Seasonal and Long-term Variations in Hydraulic Head in a Karstic Aquifer: Roswell Artesian Basin, New Mexico

Final Technical Report

August 2007

Open-File Report 503

New Mexico Bureau of Geology and Mineral Resources

Lewis Land, and Brad T. Newton

AQUIFER MAPPING PROGRAM

Mirror Lake

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Project Funding

Funding and support for this investigation were provided by the Pecos Valley Artesian Conservancy District; the New Mexico Bureau of Geology and Mineral Resources; and the Department of Research and Economic Development at the New Mexico Institute of Mining and Technology.

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An abridged version of this report has been published in the February, 2008 issue of the Journal of the American Water Resources Association.

Cover Photo: View south overlooking Mirror Lake, Bottomless Lakes State Park.

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PLATES

The following Plates are maps from Welder (1983).

I. ABSTRACT

Water levels in the karstic San Andres limestone aquifer of the Roswell Artesian Basin, New Mexico, display significant variations on a variety of time scales. Large seasonal fluctuations in hydraulic head are directly related to the irrigation cycle in the Artesian Basin, lower in summer months and higher in winter when less irrigation occurs. Longer-term variations are the result of both human and climatic factors. Since the inception of irrigated farming more than a century ago, overappropriation of water resources has caused water levels in the artesian aquifer to fall by as much as 230 ft (70 m). The general decline in hydraulic head began to reverse in the mid-1980s due to a variety of conservation measures, combined with a period of elevated rainfall toward the end of the twentieth century.

Key terms: Ground water; karst; artesian aquifer; Roswell Artesian Basin

II. INTRODUCTION

The Roswell Artesian Basin is located in the lower Pecos Valley of southeastern New Mexico (Figure 1), on the northern fringe of the Chihuahua Desert. Summers are long and hot and precipitation is sparse, averaging less than 13 inches/yr (33 cm/yr), most of which occurs as intense, localized thunderstorms during the summer monsoon season (Motts and Cushman, 1964). However, for more than 100 years the Roswell Basin has also been one of the most intensively farmed areas in the state, the principal crops being alfalfa, cotton, sorghum and chiles. The Basin derives virtually all of its irrigation water from ground water stored in an artesian carbonate aquifer and a shallow alluvial aquifer, and has been described by many workers as a world-class example of a rechargeable artesian aquifer system (e.g., Havenor, 1968).

Since the inception of irrigated agriculture in the Artesian Basin in the early 20th century, most of the discharge from both the artesian and shallow aquifers has been from wells. However, substantial natural discharge from the artesian aquifer still occurs along the Pecos River, through fractures and solution channels formed in overlying evaporitic confining beds. This natural discharge, which presently amounts to roughly 30,000 acre-ft/yr (~37 million m^3/yr) but was much greater in pre-development times (Barroll and Shomaker, 2003), is made manifest by a complex of karst springs, sinkhole lakes and extensive wetlands that occur along the west bank of the Pecos at Bitter Lakes National Wildlife Refuge (Figure 1) (Land, 2005). Along the eastern margin of the Pecos River valley, discharge from the artesian aquifer has formed a chain of large gypsum cenotes in the Seven Rivers Escarpment at Bottomless Lakes State Park (Land, 2003).

In the early history of development of the artesian aquifer, many wells flowed to the surface with yields as high as 5,700 gpm (21,500 l/min) (Welder, 1983), and high-volume springs west of Roswell fed tributary streams flowing into the Pecos River. However, decades of intensive pumping caused substantial declines in hydraulic head in the aquifer. By the mid-20th century total ground water diversions in the Artesian Basin approached 400,000 acre-ft/yr (493 million m^3) (Barroll and Shomaker, 2003), and Hantush (1957) estimated that withdrawals from the artesian aquifer exceeded recharge amounts by ~250,000 acre-ft/yr (308 million m^3/yr). By then most springs in the Artesian Basin were dry, and tributary stream flow had almost completely ceased except for rare flood events.

Increased appropriations from both the shallow and artesian aquifers had also reduced base flow into the Pecos River (Thomas, 1963; Havenor, 1968). In 1978 there were approximately 1,500 high-yielding irrigation, industrial, and public-supply wells in the Roswell Artesian Basin, and water levels in the artesian aquifer had declined in some areas by as much as 230 ft (70 m) (Welder, 1983). In 1975, a basin-wide investigation of water levels was conducted by the U.S. Geological Survey (USGS) and the New Mexico Office of the State Engineer (NM OSE). The results of that investigation, documented in a report by G.E. Welder (1983), showed significant water level declines in all areas of the Roswell Basin.

The Welder report is still widely cited and used for managing water resources in the Artesian Basin, although the data set is now over 30 years old and water levels have risen significantly since Welder's measurements were made. For this reason, the Pecos Valley Artesian Conservancy

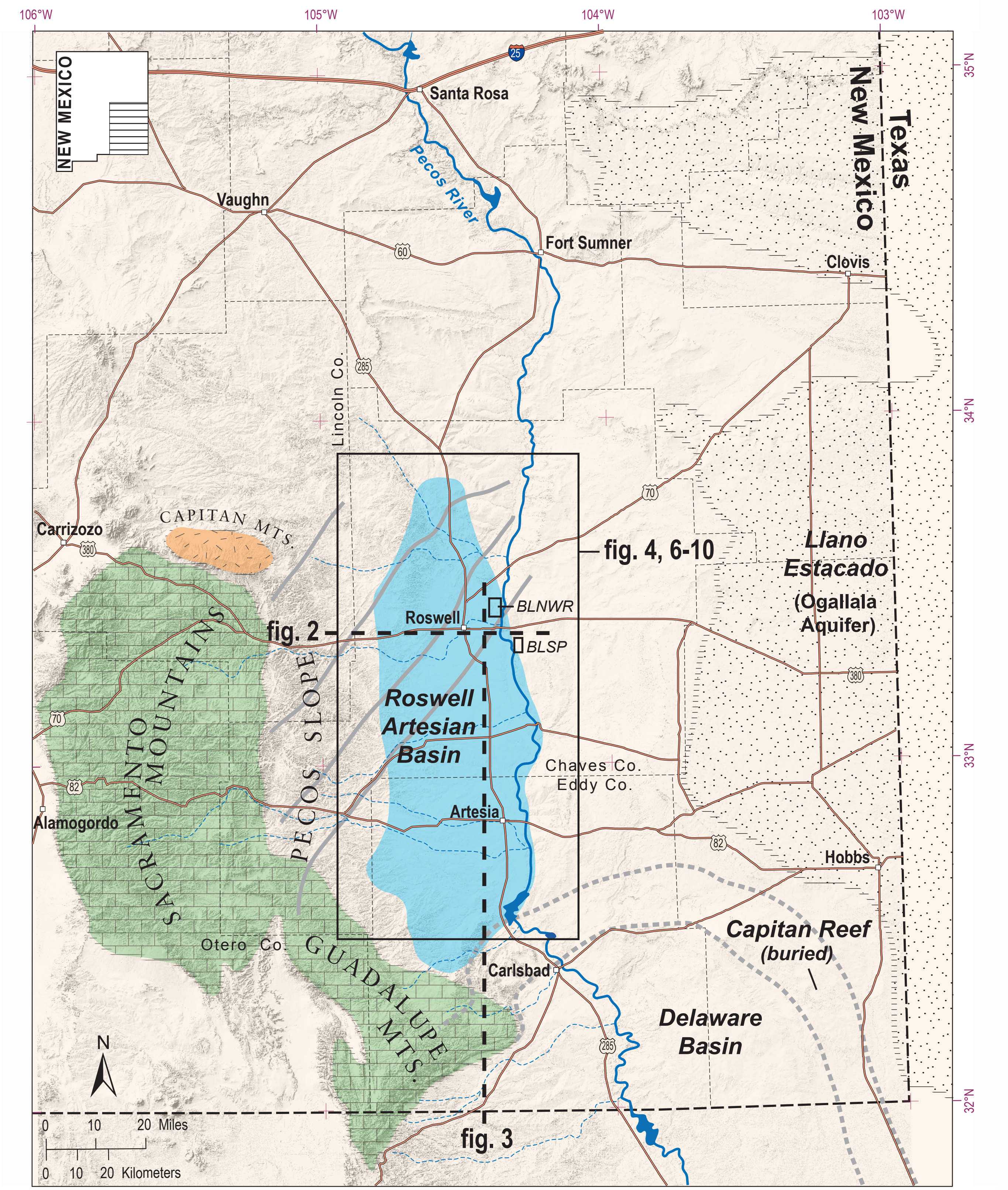


Figure 1–Regional map of southeastern New Mexico, showing location of Roswell Artesian Basin, Bitter Lakes National Wildlife Refuge (BLNWR) and Bottomless Lakes State Park (BLSP). Dashed lines show lines of section for figures 2 and 3. The Pecos Buckles are indicated by light solid lines extending northeast across the Pecos Slope. Outcrop in the eastern Sacramentos and Guadalupe Mountains consists primarily of carbonate rocks of the San Andres Formation (Sacramentos) and the Capitan Reef and backreef units of the Artesia Group (Guadalupes).

District (PVACD), the agency responsible for metering wells in the Artesian Basin, requested that the New Mexico Bureau of Geology and Mineral Resources (NMBGMR) conduct a new basin-wide study of hydraulic head in the shallow and artesian aquifers. This paper documents the results of that investigation.

III. BACKGROUND

The Roswell Artesian Basin is typically characterized as a two-aquifer system, a paradigm established by early investigators in the Basin (e.g., Fiedler and Nye, 1933). The system consists of an eastward-dipping carbonate aquifer overlain by a leaky evaporitic confining unit, which is in turn overlain by an unconfined alluvial aquifer (Figure 2). The carbonate aquifer is artesian to the east but under water table conditions in the western outcrop area on the Pecos Slope. Historically, the carbonate aquifer in the Roswell Basin is referred to as the "artesian aquifer", regardless of its confined or unconfined state. The alluvial aquifer is commonly referred to as the "shallow aquifer".

The western boundary of the Artesian Basin is defined by the intersection of the regional water table with the top of the Glorieta sandstone, the basal member of the San Andres Formation (Figure 2) (Kinney et al., 1968; Welder, 1983). Variable amounts of water move from the relatively low-permeability Glorieta into the overlying San Andres limestone, which makes up the greater part of the artesian aquifer. The Yeso Formation, a heterogeneous unit composed of siltstone, mudstone, carbonates and gypsum, serves as a lower confining unit for the artesian system.

The artesian aquifer becomes confined ~6 miles (10 km) west of the city of Roswell, where the eastward-dipping San Andres limestone passes beneath gypsum and mudstones of the

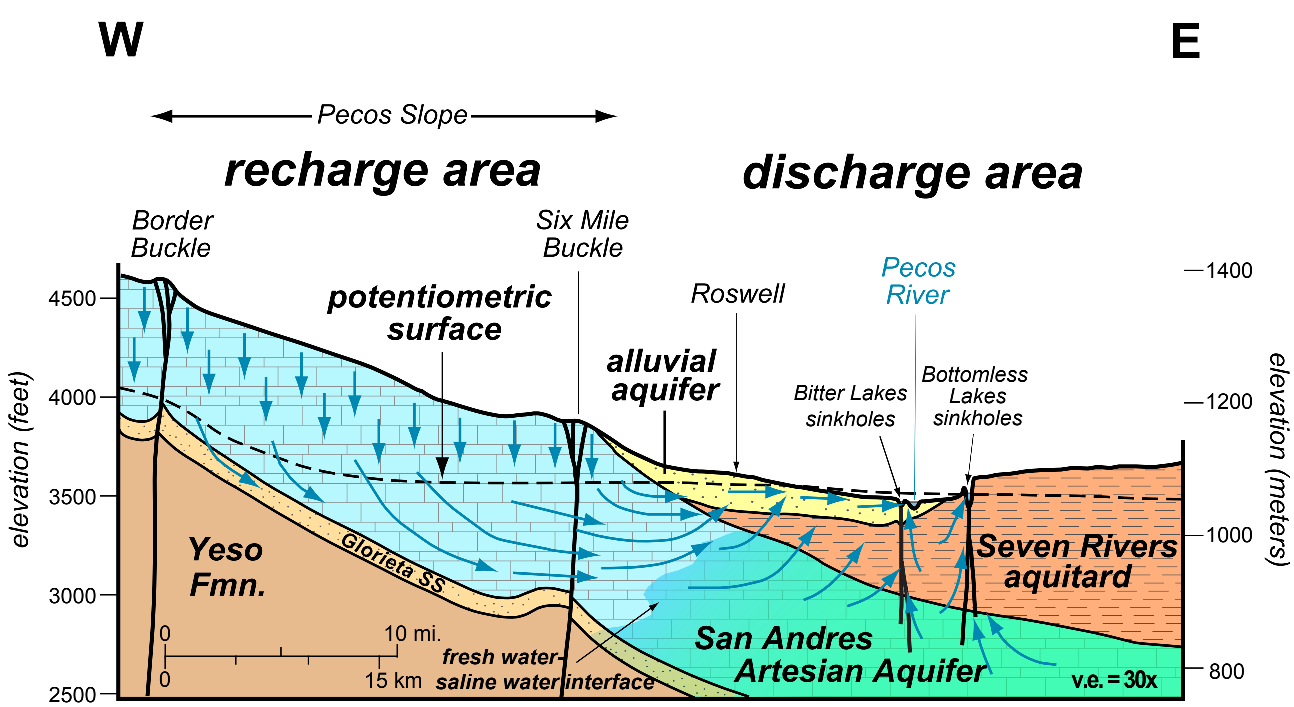


Figure 2–West-east hydrostratigraphic section illustrating regional ground water flow patterns within the artesian and shallow aquifers. Arrows indicate general direction of ground water flow. Line of section shown in figure 1.

Artesia Group. Most of the agricultural activity in the Basin is concentrated east of the confined-unconfined boundary in a 12 mile (20 km) wide strip west of the Pecos River. The eastern boundary of the Basin is a no-flow boundary along the Pecos River, across which very little ground water moves. Water along the eastern boundary flows southward within the artesian aquifer or upward through leaky confining beds into the shallow aquifer. East of the river the lower San Andres is an oil and gas reservoir, and the same interval that produces potable water for the city of Roswell a few miles to the southwest contains oil and brines with chloride concentrations as high as 39,000 ppm (Havenor, 1968; Gratton and LeMay, 1969). The west and east boundaries of the basin converge ~18 miles (30 km) north of Roswell (Welder, 1983).

The southern boundary of the basin is also regarded as a no-flow boundary, but its position is not well-defined. It is generally located (somewhat arbitrarily) along the Seven Rivers Hills north of Carlsbad, an area where the San Andres Formation begins to undergo a transition in the subsurface from shelf limestones and dolomites to shelf margin facies with lower porosity and permeability (Welder, 1983; Miller, 1969).

Artesian Aquifer

Ground water is stored in the carbonate aquifer in multiple erratically developed, highly porous and transmissive zones within the middle Permian (Guadalupian) San Andres limestone, and to a lesser extent in the overlying Grayburg Formation of the Artesia Group (Figure 3).

Water-bearing zones in the artesian aquifer rise stratigraphically from north to south, occurring near the middle of the San Andres Formation in the northern part of the Basin, and in carbonate rocks of the Grayburg Formation and upper San Andres in the southern part of the Basin near Artesia. Water-producing zones also rise stratigraphically from west to east, occurring in the basal Glorieta sandstone along the western

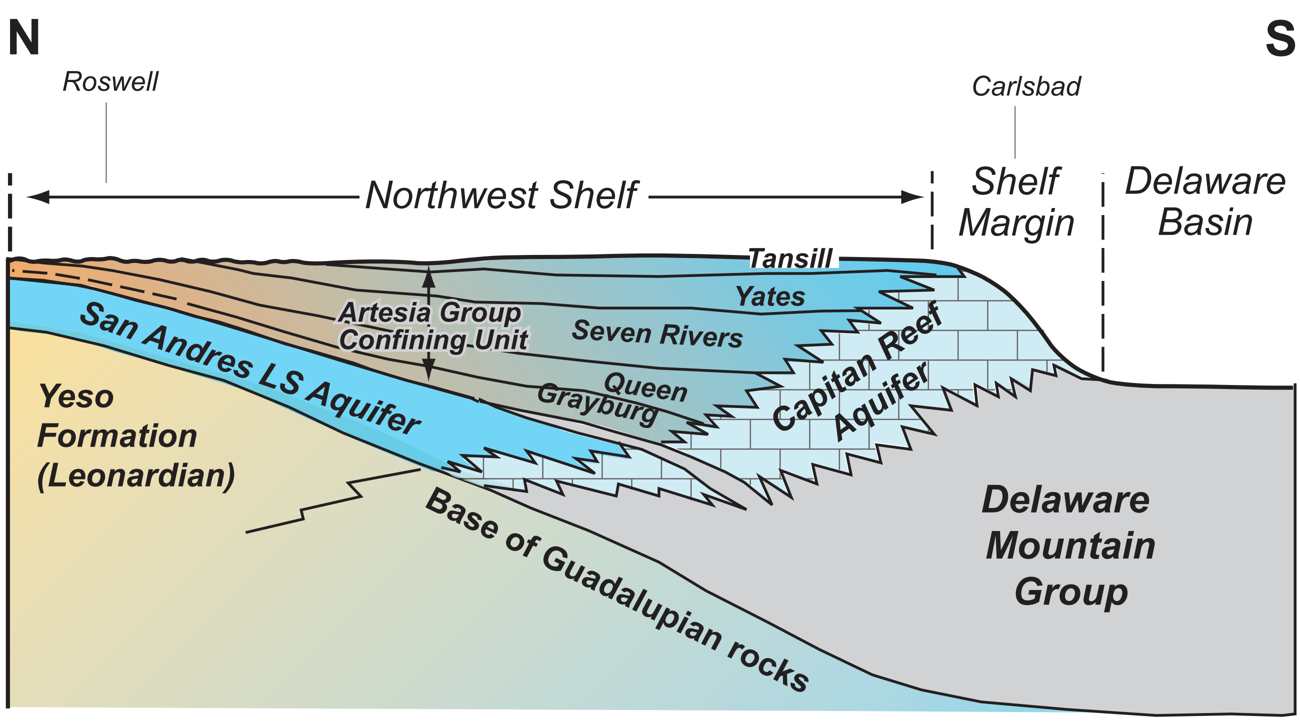


Figure 3–Diagrammatic cross-section showing shelf-to-basin facies relationships within middle Permian Guadalupian strata in southeastern New Mexico. Backreef units of the Artesia Group change facies from carbonates in the near-backreef section to interbedded evaporites and mudstone farther north, where they serve as confining beds for the artesian aquifer. Line of section shown in figure 1.

margin of the Basin, and in the upper San Andres limestone near the Basin's eastern boundary (Figure 2). Water-producing intervals range in thickness from a few inches up to 100 ft (33 m), but are usually less than 50 ft (15 m) thick. Some wells may penetrate as many as five separate producing zones. Wells producing from the artesian aquifer are completed open-hole, with casing installed only to the top of the aquifer. Small differences in head are known to occur between water-bearing zones, but hydrostatic pressures tend to equalize throughout the well bore with time (Welder, 1983). Average discharge from wells completed in the San Andres Formation is ~1,300 gpm (4,900 l/min), although high-yielding wells have been pumped for as much as 3,300 gpm (12,500 l/min). Wells producing from the Grayburg in the southern part of the Basin may yield up to 1,000 gpm (3,800 l/min) (Motts and Cushman, 1964). Hantush (1957) conducted aquifer tests in the artesian aquifer and measured transmissivities that ranged from 7,500 to 196,000 ft^2/day (700 – 18,200 m^2/day).

Kelley (1971) noted that the uppermost unit of the San Andres Formation, the Fourmile Draw Member, changes facies from south to north, grading laterally into evaporitic rocks. The San Andres is ~1,150 ft (350 m) thick in the subsurface east of the Pecos, with about 100 ft (33 m) of Glorieta sandstone at its base. However, as much as 600 ft (180 m) of evaporites have been removed from the upper part of the section by subsurface dissolution in the northwestern Artesian Basin, leaving an extensive solution breccia (Bachman, 1984, 1987). The San Andres aquifer is just 260 – 460 ft (80-140 m) thick in the vicinity of the Pecos River.

Secondary porosity in the artesian aquifer is developed in vuggy and cavernous limestones; intraformational solution-collapse breccias, or "rubble zones" (Motts and Cushman, 1964); and solution-enlarged fractures and bedding planes. Much of the porosity and permeability has formed by subsurface dissolution of evaporites within the upper 200 – 300 ft (60-90 m) of the San Andres Formation during late Permian time when the formation was exposed to erosion, and then subsequently enhanced by continued circulation of ground water (Welder, 1983). The upper San Andres is often described as having a "worm-eaten" or "honeycombed" appearance in outcrop and core due to leaching of evaporites (Fiedler and Nye, 1933; Motts and Cushman, 1964). The karstic nature of the artesian aquifer is well-illustrated by the breccia zones, particularly common in the upper San Andres, where they consist of tilted and rotated blocks of carbonate rock up to 2 ft (60 cm) in diameter, imbedded in a silt matrix. Many of the cavernous openings in the San Andres are developed within these breccia zones (Motts and Cushman, 1964), which are also intervals where lost circulation frequently occurs during drilling operations. Evidence of cavernous porosity in the subsurface includes bit drops of as much as 16 ft (5 m) during water well drilling (Havenor, 1968).

Recharge to the artesian aquifer, estimated to be ~300,000 acre-ft/yr (370 million m^3) (Barroll and Shomaker, 2003), occurs by direct infiltration from precipitation, and by runoff from intermittent losing streams that flow eastward across the Pecos Slope, a broad area east of the Sacramento Mountains where the San Andres limestone is exposed in outcrop (Figures 1 and 2). Enhanced recharge occurs through sinkholes and solution-enlarged fractures associated with the Pecos Buckles. These structures, which include the Border, Six-Mile, and Y-O Buckles (Figures 2 and 4), are wrench fault zones of probable Laramide age that extend SW-NE for several tens of miles across the Pecos Slope (Motts and Cushman, 1964; Havenor, 1968; Kelley, 1971), the area referred to by Fiedler and Nye (1933) as the Principal Recharge Area for the artesian aquifer. Areas of highest permeability in the recharge area occur along the major drainages, along structural zones, and in the vicinity of carbonate-evaporite facies boundaries (Motts and Cushman, 1964). In pre-development times, ground water flowed east and south, down gradient from the recharge area, then upward through leaky confining beds into the alluvial aquifer, and ultimately to the Pecos River (Figure 2). Nowadays most of the down-gradient flow is intercepted by irrigation wells in the Artesian Basin. Discharge from artesian wells for irrigation and municipal water supply amounts to approximately 350,000 acre-ft/yr (432 million m^3/yr), of which about one-third returns to the aquifer as irrigation return flow (Barroll and Shomaker, 2003).

Upward leakage from the artesian aquifer through overlying confining beds is an important source of recharge to the shallow aquifer. However, during extended periods of low rainfall the vertical hydraulic gradient may be reversed. In 1950, the potentiometric surface in the artesian aquifer was higher than the water table in the shallow aquifer throughout the Artesian Basin. By 1975, when water levels in the artesian aquifer were at historic lows, hydraulic head was reported to be lower than shallow water levels in some areas of the Basin (Welder, 1983).

Salinity of the Artesian Aquifer

Mineral content of ground water in the artesian aquifer rapidly increases eastward toward the Pecos River. The principal area where saline water occurs is in townships 10 and 11-S, Ranges 24 and 25-E, between Roswell and the Pecos. Saline water, as defined by Hood (1963), is water containing chloride concentrations greater than 500 parts per million (ppm). The Environmental Protection Agency recommends that water intended for human consumption not exceed 250 ppm Cl-, but slightly brackish water may still be used effectively for irrigation and watering livestock. In the freshwater-saltwater transition zone east of Roswell, water with chloride concentrations greater than 1,000 ppm is commonly used for those purposes.

Chloride concentrations range from 15 ppm in the unconfined, western part of the aquifer to as high as 7,000 ppm in a flowing artesian well east of Roswell. Discharge from that well was used as feedstock for a pilot desalination facility in the mid-20th century. Chloride also increases with depth in the aquifer. Hood (1963) reported that in the vicinity of Artesia a difference of just 100 – 200 ft in well depth can mean a difference of several hundred ppm in chloride concentration. Chloride content in the artesian aquifer is lowest in the spring, and highest in the fall after the irrigation season is over. The largest seasonal fluctuations in mineral content occur within the transition zone (Figure 2) between Roswell and the Pecos River, where chloride concentrations may display fluctuations of more than 1,500 ppm during a single irrigation cycle (Hood, 1963; Welder, 1983).

Salinity is highly variable in the sinkholes and karst springs that line the Pecos River at the discharge end of the artesian system. Chloride concentrations measured in sinkhole lakes and springs at Bitter Lakes National Wildlife Refuge (Figure 1) range from ~1,100 to 3,500 ppm, with total dissolved solids (TDS) content varying from 3,600 to 10,000 ppm. Samples collected from a submerged spring discharging from the lakebed in Lea Lake, the largest sinkhole lake at Bottomless Lakes State Park, had measured chloride concentrations of 2,950 ppm and TDS content of 7,987 ppm (Land, 2005). Land (2003) reported that water in the northernmost sink at Bottomless Lakes had a chloride content of 15,600 ppm and TDS of 38,200 ppm, greater than the salinity of seawater.

For a number of years during the mid-20th century, saltwater encroachment from the east threatened the freshwater supply for the city of Roswell. The freshwater-saltwater interface migrates westward during periods of low rainfall because of the decline in artesian pressure due to increased irrigation pumping. Extended periods of high rainfall cause an eastward retreat of the interface, since irrigation demand on the aquifer is not as great (Hood et al., 1960). Saltwater encroachment within the artesian aquifer was of particular concern during the long drought of the 1950s, but since then the position of the freshwater-saltwater interface appears to have stabilized (Dennis Karnes, PVACD, personal communication).

Artesia Group Confining Beds

Bedrock along most of the Pecos River between Roswell and Carlsbad consists of dolomites, evaporites and redbeds of the Artesia Group (Figure 3), the backreef equivalent of the Capitan Reef limestone that is exposed along the southeast flank of the Guadalupe Mountains to the south (King, 1948; Hayes, 1964; Kelley, 1971). In the Guadalupe Mountains near Carlsbad, the backreef facies consists predominantly of carbonates with some sandstone, but to the north the section becomes increasingly evaporitic. In the Roswell Artesian Basin the Artesia Group is made up of interbedded mudstone and gypsum at the surface, with thick, bedded salt and anhydrite present in the subsurface. This low-permeability facies of the Artesia Group serves as a leaky upper confining unit for the artesian aquifer. Hantush (1957) estimated that net upward leakage through confining beds amounted to 12,400 acre-ft/month (~15 million m^3/month). In the southern part of the Basin, south of Lake Arthur (Figure 4b; Plate 1), the carbonate facies of the Grayburg Formation, the lowermost member of the Artesia Group, is included as part of the artesian system.

Welder (1983) estimated that ~10% of the ground water pumped in the Artesian Basin is from moderately permeable zones in confining beds of the Grayburg, Queen and Seven Rivers Formations. Producing zones are developed in solution-enlarged fractures and bedding planes and in collapse breccias. These zones generally occur in the upper one-quarter of the section designated as the confining unit, and do not appear to be laterally extensive.

Thickness of the confining unit varies from a feather edge in the northern and western parts of the Basin to ~800 ft (250 m) in the center of the Basin, and also thickens regionally downdip to the east (Plate W-11). To the west, the confining beds are truncated by erosion. The different formations of the Artesia Group cannot be distinguished in their evaporitic facies (Motts and Cushman, 1964), but the Tansill Formation, the uppermost unit of the Artesia Group, appears to be absent in the Artesian Basin due to erosion (Figure 2). Local variations in thickness of the confining beds are caused by dissolution of gypsum in the upper part of the section (Welder, 1983).

Shallow Aquifer

The unconfined shallow aquifer is contained within valley fill alluvium deposited on the Pecos River floodplain during late Tertiary and Holocene time, as the river migrated eastward due to uplift of the Sacramento Mountains to the west (Land, 2003). The western boundary of the shallow aquifer is defined by the zero saturation line in the valley fill, which occurs roughly 12 miles (20 km) west of the Pecos River (Plate W-12). However, the western boundary is somewhat ambiguous because isolated water-bearing zones in the upper part of the Artesia Group (Grayburg and Queen Formations) also produce in that area. The shallow aquifer is hydraulically connected to the Pecos River along most of its eastern boundary. Valley fill alluvium may extend as much as 2 miles (3 km) east of the river, but it is thin and of low permeability. The shallow aquifer grades into less permeable alluvium north of Roswell and south of the Seven Rivers Hills (Figure 4a) (Welder, 1983).

The lowermost unit of the valley fill in the Artesian Basin is a quartzose conglomerate cemented to varying degrees with calcium carbonate. This unit is usually no more than 250 ft (76 m) thick and is the principal water-bearing zone within the shallow aquifer. The quartzose conglomerate is overlain by varying thicknesses of silts and clays that were probably deposited in ponds and lakes formed by solution-collapse processes in the underlying Permian evaporites. This layer is overlain by a carbonate gravel unit that blankets all the other valley fill deposits, forming a uniform slope from Permian outcrop on the Pecos Slope to the Pecos River floodplain (Lyford, 1973).

The valley fill attains a maximum thickness of ~300 ft (90 m) in three closed depressions formed in the top of the Artesia Group near Roswell, Hagerman, and Artesia along the west side of the Pecos River (Plate W-9). These depressions were probably formed by dissolution and collapse in the evaporitic units of the Artesia Group. Lyford (1973) observed that gypsum is absent in the uppermost 50 ft (15 m) of Permian bedrock in those areas where large depressions are present. In 1973 a maximum saturated thickness of ~250 ft (75 m) was reported for the shallow aquifer in the closed depressions near Hagerman and Artesia, and a saturated thickness of ~300 ft (90 m) in the depression near Roswell (Lyford, 1973).

Discontinuous water-producing zones found in the upper 50 ft (15 m) of the Artesia Group are probably hydraulically connected to the shallow aquifer. Most of the water recharging the shallow aquifer is from the underlying artesian system, either from irrigation return flow or from upward leakage through confining beds of the Artesia Group (Motts and Cushman, 1964). Precipitation and surface runoff also contribute to recharge. The direction of flow is sometimes reversed during the irrigation season when high levels of pumping reduce hydraulic head in the artesian aquifer, at which times water may flow downward from the shallow aquifer into the artesian system (Welder, 1983).

Chloride content of the shallow aquifer fluctuates in less systematic ways than in the artesian aquifer. In most areas of the Basin, increased precipitation will produce a measureable decrease in salinity in the shallow aquifer. By contrast, irrigation with brackish water derived from the artesian aquifer causes an obvious, well-defined upward trend in salinity of the shallow aquifer (Hood, 1963).

IV. MANAGEMENT OF WATER RESOURCES IN THE ARTESIAN BASIN

From the mid-1940s through early 1960s, there were ~144,000 acres (58,300 ha) of farmland under irrigation in the Roswell Artesian Basin, using water from both the artesian and shallow aquifers (the above figure includes an insignificant amount of surface water rights). Prior to 1966 ground water pumping was not metered, and irrigation pumping limits had not yet been set. Many wells were allowed to flow continuously, and it is estimated that pumping rates during this period were as high as 5 – 6 acre-ft/acre/yr (15,234 – 18,280 m^3/ha/yr) (Dennis Karnes, PVACD, personal communication). Water rights in the Roswell Basin were adjuticated in 1966, at which time metering of water wells began. Irrigated acreage was reduced to ~130,000 acres (52,600 ha) and water use was limited to 3.5 acre-ft/acre/yr (10,664 m^3/ha/yr). During the period from 1958 - 1985, in an effort to mitigate the basin-wide decline in water levels, PVACD plugged 1,518 wells. The Conservancy District also purchased almost 7,000 acres (2,800 ha) of irrigated farmland and permanently retired that land from agricultural activity (Shomaker, 2003). In 1994 - 95 the New Mexico Interstate Stream Commission (ISC) purchased and retired an additional 5,800 acres (2,350 ha) of farmland in the Artesian Basin. In 2004 a consensus plan was developed for water use on the lower Pecos River that includes a program of purchase by the ISC of 11,000 acres (4,450 ha) of water rights (both shallow and artesian) in the Artesian Basin, thereby reducing total irrigated farmland in the Basin to ~106,000 acres (43,000 ha).

V. METHODS

Potentiometric surface maps were constructed based on water level data collected in January and February, 2005 by the USGS, NM-OSE, PVACD, and NMBGMR. During winter months very little irrigation occurs, so water levels are at their highest in the Artesian Basin and are less likely to be influenced by local pumping events. Water levels were measured using standard steel tape or electric sounding tape. A few deep wells were measured using a sonar sounding device. Additional maps were prepared showing changes in hydraulic head from 1975 to 2005 and from 2004 to 2005. 1975 and 2004 water level data were derived from USGS and OSE historical records, and were also measured during the winter months when irrigation was minimal, consistent with the 2005 data set.

VI. RESULTS

Artesian Aquifer

Configuration of hydraulic head in the artesian aquifer (Figure 4b; Plate 1) indicates that the general direction of ground water flow is to the east and southeast. One of the most distinctive features of this map is a broad area east of the 3,560 ft contour encompassing ~2/3 of the Basin where the hydraulic gradient is very low (< 10 ft/mile, or 1.8 m/km). West of this contour the mapped area enters the eastern foothills of the Sacramento Mountains, where the principal aquifers are the relatively low permeability Glorieta sandstone and fractured carbonates in the Yeso Formation (Welder, 1983). The steepness of the hydraulic gradient along the western margin of the Artesian Basin requires a change in contour interval from 10 ft (3 m) to 100 ft (30 m) west of the 3,600 ft contour.The hydraulic gradient flattens abruptly a short distance east of the Border Buckle, where the San Andres limestone becomes the principal water-bearing zone (Figure 2). The low hydraulic gradient in this part of the Artesian Basin reflects the much higher permeability and transmissivity of the San Andres limestone in contrast to the Glorieta and Yeso farther west. The same phenomenon has been observed by previous workers in the Basin (e.g., Motts and Cushman, 1964; Welder, 1983).

Another conspicuous feature of the potentiometric surface is an area trending NE-SW in the southern part of the Basin, west of the village of Lake Arthur, where the hydraulic gradient is very steep (~50 ft/mile, or 5.6 m/km), a phenomenon also noted by Welder (1983), who attributed the closely-spaced contours to a lateral decrease in permeability within the aquifer. This area of steep hydraulic gradient occurs immediately northwest of the KM Fault. The KM Fault lies parallel to the Pecos Buckles and may be related to those structures. The fault apparently occurs entirely in the subsurface, although Kelley (1971) observed that the subsurface trace of the fault coincides with a pronounced southwest bend of the Pecos River, and with the northeast-trending Long Arroyo east of Lake Arthur. Like the Pecos Buckles, the KM Fault is thought to combine right-lateral motion with normal vertical displacement, and latest movement on the fault may be of Laramide age (Havenor, 1968; Kelley, 1971). The KM Fault is not well-defined on structural contour maps of the top of the San Andres Formation (Plate W-8), although Kelley (1971) mapped a displacement of as much as 200 ft (60 m) down to the southeast on the top of the lowermost Rio Bonito member of the San Andres. Kinney et al. (1968) report that the best resolution of the structure is on Mississippian-age rocks. The KM Fault clearly influences ground water flow in the southern Artesian Basin, probably by juxtaposing less permeable rocks of the Grayburg Formation to the southeast against more highly transmissive rocks to the northwest. The fault thus acts as a partial barrier to down-gradient flow, and effectively separates the southeastern part of the artesian aquifer system from the main part of the aquifer to the northwest. Hydraulic head is significantly elevated on the northwest side of the fault because of this impediment to down-gradient flow. Many strongly-flowing artesian wells occur within this area of steep hydraulic gradient northwest of the KM Fault, flowing to the surface during winter months. In contrast, wells in most other parts of the Basin have not shown such strong artesian flow for many years.

Two cones of depression occur in the southern part of the Artesian Basin, southeast of the

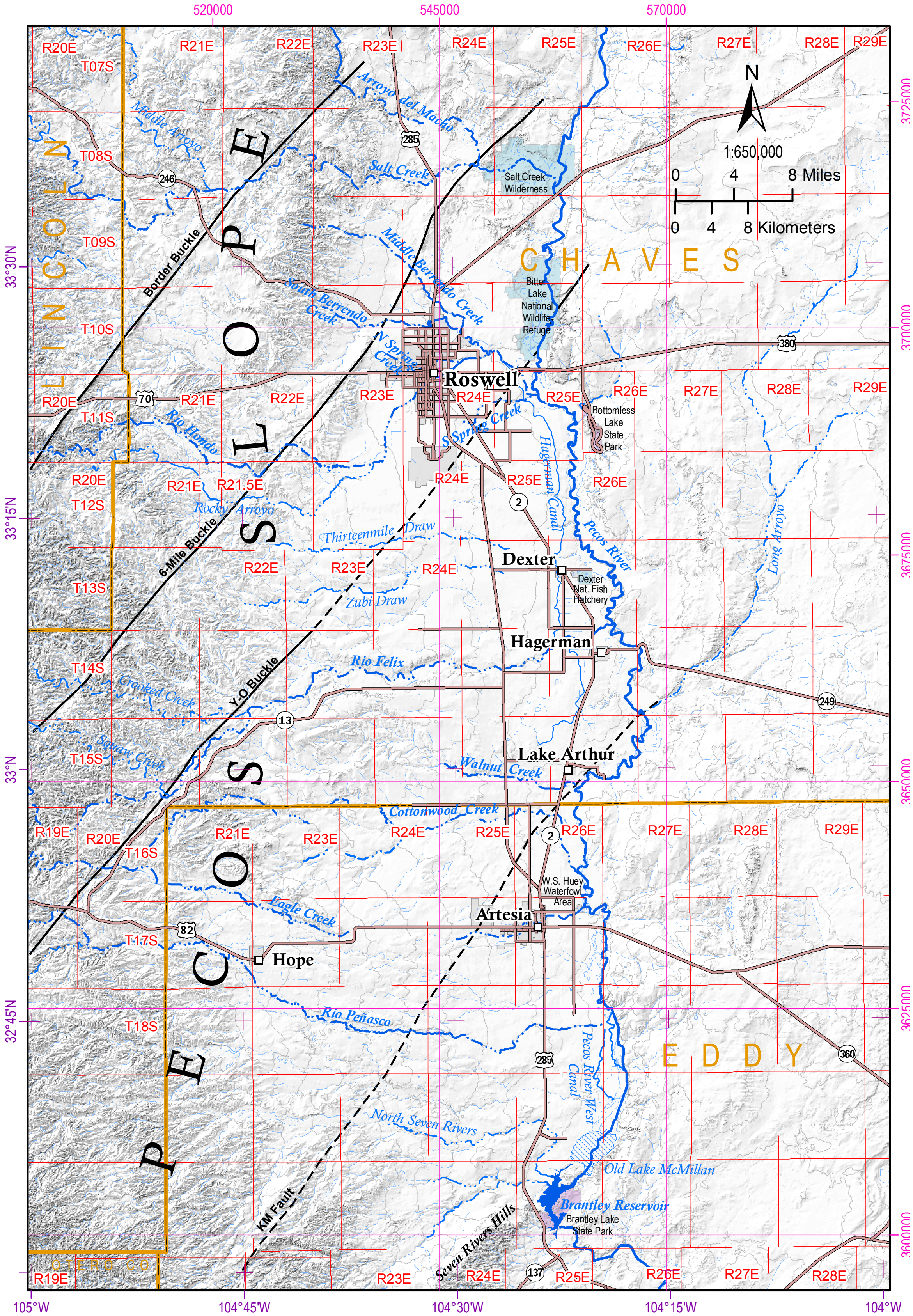
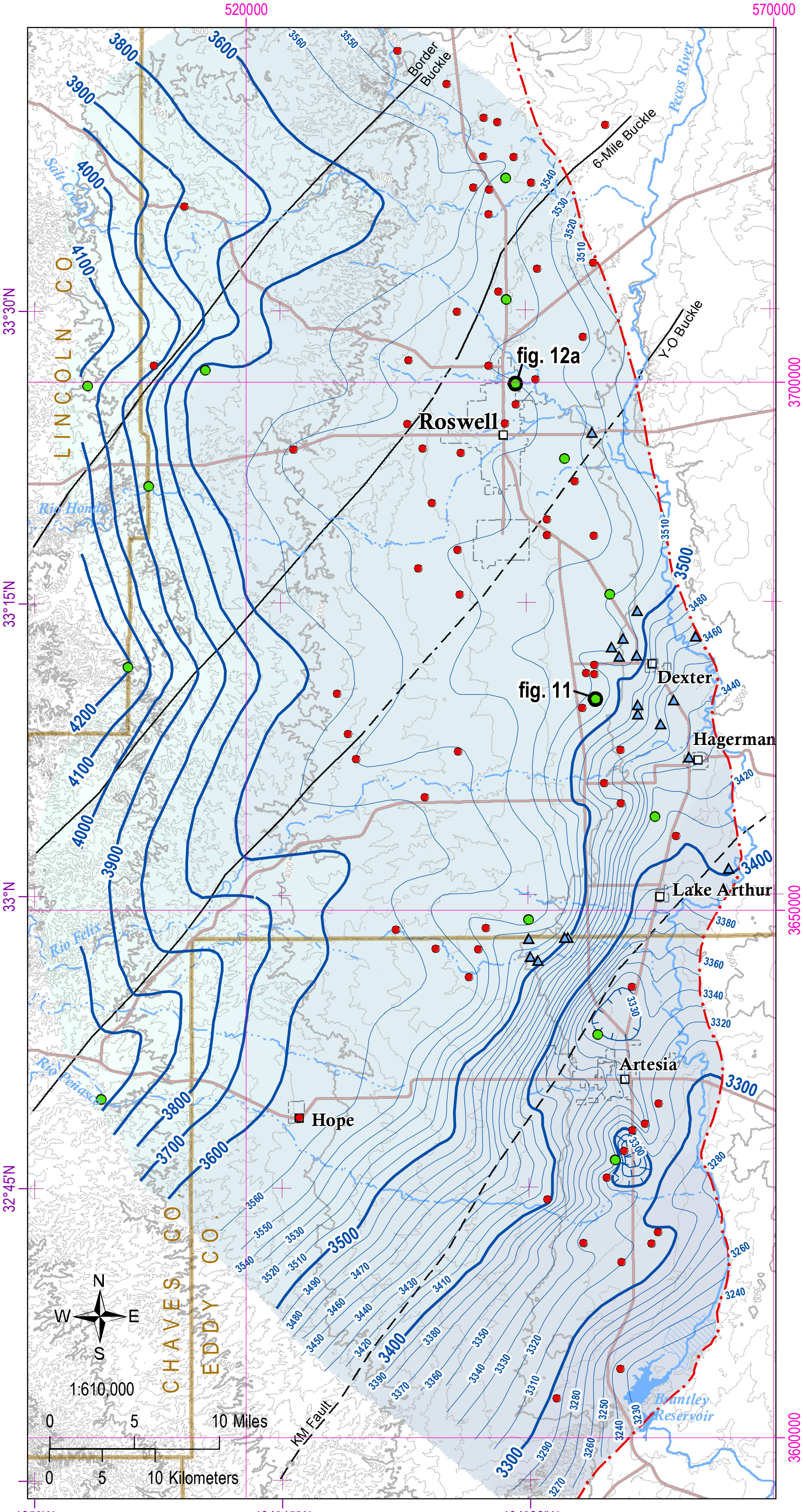


Figure 4a–Physiographic features of the lower Pecos Valley.

Figure 4b–Configuration of hydraulic head in the artesian aquifer, January-February, 2005. Contour interval = 10 ft below 3,560 ft; and 100 ft above the 3,600 ft contour. Heavy dashed line shows eastern boundary of Artesian Basin. Filled circles are wells completed in the artesian aquifer. Large green circles are observation wells. Blue triangles are flowing artesian wells. Locations of monitoring wells from figures 11 and 12-a are indicated.



KM Fault near Artesia. These features, although legitimate depressions in the potentiometric surface, also reflect in part the heterogeneous nature of the artesian aquifer. The Grayburg Formation is the principal water-bearing zone in the southern part of the Basin, where transmissivities are generally lower than to the north. However, some wells in this area also produce water from the upper part of the San Andres limestone. For example, a well centered in the small cone of depression south of Artesia is 840 ft (256 m) deep and is completed in the Grayburg (Figure 4b; Plate 1).Water levels are 40 ft (12 m) higher in the Artesia-A monitoring well, less than a mile to the southwest. The Artesia-A well was drilled to a depth of 1,007 ft (307 m) and completed in the San Andres limestone portion of the artesian aquifer.

The influence of the Pecos Buckles on ground water movement within the artesian aquifer is less obvious, but this may be due to the small number of wells measured in the western part of the Basin. The influence of the YO Buckle is shown by a trough in the potentiometric surface southeast of the Buckle near the center of the Basin (Figure 4b; Plate 1), a phenomenon also observed by previous workers (e.g., Kinney et al., 1968). There is no obvious change in hydraulic gradient associated with the Border and Six-Mile Buckles, although the potentiometric surface in the vicinity of those structures is not well-constrained because of the limited number of data points in the northwest part of the map.

Broad mounds and noses on the potentiometric surface appear to roughly coincide with east-flowing tributaries of the Pecos River, such as Cottonwood Creek and Walnut Creek, immediately south and north respectively of the Eddy-Chaves county line. Although these features are not well-defined due to limited well control in the western part of the Basin, their association with surface drainage systems on the Pecos Slope probably reflects areas of enhanced permeability along the course of these losing streams, which serve as linear recharge zones to the artesian aquifer (Duffy et al., 1978).

Artesian Aquifer: Chloride Content

Chloride data were only available for the northern part of the Artesian Basin, from the Roswell area south to the vicinity of Dexter (Figure 5; Plate 2). The most distinctive feature of the chlorides map is a broad lobe of saline water projecting toward the city of Roswell, with chloride concentrations ranging from 500 to >7,000 ppm, located in townships 10 and 11-S, ranges 24 and 25-E. This lobe of brackish water has also been reported by previous workers (e.g., Hood et al., 1960; Hood, 1963; Havenor, 1968; Welder, 1983). Hood (1963) used the 500 ppm chloride contour to define the position of the freshwater-saltwater interface in the artesian aquifer. During the mid-20th century, the interface was migrating westward at a rate of about a tenth of a mile per year (Hood et al., 1960), and threatened the municipal water supply for the city of Roswell. However, the postion of the interface appears to have stabilized in recent years. Data collected for this study show that in most areas the present position of the 500 ppm chloride contour lies a few tenths of a mile east of its position in 1978.

Shallow Aquifer

The shallow aquifer is of more limited extent than the artesian aquifer, extending to ~12 miles (20 km) west of the Pecos River (Figure 6; Plate 3). The aquifer is thin to non-existent and not much utilized in the northern part of the Basin northwest of Roswell. In general, ground water flows east through the shallow aquifer and discharges into the Pecos River. An exception to this rule is a distinctive ridge in the water table trending SW-NE near the Chaves-Eddy County line, west of Lake Arthur

The most conspicuous feature of the shallow aquifer is a broad cone of depression west of the town of Hagerman, over 12 miles (20 km) across on the N-S axis and over 120 ft (36 m) deep. Unlike most other communities in the Artesian Basin, wells in the Hagerman area are completed primarily in the shallow aquifer. The Hagerman

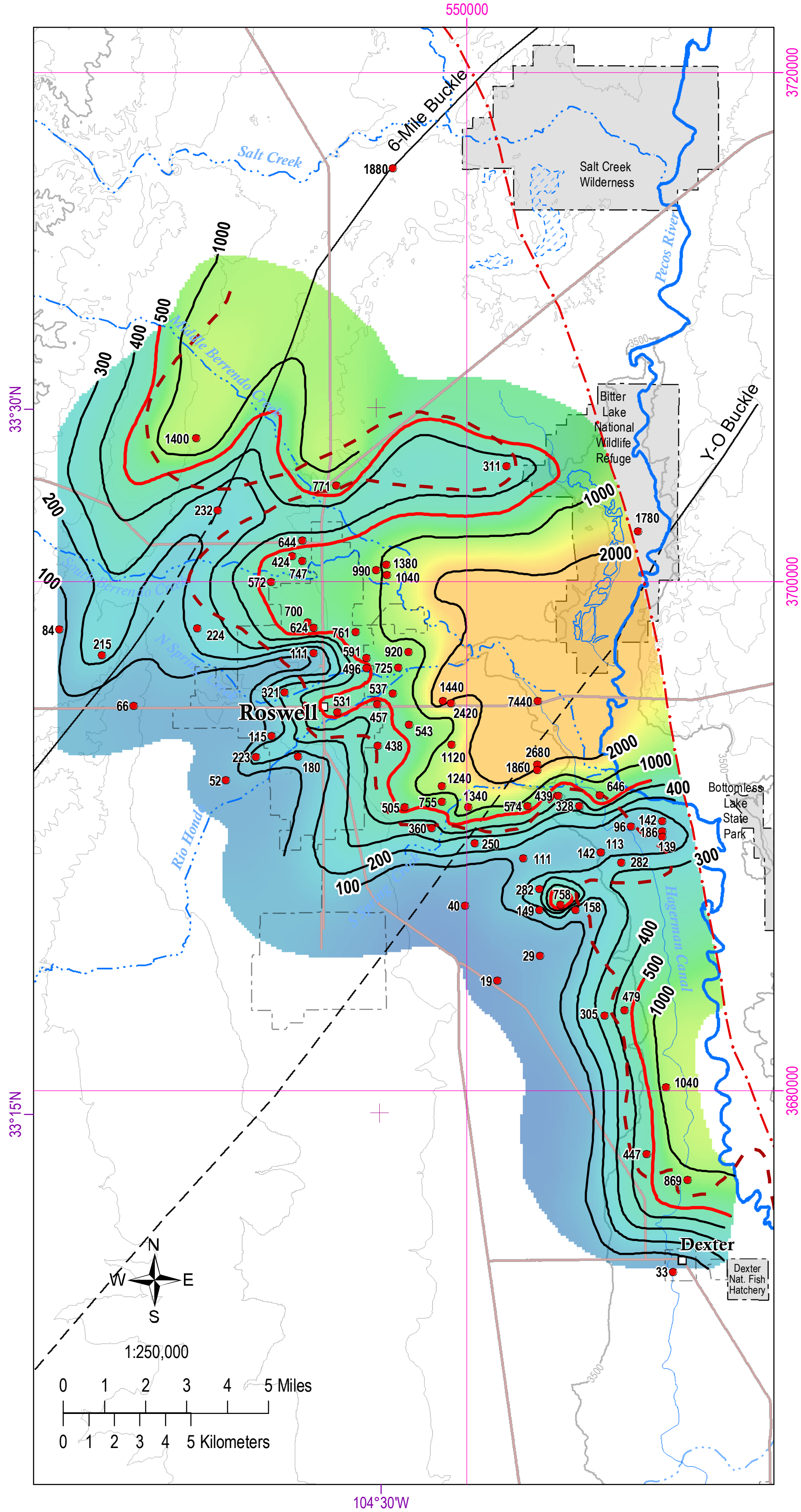


Figure 5–Chloride concentration in the artesian aquifer, March, 2005. Filled circles are wells measured for chlorides. Contour interval variable, in parts per million. Dashed line shows 500 ppm chloride concentration in the artesian aquifer in 1978, from Welder (1983). Solid red contour line indicates the present position of the 500 ppm chloride concentration.

cone of depression is a well-known phenomenon in the Artesian Basin, mentioned frequently in NM OSE and USGS reports (e.g., Garn, 1988). A less well-defined cone of depression is located west of the city of Artesia, extending for about 10 miles (16 km) from south to north and roughly 40 ft (12 m) deep. A ridge in the shallow water table west of Lake Arthur separates the Hagerman and Artesia cones of depression.

The Artesia cone of depression can be extended farther southeast and south into a broad depression in the shallow water table between highway 285 and the Pecos River. This depression is 20 to 40 ft (6 – 12 m) deep and extends to the southern terminus of the shallow aquifer near the Seven Rivers Hills.

Variations in Hydraulic Head: Artesian Aquifer

The map showing change in hydraulic head in the artesian aquifer in the 30 year period since Welder's (1983) data were collected is not well-constrained because of the smaller number of wells for which measurements are available in both 1975 and 2005. Nevertheless, the data set clearly indicates a rise in water levels in almost all areas of the Roswell Artesian Basin, ranging from 8 to 34 ft (2.4 – 10.4 m) (Figure 7; Plate 4). The greatest change in water levels since 1975 has occurred in a broad area defined by the +20 ft contour, extending from north to south across the Pecos Slope over the entire extent of the Artesian Basin. This is the area originally designated by Fiedler and Nye (1933) as the Principal Recharge Area for the artesian aquifer.

One area where water levels have risen over 30 ft (9 m) lies near the village of Hope in the southwestern part of the Basin. This area coincides with the middle reaches of the Rio Penasco. A PVACD monitoring well located on the north bank of the Rio Penasco, a few miles west of Hope, has displayed very rapid responses to storms and flash flood events in the river (Duffy et al., 1978). Such a rapid response to flood events probably reflects rapid recharge through zones of enhanced permeability associated with karstic openings in the San Andres limestone where it is exposed in the bed of the river.

Only two wells on either side of the Border Buckle on the extreme western edge of the Basin show long-term declines in water levels. These wells are located in that part of the Basin where the Glorieta sandstone is the main aquifer.

This basin-wide rise in water levels in the artesian aquifer stands in remarkable contrast to the results shown in Welder's (1983) report. The Welder report documents historic water level changes over the course of development of the artesian aquifer, including maps showing changes in head for the periods 1926-1975 (Plate W-15) and 1950-1975. Although data were limited for the earlier time periods, all of Welder's maps and hydrographs show consistent, steady declines in hydraulic head ranging from 20 – 100 ft (6 – 30 m) in all areas of the Artesian Basin. The data set used for this investigation is the first to indicate a significant reversal in that historic trend.

A comparison of water levels in the artesian aquifer between January, 2004 and January, 2005 (Figure 8; Plate 5) also shows a significant rise in head, particularly in the southern part of the Basin, where water levels rose by greater than 15 ft (5 m) in some areas. This was a period of exceptionally high rainfall for the lower Pecos valley. Total rainfall in the Roswell area in 2004 was 16 inches (42 cm), compared to average annual precipitation of 13 inches (32 cm) in this part of the state.

Variations in Hydraulic Head: Shallow Aquifer

During the period from 1975 to 2005 water levels in the shallow aquifer declined by more than 15 ft (5 m) in two sectors of the Artesian Basin, and rose an equal amount in other areas (Figure 9; Plate 6). A significant decline in water levels is indicated west of Hagerman in Townships 13 and 14-S, Range 25-E. In that area the Hagerman cone of depression, already well-defined on Welder's (1983) map of the 1975 water table (Plate W-16), has increased in depth from 75 ft (23 m) to 120 ft (36 m). In the southern

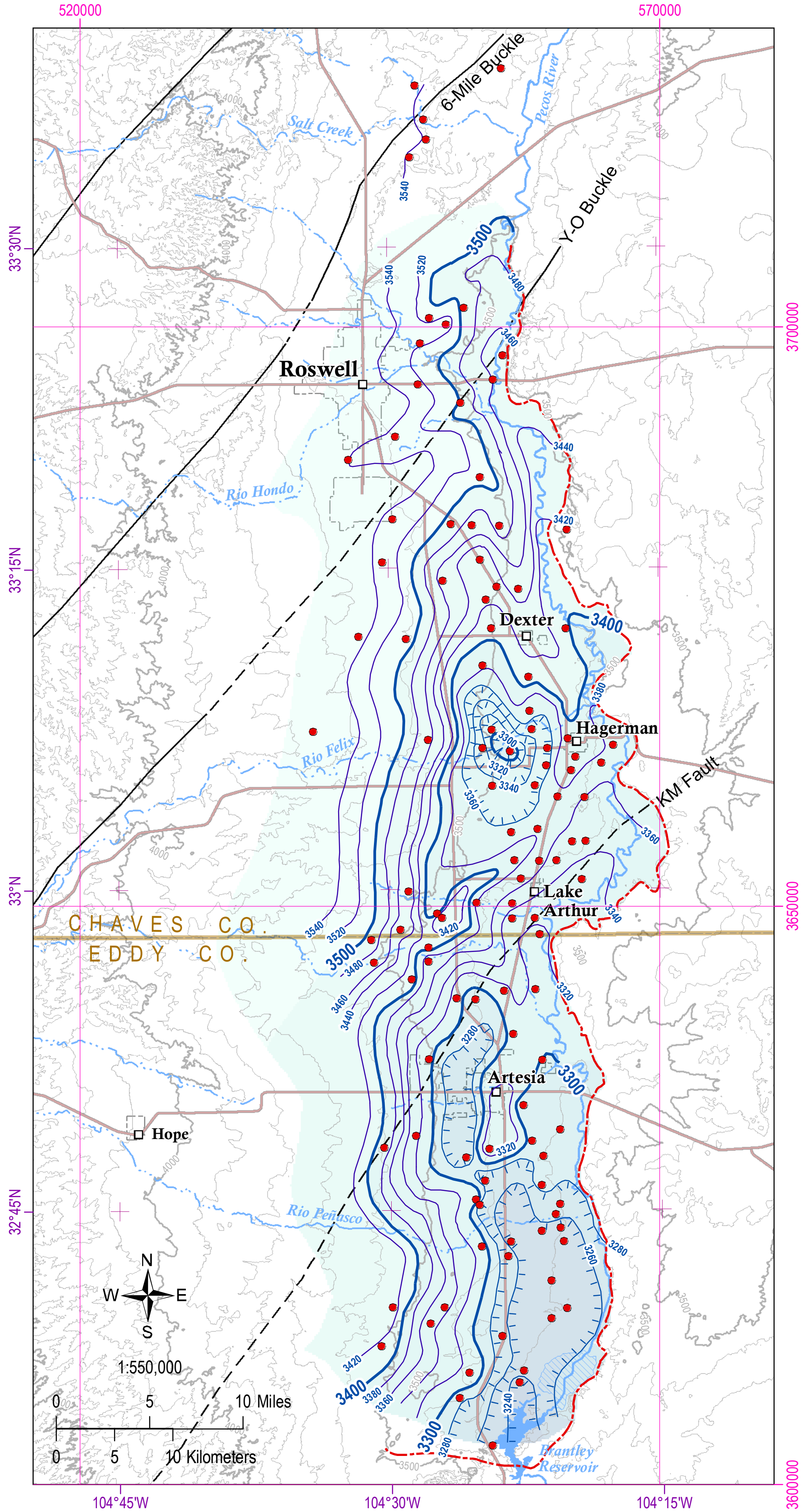


Figure 6–Configuration of the water table in the shallow aquifer, January-February, 2005. Contour interval = 20 ft (6 m). Filled circles are wells completed in the shallow aquifer.

part of the Basin the Artesia cone of depression, which was not present in 1975, is now ~40 ft (12 m) deep.

In the vicinity of Hagerman the shallow aquifer is the primary source of ground water, unlike most other parts of the Artesian Basin, and the increase in depth of the Hagerman cone of depression reflects continued exploitation of the shallow aquifer in the 30 year period since Welder's (1983) measurements were made. The area of declining water levels west and south of Artesia lies near the southern extent of the shallow aquifer, where saturated thicknesses were less than 100 ft thick in 1975 (Plate W-12), and the aquifer appears to be have been more sensitive to 30 years of extensive pumping.

In the Roswell area at the north end of the Basin, the water table in the shallow aquifer rose from 4 to 17 ft. This rise may in part reflect the leaky nature of the confining beds, which are less than 100 ft (30 m) thick in that part of the Basin (Plate W-11), permitting more efficient recharge from the underlying artesian aquifer. The rise in the water table near Roswell is thus a response to rising water levels in the artesian aquifer since 1975.

In the Hagerman-Lake Arthur area there has been a distinct rise in water levels along a SW-NE trend closely coinciding with the 2005 ridge in the water table (Figure 6; Plate 3). This area of rising shallow water levels is in a part of the Basin where PVACD purchased and retired irrigated farmland in the mid-20th century.

During the period from January, 2004 to January, 2005 water levels in the shallow aquifer rose significantly in almost all areas of the Basin, probably in response to above average precipitation in 2004 (Figure 10; Plate 7). The most significant rise in water levels occurred along the SW-NE trending ridge in the water table between Lake Arthur and Hagerman.

Artesian Aquifer: Seasonal Cycles

Variations in hydraulic head in the artesian aquifer occur on multiple time scales. The spiky character of the hydrograph for the Greenfield observation well (Figure 11a) reflects the very pronounced seasonal irrigation cycles typical of this intensively farmed area near the center of the Artesian Basin (Figure 4b; Plate 1). Water levels are at their highest during winter months, when irrigation is minimal, and in recent years have shown declines of greater than 180 ft (55 m) during the summer, when irrigation is at a maximum. Longer-term variations in the historic record are demonstrated by the scale of these fluctuations in hydraulic head. At the beginning of the period of record, in 1940, the winter-summer cycle varied by just 30 ft (9 m). As agricultural activity has expanded in the Artesian Basin through the latter half of the 20th century, the amplitude of the seasonal cycles has increased approximately fivefold.

The Greenfield well is located in a part of the Basin where many artesian wells still flow to the surface during winter months. As the Greenfield hydrograph (Figure 11a) indicates, water levels in this well were above ground level as recently as 2001. Under those circumstances, a pressure reading is measured and the apparent water level is calculated from an equation relating water pressure to hydraulic head [$D = 2.31P - k$; D is apparent head in feet above ground level, shown as a negative value; P is pressure in pounds per square inch; k is height of pressure valve above ground level].

The drawdown from pumping in the artesian aquifer is laterally extensive, reflecting the very high transmissivity of the artesian system – as much as 196,000 ft^2/day (18,200 m^2/day) in the northern part of the Basin (Hantush,1957). Thus, for a given amount of pumping the cones of depression are relatively shallow but very broad. A five-year detail of the Greenfield hydrograph (Figure 11b) illustrates the extreme sensitivity of the artesian aquifer to specific pumping events. A secondary peak in water levels occurs every year in mid-May to mid-June, superim-

Figure 7–Change in hydraulic head in the artesian aquifer, 1975-2005. Contour interval = 5 ft (1.5 m). Filled circles are wells completed in the artesian aquifer. Large green circles are observation wells.

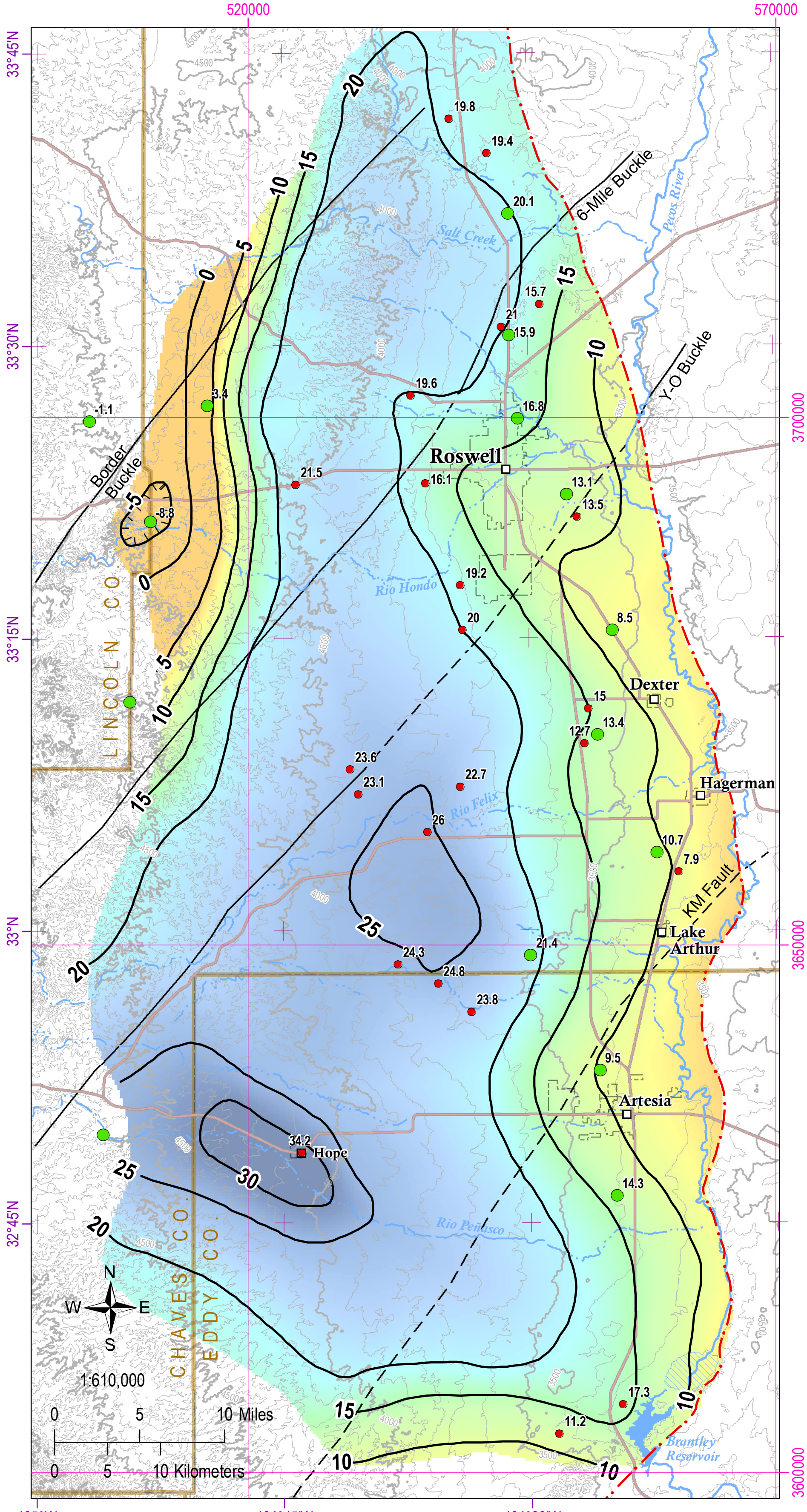


Figure 8–Change in hydraulic head in the artesian aquifer, 2004-2005. Contour interval = 5 ft (1.5 m). Filled circles are wells completed in the artesian aquifer. Large green circles are observation wells. Blue triangles are flowing artesian wells.

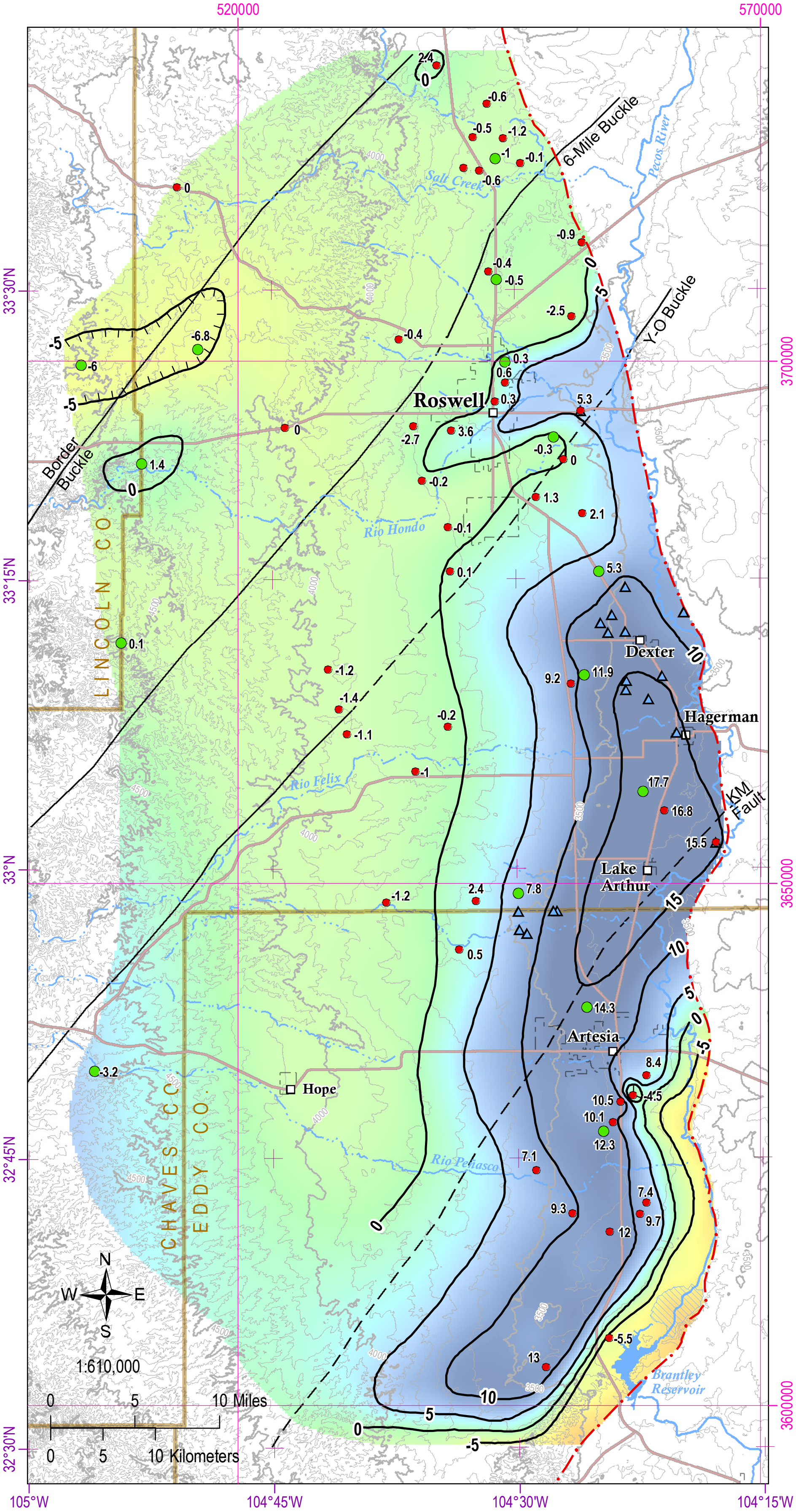


Figure 9–Change in water levels in the shallow aquifer, 1975-2005. Contour interval = 5 ft (1.5 m). Filled circles are wells completed in the shallow aquifer.

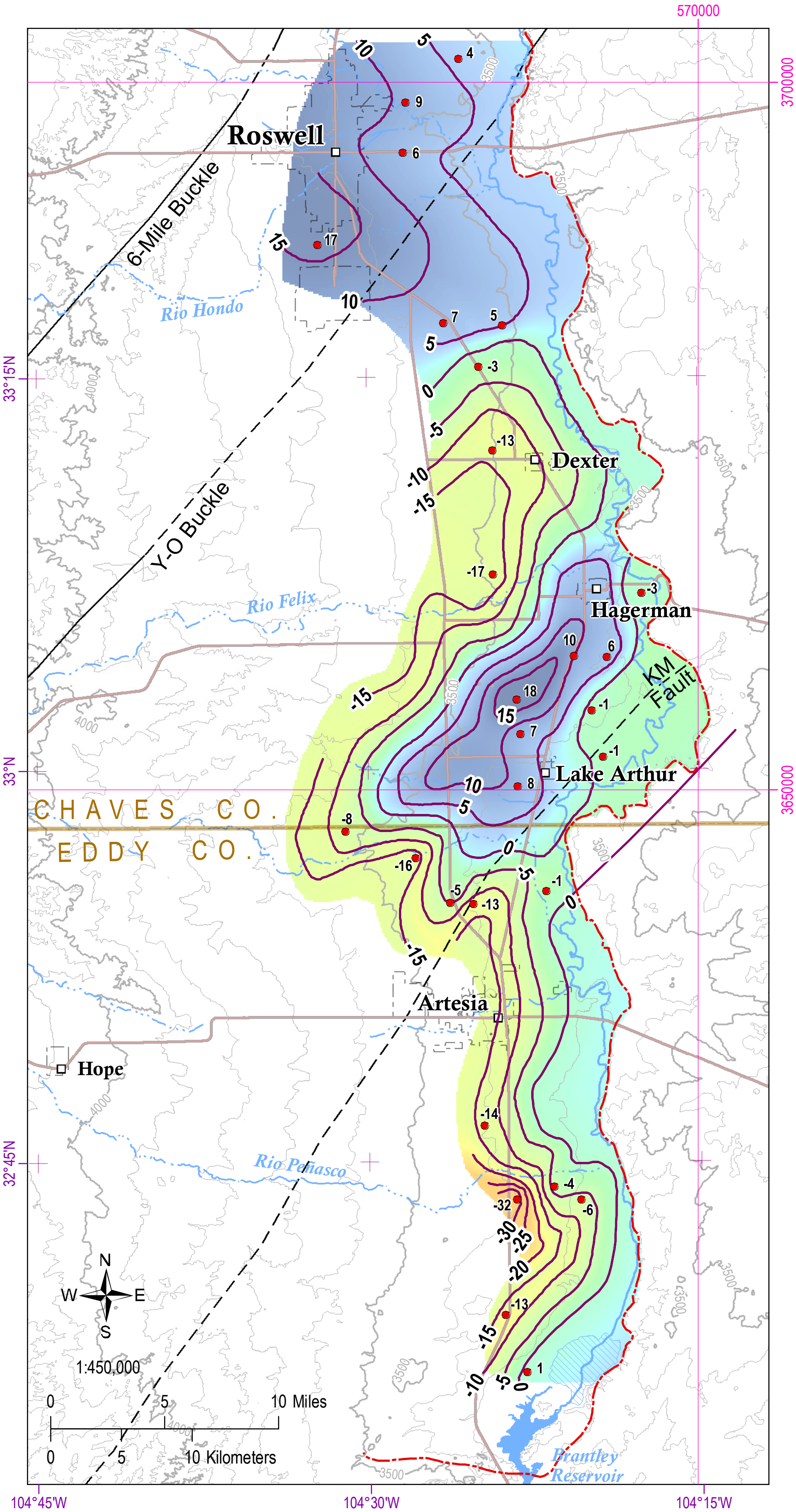
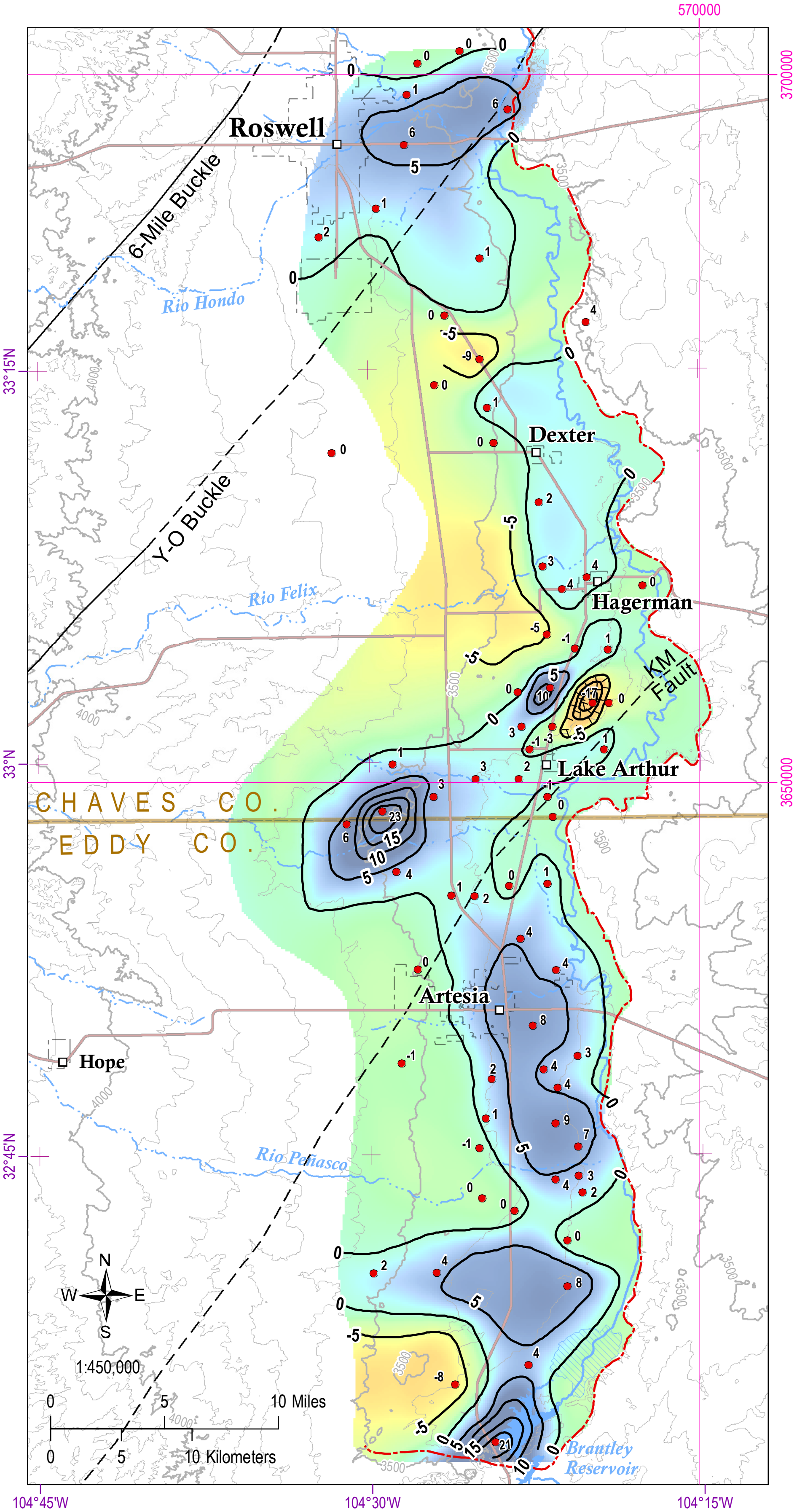


Figure 10–Change in water levels in the shallow aquifer, 2004-2005. Contour interval = 5 ft (1.5 m). Filled circles are wells completed in the shallow aquifer.



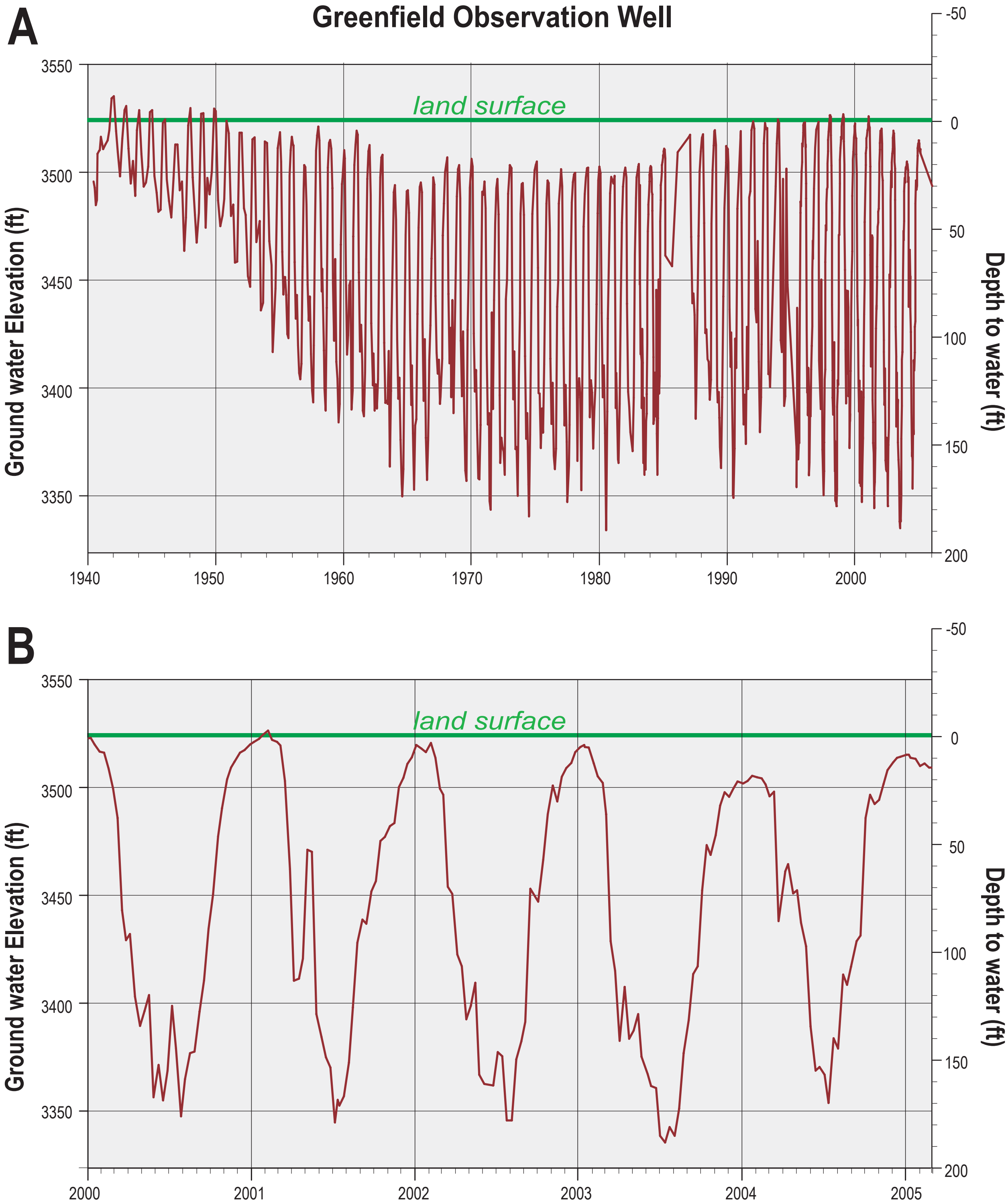


Figure 11a–Hydrograph of the Greenfield monitoring well (location shown in Figure 4b and Plate 1), showing very pronounced annual cycles and longer-term variations in hydraulic head in the artesian aquifer. At various times in the past 40 years of record the Greenfield well has flowed to the surface. Water levels shown above land surface were calculated from water pressure measurements. Deviation from the seasonal cycle in the mid-1980s is caused by an incomplete data set for the years 1985 and 1986.

Figure 11b–Detail from figure 11-A hydrograph, showing seasonal irrigation cycles over a five year period, 2000 - 2005.

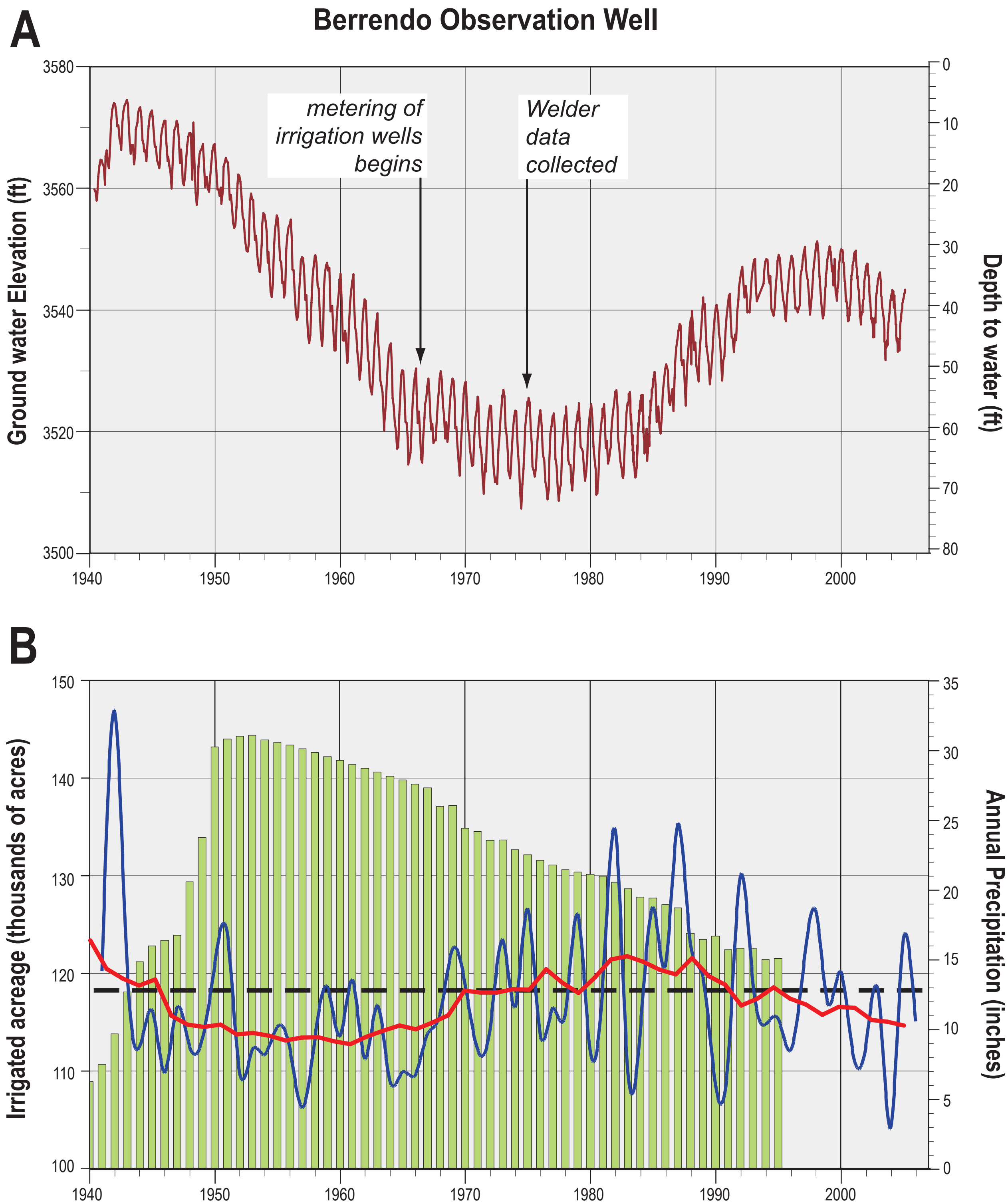


Figure 12a–Hydrograph of the Berrendo observation well (location shown in Figure 4b and Plate 1). Note difference in vertical scale compared to figure 11.

Figure 12b–Irrigated agriculture and precipitation in the Artesian Basin. Blue solid line shows annual precipitation in the Artesian Basin region, measured at the Roswell airport. Heavy dashed line indicates mean annual rainfall. Red solid line is the 10 year running mean of precipitation. Bar graph shows the amount of farmland under irrigation from both the artesian and shallow aquifers from 1940 to 1996.

posed upon the general mid-year decline in hydraulic head. This secondary peak reflects the first cutting of alfalfa, when pumping temporarily stops as the alfalfa crop is harvested.

Artesian Aquifer: Long-term Variations in Head

Water levels in the Artesian Basin have been falling since development of the artesian aquifer began early in the 20th century (Kinney et al., 1968; Welder, 1983). The rate of decline in hydraulic head increased significantly after World War II, and reached its lowest point in most areas of the Basin in the mid-1970s, at which time this decades-long trend began to reverse. The hydrograph for the Berrendo observation well (Figure 12a) shows these long-term water level variations. Higher-frequency irrigation cycles are more subdued than those shown on the Greenfield hydrograph (Figure 11) because the Berrendo well is located in a housing development within the city of Roswell, several miles from intense agricultural activity farther to the south. However, longer-term variations in head are more apparent, showing that water levels in the artesian aquifer reached an historic low in the mid-1970s, when data for the Welder report were being collected.

From the mid-1970s until around the turn of the century water levels in the artesian aquifer steadily increased. Since the year 2000 hydraulic head has begun to decline, roughly coincident with a period of extended drought in New Mexico (Figure 12b). However, water levels measured for this investigation in January-February, 2005 show an increase over head measurements in winter, 2004 (Figure 8; Plate 5), a year during which the Artesian Basin region enjoyed exceptionally high rainfall.

VII. DISCUSSION

Precipitation cycles and agricultural activity appear to be the two main factors driving longer-term variations in head in the artesian aquifer. Average annual precipitation in the Artesian Basin is ~13 inches/yr (32 cm/yr). However, annual rainfall in southeastern New Mexico displays very pronounced deviations from the mean (Figure 12b). Precipitation in 1941 exceeded 33 inches (83 cm), but for most of the period from 1945 through the late 1960s rainfall was well below average. This long period of drought coincided with a long decline in hydraulic head in the artesian aquifer. Then, beginning in the late 1970s and continuing through the mid-90s, the lower Pecos Valley experienced several years of above average rainfall, a period during which water levels in the artesian aquifer began to rise.

The expansion of irrigated agriculture during and after World War II also appears to have influenced longer-term water level cycles in the Artesian Basin. Between 1940 and 1950 the amount of irrigated farmland in the Basin increased by >30% (Figure 12b). During the period from 1943 to 1968 the area also experienced an extended period of low rainfall. This unfortunate combination of long-term drought with a period of rapidly expanding irrigation accounts for the long decline in water levels in the artesian aquifer through the mid-20th century.

Systematic water conservation measures began in the late 1950s, when the Pecos Valley Artesian Conservancy District initiated a program of purchase and retirement of irrigated farmland in parts of the Artesian Basin. Similar programs have subsequently been initiated by the New Mexico Interstate Stream Commission, and have been included in the 2004 Consensus Plan for management of water resources on the lower Pecos River. Adjudication of water rights in the mid-1960s reduced the amount of legally irrigable land in the Basin and was key to gaining control of ground water pumping. Metering of irrigation wells began in 1966, which promoted conservation and allowed enforcement of pumping limitations. At this time water use for irrigation was restricted to 3.5 acre-ft/acre/yr (10,600 m3/ha/yr). It appears that these conservation measures, combined with high levels of precipitation during the latter part of the 20th century, have contributed toward mitigating the historic decline in hydraulic head in the Artesian Basin. The same conservation and climatic factors have also helped to stabilize the position of the freshwater-saltwater interface in the artesian aquifer (Figure 5; Plate 2).

The increase in head in the artesian aquifer during the 12 month period from 2004 to 2005 is concentrated along the eastern margin of the Artesian Basin (Figure 8; Plate 5), in marked contrast to the 30 year rise in water levels in the Principal Recharge Area on the Pecos Slope to the west (Figure 7; Plate 4). It is unlikely that this short-term rise in water levels in the eastern sector of the Basin is a direct result of increased rainfall and infiltration. Rather, the increase in head is probably an indirect response to high rainfall, which caused a reduction in irrigation demand in 2004 and a resulting decrease in pumping from the artesian aquifer.

Previous workers (e.g., Havenor, 1996, 1998) have used hydrochemical data to argue that the hydrologic framework of the Artesian Basin is more heterogeneous and compartmentalized than commonly thought due to regional structural discontinuities. Such discontinuities clearly exist, as indicated by, for example, the increase in hydraulic gradient in the artesian aquifer west of the KM Fault (Figure 4b; Plate

1). However, hydraulically continuous behavior within a large sedimentary basin can sometimes be masked on a local scale by the flow-sensitive properties of ground water, such as temperature and chemical composition (Toth, 1995). The broad area affected by the 12 month rise in water levels reflects the very high regional transmissivity and hydraulic continuity of the artesian system, which very effectively permits diffusion of pressure head throughout the eastern part of the Basin.

VIII. CONCLUSIONS

The Roswell Artesian Basin provides a world-class example of a rechargeable artesian aquifer. The very high transmissivity of the aquifer results from the presence of vuggy and cavernous porosity and large solution conduits within the karstic San Andres limestone, caused in part by dissolution of primary gypsum within the formation. By the mid-1970s, almost a century of intensive pumping had resulted in very substantial declines in hydraulic head throughout the Artesian Basin. However, the current study suggests that water conservation measures first introduced in the 1950s, combined with high levels of rainfall during the latter part of the 20th century, have helped to reverse the long-term decline in hydraulic head in the artesian aquifer.

REFERENCES

Bachman, G. O., 1984, Regional geology of Ochoan evaporites, northern part of Delaware Basin: New Mexico Bureau of Mines and Mineral Resources, Socorro, NM, Circular 184, 22 p.

Bachman, G. O., 1987, Karst in evaporites in southeastern New Mexico: Sandia National Laboratories, Contractor Report SAND86-7078, 82 p.

Barroll, P. and Shomaker, J., 2003, Regional hydrology of the Roswell Artesian Basin and the Capitan aquifer, in Johnson, P., Land, L., Price, G. and Titus, F. (eds.), Water Resources of the Lower Pecos Region, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Socorro, NM, 2003 New Mexico Decision Makers Guidebook, p. 23-27.

Duffy, C. J., Gelhar, L. W., and Gross, G. W., 1978, Recharge and groundwater conditions in the western region of the Roswell Basin: New Mexico Water Resources Research Institute, Las Cruces, NM, Report 100, 111 p.

Fiedler, A. G. and Nye, S. S., 1933, Geology and groundwater resources of the Roswell Basin, New Mexico: U.S. Geological Survey Water-Supply Paper 639, 372 p.

Garn, H. S., 1988, Seasonal changes in ground-water levels in the shallow aquifer near Hagerman and the Pecos River, Chaves Co., New Mexico: U.S. Geological Survey Open File Report 88-197, 19 p.

Gratton, P. J. F. and LeMay, W. J., 1969, San Andres oil east of the Pecos, in Summers, W. K. and Kottlowski, F. E. (eds.), The San Andres Limestone, a Reservoir for Oil and Water in New Mexico: New Mexico Geological Society, Socorro, NM, Special Publication No. 3, p. 37-43.

Hantush, M. S., 1957, Preliminary quantitative study of the Roswell ground-water reservoir, New Mexico: New Mexico Institute of Mining and Technology, State Bureau of Mines and Mineral Resources Division, Socorro, NM, 118 p.

Havenor, K. C., 1968, Structure, stratigraphy, and hydrogeology of the northern Roswell Artesian Basin, Chaves County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Socorro, NM, Circular 93, 30 p.

Havenor, K. C., 1996, The hydrogeologic framework of the Roswell groundwater basin, Chaves, Eddy, Lincoln, and Otero Counties, New Mexico: Tucson, University of Arizona, Ph.D. dissertation, 274 p.

Havenor, K. C., 1998, Hydrogeochemical investigation of the major aquifers in the northern portion of the Roswell Groundwater Basin, Chaves and Eddy Counties, New Mexico: GeoScience Technologies, unpublished report, 80 p.

Hayes, P. T., 1964, Geology of the Guadalupe Mountains, New Mexico: U.S. Geological Survey Professional Paper 446, 69 p.

Hood, J. W., 1963, Saline ground water in the Roswell Basin, Chaves and Eddy Counties, New Mexico, 1958-59: U.S Geological Survey Water Supply Paper 1539-M, 46 p.

Hood, J. W., Mower, R. W., and Grogin, M. J., 1960, The occurrence of saline ground water near Roswell, Chaves County, New Mexico: New Mexico State Engineer Office Technical Report 17, 72 p.

Kelley, V. C., 1971, Geology of the Pecos country, southeastern New Mexico: New Mexico Bureau of Mines and Mineral Resources, Socorro, NM, Memoir 24, 78 p.

King, P. B., 1948, Geology of the southern Guadalupe Mountains, Texas: U.S. Geological Survey Professional Paper 215, 183 p.

Kinney, E. E., Nations, J. D., Oliver, B. J., Wagner, P. G., Siwula, T. A., and Renner, R. E., 1968, The Roswell Artesian Basin: Roswell Geological Society, Roswell, NM, 32 p.

Land, L., 2003, Evaporite karst and regional ground water circulation in the lower Pecos Valley, in Johnson, K.S. & Neal, J.T. (eds.), Evaporite Karst and Engineering and Environmental Problems in the United States: Oklahoma Geological Survey, Norman, OK, Circular 109, p. 227-232.

Land, L., 2005, Evaluation of groundwater residence time in a karstic aquifer using environmental tracers: Roswell Artesian Basin, New Mexico, in Proceedings of the Tenth Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, San Antonio, Texas, 2005: ASCE Geotechnical Special Publication no. 144, p. 432-440.

Lyford, F. P., 1973, Valley fill in the Roswell-Artesia area, New Mexico: U.S. Geological Survey Open-File Report 73-163, 26 p.

Miller, F., 1969, The San Andres reef zone, in Summers, W. K. and Kottlowski, F. E. (eds.), The San Andres Limestone, a Reservoir for Oil and Water in New Mexico: New Mexico Geological Society, Socorro, NM, Special Publication No. 3, p. 27-31.

Motts, W. S. and Cushman, R. L., 1964, An appraisal of the possibilities of artificial recharge to ground-water supplies in part of the Roswell Basin, New Mexico: U.S. Geological Survey Water-Supply Paper 1785, 86 p.

Shomaker, J., 2003, How we got here: A brief history of water development in the Pecos Basin, in Johnson, P., Land, L., Price, G. and Titus, F. (eds.), Water Resources of the Lower Pecos Region, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Socorro, NM, 2003 New Mexico Decision Makers Guidebook, p. 61-64.

Thomas, H. E., 1963, Causes of depletion of the Pecos River in New Mexico: U.S. Geological Survey Water-Supply Paper 1619-G, 14 p.

Toth, J., 1995, Hydraulic continuity in large sedimentary basins: Hydrogeology Journal, v. 3, p. 4-15.

Welder, G. E., 1983, Geohydrologic framework of the Roswell Ground-Water Basin, Chaves and Eddy Counties, New Mexico: New Mexico State Engineer, Santa Fe, NM, Technical Report 42, 28 p.

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