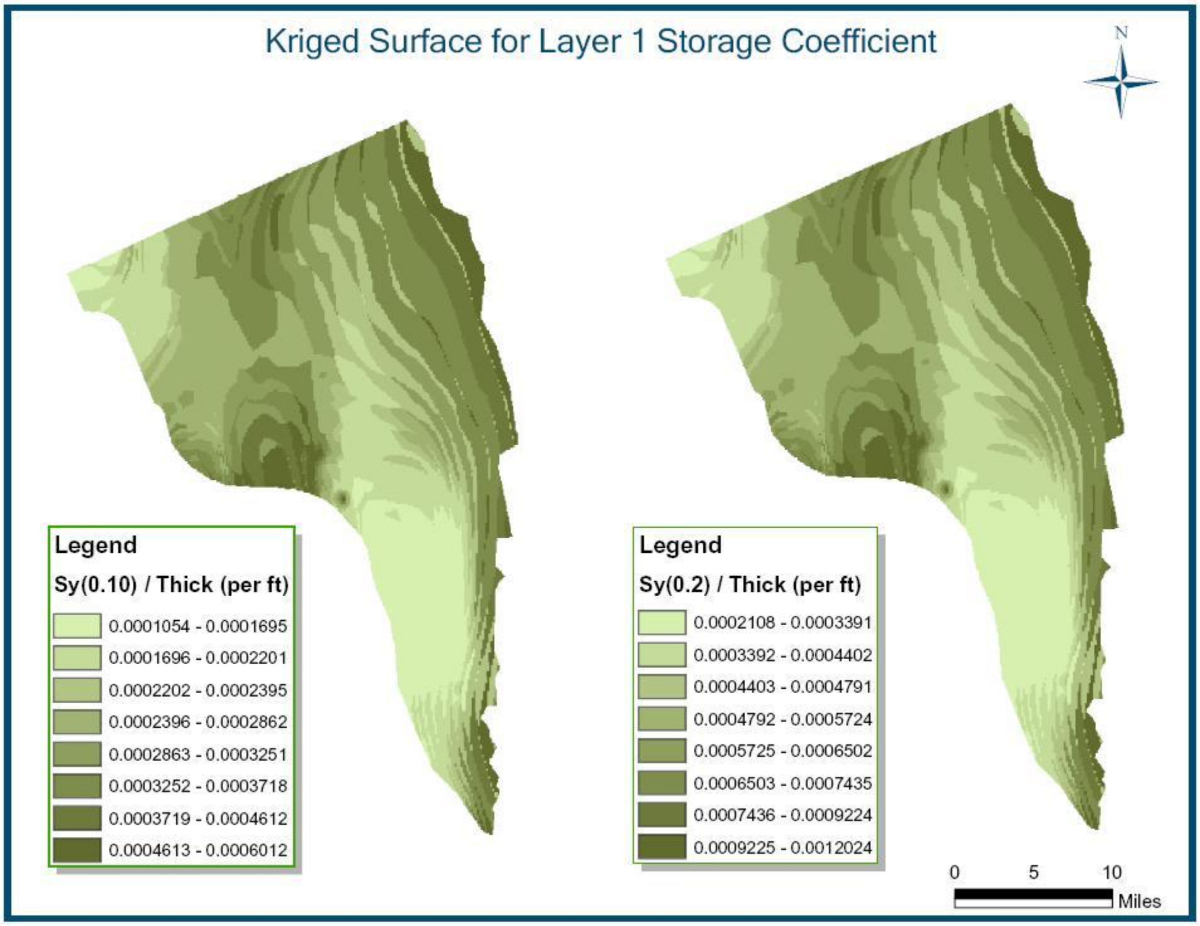


**Figure 3.5** Spatial variation of storage coefficient (specific yield/thickness) for model layer 1

### 3.2.5 Initial heads

Water table elevations in the 51 monitoring/production wells distributed across the study area (that are consistent with the hand contour values) and the contours of piezometric heads for the 1968 irrigation year were considered as initial heads during simulation. Water table elevation records were obtained from different sources including King and others (1971), Wilson and others (1981), and Shomaker and Finch (1996). Since the ground surface elevation used in the literature did not correlate with the DEM elevations, the depth to water table from the literature was considered in representing the water table elevations. As the initial water table elevations for layers 2 and 3 were not available from literature, these values were assumed in relation to the layer 1 water table surface. The 1968 irrigation season was considered as the starting time period for transient simulation, the model was simulated bi-annually (8 months primary and 4 months secondary irrigation seasons) from 1968 to 2007.

## 3.3 GROUNDWATER PUMPING

Groundwater withdrawals for municipal, domestic, and livestock use during the simulation period were considered for transient simulation. The pumping flow rates were distributed into the model files for transient historical runs, utilizing an eight month primary irrigation and a four month secondary irrigation season in order to be consistent with the OSE -2007 flow model. The pumping records were collected from Shomaker and Finch (1996) and the NMOSE *iwaters* database. Well depth and screening data were used to identify the model layers affected by pumping. Most of the domestic and livestock wells in the study area are unmetered and were assumed to tap water from the unconfined layer. To be consistent with the OSE-2007 flow model, all domestic, livestock, and multipurpose wells were assigned flow rates of 0.35, 1.0, and 1.2 ac-ft/year, respectively. A positive flow (of about 59 ac-ft/year) into the model layer 3 in the form of geothermal flows that occur at Tortugas Mountain was used in simulation (Shomaker and Finch 1996).

A total of 177 pumping wells were identified for transient simulation, of which 130 wells are either domestic, livestock, or multipurpose wells and tapping less than 100 ac-ft/year of water from model layer 1. Most of the major pumping wells were located near the Las Cruces region and tapped water from model layers 1 and 2. The spatial distribution of pumping wells across the study area and the magnitude of pumping are represented in Figure 3.6. Estimates of pumping seem to be high compared to previous modeling reports. This may be due to the higher pumping rates assigned to most of the non-metered wells and an increase in model area.

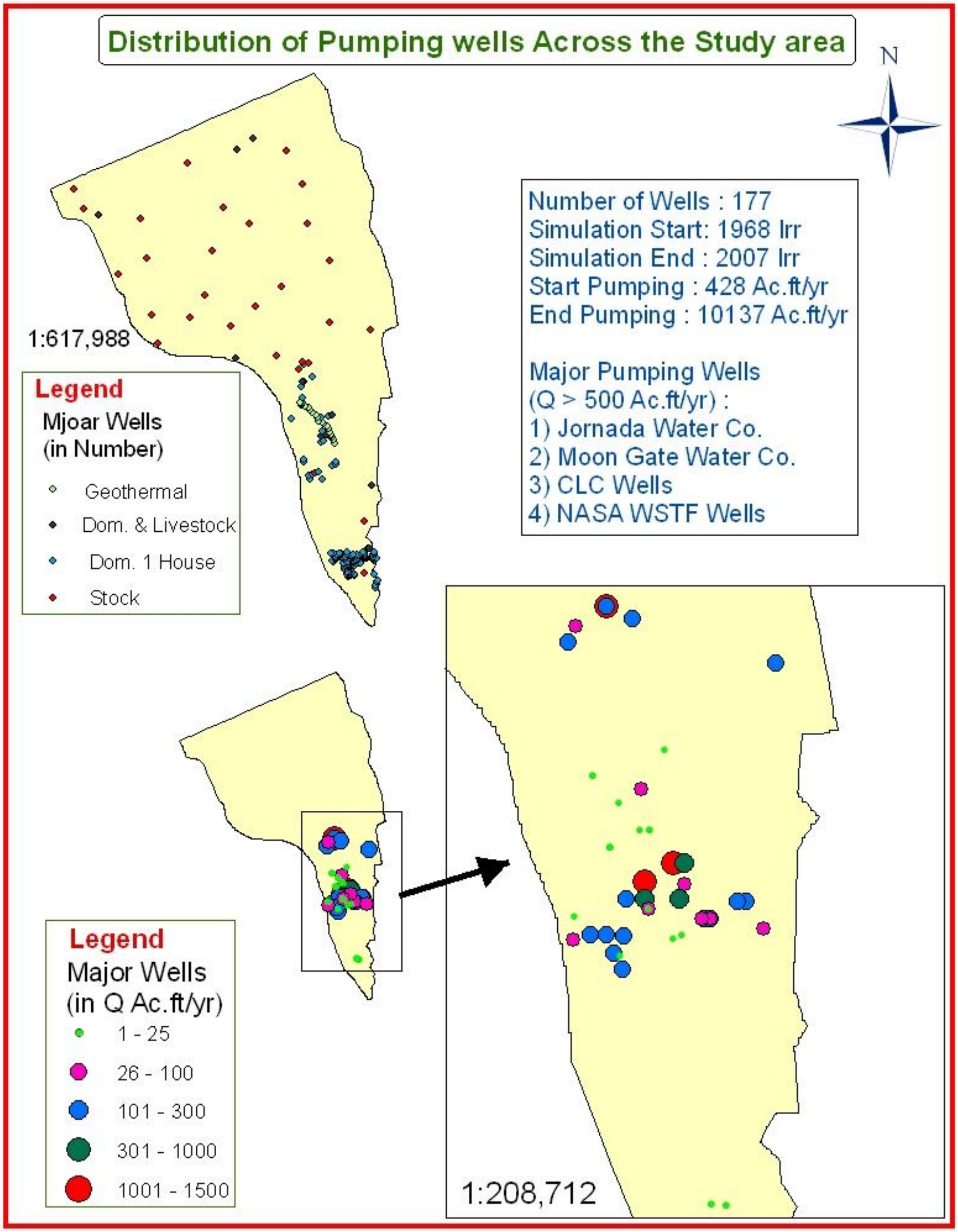


**Figure 3.6** Distribution of pumping wells across model layer 1

## 3.4 GENERAL HEAD BOUNDARY

Model boundaries were set as no-flow boundaries with the exception of a few locations where trans-basin flows were represented with a general head boundary condition. These locations include flow across the northern boundary to the left of the POR region, distributed flow at Rincon Arroyo, and the flow near the Jornada horst. Flow across the northern boundary was assumed to enter the Basin as underflow through layer 1. Rincon Arroyo was situated near the Leasburg Dam and was distributed over a significant length, representing the water leaving the Jornada Basin system. A buried horst located to the southeast of Las Cruces represents the water leaving the Jornada Basin through the upper layer. The GHB conductance factor was changed during calibration to estimate the flow across the model boundary.  Model stress components including evaporation, general head boundary, and mountain front recharge are represented in Figure 3.7.

## 3.5 EVAPOTRANSPIRATION

The New Mexico surface water bodies map was clipped to the study area for identifying the water bodies within the region of interest. Three water bodies, two at the northern boundary and one near the Jornada horst, were delineated as surface water bodies. Since precipitation is the chief source of evaporation in the study area, water from ephemeral streams reaching the water bodies during primary irrigation season was considered for simulation. The groundwater budget component due to evaporation is almost negligible mainly due to very small surface area of water bodies and arid climate of the region. The surface water body near the Jornada horst, known as Isaacks Lake was derived from the Shomaker and Finch (1996) report.

## 3.6 MOUNTAIN FRONT RECHARGE

Mountain front recharge refers to the process of aquifer recharge through infiltration of subsurface flow and flow from streams that have headwaters in the mountains. Mountain front recharge across the basin is directly related to precipitation as a result of steep terrain and relatively impervious soils. In the present study, mountain front recharge was estimated using two empirical regression methods developed for New Mexico catchments, from which the final method used in simulation was derived based on the calibration statistics obtained during inverse modeling and the similarities between the basin characteristics.

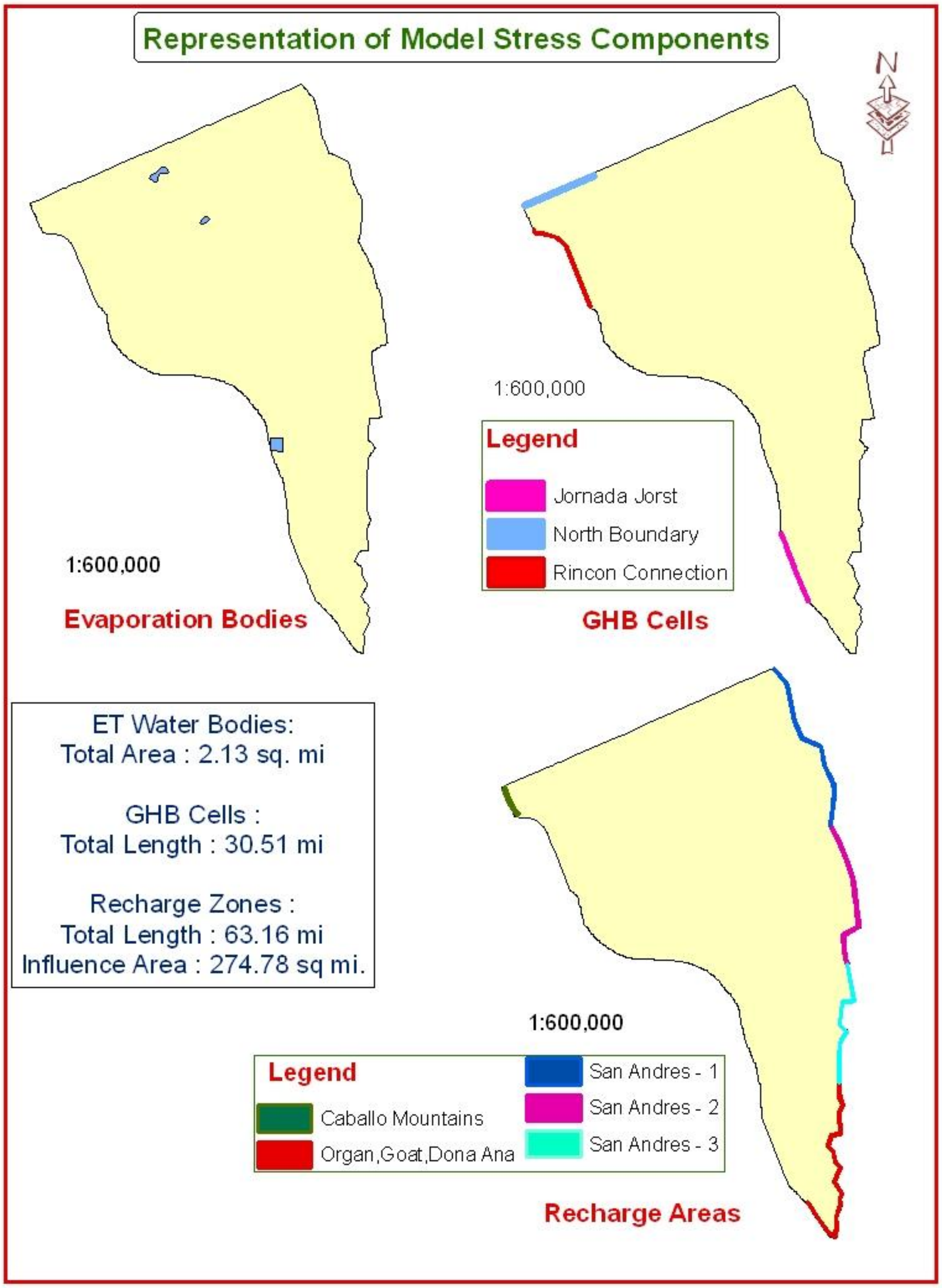


**Figure 3.7** Representation of model stress components (other than pumping)

### Method 1: Hearne and Dewey Equation

G.A. Hearne and J.D. Dewey (1988) developed a regression equation based on the data from 16 basins in northern New Mexico. This equation estimates the mean annual water yield based on winter precipitation, basin area and basin slope.

$$Q = (1.074 \times 10^{-5}) \times A^{1.216} P^{2.749} S^{0.536}$$

where,

| | |
|---|---|
| Q = mean annual recharge (cfs); | A = area of the drainage basin (square miles); |
| P = mean winter precipitation (inches); | S = slope of the basin (feet per mile) |

### Method 2: Waltemeyer Equation

Scott D. Waltemeyer (2001) developed a regression equation using the data from Tularosa Basin in New Mexico. The estimated annual stream flow based on mean annual precipitation and the drainage area is given by

$$Q = (1.7 \times 10^{-4}) \times A^{1.35} P^{1.65}$$

where, P = mean annual precipitation (inches).

The mountain front recharge parameters and the corresponding recharge flux values across the delineated sub-basins for five identified recharge zones were given in Tables 3.1 and 3.2.

**Table 3.1** Zone-wise distribution of mountain front recharge parameters (Hearne and Dewey)

| Recharge Zone | Basin Area ($miles^2$) | Avg. winter Precip. (in) | Avg. Basin Slope | Mean Annual Recharge | |
|---|---|---|---|---|---|
| | | | | cfs | ac.ft/year |
| San Andres -1 | 33.42 | 8.25 | 3.98 | 0.37 | 270.62 |
| San Andres -2 | 43.17 | 9 | 9.69 | 0.64 | 466.35 |
| San Andres -3 | 23.57 | 9.75 | 13.94 | 0.47 | 338.10 |
| Organ and Goat | 21.59 | 10.5 | 20.69 | 0.18 | 133.84 |
| Caballo | 13.68 | 8.25 | 9.88 | 0.13 | 91.71 |
| Total Recharge | | | | 1.79 | 1300.62 |

**Table 3.2** Zone-wise distribution of mountain front recharge parameters (Waltemeyer)

| Recharge Zone | Basin Area (miles$^2$) | Mean annual Precip. (in) | Mean Annual Recharge cfs ac.ft/year | |
|---|---|---|---|---|
| San Andres -1 | 33.42 | 11 | 1.01 | 734.90 |
| San Andres -2 | 43.17 | 12 | 1.65 | 1198.58 |
| San Andres -3 | 23.57 | 13 | 0.83 | 604.07 |
| Organ and Goat | 21.59 | 14 | 0.84 | 606.37 |
| Caballo | 13.68 | 11 | 0.30 | 220.06 |
| Total Recharge | | | 4.63 | 3363.98 |

Arc Hydro, an extension tool in ArcGIS was used to delineate the upland areas behind the mountain front up to the groundwater divide of the region from the 10 m DEM by identifying the flow direction and flow accumulation grid points. The delineated polygons were intersected with the precipitation and slope maps resulting in multiple sub polygons with the designated recharge parameters. The distribution of mountain front recharge parameters for the designated zones generated using Arc Hydro are represented in Figure 3.8.

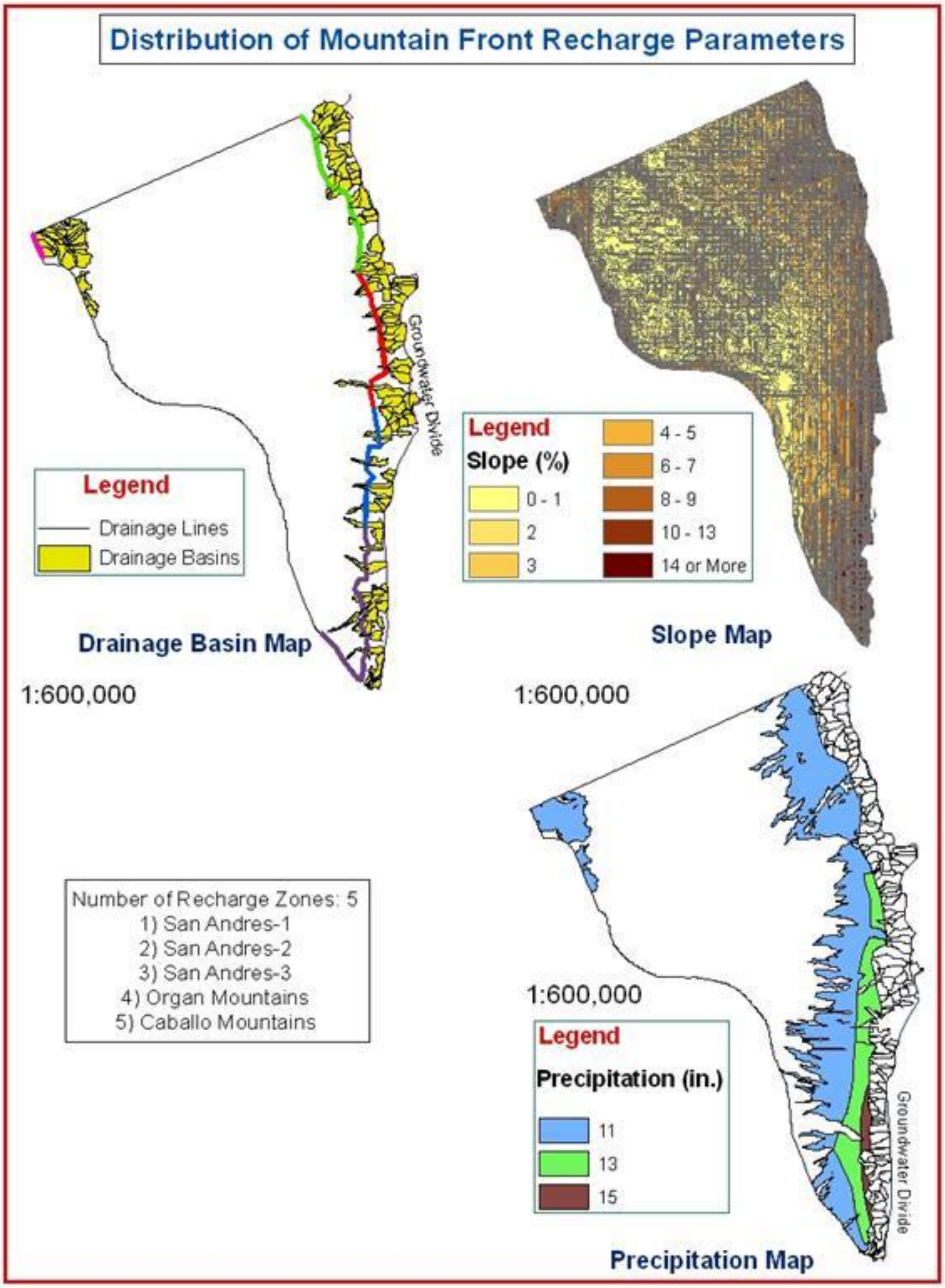


**Figure 3.8** Representation of mountain front recharge parameters

# 4. NUMERICAL SIMULATION

## 4.1 OVERVIEW

This chapter deals with the representation of model input parameters and their distribution across various packages used in simulation. The United States Geological Survey (USGS) MODFLOW-2000 was used to solve the three dimensional groundwater flow equation using finite difference technique. The GV (Version 5) was used as the graphical user interface (GUI) to MODFLOW-2000. The conceptual model and the boundary stress maps created in ArcGIS 9.2 were imported into GV for generating the basic MODFLOW packages.

## 4.2 MODEL INDEPENDENT PACKAGES

Model independent packages correspond to the packages that are necessary to run a numerical model irrespective of location of the model. These can include discretization (DIS), basic (BAS6), layer property flow (LPF), zone (ZONE), multiplier (MLT), preconditioned conjugate gradient (PCG) for solver, output control (OC), list (LST) and global (GLO) packages. The LPF package was defined using parameters (applying data value to multi-grid cells) for a convenient handling of the model parameters during sensitivity and calibration. The ZONE and MLT packages were combined in order to define the parameters that were used to modify the data input values for large parts of the model.

### 4.2.1 Areal extent and model grid

The vertical extent of the finite difference grid comprises 3 layers based on Hawley and Kennedy's (2004) hydrostratigraphic units. The model was discretized into 180 rows and 105 columns with a uniform cell size of 1,320 ft (1/4 mile), so that the area under each cell had 40 acres of land for effectively delineating the model parameters. The grid was rotated by $24.4^{\circ}$ counterclockwise from the North in order to be consistent with the OSE-2007 flow model developed for the Rincon and Mesilla Basins. The lower left corner of the grid formed the origin of the model with real world coordinates of 1,478,606 ft and 414,914 ft. The temporal extent of the model was simulated from 1968 to 2007 with 79 stress periods. Each irrigation year was further divided into primary irrigation (March to October) and secondary irrigation (November to February) seasons, for later integration of the model with the OSE-2007 flow model that was originally simulated based on irrigation seasons. Each stress period had 4 time steps with a time-step multiplier of 1.2 to characterize the temporal variation in piezometric heads. The spatial and temporal extent of the model with the layer elevations was specified in the discretization package and is represented in Figure 4.1.

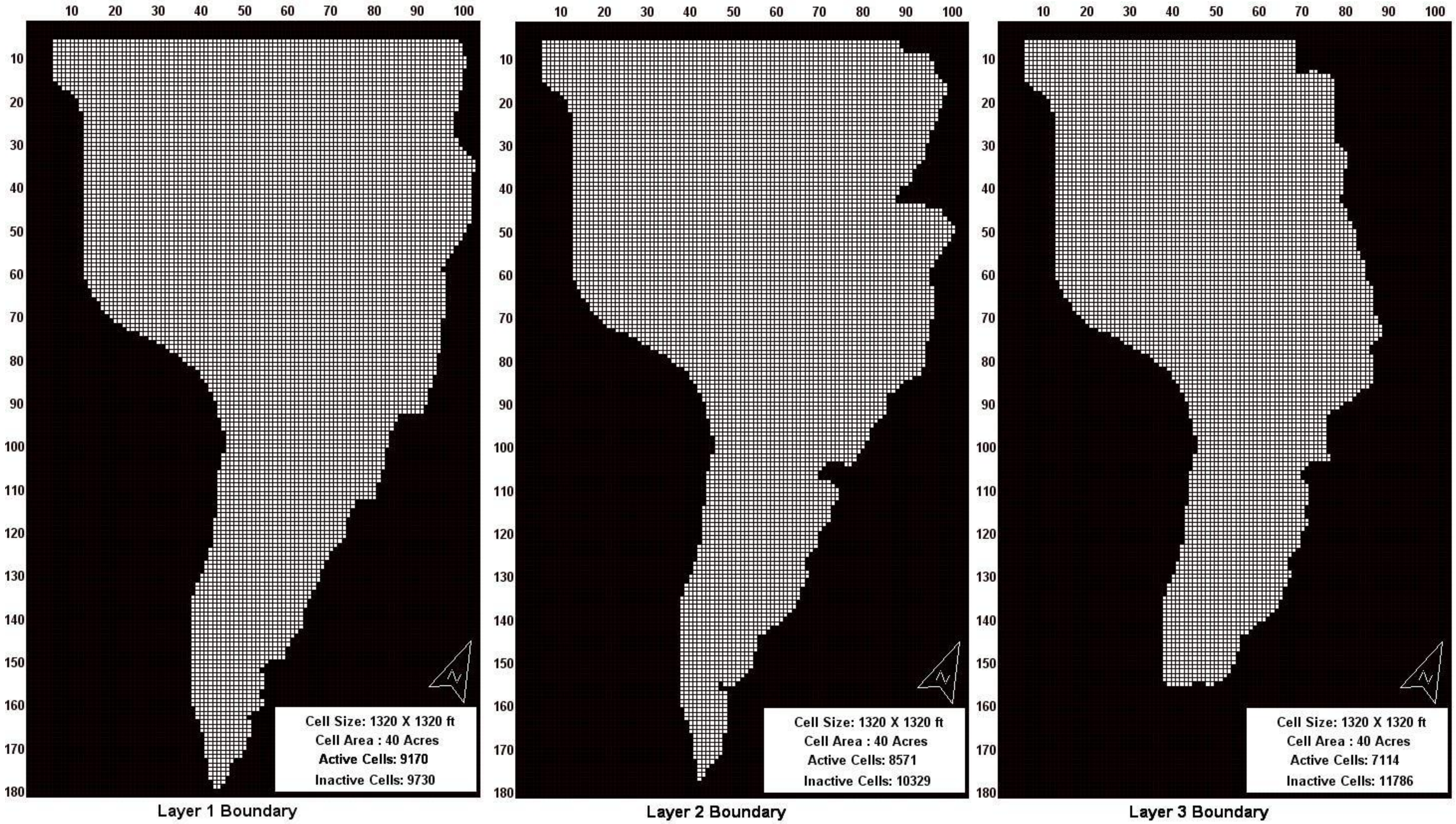


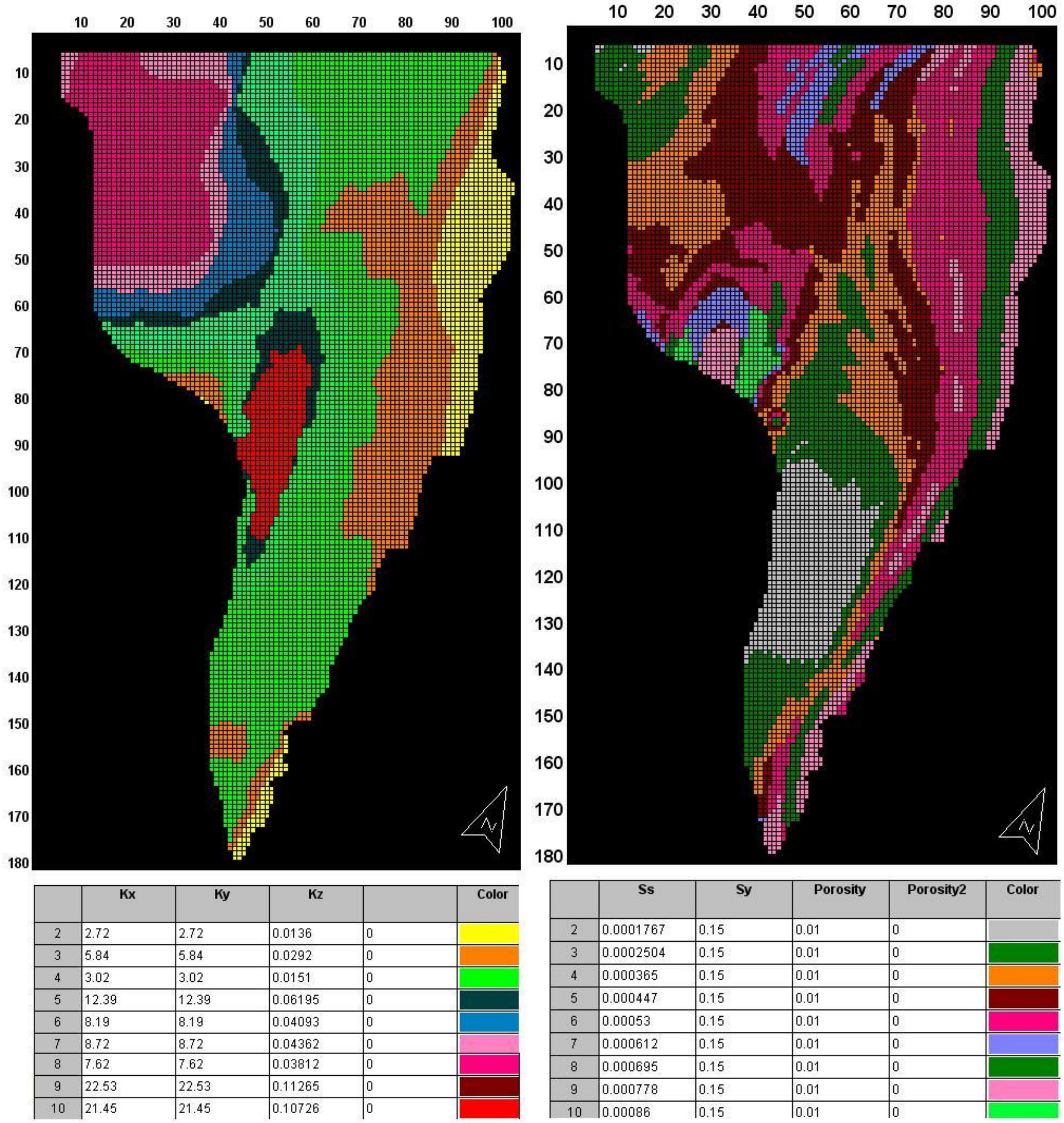
**Figure 4.1** Representation of model layers with active grid cell locations delineated in MODFLOW

### 4.2.2 Model boundary

The natural geological outcrops of the region form boundaries to the east, south, and west of the model. As the geohydrology to the north of POR was not explained in the literature (Hawley and Kennedy 2004), the northern boundary of the study area (existing between Caballo Mountains and POR) was simulated for head dependent boundary conditions. All the model cells that were within the boundary were designated as active cells and take part in simulation. Water table elevations in the 51 monitoring/production wells distributed across the study area during 1968 primary irrigation season were interpolated to generate the water table surface across the study area. The field measured head values were used as the initial condition for transient run instead of using the steady state head solution generated by a calibrated model. This results in a discrepancy between the imposed starting heads and the head field that is actually in equilibrium during the early time steps. However, the model response would reflect actual field conditions under study during the later time steps. The model boundary and the initial water levels for all three layers were specified in the basic package.

### 4.2.3 Aquifer characteristics

Aquifer characteristics such as hydraulic conductivity and storage coefficient were defined using parameters with zones representing the range in values. Hydraulic conductivity values in layer 1 were dominated by the lithofacies assemblages 1-3, 5 and 6 and were distributed across 9 zones with values ranging from 1.81(zone 2) to 28.16 ft/day (zone 9). Layer 1 was simulated as an unconfined aquifer. However, the LPF package needs both specific yield and specific storage (specific yield/specific thickness) as model input parameters for a convertible aquifer. Hence, both the values were specified in the LPF package. The zone-wise distribution of calibrated hydraulic conductivity and specific storage values for model layer 1 were delineated in Figure 4.2. Hydraulic conductivity values in layer 2 were dominated by the MSF hydrographic units with lithofacies assemblages 3-4, 7 and 9 and were distributed across 5 zones with values ranging from 0.45 (zone 13) to 4.88 ft/day (zone 17). Hydraulic conductivity values in layer 3 were dominated by the MSF and LSF deposits with lithofacies assemblages 4, 7-10 and were distributed across zones 19 to 26 with values ranging from 0.12 (zone 21) to 1.82 ft/day (zone 14). Model layers 2 and 3 were designated as confined aquifers with a constant specific storage of $5.498 \times 10^{-6}$ /ft. All the model layers were assumed to be isotropic in lateral direction as the lateral distribution in hydraulic conductivity was not available from previous investigations. The equivalent conductivity between the model layers that governs the flow was assumed to be the harmonic mean of the conductivity values across the bedding planes. A constant value of 0.005 was assumed for vertical anisotropy for all three model layers. The LPF package used in the simulation automatically calculates the transmissivity values for each model cell as the product of hydraulic conductivity and the saturated thickness of the aquifer.



|  | Kx | Ky | Kz |  | Color |
|---|---|---|---|---|---|
| 2 | 2.72 | 2.72 | 0.0136 | 0 | 🟨 |
| 3 | 5.84 | 5.84 | 0.0292 | 0 | 🟧 |
| 4 | 3.02 | 3.02 | 0.0151 | 0 | 🟩 |
| 5 | 12.39 | 12.39 | 0.06195 | 0 | ⬛ |
| 6 | 8.19 | 8.19 | 0.04093 | 0 | 🟦 |
| 7 | 8.72 | 8.72 | 0.04362 | 0 | 🟪 |
| 8 | 7.62 | 7.62 | 0.03812 | 0 | 🟥 |
| 9 | 22.53 | 22.53 | 0.11265 | 0 | 🟫 |
| 10 | 21.45 | 21.45 | 0.10726 | 0 | 🟥 |

|  | Ss | Sy | Porosity | Porosity2 | Color |
|---|---|---|---|---|---|
| 2 | 0.0001767 | 0.15 | 0.01 | 0 | ⬜ |
| 3 | 0.0002504 | 0.15 | 0.01 | 0 | 🟩 |
| 4 | 0.000365 | 0.15 | 0.01 | 0 | 🟧 |
| 5 | 0.000447 | 0.15 | 0.01 | 0 | 🟫 |
| 6 | 0.00053 | 0.15 | 0.01 | 0 | 🟥 |
| 7 | 0.000612 | 0.15 | 0.01 | 0 | 🟪 |
| 8 | 0.000695 | 0.15 | 0.01 | 0 | 🟩 |
| 9 | 0.000778 | 0.15 | 0.01 | 0 | 🟪 |
| 10 | 0.00086 | 0.15 | 0.01 | 0 | 🟩 |

**Figure 4.2** Zone-wise distribution of hydraulic conductivity (feet per day) and specific storage (per feet) in model layer 1

### 4.2.4 Miscellaneous packages

In order to solve the simultaneous equations that were generated by the finite difference method, the PCG package was used. A maximum of 100 iterations with 25 inner iterations were defined to solve the nonlinear equations. The head change criteria for convergence was assumed to be 0.001 ft.

The OC package used in simulation gives flexibility in printing and saving the output results in terms of piezometric heads, drawdowns, and volumetric budget components at the end of user specified stress periods.

## 4.3 MODEL DEPENDENT PACKAGES

Model dependent packages include the MODFLOW packages that are specific to the study area. Major groundwater flows in or out of the model occur primarily by recharge from the surrounding mountains, underflow through the model boundary, pumping from wells, and evaporation from water bodies. Recharge (RCH), evapotranspiration (EVT), well (WEL) and general head boundary (GHB) packages in MODFLOW were considered for simulation.

### 4.3.1 Mountain front recharge

As recharge to the shallow aquifer in the study area is primarily dominated by monsoon precipitation and basin slope, the Waltemeyer (2001) equation developed for the Tularosa Basin seems appropriate in estimating the mountain front recharge. Results of the calibration by evaluating different estimates of recharge will be submitted to a journal article. Residual statistics on the simulated piezometric heads during calibration also suggested that the Waltemeyer equation is more appropriate in estimating the basin recharge. A total of 3,364 ac-ft/year of recharge was estimated using this method. The mean annual recharge flows for the individual recharge zones are provided in Table 3.2. Recharge along the San Andres Mountains was further classified into three zones based on precipitation distribution. Recharge rates for each zone were estimated as the ratio of mean annual recharge to the zone area and were distributed equally among all the cells in that zone. A total of 216 finite difference grid cells with 53 in San Andres zone-1, 46 in San Andres zone-2, 39 in San Andres zone-3, 69 in Organ and Goat, and 9 in Caballo zone were represented along the basin boundaries to input the recharge fluxes. Since most of the precipitation in the study area occurs during the irrigation season, total annual recharge flux was further divided between primary and secondary irrigation seasons in ratios of 0.75 and 0.25, respectively.

### 4.3.2 Evapotranspiration

Three water bodies were identified as potential sources for evaporation in the study area. As agriculture in the study area was almost negligible, transpiration from the vegetation was not considered during simulation. A total of 52 cells with 26 in Isaacks Lake and 26 cells in the two other small lakes near the POR were used in simulation. Since precipitation is the chief source of evaporation from water bodies, the primary irrigation season was considered for ET estimation. A constant evaporation rate of $6.641 \times 10^{-6}$ ft/day from water bodies (Weeden and Maddock 1999), with an extension depth of 6 ft (OSE-2007 flow model) were specified in the EVT package. Even though groundwater levels in the region were deep enough for evaporation not to take part in simulation, the EVT package was considered in simulation to utilize effectively the surface elevations from the 10 m DEM of the study area.

### 4.3.3 General head boundary

A total of three zones were identified for representing head dependent fluxes across the model boundary. Flow across the northern boundary was assumed to enter into the basin as underflow through layer 1 (between Caballo Mountains and POR) based on the available groundwater gradient. Flow leaving the SJDM Basin to the Rincon Valley was simulated with a distributed boundary between Rincon Hills and Caballo Mountains. A buried horst located to the southeast of Las Cruces represented water leaving the SJDM Basin to the east Mesilla Basin through USF sediments.

A total of 74 cells with 19 along the northern boundary, 24 along the horst, and 31 along the Rincon connection were used in representing the flow entering or leaving the basin. Water table elevations in the adjacent model cells outside of the model boundary were used to represent the boundary head. An initial value 10 $ft^2$/day was assigned for boundary conductance and is changed during the calibration process. All the head dependent boundary cells with conductance factor and boundary head were specified in the GHB package.

### 4.3.4 Pumping

Major groundwater withdrawals through pumping were observed in the southern portion of the study area in and around the CLC. The largest municipal groundwater diverters in the southern Jornada include CLC, and Jornada and Moongate Water Company wells with pumping rates of 6.082 $ft^3$/sec, 1.353 $ft^3$/sec, and 2.105 $ft^3$/sec, respectively, in 2007. Pumping was insignificant in the central and northern part of the study area primarily due to less human activity. Domestic and livestock wells were sparsely distributed across the study area with a cumulative pumping of 0.180 $ft^3$/sec. Since agriculture was almost absent, equal pumping rates were assigned to both primary and secondary irrigation seasons. Almost all the wells in the study area are drawing water from layer 1. About 59 ac-ft/year of geothermal water was assumed to move upwards into the bottom of the aquifer, which corresponds to rows 100 to 117 and columns 51 to 56 in the model. A total of 18 cells in layer 3 with a positive flow rate of 0.00452 $ft^3$/sec/cell were assigned for simulating geothermal flow. Pumping flow rates for each stress period were defined in the well package. Variation of cumulative pumping from the entire study area during the simulation period was provided in Figure 4.3. The estimates of pumping rates used in the modeling were in accordance with previous records.

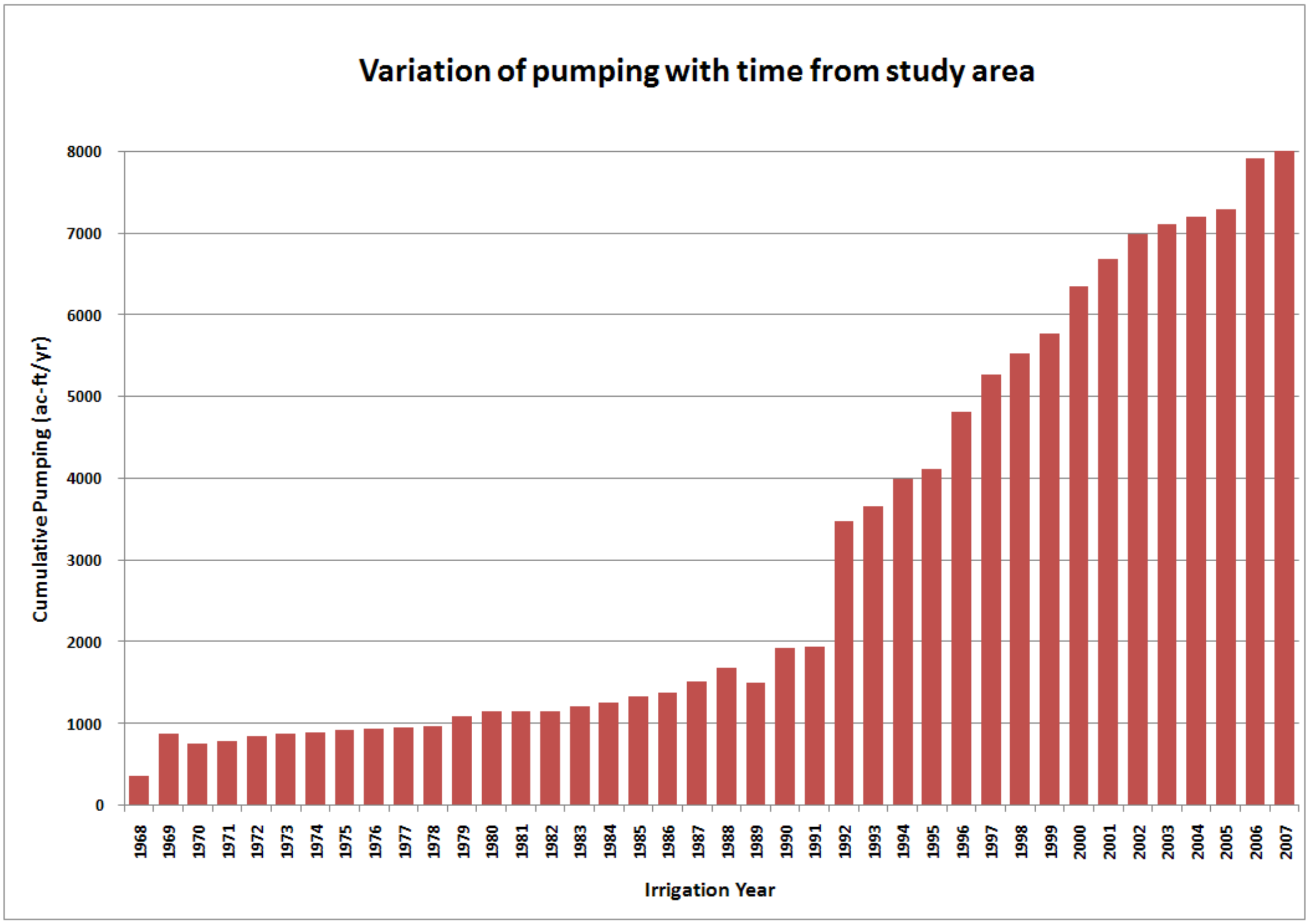


**Figure 4.3** Variation of cumulative pumping with time from the model area

## 4.4 SIMULATION

MODFLOW name file comprising all the basic and model specific packages was imported into GV for simulation and generated cell-by-cell head, drawdown, and flow files. The LPF package was defined using parameters. The ZONE and MLT packages were used in the model to support these parameters. The GHB and WEL packages were defined using list data. MODFLOW simulation created list (LST), and global (GLO) output packages that store maximum head change and residual for each iteration and the volumetric budget at the end of each time step. The GV displays the contour map of piezometric heads and drawdowns at the end of simulation period for visualizing the groundwater gradient in the study area.

## 4.5 SENSITIVITY ANALYSIS

To quantify the uncertainties in the model caused by uncertainty in estimating aquifer parameters and boundary stress components, a one-factor-at-a-time (OAT) sensitivity analysis was performed on the simulated model (Anderson and Woessner 1992). As the geological boundaries of the basin were delineated accurately by Hawley and Kennedy (2004), the geometry of the system was not changed during calibration. Classic sensitivity analysis was performed by changing one parameter at a time and observing the change in the model computed head. During the sensitivity analysis, values for hydraulic conductivity, storage coefficient, recharge rate, and boundary conductance factor were systematically changed within the given range. Statistical parameters that represent the effectiveness of sensitivity included root mean square (RMS) value, mean error (ME), sum of squared deviations in computed head, and absolute mean error.

Hydraulic conductivity values for each layer were estimated along the cross sections by the weighted average method based on the dominant lithofacies assemblages. As the range in values for hydraulic conductivity is very high among the adjacent lithofacies leading to over estimation of average values for most of the zones, hydraulic conductivity was assumed to be the most uncertain parameter in the model simulation. Zones 2, 3, 4, 5, and 7 were identified as the most sensitive parameters and were modified by a factor ranging from 0.5 to 1.5.

Specific storage for layer 1 was defined as the ratio of specific yield to saturated thickness and was identified as one of the model sensitive parameters. A range of values for specific yield from 0.1 to 0.2 were used to observe the change in magnitude of heads for the model computed cells.

## 4.6 MODEL CALIBRATION

Calibration of a groundwater flow model refers to the process of comparing the hydraulic heads after simulation with the actual field measurements using an objective function (Hill and Tiedeman 2007). Residual statistical parameters such as mean error, absolute mean error, sum of squares of residual errors, and root mean square error define the effectiveness of model calibration. Simulation is a forward modeling technique in which the hydraulic heads can be obtained as a result of inputting the parameters used in the groundwater flow equation. On the contrary, calibration is an inverse modeling technique in which the model input parameters are estimated by minimizing the objective function in terms of hydraulic heads.

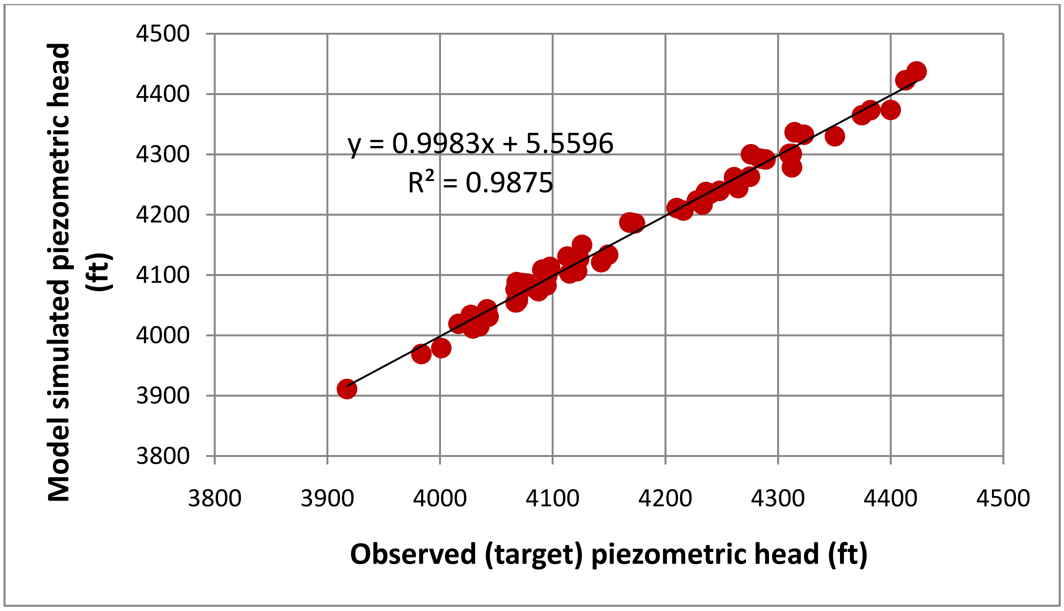
The MODFLOWP software developed by the USGS was used for performing the sensitivity and parameter estimation processes of the groundwater flow (GWF) simulation model. The MODFLOWP minimizes the residual error values using gradient method. Gradient method considers the derivative of the objective function surface. Gauss-Newton normal equations were developed by substituting the linearized approximation of the gradient in the objective function. The modified Gauss-Newton technique was used by MODFLOWP to solve the nonlinear regression equation in terms of model input parameters.

Calibration with the external inverse model (MODFLOWP) in GV is achieved in the following three ways:

(1) Calculation of calibration statistics for head,
(2) Automated parameter sensitivity analysis, and
(3) Automatic model calibration using nonlinear least squares.

In the current study, 72 analytical (target) wells during the irrigation years 1971, 1979, 1989, and 2000 were considered calibrating targets. All the target wells were distributed evenly across the central and southern part of the study area. It was assumed that the water levels in the analytical wells were measured accurately with negligible associated error. Significant differences in the water levels in the adjacent wells were observed even though the water levels in these wells were measured at the same time. During the calibration process, the model input parameters such as hydraulic conductivities, recharge fluxes, storage characteristics, and general head conductance factors were estimated such that the model output matches closely with the field measured values.

A close match between the model simulated piezometric heads and the target heads was observed and is shown in Figure 4.4 prior to model calibration. Overall, the model seemed to overestimate the heads in the areas with less water table elevations and underestimated the head in the regions with high water table elevations.



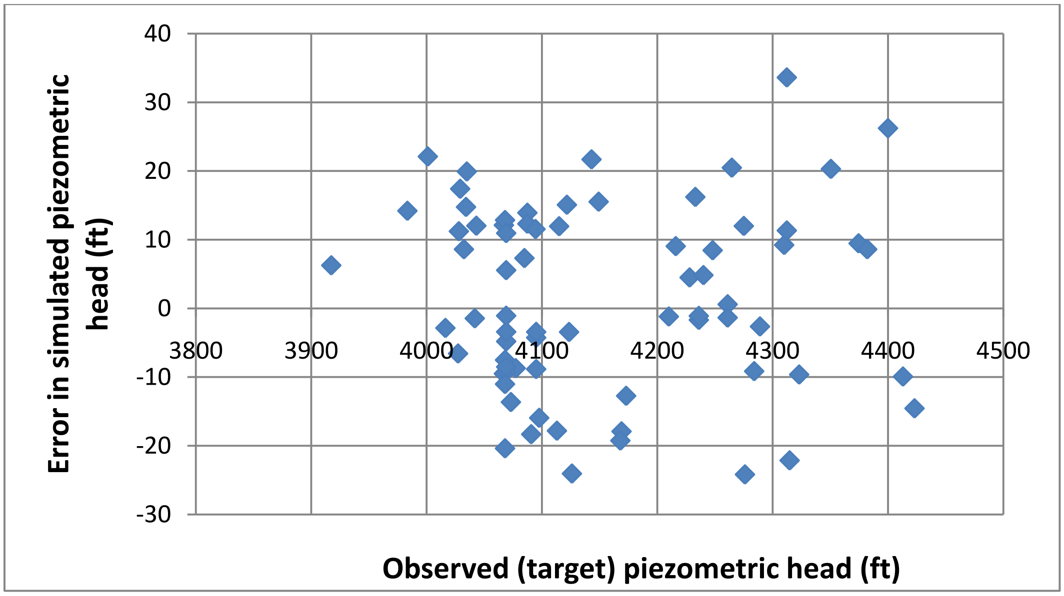


**Figure 4.4** Comparison of model simulated piezometric heads with target heads (prior to calibration)

# 5. RESULTS AND DISCUSSION

## 5.1 INTRODUCTION

This chapter presents the results of numerical simulation compared with corresponding calibration targets at the end of 1971, 1979, 1989, and 2000 primary irrigation seasons. A total of 72 piezometric head targets (collected from OSE records and NASA White Sands Testing Facility database) situated mostly in the central and eastern part of the study area were considered for model calibration. Typical statistical parameters that represent the model effectiveness include mean error (ME), root mean square of the errors (RMS), and sum of squared errors (SSE) in piezometric heads. The aquifer parameters such as hydraulic conductivity along rows and columns and specific yield for model layer 1 were identified as the most sensitive parameters to the simulated heads. Even though the boundary stresses (including recharge flux and boundary head conductance factor) were sensitive to simulation heads, their effect was almost negligible due to a lower contribution to storage. Finally, the calibrated model was simulated to present the final results in the form of volumetric budget components, contours of piezometric heads, and drawdowns at the end of the simulation period.

## 5.2 RESULTS OF SENSITIVITY ANALYSIS

Sensitivity analysis refers to the process of identifying the model parameters that have the most effect on model calibration or prediction. The purpose of sensitivity analysis is to quantify the uncertainty in the model simulated heads caused by the uncertainty in the estimates of aquifer parameters, stresses and boundary conditions. In order to identify the model sensitive parameters, an automated sensitivity run was performed in which GV runs MODFLOW several times and computes calibration statistics for each simulation. Aquifer parameters that were considered for sensitivity analysis include horizontal hydraulic conductivity (zones 2 to 10), specific storage for model layer 1 (zones 2 to 10), recharge flux, and a boundary head conductance factor along the model boundary.

The parameters that were most sensitive to the model were horizontal hydraulic conductivity and specific yield for model layer 1. Based on the uncertainty in the estimated parameters, the multiplier values for $K_x$ were varied from 0.5 to 1.5 (at 0.05 intervals) and specific yield was varied from 0.10 to 0.20 (at 0.025 intervals). The model was almost insensitive to boundary stress parameters due to their low contribution to storage and their distribution along the model boundary, far away from the calibrated target well locations. Figures 5.1 thru 5.7 show the sensitivity of the model in terms of SSE and ME to the aquifer characteristics of layer 1.

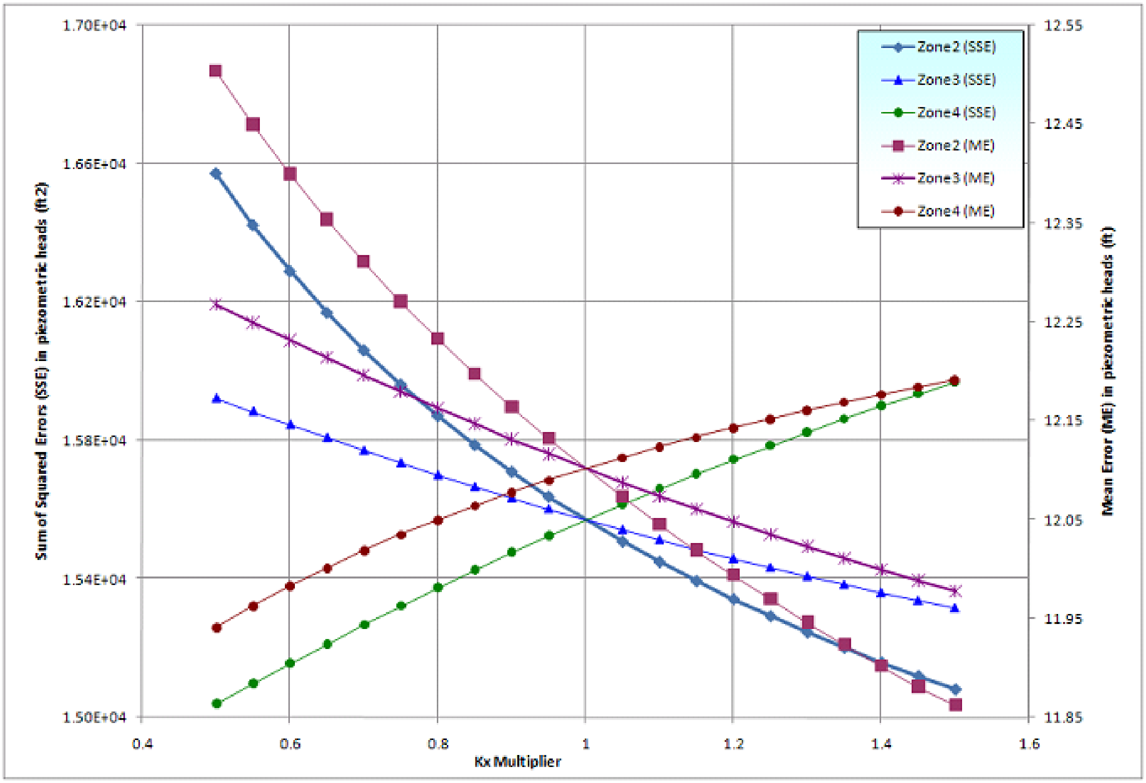


**Figure 5.1** Model sensitivity to hydraulic conductivity (zones 2 to 4) in layer 1

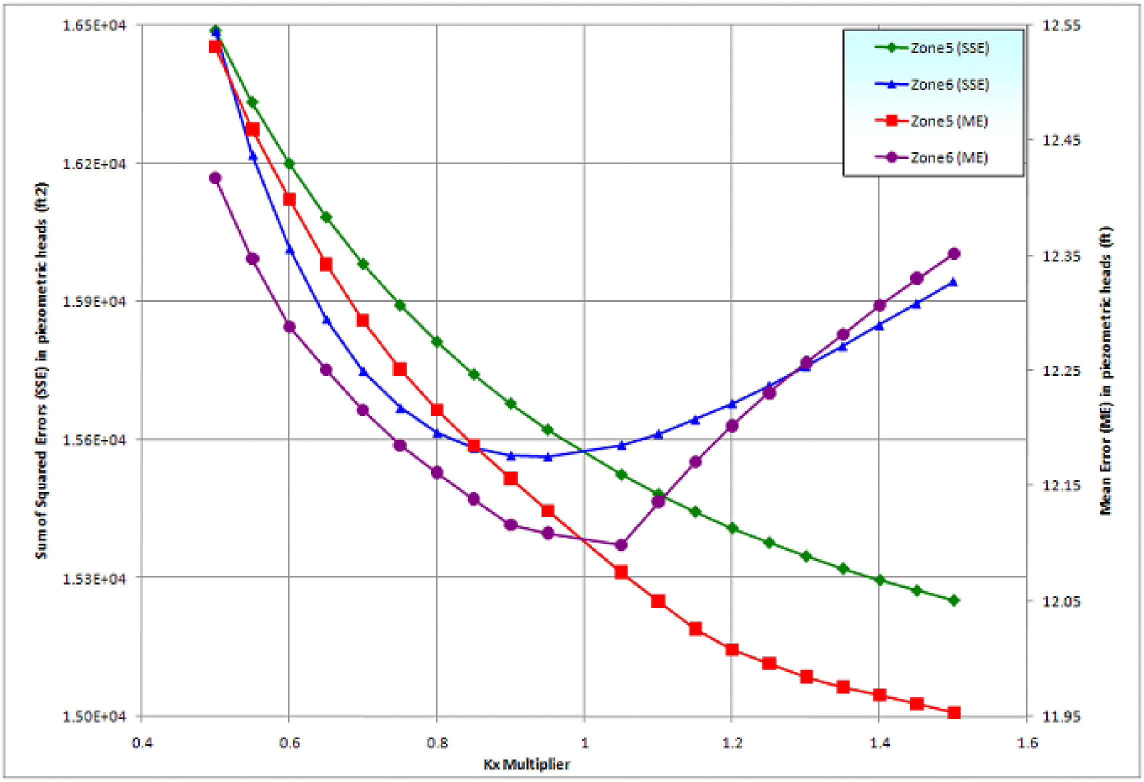


**Figure 5.2** Model sensitivity to hydraulic conductivity (zones 5 and 6) in layer 1

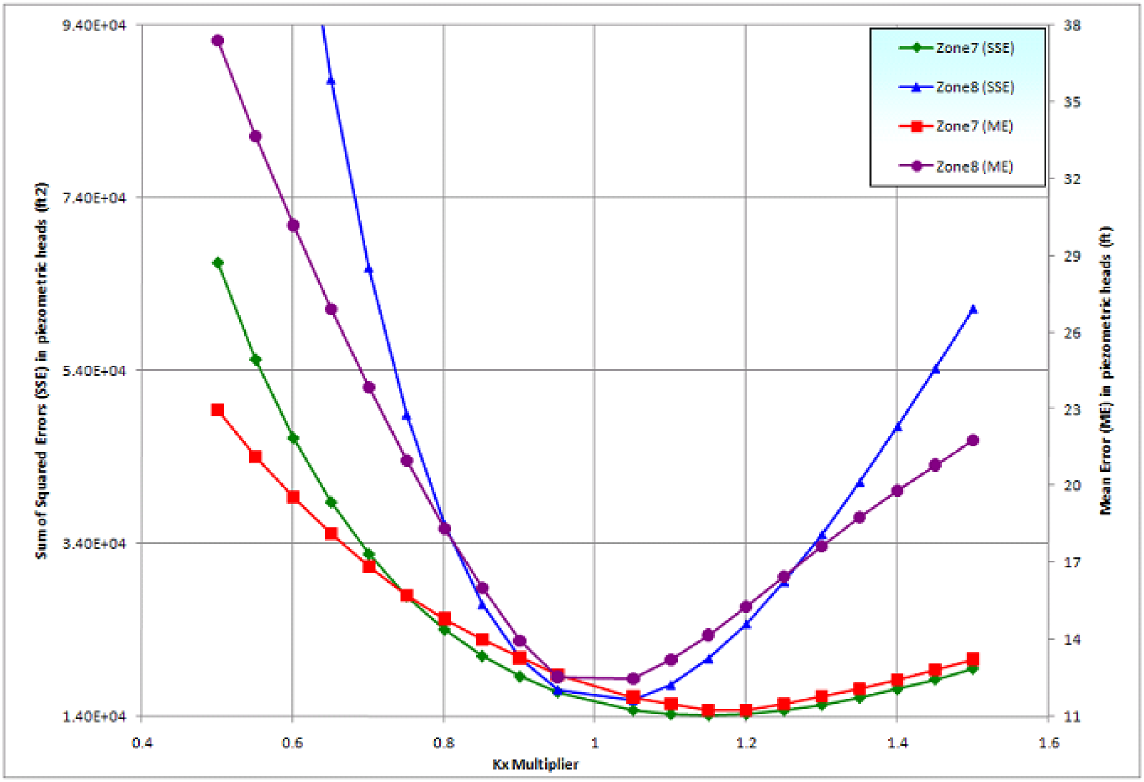


**Figure 5.3** Model sensitivity to hydraulic conductivity (zones 7 and 8) in layer 1

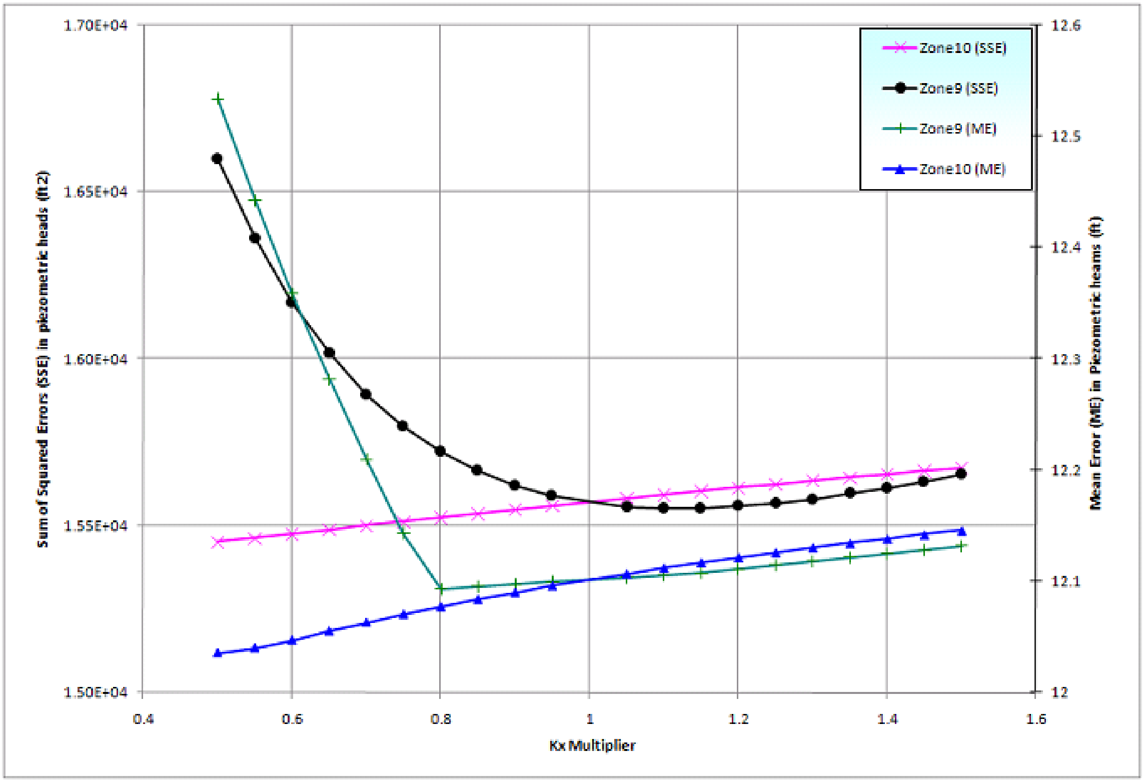


**Figure 5.4** Model sensitivity to hydraulic conductivity (zones 9 and 10) in layer 1

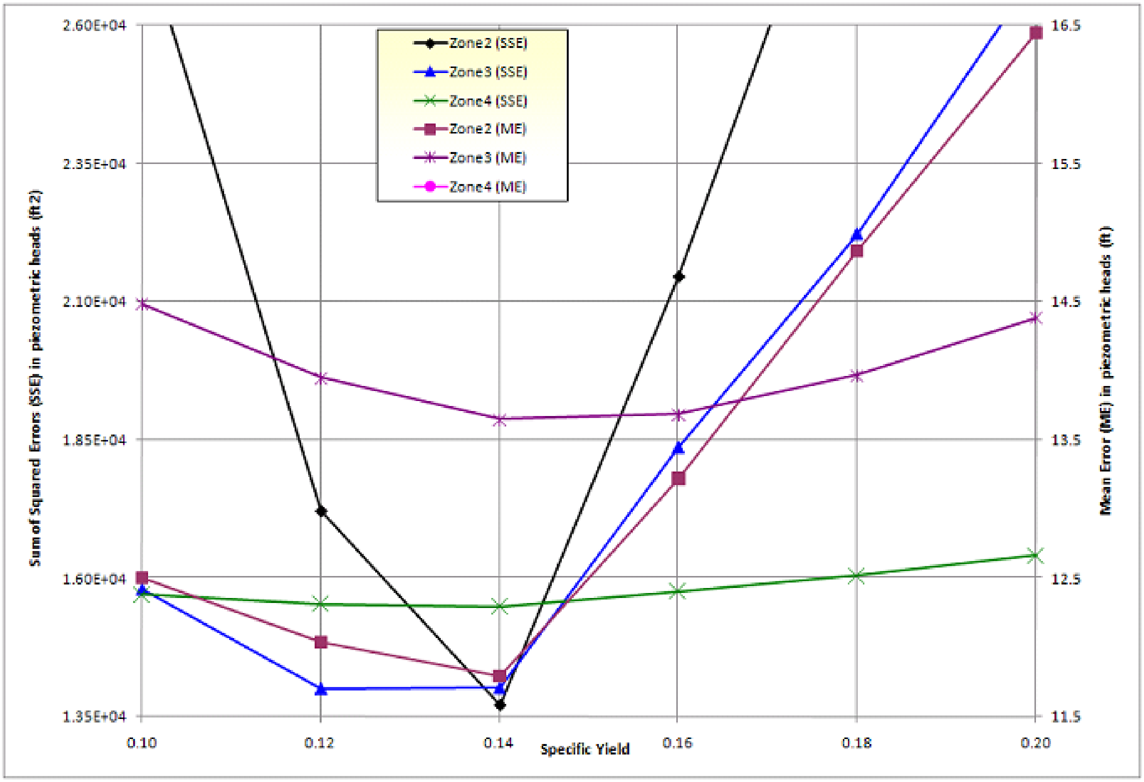


**Figure 5.5** Model sensitivity to specific yield (zones 2 to 4) in layer 1

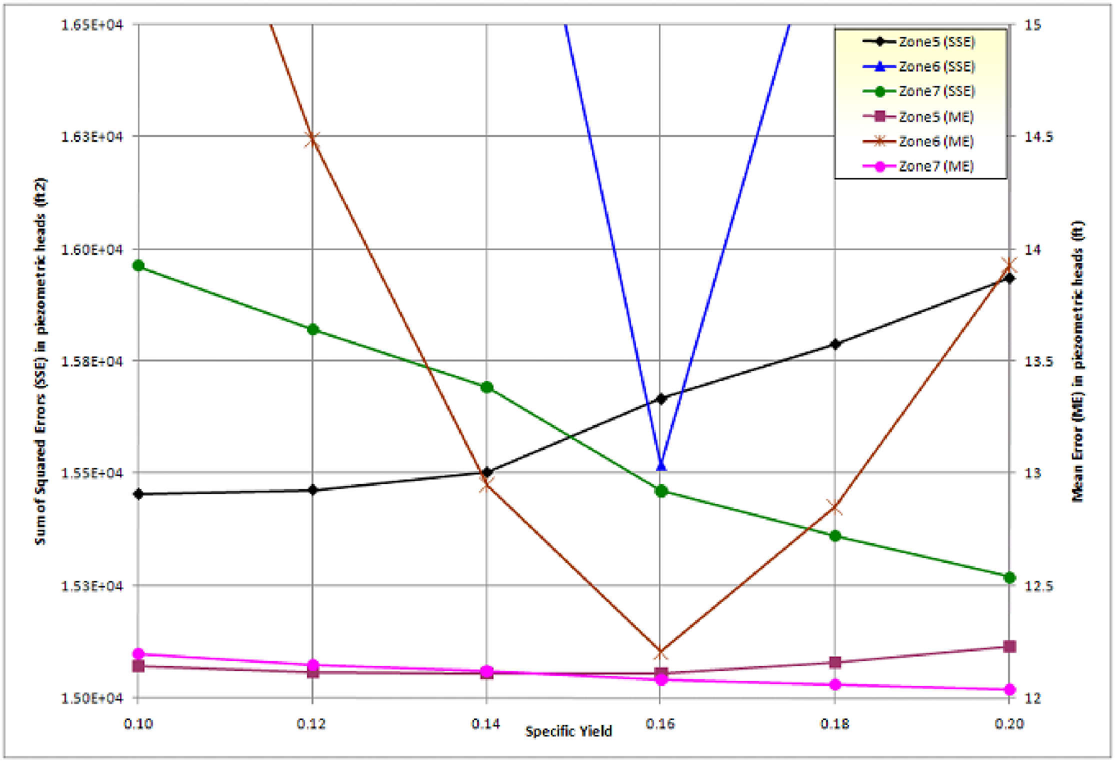


**Figure 5.6** Model sensitivity to specific yield (zones 5 to 7) in layer 1

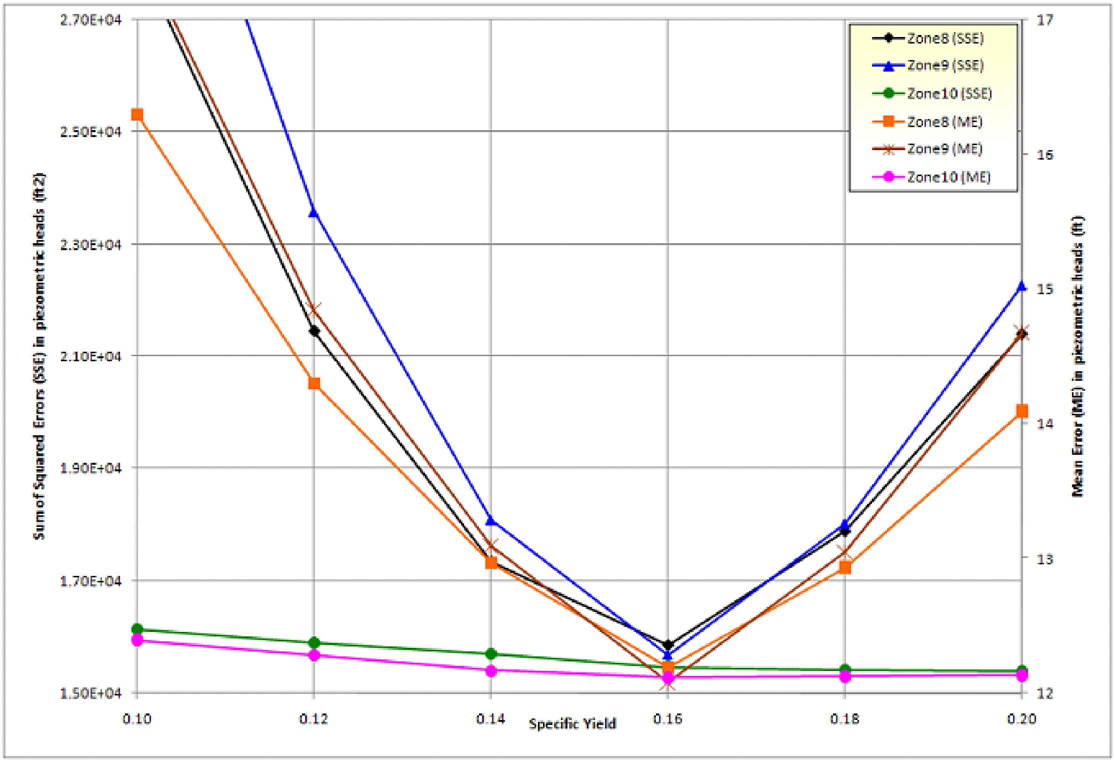


**Figure 5.7** Model sensitivity to specific yield (zones 8 to 10) in layer 1

## 5.3 RESULTS OF CALIBRATION

A total of 72 target wells were considered for calibration. Effective calibration was achieved by minimizing the error between model simulated heads and target heads. Since hydraulic conductivity and specific yield were recognized as the final sensitive parameters to the model, the initial values of these parameters were calibrated so that the parametric values would optimize the objective function. During calibration, careful thought was given to changing the model sensitive parameters. These parameters were only changed between their allowable minimum and maximum limits (Hawley and Kennedy 2004). The initial and calibrated values of the model sensitive parameters are given in Table 5.1. Estimates of mountain front recharge from the Waltemeyer equation resulted in a close match of the simulated heads over the Hearne and Dewey equation. Also, the estimates of recharge by the Waltemeyer equation were in accordance with the previously published reports. While calibrating the model, SSE was reduced from 15,450.02 ft$^2$ to 9,482.19 ft$^2$, absolute mean error was reduced from 12.04 ft to 9.40 ft, and the RMS was reduced from 14.65 ft to 11.48 ft.

The MODFLOW2000 calibration tool in GV was used for systematically changing and estimating the model sensitive parameters in order to match with the measurements. A close match between the model simulated heads and target heads was observed through the calibration process and is shown in Figure 5.8. Most of the residuals in piezometric heads were within an error of 10 feet as represented in Figure 5.9.

Water table elevations were measured in selected wells across the study area to achieve effective calibration. Measured and adjusted piezometric elevations (groundwater hydrographs) for the wells: NMSU Ranch, USDA Jornada, Las Cruces, and an unknown well are illustrated in Figures 5.10 through 5.13. It was observed that the simulated water table elevations were lower bound in the case of central and western parts of the study area whereas the model was predicting higher water table elevations in the eastern part. Adjusted values of water table elevations were converging toward the measured values in the central portion of the study area. The trend of adjusted water table elevations for the USDA Jornada range well seemed to be uncertain.

**Table 5.1** Estimated model sensitive parameters in calibration

| *Parameter* | *$K_x$ (Lateral hydraulic conductivity)* | | *$S_s$ (Specific yield / Layer thickness)* | |
|---|---|---|---|---|
| *Zone (Fig. 4.2)* | *Initial Value (fpd)* | *Calibrated value (fpd)* | *Initial Value (per feet)* | *Calibrated value (per feet)* |
| 2 | 1.81 | 2.72 | $1.99 \times 10^{-3}$ | $1.77 \times 10^{-3}$ |
| 3 | 3.89 | 5.84 | $2.82 \times 10^{-3}$ | $2.50 \times 10^{-3}$ |
| 4 | 6.04 | 3.02 | $3.65 \times 10^{-3}$ | $3.65 \times 10^{-3}$ |
| 5 | 8.26 | 12.39 | $4.47 \times 10^{-3}$ | $4.47 \times 10^{-3}$ |
| 6 | 8.19 | 8.19 | $5.30 \times 10^{-3}$ | $5.30 \times 10^{-3}$ |
| 7 | 8.72 | 8.72 | $6.12 \times 10^{-3}$ | $6.12 \times 10^{-3}$ |
| 8 | 7.62 | 7.62 | $6.95 \times 10^{-3}$ | $6.95 \times 10^{-3}$ |
| 9 | 28.16 | 22.53 | $7.78 \times 10^{-3}$ | $7.78 \times 10^{-3}$ |
| 10 | 21.45 | 21.45 | $8.60 \times 10^{-3}$ | $8.60 \times 10^{-3}$ |

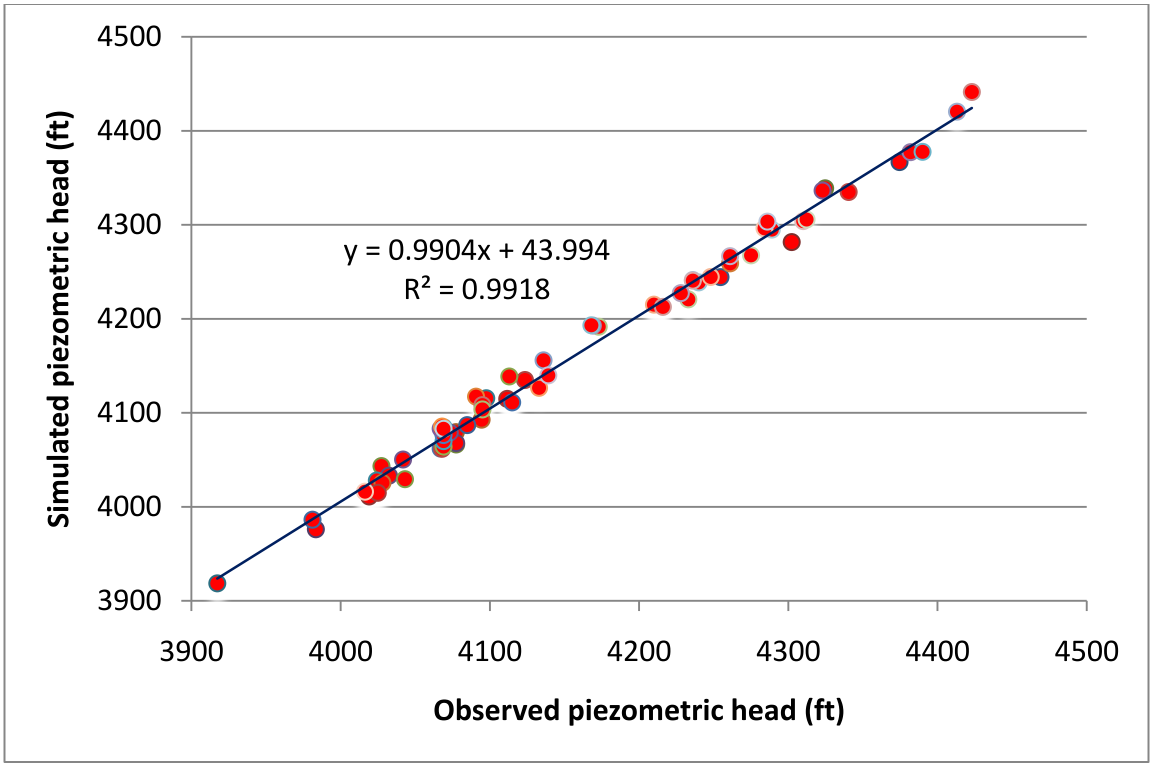


**Figure 5.8** Comparison of model calibrated heads with observed piezometric heads

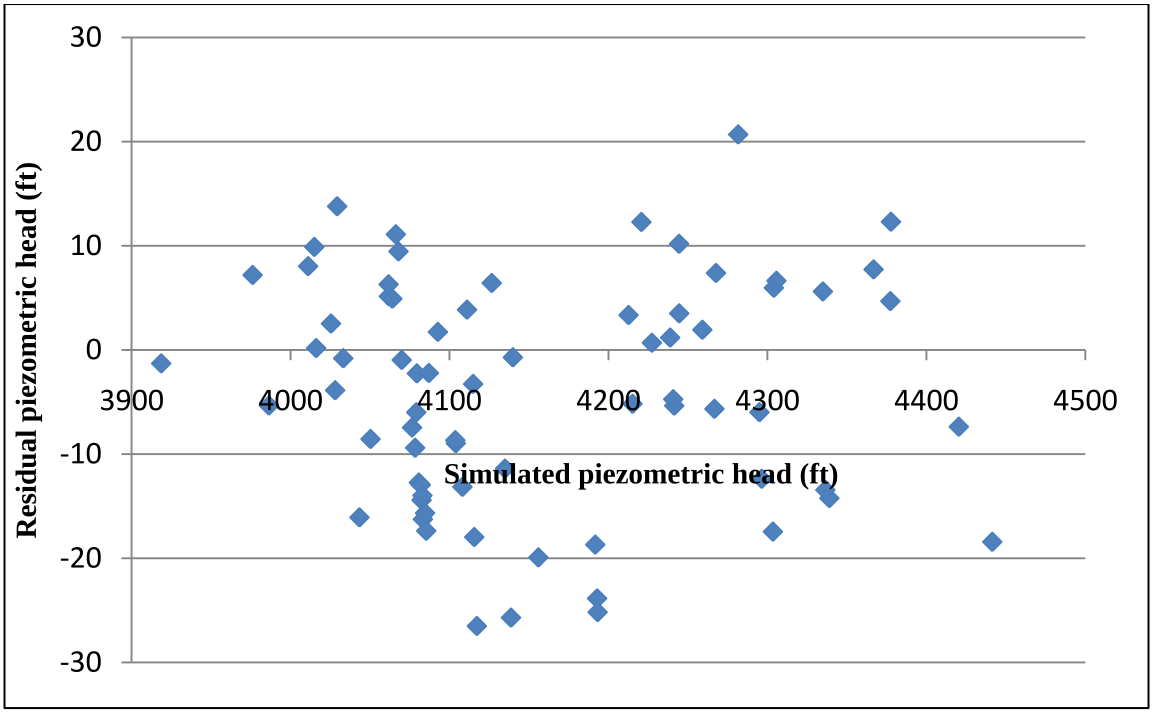


**Figure 5.9** Distribution of residuals in calibrated piezometric heads

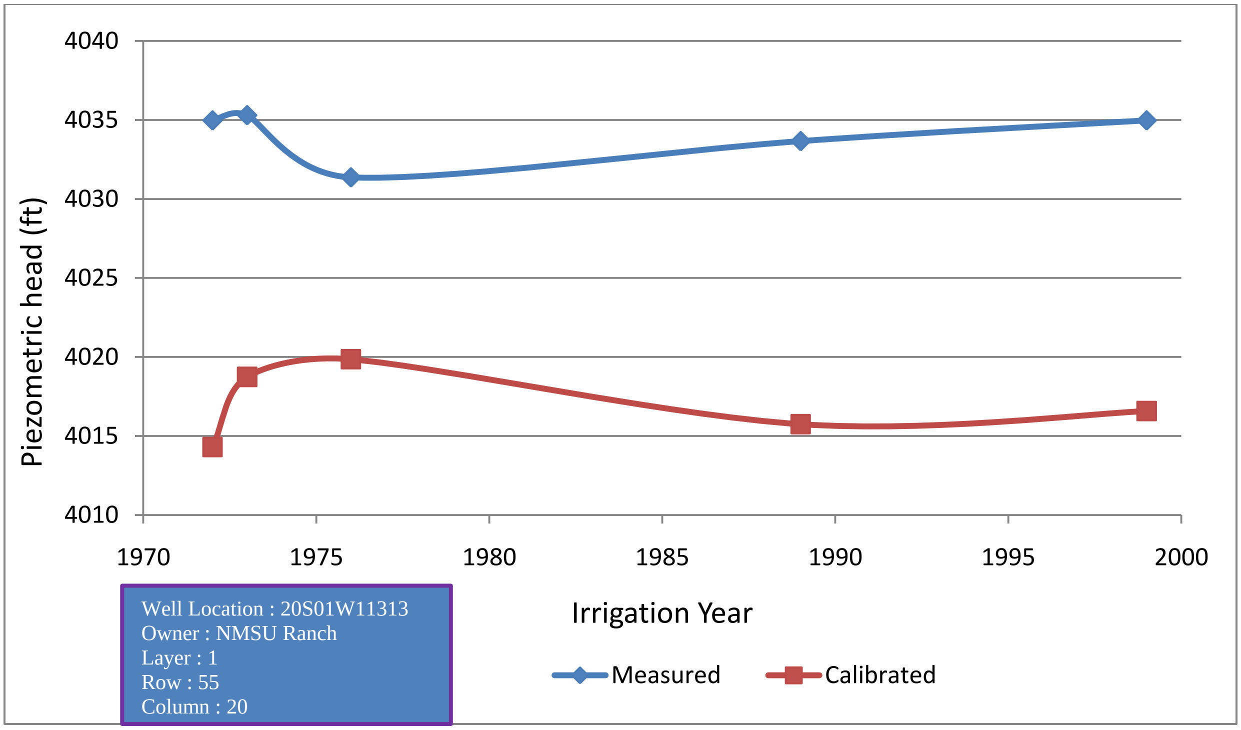


**Figure 5.10** Adjusted water table elevations (after calibration) for NMSU Ranch well

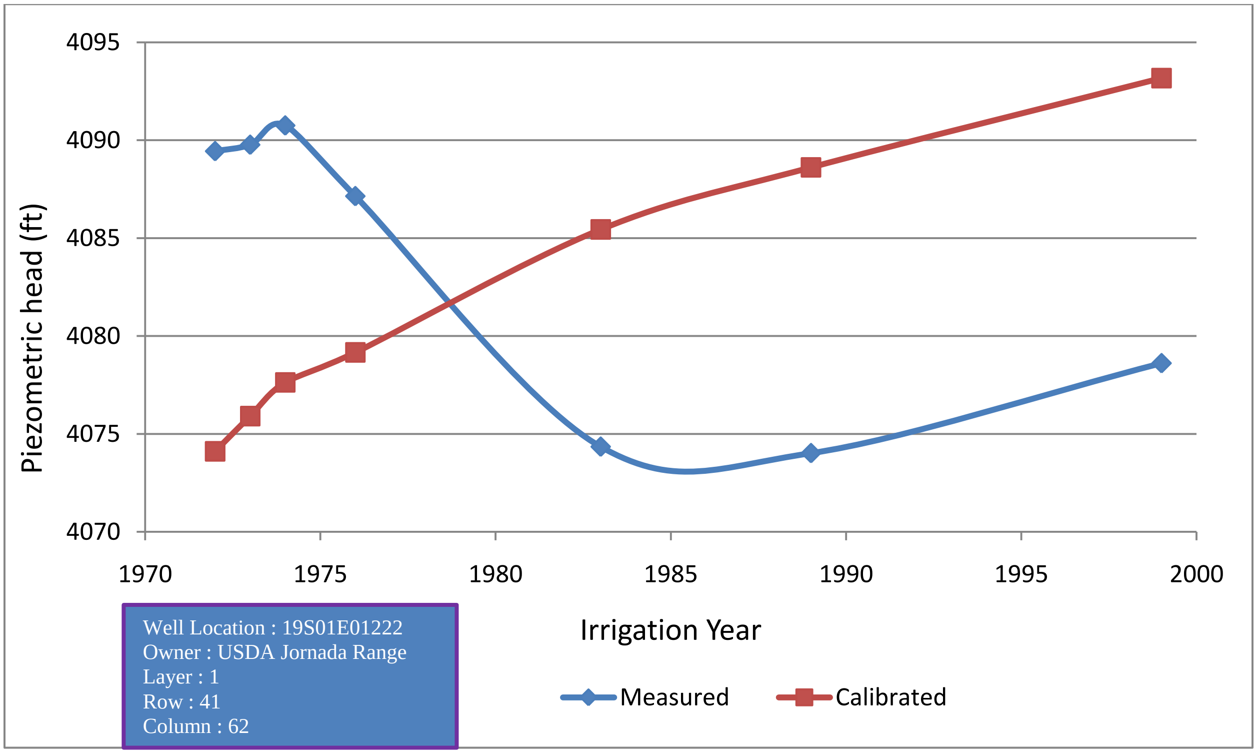


**Figure 5.11** Adjusted water table elevations (after calibration) for USDA Jornada well

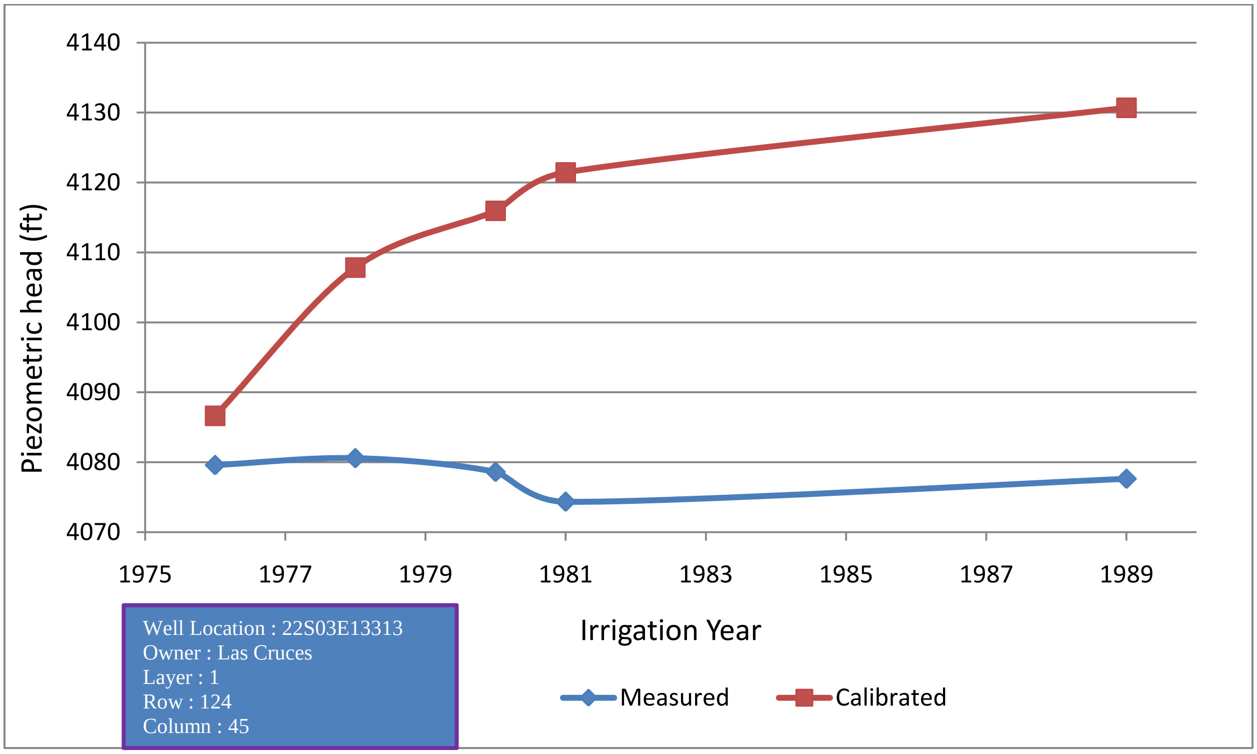


**Figure 5.12** Adjusted water table elevations (after calibration) for Las Cruces well

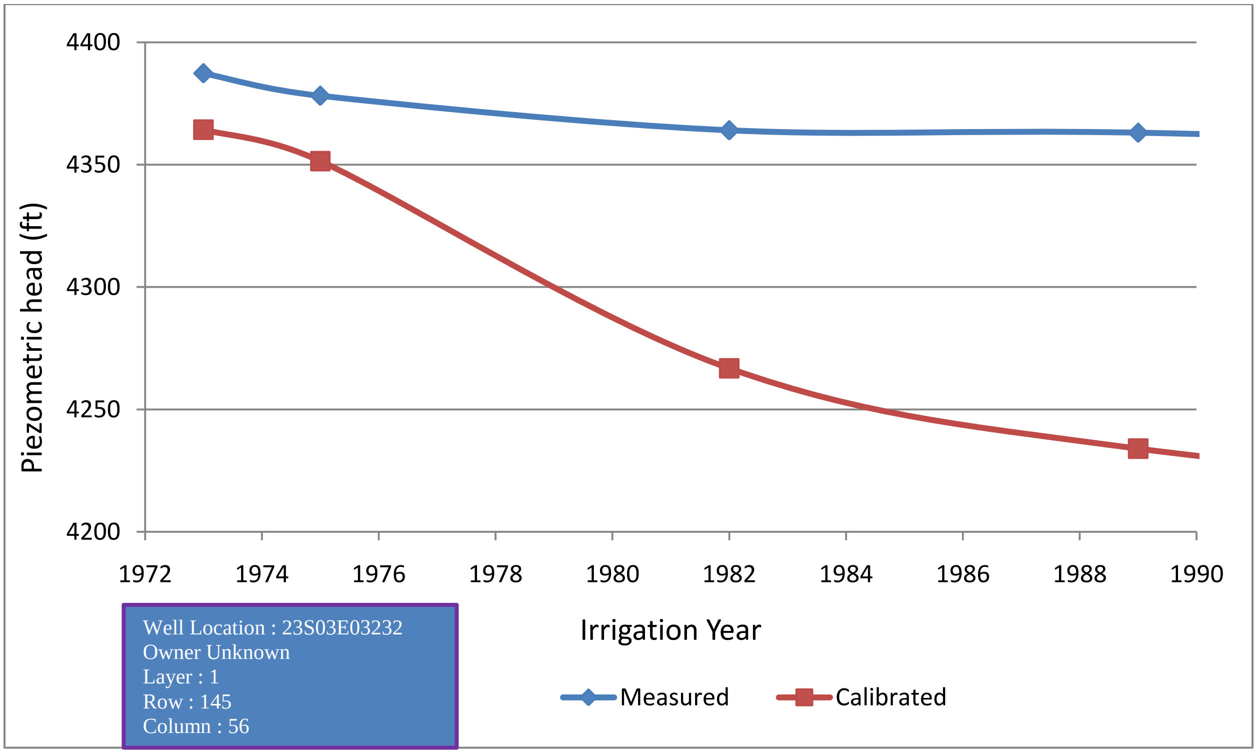


**Figure 5.13** Adjusted water table elevations (after calibration) for unknown well

## 5.4 RESULTS OF SIMULATION

Model simulation results were interpreted in terms of volumetric budget, groundwater head, and drawdown contours for each stress period. Volumetric inflows and outflows for primary and secondary irrigation seasons of selective irrigation years are depicted in Tables 5.2 and 5.3 respectively. Since the field measured piezometric heads were used for the starting condition during the transient run, the model response during initial time steps is not presented in the report. A gradual decrease in inflow through the northern boundary of the study area from the year 1987 to 2007 was observed. The inflow into the study area through northern boundary was 757 ac-ft in the year 1987 whereas this inflow was gradually reduced to 665 ac-ft in the year 2007. A constant inflow of 59 ac-ft/year was entering into the layer 3 of the model as geothermal flow. A constant inflow of mountain front recharge of 3,322 ac-ft/year was entering into layer 1 of the model. Total inflow volume entering into the model had been decreased from 59,203 ac-ft in the year 1987 to 36,935 ac-ft in the year 2007.

The outflow due to pumping was marginally increased from the year 1972 (828 ac-ft) to 1987 (1541 ac-ft). The increase in model outflow due to pumping was more rapid between the years 1987 (1541 ac-ft) and 2007 (7930 ac-ft). The outflow due to evapotranspiration seemed to be insignificant. The outflow from the SJDM Basin to the Mesilla Basin and Rincon Valley through horst and the Rincon connection was almost constant during the simulation period, and observed to be about 735 ac-ft/yr. The total outflow volume leaving the model was decreased from 59,198 ac-ft in the year 1987 to 36,930 ac-ft in the year 2007.

The location of the calibrated target wells and the contour map of simulated piezometric heads for model layer 1 is presented in Figure 5.14. Contours are drawn at 25 ft interval in the west to central portion and at 50 ft interval elsewhere. A steep gradient in water table elevation can be observed in the east to northeastern part of the study area, primarily due to a steep basin slope. The contours are sparsely distributed in the western region where in the basin fill deposits resulted in a flat gradient in water table elevations. The contours of drawdown in the southern part of the study area near Las Cruces are closely spaced and low in magnitude due to the increased pumping rates.

Kriged surface of water table elevations for the years 1968 and 2007 are illustrated in Figure 5.15. Drawdown due to pumping at any location on the map at the end of the simulation period can be obtained as the difference in pixel values of the two diagrams from Figure 5.15. The groundwater flow direction in the study area is primarily toward the northwest to west direction. It can be observed that the highest water table elevations were along the San Andres and Organ Mountain ranges and the lowest water table elevations were in the central west part of the aquifer. It can be seen that the water table elevations decreased in 2007 when compared to

1968 in the southern and southeastern part of the study area. However, the water table elevations increased in the eastern and north eastern portions of the study area.

**Table 5.2** Volumetric inflows for selective irrigation years

| Irrigation year | Irrigation Season | Storage (Ac-ft) | Geo Therm. (Ac-ft) | North Boundary (Ac-ft) | MF Recharge (Ac-ft) | Total (Ac-ft) |
|---|---|---|---|---|---|---|
| 1987 | Secondary | 18067 | 19 | 245 | 1070 | 19401 |
| | Primary | 36998 | 40 | 512 | 2252 | 39802 |
| 1992 | Secondary | 15104 | 19 | 235 | 1070 | 16428 |
| | Primary | 31043 | 40 | 493 | 2252 | 33828 |
| 1997 | Secondary | 13185 | 19 | 227 | 1070 | 14501 |
| | Primary | 27179 | 40 | 477 | 2252 | 29948 |
| 2002 | Secondary | 11753 | 19 | 220 | 1070 | 13062 |
| | Primary | 24340 | 40 | 462 | 2252 | 27094 |
| 2007 | Secondary | 10712 | 19 | 215 | 1070 | 12016 |
| | Primary | 22177 | 40 | 450 | 2252 | 24919 |

**Table 5.3** Volumetric outflows for selective irrigation years

| Irrigation year | Irrigation Season | Storage (Ac-ft) | Wells (Ac-ft) | GHB (Ac-ft) | Total (Ac-ft) |
|---|---|---|---|---|---|
| 1987 | Secondary | 18653 | 496 | 236 | 19385 |
| | Primary | 38270 | 1045 | 498 | 39813 |
| 1992 | Secondary | 15062 | 1114 | 237 | 16413 |
| | Primary | 30995 | 2345 | 500 | 33840 |
| 1997 | Secondary | 12571 | 1678 | 236 | 14485 |
| | Primary | 25929 | 3533 | 497 | 29959 |
| 2002 | Secondary | 10635 | 2177 | 235 | 13047 |
| | Primary | 22029 | 4584 | 494 | 27107 |
| 2007 | Secondary | 9213 | 2554 | 233 | 12000 |
| | Primary | 19063 | 5376 | 491 | 24930 |

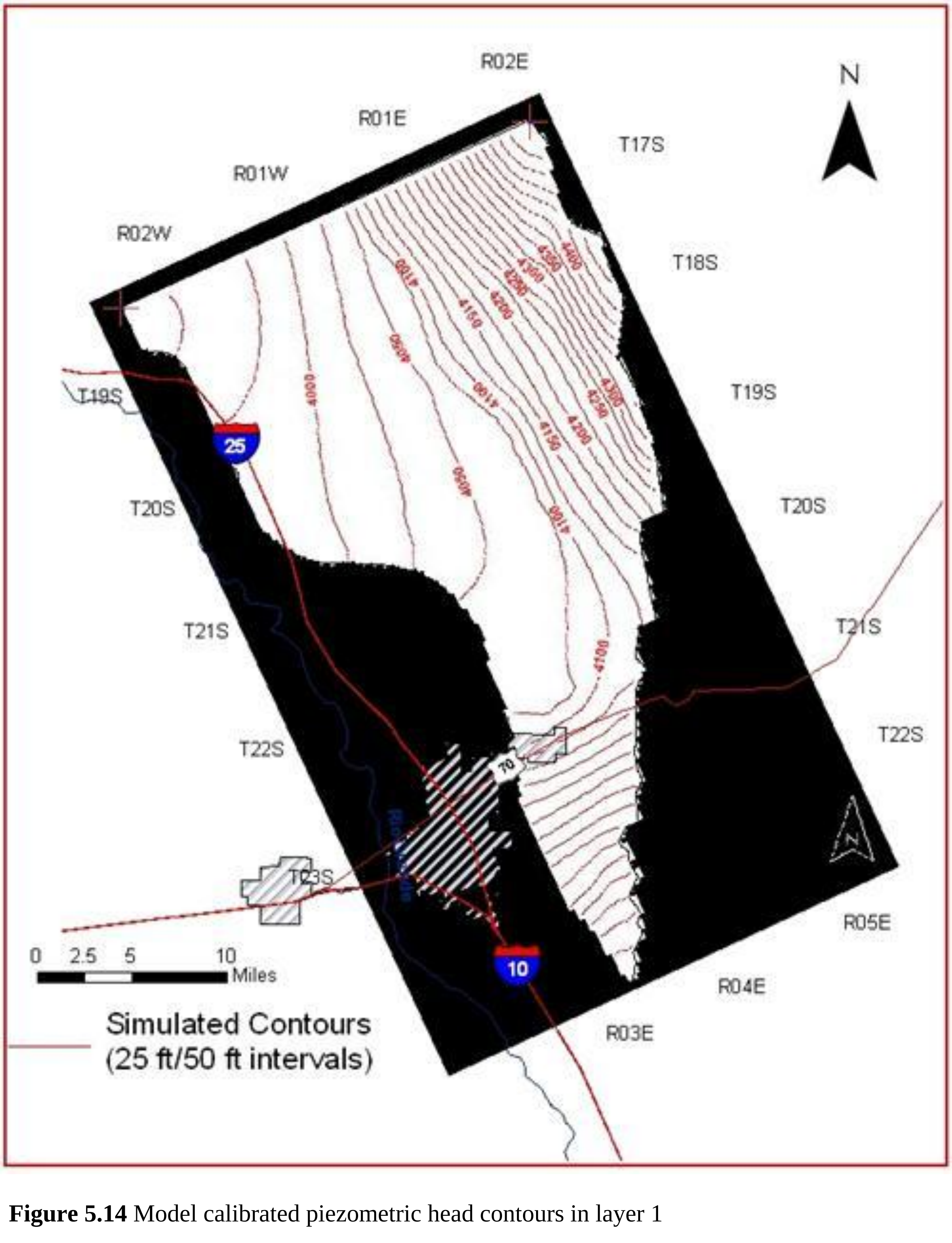


**Figure 5.14** Model calibrated piezometric head contours in layer 1

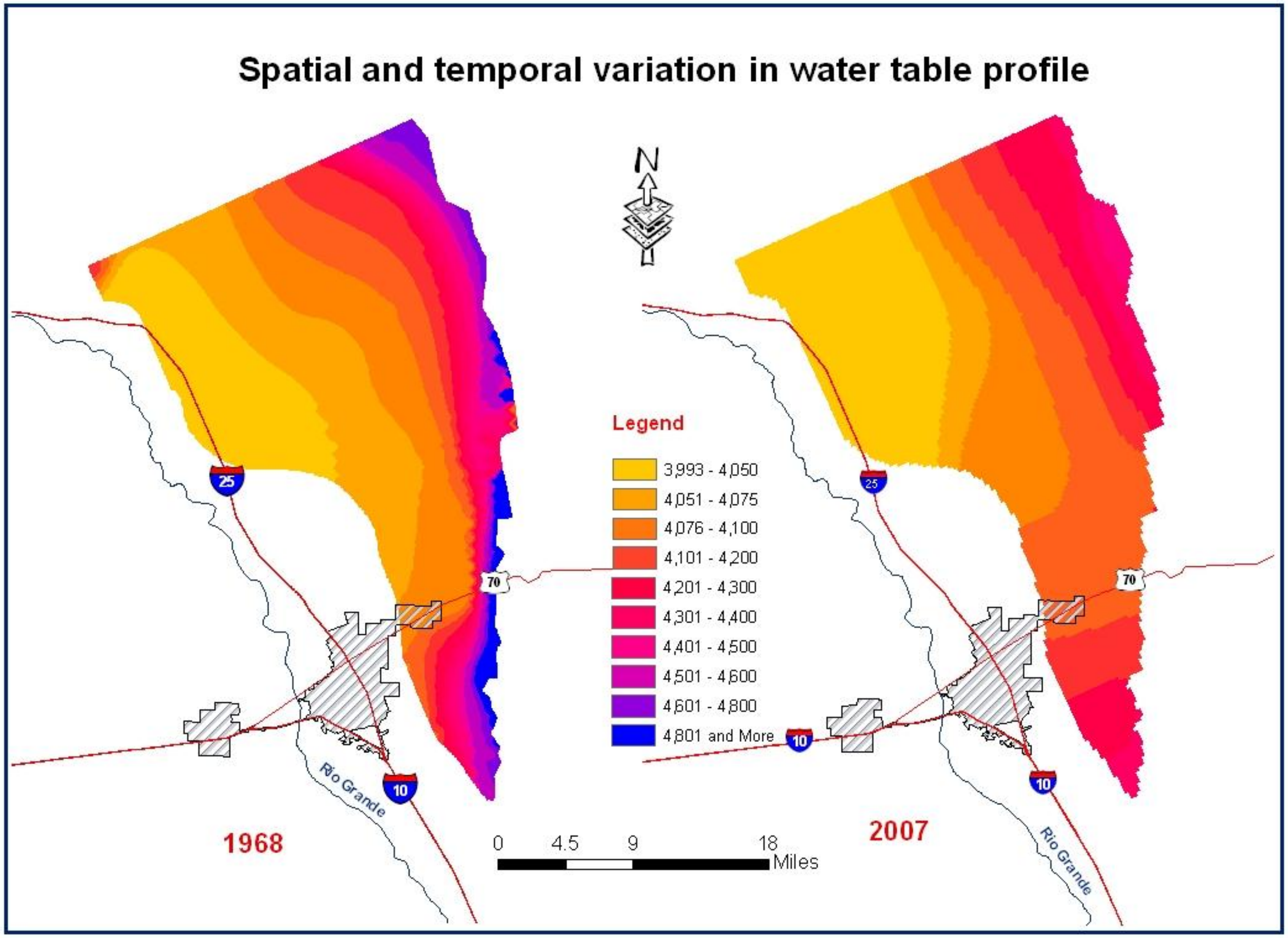


**Figure 5.15** Water table elevation surface for 1968 and 2007 primary irrigation (PI) seasons

## 5.5 DISCUSSION OF RESULTS

### 5.5.1 Sensitivity analysis

The sensitivity analysis and calibration of the model were performed by considering the target wells that represent the water table elevations in layer 1. Hence, all the parameter zones corresponding to layer 1 were considered for sensitivity analysis initially. The target wells were densely populated in the central and eastern part of the study area. Therefore, the parameter values in these regions had a greater effect on the model simulated heads. The weighted average method was used for the estimates of average hydraulic conductivity values of the layer, and the estimates were assumed to be more uncertain. Thus coefficients ranging from 0.5 to 1.5 for $k_x$ multipliers were employed in the sensitivity analysis as compensation. The results of the sensitivity analysis for dominant hydraulic conductivity zones are depicted in Figures 5.1 through 5.7. Hydraulic conductivity of zone 4 that exists in the western portion of the aquifer has an SSE value gradually increasing with an increase in the multiplier value. Hydraulic conductivities of zones 6 and 8 that exist in the eastern portion follow a parabolic change in SSE and ME with an increase in the multiplier value. However, hydraulic conductivity values of all other zones have SSE and ME values decreasing with an increase in the $k_x$ multiplier. A gradual change in SSE values with the $k_x$ multiplier was observed for zones 6 and 8 existing to the central and east of the target wells. The probable reason for this may be due to the contrast in geology of relatively thin basin fill deposits in the southwestern part and the relatively impervious San Andres cored deposits in the southeastern part of the basin. Optimum values of hydraulic conductivity of zones 2, 3, 4, 5 and 7 were obtained by considering the limits as specified by Hawley and Kennedy (2004).

The effect of the recharge flux and boundary head conductance on the model simulated heads was negligible. This may be due to a very small quantity of boundary stress components entering the model as compared to storage. Also, a very large basin area (576 $mi^2$) was responsible for most of the parameters insensitive to the model except for the aquifer properties.

A storage coefficient for layer 1, defined by the ratio of specific yield to saturated thickness, was observed as one of the sensitive parameters to the model and a specific yield of 0.15 that optimized the SSE value was used as the final calibrated value for the simulation. Since the top layer was considered as a convertible aquifer in the LPF package, specific storage for layer 1 (defined as the ratio of specific yield to saturated thickness) was varied zone-wise by changing the specific yield gradually from 0.1 to 0.2. The corresponding changes in the statistical parameters are explained by Figures 5.5 through 5.7.

### 5.5.2 Calibration

The model input parameter values that were changed during the calibration are given in Table 5.1. The change in hydraulic conductivity values of zones 6, 8, 9 and 10 before and after calibration was almost negligible. An increase in hydraulic conductivity values for zones 2, 3, and 5, and a decrease in hydraulic conductivity value for zone 4 resulted in effective calibration.

Convergence was achieved during calibration by minimizing the objective function in terms of SSE values. The residual statistical parameters of the calibration were unsupportive. This may have been due to a significant difference in the water table elevations between the adjacent wells. Unknown geology, mostly in the south-central part of the study area was assumed to be responsible for higher discrepancies in the field measured piezometric elevations, thus resulting in higher SSE values.

The model adjusted piezometric elevations in the analytical wells were poorly correlated in the central part of the aquifer. This may have been due to the poor and inconsistent maintenance of monitoring well data. Most of the measured piezometric elevations in the southern part of the study area were closely matched to the model adjusted values. Again, this may have been due to the availability of hydrogeology, knowledge of the region, and better monitoring of piezometric elevations with time. The model adjusted piezometric elevations were slightly higher in the southern part of the aquifer. This suggests that the estimated mountain front recharge in this is area could be high.

### 5.5.3 Simulation

Volumetric budget flows for selected irrigation years are depicted in Tables 5.2 and 5.3. A gradual decrease in the inflow to the model through the north boundary was observed over time. This may have been due to the increased water table elevations with time that resulted in a decreased available head, resulting in a reduced horizontal flow into the model. A constant inflow of 3,322 ac-ft/year in the form of mountain front recharge (using the Waltemeyer equation) seems to be reasonable based on the previous studies. Pumping from the basin was assumed to be the major stress component with a yield of about 8,000 ac-ft/year (in 2007). Pumping is significant in the southern part of the study area near Las Cruces. Estimates of pumping seem to be reasonable compared to the available resources, and previous literature. Since only two minor water bodies were identified as potential sources for evapotranspiration, the outflow leaving the model through evapotranspiration was almost zero. This was attributed to the scant precipitation in the study area with a greater extinction depth. Evapotranspiration from the water bodies that is directly leaving the surface before reaching the water table was not considered for simulation. The underflow to the Mesilla Basin and Rincon Valley from the southern Jornada Basin was almost constant during the simulation period. The GHB flows to the adjacent basins that were obtained from the analysis are in close agreement with the Frenzel (1992) report. Even though agriculture is absent in the southern Jornada Basin, dividing an irrigation year into primary and secondary irrigation seasons seemed to be logical from the perspective of mountain front recharge and evapotranspiration.

The water table surface of layer 1 of the model for the irrigation years 1968 and 2007 is illustrated in Figure 5.15. The groundwater flow in the study area was west to northwest. The water table gradient was steep during the initial period of simulation and flattened toward the end of the simulation. This is mainly due to the unbalanced heads across the study area, forming a steep westward gradient in water table. This has resulted in decreased water levels in the eastern to southeastern parts and in increased water levels in the west to northwestern parts of the basin. There was a significant decrease in the water table elevations from 1968 to 2007 in the southern and southeastern parts of the aquifer. One possible reason for these decreased groundwater levels may have been due to heavy pumping in these regions along with the outflow to the adjacent basins. There was an increase in water table elevations in the western part of the basin between the Doña Ana Mountains and Rincon Hills where less human activity is observed. The statistical results from model calibration are not encouraging. This may indicate that estimating hydraulic conductivity by the weighted average method using dominant lithofacies assemblages is a less effective method for estimating the average hydraulic conductivity values that range logarithmically.

# 6. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

## 6.1 SUMMARY

A numerical groundwater flow model for the southern Jornada Del Muerto Basin was developed in the present study as a part of the LRGWUO regional water plan. The summary of the entire work is provided below.

1) A numerical flow model for the southern Jornada Del Muerto Basin was developed from the hydrogeologic framework created by Hawley and Kennedy in 2004.
2) A numerical model with 3 layers, 180 rows, 105 columns, and 79 stress periods (from 1968 PI to 2007 PI) was created for simulating groundwater flow in the region.
3) MODFLOW-2000 code was used for simulation with Groundwater Vistas used as graphical user interface to MODFLOW.
4) The northern boundary of the study area was limited to the Point of Rocks region due to the absence of hydrogeology to the north of the Point of Rocks.
5) A conceptual model of the basin was created in ArcGIS 9.2 from the hydrogeologic boundaries and DEM of the study area.
6) Model boundaries were adjusted (near the horst and Rincon connection) to match with the boundaries of the adjacent groundwater basins.
7) Surface profiles of layer elevations and water table elevations were prepared from the hand-drawn contour maps in order to take into account the presence of geological faults and groundwater divides.
8) Geostatical analysis was performed on the aquifer characteristics to predict accurately the continuous surface of random variable from the measured values.
9) The Arc Hydro tool was used to delineate the drainage lines and upland areas of region (between model geological boundary and groundwater divide) for effectively distributing the mountain front recharge parameters.
10) The mountain front recharge was estimated using different empirical equations that were derived for similar catchments. The final method used in the simulation model is selected based on the calibration statistics through inverse modeling.
11) The model was constructed to be consistent with the OSE-2007 flow model that was developed for the Rincon-Mesilla Basins for future integration of all models encompassing the Lower Rio Grande administrative region.
12) Model calibration was performed with 72 analytical target wells that were evenly distributed in the central and southern part of the study area.
13) Hydraulic and storage characteristics of the top layer of the model were identified as the most sensitive parameters to the piezometric heads.

14) A close match between the measured and simulated piezometric heads was observed at the analytical well locations with an $R^2$ value of 0.9978.
15) Model simulation results are presented in the form of water budget and groundwater flow and drawdown contours for selective stress periods.
16) A gradual decrease in inflow through the north boundary, a constant inflow through recharge and geothermal flows, and a gradual decrease in the total inflow entering the entire model were observed with time.
17) A marginal increase in groundwater pumping followed by a sharp increase, a gradual decrease in outflow as underflow to the adjacent basins and a gradual decrease in the total outflow leaving the entire model were observed with time.
18) The groundwater flow in the study area was primarily toward the west to northwest and is flattened with time.
19) There was a significant decrease in the water table elevations from 1968 to 2007 in the southern and southeastern parts of the basin.
20) There was an increase in the water table elevations in the western and northwest parts of the basin where less human activity is observed.

## 6.2 CONCLUSIONS AND RECOMMENDATIONS

A three layer numerical groundwater flow model for the southern Jornada Basin was developed in the present study. The model with 180 rows, and 105 columns was simulated from 1968 to 2007 with two seasons per year. The spatial and temporal resolution of the model grid, orientation, distribution of aquifer, and storage characteristics were in consistent with the pre-existing OSE-2007 flow model for later integration of the two models. The effect of pumping, recharge from upland areas beyond the model boundary, and the underflows through the basin was evaluated on budget flows and piezometric heads across the study area. Aquifer properties of layer 1 were identified as the model sensitive parameters. Water table elevations in the 72 analytical wells were considered during calibration. The original steep gradient in water table was flattening with time due to the differential head across the boundary.

The model is now consistent with the OSE-2007 flow model and can be integrated to form a unified groundwater flow model encompassing the entire LRG administrative basin. The effect of municipal pumping within the Jornada Basin on Rio Grande depletions (resulting from decreased underflows into Rincon and Mesilla Basins) can be evaluated from the unified model. The SJDM Basin was identified as the potential groundwater source particularly in the south-central and western parts. However, the variation in quality of groundwater within the study area needs to be examined.

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