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HYDROLOGIC MODELING OF THE ESTANCIA BASIN, NEW MEXICO

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Abstract—A conceptual and numerical model (ESTAN97) representing the hydrologic conditions of the Estancia basin was developed based on the basin's geologic structure and available hydrologic data. Geographic information systems (GIS) techniques were used in preparing the model input files. The Estancia basin is a topographically closed basin in central New Mexico with an area of about 2400 mi^2. The general surface drainage and subsurface flow is toward the central part of the basin where water is discharged by evaporation from a system of playas and springs. ESTAN97 was calibrated to produce predevelopment (before 1940) and historical (1940–1996) water levels and flow conditions. Water budget analysis indicated that for the period from 1940 to 1996 about 2.08 million acre-ft of water was depleted from the basin during development. About 63% of this depletion came from aquifer storage, 34% came from salvaged evaporation and 3% was captured from neighboring basins. The historical development has resulted in water-level declines of about 60 ft at the main pumping centers and the disruption of the Antelope and Estancia springs. Population projections were used to estimate future growth in domestic and public water-supply uses. Future irrigation use was assumed to decrease by 5% from 1996 uses. The results indicated that aquifer storage would maintain future development for at least 40 more years. It is expected that water levels at the main pumping centers will drop an additional 60 ft by the year 2036.

INTRODUCTION

This paper reports on the development of a numerical hydrologic model (ESTAN97) of the Estancia basin utilizing all available data sources. ESTAN97 is a three-dimensional regional ground-water-flow model suitable for use in water resources planning in the basin.

The Estancia basin in central New Mexico is a topographically closed basin with an area of 2400 mi^2. The watershed boundary of the basin covers portions of Santa Fe, Bernalillo, and Lincoln Counties and much of Torrance County as shown in Figure 1. The basin is surrounded by uplifts on the west (Manzano Mountains and Monte Largo), intrusions on the northwest (South Mountain and San Pedro Mountains), a north-plunging syncline on the north, exhumed Precambrian bedrock on the east (Pedernal Hills), and a syncline on the south that plunges into Socorro County below Mesa de Los Jumanos (Broadhead, 1997). The basin includes important geologic structures such as a bedrock horst (Lobo Hill) separating the basin near Moriarty into north and south parts, a deep Pennsylvanian structural basin on the eastern side of the basin, and a fault-zone extending northeast of Lobo Hill.

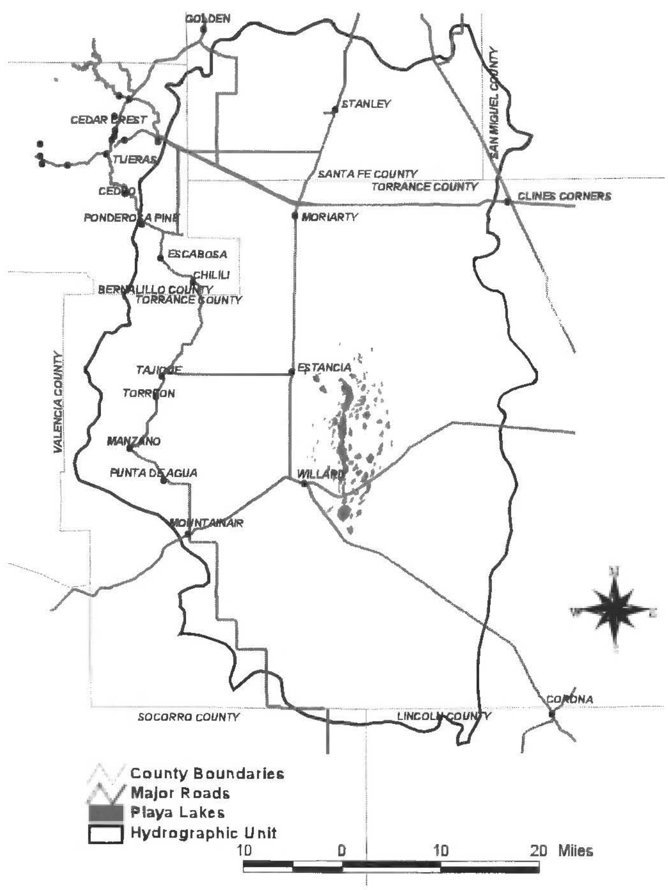

FIGURE 1. Location Map of the Estancia basin.

The hydrogeology of the Estancia basin has been the subject of several previous investigations. Meinzer (1911) provided data and analysis of the basin's predevelopment conditions and estimated annual natural discharge from the basin to be about 81,000 acre-ft (AF). Smith (1957) provided a thorough hydrologic study of Torrance County and developed a water-level map for the central and southern areas of the basin. Titus (1973) described the geology of the basin and provided information about the inferred distribution of bedrock units in the subsurface. Titus also cited estimates of 50,000 acre-ft per year (AFY), 27,000 AFY, and 36,000 AFY for the natural discharge from the basin. The New Mexico Bureau of Mines and Mineral Resources (Lattman and Rose, 1987) developed a geologic map for the northern part of the basin that delineates the subsurface distribution of bedrock units. W. M. Turner and J. Johnson (unpublished report to Estancia Water Cooperative, 1992) identified cavernous zones in limestone units of the Madera Group in a four-mile-wide band from Antelope Spring to Buffalo Draw. Broadhead (1997) described the deep subsurface geology of the basin.

White (1994) reported on the hydrologic conditions of the basin for the period from 1950 to 1985, including information about changes in water-level changes and water quality. John Shomaker & Associates, Inc., Southwest Land Research, Sheehan, Sheehan & Stelzner, P. A., and Livingston Associates, Inc., (unpublished report prepared for Torrance County, New Mexico, 1997) completed a comprehensive investigation of the water resources in the basin for planning purposes.

GEOLOGIC SETTING

The surface geology of the Estancia basin is shown in Figure 2. The Precambrian basement is overlain by limestone, sandstone, and shale of the Pennsylvanian Madera Group; mudstone, siltstone and sandstone of the Permian Abo and Yeso formations; and sandstone and limestone of the Permian San Andres and Glorieta formations. Overlying Mesozoic units are present in the northern portion of the basin. Bedrock units are overlain by unconsolidated alluvium up to 400 ft thick. The older valley fill consists of alluvium that may be correlative to the Ogallala Formation (Titus, 1969) and the youngest fill consists of Pleistocene lake beds (Meinzer, 1911).

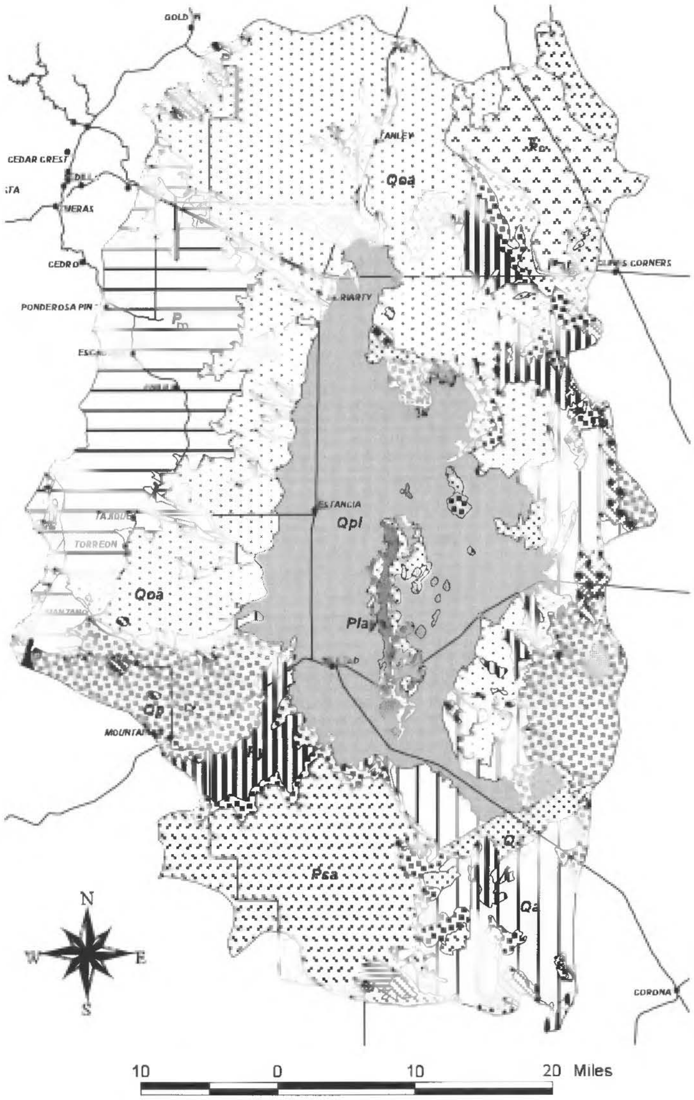

FIGURE 2. Geologic Map of the Estancia basin. Qa, Alluvium; upper and middle Quaternary; Ql, Landslide deposits and colluvium; Qe, Eolian deposits; Qoa, Older alluvial deposits of upland plains and piedmont areas, and calcic soils and eolian cover sediments of High Plains region; Qpl, Lacustrine and playa-lake deposits Qp, Piedmont alluvial deposits: upper and middle Quaternary; To, Ogallala Formation, alluvial and eolian deposits, and petrocalcic soils of the southern High Plains; Ti, Tertiary intrusive rocks undifferentiated; Km, Mancos Shale divided into Upper and Lower parts by Gallup Sandstone; Jsr, San Rafael Group, consists of Entrada Sandstone, Todilto, and Summerville formations; TR,Triassic rocks, undivided; continental red beds; TRc, Chinle Group, Upper Triassic, includes Moenkopi Formation (Middle Triassic) at base in many areas; TRr, Redonda Formation; TRs, Santa Rosa Formation, Carnian, includes Moenkopi Formation (Middle Triassic) at base in most areas; P, Permian rocks, undivided; Pat, Artesia Group, shelf facies forming broad south-southeast trending outcrop; Psa, San Andres Formation, limestone and dolomite with minor shale, Guadalupian in south, in part Leonardian to north; Pg, Glorieta Sandstone, texturally and mineralogically mature, high-silica quartz sandstone; Psg, San Andres Limestone and Glorieta Sandstone, Guadalupian and Leonardian; Py, Yeso Formation, sandstones, siltstones, anhydrite, gypsum, halite, and dolomite, Leonardian; Pa, Abo Formation, red beds, arkosic at base, finer and more mature above; PR, Pennsylvanian rocks, undivided, in Sangre de Cristo Mountains may include PRm, Madera Formation (Limestone, or Group), in Manzano Mountains includes Los Moyos Limestone; PRs, Sandia Formation predominately clastic unit (commonly arkosic) with minor black shales; Yp, Middle Proterozoic plutonic rocks (younger than 1600 Ma); Xm, Lower Proterozoic metamorphic rocks, dominantly felsic volcanic, volcaniclastic. Reference: Gregory, N., Green, N. G., and Jones, G. E., 1997, The digital geologic map of New Mexico in ARC/INFO Format, United States Department of the Interior Geological Survey, Open-file Report OF-97-52.

Precambrian rocks consisting of granite, schist, gneiss and quartzite (Titus, 1973) crop out in the higher parts of the Manzano Mountains, in the Pedernal Hills, and at Lobo Hill.

Pennsylvanian rocks include the Sandia Formation and the Madera Group. The Sandia Formation consists of sandstone, shale, and subordinate limestone with a thickness ranging from 10 to 250 ft (Kelley and Northrop, 1975). The Madera Group consists of a basal, limestone-dominated unit that grades upward into more clastic units. It crops out on the eastern dip-slope of the Manzano Mountains and plunges beneath the surface eastward. The thickness of the Madera Group varies from a few hundred feet in the Manzano Mountains to more than 3500 ft in a narrow structural trough east of Laguna del Perro (Broadhead, 1997).

Permian rocks include the Abo, Yeso, Glorieta, and San Andres formations. The Abo Formation outcrops in the southwestern part of the basin. The Abo consists of sandstone and is about 900 ft thick. The Yeso Formation outcrops in the eastern and southern portion of the basin and consists of sandstone, limestone, and gypsum. The Yeso is up to 1000 ft thick (Smith, 1957).

The Glorieta crops out in the eastern and southern areas of the basin and is an important aquifer in the central valley north of Moriarty. The Glorieta consists of quartz sandstone and ranges in thickness from 100 to 280 ft (Smith, 1957). The San Andres crops out at a few places in the eastern part of the basin and caps Chupadera Mesa in the southern part of the basin. The San Andres is 200–300 ft thick on Chupadera Mesa and thins to about 100 ft at the northeast rim of the basin (Smith, 1957), and consists of limestone containing numerous solution channels and beds of gypsum, sandstone, and siltstone (White, 1994).

Mesozoic rocks include the Triassic Chinle Group, the Jurassic Morrison Formation, and the Cretaceous Dakota Sandstone and Mancos Shale. These rocks crop out in an area north and west of Clines Corners and underlie the valley fill in the northern part of the basin.

Quaternary sediments include an alluvial unit (valley fill) and a pluvial lake-bed unit. The alluvium consists of sand, gravel, silt, and clay and covers much of the basin. The lake deposits occur in the central part of the basin, up to an elevation of 6200 ft above mean sea level (ft amsl). The combined thickness of the alluvial materials and the lake-bed sediments ranges from about 400 ft in a narrow zone along the north–south axis of the basin to a few feet along the edge of the basin (Fig. 3). The thickness of the lake deposits ranges from 100 ft along the north–south basin axis (Titus, 1969) to less than 20 ft around the margin of the unit.

HYDROLOGIC SETTING

The movement of both surface and subsurface water in the Estancia basin is toward the center of the basin where it discharges by evaporation. The major source of recharge to the basin is precipitation on the Manzano Mountains. The major discharge areas are Laguna del Perro and other nearby saline lakes and playas.

Discharge

Meinzer (1911) estimated discharge from the playas to be 81,000 AFY based on the area of playas and potential evaporation rate. Smith (1957) estimated the evaporative discharge from the salt lakes to be about 50,000 AFY and DeBrine (1971) estimated it to be between 27,000 and 30,000 AFY. Titus (1973) provided chemical analysis of water from the playas and suggested that evaporation from the playas may be three-fourths of the fresh water equivalent due to the high concentrations of dissolved salts. Data from a weather station at Estancia indicate that pan evaporation typically is 30–35 in. per year (John Shomaker & Associates, Inc., et al., unpublished report prepared for Torrance County, New Mexico, 1997).

Underflow between the Estancia basin and neighboring basins is not thought to be a major component of the hydrologic system. Titus (1973) discussed leakage from the Estancia basin to the south (Tularosa basin) and to the north (Galisteo basin). He concluded that flow to the Tularosa basin to the south, if it exists, would be insignificant. He also

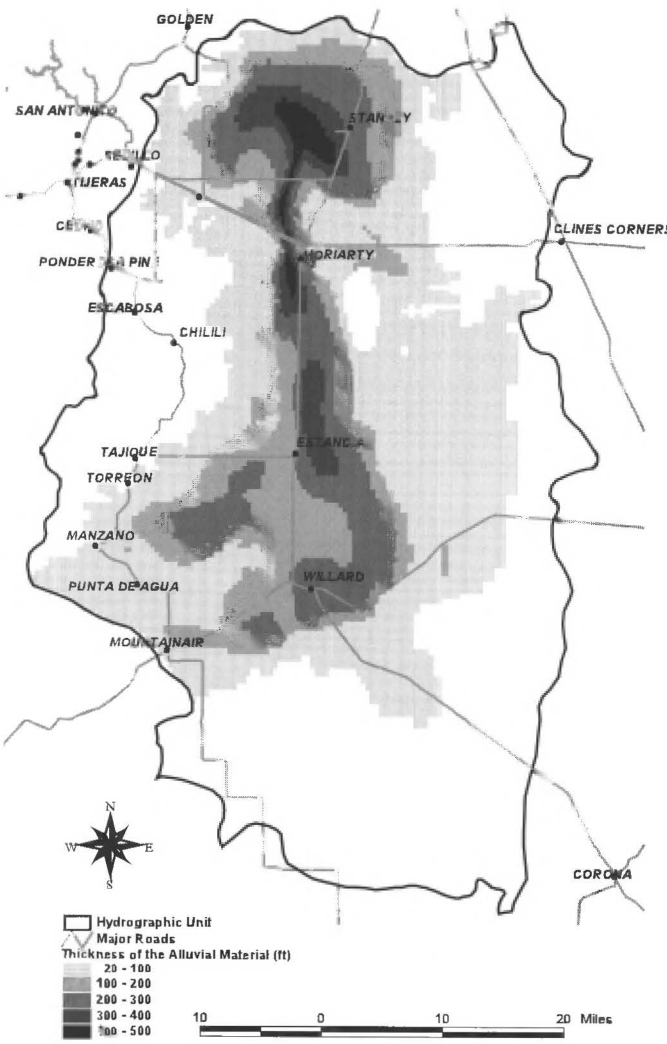

FIGURE 3. Thickness of the valley fill.

speculated that leakage to the north might be more significant.

Recharge, runoff, and springs

The main source of ground-water recharge within the basin is rainfall and snowmelt from highlands around the basin periphery (mountain-front recharge). Annual precipitation ranges from 11 to 23 in. east to west across the basin from Pedernal to Sandia Crest (John Shomaker & Associates, Inc., et al., unpublished report prepared for Torrance County, New Mexico, January 1997). The mountain slopes that produce surface runoff include the Manzano Mountains, Pedernal Hills, South Mountain, and the San Pedro Mountains, (Smith, 1957). Runoff from these slopes is also indicated from data compiled by the U.S. Soil Conservation Service (SCS, 1972). John Shomaker & Associates, Inc., et al., (unpublished report prepared for Torrance County, New Mexico, 1997) estimated basin recharge to be 37,774 AFY.

A surface-water reconnaissance study of water supply in the Estancia basin performed in 1961 by the New Mexico State Planning Office (1967) indicated that streams emerging from the western side of the basin (Manzano Mountains) discharge about 8100 AFY to the basin fill. Data compiled by the SCS (1972) indicate that runoff within the basin totals about 7900 AFY. The U.S. Geological Survey (USGS) measures annual peak flows in six selected drainages. Reported peak flows vary from zero to thousands of cubic feet per second (cfs) (White, 1994).

Meinzer (1911) discussed the two largest springs in the basin (Estancia Spring and Antelope Spring) and estimated that their yield did not exceed several hundred AFY. Recently, the USGS has inventoried springs within Torrance and Bernalillo Counties (White and Kues, 1992). The discharge of springs in Torrance County presently ranges from less than one to 20 gallons per minute (gpm) and from one to 30 gpm in Bernalillo County.

Hydraulic parameters

The Madera Group is the principal aquifer in the northwest and west-central part of the Estancia basin. The Madera Group provides water to wells through fractures that resulted from faulting or that developed as solution channels and caverns. Titus (1980) reported that the specific yield of the Madera is less than 0.01. John Shomaker & Associates, Inc., et al., (unpublished report prepared for Torrance County, New Mexico, 1997) reported that the specific yield of the Madera ranges from 0.05 to 1.1×10^{-4}. Two transmissivity zones have been identified in the Madera limestone, a low and a high zone (N. G. Shafike and W. P. Balleau, unpublished report to Entranosa Water and Wastewater Cooperative, 1998). Transmissivity in the low zone ranges from 300 to 3000 ft^2 per day (ft^2/day). Transmissivity in the high zone ranges from 10,000 to 100,000 ft^2/day.

The Abo Formation is not a major aquifer in the study area. Analysis of four pumping tests conducted in the Abo Formation near Punta de Agua resulted in transmissivities ranging from 57 to 1845 ft^2/day. Smith (1957) reported that a 400-ft well completed in the Abo Formation yielded 3.0 gpm. The specific yield of the Abo Formation northwest of the basin was reported to be 0.1 (John Shomaker & Associates, Inc., et al., (unpublished report prepared for Torrance County, New Mexico,1997). The Yeso Formation is considered to be a more productive unit than the Abo Formation, and is the principal aquifer north and east of Chupadera Mesa. Smith (1957) reported that wells completed in the Yeso Formation yielded from several to more than 3000 gpm. Available pumping test data shows the transmissivity of the Yeso Formation ranges from 5 to 2092 ft^2/day.

The Glorieta Formation is the principal aquifer north, south and east of Lobo Hill. Wells drilled in the Glorieta Sandstone may produce more than 1000 gpm in areas where the unit is extensively fractured. Pumping test data indicate that the transmissivity ranges from 9800 to 250,888 ft^2/day, and the specific yield is about 0.05. The Chinle and younger Mesozoic units provide water in the northeastern area of the basin. Pumping test data for these units are not available. Smith (1957) reported that two wells completed in these units provide adequate water for stock and domestic purposes.

The alluvial valley fill is the aquifer tapped by most of the irrigation wells in the Estancia basin. Analysis of the available pumping test data indicates that the transmissivity of the valley fill ranges from 200 to 100,000 ft^2/day. The specific yield of the valley fill was reported by the Office of the State engineer (OSE) to be 0.125. The lake-bed deposits are assumed to have low permeability.

CONCEPTUAL MODEL

A conceptual model of the Estancia basin was developed based on an understanding of the basin's hydrologeologic system formulated using available data from previous studies of the basin. The conceptual model was translated into the ESTAN97 mathematical model using the capabilities of the MODFLOW program (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996) and GIS techniques to prepare the model input files. The general ground-water-flow system of the Estancia basin is simulated assuming that net recharge occurs on the periphery of the basin, with the highest rates on the Manzano Mountains, and that discharge occurs primarily by evaporation from the salt lakes and playas, with minor leakage to the north and south.

The New Mexico State Planning Office (1967) estimate of 8100 AFY of mountain front recharge is applied in the model as average annual runoff values proportional to the catchment area. This runoff is placed in the model in the top reaches of watercourses in the Manzano Mountains and is routed to the mountain front alluvium. Some of this water soaks into the subsurface throughout the watercourses, with individual watercourses gaining or losing water according to relative levels

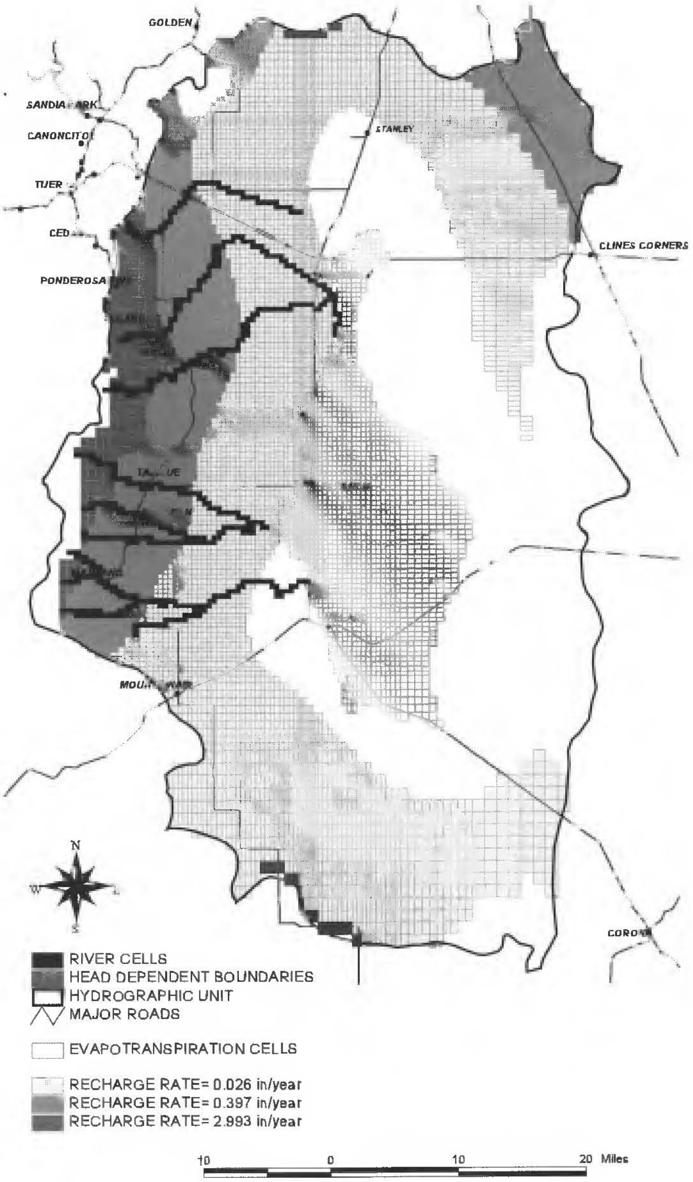

FIGURE 4. Model boundary conditions.

of the stream stage and the aquifer water level. Perennial springs in mountain watercourses are simulated in this way so that they may respond to the effects of pumping. Intermittent, isolated or perched springs are not simulated. The major historical spring discharge sites at Estancia Spring and Antelope Spring are treated as short watercourses fed by ground water that are able to respond to aquifer water levels.

Playa evaporation is considered to be 30,000 AFY based on the estimate of Titus (1973). These estimates reflect water budget analysis based on playa lake area and potential evaporation rates. Evaporation is represented in the model on the lake-bed sediments in the central area of the basin as shown in Figure 4. The maximum evaporation rate is 2 ft per year. Evaporation is assumed to cease at a depth of 12 ft below land surface.

Recharge is apportioned to the area of highest surface runoff on the assumption that runoff and recharge are positively correlated. The runoff zones mapped by the SCS (1972) were used to indicate recharge zones, and recharge is specified in amounts (22,000 AFY of direct recharge and 8100 AFY of mountain-front runoff) to equal the estimated playa discharge.

The relatively small amounts of discharge to the north and south are provided by setting constant head boundaries at elevations interpreted from wells or springs near regional discharge points. The northern discharge to the Galisteo basin is considered to be routed through the Glorieta aquifer. The nearest perennial stream reach in the Galisteo basin lies at an elevation of about 6100 ft amsl. Ground-water levels in the northern Estancia basin are at 6200 ft amsl. The reference head in the northern model boundary in the Glorieta aquifer was set at 6180 ft msl to simulate discharge toward the Galisteo basin. Constant head boundaries on the south are set at the observed water table elevation in the Yeso Formation to simulate discharge toward the Tularosa basin. The northern constant heads were converted to a general head boundary in the transient simulation to simulate water level declines in the northern boundary. Recharge from the Sandia Mountains to the Estancia basin through the northwest boundary is simulated in the Madera aquifer as shown in Figure 4.

The thickness of each geologic formation and the observed predevelopment water level map (USGS monitoring wells database) were used to construct the saturated thickness of each formation, the extent of each layer, and the top and bottom elevations for the model layers. The intersection of the predevelopment water table map with the geologic formations was used to determine the top of the saturated portion of each formation, as shown in Figure 5.

The model grid covers the watershed boundary of the Estancia basin with a grid size varying from 1000 ft by 1000 ft along the north–south basin axis to 5000 ft by 5000 ft along the basin edges. Five layers are represented in the vertical direction, with each layer corresponding to a geologic formation, except for the alluvium that is divided between

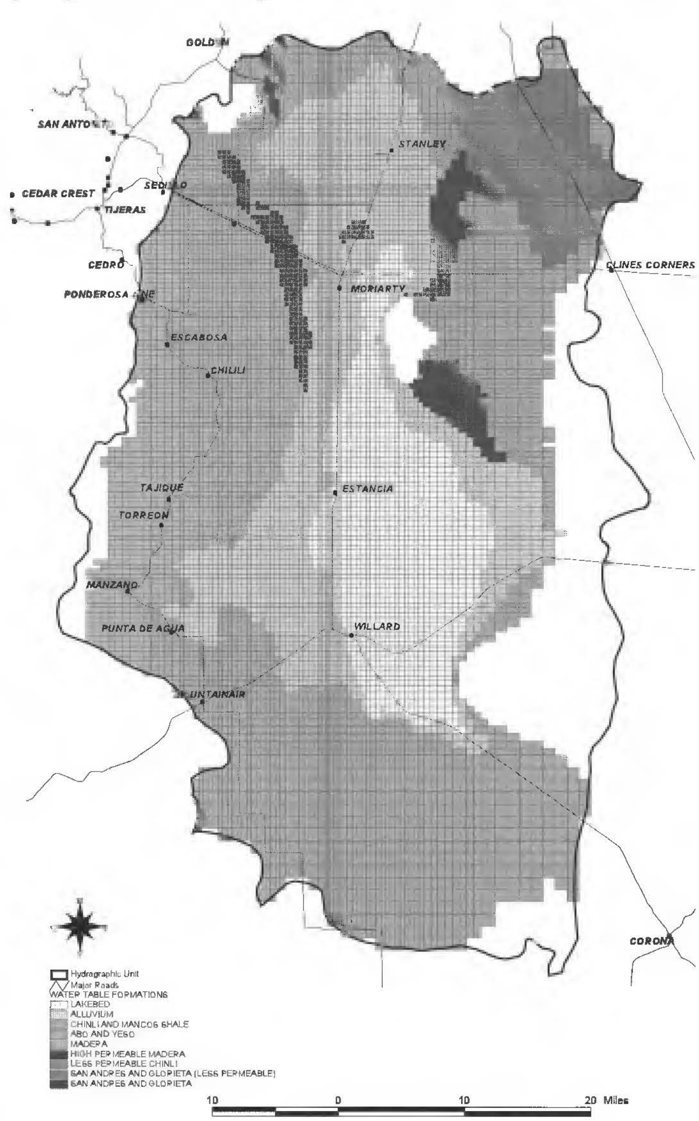

FIGURE 5. Model water table cells and formations.

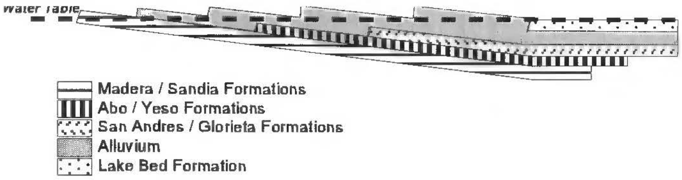

FIGURE 6. Schematic diagram of the conceptual model.

model layers one through four. Model layer one represents the lake bed and alluvium, model layer two represents the Mesozoic units and alluvium, model layer three represents the Glorieta and San Andres units and alluvium, model layer four represents the Abo and Yeso units and alluvium, and model layer five represents the Madera aquifer. The arrangement of the layers and formations is shown schematically in Figure 6. The zonation of hydraulic properties within each layer generally follows the concept of hydrostratigraphic units. Extensive areas of each rock unit are characterized by a single hydraulic property, but with variable formation thickness from cell to cell.

Table 1 shows the range of values for hydraulic parameters of the geologic formations represented in ESTAN97. These ranges were compiled based on published information and were used to constrain the calibration and sensitivity tests of the model.

The Madera is assigned three zones of hydraulic conductivity (Fig. 7). A relatively high value is assigned to the area of extensive fracture flow in the northwestern part of the basin. A lower value is assigned to the crest and slope of the Manzano Mountains, and the lowest value is assigned to the deep Perro subbasin to the west, where the formation contains less limestone and is more silty (Broadhead, 1997). The Chinle is combined with younger Mesozoic units on the eastern side of the Estancia basin and assigned a lower hydraulic conductivity than for Mesozoic rocks on the northern side of the basin, which occur in a structurally disturbed syncline.

Precambrian rocks are not represented directly in the ground-water-flow model, but form the impermeable boundary of the bottom layer. A contour map (Titus, 1973) of the top of the Precambrian rocks was utilized in the model. This representation is in general agreement with the recent map of the Precambrian bedrock developed by Broadhead (1997) as shown in Figure 8.

Vertical hydraulic gradients are known to be present (Titus, 1980) in certain areas of steep terrain and near ground water divides in the Madera aquifer. Perched water and isolated, local flow systems are also present in the mountains. Intraformational vertical flow and isolated water features are not intended to be represented by the layering and zonation concepts in ESTAN97. Vertical differences in hydraulic conductivity within each model layer are also not represented. However, vertical gradient and hydraulic conductivity differences between formations and model layers are represented in the model.

The model has been designed to simulate the regional flow and head conditions due to five-year average, historical stress periods. Seasonal or annual wet and dry periods are assumed to cause fluctuations around the average conditions simulated in the model. Seasonal and year-to-year fluctuations are apparent in the long-term hydrographs of the mountain areas. The 1980s were a wet period and appear to have caused a significant water-level rise in wells completed in the Madera aquifer. Sensitivity to a temporary increase in recharge has been tested by the

TABLE 1: Range of aquifer hydraulic parameters with limits.

	T (ft^2/day)		K (ft/day)		Specific yield	
Formation	Lower	Upper	Lower	Upper	Lower	Upper
Madera Limestone						
Silty Zone	30	300	0.01	0.10	0.005	0.01
Low Zone	500	1,000	0.50	2	0.005	0.03
High Zone	15,000	30,000	10	20	0.005	0.03
Abo/Yeso	50	300	0.01	0.50	0.01	0.03
Glorieta/San Andres	10,000	30,000	25	50	0.05	0.10
Alluvium	2,000	8,000	10	30	0.01	0.15
Mesozoic	1	1,000	0.0001	0.01	0.01	0.05
Lake Bed	1	50	0.01	0.50	0.01	0.05

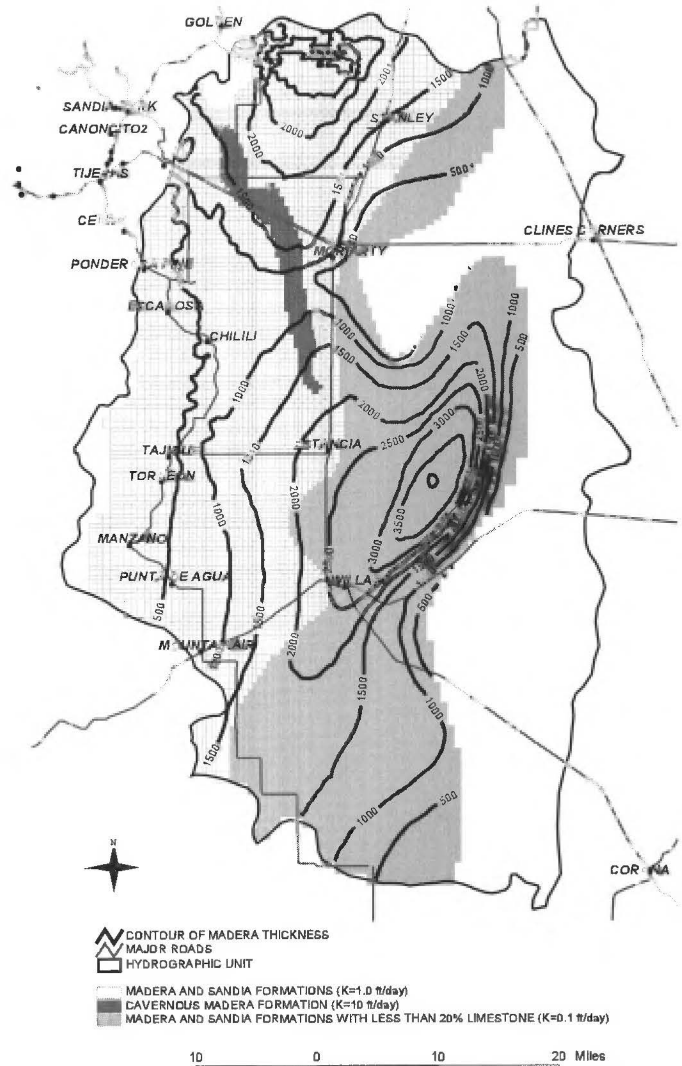

FIGURE 7. Hydraulic conductivity zones and thickness map of the Madera and Sandia formations.

model (N. G. Shafike and W. P. Balleau, unpublished report to Entranosa Water and Wastewater Cooperative, 1998).

The stress on the aquifer due to withdrawal of water by wells is assumed to be the net amount of depletion after return flow is accounted for. Irrigation return flow is assumed to reach the water table due to the areal extent of water loading. Domestic and public supply return flows are assumed to reach the water table in the Madera Group, but not in the valley fill.

HISTORY OF WATER USE

Historic diversion and depletion of ground water in the Estancia basin has been estimated in five-year time steps for the period from 1940 to 1996 as shown in Table 2. Sources of data regarding the historical use of ground water in the basin include an electronic database of water-permits maintained by the OSE, water use data maintained by the USGS and published and unpublished references (SCS, 1971; Lansford et al., 1980; SCS 1982; John Shomaker & Associates, Inc., et al., unpublished report prepared for Torrance County, New Mexico, 1997). Depletion totaled 46,321 AF in 1995 and diversions were 60,464 AF, or 29% of the permitted amount of 209,870 AFY (OSE water-permits database as of September 1997). Depletion in the basin has occurred primarily due to three uses: irrigation, public supply, and domestic consumption. Irrigation has been the largest consumer of ground water in the basin (about 94% of total depletion), with large-scale withdrawals

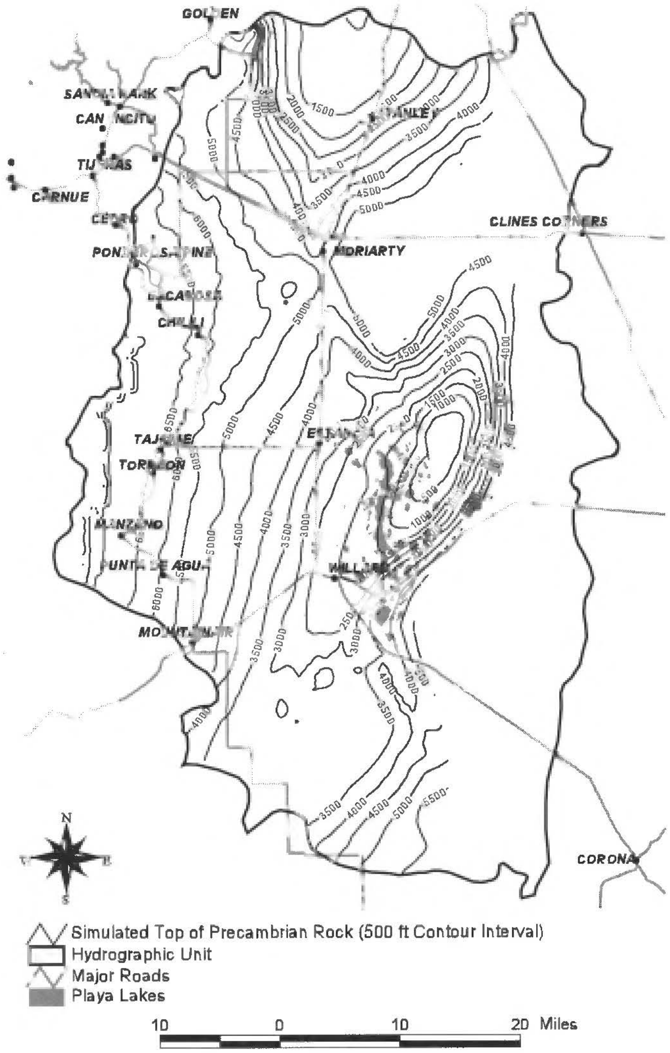

FIGURE 8. Simulated top of Precambrian rocks.

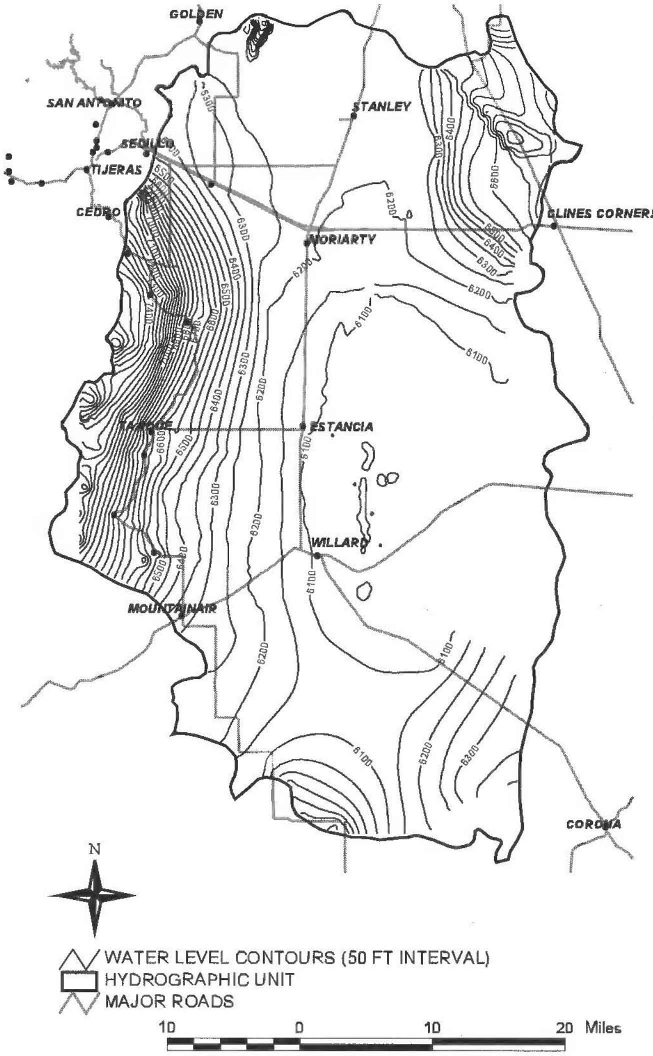

FIGURE 9. Simulated predevelopment water levels.

commencing about 1950 (White, 1994). The bulk of the irrigated acreage historically has been in the central portion of the basin, in southern Santa Fe County and north-central Torrance County.

Net depletion of ground water for irrigation of cropland was calculated in accordance with water-use statistics for the basin compiled in Wilson (1992). A total of 54,440 AF of ground water was diverted for irrigation of 24,590 acres in 1990. Return flow to the alluvial aquifer of the basin is calculated to total 13,245 AF, based on estimates of on-farm efficiency and incidental depletions for the three types of irrigation systems present in the basin (flood, drip, and sprinkler). The net depletion

TABLE 2: Historical ground-water diversions and depletion in Estancia Basin.

	IRRIGATION			DOMESTIC				PUBLIC SUPPLY		TOTALS	
Year	Total irrigated acreage	Net depletion (AFY)	Diversion[1] (AFY)	Domestic depletion[2] (AFY)	Stock depletion (AFY)	Total depletion, stock and domestic (AFY)	Total diversion, stock and domestic (AFY)	Depletion (AFY)	Diversion (AFY)	Total depletion (AFY)	Total diversion (AFY)
1940–1945	160	268	354	2	259	261	261	293	293	822	908
1945–1950	250	419	554	4	285	289	289	346	346	1054	1189
1950–1955	19,000	31,829	42,066	6	309	315	315	409	409	32,553	42,790
1955–1960	25,000	41,880	55,350	10	330	340	340	483	483	42,703	56173
1960–1965	20,000	33,504	44,280	17	349	366	367	571	571	34,441	45218
1965–1970	20,000	33,504	44,280	29	367	396	398	675	675	34,575	45,353
1970–1975	25,930	43,438	57409	44	384	428	437	798	798	44,664	58,644
1975–1980	28,440	47,643	62,966	77	399	476	491	943	943	49,062	64,400
1980–1985	34,360	57,560	76,073	125	414	539	573	1115	1115	59,214	77,761
1985–1990	32,055	53,699	70,970	215	427	642	701	1317	1317	55,658	72,988
1990–1995	24,590	41,193	54,442	369	440	809	913	1557	1557	43,559	56,912
1995–1996	25,915	43,413	57,376	635	452	1087	1267	1821	1821	46,321	60,464
										2,084,143	2,732,605

[1]Based on 1990 diversion rate of 2.214 af/acre
[2]Includes 50% return flow on Madera

of ground water for irrigation is 41,193 AF for 1990. The weighted net depletion of ground water for irrigation of cropland in the basin is 1.675 AFY/acre. Water-use statistics for the basin compiled in Wilson and Lucero (1997) result in a similar weighted net depletion of 1.698 AFY/acre.

The category of domestic use includes ground-water depletion from both domestic and stock wells. The total diversions of ground water for domestic wells in the basin for 1990 was taken from John Shomaker & Associates, Inc., et al. (unpublished report prepared for Torrance County, New Mexico, 1997) as 473 AFY. This amount is based on an estimated population in the basin of 6600 persons served by domestic wells and a per capita consumption of 64 gallons per day (gpd) (Wilson, 1992). It is assumed that no return flow occurs as a result of domestic or stock uses in the alluvium, and 50% of domestic use is returned on the Madera. The time trend of ground-water depletion due to domestic use was indexed to the annual percent of growth (11.5%) in domestic water permits for the period from 1940 to 1996 from the OSE water-permits database.

Depletion of ground water due to stock wells is taken from John Shomaker & Associates, Inc., et al. (unpublished report prepared for Torrance County, New Mexico, 1997) as 440 AFY in 1990. This amount is based on the number of livestock reported by various Federal and State agencies and per capita water requirements. The time trend of ground-water depletion due to livestock use was indexed to the logarithmic trend of growth in stock water permits for the period from 1940 to 1996 from the OSE water-permits database.

The category of public supply includes depletion of basin ground water due to public water-supply systems and from industrial and commercial uses. The total diversion for public supply was taken from John Shomaker & Associates, Inc., et al. (unpublished report prepared for Torrance County, New Mexico, 1997) as 1821 AFY in 1995. It is assumed that no return flow occurs as a result of the uses in this category in the alluvium, and that 50% is returned on the Madera Group. The time trend of ground-water depletion due to the category of public supply was indexed to the annual percent (3.4%) of growth in public-supply water permits for the period from 1940 to 1996 from the OSE water-permits database.

PREDEVELOPMENT CONDITIONS

The model was calibrated against predevelopment water level and flow conditions (i.e., prior to 1940). The USGS water-level database was used to generate a predevelopment water level map, and other sources were used to estimate spring flow and playa discharge. Combined manual and automated (MODFLOWP, Hill, 1991) calibration techniques were used during the calibration process. Initially, all model layers were assumed to be isotropic (Kx = Ky = Kz). The vertical conductance between model layers was calculated using the harmonic mean of the vertical leakance (Kz/(z) for the interface between layers. Two calibration criteria were used during the calibration

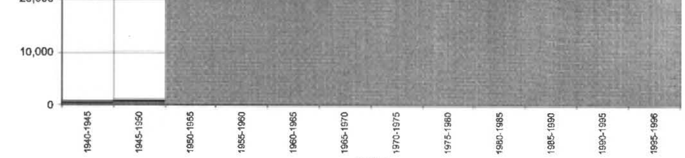

FIGURE 10. Simulated net total pumping in the Estancia model.

process, the root mean square error (RMSE) and the bias. Figure 9 illustrates the simulated water-table elevation. The water levels in the study area range from 7400 ft amsl on the top of the Manzano Mountains to 6050 ft amsl in the central part of the Estancia basin (playa area). The calibration target was to match the observed water levels within 10% of the maximum head change in the basin (7400 – 6050 = 1350 ft), thus, a RMSE of 135 ft is considered acceptable. The computed RMSE for 386 observations is 88 ft, and the correlation coefficient is $R^2 = 0.94$. The bias is –14 ft, which represents the average error in predicting water levels. These criteria are considered acceptable for the regional water level map in the Estancia basin. The model-simulated water levels closely up to an elevation of 6400 ft amsl, and less closely at higher elevations.

In steady-state conditions, the direct recharge and mountain front recharge will balance the discharge by evaporation and outflow to the Galisteo and Tularosa basins. Total recharge of 30,100 AFY is balanced with 26,430 AFY of actual evaporation, 3930 AFY of discharge to the Galisteo basin, 420 AFY of discharge to the Tularosa basin and inflow of 900 AFY to the Madera Group in the northwestern part of the basin. Model results indicate that Estancia and Antelope springs gain (discharge) about 90 AFY each.

HISTORICAL SIMULATIONS

The computed predevelopment head and flow conditions were used as a starting point for a transient run that simulates historical conditions from 1940 to 1996. Top and bottom elevations of geologic formations were prescribed in the model allowing model layers to dewater or transform from elastic storage to specific yield under pumping stresses. Assigned specific yields are 5% for the lake bed, 12.5% for the basin fill, 1.0% for the Chinle, 5.0% for the Glorieta and San Andres, and 1.0% for the other formations. Elastic storage in the model is assigned a value of $2x10^{-6}$ per foot of thickness.

Simulated pumping rates are illustrated in Figure 10 and are distributed over 5-year stress periods. Irrigation wells are placed according to the irrigation area visible in 1995 LANDSAT imagery. Net depletion due to irrigation is distributed proportionally to model cells in the areas of irrigated acreage. Stock and domestic wells are placed in historic permitted locations in 10-year intervals, with rates distributed equally. All wells are simulated in the first saturated layer, unless the well is located in a lake-bed cell. In these cases pumping is moved to the alluvial layer below.

Figure 11 shows the simulated drawdown contour map at the end of 1995. The results show three centers of water level decline amounting to about 80-ft north of Moriarty, 40 ft west of Estancia, and 60 ft near Willard, similar to that illustrated by White (1994). Figure 12 shows the observed versus simulated well hydrographs. The simulated initial heads are within a few tens of feet of observed head, and the trends of the drawdown are suitable for making projections for future planning scenarios. Analysis of the simulated flow conditions in 1996 indicated that the sources of water that supply the 46,250 AFY of consumption are 51% storage depletion and 49% captured evaporation and boundary flow. For the entire period from 1940 to 1996, the aquifer storage provided 63% and captured evaporation and boundary flow provided 34% of the total depletion (about 2.08 million AF). The model results indicate that historical development in the basin caused Antelope and Estancia springs to dry up, as observed.

FUTURE PROJECTIONS

Future hydrologic conditions are projected for the period from 1996 to 2036, representing a 40-year planning period. This scenario is intended to reflect reasonable expectations for future water use in the Estancia basin. Public water supply and domestic water use is projected to grow from 3088 AFY of diversion in 1995 to 9253 AFY of diversion in year 2040 based on an exponential growth trend. Irrigated acreage is expected to decrease from the 1995 level of 25,915 acres by about 5% to 24,640 acres in year 2000, and to remain steady after that time. Irrigation in the year 2000 and later would divert about 54,500

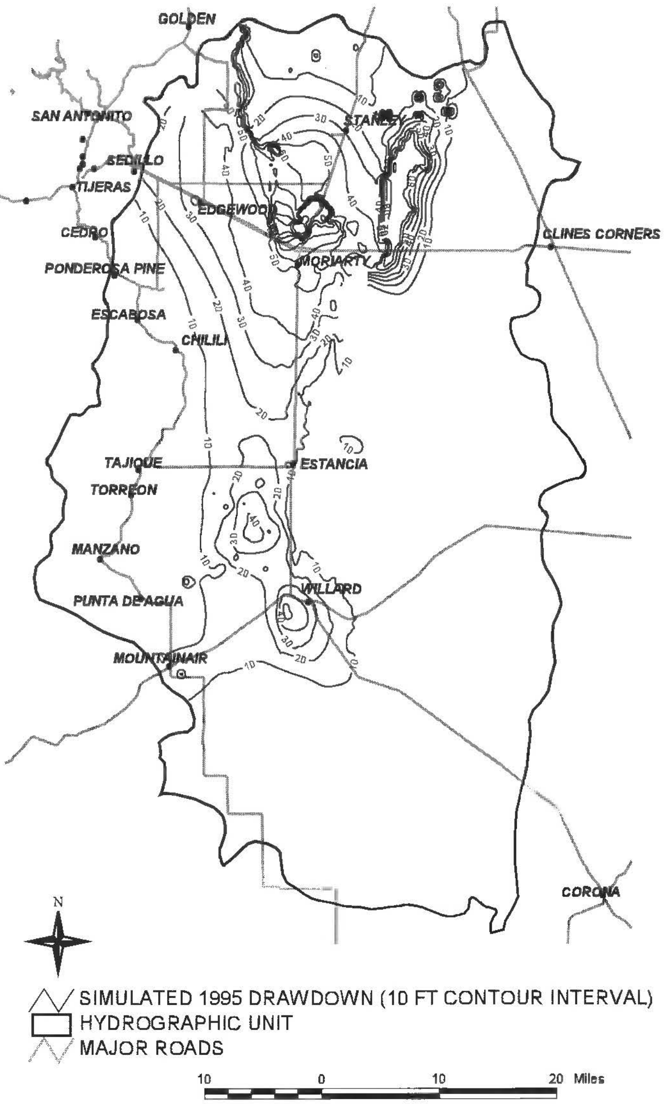

FIGURE 11. Simulated 1995 watertable drawdown.

AFY and deplete about 41,300 AFY.

Table 3 illustrates the projected amounts of ground-water diversions and depletions in the Estancia basin through the year 2040. The rate of domestic and public water use is expected to remain steady at the 1995 per-capita usage of 75 gpd. Under this assumption, domestic and public supply diversions will grow at the same rate as the population. Population projections for the basin shown in Table 3 are the highest of four scenarios listed in John Shomaker & Associates, Inc., et al. (unpublished report prepared for Torrance County, New Mexico, 1997). The percentage of domestic return flow is projected to hold steady at current levels of about 22% of domestic diversion.

Drawdown at year 2036 resulting from simulation of future withdrawals is illustrated in Figure 13. The amount of water level decline in the next 40 years is about 60 ft at the main pumping centers. Model results indicate that aquifer storage is the main supply for future development (about 80% by volume) and that more flow will be captured from the northern boundary of the Estancia basin.

SUMMARY AND CONCLUSIONS

The Estancia basin hydrologic model, ESTAN97, provides a mathematical method for simulating the sources of water that supported historical development of the basin and for calculating the projected effects of proposed future management actions in the basin. The model has been calibrated to match predevelopment water level and flow conditions and to match 57 years of historic development. The model is suitable in projecting average hydrologic effects on the scale of 1000- to 5000-ft grid cells. It may not simulate particular features of specific sites on a smaller scale. The model has the capability to calculate changes in water level, flow paths and rates and capture of water from discharge points.

Irrigation depletions represent about 94% of all water depletions, which totaled 46,300 AF in 1996. Flow conditions at 1996 indicated that about 49% of total basin depletion is captured from springs, basin outflow, and evaporation from the playa lakes and 51% is derived from reduction in aquifer storage. Stored water at this time was being depleted at a rated of about 22,750 AFY.

Future projections indicate that, with growth in public supply and domestic use, and with agricultural water use continuing at a level just below current levels, the amount of water level decline in the next 40 years will be about 60 ft at the main pumping centers. The model results indicate that aquifer storage is the main supply for future development and more flow will be captured from the northern boundary of the basin.

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TABLE 3. Historical ground-water diversions and depletion in Estancia basin.

		IRRIGATION			DOMESTIC					PUBLIC SUPPLY		TOTALS	
Year	Projected population[1]	Total irrigated acreage	Net depletion (AFY)	Diversion[2] (AFY)	Domestic depletion[3] (AFY)	Domestic diversion (AFY)	Stock depletion & diversion (AFY)	Total depletion, stock and domestic (AFY)	Total diversion, stock and domestic (AFY)	Depletion (AFY)	Diversion (AFY)	Total depletion (AFY)	Total diversion (AFY)
1995	31,018	25,915	43,413	57,376	635	815	452	1,087	1,267	1,821	1,821	46,321	60,464
2000	37,312	24,638	41,274	54,549	765	980	476	1,241	1,456	2,191	2,191	44,706	58,196
2005		24,638	41,274	54,549	857	1,121	500	1,375	1,621	2,528	2,528	45,177	58,698
2010	48,818	24,638	41,274	54,549	1,001	1,283	526	1,527	1,809	2,866	2,866	45,667	59,224
2015		24,638	41,274	54,549	1,135	1,455	554	1,689	2,009	3,276	3,276	46,239	59,834
2020	62,800	24,638	41,274	54,549	1,287	1,650	582	1,869	2,232	3,687	3,687	46,830	60,468
2025		24,638	41,274	54,549	1,447	1,865	613	2,060	2,478	4,147	4,147	47,481	61,174
2030		24,638	41,274	54,549	1,628	2,087	644	2,272	2,731	4,664	4,664	48,210	61,944
2035		24,638	41,274	54,549	1,831	2,347	678	2,509	3,025	5,245	5,245	49,028	62,819
2040	100,490	24,638	41,274	54,549	2,059	2,640	713	2,772	3,353	5,900	5,900	49,946	63,802

[1]Source: John Shomaker & Associates, Inc., and others (1997)
[2]Based on 1990 diversion rate of 2.214 AF/acre
[3]Includes 50% return flow on Madera, none on alluvium

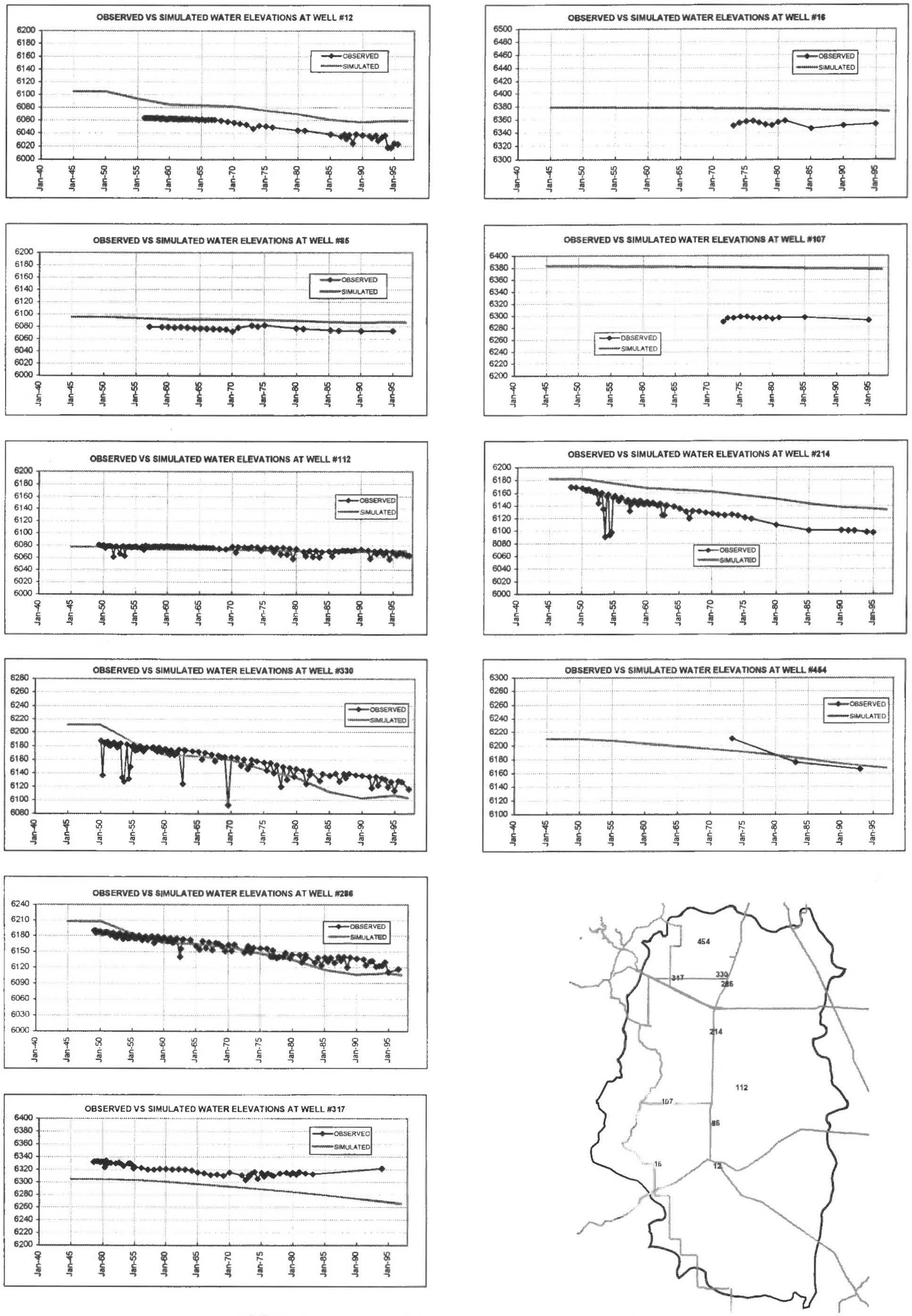

FIGURE 12. Comparison of simulated and observed water-level trend.

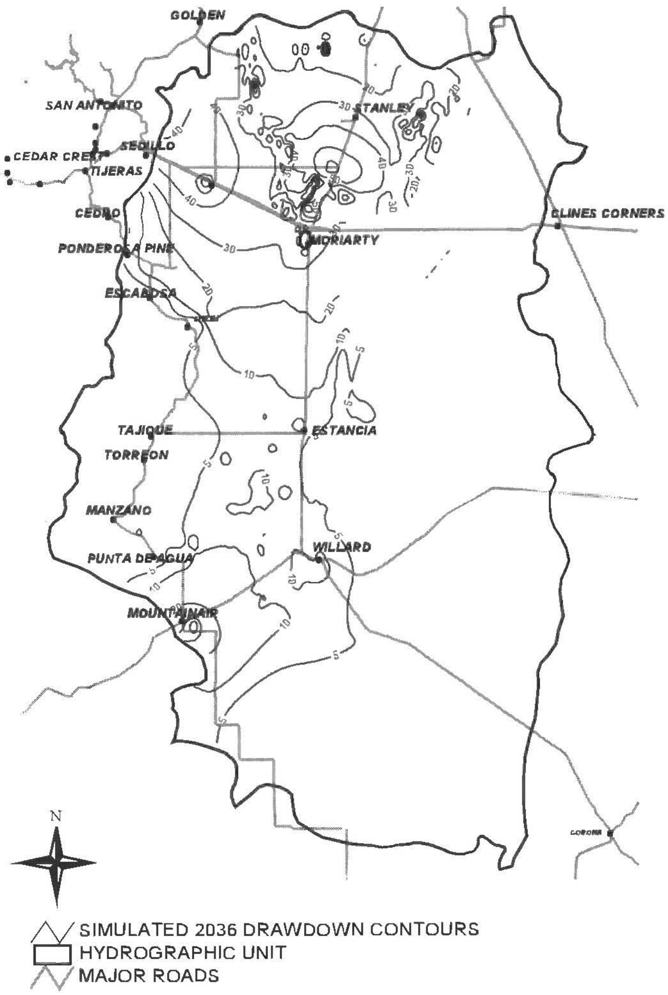

FIGURE 13. Simulated 2036 water-table drawdown.

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