Hydrogeology of Rattlesnake Springs:

Eddy County, New Mexico.

Erika M. Bowen
Hydrology Program
Earth and Environmental Science Department
New Mexico Institute of Mining and Technology
801 Leroy Place
Socorro, NM 87801

INDEPENDENT STUDY PAPER

Submitted in Partial Fulfillment of the
Requirements for the degree of

Master of Science in Hydrology

Acknowledgments

This project could not have been completed without the knowledge and support granted by many individuals, to whom I owe thanks.

I would like to acknowledge my advisor, Dr. Brian McPherson, for his continual support and time invested. I would also like to thank Dr. Fred Phillips and Dr. Dave Johnson, the other members of my committee, for reviewing this manuscript and providing support throughout the study.

My thanks also go the individuals of the National Park Service who made this project available for study. My thanks go to Gary Vequist who added direction to the work accomplished, Barry Munyan who aided with his valuable insight into the history of Rattlesnake Springs and the area surrounding it, and also Bill Route and Dave Romero.

Additional thanks go to the Bureau of Land management, the State Engineer's Office, and the United States Geologic Survey for providing assistance and vital information on the region.

I would also like to thank the Ballard, Miller, Hood, and Stell families for allowing me assess to their lands and wells.

ABSTRACT

Rattlesnake Springs is a large flowing artesian spring discharging from the upper Black River valley in the southeastern portion of Eddy County, New Mexico. Rattlesnake Springs emanates from a well-indurated, karstic, limestone conglomerate unit within Slaughter Canyon alluvial fan that lies between the geologic provinces of the Delaware Basin and the Guadalupe Reef Escarpment. Observed variation in water chemistry and local geology is explained by proposed development of the Slaughter Canyon alluvial fan.

The alluvial wedge of the upper Black River valley is not hydraulically connected to either of the surrounding regional aquifers. The Capitan aquifer within the Guadalupe Reef is removed from the alluvial aquifer by elevation and other geologic constraints. The Castile Formation underling the alluvium restricts flow because it consists of gypsum of extremely low hydraulic conductivity.

The proposed conceptual model consists of flow through the system as originating dominantly from high intensity short duration precipitation events in the summer months. Surface flow and groundwater flow within the Slaughter Canyon alluvial sediment discharges into the head of the Slaughter Canyon alluvial fan. Additional recharge sources are infiltration from areal precipitation and flow from perched aquifers within the Capitan Limestone. Karstic channels formed in the limestone conglomerate constrain flow in the alluvial aquifer. The alluvium discharges to surface drainage either through springs or directly to the Black River.

A numerical model was constructed and calibrated to analyze the proposed conceptual model of the system. The numerical model demonstrates the observed dependence of discharge of Rattlesnake Springs on annual precipitation. The calibrated numerical model shows that a larger portion of recharge into the system is from the reef-front than originally estimated. Manipulation of the model shows no case in which contamination from the nearby Washington Ranch natural gas injection facility may intersect the flow paths to the Springs. The current agricultural withdrawals from the system have a minimal impact on the system. Future developments of the upper Black River valley could have significant impacts on the system due to the karstic nature of flow.

Table of Contents

Title Page....i
Acknowledgments.... ii
Absract.... iii
Table of Contents.... v
Tables and Figures.... vii

1. Introduction....1

2. Geology....4
  2.1 Basin and Reef System....4
  2.2 Delaware Basin....4
    2.2.1 Guadalupe Reef Escarpment....5
  2.3 Alluvium....7
    2.3.1 Slaughter Canyon Alluvial Fan....7
    2.3.2 Soils....9
  2.4 Geologic History....11

3. Climate....23

4. Hydrogeology....27
  4.1 Regional Flow....27
    4.1.1 Groundwater....27
    4.1.2 Surface Water....29
  4.2 Local Characteristics....30
    4.2.1 Water Chemistry....31
    4.2.2 Tritium....32
    4.2.3 Discharge at Rattlesnake Springs....33
    4.2.4 Aquifer Heterogeneity....35
  4.2.5 Pumping Tests....36

5. Conceptual Model....46
  5.1 Geologic Framework....46
  5.2 Water Balance....49

Table of Contents continued:

6. Numerical Model 54
  6.1 MODFLOW 54
  6.2 Model Construction 56
    6.2.1 Model Domain 56
    6.2.2 Initial and Boundary Conditions 58
  6.3 Calibration 61
  6.4 Base Model 61

7. Model Calibration 67
  7.1 Model Domain 67
  7.2 Initial Conditions 69
  7.3 Boundary Conditions 70
  7.4 Storage Properties 72

8. Model Results 78
  8.1 Climatic Affects 78
  8.2 Withdrawals 80
  8.3 Constant Head Boundaries 82
  8.4 Contaminants 83
  8.5 Groundwater Residence Time 84
  8.6 Uncertainties 85

9. Summary and Conclusions 95
  9.1 Conceptual and Numerical Model 95
  9.2 Rattlesnake Springs Discharge 97
  9.3 Contamination 98
  9.4 Summary 99

10. Assessment 100
  10.1 Assessment 100
  10.2 Maintenance 101
  10.3 Further Work 101

References 104
Appendix A 108
Appendix B 128
Appendix C 148

Tables and Figures

Figure 1.1: Location of Rattlesnake Springs in southern Eddy County, NM. The geographical relationships of the study area to the Guadalupe Reef Escarpment and the Delaware Basin are shown. 3

Figure 2.1: Schematic cross section of the Slaughter Canyon alluvial fan. Relation to the elevation of the Guadalupe Reef escarpment and the depth of the Capitan aquifer is shown. 15

Figure 2.2: Stratigraphic cross section through the Guadalupe Reef Escarpment showing relation between reef and basin sediments of Permian age. Cross section is taken slightly east of the Carlsbad Caverns 16

Figure 2.3: Location of oil and gas deposits in Eddy County and Lea County, New Mexico. The Washington Ranch facility is located in southern Eddy County. The moderate size, isolation, and remoteness of the Washington Ranch deposit from urban areas are the characteristics that motivated the location of El Paso Natural Gas' injection facility 17

Figure 2.4: Conceptual cross sections through the Slaughter Canyon alluvial fan based on well log data. Note the discontinuous nature of the limestone conglomerate near the Black River. 18

Figure 2.5: Proposed conceptual model of development of the Slaughter Canyon alluvial fan. A) Initial development of a small high angle alluvial fan with initial incision of the Slaughter Canyon drainage system. B-D) Represents shifting areas of deposition as the fan migrates, most likely in response to Pleistocene glacial/interglacial cycles. E) Current small area of active deposition with channel incision and fluvial process dominating over the majority of the fan surface. 19

Figure 2.6: Soil formation in the upper Black River valley. Slaughter Canyon alluvial fan is characterized by Upton or Reagan type calcareous soils. Areas over the Castile are dominated by gypsiferous soils 20

Table 2.1: List of soil types and properties in the upper Black River valley. 21

Figure 2.7: North-south cross section of the Pennsylvanian strata though the Delaware Basin 10 miles east of Rattlesnake Springs. 22

Tables & Figures continued:

Figure 3.1: Average monthly temperature and potential evapotranspiration (Blaney-Criddle method) from the Carlsbad municipal airport gauge and average monthly precipitation from the Carlsbad, CCNP, and Caverns City gauge. 25

Figure 3.2: Yearly precipitation totals and average for the Carlsbad municipal airport, Carlsbad Caverns National Park, and Cavern City gauge. The average precipitation (12.63 inches) and the moving average depicting long term variations are shown. 26

Figure 4.1: Groundwater flow in the Capitan aquifer and Basin aquifers shown in map view (Hill, 1996). Flow within the Delaware Basin is controlled by the Capitan Limestone. The Capitan in Eddy County discharges to the Pecos River. In the buried portion of the Capitan, flow is to the Hobbs Channel. .. 38

Figure 4.2: Distribution of springs in the upper Black River valley and location of major alluvial fans. Rattlesnake Canyon is the only major canyon through the Guadalupe Reef Escarpment that does not have an associated fan. 39

Figure 4.3: Water chemistry of the upper Black River valley. Samples are from groundwater, springs, and the Black River. Records usually only list hardness and conductance. Conductance for the area can be taken as representative of the sulfate content and hardness and the carbonate content. 40

Figure 4.4: Piper diagram of water chemistry. The 12 samples shown were analyzed for this project. 41

Figure 4.5: Areal distribution of water chemistry in the upper Black River valley. 42

Figure 4.6: Location of samples and values of tritium analysis. 43

Figure 4.7: Discharge data for Rattlesnake Springs. No continuous data is available for the time period before 1984. Data before June 1989 was overestimated by ~50%. The lower figure shows a correction by reducing pre 1989 data by 50%, although the reliability of this earlier data is low. 44

Figure 4.8: Current agricultural plot in the upper Black River valley. 45

Figure 5.1: Cartoon of conceptual model, showing recharge sources into the alluvium of the upper Black River valley. 51

Tables & Figures continued:

Figure 5.2: Distribution of the Castile Formation at the surface in the upper Black River valley. Note the restriction in the alluvial sediments between the Castile at the terminal end of the upper perennial reach of the Black River. .52

Table 5.1: Summary of simple water balance. 53

Figure 6.1: Grid system used for simulation of Rattlesnake Springs aquifer showing numbered observation wells, injection wells and conductivity zones. 63

Figure 6.2: Extended grid domain used for location of the western boundary. Grid is 100 columns by 56 rows by 20 layers. The 460 contour is close to perpendicular to the southern boundary. Shaded cells are those removed for the remaining simulations. The darker shaded area indicates the 460 m constant head cells. 64

Table 6.1: Conductivity and storage values. 65

Table 6.2) Range of values for hydraulic properties. Karst limestone was the base used for the numerical model. Gravel media also produces values in the same range as karst. Sand and clay values are also given for comparison. ...66

Figure 7.1: Sensitivity analyses for boundary conditions. Results for recharge sources within the model domain: Slaughter Canyon recharge, slope recharge, areal recharge, and the western constant head boundary................74

Figure 7.2: Sensitivity analyses for boundary conditions. Results for discharge parameters. Rattlesnake Springs is simulated as a pumping well for these results. Agricultural pumping rates are constant and the total is plotted......75

Figure 7.3: Sensitivity analyses for storage values. Note that porosity values have no effect on the system. 76

Table 7.1: Summary of the volumes in and out of the system for the steady-state base case. 77

Tables & Figures continued:

Figure 8.1: (top) Results of discharge values produced by using measured precipitation values input seasonally into the model against measured discharge values of Rattlesnake Springs. (bottom) Expansion of August 1989 -- March 1995. Correlation between the measured and calculated discharges, calculated values are not able to track the large fluctuations of the measured data....87

Figure 8.2: Simulated fluctuation in the observation wells at the distal portion of the Slaughter Canyon alluvial fan and Rattlesnake Springs due to an average seasonal input....88

Figure 8.3: Effect of increased withdrawals from the two nearest agricultural wells #8 #11 to Rattlesnake Springs. The loss in volume to the Springs is slight whereas there is a greater loss in discharge of the Black River....89

Figure 8.4: Declining elevation of the western constant head boundary to simulate decreasing recharge from up-gradient....90

Figure 8.5: Decreasing elevation of the Black River to simulate declining base level in the model domain....91

Figure 8.6: Capture zones of Rattlesnake Springs and the Black River....92

Figure 8.7: Flow paths from recharge sources, Slaughter Canyon, reef-front wells....93

Figure 8.8: Particle tracking from the Washington Ranch injection facility....94

1. Introduction

Rattlesnake Springs is a high-discharge artesian spring located in southern Eddy County, New Mexico (figure 1.1). Rattlesnake Springs discharge from a small alluvial wedge between the Gypsum Plain of the Delaware Basin and the Guadalupe Reef Escarpment. Additionally, Rattlesnake Springs serves as the sole water supply source for Carlsbad Caverns National Park and provides a vital wetland habitat supporting several species of threatened birds and fish. The National Park Service has become concerned about the aquifer due to agricultural development that started in 1948 and shallow groundwater contamination from the nearby Washington Ranch natural gas injection facility. These concerns have prompted the National Park Service to sponsor this study of the aquifer supplying Rattlesnake Springs. In terms of study, the alluvial upper Black River valley has been mostly neglected, though the surrounding hydrogeology is well established (Hill, 1996).

Several previous studies have been performed on Rattlesnake Springs. Hale (1955) examined the general trend of groundwater flow in the immediate area. Additional papers on Rattlesnake Springs reported the pattern of discharge (Cox, 1963), and discussed the drilling of test wells and pump tests on the production well for the Park Service (Mourant and Havens, 1964). Sares (1984) reported on the geomorphology and hydrology of Chosa Draw, located in the Gypsum Plain near Rattlesnake Springs. This report provided information on the Black River alluvium and karst formation in the area. Although finite difference models of karstic or fractured limestone aquifers are rare, this type of numerical model has been successfully applied to areas similar to Rattlesnake Springs (Angelini and Dragoni, 1997).

The first phase of this study was to collect and assess all available data for the aquifer supplying Rattlesnake Springs. A summary of the geology was then formulated along with a proposal for the sequence of alluvium deposition. Next, a conceptual model of flow through the system was developed. Finally, a numerical model, constructed based on the assumptions from the geologic and conceptual models, was used to test the possible range of parameters in the system and to predict future effects.

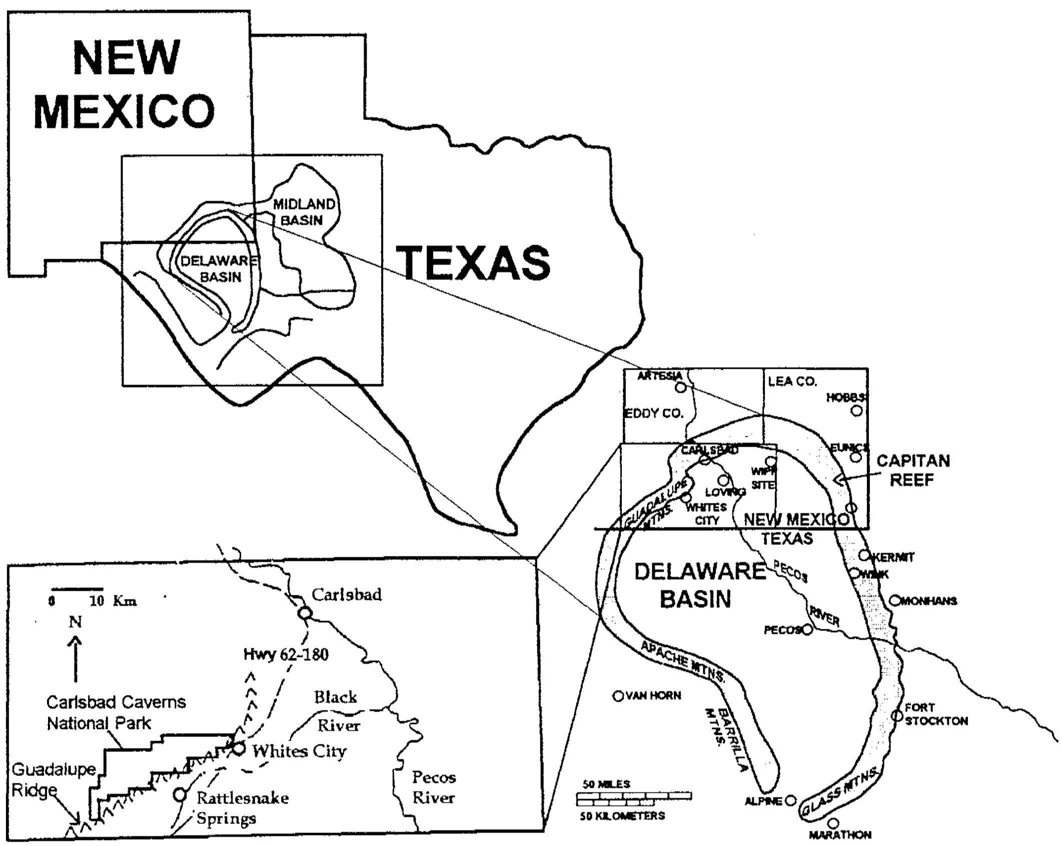


Figure 1.1: Location of Rattlesnake Springs in southern Eddy County, NM. The geographical relationships of the study area to the Guadalupe Reef Escarpment and the Delaware Basin are shown.

2. Geology

2.1 Basin and Reef System

Rattlesnake Springs is located in the upper Black River valley in southern Eddy County close to the New Mexico-Texas border (figure 1.1). Groundwater flow is driven by precipitation providing recharge in the topographically high Guadalupe Reef Escarpment (figure 2.1) and flowing to the low-lying Delaware Basin. The gypsum Castile Formation acts as a regional aquitard forcing groundwater flow to the surface.

2.2 Delaware Basin

The Delaware Basin is a 13,000 mi^2 (33,670 km^2) sedimentary basin that is part of the larger 90,000 mi^2 (233,100 km^2) Permian Basin (figure 1.1) located in New Mexico and West Texas. Basin stratigraphy consists of the Castile Formation overlying the Delaware Mountain Group of the Bell Canyon, Cherry Canyon, and Brushy Canyon formations (figure 2.2). These formations consist of sandstone, shales, and minor carbonates. The lower Permian is represented by the Bone Springs Limestone. Beneath the Permian deposits are Pennsylvanian deposits of the Canyon, Cisco, Atoka, Strawn, and Morrow formations (Christiansen, 1989).

The Morrow Formation is the most significant source for natural gas in southeastern New Mexico and comprises most of the Pennsylvanian deposit, roughly 1,900 ft (580 m) thick (Hill, 1996). The Morrow-age Washington Ranch hydrocarbon reservoir is located (figure 2.3) in the upper Black River valley, at a depth of ~ 7,000 feet (2,133 m).

The Castile Formation, along with the Salado Formation, crops out over an area of 1,000 mi^2 (2600 km^2) in New Mexico and west Texas. It is either present at the surface in the upper Black River valley or is overlain by alluvium. The Castile is comprised of seven alternating units of anhydrite and halite with a measured depth in the field area of up to 1014 ft (309 m). The halite units were removed by dissolution from the western portion of the basin, with collapse breccias recording their removal. The Castile anhydrite consists of fine (1.8-1.9 mm) laminations that are highly continuous throughout the basin (Hill, 1996).

2.2.1 Guadalupe Reef Escarpment

Lithology and deposition of the Permian Reef are distinct enough to warrant separate consideration from the Delaware Basin stratigraphy. The Guadalupian aged strata are thoroughly characterized because the Guadalupe Mountains contain the most extensive and accessible outcrop of late Permian rock. During the Guadalupian epoch, conditions were favorable for the formation of massive sponge-algae reefs, the oldest of which is the Goat Seep

Dolomite. The Goat Seep originated as a carbonate bank and grew into a massive, high-angle reef up to 1300 ft (400 m) thick. This formation has been thoroughly dolomitized, has high porosity, and contains few primary structures (Hill, 1996).

The Capitan Limestone formed in the mid- to late-Guadalupian, subsequent to deposition of the Goat Seep Dolomite. This unit consists of two members, the massive reef member and the bedded forereef member. The Capitan Limestone is 1,500 -- 2,000 ft (450 -- 600 m) thick and interfingers with the Bell Canyon Formation in the Delaware basin. The Capitan extends basinwards past the Goat Seep (figure 2.2) showing the lateral progradation of the reef (Hill, 1996).

The Artesia Group was deposited in the backreef lagoon while the Goat Seep and Capitan reefs were rimming the basin. The Artesia Group consists of the Grayburg, Queen, Seven Rivers, Yates, and Tansill Formations (figure 2.2). All of the Artesia Group formations grade laterally from carbonates nearest the reef, to evaporites, and to clastic red beds nearest the paleo-shore. Vertical facies changes are also apparent within the Artesia Group, induced by shoreline movement towards the reef crest as time elapsed (Hill, 1996). The evaporite contact of the Artesia Group is important because hydrocarbons are trapped by the up-dip evaporite facies forming some of the major oil fields associated with this structure (Hill, 1996).

2.3 Alluvium

2.3.1 Slaughter Canyon Alluvial Fan

Rattlesnake Springs discharges from a karstic, well-indurated limestone conglomerate (figure 2.4). This unit is locally exposed near Rattlesnake Springs along the Black River and is recorded in the subsurface in water well logs. The unit is highly discontinuous around Rattlesnake Springs, originally described as "stringers" (Hale, 1955). The limestone conglomerate is described in Sares' (1981) study of the alluvium related to Chosa Draw:

> "Limestone conglomerate, clast supported, clasts range from less than 2 mm to 23 cm (B-axis). Clasts well rounded. Unit very well indurated, unit breaks across clasts. Many clasts partially or totally removed by solution. Clasts locally Mn coated. Upward fining sequences of sand and gravel interbedded with hard variegated mudstone. Unit locally deformed by solution."

Alluvium in the upper Black River valley may be classified under one of three different time frames of deposition: late Tertiary (Miocene-Pliocene) alluvium related to the onset of the Basin and Range province, Pleistocene alluvium related to glacial/inter-glacial sedimentation, or Quaternary (unconsolidated) alluvium (Hill, 1996). Based on its distribution, the limestone conglomerate is derived from the large alluvial fan emanating from Slaughter Canyon. The highly-cemented and karstic structure of the limestone conglomerate indicates that it originated during either the Miocene-Pliocene or Pleistocene epochs. Deposition of the aquifer unit may have occurred in either of the two time frames or throughout both. Quaternary alluvium is too young to have been cemented and karstified. No detailed studies or drilling programs have been performed on the area around Rattlesnake Springs, so no reliable age estimates can be made. Interpretations of the shallow geology are based on published soil information and a few shallow well logs as well as other studies done in the region. The field area was traversed to substantiate published material.

Alluvial fans in a temperate climate are characterized by migration of a channel system as sediment accumulates. Fans prograde and grow by shifting the active lobe. Fans are also characterized by down-gradient variations from coarser to finer sediments (Collinson, 1996). Debris flow deposits are most common near the apex of the fan while fluvial processes often dominate towards the distal portion. Alluvial fans grade into other alluvial deposits down-gradient producing an indistinct distal boundary (Rachocki, 1980). Rattlesnake Springs is located roughly 5 miles from the mouth of Slaughter Canyon, at the very distal portion of the alluvial fan. The distance indicates that the limestone conglomerate source of Rattlesnake Springs might have been deposited during a wetter time period, most likely one of the intermittent wetter glacial periods of the Pleistocene epoch or potentially originating as far back as the Miocene (Hill, 1996). The increased precipitation during these periods would have allowed greater sediment transport. This could produce downcutting near the head of the alluvial fan (Rachocki, 1980) and coarser fluvial material might be conveyed to distal channels, producing the observed stringers. The drier intervals are typically dominated by active deposition near the head of the fan allowing only finer sediments, clay and silt, to reach the distal portions. Additionally, the shifting nature of alluvial fans could produce a barrier of finer sediment or soil between lobes of the fan complex resulting in the hydrologic barrier shown by the water chemistry data (discussed in section 4.2.1).

This typical pattern of formation for alluvial fans provides an explanation for the observed discontinuity of the subsurface geology near Rattlesnake Springs. A proposal of fan development for the Slaughter Canyon alluvial fan is presented in figure 2.5. The schematic diagrams show the initial development of a small high-angle alluvial fan with initial incision of the Slaughter Canyon drainage system. During previous wetter intervals, shifting areas of deposition occurred as the fan migrated. The current expression of the Slaughter Canyon fan is a small area of active deposition with channel incision and fluvial process dominating over the majority of the fan surface.

2.3.2 Soils

The majority of the soils in the Rattlesnake Springs study area formed either over coarse carbonate alluvium or on Castile gypsum. The soil distribution in the upper Black River valley (figure 2.6) shows Upton soils (table 2.1) occur close to the reef escarpment, on hills and ridges, and on the proximal portion of the Slaughter Canyon alluvial fan (Chugg *et al.*, 1971). Upton soils contain well-developed carbonate horizons, up to stage IV or higher (explanation of soil classification: Ritter *et al.*, 1995), showing a long time period of development and stability of the surface. Stage IV and higher carbonate horizons, similar to those in the study area, have been shown to date to the mid-to-late Pleistocene (Ritter *et al.*, 1995). Although soil development rates vary depending upon source material and climate, a rough correlation indicates that the Slaughter Canyon alluvial fan has been stable since the Pleistocene, lending support for a Pleistocene or older age for the aquifer conglomerate. The soil map shows three main soil types on the Slaughter Canyon fan. This differentiation of soil development lends support to proposed shifting lobes of the Slaughter Canyon fan, since concurrent deposition would not produce the observed distribution.

Agricultural development in the upper Black River valley is limited to Reagan and Karro soils (table 2.1). These soil types occur on plains and lows at the distal portion of the Slaughter Canyon alluvial fan. The majority of the soils in the field area are classified adequate only for native pasture and wildlife habitat with careful management since re-vegetation is difficult (Chugg *et al.*, 1971).

2.4 Geologic History

Although deposition in the Delaware Basin and formation of the Guadalupe Reef occurred during the Permian, ~250 million years ago, or before, the region has only been up-lifted and subject to erosion relatively recently. The following is a geologic history of the area to provide a time-frame for the geologic events producing the observed geomorphology in the upper Black River valley.

Pennsylvanian strata are important in the area of Rattlesnake Springs since the Pennsylvanian Morrow Formation is the natural gas producer and reservoir for the Washington Ranch facility. Lower Pennsylvanian (Morrowan epoch) deposits (figure 2.7) in the Delaware Basin are predominantly shale and sandstone (Cheeseman, 1978). Above the Morrow Formation are the Atoka, Strawn, Canyon, and Cisco formations consisting of primarily limestone and shale. These two formations are also significant natural gas producers and reservoirs, though not within the study area (Cheeseman, 1978). Natural gas is produced from all of the reservoir units and additionally from deeper Ordovician, Devonian, and Silurian strata. This lower Paleozoic section has been very sparsely drilled due to the overlying accumulation of up to 15,000 ft (4,500 m) of Permian strata (Hill, 1996).

Renewed tectonic activity in the early Permian (Wolfcampian epoch) caused rapid sinking of the Delaware basin and deposition of thick sequences of clastics in the southern portions of the basin. Shelf limestone and reef deposits formed in the northern portions of the basin at this time. At the end of the Wolfcampian, subsidence resumed and thick accumulations of the Bone Springs Limestone were deposited on the northern edge of the basin (Hill, 1996). During the 8-9 million years of the mid-Permian (Guadalupian epoch) the inland sea shrank and became confined to the area of the Delaware Basin. The restriction to the Delaware Basin produced conditions favorable for the formation of massive sponge-algae reefs, the first of which is the Goat Seep Dolomite (figure 2.2). Following deposition of the Goat Seep Dolomite, the massive Capitan Limestone was deposited. While the reefs were rimming the basin, the Artesia Group was deposited in the backreef lagoon and the mixed clastic and carbonate Bell Canyon Formation filled the basin (Hill, 1996).

The Late Permian Ochoan epoch was a time of drastic change within the Delaware Basin. Sedimentation went from normal marine to evaporite-dominated as the basin was cut off from ocean influence. During the Ochoan, the Delaware Basin filled with up to 4,000 ft (1,200 m) of evaporites comprising the Castile, Salado, and Rustler Formations. By the end of the Ochoan the basin emerged and was completely removed from oceanic influence as evidenced by the terrestrial Dewey Lake Formation (Hill, 1996).

At the end of the Paleozoic and through the start of the Mesozoic the Marathon-Ouachita thrust induced uplift of the basin from the southeast. The Triassic was characterized by erosion, with up to 400 ft (120 m) of Permian evaporites potentially removed. Renewed subsidence of the northeastern portion of the Delaware Basin in the Late Triassic allowed up to 300 m of terrestrial Chinle Formation deposits to accumulate. During the Jurassic no deposits are recorded in the Delaware, with up to a 90 million year hiatus and possible erosion and alteration (Hill, 1996).

Weak subsidence in the Early Cretaceous allowed a period of multiple shallow transgressions to inundate the low-lying area. The Cretaceous seas are responsible for only ~100 m of sediment deposition. By the Late Cretaceous, the Laramide orogeny caused the last known regression. The Laramide orogeny caused uplift of the entire southwestern portion of the Unites States to 4000 ft (1200 m) or more above sea level (Hill, 1996).

Laramide tectonism ended by the Eocene, followed by a period of general quiescence. During the Paleocene, Eocene, and Oligocene, erosion was the dominant process except for some volcanic extrusive and intrusive events primarily in southern portions of the basin. Basin and Range tectonism was the main driving process during the Miocene and Pliocene. The Guadalupe, Delaware, Apache, and Glass mountains were raised along with other fault block mountains of the Rocky Mountain chain. This new period of uplift produced extensive amounts of sediment. This sediment was transported eastward and deposited in a broad band from South Dakota through Texas and New Mexico, forming the Ogallala Formation. The deposits are primarily fluvial valley fill sediments that vary widely in composition, depending on the local source (Hill, 1996). Regional classification of surfaces distinguishes alluvium in the upper Black River valley as part of the Ogallala formation (Hill, 1996), though no detailed studies have confirmed this.

The Pleistocene was a time of varying wet glacial periods with drier interglacials. Alluvial deposits continued to fill topographic lows while terrace development along the Pecos river system continued. Sediments related to the Basin and Range erosion/deposition system and glacial period Pleistocene deposits are difficult to distinguish due to the similarity of variation in sources and climate throughout the Tertiary and Quaternary (Hill, 1996). The climate was warm and moist with abundant stream flow during the Miocene. By the Pliocene the climate was drier with intermittent stream flow allowing caliche soils to develop. During glacial periods of the Pleistocene the climate was again moist, allowing for increased sediment transport similar to conditions in the Miocene (Hill, 1996).

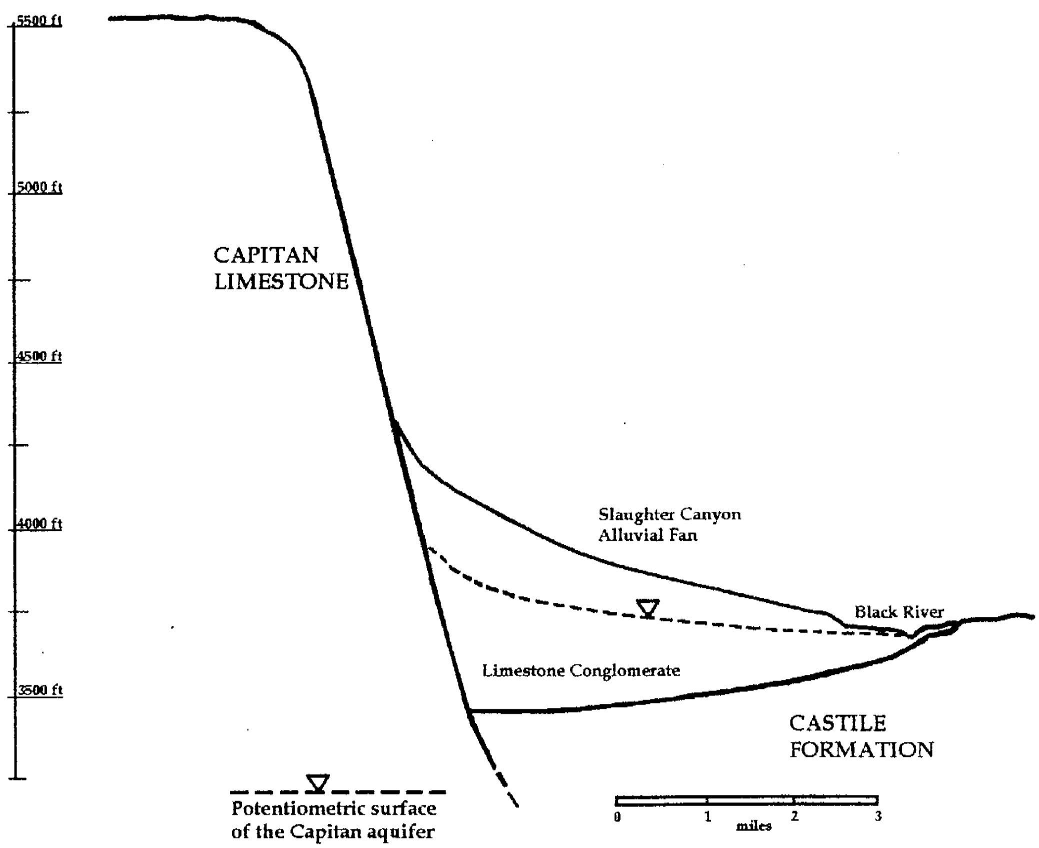


Figure 2.1: Schematic cross section of the Slaughter Canyon alluvial fan. Relation to the elevation of the Guadalupe Reef escarpment and the depth of the Capitan aquifer is shown.

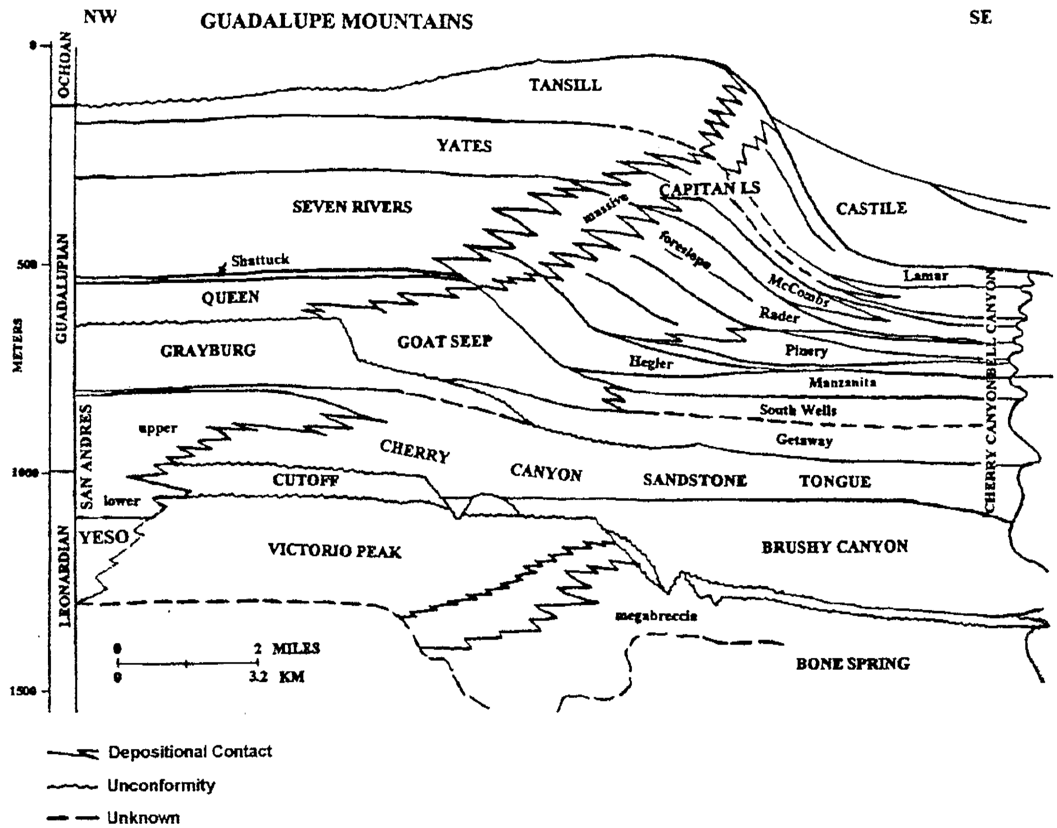


Figure 2.2: Stratigraphic cross section through the Guadalupe Reef Escarpment showing relation between reef and basin sediments of Permian age. Cross section is taken slightly east of the Carlsbad Caverns (Hill, 1996).

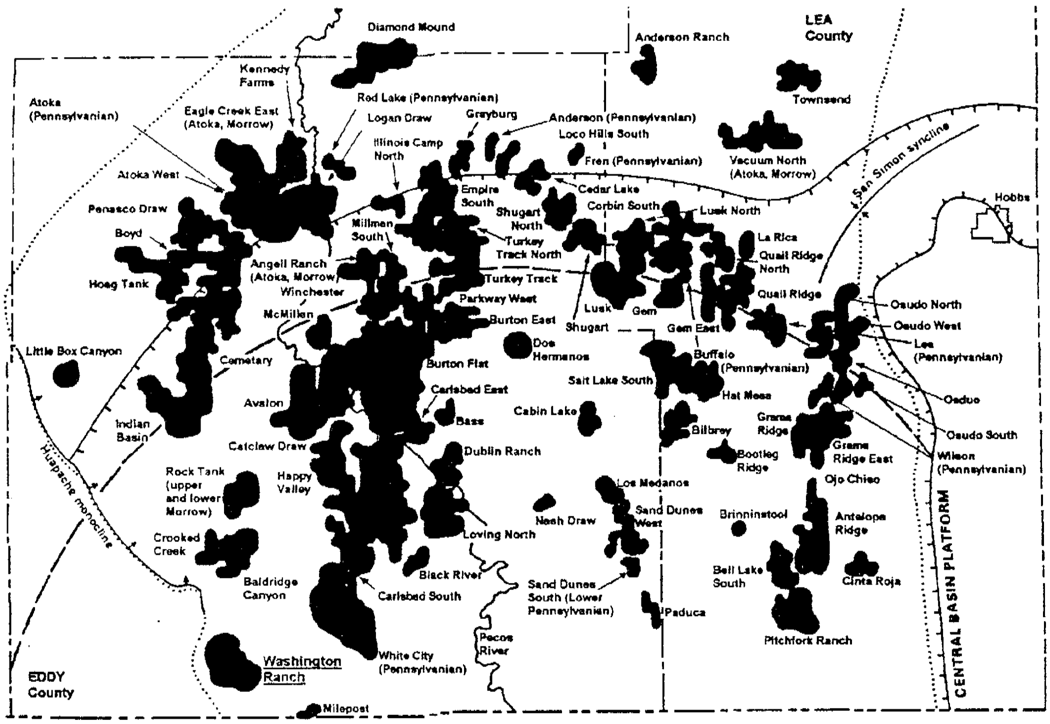


Figure 2.3: Location of oil and gas deposits in Eddy County and Lea County, New Mexico. The Washington Ranch facility is located in southern Eddy County. The moderate size, isolation, and remoteness of the Washington Ranch deposit from urban areas are the characteristics that motivated the location of El Paso Natural Gas' injection facility (Hill, 1996).

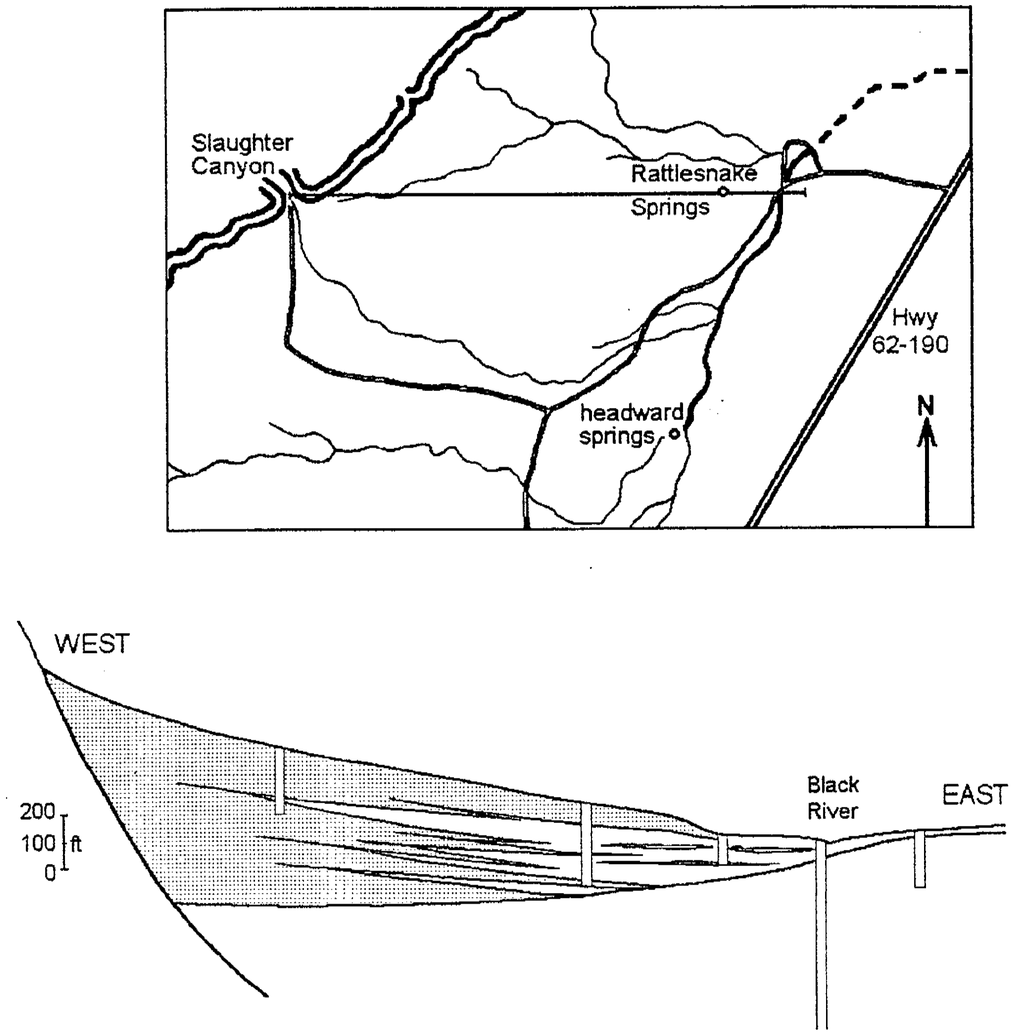


Figure 2.4: Conceptual cross sections through the Slaughter Canyon alluvial fan based on well log data. Note the discontinuous nature of the limestone conglomerate near the Black River.

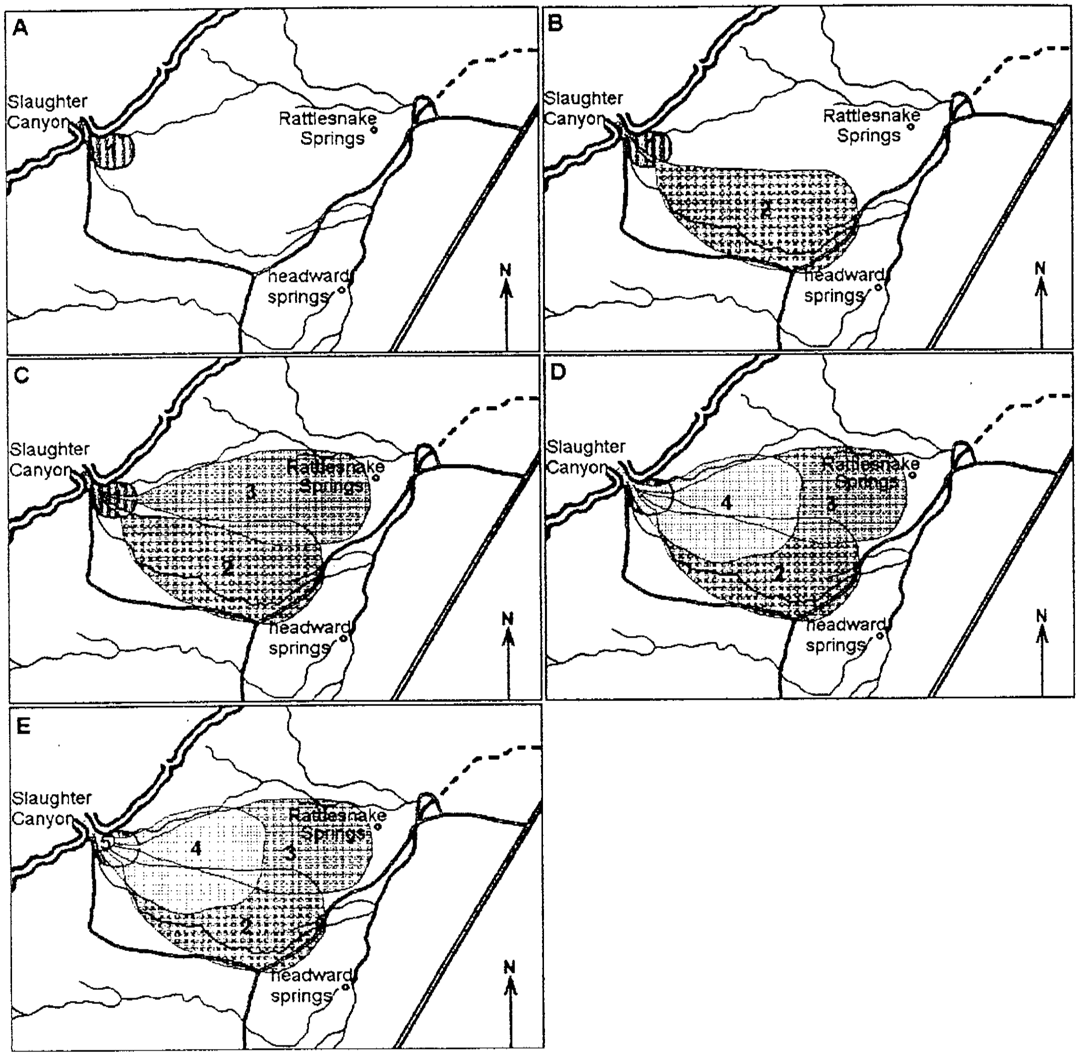


Figure 2.5: Proposed conceptual model of development of the Slaughter Canyon alluvial fan. A) Initial development of a small high angle alluvial fan with initial incision of the Slaughter Canyon drainage system. B-D) Represents shifting areas of deposition as the fan migrates, most likely in response to Pleistocene glacial/interglacial cycles. E) Current small area of active deposition with channel incision and fluvial process dominating over the majority of the fan surface.

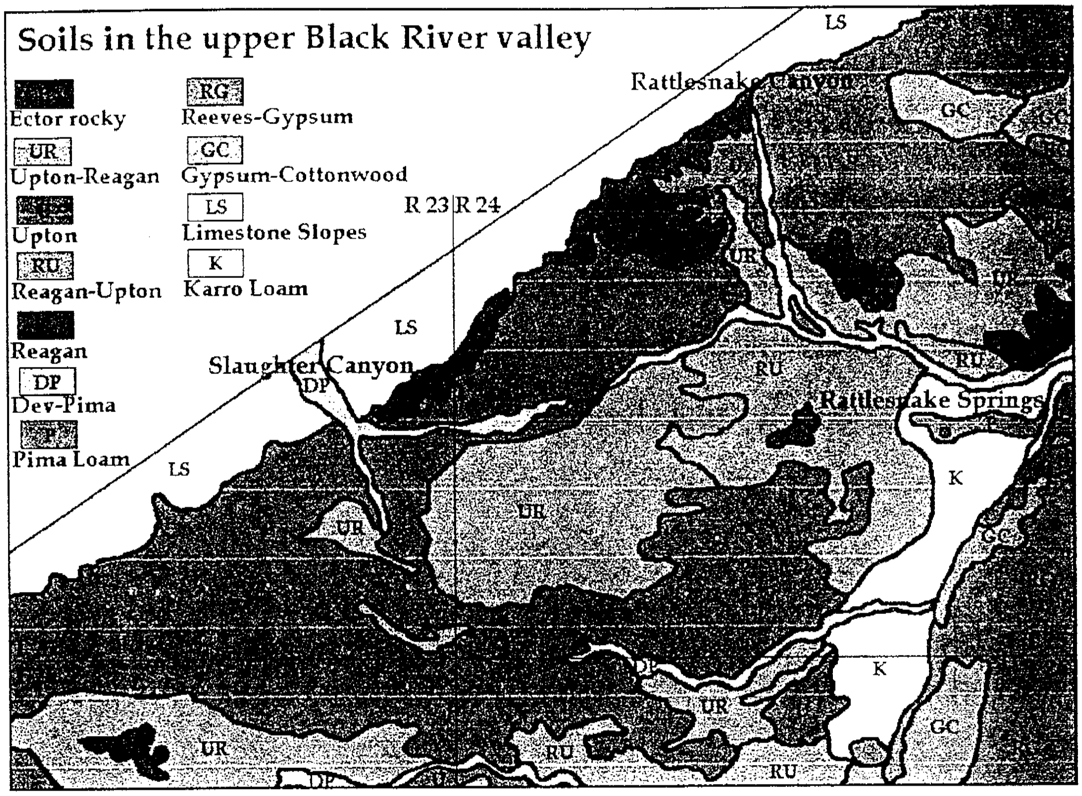


Figure 2.6: Soil formation in the upper Black River valley. Slaughter Canyon alluvial fan is characterized by Upton or Reagan type calcareous soils. Areas over the Castile are dominated by gypsiferous soils. (Chugg, 1971).

Type	Description
Upton	Developed on old alluvium derived from calcareous sedimentary rocks. Soils are shallow to very shallow over caliche or cemented gravel. They typically consist of a thin surface coating of gravel over a thin (~6 in) horizon of brown gravely loam. Carbonate development may be Stage IV or higher. Run-off is slow to moderate with moderate permeability. The water holding capacity is low to very low. Vegetation is restricted by the caliche and low fertility.
Reagan	Deep, well-drained, moderately dark-colored, calcareous loams developed in old alluvium derived from calcareous sedimentary rocks. Reagan soils may contain soft caliche or gypsiferous zone at depths lower than 48 inches that may restrict roots. These soils are moderately fertile, runoff is slow, permeability is moderate, organic matter is low, and water holding capacity is high. Areas with Reagan soils are some of the most productive irrigated lands in Eddy County.
Reeves	Calcareous soils developed over gypsiferous rock. Typical profile is clay loam horizons (~20 in) overlaying a finely crystalline gypsum horizon over weathered gypsum. Run-off is slow, permeability is moderate, and water holding capacity is low to moderate. Vegetation cover is poor, the organic content is low, and the fertility is moderate.
Gypsum lands	Areas of eroded exposures of gypsum, occurs along with very shallow soil. Surface gypsiferous materials vary from white chalky earth to hard crystalline gypsum. Soils are week and dominated by gypsum crystals. Surface run-off is rapid and the water holding capacity is low. Vegetation is limited due to salinity though the area is well drained.
Cotton-wood	Shallow, light colored, calcareous soils developed over gypsum. Horizons consists of light colored loam (~9 in) underlain by gypsiferous material. Soils are subject to severe erosion if vegetation is lost. Surface layer is moderately permeable, the underlying gypsum is slowly permeable. The surface crusts upon drying and the water holding capacity is low to very low.
Ector	Well-drained, calcareous, stony, shallow to very-shallow soils formed over limestone bedrock. Soils have moderate permeability and low to extremely-low water holding capacity. Areas have many exposures of bedrock which aid in stabilization, otherwise these areas are subject to water erosion.
Pima	Fertile, deep, well-drained, moderately dark-colored, calcareous soils form in flood plains of narrow drainageways. These soils have slow run-off, moderately-slow permeability, high water holding capacity, and deep effective rooting depth. Areas subject to periodic flooding.
Karro	Light-colored, strongly-calcareous, loamy soils developed in deep old alluvium, derived from carbonate sedimentary rock. Soils are highly susceptible to wind erosion with moderate permeability, high water holding capacity, and low organic material. Carbonate horizons occur at about 46 inches depth. Soil tends to be enriched with lime from upland runoff and groundwater.

Table 2.1: List of soil types and properties in the upper Black River valley.

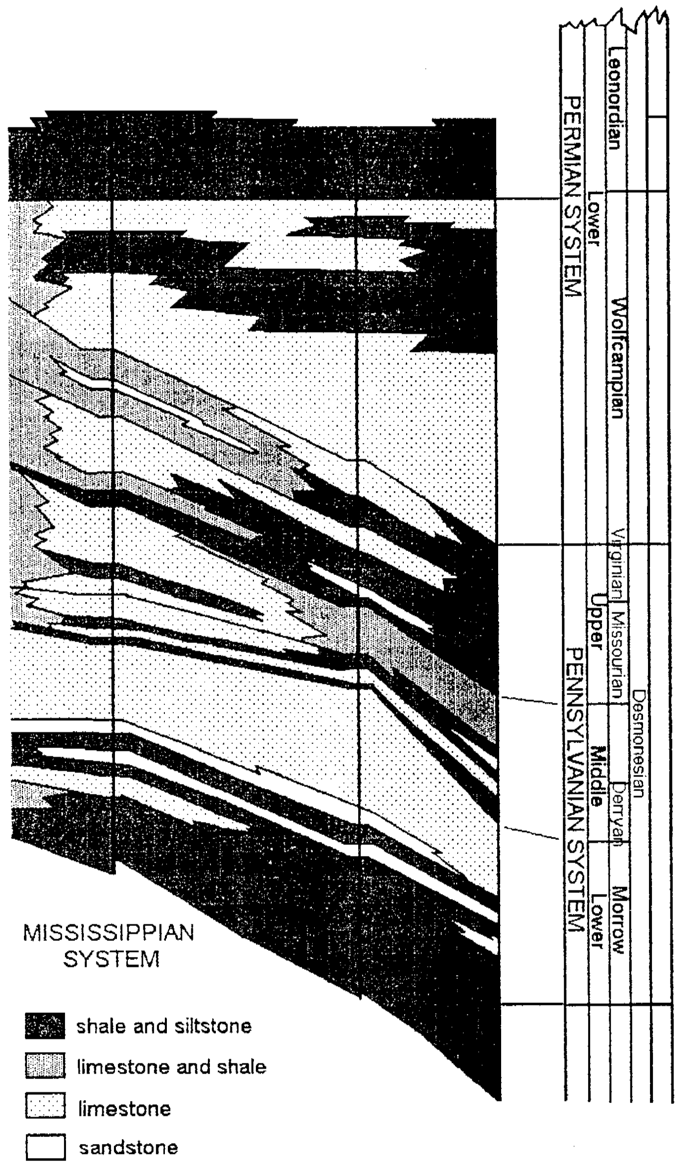


Figure 2.7: North-south cross section of the Pennsylvanian strata though the Delaware Basin 10 miles east of Rattlesnake Springs (Meyers, 1968).

3. Climate

Rattlesnake Springs is located in a semiarid region. The average rainfall is 12.36 inches per year, from the Carlsbad Caverns gauge and the two gauges at Carlsbad city. The majority (80%) of the precipitation occurs in the months May-October while 50% occurs in July-September as high intensity short duration events (figure 3.1). High intensity rainfall events have the potential to produce considerable run-off even over the dry, porous sediments of the region. Precipitation is greater on the Guadalupe Reef Escarpment than in the Delaware Basin by about 5 inches, based on comparison of averages for total precipitation by elevation and location in the nearest 8 rain gauges around Rattlesnake Springs (Appendix C).

There have been noticeable variations in the annual rainfall pattern for the region (figure 3.2). From 1951 to 1956 the average rainfall was only 7.80 inches. This was the most severe drought on record for the region. This drought was responsible for lowering discharge from Rattlesnake Springs. The wettest year on record for Carlsbad Caverns is 1941 with 43.23 inches, and the driest is 1952 with 4.47 inches. At present, precipitation appears to be close to average, while the mid 1970's through mid 1980's were above average.

The mean annual temperature is 61°F (Sares, 1984). Average frost-free season ranges from 195-220 days per year (Chugg, 1971). Temperature varies from a recorded low of -17°F to a high of 112°F (Tallman, 1993).

Potential evapotranspiration exceeds precipitation throughout the year (figure 3.1), although the high intensity nature of the precipitation events allows for run-off and infiltration (Sares, 1984). Rangeland in southeastern New Mexico, such as the upper Black River valley, has an average evapotranspiration rate from 89%-98% with 96% being the best value for the region (Hunter, 1984). Groundwater extracted for irrigation is subjected to an additional average 58% loss to evapotranspiration (Hunter, 1984).

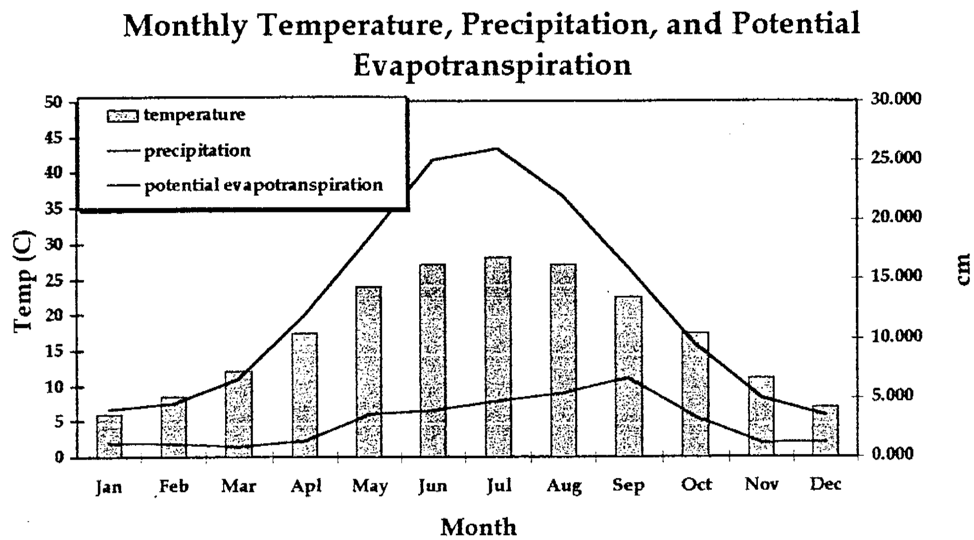


Figure 3.1: Average monthly temperature and potential evapotranspiration (Blaney-Criddle method) from the Carlsbad municipal airport gauge and average monthly precipitation from the Carlsbad, CCNP, and Caverns City gauge.

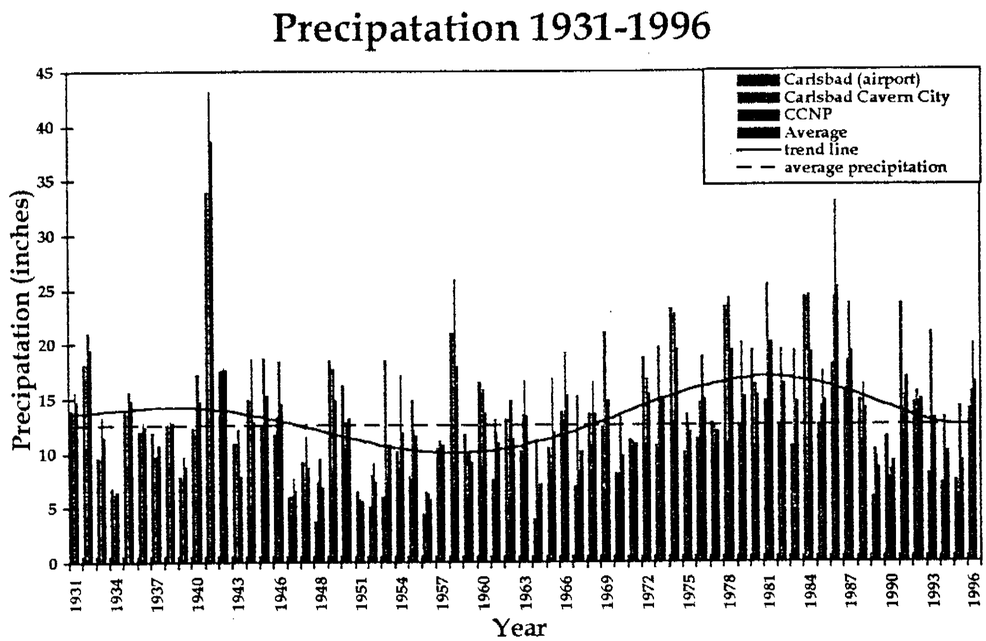


Figure 3.2: Yearly precipitation totals and average for the Carlsbad municipal airport, Carlsbad Caverns National Park, and Cavern City gauge. The average precipitation (12.63 inches) and the moving average depicting long term variations are shown.

4. Hydrogeology

4.1 Regional Flow

Due to the geologic and economic significance of the Delaware Basin and Guadalupe Reef Escarpment, regional-scale flow has been well characterized within Eddy County. Regional flow is driven primarily by the topography of the Guadalupe Mountains and Reef Escarpment and the regional dip of the basin sediments to the east induced by Basin and Range faulting. Flow within the reef and backreef facies is confined within the Capitan aquifer and is separated from the basin aquifers in the northern portion of the Delaware Basin.

4.1.1 Groundwater

Groundwater flow for the southern portion of Eddy County is northeast towards the Pecos River (figure 4.1). The two main aquifers for the region are the Capitan aquifer consisting of the reef complex units and the deeper basin aquifers within the Delaware Basin. The Brushy Canyon, Cherry Canyon, and Bell Canyon formations of the Delaware Mountain group are known as the basin aquifers (figure 4.1). These formations consist of predominantly sandstone and siltstone with some carbonate. The carbonate units serve as aquifers while the siliclastics beds act as confining units and transmit little water (Hill, 1996). Also within the Delaware Basin are Castile, Salado, Rustler, and Dewy Lake

Formations, all Ochoan in age. The Castile and Salado act as regional aquitards (Hill, 1996).

The Capitan aquifer includes the Capitan Limestone, the Goat Seep Dolomite and all of the Artesia Group (backreef), collectively acting as a connected hydrologic unit (figure 2.2). Water is mostly confined to the reef limestone by the Castile Formation towards the basin and shelf evaporites in the backreef. Vertical migration out of the aquifer is hindered by a tongue of the Cherry Canyon sandstone. Water quality within the Capitan aquifer varies both laterally and vertically from 300 to 31,700 mg/L TDS (total dissolved solids). Most of the lower quality water is derived from the back-reef evaporite facies while water within the Capitan Limestone is of good quality (300-700 TDS: Hill, 1996).

The Castile Formation acts as a regional aquitard to groundwater flow, both laterally and to vertical artesian flow. Two exceptions exist: the lower Castile aquifer in the Anhydrite I unit, which is perched on the Lamar limestone of the Bell Canyon Formation, and a hypothetical upper aquifer (Hill, 1996) that is an avenue for dissolution in the lower Salado Formation. The Anhydrite II unit of the Castile Formation is exposed around the Rattlesnake Springs area and serves as a regional aquitard, though flow occurs along the Castile-alluvium contact as shown by the prevalence of cave and karst formations along this contact (Sares and Wells, 1987).

Due to the low-lying nature of the area until the Laramide orogeny, groundwater was most likely stagnant and highly mineralized. The Laramide uplift allowed for the start of effective circulation through the present aquifers, that were subsequently altered by Basin and Range block faulting and tilting (Hill, 1996).

4.1.2 Surface Water

Surface water is scarce due to the semiarid climate of southern New Mexico. Perennial surface water in the study area is limited to artesian springs and the upper stretch of the Black River. Ephemeral surface drainage systems flow sporadically within the Reef Complex in response to heavy rainfall events and even less frequently on the alluvial fans.

Several springs are located within the alluvium and Castile Formation along the base of the Reef Escarpment. Springs such as Rattlesnake Springs, the "headward springs," Castle Springs, and Blue Springs are associated with discharging water from the alluvial fans of the major drainage systems of the Escarpment (figure 4.2). Rattlesnake Canyon is the only drainage system from the Guadalupe Reef Escarpment that does not have an associated alluvial fan or springs. Smaller springs within the Castile follow the same trend as those discharging from alluvium. The "headward springs" are a series of small springs discharging at the start of the perennial upper Black River. These springs have been called the "headward springs" in earlier reports (Hale, 1955; Cox, 1963), but are not officially named.

There are only three perennial surface water streams in Eddy County: Black River, Cottonwood Creek, and the Pecos River. The Pecos River is a large (~0.9 m^3/sec) north-to-south flowing river and defines local base level. Cottonwood creek is a small spring fed stream in northern Eddy County. The Black River is the last perennial tributary to the Pecos before it enters Texas and has an average discharge of ~0.3 m^3/sec. The Black River is perennial for the upper 6 miles (10 km), then ephemeral for the following 11 miles (17 km), and perennial for the lower 20 miles (32 km) before entering the Pecos River (Sares, 1984).

4.2 Local Characteristics

Although the regional characteristics of groundwater flow are well constrained, the immediate area around Rattlesnake Springs has been studied little. Groundwater and geologic data for detailed analysis are sparse. Few wells are available for groundwater sampling, and those are not evenly distributed. More data are available along the Black River than closer to the Guadalupe Reef Escarpment. Inside Carlsbad Caverns National Park, no shallow wells are available. Sporadic measurement of the conductance and hardness of groundwater and surface water have been performed by the New Mexico State

Engineer's Office. Additional water chemistry was collected and sampled as part of this project at 10 sites (appendix C). Discharge data are available for Rattlesnake Springs, although these data have not been continuously recorded. Few detailed well logs are available, those for shallow water wells often do not contain geologic descriptions and well logs for oil and gas wells often do not record near the surface.

4.2.1 Water Chemistry

There are three distinct groupings of water chemistry for surface and groundwater in the area of Rattlesnake Springs (figure 4.3). Group I is water that is low in sulfate, 0-200 ppm SO_3, and high in alkalinity, >250 ppm HCO_3, indicating an origin from a primarily carbonate aquifer. Group II consists of waters intermediate in sulfate, roughly 600-800 ppm SO_3, and alkalinity > 225 ppm HCO_3. Group III contains water with high sulfate content and < 250 ppm HCO_3. A piper diagram of 12 water chemistry samples run for this project also shows the differentiation of water chemistry (figure 4.4).

Group I is limited to Rattlesnake Springs, a few of the irrigation wells and domestic wells in the near vicinity of Rattlesnake Springs, and wells on the proximal portions of the Slaughter Canyon alluvial fan. Group II includes the Ballard irrigation wells in the area of report natural gas contamination. Water of similar quality also discharges from Castle Springs and Blue Springs. Group III includes the "headward springs," a few springs that discharge from the Castile Formation, and the majority of flow in the Black River.

The grouping of the water chemistry, viewed with the areal distribution (figure 4.5), supports the concept of discrete flow paths through different substrate types to produce the observed variability. Group I flows through mostly carbonate rock as evidenced by the low sulfate. Group III waters flow through predominantly sulfate media. Group II is intermediate, the flow path to produce this water chemistry contains both carbonate and sulfate media. Gypsum, with solubility of 23.14 mmol/L, is considerably more soluble than calcite, 0.06 mmol/L (Appelo and Postma, 1994). Because of this, gypsum will induce a stronger chemical signature on groundwater than calcite during an equivalent amount of time.

Information for water chemistry is based on sampling performed in June 1997 and State Engineer's Office records. Basic water chemistry, alkalinity, conductance, and TDS, are recorded for wells when first drilled. A fairly complete record exists for most wells, though the wells were drilled before 1952 and accuracy is questionable.

4.2.2 Tritium

Tritium is ^{3}H that is generated in the upper atmosphere by cosmic radiation and decays with a half-life of 12.26 years once precipitated (Gross *et al.*, 1976). Tritium content was measured from water at four sites (figure 4.6) chosen along what was believed to be the dominant flow direction between Slaughter Canyon and Rattlesnake Springs. Figure 4.5 shows the location of the wells sampled and the results along with the uncertainty in measurement. The uniformly low values indicate a young age for the water in the aquifer. Comparison to measured values of tritium in precipitation indicate that the age of the water discharging to Rattlesnake Springs is less than 15 years old. Measured values of tritium in the groundwater are uniformly lower than precipitated values and half-life calculations do not correlate to a direct match with precipitation values. This is due to mixing of the newly infiltrated water with older water within the aquifer producing a lower tritium content than calculated (Gross *et al.*, 1976). The dual porosity regimes in the alluvium aid this process. Measured tritium values and additional details are provided in Appendix C.

4.2.3 Discharge at Rattlesnake Springs

Discharge data for karstic springs is often used for hydrograph analysis when a clear correlation between precipitation events and discharge is apparent. For Rattlesnake Springs this type of analysis cannot be performed since no clear relationship exists. This is most likely due to the distance between Rattlesnake Springs and the recharge zone, the heterogeneity of the system, and the possibility of multiple flow pathways. The discharge data for Rattlesnake Springs are still useful for modeling the system and providing information on long-term and seasonal discharge patterns.

Data on the discharge of the Springs have been problematic because continuous records have not been kept. Continuous records exist only for the time period of 1984 to the present (figure 4.7). Re-calibration of the flume system in 1989 shows that prior records were biased towards overestimating the actual discharge by up to 50%. The pre-1989 data were therefore decreased by 50% to allow correlation.

Discharge amounts are generally highest in winter and lowest in summer. The highest discharge values typically occur in March and the lowest are typically in August. Daily fluctuations appear to be produced by seasonal pumping of nearby irrigation wells and minor fluctuations are caused by evapotranspiration and changes in the barometric pressure. Examining the data since 1989 shows a sustained high flow of 4.3 cfs (cubic feet per second) in April 1990 and a low flow of 2.2 cfs in August 1994. The average discharge was 3.2 cfs during 1989-1997.

4.2.4 Aquifer Heterogeneity

Beyond general knowledge of the depositional nature of alluvial fans, there are several indicators to support the heterogeneity of the aquifer supplying Rattlesnake Springs in the immediate vicinity.

Four wells were drilled around Rattlesnake Springs in 1963 when the Park Service installed a production well. Variation in lithology, yield, and specific conductance shows the heterogeneity of the system (Appendix A). Yield was dependent on penetration of the wells with karstic channels within the alluvium. Yields of the four wells drilled varied from >10 gpm to <1,000 gpm. The production well has a higher conductance than Rattlesnake Springs, 750 mΩ in contrast to an average 600 mΩ for the pools (Mourant and Havens, 1964). This difference shows that there are measurable differences in the water quality along different flow paths in the near vicinity of the Springs.

Measurable variations in the conductance of water sampled at various points in the Rattlesnake Springs pool provide additional support for the heterogeneity of the system. The water within the concrete intake to the sump is 630 mΩ. Water conductance is 570 mΩ in the pool, taken at the staff gauge. These differences were measured when the pool was at a low stand, 5.5 ft deep at the staff gauge. Multiple sources to Rattlesnake Springs are also supported by the decrease in the water conductance as the pool elevation lowers in the summer (Mourant and Havens, 1964). This shows that as total discharge varies, different flow paths with different conductances dominate, varying the conductance in the Rattlesnake Springs pool.

4.2.5 Pumping Tests

The National Park Service is entitled to 105 acre-feet per year of water from Rattlesnake Springs for Carlsbad Caverns National Park and irrigation of Rattlesnake Springs property. The Park Service installed a production well in 1963 to ensure supply during low-stands of Rattlesnake Springs. Pumping tests were performed twice on the well providing coefficients of transmissivity of 890,000 and 940,000 gallons per minute per foot (0.135 m^2/sec and 0.128 m^2/sec; Mourant and Havens, 1964). These values were obtained with the time-drawdown method for a single well (Domenico and Schwartz, 1990). Drawdown was not corrected for possible interference produced by the agricultural wells. The nearby water supply well for the Washington Ranch facility was measured at a lower 60,000 gallons per day per foot (0.0283 m^2/sec).

Irrigation from wells in the upper Black River valley started in 1946, and by 1952 670 acres were being irrigated with groundwater in the upper Black River valley. Currently there are approximately 530 acres of land leased for agricultural irrigation near Rattlesnake Springs (figure 4.8). These are from two leases that are granted a total 1,329.2 acre-feet of water per year through the use of 5 high capacity wells. A detailed study of the effects of irrigation pumping was conducted from March 15 through April 3, 1961. Three wells (figure 4.8) all with 1,200 gpm capacities, were examined and wells 8 and 11 have a direct effect on the discharge of Rattlesnake Springs. Pumping from these irrigation wells lowered water levels in the observation well and Rattlesnake Spring's pool within 2 hours (Cox, 1963). Well 13 has almost no effect on Rattlesnake Springs (Cox, 1963). The Carlsbad Caverns National Park water-supply well withdraws at a lesser rate, 250 gpm, and does not affect spring flow.

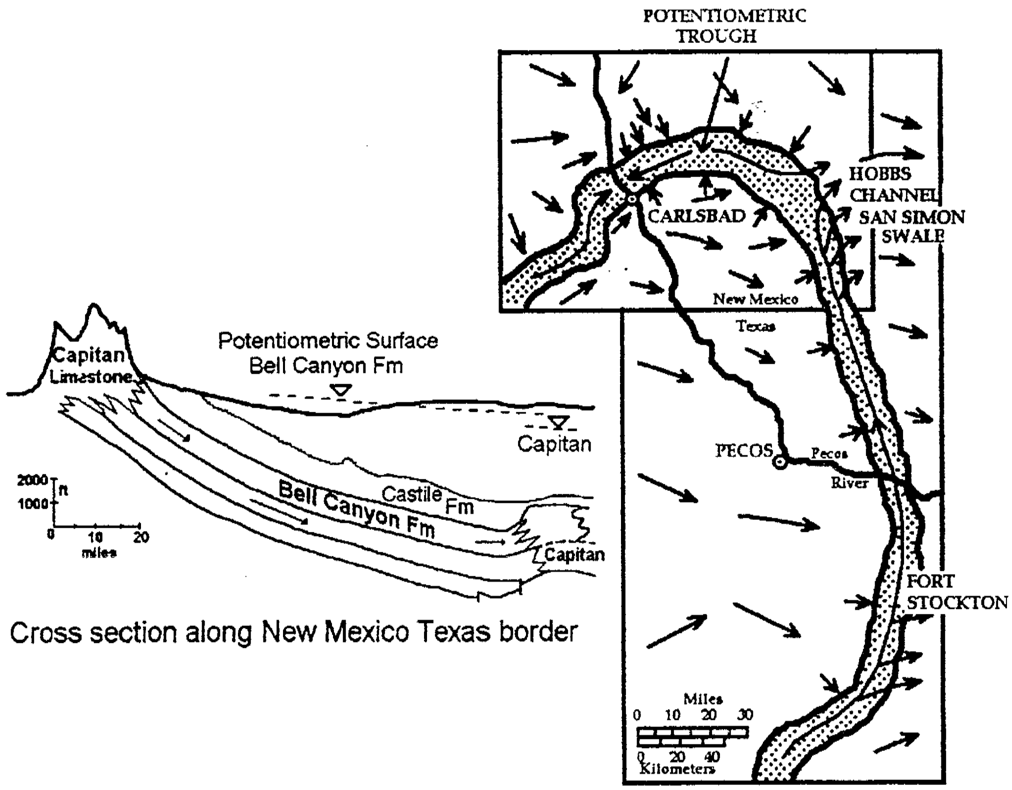


Figure 4.1: Groundwater flow in the Capitan aquifer and Basin aquifers shown in map view (Hill, 1996). Flow within the Delaware Basin is controlled by the Capitan Limestone. The Capitan in Eddy County discharges to the Pecos River. In the buried portion of the Capitan, flow is to the Hobbs Channel.

Spring Distribution

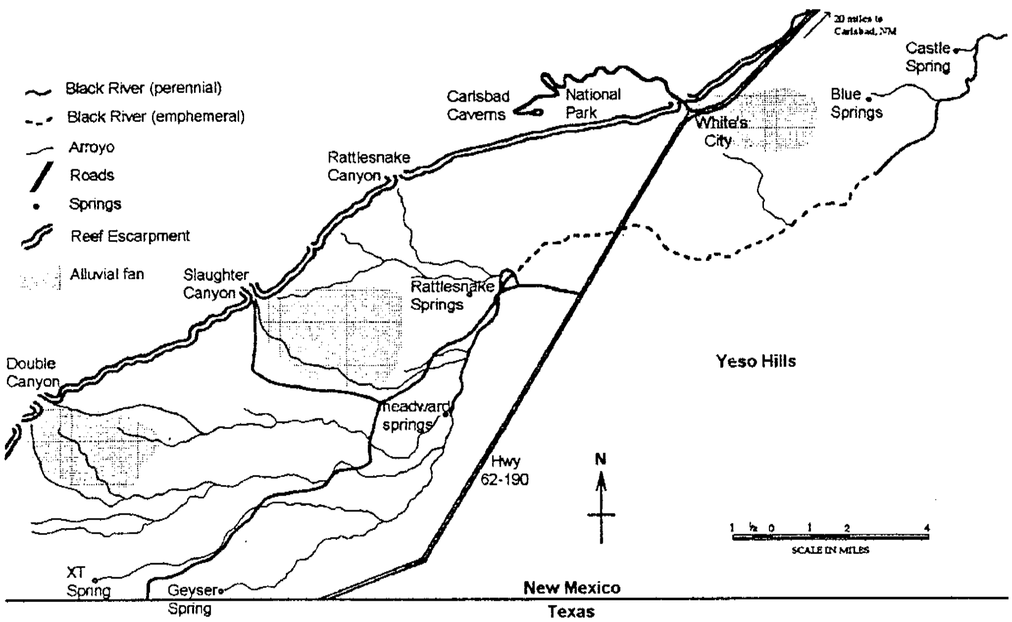
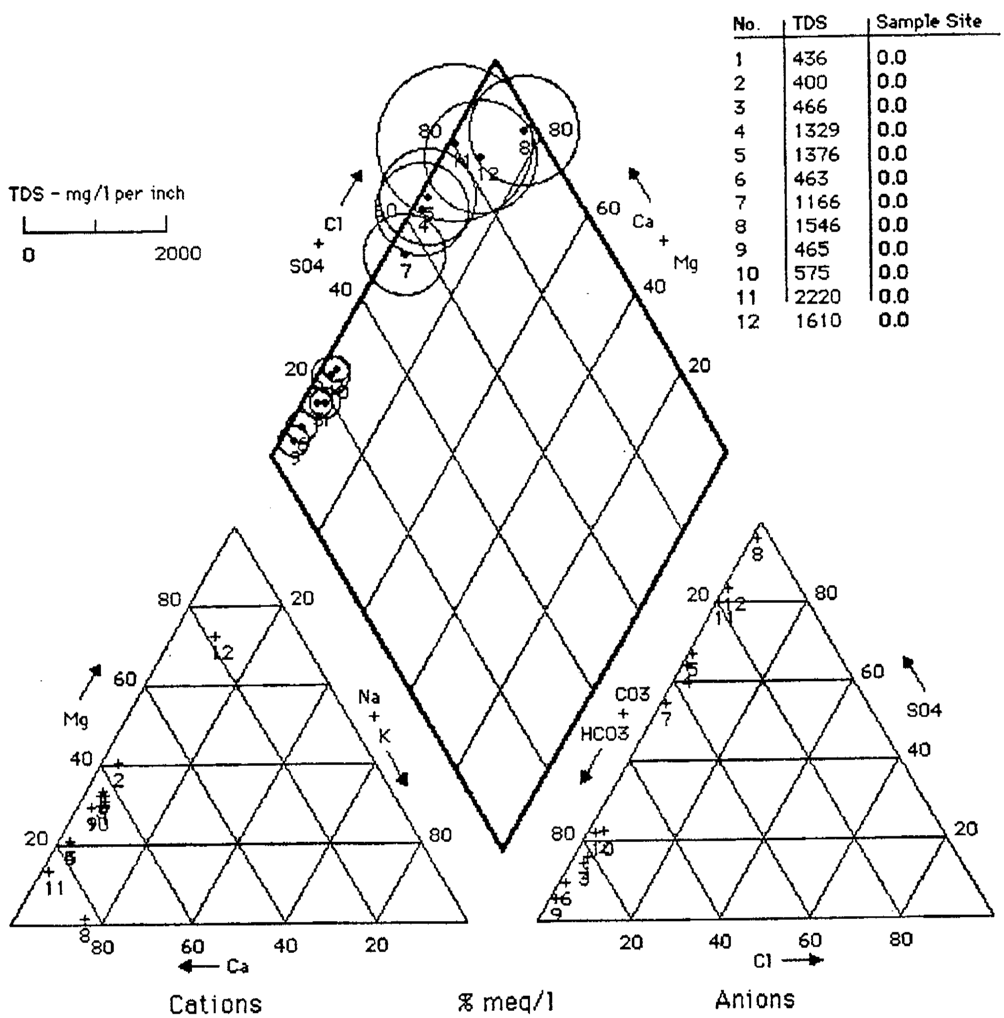


Figure 4.2: Distribution of springs in the upper Black River valley and location of major alluvial fans. Rattlesnake Canyon is the only major canyon through the Guadalupe Reef Escarpment that does not have an associated fan.



No.	TDS	Sample Site
1	436	0.0
2	400	0.0
3	466	0.0
4	1329	0.0
5	1376	0.0
6	463	0.0
7	1166	0.0
8	1546	0.0
9	465	0.0
10	575	0.0
11	2220	0.0
12	1610	0.0

Figure 4.4: Piper diagram of water chemistry. The 12 samples shown were analyzed for this project.

Aerial distribution of water chemistry data

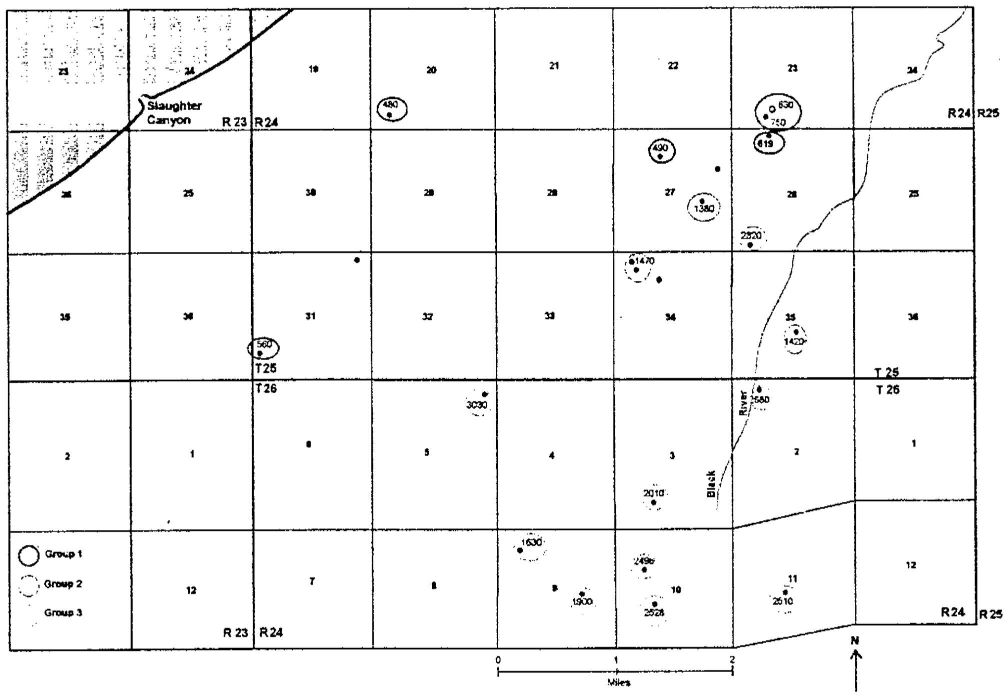
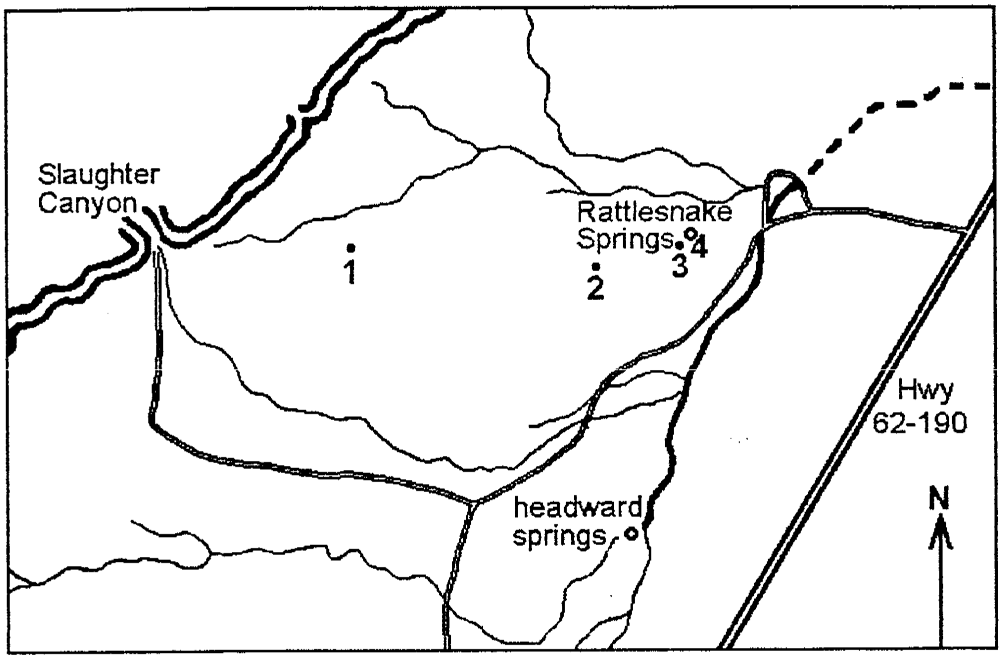


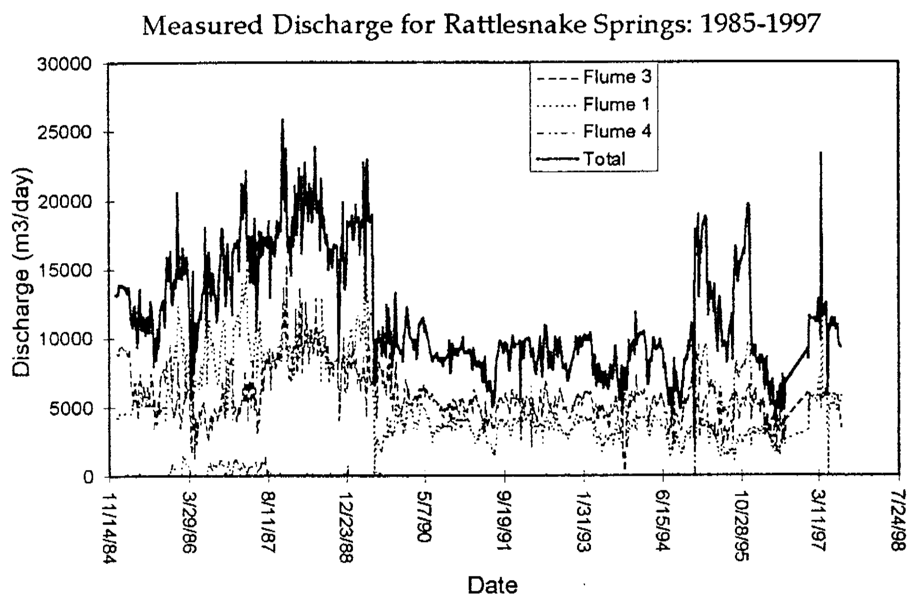
Figure 4.5: Areal distribution of water chemistry in the upper Black River valley.



Sample	Use	Owner	TU	Error
1	stock	Joe Stell	3.77	0.95
2	domestic	EPNG	2.59	0.89
3	domestic	CCNP	3.86	1.10
4	spring	CCNP	2.75	0.86

EPNG = El Paso Natural Gas
CCNP = Carlsbad Caverns National Park
TU = Tritium Units: 1 atom of tritium per 10^{18} atoms of hydrogen

Figure 4.6: Location of samples and values of tritium analysis.



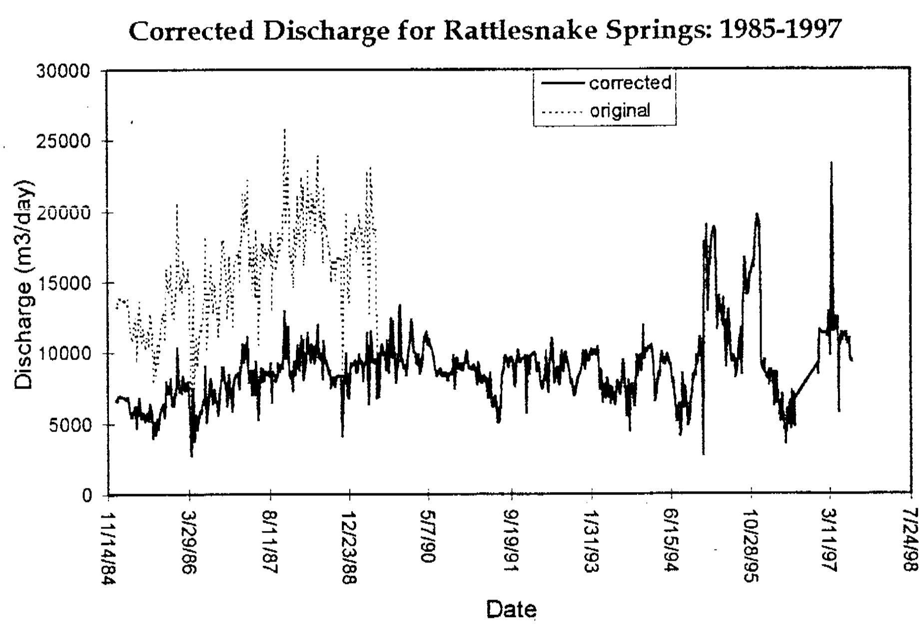


Figure 4.7: Discharge data for Rattlesnake Springs. No continuous data is available for the time period before 1984. Data before June 1989 was overestimated by ~50%. The lower figure shows a correction by reducing pre 1989 data by 50%, although the reliability of this earlier data is low.

Distribution of agricultural wells

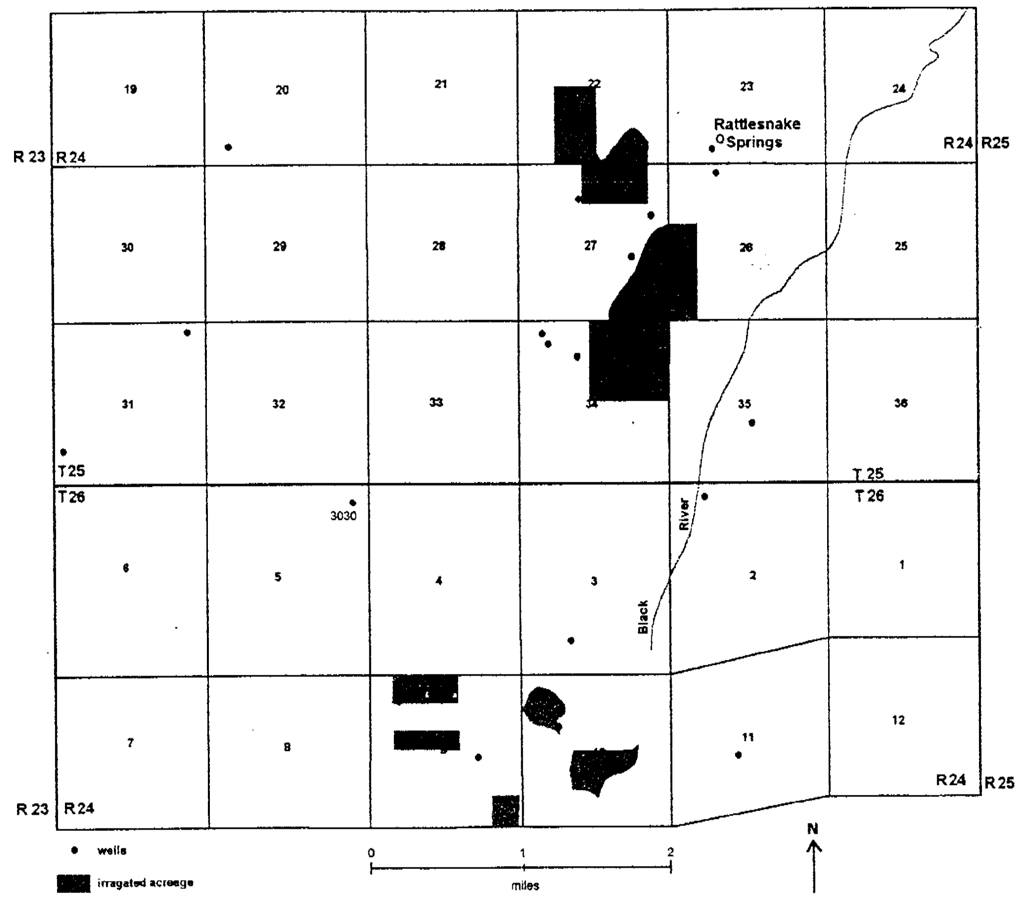


Figure 4.8: Current agricultural plot in the upper Black River valley. Based on Hale's (1955) map and 1989 EPNG areal photograph.

5. Conceptual Model

5.1 Geologic Framework

Groundwater flow in the upper Black River valley is roughly parallel to surface water. Flow is perpendicular adjacent to the reef escarpment then joins the north-east trend of the Black River flowing towards the Pecos River. Confining conditions within the aquifer allow for flowing artesian conditions at the foot of Slaughter Canyon alluvial fan manifested locally by Rattlesnake Springs and the "headward springs." This trend is also observed at other locations along the Reef Escarpment, such as Castle Springs and Blue Springs that are both associated with Walnut Canyon, that feed the lower perennial stretch of the Black River (figure 4.2).

Groundwater flow through the aquifer supplying Rattlesnake Springs is controlled geologically by the Slaughter Canyon alluvial fan. Flow is conceptualized as originating from recharge due to high-intensity precipitation events over the Guadalupe Reef Escarpment. This produces overland flow through the Slaughter Canyon drainage system to the proximal portions of the alluvial fan (figure 5.1). The alluvium in the stream channels of the final reach of Slaughter Canyon and the very proximal portion of the fan, roughly 1 mile in length, are coarse, highly porous, and poorly vegetated. Clast size is in the gravel to boulder range, allowing rapid infiltration. Hydraulic conductivity of such a matrix is typically between 3×10^{-2} to 3×10^{-4} m/sec (Domenico and Schwartz, 1990). Run-off within the Slaughter Canyon drainage system that exceeds evapotranspiration losses will infiltrate into the stream channel alluvium and recharge the alluvial fan. Additionally, a portion of the recharge from the Capitan Limestone within the Slaughter Canyon drainage basin discharges into the stream channel alluvium and is transported to the head of the fan. The majority of precipitation over the Slaughter Canyon drainage basin that infiltrates the Capitan Limestone is believed to recharge the Capitan aquifer, not the alluvial aquifer. Although the majority of recharge goes to the Capitan aquifer, additional recharge is provided to the alluvial aquifer by perched aquifers discharging from within the foreslope of the Guadalupe Reef.

I hypothesize that flow within the Slaughter Canyon alluvial fan is controlled by karst channels within the limestone conglomerate. Flow in the proximal portions of the alluvial fan is through a fairly uniform coarse medium. As flow progresses from the mouth of the canyon, it is localized within channels due to the heterogeneity of the system. Paleo-stream channels will have coarser carbonate material, producing the modern preferential flow paths. These channels produce the stringers of conglomerate seen in the distal portions of the fan. These stringers are isolated between finer silt and clay dominated sediments. Flow within the limestone conglomerate over time produced karstic channels. The karstic channels produce mostly isolated, discrete flow paths. The stream channel pattern most common for alluvial fans is a braided system, this could produce some interconnection of paleo-channels.

Rattlesnake Springs is an artesian spring produced by an impediment to flow. This impediment is a narrowing of the alluvial sediments between the Castile Formation that outcrops at the surface on both sides of the Black River at its distal portion (figure 5.2). At the terminal portion of the upper perennial stretch of the Black River, the alluvial sediments along the Black River widen and flow returns to the subsurface. Confining conditions are produced within the alluvial fan by the fine sediments between the karst channels acting to prevent vertical flow.

The deeper pathways of flow within the Slaughter Canyon alluvial fan come in closer contact to the upper portions of the Castile anhydrite that induces the observed higher sulfate signature. Based on this assumption, it is assumed that flow through the El Paso Natural Gas injection facility, which has the Group II chemical signature, belongs to an older deeper lobe of the alluvial fan, which discharges directly to the gaining stretch of the Black River or is lost to the Castile Formation. Flow to Rattlesnake Springs is hypothesized to occur through an upper, younger alluvial lobe that has limited contact with the Castile Formation. All proposed lobes of the alluvial fan complex are assumed as connected in the proximal portions of the fan.

The Castile Formation is a regional aquitard with low conductivity. Evaporites have some of the lowest conductivity of any natural media. Typical anhydrite conductivity values range from 2×10^{-8} - 4×10^{-13} m/sec. The highly soluble nature of gypsum and anhydrite also contribute to its low permeability by allowing annealing of fissures (Ford and Williams, 1989). In the Gypsum Plain, karst has been shown to form within anhydrite and gypsum in the unsaturated zone (Sares, 1984). The Castile underneath the alluvium in the upper Black River valley is at 100-150 m (300-500 ft) depth and should provide an effective hydraulic barrier since it is below the regional water table. Limited flow within the Castile Formation is concentrated along contacts (Hill, 1996), so the potential for flow paths along the upper contact with the Castile exists.

5.2 Water Balance

A simple water balance was calculated to check the initial assumptions of values for the system. The concept is that for a system:

Outputs = Inputs - Changes in Storage

For an initial look at the Rattlesnake Springs aquifer, it is assumed that the system is in equilibrium, meaning that there is no change in storage. Inputs are produced by infiltration at the mouth of Slaughter Canyon. A lesser amount of infiltration is generated by run-off from the foreslope of the Guadalupe Reef Escarpment. Throughflow is from small perched aquifers in the Capitan, assumed as 1/5 the recharge from Slaughter Canyon alluvial fan. Additional input to the alluvial fan is from areally distributed precipitation based on the annual average, 12.63 inches per year.

An outputs from the system is discharge from Rattlesnake Springs, estimated at an average flow of 3.2 cfs. Discharge also occurs from the "headward springs" estimated at 1.0 cfs (Hale, 1955). The Black River is a gaining stream for a portion of the upper reach. Direct groundwater discharge into this portion of the system is estimated as 1.3 cfs based on measured flow for the time period 1952-1954 (Hale 1955). Five nearby agricultural wells, belonging to two leases allotted 1,329.2 acre-feet per year, produce an additional loss. The Bell Canyon Formation at the Washington Ranch facility is at 850-1000 ft depth so losses to this formation through the Castile will be assumed as negligible. No losses to the Castile are considered because of its low permeability.

The simple water balance (table 5-1) produces a close match between input and outputs. It does show that additional inputs to the system, such as throughflow from the Capitan Limestone, are required since recharge from precipitation cannot balance the discharges from the system. The slightly higher values for inputs show that the evapotranspiration losses through the Slaughter Canyon reach are most likely higher than the assumed 80%.

Conceptual Model

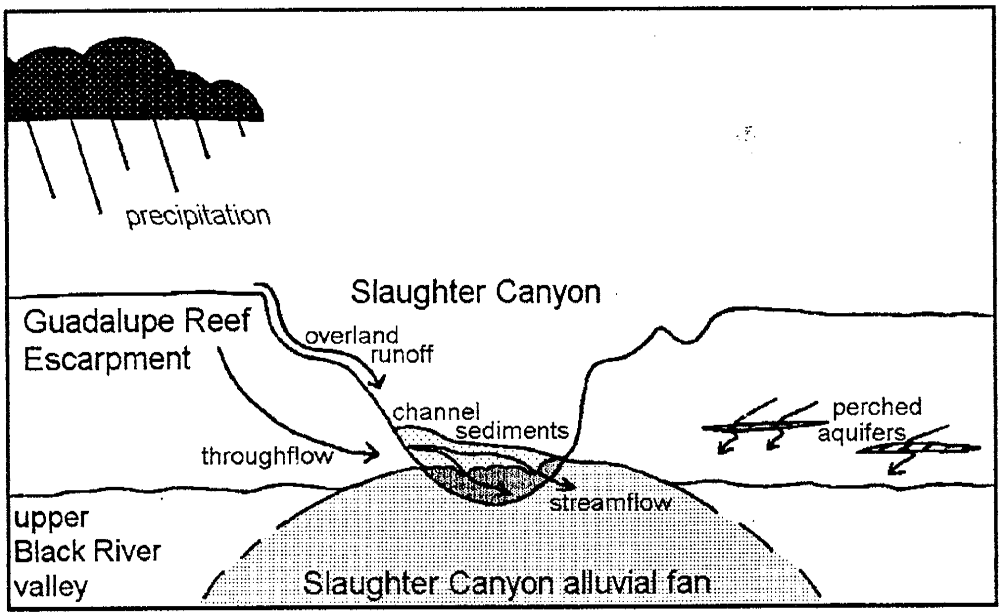


Figure 5.1: Cartoon of conceptual model, showing recharge sources into the alluvium of the upper Black River valley.

Distribution of the Castile Formation

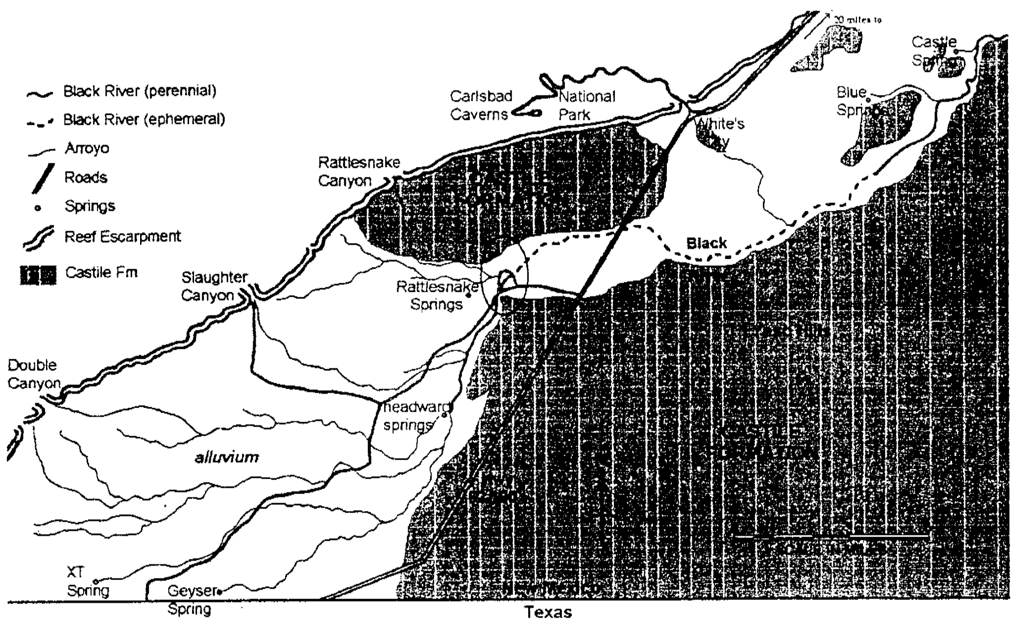


Figure 5.2: Distribution of the Castile Formation at the surface in the upper Black River valley. Note the restriction in the alluvial sediments between the Castile at the terminal end of the upper perennial reach of the Black River.

Input					Output	
Source	Area mi^2	cfs	Evapotranspiration losses	cfs	Discharge	cfs
Slaughter Canyon	20	18.13	80%	3.63	Rattlesnake Springs	3.2
Reef-front	5	4.53	80%	0.91	Black River	1.0
Areal Recharge	13	11.78	96%	0.47	"headward springs"	1.3
Perched aquifers		0.73		0.73	Agricultural pumping	0.03
					Castile Fm.	0
Total				5.73		5.53

Table 5.1: Summary of simple water balance.

6. Numerical Model

6.1 MODFLOW

In order to test the conceptual model, a numerical model of the Slaughter Canyon alluvial fan and surrounding area was developed. The Unites States Geologic Survey's MODFLOW code was used for this task (McDonald and Harbaugh, 1984). MODFLOW is a three-dimensional modular finite difference groundwater flow model that can be applied to a wide variety of groundwater problems. MODLFOW has been extensively tested and has been accepted in a large number of United States court cases (Leake, 1997). The modular design allows for the optional use of various features such as wells, drains, precipitation, evapotranspiration, and rivers as well as a variety of initial conditions, boundary conditions, and solvers. MODLFOW is also designed to allow other programs to run in conjunction with the code, such as MODPATH that provides particle tracking and MT3D which calculates contaminate transport. A graphical user interface, Visual MODFLOW, was employed in this study. This interface runs the most recent, 1996, version of MODFLOW.

MODFLOW is based on the equation for three-dimensional movement of groundwater through porous media:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t}$$

where:

x, y, z cartesian coordinates

h potentiometric head (L)

K hydraulic conductivity (L/t)

W volumetric flux per unit volume and represents sources or sinks (t^{-1})

S_s specific storage of the porous material (L^{-1})

t time (t)

The governing equation requires (1) saturated porous media, (2) Darcy's law to apply, (3) the density of groundwater to be constant, and (4) the principal directions of horizontal hydraulic conductivity to not vary within the system. These criteria are met for the Rattlesnake Springs system.

One of the main considerations with using MODFLOW is the foundation on Darcy's law that assumes linear laminar flow. Flow within pipes or other openings will be first linear and laminar than non-linear to turbulent with increasing velocities. It has been proven that Darcy's law holds true for flow where Reynold's number is between 1 and 10 (Ford and Williams, 1989). Karstic openings of sufficient size to produce non-linear flow conditions, greater than 3.3 ft (1 m), are unlikely to occur within the bounds of the geology of the Slaughter Canyon fan.

One may simulate karstic flow using either (1) an equivalent porous media approach or (2) a dual porosity approach. MODLFOW is limited to the former, equivalent porous media approach. This is probably not a significant limitation since MODFLOW has been successfully used for simulating flow through karst regions (Angelini and Dragoni, 1997). In the karstic areas of the model domain, only flow through the "quick" pathways (i.e. the dissolution channels) is represented. Since this is the majority of flow, an equivalent porous media approach remains valid. In any case, not enough data is available to construct a dual porosity model.

6.2 Model Construction

6.2.1 Model Domain

The mesh (figure 6.1) used for the simulations consists of 13 layers of 100 ft (30.5m) each. Each layer contains 81 columns and 56 rows at $^{1}/_{8}$ mile (201.2m) each. A datum was set at 2975 feet (906.8m) above sea level as the base of the model domain. This corresponds to 600 feet (183m) below the endpoint of the perennial stretch of the Black River, the lowest point in the study area.

An extended mesh (figure 6.2) was used to examine the area extending to the point where the southern model boundary contacts the Capitan Limestone near Double Canyon. This mesh was truncated for the remaining simulations because of a lack of data for this far western section and to aid in the speed of modeling. Since the equipotential lines are essentially perpendicular to the southern boundary at 460 m, this equipotential was used to truncate the model domain. The cells that contained the 460 m equipotential were replaced with equivalent constant head cells and the western-most 19 columns were removed. This new constant head boundary negates the need to model the western-most portion of the Black River valley where little data is available.

The hydraulic conductivity distribution used within the model domain is based on the proposed conceptual model of development of the upper Black River valley. Five hydraulic conductivity zones are used in the model (figure 6.1). Few zones were used since minimal information on the subsurface characteristics is available. A typical hydraulic distribution of decreasing conductivity away from the sediment sources (Rachocki, 1980) does not apply to this system. Increasing karstification away from the canyon sources creates a pattern of increasing conductivity away from the head of Slaughter Canyon. This is the basic pattern shown by increasing conductivity from zone 1 through zone 3 (table 6.1). The remaining two conductivity zones were added to aid in matching the water table. The hydraulic conductivity value used for zone 3 was based from measured values from the Carlsbad Caverns production well and the El Paso Natural Gas domestic water well (section 4.2.5). Other values used were based on literature values for the assumed media (table 6.2). All values used are in the hydraulic conductivity range for gravel or karst limestone. Values were refined for the numerical model by trial-and-error matching to observed heads for optimization.

Storativity and porosity values are modeled as constant throughout the mesh domain (table 6.1). Whereas some conductivity measurements have been taken on well tests, no storage values have been measured in the upper Black River valley. Values used in the numerical model were chosen from known ranges taken from literature and fitted by trial and error. Since flow is presumed dominantly in karstic channels, storage plays a very minor role in groundwater flow in the upper Black River valley.

Additional parameters are necessary for running MODFLOW. A variety of different numerical solutions to the governing equation are available. The preconditioned conjugate-gradient 2 (PGC2) method (Hill, 1990), was chosen since this solver monitors the residual, the sum difference in mass across cells, as well as variations in head. Additionally the layers within the model domain were defined as variable unconfined/confined which allows fluctuations in the water table surface and variable confining conditions within layers.

6.2.2 Initial and Boundary Conditions

Specification of both initial and boundary condition is required for solution of the governing equation. Initial conditions define the state of the aquifer at the start of the simulation and boundary conditions define the area outside the model domain. The initial condition selected was to have the aquifer fully saturated, all layers at 457.5 m potential, at the start of all simulations.

Boundary conditions are of two types, constant head or flux boundaries. Constant head boundaries define a set potential. Constant head boundaries were used to simulate the Black River and the up-gradient portion of the Black River valley (figure 6.1). The Black River was represented by allowing MODFLOW to calculate the gradient between the elevation of the "headward springs," 212 m above datum, and the elevation at the end portion of the perennial portion of the Black River, 184 m above datum. The Black River defines the base level of the system and is the main discharge zone. The constant head boundary used for the western portion of the model domain is justified from the larger model domain. This boundary simulates flow originating from the canyons closer to the Guadalupe Mountains.

The most common type of flux boundary is the no-flow boundary. No-flow boundaries are parallel to flow lines. This requires no-flow boundaries to be perpendicular to equipotentials. The model's southern boundary was defined as a no-flow boundary because it is parallel to the basic west-east flow direction. The area around the headwaters of the Black River presents an area of converging flow in the model domain that the southern no-flow boundary does not accurately represent. The use of a no-flow boundary in the southeastern portion of the model domain is not fully justified due to the converging flow to the "headward springs." No other option is feasible due to the geometry of the upper Black River valley. Extending the boundary south, to reduce this error, would require including all of the upper Black River valley into Texas, for which there is insufficient data. Also, a larger grid greatly increases computational time if resolution is to be maintained.

The contact of the alluvium aquifer with the surrounding Capitan and Castile Formations was represented as a no-flow boundary. Flow into the Castile Formation was assumed to be negligible due to its extremely low permeability. The Capitan Formation and aquifer are hydraulically removed from the alluvial system due the difference in elevation between the two systems (figure 2.1). The sloping fore-reef beds of the Capitan Limestone act as a geologic barrier allowing this separation of the aquifers. Some recharge was hypothesized to enter the alluvial aquifer along this contact from small perched aquifers and runoff from the fore-slope. Injection wells were added roughly every mile along the base of the Guadalupe Reef Escarpment to simulate these potential sources.

Additional stresses added to the system are wells, drains, and areal recharge. The main source of recharge to the system is through Slaughter Canyon that was simulated as an injection well. Recharge into the system cannot be provided solely by Slaughter Canyon and accurately reflect the observed water table without the additional reef-front wells. Eight large-capacity agricultural wells were also explicitly simulated in the model. Areal recharge is applied to the top active cell in each column across the model domain to represent gains from precipitation. In the sensitivity simulations, Rattlesnake

Springs was simulated as a pumping well to allow control of the discharge rate. During runs designed to examine the effect on discharge, Rattlesnake Springs were simulated as a drain calibrated to allow the same amount of discharge.

6.3 Calibration

Calibration of the model was performed by matching calculated heads to observed levels in 19 observation wells throughout the domain (figure 6.1). Observation wells were either domestic, stock, or agricultural wells. Water levels were provided by routine measurements from the New Mexico State Engineer's Office. Calibration included slight adjustments to the hydraulic conductivity distribution, based on the hypothesized fan development, to most accurately define the observed heads. Recharge rates for Slaughter Canyon were matched by trial and error based upon the conceptual model and water balance. Conductivity, specific storage, specific yield, and porosity were fitted by trial and error within ranges of values taken from literature. Areal recharge, agricultural withdrawals, spring discharge, constant head boundaries, and mesh geometry are based on measured values.

6.4 Base Model

Calibration of the model domain provided a steady-state base model that closely simulated the current flow regime in the studied region of the upper

Black River valley. This base model represented Slaughter Canyon as an injection well at +7300 m^3/day. Additional reef-front recharge through the 11 injection wells added +1760 m^3/day. Rattlesnake Springs was simulated as either a pumping well at -7908 m^3/day, based in 3.2 cfs average discharge from 1989-1997, or as a series of four drains arranged vertically at 51.25 m^2/day conductance that produce the equivalent discharge. Areal recharge was applied at 13mm/year. This rate corresponded to a 4% infiltration rate from an average 12.63 inches of precipitation per year. The base model was used to examine effects of changing stresses on the system and the potential impact on the water supply to Rattlesnake Springs and the surrounding area.

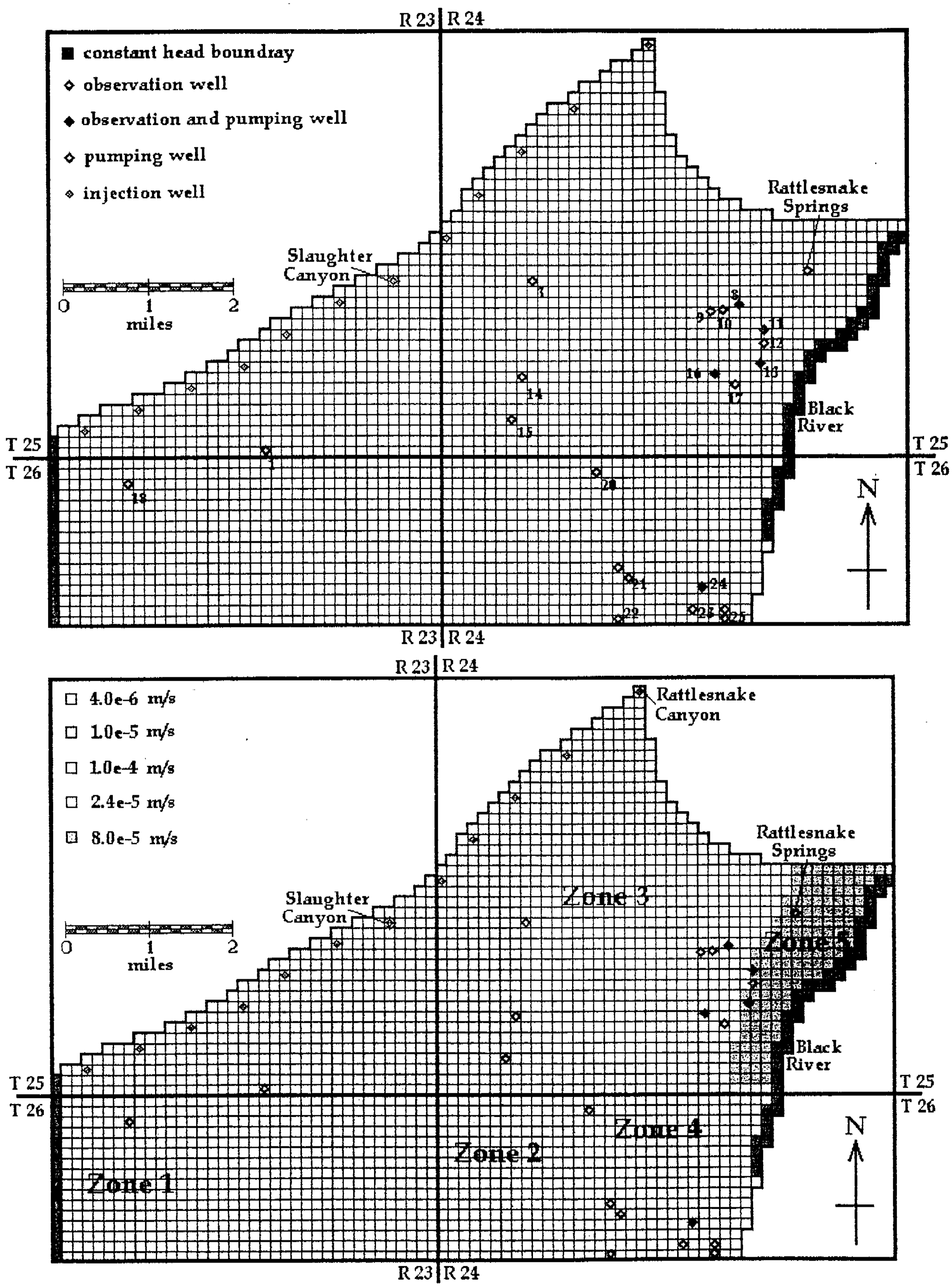


Figure 6.1: Grid system used for simulation of Rattlesnake Springs aquifer showing numbered observation wells, injection wells and conductivity zones.

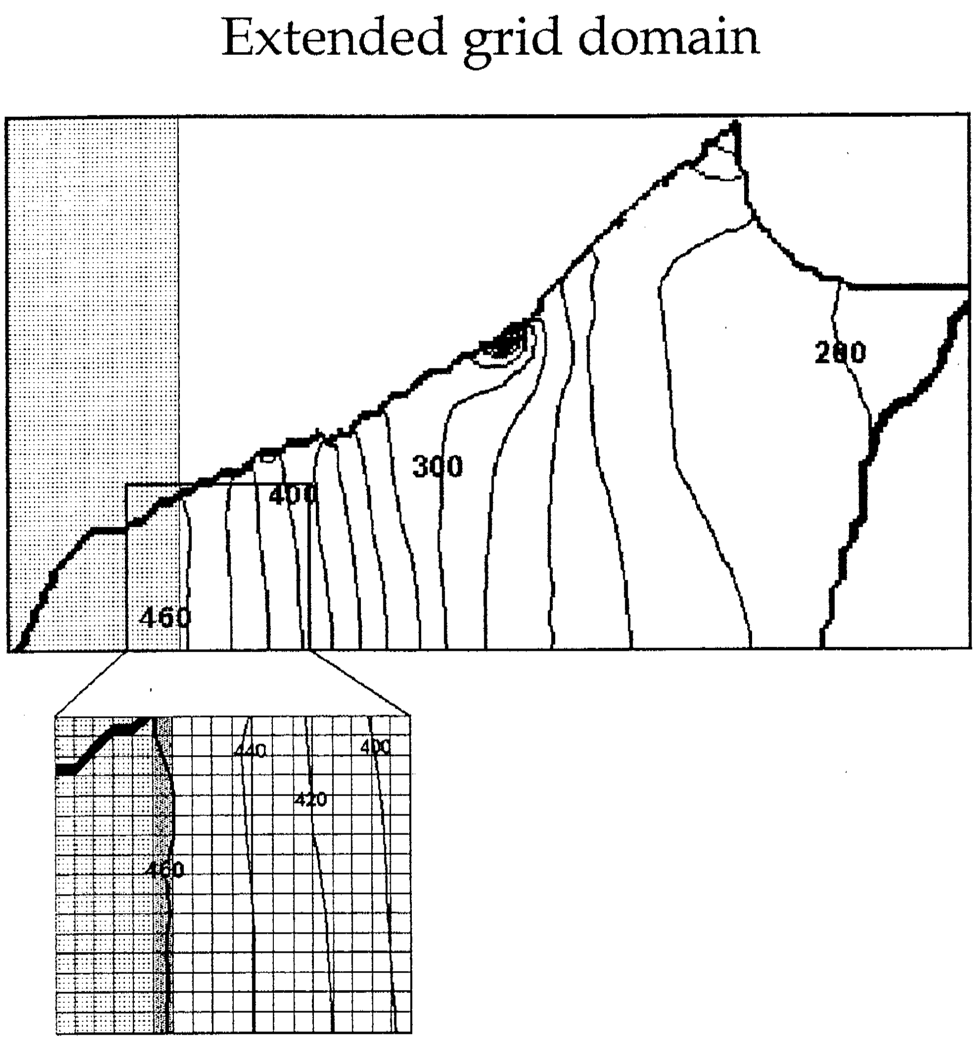


Figure 6.2: Extended grid domain used for location of the western boundary. Grid is 100 columns by 56 rows by 20 layers. The 460 contour is close to perpendicular to the southern boundary. Shaded cells are those removed for the remaining simulations. The darker shaded area indicates the 460 m constant head cells.

Zone	Hydraulic Conductivity	Specific Storage	Specific Yield	Effective Porosity	Total Porosity
1	4.0×10^{-6}	8.0×10^{-5}	0.0001	0.001	0.01
2	1.0×10^{-5}	8.0×10^{-5}	0.0001	0.001	0.01
3	1.0×10^{-4}	8.0×10^{-5}	0.0001	0.001	0.01
4	2.4×10^{-5}	8.0×10^{-5}	0.0001	0.001	0.01
5	8.0×10^{-5}	8.0×10^{-5}	0.0001	0.001	0.01

Table 6.1: Conductivity and storage values.

Hydraulic conductivity

Author	Media	Range of values
Domenico & Schwartz	karst and reef limestone gravel sand clay	$1x10^{-6}$ -- $2x10^{-2}$ m/sec $3x10^{-4}$ -- $3x10^{-2}$ m/sec $9x10^{-7}$ -- $5x10^{-4}$ m/sec $1x10^{-11}$ -- $2x10^{-9}$ m/sec
Ford and Williams*	fissured limestone karstic limestone	$6x10^{-2}$ -- 1.0 m^2/sec $2x10^{-3}$ -- 1.0 m^2/sec
White	karst limestone gravel sand shale	10^{-6} -- 10.0 m/sec 10^{-3} -- 10^{-1} m/sec 10^{-3} -- 10^{-2} m/sec 10^{-13} -- 10^{-9} m/sec

*Ford and Williams reported values as transmissivity not conductivity.

Specific yield

Author	Media	Range of values
Batu	limestone gravel sand clay	0 -- 0.36 % 0.13 -- 0.44 % 0.16 -- 0.46 % 0.01 -- 0.18 %

Specific storage

Author	Media	Range of values
Batu	rock fissured rock sound clay sand (loose)	$6.89x10^{-5}$ -- $3.28x10^{-6}$ less than $3.28x10^{-6}$ $2.03x10^{-3}$ -- $9.19x10^{-4}$ $1.02x10^{-3}$ -- $4.92x10^{-4}$
Ford and Williams	fissured limestone karstic limestone	2.4 -- 0.1 % 5 -- 1 %

Table 6.2: Range of values for hydraulic properties. Karst limestone was the base used for the numerical model. Gravel media also produces values in the same range as karst. Sand and clay values are also given for comparison.

7. Model Calibration

Sensitivity analyses were performed for all parameters used in the model domain. This was done to provide information on the limitations of the numerical model, to assess the behavior of the model, and achieve an understanding of the accuracy of the representation. Sensitivity simulations were performed by holding all properties constant from the base case except for varying the property in question. The effects on flow patterns and water levels in the observation wells were the criteria used for comparison. Properties were examined in either transient or steady state conditions. Details of all runs used for this report are listed separately in Appendix B.

7.1 Model Domain

The model domain encompasses the construction of the model grid and choice of MODFLOW options used for simulation of groundwater flow. Parameters considered are heterogeneous/homogenous, conductivity distribution, solver type, solver parameters, anisotropy, re-wetting, and layer type.

Variations in hydraulic conductivity, K, are necessary to match heads across the model domain. The initial attempt to model the aquifer utilized a homogeneous domain. These simulations produced direct flow from the western constant head boundary to the Black River boundary. All of the heads calculated in the observation wells were considerably higher than observed and the volumes moving through the system were unreasonably large. In order to match heads across the domain, lower conductivity was needed at the western boundary and near the reef-front. The hydraulic conductivity distribution used was based on the limited geologic data available from well logs in the upper Black River valley and on the knowledge of the formation of alluvial fans. Because of the paucity of data, as few hydraulic conductivity zones as possible were used for calibration of the model. Anisotropy is common in natural media. Because of the way in which the model domain was constructed and the distribution of hydraulic conductivity, anisotropy could not be added to the system. Vertical anisotropy prevents flow from going down the dip of the alluvial fan as it would in nature. Horizontal anisotropy could be applied within the Slaughter Canyon alluvial fan to simulate the flow control of the dissolution channels. This anisotropy was not applied since constraints on the paleo-channel distribution are not available. The orientation of the paleo-channel system is assumed to be west to east, but this has not been substantiated.

Solver parameters of the governing equation have a significant impact on the solution of the numerical model. The decision to use the PGC2 solver (Hill, 1990) resulted in no other solver producing convergence for the calibrated base case. The decision not to use the rewetting option also effects the outcome of the model. The rewetting option would most likely allow increased accuracy in transient simulations, though its instability prevented its use. MODFLOW allows designation of types of aquifers for each layer. The options are confined, unconfined, or variable. The designation of layer type also effects the solution of the governing equation. Since the geometry of the Slaughter Canyon alluvial fan is sloping, the variable option was employed. Simulations run with variations of layer type, variable or unconfined, and examination of the base model indicates that the solution of flow in the domain indicates that the aquifer supplying Rattlesnake Springs is mostly unconfined.

7.2 Initial Conditions

Initial and boundary conditions are required for the solution of the governing equation through time. Initial conditions describe the model domain at the start of the simulation. MODFLOW allows the specification of initial heads as either constant by layer or inputted for each cell through a set file type. Due to the design of the code, MODFLOW does not effectively rewet drained cells. For all sensitivity simulations run initial conditions were specified as constant for all layers at the default of 457.5 m.

7.3 Boundary Conditions

Boundary conditions were the main focus of the calibration portion of the modeling study. The model is highly sensitive to many of the factors that were unknown, most of which are boundary conditions.

The model was most sensitive to the rate of recharge from the Slaughter Canyon injection well (figure 7.1). The Slaughter Canyon drainage system through the associated alluvial fan is the main source of recharge supplying Rattlesnake Springs. The conceptual water balance for the system estimated a recharge rate of 3.63 cfs (8881 m^3/day). A slightly lower value of 7300 m^3/day provided the closest match to observed head levels in the system. This is balanced by a greater rate of recharge through the reef-front than conceptualized. The best-fit value of 160 m^3/day for the reef-front wells showed that the recharge provided by this is roughly a quarter of that from Slaughter Canyon. Increasing the recharge from Slaughter Canyon to compensate for the amount from slope wells did not allow as accurate a fit of the observed head distribution.

The model was also highly sensitive to the elevation specified for the western constant head boundary. This represents all flow from up-gradient in the system that should also vary with fluctuations in the precipitation. Wells which have been sampled numerous times in the model domain appear to only fluctuate $\pm$ 1m (Appendix C). This indicates that the choice of a constant head of

460 m for the western boundary was an acceptable choice, since normal fluctuations in the water table are slight. Variation of the western boundary to 440 m and below produced erroneous data (figure 7.1) since the nearest reef-front injection wells became inactive. This limited this boundary to a ±10 m variation in further simulations. Roughly 20% (table 7.1) of the recharge into the system was provided through the western constant head boundary. Flow from this source was not considered in the conceptual model. This impacts the Black River, not Rattlesnake Springs.

Areal recharge was affected by limitation in the MODFLOW code. MODFLOW applies recharge to the top-most active cell in the model domain or the top layer only. Due to the topography changes in the model domain, recharge is applied to the top-most active cell. MODFLOW also limits a variation in distribution of recharge to the top layer. Because of this limitation, additional areal recharge near the reef-front could not be simulated. This was compensated for by the slope injection wells. Additionally the volume of recharge added to the system varied during other sensitivity runs, though the rate was not changed. This may be a function of MODFLOW maintaining a mass balance or due to variation in the drainage of cells in the western portion of the model domain.

The other constant head boundary, the Black River, represents base level in the system. Since the model was constructed around this value, the model domain does not allow variation of this parameter. Decreasing the elevation of the constant head cells would drop the elevation of the river into the inactive cells below the river channel which MODFLOW does not allow. Variation of this parameter would require a modified mesh.

Rattlesnake Springs was modeled as a pumping well, for the sensitivity simulations, to allow a set discharge rate. The rate of discharge from the pumping well was limited to under -11,000 m^3/day (figure 7.2). This was not a factor for the remaining simulations since Rattlesnake Springs was modeled as a drain for the calibrated simulations. The removal of water at Rattlesnake Springs, by either a well or a drain, was one point of deviation of the model from nature. In the actual system, water from the springs is returned as throughflow to the Black River stream channel. This difference should only affect the model domain in the small area between the Springs and the Black River. Agricultural withdrawals have the least influence on the system of any boundary condition considered (figure 7.2).

7.4 Storage Properties

Sensitivity simulations for storage values were run with transient simulations because storage does not have an effect in steady-state simulations. Simulations were run with consistent values for seven time steps. Values used for comparison were those at the end of the 3650 day simulation. Storage has a small influence on the system. Of the storage terms, specific yield has a greater effect than specific storage (figure 7.3). This also shows that the majority of the system is behaving as an unconfined aquifer. Porosity, both total and effective, has no influence at all due to the way the solver handles the governing equation.

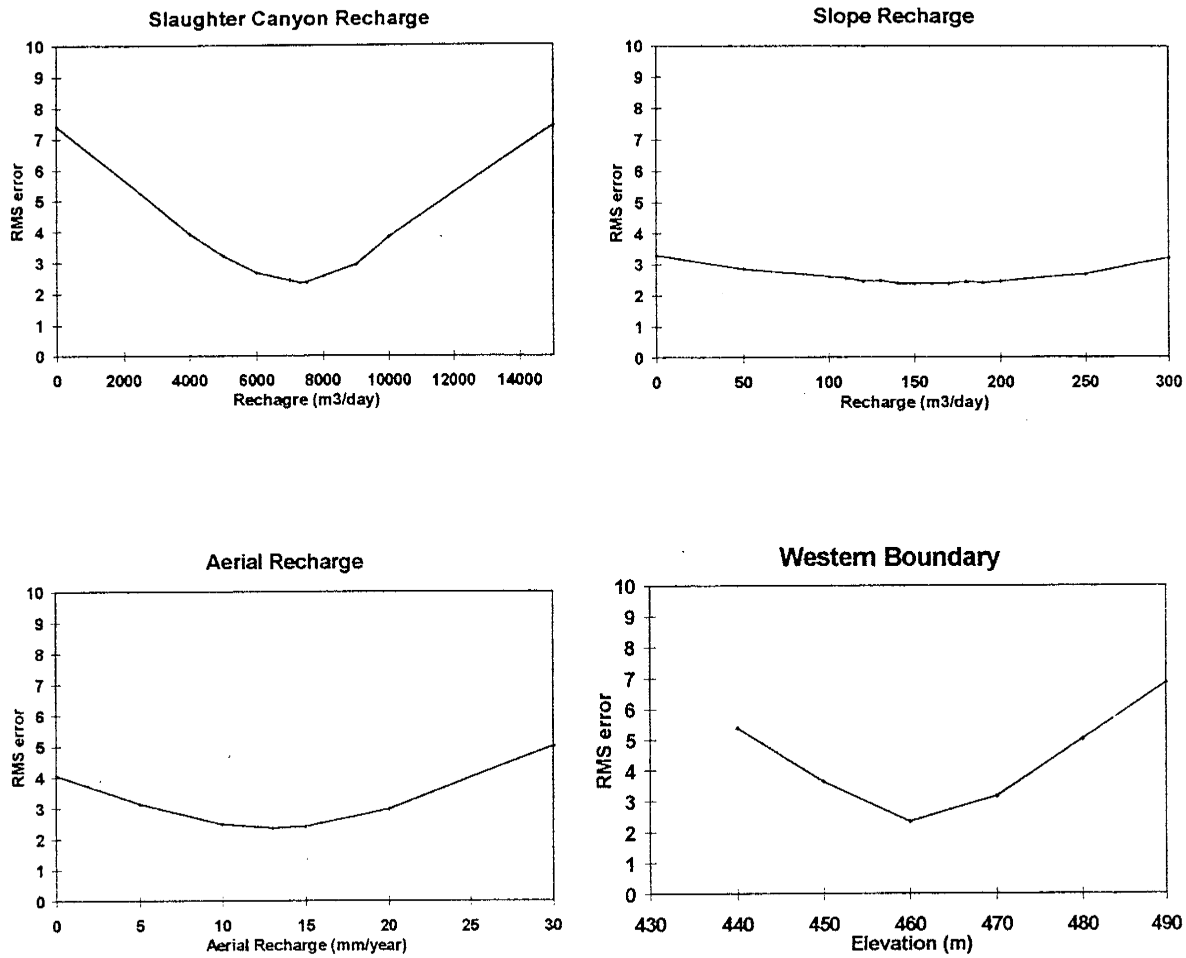


Figure 7.1: Sensitivity analyses for boundary conditions. Results for recharge sources within the model domain: Slaughter Canyon recharge, slope recharge, areal recharge, and the western constant head boundary.

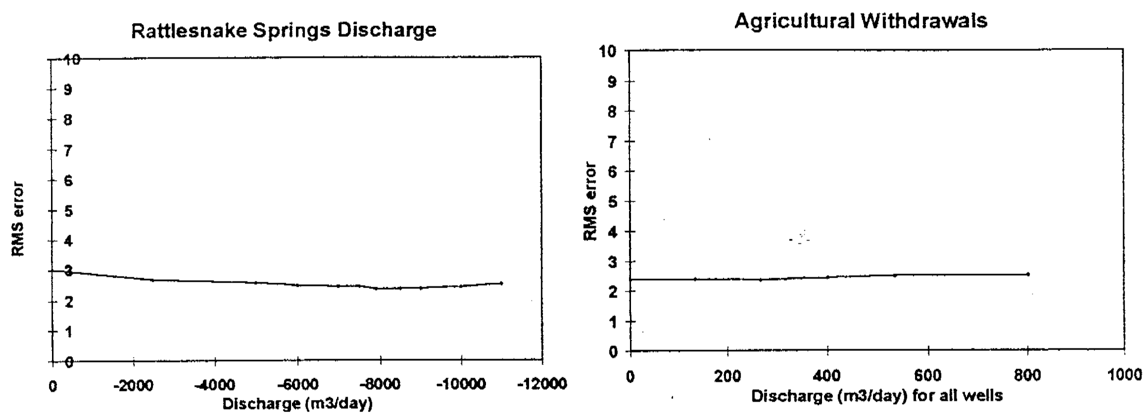


Figure 7.2: Sensitivity analyses for boundary conditions. Results for discharge parameters. Rattlesnake Springs is simulated as a pumping well for these results. Agricultural pumping rates are constant and the total is plotted.

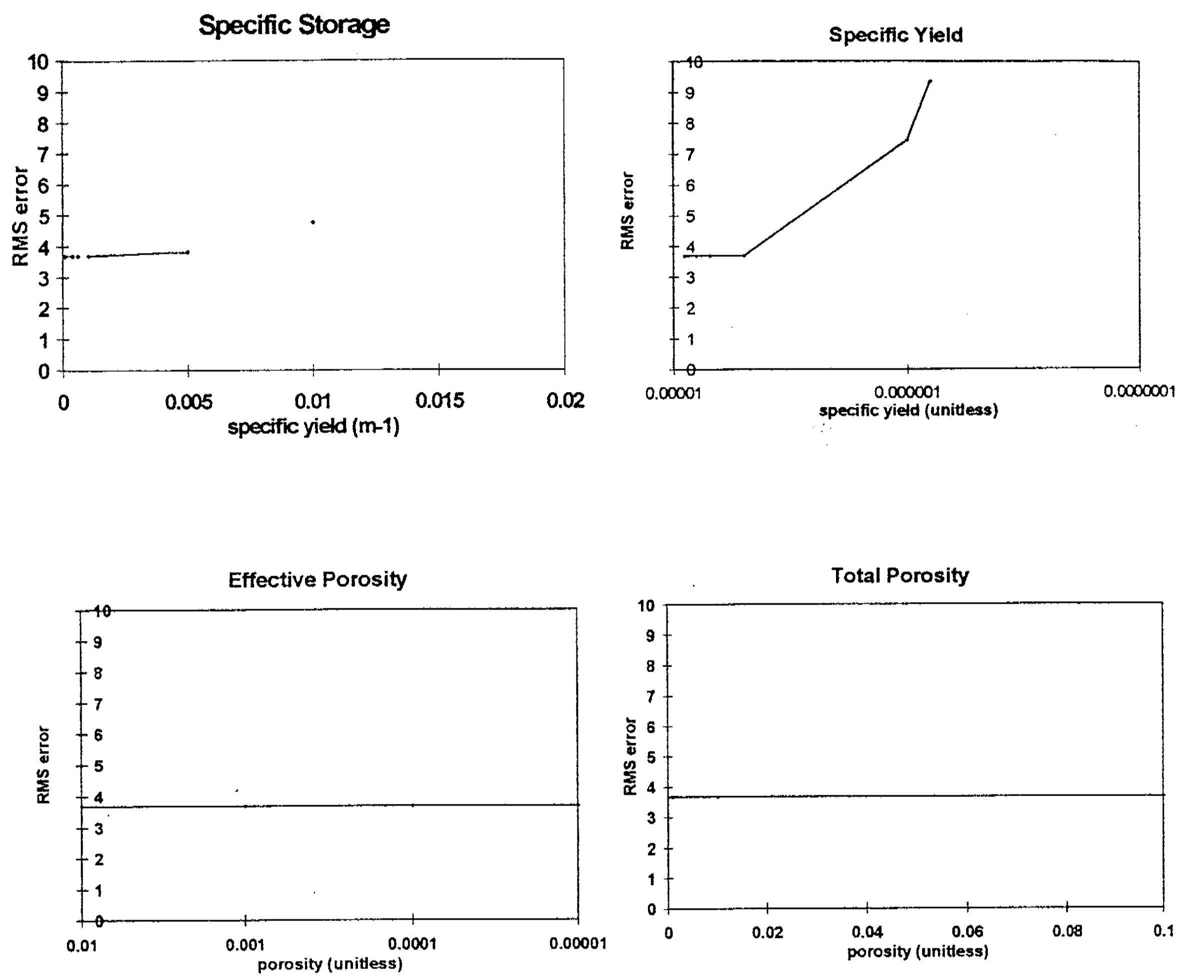


Figure 7.3: Sensitivity analyses for storage values. Note that porosity values have no effect on the system.

Volumes calculated from the steady-state base case.

<table>
<tr><td colspan="5">IN</td></tr>
<tr><td rowspan="2">constant head</td><td colspan="2">wells</td><td rowspan="2">recharge</td><td rowspan="2">total</td></tr>
<tr><td>S.C.</td><td>reef-front</td></tr>
<tr><td rowspan="2">3196.6
20.3%</td><td>7300
46.3%</td><td>1760
11.1%</td><td rowspan="2">3521.6
22.3%</td><td rowspan="2">15778.2
100%</td></tr>
<tr><td colspan="2">9060.0
57.4%</td></tr>
</table>

<table>
<tr><td colspan="5">OUT</td></tr>
<tr><td rowspan="2">constant head</td><td colspan="2">wells</td><td rowspan="2">recharge</td><td rowspan="2">total</td></tr>
<tr><td>RSS</td><td>ag.</td></tr>
<tr><td rowspan="2">7603.0
48.2%</td><td>7908
50.1%</td><td>267.3
1.7%</td><td rowspan="2">0.0
0.0%</td><td rowspan="2">15778.3
100%</td></tr>
<tr><td colspan="2">8175.3
51.8%</td></tr>
</table>

Table 7.1: Summary of the volumes in and out of the system for the steady-state base case.

8. Model Results

The base model provides a reference point for examining perturbations on the modeled system. This was done to estimate future effects on Rattlesnake Springs. The match of the numerical model to measured discharge of Rattlesnake Springs was examined. Fluctuations of the observation wells with an average seasonal input were also calculated. Additional scenarios such as increased agricultural withdrawals, declining recharge from up gradient, and declines in the Black River were explored. The capture zone for Rattlesnake Springs and the flow paths through the Washington Ranch facility were also examined to assess risks to contamination.

8.1 Climatic Affects

The greatest effect on Rattlesnake Springs is climatic variation. As seen during the 1950's drought, the levels of discharge can be significantly affected by severe decreases in annual precipitation. With the same correlation, the discharge from the Springs should be seen to increase with extended increases in precipitation. A long-term correlation with precipitation is not currently feasible due to the paucity of continuous records.

A simulation of 15 years duration, 1983-1997 was run and compared to the measured discharges of Rattlesnake Springs (figure 8.1). The measured precipitation from the nearest 6 rain gauges (Appendix B) was averaged by three month intervals to provide the precipitation input function. The measured discharges for 1985-1989 showed a strong deviation from the calculated discharges due to incorrect calibration of the flume system during this time period. Erroneous measurements are part of the data, but the fluctuations can still be used for correlation. An expanded set (figure 8.1) from October 1989 through March 1995 showed that there was a correlation between the numerical model and the measured data. The calculated values vary from the measured, in that the large fluctuations of the Springs were not matched. This was due to the three month time interval used which averages precipitation into seasonal values. The averaging eliminates the short-duration high-intensity nature of precipitation in the area and provided a constant recharge rate. The fluctuations of the Springs are often on a daily to weekly frequency, which cannot be tracked without equivalent precipitation data, that was not available. The annual high to low trend was mostly matched. I feel this indicates that the model can be used to estimate seasonal and longer variations.

The effect of seasonality in the Slaughter Canyon system was examined with the numerical model. This was done by using a seasonal step function to represent recharge through Slaughter Canyon. The recharge function was calculated based on monthly average precipitation at the Carlsbad Caverns rain gauge for the entire record (Appendix B). Figure 8.2 shows the response of the observation wells at the distal portion of the Slaughter Canyon alluvial fan was to have ±1 m variation in water levels seasonally. This corresponds to the 1-2 ft recorded fluctuations in wells in the Slaughter Canyon alluvial fan between 1952-1953. Measurements of wells near Rattlesnake Springs in this time period showed a higher variability.

The model also demonstrated that calculated water levels showed a similar variation to the recharge function but with a lag of roughly a season (figure 8.2). The highest recharge, 48%, occurred in the months July through September. The highest water levels occurred in the following months with the peak in November. The lower recharge months of October-March were reflected in the decreasing water levels reaching their minimum in the following August.

The seasonal fluctuations were also shown in the discharge at Rattlesnake Springs (figure 8.2). As shown, a variation of 114 m3/day existed between the low-flow of the mid summer and the high-flow of winter. This indicates that the observed variation in discharge is partly an effect of the seasonality of the recharge and not solely due to agricultural withdrawals in the summer months.

8.2 Withdrawals

The numerical model suggests that current agricultural withdrawals from the system have a minimal effect on the output of the Springs. The sensitivity simulations showed that the current agricultural withdrawals are insignificant when compared with the total volume of the system. In order to further examine future effects of agricultural practices, transient simulations were run with steadily increasing pumping rates from the two wells nearest Rattlesnake Springs (figure 8.3). Cox (1963) showed the almost immediate effect of reduced discharge from Rattlesnake Springs when the agricultural wells were pumping. By the water chemistry data only well #8 (figure 6.1) is within the flow path to Rattlesnake Springs. For 1995-1997, this well used an average 303 acre-feet per year, equivalent to 12% of the discharge of the Springs. Although the effects of agricultural pumping were seen at Rattlesnake Springs, the numerical model did not calculate a noticeable decrease in the cumulative volume discharged per year with increased pumping, until rates were increased drastically. An increase in pumping rate up to 2 orders of magnitude (figure 8.3) from the two nearest wells showed a decrease in the discharge at Rattlesnake Springs, but the greatest impact is to the Black River. This indicates that down-stream users, not Rattlesnake Springs, would feel the greatest effect of additional development in the upper Black River valley.

Future agricultural development in the upper Black River valley is unlikely because of New Mexico's current policies on water rights. For the Pecos River Basin, interstate compacts mandate that a set volume of water must flow through the Pecos River to Texas. In order to maintain this, the State's current policy in Eddy County is to buy and retire water rights. Additionally, it is shown here that further development will affect the water balance for down-stream users.

8.3 Constant Head Boundaries

Variation of the boundary conditions represents changes in the system outside the modeled area. Simulations of decreasing elevation in the western constant head boundary and the Black River boundary were run to estimate changes from both up-gradient and down-gradient.

A simulation of decreasing the elevation of the constant-head western boundary was performed to examine effects of changing conditions up-gradient. This simulation (figure 8.4) showed a similar influence on both the discharge of Rattlesnake Springs and a decrease in the discharge through the Black River, although there is a slightly greater effect on the Black River.

Decreasing the elevation of the Black River while maintaining the same gradient was performed to examine the effect of decreasing base level in the upper Black River valley. Due to the construction of the original grid, the model mesh had to be slightly modified at the distal portion of the Black River to allow the sinking of the stream. This produced a 1.3% change in the RMS (root mean squared) error of the system. The new mesh showed (figure 8.5) a 21.6% decrease in the discharge of Rattlesnake Springs with a 10 m drop in elevation of the Black River. Additionally, the decreases in discharge from Rattlesnake Springs appeared to be linearly correlated to the decrease of the Black River (figure 8.5). This demonstrated that changes to base level in the system will have a proportional effect on Rattlesnake Springs. A greater than 20m drop in elevation of the Black River will cause errors in the numerical model, represented by inactivation of agricultural wells nearest the river. This demonstrated that decreasing base level will also have a strong effect on the irrigators in the upper Black River valley.

8.4 Contaminants

The simulated capture zone of Rattlesnake Springs showed that all of the discharge of the Springs originated directly from Slaughter Canyon (figure 8.4) or from the reef-front. The flow emanating from Slaughter Canyon discharged mostly to Rattlesnake Springs although a portion bypassed to the south and discharged to the Black River (figure 8.5). None of the discharge of Rattlesnake Springs was shown to come from up-gradient in the Black River valley.

Particle tracking with MODPATH showed (figure 8.6) that even with no anisotropy in the system, a conservative case, the flow paths from the injection wells at Washington Ranch injection facility did not intersect flow to Rattlesnake Springs. This is corroborated by the absence of natural gas constituents from the recorded contamination at the Washington Ranch facility in routine monitoring of the springs. Groundwater contamination has been reported in varying degrees near the injection facility since 1984. Since no contamination has reached Rattlesnake Springs in this time period, I feel that groundwater flow is sufficiently separated by geological barriers and karst channels and by orientation of the hydraulic gradient, to prevent contamination from the facility from reaching Rattlesnake Springs. My examination of the area with a numerical model showed no set of conditions that would allow flow from the facility to the Rattlesnake Springs area.

The area does not lend itself to contaminant modeling since insufficient data was available. Additionally, contamination in karst systems does not behave in the gradually spreading plume of a typical porous media. In karst systems, contaminants converge towards a channel and move rapidly down gradient. The geometry of the karst conduits determines the shape and nature of the plume producing a distribution more analogous to surfacewater than groundwater (Quinlan and Ewers, 1985; in Domenico and Schwartz, 1990).

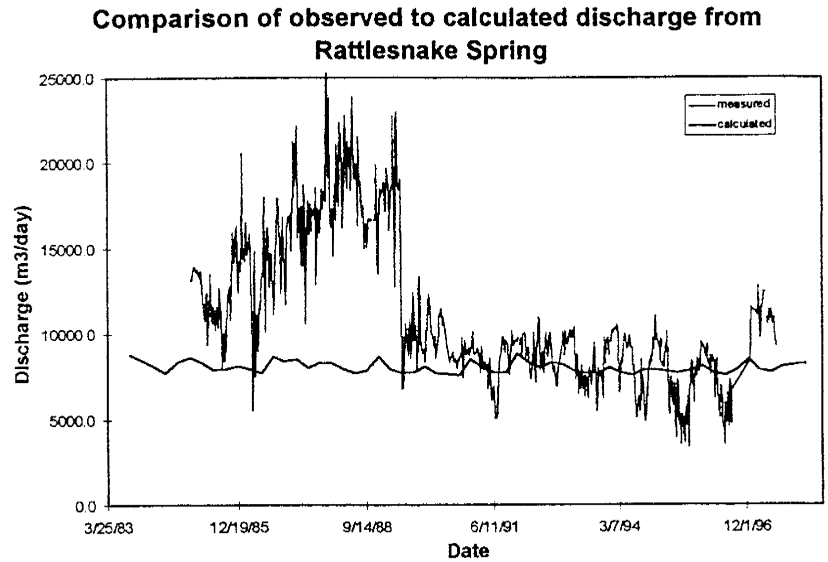
8.5 Groundwater Residence Time

The residence time of water through the system was calculated from the numerical model. The travel time predicted by the numerical model for the majority of flow from Slaughter Canyon to Rattlesnake Springs is 7-9 years. Deeper pathways of flow produced significantly longer residence times, up to ~50 years. The average travel time through the aquifer predicted by the numerical model was corroborated by the tritium measurements (section 4.2.2) and supports a young age for the water supplying Rattlesnake Springs. The rapid travel times through the aquifer support the assumption of karstic media. Additionally, the travel times imply that contamination up-gradient of Rattlesnake Springs would manifest rapidly.

8.6 Uncertainties

There are several layers of uncertainties inherent in modeling a hydrogeologic system. The numerical model is based on assumptions derived from the conceptual and geologic models of the system. This may seem circular, but using a numerical model to assess the validity of a conceptual model is an accepted procedure. The numerical model serves to provide information on the validity of the qualitative assumptions.

The following is a brief discussion of the uncertainties particular to the system studied. The actual structure of the alluvial fan is unknown together with the nature and distribution of the limestone conglomerate. Hydrogeologic uncertainties include the exact nature of the flow barriers, as expressed in the water chemistry. Also unclear was the nature of the geologic separation between the Capitan and alluvial aquifers. The contact of the alluvium with the Castile formation is also uncertain. The model treats this contact as no-flow, although if karst exists along this contact it would represent a conduit of flow not explicitly treated. This has the greatest impact on the northern section of the model, near Rattlesnake Canyon. Hydraulic parameters in the numerical model that are not substantiated by any other data include the storage parameters and recharge through the reef-front. The validity of the southern boundary is an additional uncertainty in the numerical model. Effects produced by evaporation losses and barometric fluctuations were not considered in the model.



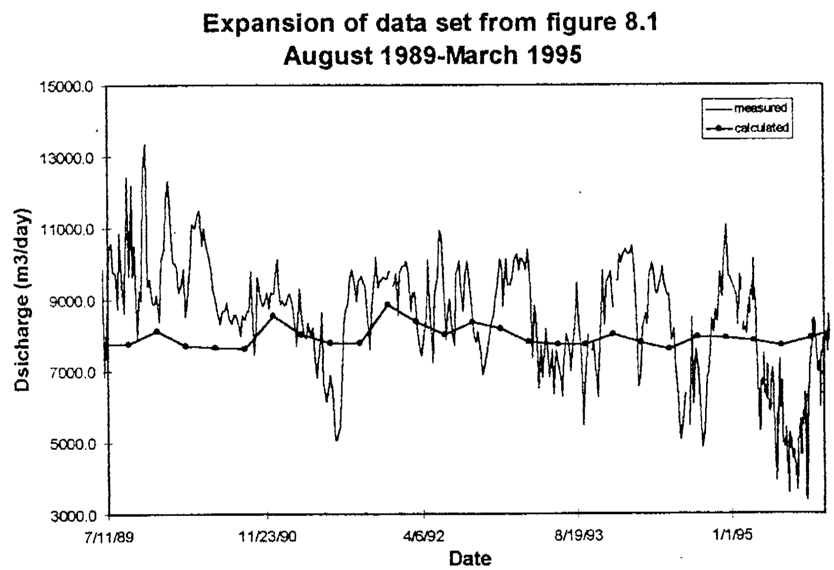
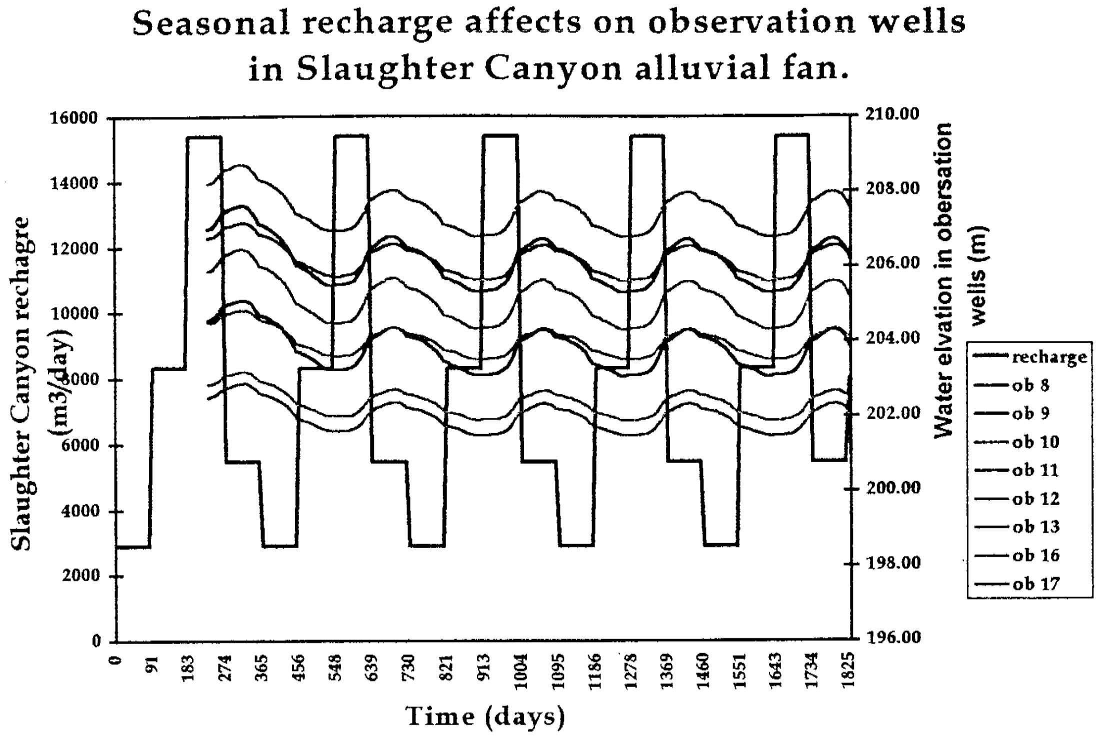


Figure 8.1: (top) Results of discharge values produced by using measured precipitation values input seasonally into the model against measured discharge values of Rattlesnake Springs. (bottom) Expansion of August 1989 – March 1995. Correlation between the measured and calculated discharges, calculated values are not able to track the large fluctuations of the measured data.



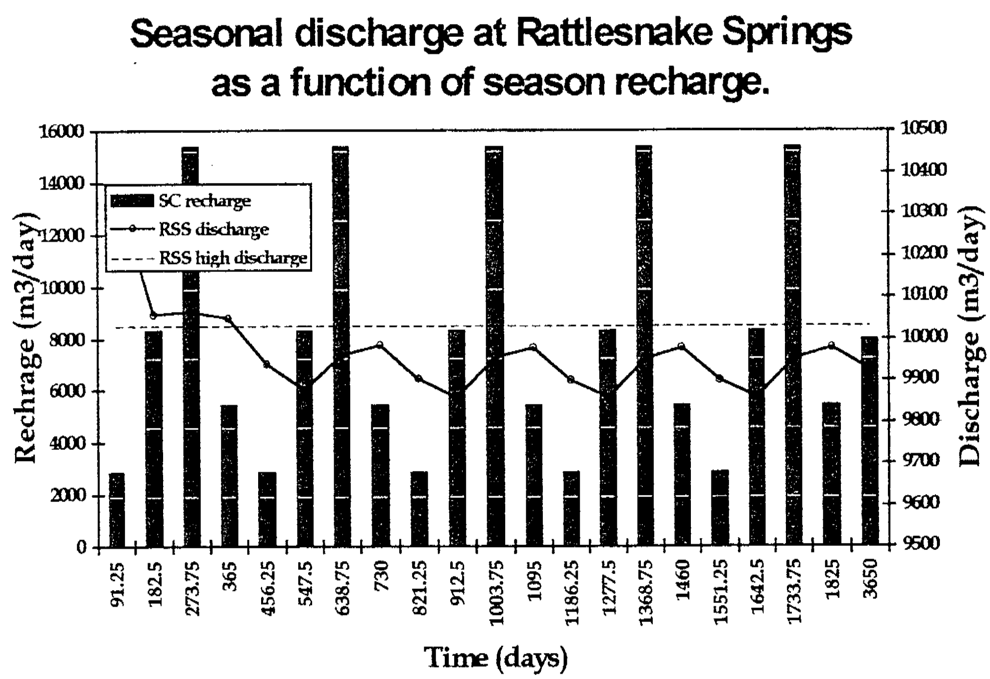


Figure 8.2: Simulated fluctuation in the observation wells at the distal portion of the Slaughter Canyon alluvial fan and Rattlesnake Springs due to an average seasonal input.

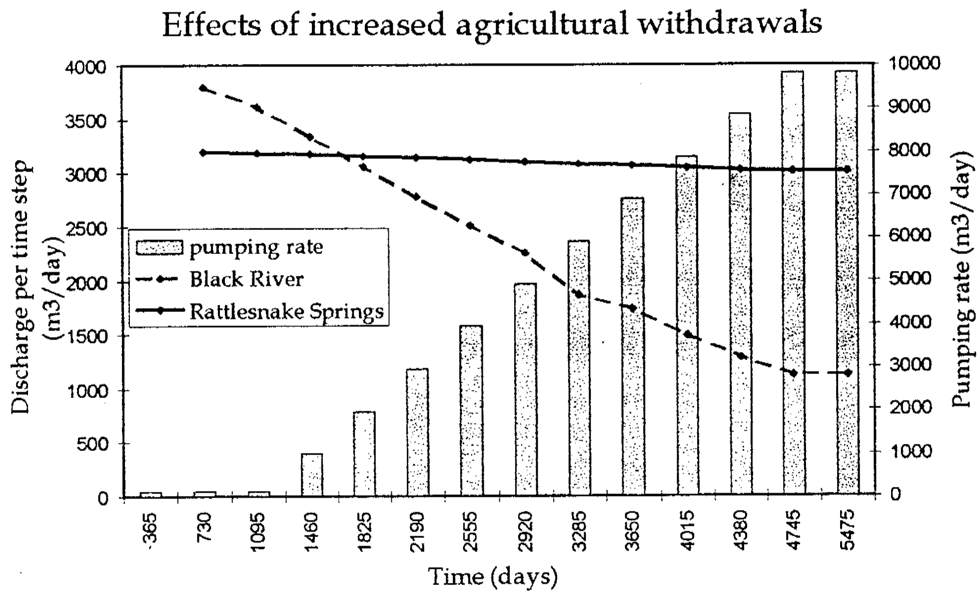


Figure 8.3: Effect of increased withdrawals from the two nearest agricultural wells #8 #11 to Rattlesnake Springs. The loss in volume to the Springs is slight whereas there is a greater loss in discharge of the Black River.

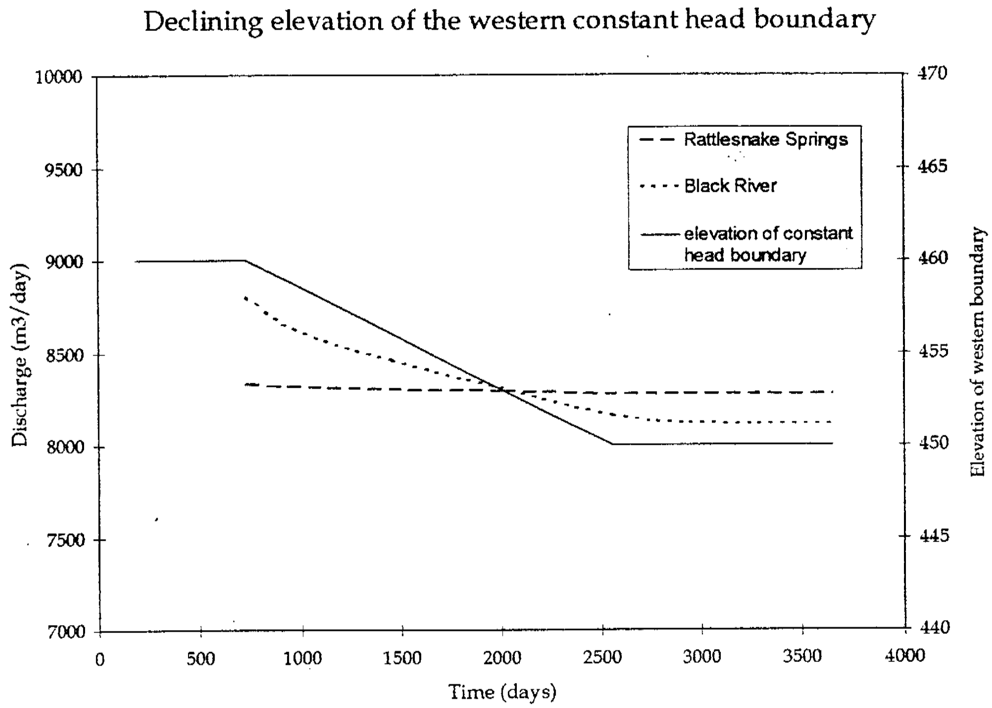


Figure 8.4: Declining elevation of the western constant head boundary to simulate decreasing recharge from up-gradient.

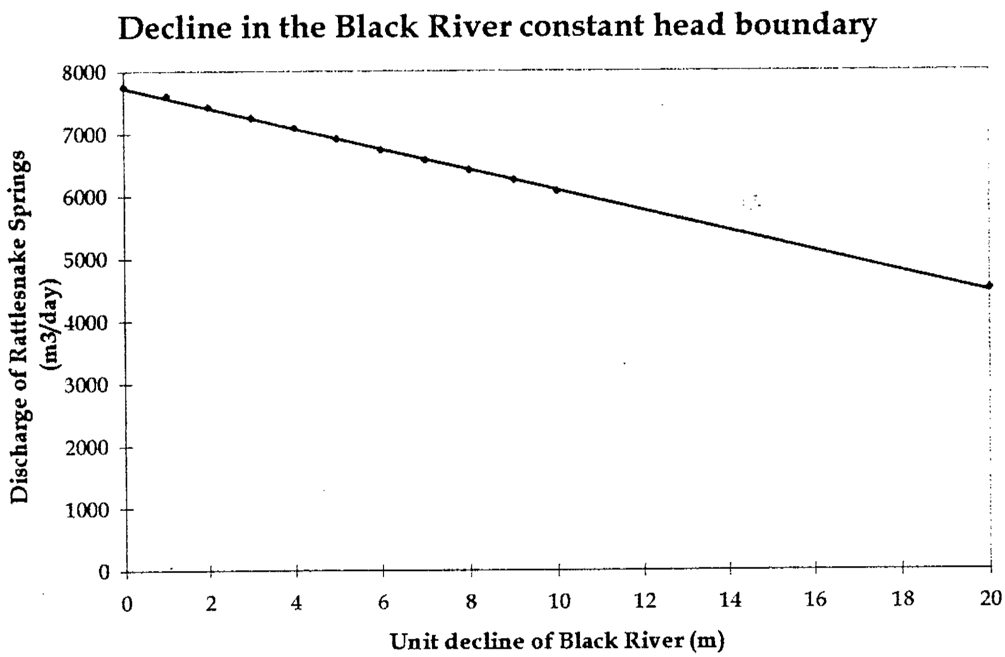
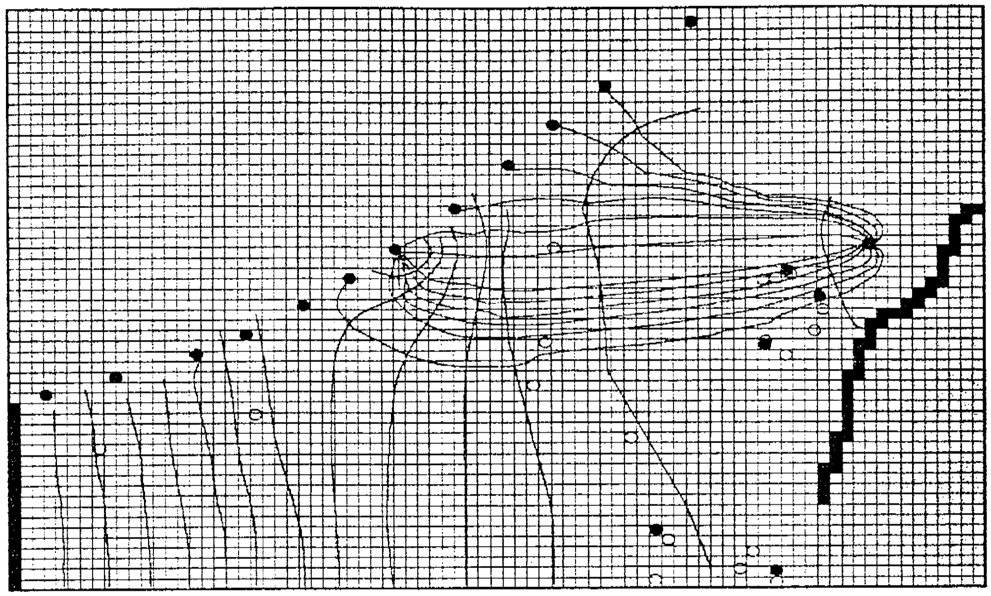


Figure 8.5: Decreasing elevation of the Black River to simulate declining base level in the model domain.

Capture Zone of Rattlesnake Springs



Capture Zone of the Black River

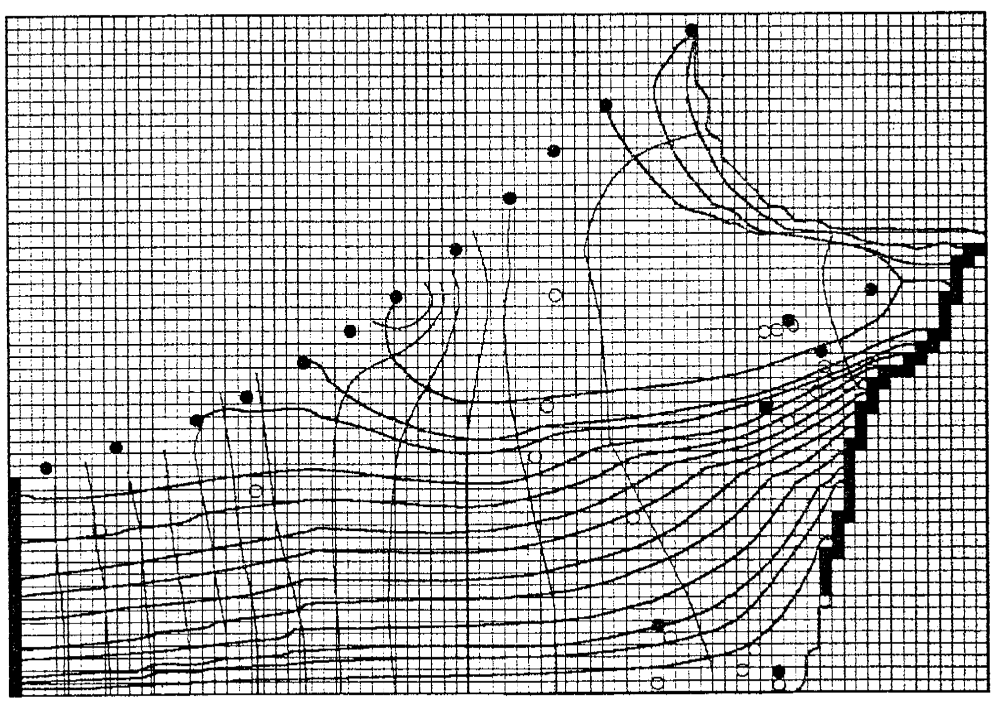
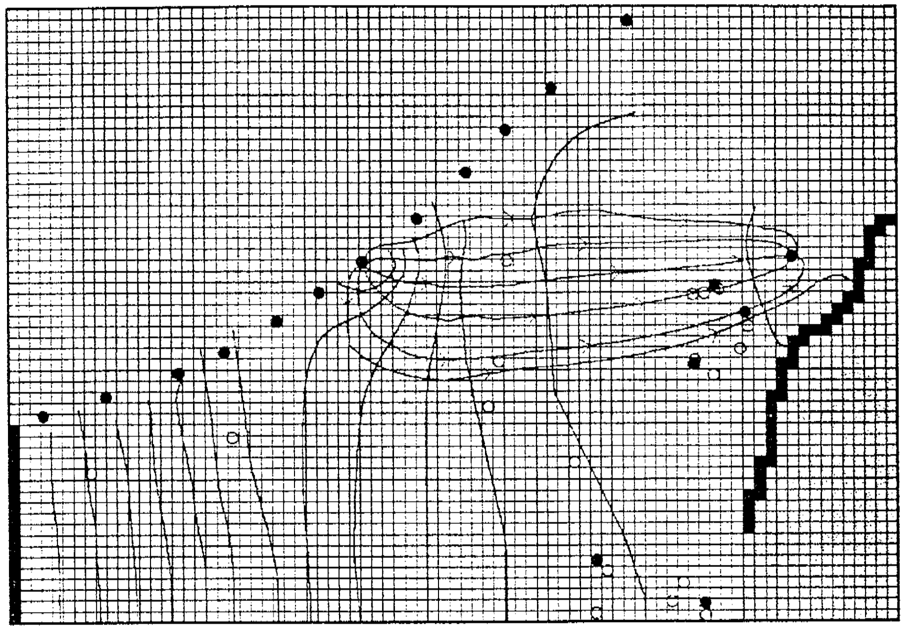


Figure 8.6: Capture zones of Rattlesnake Springs and the Black River.

Pathlines from Slaughter Canyon



Pathlines from slope wells

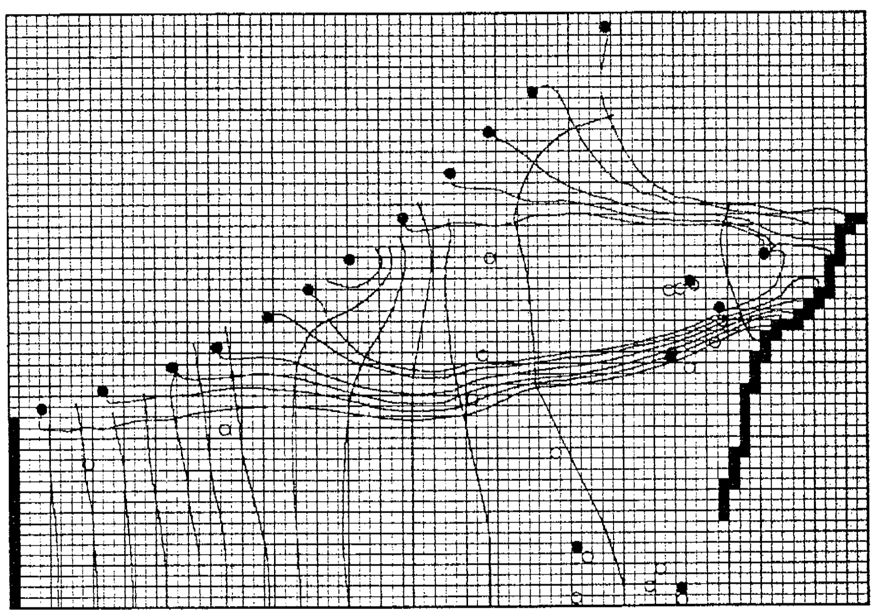


Figure 8.7: Flow paths from recharge sources, Slaughter Canyon, reef-front wells.

Area of flow from the Washington Ranch facility

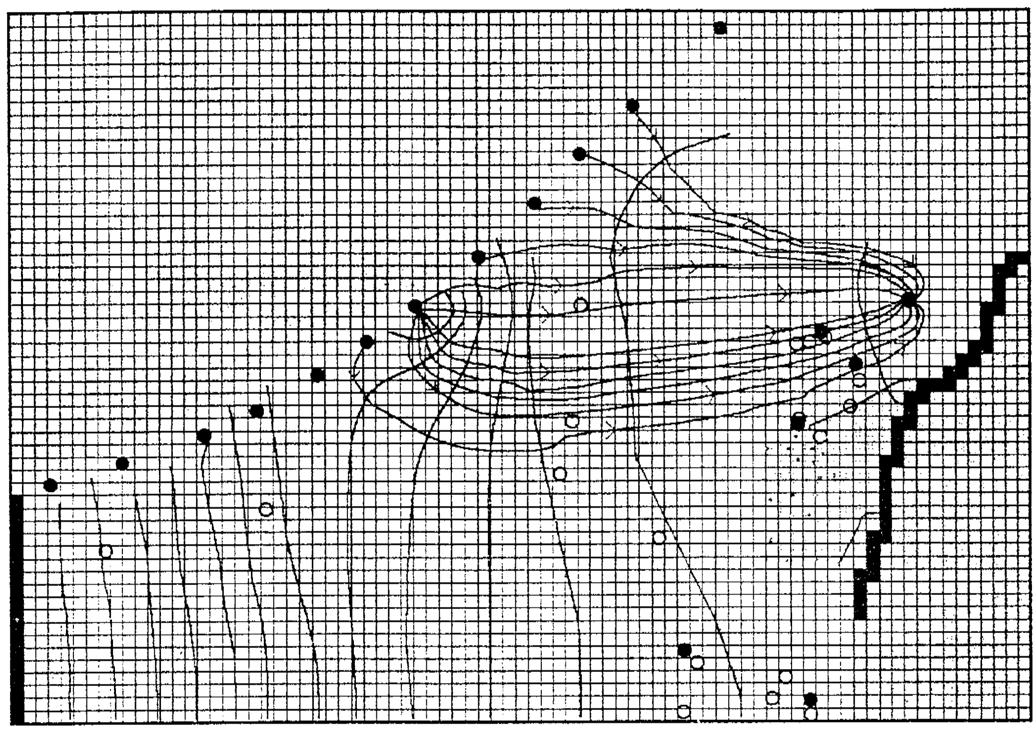


Figure 8.8: Particle tracking from the Washington Ranch injection facility.

9. Summary and Conclusions

The purpose of this study was to assess the aquifer supplying Rattlesnake Springs. This was performed by first analyzing the geology of the system. Considering the proposed geology of the system and the hydrologic information available, a conceptual model of flow through the system was developed. The conceptual model provided a basis for construction of a numerical model. The numerical model was employed to assess the validity of assumptions by providing a mathematical simulation that behaves as a close approximation to the actual system.

9.1 Conceptual and Numerical Model

The originally proposed conceptual model of the system was largely corroborated by the numerical model. Aspects of the system examined with the numerical model were the hydraulic conductivity values and distribution, the rates from recharge and discharge sources of the system, storage properties, and boundaries. The most significant difference was that a match in head levels across the system was best achieved by a lower rate in recharge through Slaughter Canyon and a greater rate through the reef-front. Additionally, flow from up-gradient in the Black River valley was not considered in the conceptual model. The numerical model demonstrated that a considerable portion of flow to the Black River derives from up-gradient sources. Not all of the components of the conceptual model could be tested with the numerical model. The geology of the system cannot be constrained without a geophysical survey or drilling program.

The numerical model developed to represent the Rattlesnake Springs system matches some of the seasonal variation observed. The numerical model was unable to match the high-magnitude, short-term fluctuations of the system. This is because short term events, like summer thunder storms, are lost during the averaging of monthly precipitation that was done to produce the model inputs.

The numerical model has internal limitations. All of the recharge sources have lower limits. With decreasing water levels in the system, reef-front wells on the western, higher-elevation, portion of the system deactivate when the water table drops below the wells screened interval. This causes additional loss of recharge since reef-front recharge is simulated with injection wells.

Specific concerns dealing with the aquifer of Rattlesnake Springs are the threat of contamination from the Washington Ranch facility and depletion from agricultural withdrawals. These concerns were discussed in detail in the following sections.

9.2 Rattlesnake Springs Discharge

The discharge from Rattlesnake Springs is controlled by annual precipitation. Fluctuations in annual precipitation are transmitted by the system and observed as seasonal variations in discharge. Flow through the system is fast, with the average residence time of 7-9 years from Slaughter Canyon to Rattlesnake Springs. This is corroborated by tritium measurements which show the age to be less than 15 years. Major climate variations, such as extended drought, will produce severe decreases in the discharge of the Springs, and in severe enough cases to potentially produce no flow. Even in such a case, the water supply to Carlsbad Caverns National Park's well should remain sufficient due to the well's location at the distal portion of the system. Wells located up-gradient in the upper Black River valley system will have a greater risk of depletion.

The current agricultural development within the upper Black River valley has been in effect for over 40 years and can be considered part of the current equilibrium. The current agricultural impact is minimal. Though pressure effects from agricultural pumping are felt almost instantaneously at Rattlesnake Springs, the decrease in the total volume discharged is slight. Modeled increases in agricultural withdrawals did not show a significant effect on the discharge of Rattlesnake Springs, although additional withdrawals directly from karst channels supplying the springs would have a direct effect on flow. Although the numerical model did not show agricultural withdrawals to have much effect on Rattlesnake Springs, the numerical model showed the elevation of the Black River has a strong effect on the discharge of Rattlesnake Springs.

9.3 Contamination

El Paso Natural Gas' Washington Ranch injection facility has produced reported contamination in portions of the upper Black River valley. Due to the water table and the geologic constraints within the area, contamination from Washington Ranch injection wells should not reach Rattlesnake Springs under the present conditions. Any potential future contamination is modeled to flow east to slightly north-east, discharging to the Black River. The model predicts that after reaching the losing portion of the Black River, the contamination should be contained within the alluvial channel of the Black River until it either naturally decays, is lost to evapotranspiration, or is added to the shallow karstic evaporite aquifer. No foreseeable occurrences should alter the flow regime in the upper Black River valley significantly enough to produce flow from El Paso Natural Gas' facility to Rattlesnake Springs.

9.4 Summary

Components of the conceptual model tested represent the actual system with two exceptions. The amount of recharge through the reef-front is greater than predicted with a corresponding lesser amount through Slaughter Canyon alluvial fan. Up-gradient sources produces a large portion of the flow to the Black River.

1) The numerical model produces results equivalent to the seasonal trend of measured discharge from Rattlesnake Springs.
2) Discharge from Rattlesnake Springs is controlled by annual precipitation.
3) Contamination from the Washington Ranch injection facility is unlikely to encounter Rattlesnake Springs under any condition examined.
4) Agricultural withdrawals have a minimal effect on Rattlesnake Springs at the current rate of pumping.

10. Assessment

10.1 Assessment

Rattlesnake Springs is most sensitivity to climatic influences. Variations in the yearly precipitation will either increase or decrease the amount of discharge. Although agricultural withdrawals decrease the volumes in the system slightly, the current use does not have a significant impact. Further development up-gradient in the upper Black River valley may pose a threat to the water quality and quantity. Because the system is dominated by karstic flow, contamination in the flow path to the Springs would arrive quickly and have an almost immediate effect.

Additional development within the upper Black River valley is unlikely. There are few economic resources available and additional water rights are unlikely to be granted by the state of New Mexico. If the State makes significant changes in the water policy, development could pose a threat.

Rattlesnake Springs is not currently at risk from contamination out of the Washington Ranch injection facility.

10.2 Maintenance

Maintenance of the Rattlesnake Springs area is vital to preservation of the riparian habitat this area provides, and for future monitoring and protection of CCNP water rights.

The flume system controlling the discharge from the Rattlesnake Springs pool plays a vital role in providing both discharge measurements and wildlife habitat. The concrete-lined channels have settled in a few sections within the Park land, producing areas prone to overflow from the channels if algae growth restricts flow. Restricted flow within the channel system produces false high readings in the Parshall flume, causing inaccuracies in measurements of the discharge. The effect of inadequate flume maintenance has previously been demonstrated, by the 50% error in flow measurement, before the flumes were re-calibrated at the beginning of 1989. For Carlsbad Caverns National Park to protect its water rights, accurate measurements must be maintained.

10.3 Further Work

A geophysical survey or a drilling program of the upper Black River valley, particularly the Slaughter Canyon alluvial fan, would aid in the characterization of groundwater flow in the area. Refraction and reflection seismic surveys are the most common, and most detailed type of shallow geophysical method available (Burger, 1992). These methods may be able to provide information on the depth to water in the upper Black River valley. Refraction and reflection will be unable to provide much information regarding the characteristics within the alluvial fan due to complications from the heterogeneity of the system because the majority of the material being dealt with is unconsolidated and dry. Additionally these types of surveys would be limited by funding since the depth of the alluvial fan would require a large source for generating the seismic wave.

Resistivity has been used at many sites to locate buried channels. Electrical resistivity in the shallow subsurface is controlled by the amount of water present and the salinity of the water (Burger, 1992). These two characteristics would be useful for locating karstic areas and delineating the chemical divide seen in the upper Black River valley. Limestone has a higher resistivity than clay and karst voids have an infinite resistivity (Burger, 1992). A resistivity study in the upper Back River valley would be complicated by the extreme heterogeneity of the system, but in the immediate area of Rattlesnake Springs several detailed well logs are available from the 1963 test drilling which are necessary for this type of survey.

Gravity surveys have also been used to map karst terranes. This type of survey is more complicated since it is extremely sensitive to changes in elevation and gravitational tides. Additionally, for the upper Black River valley, the densities of the materials being dealt with, limestone and clay, are very similar.

Gravity surveys are very powerful when combined with resistivity survey for mapping karst terranes (Burger, 1992).

References

Anderson, P. F., 1993, A manual of instructional problems for the U.S.G.S MODFLOW model. U.S. Environmental Protection Agency; Ada, OK., report EPA/600/R-93/010, 254 pp.

Angelini, P., and Dragoni, W., 1997, "The problem of modeling limestone springs: the case of Bagnara (north Apennines, Italy)" Ground Water vol. 35, no. 4., 612-618 pp.

Appelo, C. A. J. and Postma, D., 1994, Geochemistry, Groundwater and Pollution. A. A. Balkema; Rotterdam, Netherlands., 536 pp.

Batu, V., 1998, Aquifer Hydraulics: A Comprehensive guide to Hydrogeologic Data Analysis. John Wiley and Sons; New York., 727 pp.

Cheeseman, R. J., 1978, "Geology and oil/potash resources of Delaware Basin, Eddy and Lea Counties, New Mexico." Circular 159; New Mexico Bureau of Mines and Mineral Resources, Socorro., 88 pp.

Chugg, J. C., Andreson, G. W., King, D. L., and Jone, L. H., 1971, Soil Survey of Eddy Area, New Mexico. U.S. Soil Conservation Service., 153 pp.

Collinson, J. D., 1996, "Alluvial sediments." in Sedimentary Environments: Processes, Facies and Stratigraphy. Blackwell Science, Cambridge, MA., 688 pp.

Cox, E. R., 1963, "Effects of three irrigation wells on the flow of Rattlesnake Springs, Eddy County, New Mexico, February 1, 1962, to February 1, 1962." United States Department of the Interior; United States Geological Survey., 37 pp.

Domenico, P. A., and Schwartz, F. W., 1990, Physical and Chemical Hydrogeology. John Wiley and Sons, New York NY., 824 pp.

Ford, D. C., and Williams, P.W., 1989, Karst Geomorphology and Hydrology. Unwin Hyman, Boston MA., 601 pp.

Gross, G. W., Hoy, R. N., and Duffy, C. J., 1976, Application of environmental tritium in the measurement of recharge and aquifer parameters in a semi-arid limestone terrain. New Mexico Water Resources Research, New Mexico State University; Las Cruses, report 080., 212 pp.

References continued:

Hale, J. R., 1955, "Ground-water conditions in the vicinity of Rattlesnake Springs, Eddy County, New Mexico." State of New Mexico: State Engineer Office; prepared in cooperation with the Geological Survey and National Park Service, United States Department of the Interior, report 3., 54 pp.

Harbaugh, A. W. and McDonald, M. G., 1996, User's Documentation for MODLFOW-96, and update to the U.S. Geological Survey Modular Finite-Difference Ground-Water Flow Model. U.S. Geological Survey, Open -File Report 96-485; Reston, Virginia., 56 pp.

Hendrickson, G. E., and Jones, R. S., 1952, Geology and Groundwater Resources of Eddy County, New Mexico. New Mexico Bureau of Mines and Mineral Resources, Ground-water Report no. 3. New Mexico Institute of Mining and Technology, Socorro., 166 pp.

Hill, C. A., 1996, Geology of the Delaware Basin, Guadalupe, Apache, and Glass Mountains New Mexico and West Texas. Permian Basin Section - Society of Economic Paleontologists and Mineralogists, publication no. 96-39., 480 pp.

Hill, M. C., 1990, Preconditioned conjugate-gradient 2 (PCG2), a computer program for solving ground-water flow equations. U.S. Geological Survey, Water-Resources Investigation Report 90-4048; Denver, Colorado., 43 pp.

Hunter R. L., 1984, A Regional Water Balance for the Waste Isolation Pilot Plant (WIPP) Site and Surrounding Area. Sandia National Laboratories, Albuquerque, New Mexico., report SAND84-2233., 83 pp.

Leake, S. A., 1997, Modeling Ground-water Flow with MODFLOW and Related Programs. U.S. Geologic Survey, Fact Sheet: FS-121-97., 4 pp.

McDonald, M. G. and Harbaugh, A. W., 1984, A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model. U.S. Geological Survey, Open-File Report 83-875., 502 pp.

McDonald, M. G. and Harbaugh, A. W., 1988, Techniques of water-Resource Investigation of the Unites States Geological Survey: A Modular Three-Dimensional Finite Difference Ground-Water Flow Model. U.S. Geological Survey, Book 6 chapter A-1., 528 pp.

References continued:

Mercer, J. W., 1987, Compilation of Hydrologic Data from Drilling the Salado and Castile Formations Near the waste Isolation Pilot Plant (WIPP) Site in Southeastern New Mexico. Sandia National Laboratories, Albuquerque, New Mexico, report SAND 86-0954., 39 pp.

Meyers, R. F., 1966, Geology of Pennsylvanian and Wolfcampian Rocks in Southeast New Mexico. New Mexico Bureau of Mines and Mineral Resources, Socorro., Memoir 17., 123 pp.

Mourant, W. A. and Havens, J. S., 1964, "Rattlesnakes Springs test drilling, Eddy County, New Mexico." U.S. Geologic Survey. 17 pp.

Quinlan, J. F., and Ewers, R. O., 1985, Ground water flow in limestone terranes: Strategy, rationale and procedure for reliable efficient monitoring of ground water quality in Karst area. Fifth National Symposium and Exposition on Aquifer restoration and Ground Water Monitoring, Proceedings, Dublin, Ohio., 197-234 pp.

Rabinowitz, D. D., Gross, G. W., and Holmes, C. R., 1977, "Environmental tritium as a hydrometeorologic tool in the Roswell basin, New Mexico; I. Tritium input function and precipitation-recharge relation." Journal of Hydrology, vol. 32, 3-17 pp.

Rachocki, A., 1980, Alluvial Fans: An attempt at empirical approach. John Wiley and Sons, New York., 157 pp.

Richard, M., 1988a, "Natural gas contamination at Rattlesnakes Springs, Carlsbad Caverns National Park: review of the geohydrology in the vicinity of Rattlesnakes Springs and the contamination problem." report no. 1 of 4., Colorado State University., 27 pp.

Richard, M., 1988b, "Natural gas contamination at Rattlesnakes Springs, Carlsbad Caverns National Park: report of the first field investigation, August 1988." report no. 2 of 4., Colorado State University., 19 pp.

Richard, M., 1989a, "Natural gas contamination at Rattlesnakes Springs, Carlsbad Caverns National Park: report of the second field investigation, March 1989." report no. 3 of 4., Colorado State University., 18 pp.

References continued:

Richard, M., 1989b, "Natural gas contamination at Rattlesnakes Springs, Carlsbad Caverns National Park: final summary of the investigation." report no. 4 of 4., Colorado State University., 16 pp.

Ritter, D. F., Kochel, R. C., and Miller, J. R., 1995, Processes Geomorphology: Third Edition. Wm. C. Brown Publishers, Dubuque, IA., 546 pp.

Sares, S. W., 1984, Hydrologic and Geomorphic Development of a Low Relief Evaporite Karst Drainage Basin, Southeastern New Mexico. Masters Thesis, University of New Mexico, Las Cruces., 123 pp.

Tallman, R. S., 1993, Conceptualization and Characterization of the Hydrologic System in the Carlsbad Caverns National Park Region, New Mexico. Masters Thesis, Colorado School of Mines, Golden., 121 pp.

Viessman, W. J., and Lewis, G. L., 1996, Introduction to Hydrology; 4th Edition. Harper Collins College Publishers; New York., 760 pp.

White, W. B., 1988, Geomorphology and Hydrology of Karst Terrains. Oxford University Press, New York., 464 pp.

-------, 1960, Federal Supplement, volume 184. U.S. District Court D. New Mexico, Civil Case no. 4194., 14 pp.

-------, 1976, Water Resources Data for New Mexico. Water year 1976. U.S. Geological Survey Water-data report NM-76-1., 655 pp.

-------, 1978, Water Resources Data for New Mexico. Water year 1978. U.S. Geological Survey Water-data report NM-78-1., 677 pp.

-------, 1981, Water Resources Data for New Mexico. Water year 1981. U.S. Geological Survey Water-data report NM-81-1., 704 pp.

-------, 1984, Water Resources Data for New Mexico. Water year 1984. U.S. Geological Survey Water-data report NM-84-1., 485 pp.

-------, 1994, Water Resources Data for New Mexico. Water year 1994. U.S. Geological Survey Water-data report NM-94-1., 581 pp.

Appendix A

Literature Review

Table of Contents

Table of Contents 108
Figures & Tables 108
A) Literature Review 109
A-1) Early Development 109
A-2) The 50's Drought 111
A-3) NPS Development 112
A-4) Natural Gas Contamination 115
Washington Ranch Injection Facility 115
Contamination 116

Figures & Tables

Table A-1: Results of Rattlesnake Springs 1963 test drilling. 121
Table A-2: Variation in recorded water chemistry in two wells 2,400 feet apart in the Slaughter Canyon alluvial fan. 122
Table A-3: List of all the Washington Ranch Facility wells and dates of casing repair and plugging. 123
Table A-4: Results from liquid phase testing from bradenheads of wells #9 and #14 of the Washington Ranch Facility, 1991. Well #9 also had an organic drip phase present. 124
Table A-5: Gas phase composition of select wells from the Washington Ranch Facility, 1991. 125
Figure A-1: Location of near-by groundwater wells that effect the discharge of Rattlesnake Springs and location of the four wells drill by the National Park Service in 1963. Location of wells 25.24.27.124 and 25.24.27.421 that are 2,400 ft apart. 126
Figure A-2: Map-view location of all Washington Ranch Facility wells and outline of the storage area. Also shown are the groundwater wells sampled.127

A) Literature Review

Included in this section is a chronological summary of literature available on the Rattlesnake Springs area. The data has come from numerous sources and is included as a reference for future inquiries.

Several studies in the Rattlesnake Springs area have been performed since its initial development. Two main time periods of concern have occurred for the Springs, the first in the 1950-1960's when a drought caused decreased discharge and secondly in the 1980's when natural gas contamination was reported from El Paso Natural Gas' Washington Ranch Injection Facility in near-by groundwater wells.

A-1) Early Development

The upper Black River valley was first settled in the late 1800's. The initial water rights to Rattlesnake Springs were granted to Henry Harrison with a priority date of 1880 (Federal Supplement, 1960). This is the oldest water right in the upper Black River valley. A few early measurements of the discharge of the Springs were taken. In 1908 the earliest records of the discharge of Rattlesnake Springs were recorded at 4.23 cfs and 5.35 cfs. In 1923 the Springs were recorded as discharging at 4.72 cfs (Federal Supplement, 1960).

Carlsbad Caverns was first set aside as a national monument in 1923. Originally water for the Park was obtained from small springs within the Park's boundaries. The National Park Service acquired the 79.87 acres of land including Rattlesnake Springs in 1934 specifically for the water rights. This purchase included 105 acre feet of water rights from the Springs with the priority date of 1880. After the acquisition of the property the original seeps of Rattlesnake Springs where enclosed in the current developed pool and the concrete sump was constructed. A seven and a half mile pipeline was installed to provide water to the visitor's center atop the Guadalupe Reef Escarpment.

From 1942-1944, a Civilian Conservation Corps camp was located at Rattlesnake Springs. The CCC built many public works projects including development around Rattlesnake Springs. Many of the improvements to the Rattlesnake Springs area date from this time period such as the CCC manager's house which now houses NPS personnel at Rattlesnake Springs. The most notable development which has since been removed was construction of a series of duck ponds along the course of the natural discharge channel. These ponds were unable to hold water and abandoned between 1952-1954 (Federal Supplement, 1960).

A-2) The 50's Drought

The first published study of Rattlesnake Springs was conducted by the New Mexico State Engineer's Office in 1955. The report was initiated by the Park Service due to concern over a drop in discharge from the Rattlesnake Springs aquifer due to the 50% less than average rainfall from 1951-1953 that coincided with the installation of irrigation wells in the aquifer supplying Rattlesnake Springs. Hale (1955) stated that increases in irrigation could cause the springs to stop flowing towards the end of the irrigation season.

Partially based upon Hale's findings, the United States, on behalf of the Park Service, initiated a court case against several of the local irrigators to prevent the use of groundwater for agricultural irrigation in the upper Black River valley. The decision of June 14, 1960 was held that the evidence was insufficient to establish that great and irreparable damage would result to the United States at the present time, or in the foreseeable future as a result of the defendants' use of their wells.

The defendants in the case all irrigate with ground water provided by wells drilled before the area was included in the extension of the Carlsbad Underground Water Basin by the State Engineer of NM in October 21, 1952. No new permits for agricultural rights have been granted since this time. The Carlsbad Basin has been closed to further development except for wells drilled to supplement surface water rights. Due to the Pecos river legislation (reference) between New Mexico and Texas, it is unlikely that any new water rights be granted in the upper Black River valley.

A-3) NPS Development

The outcome of the District Court case mandated a one year study of the flow of Rattlesnake Springs. This results of this study prompted the National Park Service to install a production well for the acquisition of water for Carlsbad Caverns. The one year study of the flow of Rattlesnake Springs, 1961-1962, displayed that the measured flow of Rattlesnake Springs varied from 0.17-4.7 cfs from 1952 through 1961. Pumping from the two nearest agricultural wells, 25.24.27.124 and 25.24.27.421, at 1200 gpm directly affect the flow of the springs within 2 hours. Well 25.24.34.122a, that flows at 1200 gpm, is 1.7 miles southwest of the springs and has little effect (figure A.1). The park pumps 90 gpm from the pool which does not affect the flow of the springs or the groundwater levels (Cox, 1963). Water levels are generally highest in winter and lowest in summer. During the period of the study the highest water levels occurred in March, prior to pumping, and the lowest was in August. Day fluctuations appear to be caused by cyclic pumping of nearby irrigation wells. Minor fluctuations are caused by evapotranspiration and changes in the barometric pressure (Cox, 1963).

When irrigation wells south of the springs were pumped, the water level in the Rattlesnake Springs pool was sometimes insufficient for the Park's needs (Mourant and Havens, 1964). The Park Service decided to install a shallow well for supplementing their water rights, as suggested in the 1959 court case. Four test wells were drilled in 1963 in the near vicinity of Rattlesnake Springs with only one of the wells being able to produce the necessary 250 gallons per minute (table A1).

The drilling of the four wells provides some of the only data on the heterogeneity in the Rattlesnake Spring area (table A1). The yields from the wells varied from <10 gpm to ~1,000 gpm depending on whether the limestone conglomerate was encountered and the thickness of the unit. Additionally, the conductance varied from 620 mΩ to 802 mΩ. The variation in conductance possibly indicates discrete pathways of flow. Also, the lower values of conductivity, 620 and 661 mΩ, were from wells which had no significant flow from the limestone conglomerate.

Additional support for the idea of discrete channels in the Slaughter Canyon aquifer system are wells 25.24.27.124 and 25.24.27.421 (figure A.1). These wells have had simple water chemistry measurements (table A.2) since the early 1950's. These wells are only 2,400 feet apart and after extensive pumping large differences in water chemistry still exist. This either supports Hale's assumption of conglomerate stringers or shows that the dissolution channels are well defined and separated by relatively impervious material to produce isolated flow paths.

Additional indications of the aquifer heterogeneity supplying Rattlesnake Springs were shown by Cox (1963). Variations in the water conductance sampled and recorded at various points in the pool. This indicates that the seeps into the pools have different sources shown by the slight differences in conductance.

As part of the test drilling study, two pump tests were performed on the new production well for the Park (Mourant and Havens, 1964). The production well was pumped for five and a half hours on Aug 22 and for 24 hours on August 26-27, 1963. Fluctuations in the pool and observation well were recorded along with water levels and pumping rates at the well. Measurements where made by closing off one of the discharge channels and redirecting the discharge from the well through the Parshall flume. The pumping rate varied from 290-260 gpm (Mourant and Havens, 1964). Part of the observed drawdown may have been caused by pumping from irrigation wells for which no correction was made. Additionally, barometric changes and boundary effects may also of had and affect on the results. The specific capacity calculated for the first few minutes of drawdown was 1350 gpm per foot. The effective specific capacity was 540 gpm after 4 hours. The coefficient of transmissivity was determined graphically as 890,000 and 940,000 gallons per day per foot for the two test sets (Mourant and Havens, 1964).

A-4) Natural Gas Contamination

The second main time period of concern for Rattlesnake Springs was in response to natural gas contamination of groundwater in nearby groundwater wells. A natural gas field was developed in the upper Black River valley in the 1970s and exhausted by 1981. By 1984, 23 gas injection/withdrawal wells were in service from El Paso Natural Gas' Washington Ranch Gas Storage Project within two miles of Rattlesnake Springs. Rattlesnake Springs is approximately 1.25 miles from the EP gas injection field.

Washington Ranch Injection Facility

The El Paso Natural Gas Injection Facility, BLM lease 22207-NM, known as the Washington Ranch Facility, is located in township 25 south, range 24 east, section 34 & 33 (figure A.2). This area was first developed for natural gas extraction in 1971 by Cities Service Oil Co. (CitCo) from leases granted in 1963. In 1981 CitCo, Black River Corp., and Arapohoe Gas Limited granted El Paso Natural Gas all rights and leases to the Morrow formation (BLM lease 22207, 0456187, and 0525452-A). Lease 22207 was developed into the Washington Ranch Injection Facility by using 10 existing wells and drilling 18 new wells into the Morrow formation. Four of these wells are used as observation wells to ensure reservoir integrity.

The Bell Canyon Formation which underlies the Castile Formation is an oil producing unit. It was tilted a few degrees to the northeast during the uplift of the Guadeloupe mountains. This produced flow through the Castile formation and also produced hydrogen sulfide and carbon dioxide gases (Hill, 1997). The Morrow Canyon Formation which underlies the Bell Canyon at approximately 7,000 feet (2134 m) depth in the upper BR valley is the source of natural gas for the area and is the target of the injection facility.

Contamination

In 1982 Sprester and Ubribe reported bacteriological contamination of the Miller well sprinkler system with murky water and sulfide contamination. This resulted from back siphoning from a stock tank into the supply well. These authors suggested that this problem was widespread in the upper Black River valley. However, in a report by Dr. Richard of Colorado State University Department of Environmental Health, it is stated that this is most likely uncommon and that the reported coliform counts were not high values (Richard, 1988).

The first indications of possible natural gas contamination were noticed in 1982 by Mr. Collwell who claimed a slight "lemon" taste to the water and oil slicks on water wells. Mr. Ballard also first noticed problems in his two wells in 1982. This included tastes, odors, discolored (black) water, and significant corrosion to his irrigation wells and casing. Testing in 1984 reveled benzene contamination at 9 and 19 ppb. and the presence of polycyclic aromatic hydrocarbons which matched the gas being injected. John Ballard filed a case which was heard in 1989 (Richard). The case was reported to have been settled out of court.

Dr. Richard was requested by the National Park Service to conduct an investigation into the possible impacts of the reported contamination. In his 1987 field visit he observed extreme corrosion of the wells, black colored water, strong sulfide small, and black staining of bathroom fixture, concrete ditches, lack of aquatic growth in stock tanks filled with contaminated water. John Ballard reported that crops would not grow with the he contaminated water and that livestock would refuse to drink it. Possible contamination was observed in the Smart house located 0.8 miles north of the Ballard house in the summer of 1987. George Smart reported debris in his domestic well, a sulfide/petroleum odor, and nausea from bathing in it. Dr. Richard noticed a sulfide smell in the water. Smart also reported pump corrosion for the first time since installation in 1951. From visual observations during Dr. Richard's three trips to the Rattlesnake Springs area water contamination appeared to decline. This may be due to repairs of gas injection wells completed in 1984 (table A.3). To date no contaminates have been reported at Rattlesnake Springs and it appears that the contamination plume either by-passed the Springs to the south or was attenuated (Richard, 1989). "What is being observed may be the aftermath of a limited time natural gas leak to the upper Black River Valley alluvium aquifer." (Richard: report #3). Richard (1988) also reported the appearance of contamination at Blue Springs. Hale (1955) hypothesized that Blue Springs may be the terminal discharge point of the upper Black River aquifer.

Natural gas contamination was not shown in the CSU sampling for benzene, toluene, or xlyene levels above 1 (or 0.5) ppb. though the slightly lower pH, the presence of H_2S, and the low dissolved oxygen may be by-products of contamination. All of these signatures may also be caused by the release and oxidation of methane by microbes (Richard. 1989).

Due to the initial contamination around the Washington Ranch Facility, El Paso Natural Gas repaired most of the injection/withdrawal wells between 1982-1984 (table A.3). El Paso Natural Gas had reported problems with the casing of their injection wells which are believed to be the source of the early groundwater contamination (Richard, 1988). A letter from EPNG to the NMOCD in 1988 stated that reservoir integrity is maintained and tested by periodic testing casing pressures at each injection/withdrawal well. This letter stated that current contamination was likely a result of past practices and not of the current activities (Richard, 1988).

In the 1990's, the New Mexico Oil Conservation District (NMOCD) became involved in the reported contamination from the Washington Ranch

facility. The NMOCD requested bradenhead liquid and gas samples be taken from specified wells and a soil gas survey in 1991 (table A.4 and A.5). The soils survey only showed combustible levels of gas around well #9. The early 1990's survey prompted re-casing of most of the injection wells between 1991-1995 and the plugging of wells #2, 6, 8, 12, 18, and observation well #2 (table A.3).
In 1996 the NMOCD has required El Paso Natural Gas to perform a groundwater survey. No results were available at the time of review. Since 1991 both El Paso Natural Gas and NMOCD have agreed that there is natural gas contamination around the Washington Ranch Facility.

Other testing related to the contamination around the Washington Ranch Facility has been performed. In 1992 water analysis was performed on George Smart's private well (figure A.2) that showed no natural gas contamination but did show elevated levels of nitrogen which are indicative of septic, agricultural, or livestock contamination. A 1995 study performed by Dr. Goldberg, Extension Plant Pathologist of New Mexico State University showed that Smart's well was contaminated with an undetermined petroleum fraction. This test was for screening purposes and suggested further EPA approved sampling (cooperative extension service memo, 1995).

If natural gas contamination reached RSS the effects would be similar to those observed in the contaminated areas. Compounds of concern would be aromatic hydrocarbons and polycyclic aromatic hydrocarbons which have been shown to be carcinogens if consumed at low levels for extended time. The most significant effect would be from sulfide. Aesthetic and economic impacts would be the most noticeable. Tastes and odors would be offensive and corrosion of metal components of the water supply pipe line and pumping facilities could cause significant economic damage. The first signs of contamination would be sulfide smell at the Park's production well and the Springs. Also an increase in the amount of chlorine added to the Parks' water would be needed to maintain desired levels of free residual chlorine due to the reaction of sulfide with free chlorine. More extensive groundwater contamination would require additional water treatment and steps such as granular activated carbon filtration before chlorinating.

Well #	25.24.23.334	25.24.23.334c	25.24.23.334d	25.24.23.332
Location	160 ft south &430 ft west of RSS	40 ft S & 30 ft E of NE corner of RSS	230 ft S & 220 ft W of RSS	1,000 ft W-NW of RSS
Altitude	3,638	3,634	3,636.46	3,650
Total Depth	200 ft	200 ft	128 ft, plugged to 118	125 ft
Date Completed	July 1963	August 1963	August 1963	August 1963
Completion Record	Casing pulled and hole plugged with mud	Casing pulled and hole plugged with mud	Hole cemented from 128-118. Perforated liner 98-118.	Casing pulled and hole plugged with mud
Water Bearing Formation	< 10 gpm from sand & gravel &clay from 10-42 ft	~170 gpm from conglomerate 2-7 & 33-35 ft.	~1000 gpm from 92-94 & 102-118 ft. from conglomerate.	~10 gpm from seep at ~ 45 ft.
Log	0-42 soil, clay, gravel 42-200 buff plastic clay	0-7 ft clay & congl. 7-33 clay, minor gravel 33-35 conglomerate 35-200 clay	0-5 soil & clay 5-30 95% gray clay 5%sand &gravel 30-40 95% br. clay 5% sand & gravel 40-92 clay 92-94 congl. 94-102 clay & congl. 102-118 congl.	0-1 soil 1-10 gravel & congl. 10-66 90%brown clay 10%gravel 66-69 congl. (no water) 90-125 dr. gray clay
Chemistry	Sulfate: 115 ppm Chloride: 8.4 ppm Conduct.: 661 mΩ	Sulfate: 196 Chloride: 7.2 Conduct.: 802	Sulfate: 187 Chloride: 5.6 Conduct: 750	Conduct.: 620

Table A-1: Results of Rattlesnake Springs 1963 test drilling.

	Well 25.24.27.124		Well 25.24.27.421	
Date	ppm sulfate	conductance mΩ	ppm sulfate	conductance mΩ
Jun/Apr 1952	39	523	621	1380
July 1963	65	597	728	1590
July 1997	46	515	574	1370

Table A-2: Variation in recorded water chemistry in two wells 2,400 feet apart in the Slaughter Canyon alluvial fan.

Well #	Repaired (80's)	Repaired (90's)	Other
WI 1*	1/26/82	7/8/93	
WI 2*			plugged 10/23/93
WI 3*	1/26/82	3/28/91^	
WI 4*	1/26/82	3/25/92^	
WI 5*	5/26/72^	3/25/92^	
WI 6*			plugged 12/14/94
WI 7	7/13/84	10/23/95	added cement 4/5/94
WI 8			plugged 4/22/94
WI 9	7/13/84	8/17/93	noise log 12/13/91
WI 10	9/10/84	2/17/93^	
WI 11	9/10/84	8/8/94	
WI 12			plugged 6/30/94
WI 13	9/10/84	4/29/94	
WI 14	9/10/84	5/3/94	
WI 15			plugged 1/6/83
WI 16	7/13/84	6/3/94	
WI 17	4/24/84	-------	
WI 18			plugged 4/26/94
WI 19	7/19/84	2/17/93	
WI 20	9/10/84	-------	
WI 21	9/10/84	9/2/94	
WI 22	7/13/84	8/16/94	
WI 23	9/10/84	9/25/95	
WI 24	7/13/84	8/29/94	
OB 1		5/30/95	
OB 2		9/27/95	plugged 12/8/95
OB 3		1/8/95	
OB 4	---	---	---

*pre-existing wells
^inspect and cement

Table A-3: List of all the Washington Ranch Facility wells and dates of casing repair and plugging.

	Well #9		Well #14		Well #9 organic	
Cl (ppm)	11000		2100			
TDS (mmhos)	17330		4990			
pH	7.94		8.17			
		detection limit		detection limit		detection limit
Benzene	710	200	<1.0	1.0	330	200
Toluene	2400	200	4.8	1.0	4000	200
Ethyl Benzene	200	200	9.9	1.0	1500	200
Xylenes	3000	200	43.0	1.0	18000	200

Table A-4: Results from liquid phase testing from bradenheads of wells #9 and #14 of the Washington Ranch Facility, 1991. Well #9 also had an organic drip phase present.

Well #	1	6	7	9	14	16	19	22
He								
H_2S								
CO_2			0.02	0.35				
N_2	1.90	3.18	2.13	0.56	2.78	3.10	3.15	3.16
C_1	94.00	93.66	94.25	96.12	94.25	93.35	94.02	93.99
C_2	2.97	2.79	2.84	2.20	2.20	2.78	2.36	2.83
C_3	0.73	0.37	0.57	0.54	0.47	0.53	0.38	0.38
IC_4	0.12	trace	0.07	0.08	0.10	0.07	0.06	0.06
C4	0.19		0.12	0.15	0.11	0.17	0.03	0.03
IC_5	0.09		trace	trace	0.09	trace		
C_5	trace		trace	trace	trace	trace		
C_6	trace		trace	trace		trace		
C_7								
Total	100%	100%	100%	100%	100%	100%	100%	100%
S (ppm)	0.0	0.22	1.4	1000	0.77	0.6	0.2	1.45

Table A-5: Gas phase composition of select wells from the Washington Ranch Facility, 1991.

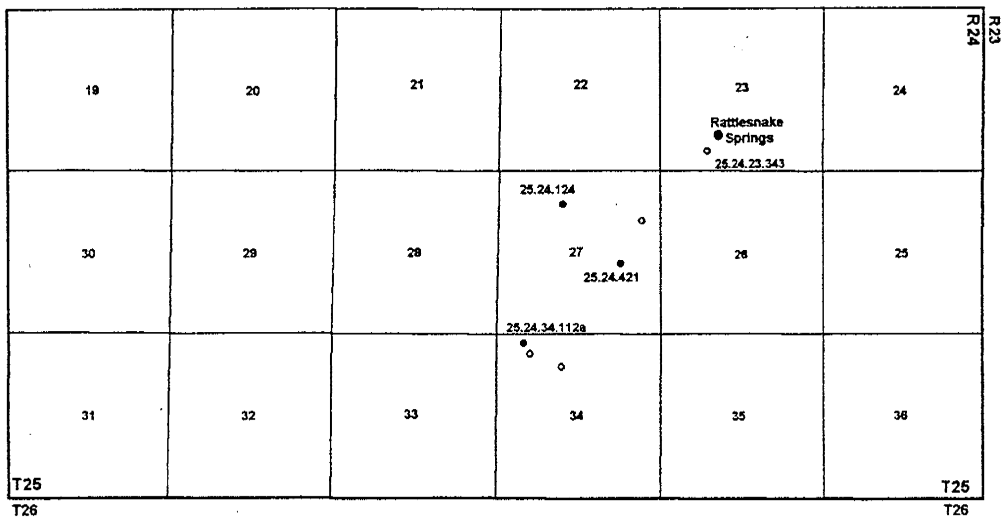


Figure A-1: Location of near-by groundwater wells that effect the discharge of Rattlesnake Springs and location of the four wells drill by the National Park Service in 1963. Location of wells 25.24.27.124 and 25.24.27.421 that are 2,400 ft apart (table A2).

Washington Ranch injection facility

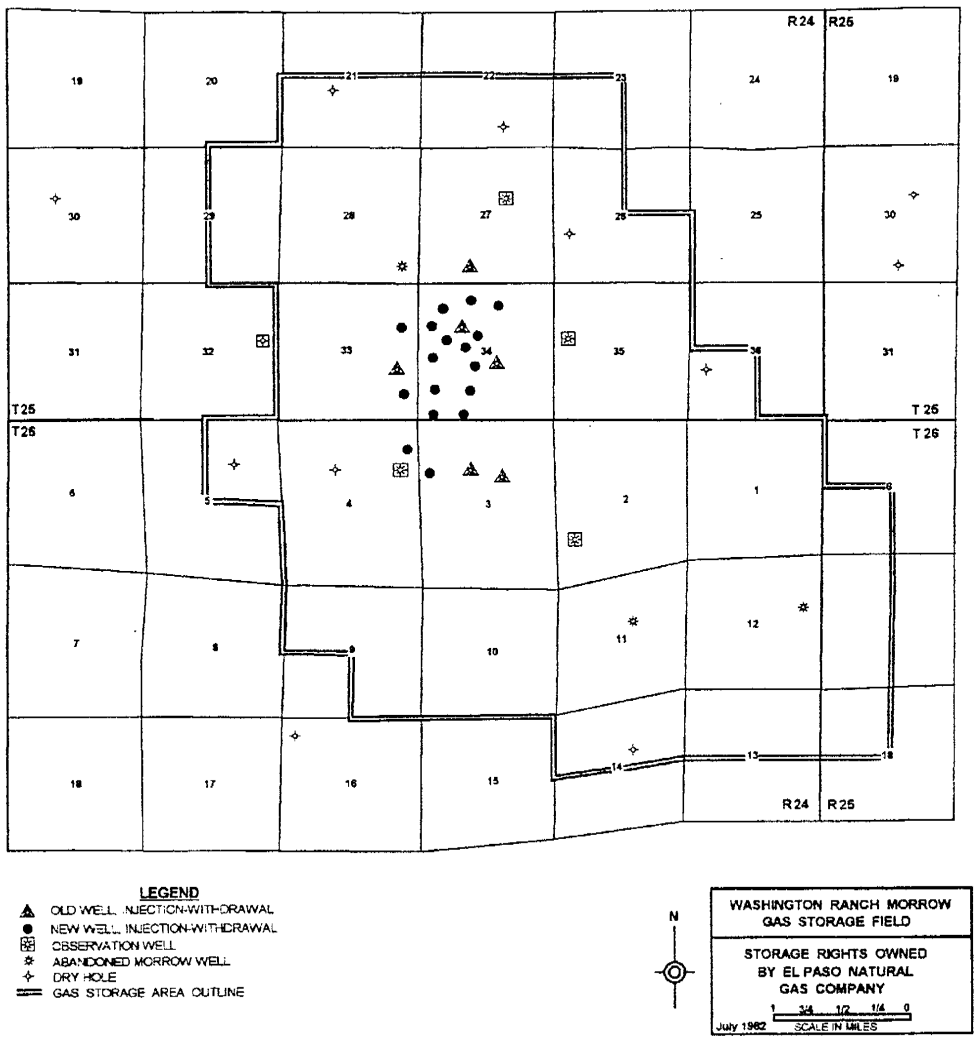


Figure A-2: Map-view location of all Washington Ranch Facility wells and outline of the storage area. Also shown are the groundwater wells sampled.

Appendix B

Details of model construction and sensitivity

Table of Contents

B) Model Runs 129
B-1) Model Domain 130
B-1.1) Homogeneous/Heterogeneous 130
B-1.2) Conductivity Distribution 131
B-1.3) Anisotropy 132
B-1.4) Solver type 133
B-1.5) Layer type 134
B-1.6) Re-wetting 135
B-2) Initial Conditions 136
B-3) Boundary Conditions 137
B-3.1) Slaughter Canyon 138
B-3.2) Slope Recharge 139
B-3.3) Areal Recharge 140
B-3.4) Western Boundary 141
B-3.5) Rattlesnake Springs 142
B-3.6) Agricultural Withdrawals 143
B-4) Storage 144
B-4.1) Specific Yield 145
B-4.2) Specific Storage 146
B-4.3) Porosity 147

B) Model Runs

The following are sections detailing all of the model runs used in this report. They are grouped by the following sections; model domain, initial conditions, boundary conditions, storage, and calibrated runs. Model domain defines the basic parameters used to define the study area. Initial and boundary conditions provide the sensitivity of the model to each of parameters needed for solution of the governing equations of groundwater flow. Storage defined the parameters needed for time dependent simulations. Calibrated runs are simulations based off of the calibrated base model used to explore the responses of the system to variations and similarity to measured data.

Shown within each sections are tabled values for each of the sensitivity analysis run used. Numbers in italic show erroneous values produced by limitation of the model. The center column outlined is the best match used for generation of the base model.

B-1) Model Domain

The model domain encompasses the construction of the model grid and options used for simulation of groundwater flow. Parameters considered are heterogeneous/homogenous, conductivity distribution, solver type, solver parameters, anisotropy, calibration, re-wetting, and layer type.

B-1.1) Homogeneous/Heterogeneous

Variations in hydraulic conductivity (K) are necessary to match heads across the model domain. A series of homogenous simulations were run. These simulations would produce direct flow from the western constant head boundary to the Black River boundary. All of the heads calculated were considerably higher than those observed. Increasing the conductivity produces a closer match to the observed head distribution, but the volumes moving through the system are unreasonably high.

Hyd. Conductivity	Error			IN (m^3)			OUT (m^3)		
	Mean	Mean absolute	RMS	const. head	wells	recharge	const. head	wells	recharge
.01	25.54	26.33	27.96	10930116	9060.0	3582.2	10934584	8175.3	0.0
.001	25.74	26.51	28.17	1091542	9060.0	3582.2	1096009	8175.3	0.0
.0001	27.55	28.22	30.17	107329	9060.0	3582.2	111796	8175.3	0.0
.00001	53.42	53.42	57.20	7907	9060.0	3595.1	20132	430.9	0.0
.000001	NC								

NC = non-convergence.

B-1.2) Conductivity Distribution

The hydraulic conductivity distribution is based on the limited geologic data available from well logs in the upper Black River valley and on the knowledge of the formation of alluvial fans. Because of the paucity of data, as few hydraulic conductivity zones were used as possible for calibration of the model. Zone 3 is the representation of the dissolutioned limestone conglomerate of the Slaughter Canyon alluvial fan. Figure 6.1 shows the lower conductivity zones 1 and 2 in the western portion of the grid and near the reef Escarpment. These two zones represent areas where finer material dominate or areas of newer carbonate deposit, where karst has not yet formed. Zone 4 is the area south of the Slaughter Canyon alluvial fan. This zone contains the area of converging flow to the head of the Black River. Additionally, the conductivity in zone 4 is lower then zone 3, since in following with the conceptual model this area has a diminished amount conglomerate present and more clay and silt. Zone 5 was added to aid in the modeling of the Black River. Because the conductivity within the conglomerate is so high, a lower conductivity zone was added around the river to prevent the fan from equilibrating to the level of the Black River. This also coincides with the conceptual model since at the very distal portion of the alluvial fan, fine sediment should again dominate. This matches with the idea of a hydraulic barrier at the location of Rattlesnake Springs producing the flowing artesian conditions seen. Lower conductivity in the northern portion of the model domain is assumed. This assumption is not significant since flow from this area of the mesh is minimal.

B-1.3) Anisotropy

Both vertical and horizontal anisotropy were examined in the system. Vertical anisotropy is common in geologic media due to layering during deposition. This produces preferential flow in the horizontal plain. Typical conductance in the vertical direction is one or two orders of magnitude lower than in the horizontal. Anisotropy in the horizontal plain is more difficult to characterize.

In the Slaughter Canyon alluvial fan, original deposition was in sloping beds, not horizontal beds. This makes defining vertical anisotropy difficult. Additionally the sloping hydraulic conductivity zones used to mimic the system do not allow implementation of vertical anisotropy since this forces flow within a conductivity zone in the horizontal plain instead of down dip.
Horizontal conductivity is most likely present in the Slaughter Canyon system due the paleo-channel system. There is no direct data on the distribution of the stringers of the system, hence no accurate controls on horizontal anisotropy can be made. Horizontal anisotropy can be assumed as the dominant direction of flow. Implementing this would just reduce the amount lateral dispersion. Since contaminant modeling was not done, this is not an issue and as shown, the addition of horizontal anisotropy in zone 3 does not significantly change the results of the model. Adding anisotropy to zones where there is significant flow that deviates from the basic west-east flow pattern does change the results significantly. This would not be justifiable anyway.

Vertical anisotropy (Order of magnitude)	Error			IN (m^3)			OUT (m^3)		
	Mean	Mean absolute	RMS	const. head	wells	recharge	const. head	wells	recharge
1	0.936	3.078	3.816	4619.4	9060.0	3556.2	9060.9	8175.3	0.0
2	0.814	2.940	3.689	4640.2	9060.0	3567.8	9093.2	8175.3	0.0

Values are decreases in the order of magnitude of the vertical component of hydraulic conductivity for all conductivity values used.

Horizontal anisotropy (Order of magnitude)	Error			IN (m^3)			OUT (m^3)		
	Mean	Mean absolute	RMS	const. head	wells	recharge	const. head	wells	recharge
1	0.936	3.078	3.816	4619.4	9060.0	3556.2	9060.9	8175.3	0.0
2	0.814	2.940	3.689	4640.2	9060.0	3567.8	9093.2	8175.3	0.0

B-1.4) Solver type

MODFLOW allows the choice of different solvers for the solution of the governing equation. The choice allows maximization of computing power and accuracy of solution. The preconditioned conjugate-gradient 2 (PGC2) method (Hill, 1990), was chosen since it calculates both the difference in head per each iteration but also the difference in residual. As seen in the sensitivity runs, since the model was calibrated with the PGC2 solver, none of the other solver provide convergence. In earlier preliminary model domains, the other solvers provided convergence, but with higher error.

Criterion	Error			IN (m^3)			OUT (m^3)		
Value used	Mean	Mean absolute	RMS	const. head	wells	recharge	const. head	wells	recharge
1	-0.339	1.851	2.358	3196.6	9060.0	3521.6	7603.0	8175.3	0.0
0.1	-0.339	1.851	2.358	3196.6	9060.0	3521.6	7604.8	8175.3	0.0
0.01	-0.339	1.851	2.358	3196.6	9060.0	3521.6	7603.0	8175.3	0.0
0.001	-0.333	1.852	2.359	3193.5	9060.0	3521.6	7616.5	8175.3	0.0

Convergence factor for both head change and residual for PGC2 solver.

Criterion	Error			IN (m^3)			OUT (m^3)		
Value used	Mean	Mean absolute	RMS	const. head	wells	recharge	const. head	wells	recharge
PGC2	-0.339	1.851	2.358	3196.6	9060.0	3521.6	7603.0	8175.3	0.0
SIP	NC								
SOR	NC								
WHS	NC								

Difference in solver type. SIP is strongly implicit method. SOR is slice successive over-relaxation method.

B-1.5) Layer type

MODFLOW allows designation of types of aquifers for each layer. The options are type 0, confined; type 1, unconfined; or variable unconfined/confined with either type 3, variable S (storage) and T (transmissivity), or type 2, variable S and constant T. The designation of layer type strongly effects how the governing equation is solved. Type 1, unconfined, is only allowed to be selected for the upper layer of the mesh. Due to this limitation, simulations were run with type 1 as the upper layer in the mesh and either type 0, 2, or 3 for the layers beneath to examine the effects. Type 2 did not produce convergence because of the conductivity distribution of the model. Since the conductivity zones in the mesh where made to slope with the geometry of the alluvial fan, conductivity zones cut across layers which is not compatible with type 2 designation. Type 3 was chosen for simulating the Rattlesnake Springs aquifer since the unit is a surfical alluvial aquifer with some confining conditions. Conceptually the upper portion of the aquifer is behaving as a water-table aquifer with flow within the dissolution channels acting under mostly confined conditions. Designation of the all layers in the mesh allows MODFLOW to vary between confined to unconfined conditions as necessary with the rising and lower of the water table.

Layer	Error			IN (m³)			OUT (m³)		
Type used	Mean	Mean absolute	RMS	const. head	wells	recharge	const. head	wells	recharge
type 0	-5.340	6.645	11.772	8092.2	9060.0	3608.1	2585.3	8175.3	0.0
type 2	NC								
type 3	-0.339	1.851	2.358	3196.6	9060.0	3521.6	7603.0	8175.3	0.0
type1/0	-6.627	7.684	14.275	7441.1	9060.0	3593.7	1919.9	8175.3	0.0
type1/2	NC								
type1/3	-0.186	1.953	2.432	3338.5	9060.0	3525.9	7749.3	8175.3	0.0

NC = non-convergence
type 0 confined
type 1 unconfined
type 2 confined/unconfined variable S constant T
type 3 confined/unconfined variable S & T

B-1.6) Re-wetting

MODFLOW allows a re-wetting option. Without this option, mesh cells that drain stay drained. Re-wetting is a new option in the MODFLOW-96 code and is not completely stable. Re-wetting is calculated with either a re-wetting factor or a threshold (difference in water level) value. Neither of these options appears to affect the out-come. The re-wetting code also allows re-wetting from cells to the bottom or from the bottom and sides. Under no conditions was I able to get the code to run with the later option. My simulations were first run with re-wetting, but the model became unstable in transient simulations with greater than five time steps. Because of this, the re-wetting option was not used. The main area affected by not using the re-wetting option are cells in the upper top three layers near the western boundary.

Re-wetting	Error			IN (m^3)			OUT (m^3)		
Option used	Mean	Mean absolute	RMS	const. head	wells	recharge	const. head	wells	recharge
no re-wet	-0.339	1.851	2.359	3196.6	9060.0	3521.6	7603.0	8175.3	0.0
factor-b	0.683	2.824	3.573	4588.5	9060.0	3521.6	8994.9	8175.3	0.0
threshold-b	0.683	2.824	3.573	4588.5	9060.0	3521.6	8994.9	8175.3	0.0
factor*	NC								
threshold*	NC								

NC = non-convergence. Factor-b and threshold-b were run with cells only being re-wetted from below. Factor* and threshold* were run with re-wetting from cells to the side and below. The default factor of 1 was used and threshold of 0.01 m.

B-2) Initial Conditions

Initial conditions and boundary conditions are required for the solution of the governing equations of groundwater flow through time. Initial conditions describe the model domain at the time of the start of the simulation. MODFLOW allows the specification of initial heads either constant by layer or inputted for each cell through a set file type. Both of these options where explored to optimize the model. Ideally the numeric model should converge to the same solution independent of the initial conditions given, though this is not the case. Due to the design of the code, MODFLOW does not effectively re-wet drained cells. Though the capacity to re-wet drained cells has been added, MODFLOW still drains cells more easily than re-wetting. Based on this, initial conditions which provide an initially completely saturated system provide the most efficient results.

For all sensitivity simulations run initial conditions were specified as constant for all layers at the default of 457.5 m. This provides initial saturated conditions. For all the transient simulations run, the head distribution was used for the initial conditions.

Initial Head used	Error			IN (m^3)			OUT (m^3)		
	Mean	Mean absolute	RMS	const. head	wells	recharge	const. head	wells	recharge
460	-0.351	1.848	2.358	3182.0	9060.0	3520.2	7587.0	8175.3	0.0
457.5	-0.339	1.851	2.359	3196.6	9060.0	3521.6	7603.0	8175.3	0.0
400	-0.389	1.9135	2.430	3051.5	9060.0	3510.1	7446.5	8175.3	0.0
300	-7.069	7.289	13.65	954.7	8420.0	3143.9	4343.3	8175.3	0.0
200	-11.480	11.480	13.29	6041.1	480.0	2594.7	940.7	8175.3	0.0
100	NC								
base heads	-0.342	1.849	2.357	3197.3	9060.0	3523.1	7605.2	8175.3	0.0

B-3) Boundary Conditions

Boundary conditions are required along with initial conditions for the solution of the governing equations of groundwater flow. Boundary conditions serve to define the system outside the region of interest. These consist of constant head boundaries and flux boundaries. At a constant head boundary the water potential is set and flow must be right angles to the boundary. The implementation of constant head boundaries in MODFLOW allows water to flow from or into a constant head cell allowing recharge or discharge from the system. The other type of boundary is where a flux is specified. The most common type of flux boundary is the no-flow boundary which defines a zero flux. At a no-flow boundary the boundary must be colinear with the lines of flow and perpendicular to equipotentials. No-flow boundaries are implemented in MODFLOW at the edges of the domain that are not otherwise constrained. Additionally contacts with inactive cells are no-flow boundaries unless otherwise specified. Constant flux boundaries are not easily implemented in MODFLOW.

B-3.1) Slaughter Canyon

Recharge from the Slaughter Canyon drainage system through the associated alluvial fan is the main source of recharge supplying Rattlesnake Springs. Recharge rate of Slaughter Canyon was calibrated by varying rates of injection. The conceptual water balance for the system estimated a recharge rate of 3.63 cfs (8881 m^3/day). A value slightly lower values of 7300 m^3/day provides the closest match to observed head levels in the system. This is balanced by a greater rate of recharge through the reef-front than conceptualized.

Constant Values

Slope wells = +160 m^3/day (x11 wells = 1760 m^3/day)
Areal recharge = +13 mm/year
Rattlesnake Springs = -7908 m^3/day
Agricultural wells = -267.28 m^3/day
Western constant head boundary = 460 m elevation
Black River = 212-184 m elevation

S.C.	Error			IN (m^3)			OUT (m^3)		
Value used	Mean	Mean absolute	RMS	const. head	wells	recharge	const. head	wells	recharge
0	-6.203	6.203	7.426	5119.2	1760.0	3500.0	2204.3	8175.3	0.0
4000	-2.927	3.232	3.915	3695.8	5760.0	3515.9	4796.3	8175.3	0.0
5000	-2.016	2.567	3.215	3439.1	6760.0	3514.4	5538.2	8175.3	0.0
6000	-1.316	2.017	2.671	3325.9	7760.0	3518.7	6429.4	8175.3	0.0
7000	-0.462	1.917	2.442	3355.9	8760.0	3525.9	7466.7	8175.3	0.0
7300	-0.339	1.851	2.359	3196.6	9060.0	3521.6	7603.0	8175.3	0.0
7500	-0.160	1.897	2.378	3201.8	9260.0	3523.1	7809.6	8175.3	0.0
8000	0.379	2.119	2.559	3306.0	9760.0	3528.8	8419.7	8175.3	0.0
9000	1.116	2.414	2.935	3154.7	10760.0	3533.2	9272.7	8175.3	0.0
10000	2.111	3.092	3.836	3127.3	11760.0	3536.0	10248.1	8175.3	0.0
15000	5.700	5879	7.410	2986.2	16760.0	3543.2	15114.2	8175.3	0.0

B-3.2) Slope Recharge

Injection rates for all 11 slope wells was varied over 0 to 300 m^3/day. Slope recharge wells are used to aid in matching head across the model domain. The slope wells are conceptualized as representing recharge from precipitation run-off from the Reef Escarpment and from perched aquifers within the Capitan Limestone. Increasing the recharge from Slaughter Canyon to compensate for the amount from slope wells does allow as accurate a fit of the observed head distribution. The best fit value of 160 m^3/day for all wells shows that the recharge provided by the reef-front is roughly a quarter of that from Slaughter Canyon.

Constant Values

Slaughter Canyon recharge = +7300 m^3/day
Areal recharge = +13 mm/year
Rattlesnake Springs = -7908 m^3/day
Agricultural wells = -267.28 m^3/day
Western constant head boundary = 460 m elevation
Black River = 212-184 m elevation

S.R.	Error			IN (m^3)			OUT (m^3)		
Value used	Mean	Mean absolute	RMS	const. head	wells	recharge	const. head	wells	recharge
0	-1.795	2.485	3.294	3705.4	7300.0	3515.8	6346.0	8175.3	0.0
50	-1.420	2.220	2.853	3468.0	7850.0	3517.3	6660.1	8175.3	0.0
100	-0.827	1.980	2.591	3462.2	8400.0	3523.1	7210.1	8175.3	0.0
110	-0.738	1.948	2.550	3436.3	8510.0	3524.5	7295.6	8175.3	0.0
120	-0.731	1.876	2.450	3297.8	8620.0	3518.7	7261.3	8175.3	0.0
130	-0.578	1.889	2.469	3355.6	8730.0	3525.9	7436.4	8175.3	0.0
140	-0.537	1.836	2.388	3236.5	8840.0	3518.7	7420.0	8175.3	0.0
150	-0.432	1.843	2.369	3218.8	8950.0	3520.2	7513.8	8175.3	0.0
160	-0.339	1.851	2.359	3196.6	9060.0	3521.6	7603.0	8175.3	0.0
170	-0.240	1.863	2.359	3147.4	9170.0	3518.7	7660.9	8175.3	0.0
180	-0.060	1.957	2.423	3254.2	9280.0	3525.9	7884.9	8175.3	0.0
190	-0.027	1.891	2.380	3131.1	9390.0	3523.1	7868.9	8175.3	0.0
200	0.108	1.972	2.444	3175.8	9500.0	3525.9	8026.6	8175.3	0.0
250	0.578	2.065	2.651	3018.0	10050.0	3527.4	8420.2	8175.3	0.0
300	-1.795	2.484	3.294	3705.4	10600.0	3531.7	9029.4	8175.3	0.0

S.R.	Error			IN (m^3)			OUT (m^3)		
Value used	Mean	Mean absolute	RMS	const. head	wells	recharge	const. head	wells	recharge
9600 SC 0 Slope	-0.514	2.124	2.732	3397.0	9060.0	3518.7	7800.6	8175.3	0.0

Simulation of no slope recharge and increase recharge from Slaughter Canyon to compensate for the loss.

B-3.3) Areal Recharge

The value of 13 mm/year was taken from measured values of 89% - 98% evapotranspiration for open range land in south-eastern New Mexico, 96% being the best value (Hunter, 1984). The average precipitation rate for the study area is 12.63. A 96% loss corresponds to 12.8 mm/year (~13mm/year) recharge. This value of 13 mm/year was assumed to be known for the simulations and only varied to examine the numeric model's sensitivity.

MODFLOW applies recharge to the top most active cell in the model domain or the top layer only. Due to the topography changes in the model domain, recharge is applied to the top most active cell. MODFLOW also limits a variation in distribution of recharge to the top layer. Because of this limitation additional recharge near the reef-front cannot be simulated, though this is compensated for by the slope injection wells.

Additionally the amount of recharge calculated during variation of other parameters varies. This may be a function of MODFLOW maintaining a mass balance or due to variation in the drainage of cells in the western portion of the model domain.

Constant Values

Slaughter Canyon recharge = +7300 m^3/day
Slope wells = +160 m^3/day (x11 wells = 1760 m^3/day)
Rattlesnake Springs = -7908 m^3/day
Agricultural wells = -267.28 m^3/day
Western constant head boundary = 460 m elevation
Black River = 212-184 m elevation

A.R.	Error			IN (m^3)			OUT (m^3)		
Value used	Mean	Mean absolute	RMS	const. head	wells	recharge	const. head	wells	recharge
0	-3.109	3.440	4.073	4047.8	9060.0	0.0	4932.5	8175.3	0.0
5	-1.985	2.549	3.137	3705.5	9060.0	1353.4	5943.7	8175.3	0.0
10	-0.982	1.933	2.491	3309.4	9060.0	2706.7	6900.9	8175.3	0.0
13	-0.339	1.851	2.359	3196.6	9060.0	3521.6	7603.0	8175.3	0.0
15	0.136	1.972	2.417	3151.4	9060.0	4066.7	8102.9	8175.3	0.0
20	1.248	2.418	2.971	2988.2	9060.0	5423.6	9296.5	8175.3	0.0
30	3.504	4.046	5.022	2733.7	9060.0	8149.1	11767.7	8175.3	0.0

B-3.4) Western Boundary

Western boundary was varied from 430-490 m in elevation. The values of 460 m elevation for the base case was taken from simulating a larger grid domain and taking the 460 m contour which ran perpendicular to the southern boundary to the northern boundary with little inflection. Sensitivity analysis of this parameter was done to estimate the dependence of the numeric model on this value, not to constrain it by comparison to known values. Variation in this value also serves to simulate variation in recharge from up gradient in the valley. The decrease in the well input at the 440 m simulation is caused by the western most slope injection well deactivating due to the water table dropping below the screened interval on the simulation. At the 430 m elevation the model no longer converges.

Constant Values

Slaughter Canyon recharge = +7300 m^3/day
Slope wells = +160 m^3/day (x11 wells = 1760 m^3/day)
Areal recharge = +13 mm/year
Rattlesnake Springs = -7908 m^3/day
Agricultural wells = -267.28 m^3/day
Black River = 212-184 m elevation

Variations in the elevation of the western constant head boundary.

W.B.	Error			IN (m^3)			OUT (m^3)		
Value used	Mean	Mean absolute	RMS	const. head	wells	recharge	const. head	wells	recharge
490	2.923	4.162	6.846	4486.5	9060.0	3536.0	8907.4	8175.3	0.0
480	1.789	3.265	5.022	3922.0	9060.0	3527.4		8175.3	0.0
470	0.739	2.433	3.174	3539.6	9060.0	3523.1	7949.4	8175.3	0.0
460	-0.339	1.851	2.359	3196.6	9060.0	3521.6	7603.0	8175.3	0.0
450	-1.420	2.490	3.174	2838.6	9060.0	3514.4	7237.8	8175.3	0.0
440	-2.466	3.251	5.378	2528.1	8900.0	3502.9	6755.7	8175.3	0.0
430	NC								

NC = non-convergent

B-3.5) Rattlesnake Springs

The average values of discharge, 3.2 cfs, was used to simulate Rattlesnake Springs for the base case. Rattlesnake Springs was modeled as a pumping well while the sensitivity of the other boundary conditions was examined to allow control of the rate. For studies of the response of the system Rattlesnake Springs is simulated as a series of drains. A series of sensitivity analysis were also run to match the drain parameters to allow the same amount of discharge as the pumping well during the base case.
When Rattlesnake Springs is simulated as a pumping well with rates of more than -11,000 m3/day, the rate is greater than the surrounding conductivity allows which inactivates the well. This can be compensated for by increasing the screened interval, but doing this allows a greater cone of depression which produces an increased effect on the nearest observation wells. This is not a concern since this great of a value of withdrawal is not used in any other simulations.

Constant Values

Slaughter Canyon recharge = +7300 m^3/day
Slope wells = +160 m^3/day (x11 wells = 1760 m^3/day)
Areal recharge = +13 mm/year
Agricultural wells = -267.28 m^3/day
Western constant head boundary = 460 m elevation
Black River = 212-184 m elevation

Variations in the withdrawal rate from Rattlesnake Springs (well).

RSS	Error			IN (m^3)			OUT (m^3)		
Value used	Mean	Mean absolute	RMS	const. head	wells	recharge	const. head	wells	recharge
-0	1.375	2.362	3.029	3116.3	9060.0	3520.2	15429.2	267.3	0.0
-2500	0.821	2.117	2.680	3101.1	9060.0	3520.2	12914.0	2767.3	0.0
-5000	0.424	2.113	2.565	3287.3	9060.0	3525.9	10606.2	5267.3	0.0
-6000	0.141	2.024	2.474	3257.4	9060.0	3525.9	9576.3	6267.3	0.0
-7000	-0.063	1.986	2.446	3272.7	9060.0	3525.9	8591.6	7267.3	0.0
-7500	-0.140	1.979	2.450	3320.9	9060.0	3525.9	8139.7	7767.3	0.0
-7908	-0.339	1.851	2.359	3196.6	9060.0	3521.6	7603.0	8175.3	0.0
-8500	-0.466	1.850	2.367	3213.6	9060.0	3518.7	7025.0	8767.3	0.0
-9000	-0.567	1.837	2.374	3236.8	9060.0	3518.7	6548.3	9267.3	0.0
-10000	-0.796	1.858	2.425	3390.8	9060.0	3520.2	5703.8	10267.2	0.0
-11000	-0.931	1.977	2.533	3644.7	9060.0	3525.9	4963.8	11266.8	0.0
-13000	*1.366*	*2.330*	*2.990*	*3032.0*	*9060.0*	*3518.7*	*15074.7*	*536.2*	*0.0*
-15000	*1.357*	*2.375*	*3.019*	*3100.3*	*9060.0*	*3523.1*	*15106.1*	*577.6*	*0.0*

B-3.6) Agricultural Withdrawals

Agricultural withdrawals are based on the permitted water right of the irrigated acreage within the model domain. The acre-feet/year right is converted to m^3/day for the base case. Leases which contain more than one irrigation well have the total divided evenly for all wells involved. The amount is varied by increasing or decreasing all wells by a factor. Within the range examined agricultural withdrawals have the least effect on the system.

Constant Values

Slaughter Canyon recharge = +7300 m^3/day
Slope wells = +160 m^3/day (x11 wells = 1760 m^3/day)
Areal recharge = +13 mm/year
Rattlesnake Springs = -7908 m^3/day
Western constant head boundary = 460 m elevation
Black River = 212-184 m elevation

Variations in agricultural withdrawals.

A.W.	Error			IN (m^3)			OUT (m^3)		
Value used	Mean	Mean absolute	RMS	const. head	wells	recharge	const. head	wells	recharge
0	-0.090	1.944	2.379	3279.3	9060.0	3525.9	7957.4	7908.0	0.0
133.64	-0.155	1.944	2.401	3299.4	9060.0	3525.9	7843.8	8041.6	0.0
267.28	-0.339	1.851	2.359	3196.6	9060.0	3521.6	7603.0	8175.3	0.0
400.92	-0.377	1.914	2.429	3290.2	9060.0	3524.5	7565.9	8308.9	0.0
534.56	-0.444	1.957	2.490	3324.1	9060.0	3525.9	7467.5	8442.5	0.0
801.84	-0.709	1.958	2.521	3202.6	9060.0	3518.7	7071.5	8709.8	0.0

B-4) Storage

Storage values used in MODFLOW are specific storage for confined aquifers, specific yield for unconfined aquifers, and total and effective porosity. The base values are chosen from literature values for storage properties. Specific storage (Ss) is the amount of water released from storage due to compaction of the aquifer material and water. The use of 8.0×10^{-6} 1/m for specific storage is taken as a mid-range value from studies of fissured rock (Domenico and Mifflin, 1965*). This is based on the assumption that the limestone conglomerate is lithified throughout the aquifer. Specific yield (Sy) is the amount of water released from drainage of an unconfined aquifer. Since flow in karstic limestone is similar to flow through open pipes, an aquifer will yield almost all the water in storage if freely drained (Ford and Williams, 1989). Typically specific yields can be up to 40% (Johnson, 1967*). Porosity (n) is the amount of void space in the rock mass. Primary porosity is generated by voids from initial sedimentation and intercrystalline space. Primary voids are diminished with compaction and cementation. Typical values of limestone porosity are 5-15% (Croff et al., 1985*). Later mechanical and chemical process, such as karst formation, produce secondary porosity. Karst solution can produce secondary porosity of up to 3.5% in otherwise dense rocks, though it is usually no more than 1% (Ford and Williams, 1989). Effective porosity (n_e) reflects only those voids which are hydrologically connected. For karstic aquifers this values usually reflects the secondary porosity.

Sensitivity simulations for these values were run as transient simulations since storage does not have an effect in steady state conditions. Simulations were run with consistent values for five time steps. Values used for comparison were those at the end of the 3650 day simulation. All of the simulations were run at a 0.01 head and residual change criterion with the PGC2 solver and modified incomplete Cholesky preconditioning method. All layers were of Type-3, variable confined/unconfined aquifer with variable storage and transmissivity.

B-4.1) Specific Yield

The storage property that the numerical model constructed in most sensitive to is specific yield. This is because the majority of the aquifer is calculated as unconfined which corresponds to actual system.

There are inconsistencies in the convergence of the model with respect to specific yield. These are not currently explained but are believed to be because of numerical instability in the code.

The higher values of specific yield produce larger volumes of water held in storage. This conflicts with the proposed conceptual model of geology of the area.

Constant Values

Specific storage (Ss) = 8.0×10^{-6} 1/m
Effective porosity (n_e) = 0.0001
Total porosity (n) = 0.01
Slaughter Canyon recharge = +730 m^3/day
Slope wells = +160 m^3/day (x11 wells = 1760 m^3/day)
Areal recharge = +13 mm/year
Rattlesnake Springs = -7908 m^3/day
Agricultural wells = -267.28 m^3/day
Western constant head boundary = 460 m elevation
Black River = 212-184 m elevation

Variations in specific yield.

Sy	Error			IN (m^3)				OUT (m^3)			
Value used	Mean	Mean absolute	RMS	storage	const. head	wells	rech.	Storage	const. head	wells	rech.
0.01	2.511	3.957	4.770	2006.1	4398.9	9060.0	3572.1	2.883	10859.0	8175.3	0.0
0.009	NC										
0.005	1.023	3.054	3.800	293.7	4579.9	9060.0	3572.1	2.990	9327.4	8175.3	0.0
0.001	0.768	2.914	3.684	0.080	4610.7	9060.0	3572.1	2.883	9064.7	8175.3	0.0
0.0009	NC										
0.0008	NC										
0.0006	0.768	2.914	3.684	3.9E-3	4610.7	9060.0	3572.1	2.884	9064.6	8175.3	0.0
0.0005	NC										
0.0004	0.769	2.914	3.684	2.9E-4	4610.7	9060.0	3569.2	1.6E-05	9064.9	8175.3	0.0
0.0001	0.769	2.914	3.684	1.1E-4	4610.7	9060.0	3569.2	3.5E-06	9064.8	8175.3	0.0

NC = non-convergent

B-4.2) Specific Storage

The specific storage of a system applies to confined aquifer. Since this MODFLOW is allowed to calculate variances between confined and unconfined conditions it used both specific storage and specific yield.

For the simulations above 1.0E+1, the Rattlesnake Springs injection well was inactivated. This is due to the decreased storage capacity no longer allowing sufficient release of water to the well, causing it to drain the screened interval and inactivate. For simulations run with a specific storage of 1.0E+5 and greater the model would not converge. This are values of specific storage which correspond to unconsolidated sediment which do not apply to the limestone conglomerate.

Constant Values

Specific yield (Sy) = 0.0001
Effective porosity (n_e) = 0.0001
Total porosity (n) = 0.01
Slaughter Canyon recharge = +730 m^3/day
Slope wells = +160 m^3/day (x11 wells = 1760 m^3/day)
Areal recharge = +13 mm/year
Rattlesnake Springs = -7908 m^3/day
Agricultural wells = -267.28 m^3/day
Western constant head boundary = 460 m elevation
Black River = 212-184 m elevation

Variations in specific storage

	Error			IN (m^3)				OUT (m^3)			
Value used	Mean	Mean absolute	RMS	storage	const. head	wells	rech.	Storage	const. head	wells	rech.
0.00008	NC										
0.00001	NC										
0.000009	0.770	2.916	3.685	1.3E-04	4610.4	9060.0	3569.2	8.6E-06	9064.6	8175.3	0.0
0.000008	0.769	2.914	3.684	1.1E-04	4610.7	9060.0	3569.2	3.5E-06	9064.8	8175.3	0.0
0.000007	0.770	2.916	3.685	4.7E-05	4610.5	9060.0	3569.2	4.0E+00	9064.6	8175.3	0.0
0.000005	0.776	2.922	3.690	1.5E-05	4609.7	9060.0	3569.2	0.0E+00	9063.7	8175.3	0.0
0.000001	*5.675*	*6.773*	*7.419*	*1.2E-05*	*4509.1*	*9060.0*	*3502.9*	*3.9E-07*	*16805.0*	*267.3*	*0.0*
0.0000008	*7.638*	*8.589*	*9.336*	*7.9E-06*	*4503.1*	*9060.0*	*3489.9*	*2.1E-07*	*16786.0*	*267.3*	*0.0*

NC = non-convergent

B-4.3) Porosity

MODFLOW allows the specification of both total porosity, the total void ratio, and effective porosity, the interconnected portion of the porosity. Porosity should control the hydraulic conductivity and storage properties. Since MODFLOW requires specification of these values and does not allow variations of porosity with time, the porosity term does not affect the solution of the governing equation. As seen in the sensitivity runs with variations in both effective porosity and total porosity, there was no effect on the model.

Constant Values

- Specific storage (Ss) = $8.0x10^{-6}$ 1/m
- Specific yield (Sy) = 0.001
- Slaughter Canyon recharge = +730 m^3/day
- Slope wells = +160 m^3/day (x11 wells = 1760 m^3/day)
- Areal recharge = +13 mm/year
- Rattlesnake Springs = -7908 m^3/day
- Agricultural wells = -267.28 m^3/day
- Western constant head boundary = 460 m elevation
- Black River = 212-184 m elevation

Variations in effective porosity.

	Error			IN (m^3)					OUT (m^3)		
Value used	Mean	Mean absolute	RMS	storage	const. head	wells	rech.	storage	const. head	wells	rech.
0.01	0.7685	2.9138	3.6839	0.0	4610.7	9060.0	3569.2	0.0	9064.8	8175.3	0.0
0.001	0.7685	2.9138	3.6839	0.0	4610.7	9060.0	3569.2	0.0	9064.8	8175.3	0.0
0.0001	0.7685	2.9138	3.6839	0.0	4610.7	9060.0	3569.2	0.0	9064.8	8175.3	0.0
0.00001	0.7685	2.9138	3.6839	0.0	4610.7	9060.0	3569.2	0.0	9064.8	8175.3	0.0

Variations in total porosity.

	Error			IN (m^3)				OUT(m^3)			
Value used	Mean	Mean absolute	RMS	storage	const. head	wells	rech.	storage	const. head	wells	rech.
0.1	0.7685	2.9138	3.6839	0.0	4610.7	9060.0	3569.2	0.0	9064.8	8175.3	0.0
0.01	0.7685	2.9138	3.6839	0.0	4610.7	9060.0	3569.2	0.0	9064.8	8175.3	0.0
0.001	0.7685	2.9138	3.6839	0.0	4610.7	9060.0	3569.2	0.0	9064.8	8175.3	0.0
0.0001	0.7685	2.9138	3.6839	0.0	4610.7	9060.0	3569.2	0.0	9064.8	8175.3	0.0

Specific yield greater than total porosity.

	Error			IN (m^3)				OUT (m^3)			
Value used	Mean	Mean absolute	RMS	storage	const. head	wells	rech.	storage	const. head	wells	rech.
0.1 0.01	23.3775	23.3775	25.7066	35262.0	2126.3	9060.0	3598.0	0.0	41870.8	8175.3	0.0
0.0001 0.00001	0.7685	2.9138	3.6839	0.0	4610.7	9060.0	3569.2	0.0	9064.8	8175.3	0.0

Top number is specific yield and the lower number is total porosity, effective porosity was an order of magnitude lower than total porosity.

Appendix C

Groundwater and geologic data used in the upper Black River valley.

Table of Contents

Table of Contents....................148
Figures & Tables....................148
C) Data used....................149
C-1) Geology....................151
C-2) Groundwater chemistry....................154
C-3) Agricultural withdrawals....................157
C-4) Tritium analysis....................158
C-5) Precipitation....................163

Figures & Tables

Figure C.1: Well numbering system used by the New Mexico State Engineer's Office....................150
Table C.1: Water chemistry from samples analyzed as part of this project....................154
Table C.2: Water chemistry records from the State Engineer's Office....................156
Table C.3: Measured pumped volumes for wells used in model domain. From New Mexico State Engineer's Office....................157
Figure C-2: Comparison of half-life decays. Top) measured tritium. Bottom) Half-life decays from recorded values in precipitation....................159

C) Data used

Included is the data used to understand the geology and hydrology of the upper Black River valley.

The well numbering system used (figure C-1) by the state of New Mexico represents wells by their township, range, and section followed by series of numbers locating the well within the section by quadrant. If more than one well is present in the area, the wells are appended with letters designating the wells in chronological order.

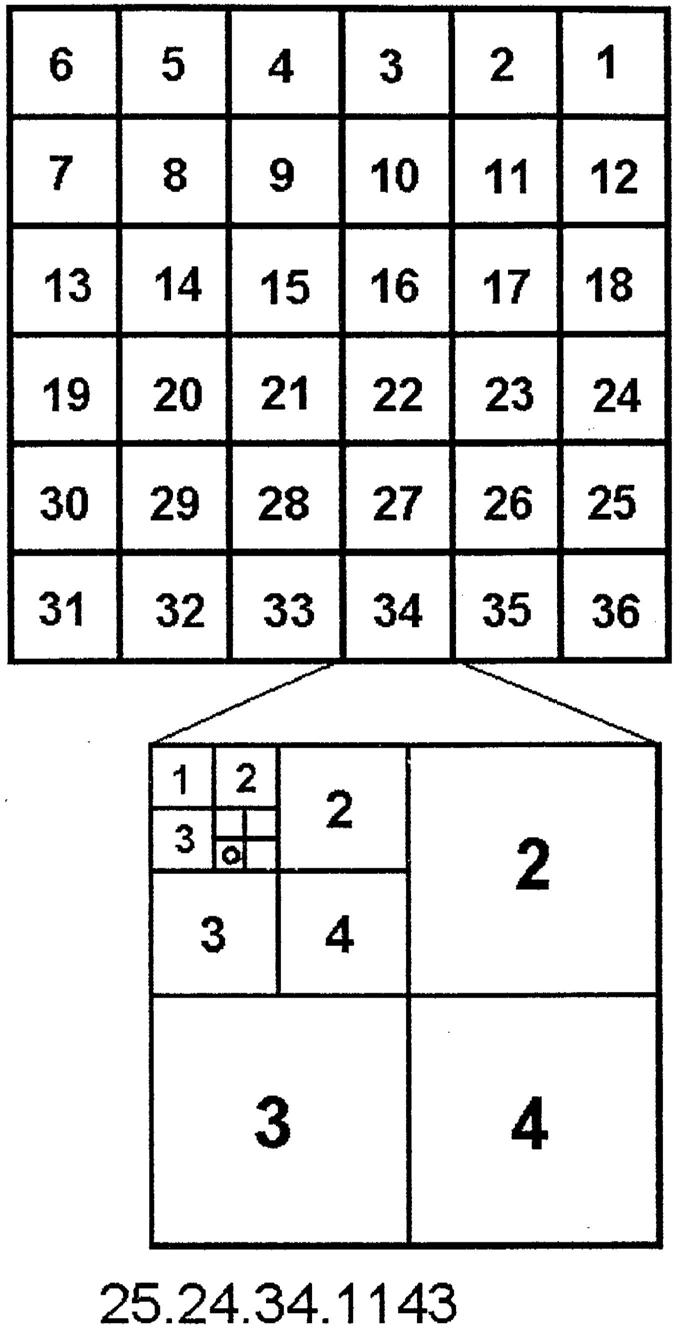
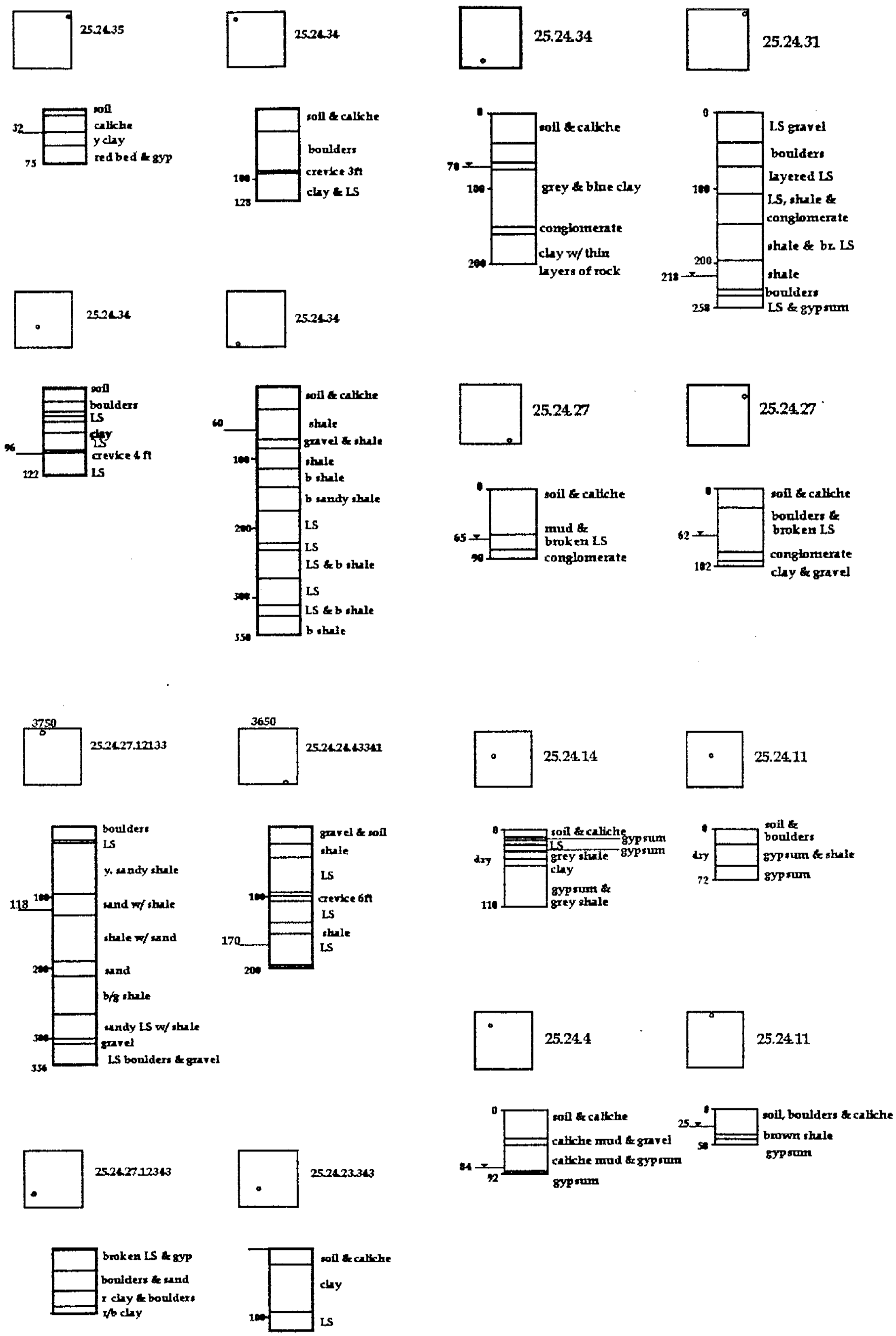


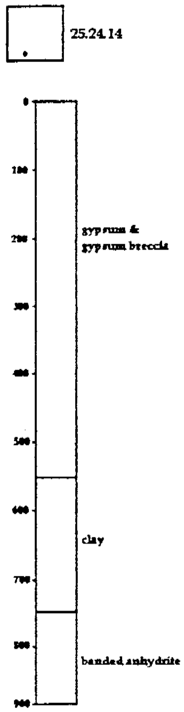
Figure C.1: Well numbering system used by the New Mexico State Engineer's Office. Diagram shows determination of location within a section.

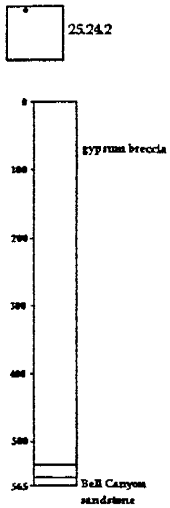
C-1) Geology

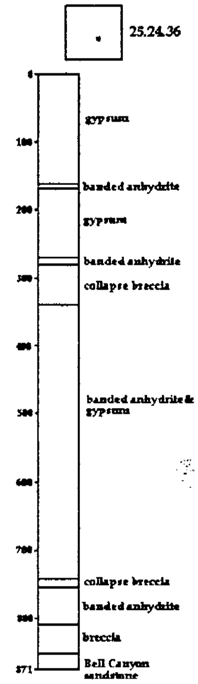
Geologic data was obtained primarily from the drilling logs of shallow groundwater wells obtained from the State Engineer's Office of New Mexico. Drilling logs are required to be submitted, though the level of detail is not controlled.

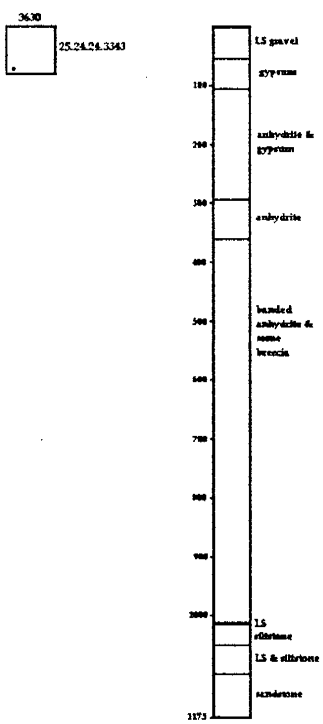
Additional information on geology for the area is available from geologic studies published. Hill (1996) provides a good over-view of the Delaware Basin and Guadalupe Reef.


25.24.35
soil
caliche
y clay
red bed & gyp
32
75
25.24.34
soil & caliche
boulders
crevice 3ft
clay & LS
100
128
25.24.34
soil & caliche
grey & blue clay
conglomerate
clay w/ thin layers of rock
0
70
100
200
25.24.31
LS gravel
boulders
layered LS
LS, shale & conglomerate
shale & br. LS
shale
boulders
LS & gypsum
0
100
200
218
258
25.24.34
soil
boulders
LS
clay
LS
crevice 4 ft
LS
96
122
25.24.34
soil & caliche
shale
gravel & shale
shale
b shale
b sandy shale
LS
LS
LS & b shale
LS
LS & b shale
b shale
60
100
200
300
350
25.24.27
soil & caliche
mud & broken LS
conglomerate
0
65
90
25.24.27
soil & caliche
boulders & broken LS
conglomerate
clay & gravel
0
62
102
3750
25.24.27.12133
boulders
LS
y. sandy shale
sand w/ shale
shale w/ sand
sand
b/g shale
sandy LS w/ shale
gravel
LS boulders & gravel
118
100
200
300
336
3650
25.24.24.43341
gravel & soil
shale
LS
crevice 6ft
LS
shale
LS
100
170
200
25.24.14
soil & caliche
gypsum
LS
gypsum
grey shale
clay
gypsum & grey shale
0
dry
110
25.24.11
soil & boulders
gypsum & shale
gypsum
0
dry
72
25.24.4
soil & caliche
caliche mud & gravel
caliche mud & gypsum
gypsum
0
84
92
25.24.11
soil, boulders & caliche
brown shale
gypsum
0
25
50
25.24.27.12343
broken LS & gyp
boulders & sand
r clay & boulders
r/b clay
25.24.23.343
soil & caliche
clay
LS
100


25.24.14
gypsum &
gypsum breccia
clay
banded anhydrite


25.24.2
gypsum breccia
Bell Canyon
sandstone
565


25.24.36
gypsum
banded anhydrite
gypsum
banded anhydrite
collapse breccia
banded anhydrite &
gypsum
collapse breccia
banded anhydrite
breccia
Bell Canyon
sandstone


3630
25.24.24.3343
LS gravel
gypsum
anhydrite &
gypsum
anhydrite
banded
anhydrite &
some
breccia
LS
siltstone
LS & siltstone
sandstone
1173

C-2) Groundwater chemistry

Water chemistry is periodically analyzed by the state of New Mexico for the purpose of general surveying. Additionally, 10 sites were sampled as part of this project.

Samples taken summer 1997.

	Field			Laboratory		
Location	Temp	pH	conductance	pH	conductance	alkalinity
25.24.31.144	24	7.39	469	7.16	500	258.8
25.24.20.333	25	8.44	438	8.09	440	229.5
25.23.27.132	24	6.91	507	7.23	480	292.0
25.24.34.112a	22	6.72	1550	6.78	1460	248.6
25.24.34.112	23	6.95	1480	6.82	1420	233.3
25.24.27.124	22	6.87	515	7.22	480	281.8
25.24.27.224	21	6.66	1370	6.80	1300	293.2
24.25.34.23	23	6.54	1660	7.08	1600	19.1
24.25.34.23	22	6.89	1680	7.47	1580	19.1
25.24.23.343s				7.08	630	280.5
25.24.23.343				7.41	590	285.6
25.24.26.433	28	7.17	2110	7.59	1960	198.9
25.24.23.343				7.12	1970	158.1

	Anions				Cations			
Location	No3-	F-	SO4-	Cl-	Na	Ca	Mg	K
25.24.31.144	8.74	0.20	39.9	5.3	6.9	86.7	25.6	2.39
25.24.20.333	2.71	0.16	54.7	4.6	4.1	69.7	30.6	1.95
25.23.27.132	3.26	0.16	40.8	4.7	4.6	90.3	27.8	1.71
25.24.34.112a	0.06	0.38	732.4	7.1	10.0	281.8	46.7	1.94
25.24.34.112	1.74		777.8	6.2	9.5	296.0	48.8	1.84
25.24.27.124	3.27	1.69	46.4	5.3	4.5	89.9	28.8	2.20
25.24.27.224	2.80	0.28	574.0	8.8	16.4	204.9	64.2	1.80
24.25.34.23	0.18	0.55	1053.7	6.3	78.1	381.0	3.5	5.05
24.25.34.23	0.30	0.24	1057.3	6.1	65.7	370.3	3.4	2.87
25.24.23.343s	2.49	0.18	25.9	4.8	4.9	113.4	29.8	1.99
25.24.23.343	1.89	0.19	132.8	6.1	4.9	113.2	30.0	1.15
25.24.26.433	1.47	0.49	1321.8	5.0	10.7	621.0	59.4	2.56
25.24.23.343	0.69	0.99	1347.2	6.8	11.5	23.6	57.6	2.58

Table C.1: Water chemistry from samples analyzed as part of this project.

Date	Location	Chloride ppm	Conductance (mΩ)
8/6/85	25.24.11.122424	13	2527
6/25/87	25.24.11.122424	8	2536
4/7/92	25.24.11.122424	70	2720
9/4/52	25.24.11.211311	16	2520
8/3/83	25.24.14.431344	22	2400
6/25/87	25.24.14.431344	2	2203
4/2/92	25.24.14.431344	61	2300
5/16/52	25.24.16.41311	9	2420
4/7/92	25.24.16.41311	130	2190
5/16/52	25.24.20.333211	4	480
3/26/92	25.24.20.333211	27	530
3/11/92	25.24.23.343242s	65	740
6/25/87	25.24.23.343341	6	623
10/1/52	25.24.26.12120	6	619
5/15/52	25.24.26.33430	7	2320
7/15/53	25.24.27.12434	25	490
8/5/87	25.24.27.132222	62	878
4/6/52	25.24.27.421121	8	1380
7/15/53	25.24.27.421121	43	1380
5/15/52	25.24.31.331144	10	578
8/8/85	25.24.31.331144	6	560
6/24/87	25.24.31.331144	4	550
7/15/53	25.24.34.112231	39	1072
8/8/85	25.24.34.112231	11	1248
8/5/87	25.24.34.112231	16	1346
4/1/92	25.24.34.112231	37	1470
4/29/92	25.24.35.41310	110	2740
6/30/87	25.25.3.31333	10	2380
4/1/92	25.25.4.14424a	122	2850
8/6/85	25.25.4.42420	42	2471
10/9/87	25.25.5.41124	25	2294
4/1/92	25.25.5.41124	25	2290
6/30/87	25.25.12.322331	6	1439
3/24/92	25.25.12.322331	33	1430
11/20/53	25.25.12.324433	1520	2050
7/1/87	25.25.14.431421	186	2932
3/24/92	25.25.14.431421	250	3090

11/6/53	25.25.16.141334	5	1040

Continued.

Date	Location	Chloride ppm	Conductance (mΩ)
3/31/92	26.23.3.11111	16	530
8/27/97	26.23.3.11111	4	380
9/11/97	26.23.6.33443	24	490
8/5/87	26.23.6.343342	30	548
3/31/92	26.23.6.34343	55	610
7/28/83	26.24.2.122142	13	2564
8/3/83	26.24.2.122142	9	2430
8/8/85	26.24.2.122142	8	2492
6/30/87	26.24.2.122142	6	2465
4/29/92	26.24.2.122142	40	2680
6/18/52	26.24.3.3411431	9	2010
3/25/92	26.24.5.22424	220	3030
9/11/52	26.24.9.114111	64	1500
7/13/54	26.24.9.114111	7	1630
10/7/87	26.24.9.114111	12	1502
7/1/87	26.24.9.42114	4	2173
4/1/92	26.24.9.42114	38	2240
8/27/97	26.24.9.42114	8	1900
7/30/52	26.24.9.443111	28	2050
7/15/53	26.24.10.131322	28	2011
10/7/87	26.24.10.131322	11	2496
4/24/52	26.24.10.24310	28	2640
7/15/53	26.24.10.32114	25	2400
8/8/85	26.24.10.32114	10	2528
7/1/87	26.24.10.33224	16	1889
2/6/53	26.24.10.341113	28	3200
1/22/48	26.24.11.31241	11	2540
6/30/87	26.24.11.31241	6	1803
4/29/92	26.24.11.31241	36	2350
8/27/97	26.24.11.31241	26	2510
8/28/97	26.24.12.44243	22	2350

Table C.2: Water chemistry records from the State Engineer's Office.

C-3) Agricultural withdrawals

	25.24.27.421		25.24.27.124		25.24.34.112		25.24.27.43		25.24.34.112	
Date	acre-ft	m^3	acre-ft	m^3	acre-ft	m^3	acre-ft	m^3	acre-ft	m^3
1/4/95										
4/3/95	38.3	20.9	50.3	27.5	33.5	18.3	0.0	0.0	19.1	10.4
7/12/95	160.4	87.6	298.4	162.9	96.7	52.8	48.1	26.3	19.9	10.9
10/12/95	85.4	46.6	156.3	85.4	71.9	39.3	58.8	32.1	58.7	32.1
1/5/96	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.2
4/17/96	35.7	19.5	66.9	36.6	19.1	10.4	11.8	6.5	20.9	11.4
7/9/96	86.7	47.4	88.9	48.6	85.5	46.7	25.4	13.9	49.6	27.1
10/6/96	66.5	36.3	117.8	64.4	77.5	42.3	0.0	0.0	39.5	21.6
1/16/97	14.5	7.9	10.8	5.9	25.7	14.0	0.0	0.0	13.8	7.5
4/30/97	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	21.8	11.9
7/17/97	102.5	56.0	104.6	57.1	46.3	25.3	7.9	4.3	23.7	13.0
10/7/97	55.4	30.3	21.5	11.7	67.2	36.7	15.6	8.5	28.1	15.3
1/8/98	5.1	2.8	0.0	0.0	16.8	9.2	-0.2	-0.1	6.9	3.8
4/22/98	30.0	16.4	0.0	0.0	43.1	23.5	0.0	0.0	20.2	11.1
7/14/98					72.1	39.4			32.7	17.9

	26.24.10.133		26.24.9.111		26.24.10.321	
Date	acre-ft	m^3	acre-ft	m^3	acre-ft	m^3
1/4/95						
4/3/95	5.3	2.9		0.0		
7/12/95	33.7	18.4			1.8	1.0
10/12/95	10.6	5.8			156.6	85.5
1/5/96	5.2	2.8	0.2	0.1	116.5	63.6
4/17/96	0.1	0.0			0.0	0.0
7/9/96	9.0	4.9			42.0	23.0
10/6/96	1.3	0.7	0.0	0.0	122.0	66.6
1/16/97	0.1	0.0	44.4	24.2	62.1	33.9
4/30/97	0.8	0.4	36.6	20.0	21.7	11.9
7/17/97	3.8	2.1	26.8	14.6	0.5	0.3
10/7/97	1.8	1.0	100.8	55.1	122.3	66.8
1/8/98	0.0	0.0	58.7	32.1	68.5	37.4
4/22/98	1.8	1.0	0.0	0.0	105.2	57.5
7/14/98			36.2	19.8	19.0	10.4

Table C.3: Measured pumped volumes for wells used in model domain. From New Mexico State Engineer's Office.

C-4) Tritium analysis

Background

Tritium is generated in the upper atmosphere by cosmic radiation. A tritium peak was generated by the above ground nuclear testing from 1951-1963. This peak can be used as an environmental tracer. In New Mexico tritium levels in precipitation reached a high in 1963 at ~10,000 TU (Gross *et al.*, 1976). Tritium concentrations are recorded in TU (tritium units) that corresponds to one tritium atom per every 10^{18} hydrogen atoms. Tritium measurements for New Mexico are recorded four times yearly and are published in the Water Resources Data for New Mexico.

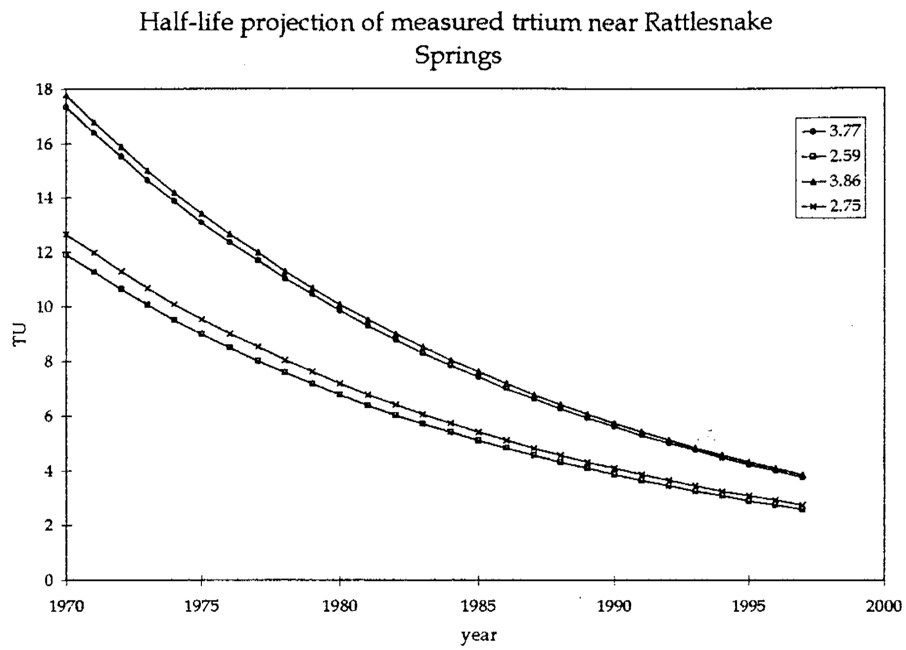
Tritium under goes radioactive decay with a half life of 12.26 years (Gross *et al.*, 1976). This allows its use for the comparative age dating of groundwater.

Measurements

Tritium analysis was done on four wells across the study area. The wells were selected at points along the flow path from Slaughter Canyon to Rattlesnake Springs. The results are all within the same error range. This shows that the flow through the system is fast since there has been indeterminable amounts of tritium decay across the 3.4 miles separating the Stell's well from Rattlesnake Springs.

A tritium input function is constructed for the area based on the precipitation and infiltration rates. For the study area, the constructed tritium input function based on Rabinowirtz's (1975) work produced input levels of less than 1 TU. The input function used in earlier studies was for matching measured tritium levels to the bomb pulse with use of dispersion modeling. This does not apply to the local area since residence times are to short for bomb pulse correlation.

Measured tritium values were compared against the amounts of tritium precipitated. This showed that the measured concentrations cannot be backed to a precipitated value. It was shown in studies on the Roswell basin that measured tritium levels were consistently lower than predicted (Gross et al. 1976). This was due to mixing with older water within the aquifer. This concept is quite applicable to the Rattlesnake Springs study area since three porosity regimes exist, the primary and secondary limestone conglomerate porosity and the porosity of the surrounding clays and silt deposits. With this in mind, the concentrations measured could correspond to meteoric water precipitated from 1982 till the present. This does rule out the age of the water to be more than 15 years old. One additional piece of information that the tritium produces is that the levels are relativity constant across the sampled area. This supports the high conductivity measured for the alluvium. This also supports a fairly young age for the water with a portion of the tritium loss being due to diffusion into and out of the lower permeability materials of the aquifer.



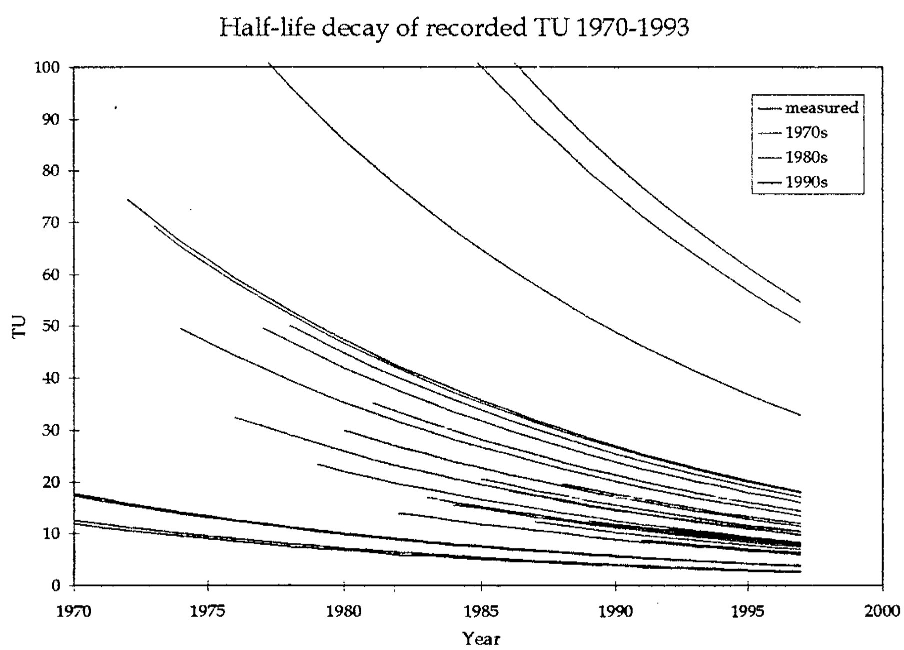


Figure C-2: Comparison of half-life decays. Top) measured tritium. Bottom) Half-life decays from recorded values in precipitation.

Measured TU in precipitation (Albuquerque, NM) and input function.

Year	month TU sample	precip. (in)	TU	f	recharge	TU input function
1970	Feb	1.96	259.0	0.0006	0.0012	0.3149
	May	1.83	404.0	0.0006	0.0011	0.4282
	Aug	7.64	168.0	0.0024	0.0185	3.1032
	Nov	1.85	103.0	0.0006	0.0011	0.1116
1971	Feb	0.47	468.0	0.0001	0.0001	0.0327
	May	1.23	226.0	0.0004	0.0005	0.1082
	Aug	7.17	213.0	0.0023	0.0163	3.4652
	Nov	1.42	45.1	0.0004	0.0006	0.0288
1972	Feb	0.58	124.0	0.0002	0.0001	0.0132
	Aug	2.14	62.1	0.0007	0.0014	0.0900
	Nov	11.74	37.1	0.0037	0.0436	1.6182
		2.38		0.0008	0.0018	
1973	Feb	3.77	84.6	0.0012	0.0045	0.3805
	May	1.41	98.6	0.0004	0.0006	0.0620
	Aug	8.43	42.6	0.0027	0.0225	0.9580
	Nov	1.20	51.5	0.0004	0.0005	0.0235
1974		0.59		0.0002	0.0001	
		0.88		0.0003	0.0002	
	Aug	17.59	62.0	0.0056	0.0979	6.0707
	Nov	3.68	37.2	0.0012	0.0043	0.1594
1975		2.00		0.0006	0.0013	
	May	2.26	114.0	0.0007	0.0016	0.1843
		7.27		0.0023	0.0167	
		0.85		0.0003	0.0002	
1976		0.38		0.0001	0.0000	
		4.33		0.0014	0.0059	
		11.75		0.0037	0.0437	
	Nov	2.37	32.4	0.0008	0.0018	0.0576
1977	Feb	1.88	33.8	0.0006	0.0011	0.0378
	May	4.17	84.0	0.0013	0.0055	0.4622
	Aug	1.60	38.9	0.0005	0.0008	0.0315
	Nov	2.83	41.9	0.0009	0.0025	0.1062
1978	Feb	1.23	60.3	0.0004	0.0005	0.0289
	May	4.93	77.1	0.0016	0.0077	0.5930
	Aug	15.26	40.1	0.0048	0.0737	2.9551
	Nov	2.71	22.7	0.0009	0.0023	0.0528

Year	month TU sample	precip. (in)	TU	f	recharge	TU input function
1979	Feb	0.65	27.4	0.0002	0.0001	0.0037
		3.75		0.0012	0.0045	
	Aug	7.89	25.5	0.0025	0.0197	0.5024
	Nov	0.65	17.1	0.0002	0.0001	0.0023
1980	Feb	1.06	26.3	0.0003	0.0004	0.0094
	May	1.66	53.6	0.0005	0.0009	0.0467
	Aug	13.35	13.4	0.0042	0.0564	0.7558
	Nov	0.25	26.5	0.0001	0.0000	0.0005
1981	Feb	2.38	43.2	0.0008	0.0018	0.0774
	May	3.66	48.2	0.0012	0.0042	0.2043
	Aug	13.06	38.1	0.0041	0.0540	2.0565
	Nov	1.03	11.7	0.0003	0.0003	0.0039
1982		0.68		0.0002	0.0001	
		4.39		0.0014	0.0061	
		8.20		0.0026	0.0213	
	Nov	3.90	14.0	0.0012	0.0048	0.0674
1983	Feb	1.20	14.1	0.0004	0.0005	0.0064
	May	1.76	29.3	0.0006	0.0010	0.0287
	Aug	5.96	15.1	0.0019	0.0112	0.1697
	Nov	5.05	9.5	0.0016	0.0081	0.0767
1984	Feb	0.50	20.8	0.0002	0.0001	0.0016
		10.18		0.0032	0.0328	
		9.13		0.0029	0.0264	
	Nov	4.67	10.3	0.0015	0.0069	0.0711
1985	Feb	1.86	26.9	0.0006	0.0011	0.0295
	May	4.98	18.9	0.0016	0.0078	0.1483
	Aug	6.59	14.7	0.0021	0.0137	0.2020
	Nov	4.03	21.6	0.0013	0.0051	0.1110
1986	Feb	0.52	20.5	0.0002	0.0001	0.0018
	May	19.18	27.5	0.0061	0.1164	3.2014
	Aug	6.46	16.7	0.0020	0.0132	0.2205
	Nov	6.85	7.9	0.0022	0.0148	0.1173
1987	Feb	3.44	12.9	0.0011	0.0037	0.0483
	May	10.70	20.4	0.0034	0.0362	0.7391
	Aug	7.84	7.8	0.0025	0.0195	0.1517
	Nov	1.64	7.8	0.0005	0.0009	0.0066

Year	month TU sample	precip. (in)	TU	f	recharge	TU input function
1988	Feb	0.90	29.2	0.0003	0.0003	0.0075
	May	1.44	19.3	0.0005	0.0007	0.0127
	Aug	13.72	14.6	0.0043	0.0596	0.8697
	Nov	0.22	15.6	0.0001	0.0000	0.0002
1989	Feb	0.69	9.7	0.0002	0.0002	0.0015
	May	1.65	22.0	0.0005	0.0009	0.0190
	Aug	6.96	12.8	0.0022	0.0153	0.1962
	Nov	0.36	5.4	0.0001	0.0000	0.0002
1990	Feb	0.46	19.5	0.0001	0.0001	0.0013
	May	1.28	9.4	0.0004	0.0005	0.0049
	Aug	6.53	12.3	0.0021	0.0135	0.1660
	Nov	0.16	5.9	0.0001	0.0000	0.0000
1991	Feb	1.29	10.3	0.0004	0.0005	0.0054
	May	2.73	8.2	0.0009	0.0024	0.0193
	Aug	7.15	10.2	0.0023	0.0162	0.1650
	Nov	4.04	6.3	0.0013	0.0052	0.0325
1992	Feb	1.73	10.9	0.0005	0.0009	0.0103
	May	8.06	12.4	0.0026	0.0206	0.2549
	Aug	4.20	10.0	0.0013	0.0056	0.0558
	Nov	0.63	10.2	0.0002	0.0001	0.0013
1993	Feb	1.16	7.5	0.0004	0.0004	0.0032
	May	2.49	15.5	0.0008	0.0020	0.0304
	May	4.86	20.3	0.0015	0.0075	0.1517
	Aug	2.05	8.6	0.0006	0.0013	0.0114
1994	May	0.64	9.6	0.0002	0.0001	0.0012

C-5) Precipitation

Precipitation measurements were used from the eight nearest gauges. Values were taken from the National Oceanic and Atmospheric Association (NOAA) web-server. Precipitation measurements were recorded by monthly totals. Units are in hundredths of inches.

No gauges are available in the Slaughter Canyon drainage system. The Carlsbad Caverns gauge is the closest, though precipitation amounts vary greatly over short distances in the area. Precipitation over the Guadalupe Reef and Guadalupe mountains is roughly 5 inches greater on average than within the Delaware Basin.

Carlsbad Caverns, NM. Gauge no. 291480

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1931	129	56	17	481	100	22	82	145	122	53	145	204	1556
1932	46	200	69	13	172	133	160	172	855	158	0	125	2103
1933	7	146	7	12	12	128	342	101	488	65	19	2	1329
1934	4	0	58	27	137	38	23	173	24	109	7	10	610
1935	12	56	0	114	158	271	54	186	530	39	88	56	1564
1936	71	0	11	6	377	66	213	88	308	69	45	29	1283
1937	1	24	147	7	286	3	15	201		199	31	59	973
1938	97	28	0	38	25	400	196	64	320	90	2	30	1290
1939	29	18	76	0	64	101	227	165	20	202	39	30	971
1940	29	46	0	42	274	360	43	330	13	429	139	14	1719
1941	68	68	359	178	1091	329	412	176	1230	251	71	90	4323
1942	37	19	7	140	37	235	165	569	248	179	4	145	1785
1943	4	0	3	23	80	212	596	10	103	17	30	136	1214
1944	75	74	4	6	59	362	99	472	501	18	137	53	1860
1945	62	10	15	40	47	41	434	287	102	374	0	25	1437
1946	105	0	20	4	61	94	221	389	614	244	34	57	1843
1947	91	0	34	40	100	92	42	98	101	63	54	50	765
1948		110	4	14	253								381
1948	28					243	157	69	16	73	0	44	630
1949	237	35	32	76	167	163	292	130	485	100		52	1769
1950	0	23	0	19	34	115	439	170	260	230	0	0	1290
1951	8	30	148	9	55	24	51	61	30	21	7	3	447
1952	9	10	13	114	68	178	338	18	81	0	66	13	908
1953	3	6	2	68	119	207	116	61	1	98	11	94	786
1954	0	0	0	581	204	31	65	290	16	512	0	14	1713
1955	77	4	25	13	31	86	272	40	286	311	34	30	1209
1956	7	30	0	8	61	98	95	291	0	25	0	22	637
1957	13	53	69	57	114	21	148	179	62	365		0	1081
1958	228	154	140	103	51	315	146	391	501	499	51	10	2589
1959	18	29	24	32	273	80	213	146	58	65	14	55	1007
1960	64	48	51	5	19	201	372	288	72	267	7	187	1581
1961	131	10	20	6	202	129	103	145	113	202	122	4	1187
1962	84	26	24	46	23	51	441	59	518	122	47	43	1484
1963	21	31	7	266	120	229	81	818	17	33	9	30	1662
1964	6	29	11	0	52	166	53	53	207	17	10	21	625
1965	1	32	22	5	511	79	116	86	589	0	124	113	1678
1966	52	4	24	133	44	191	4	1171	284	18	0	0	1925
1967	0	8	6	11	5	386	158	45	95	3	30	77	824

Carlsbad Caverns, NM. Continued.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1968	142	86	167	32	210	12	468	294	5	15	220	1	1652
1969	0	16	83	32	18	20	149	119	78	403	58	124	1100
1970	7	88	101	0	45	138	173	184	407	175	0	10	1328
1971	26	18	3	34	68	21	255	256	206	31	9	102	1029
1972	58	0	0	0	159	55	215	448	511	178	58	2	1684
1973	146	227	4	6	81	54	303	55	485	119	1	0	1481
1974	49	0	10	5	60	23	58	671	1030	266	28	74	2274
1975	50	124	26	18	106	102	311	99	317	4	5	76	1238
1976	26	1	11	117	238	78	515	20	640	133	104	0	1883
1977	47	13	128	156	169	92	28	112	20	274	9	0	1048
1978	15	61	47	51	186	256	101	188	1237	131	140		2413
1979	32	21	12	2	164	209	350	350	89	2	0	63	1294
1980	43	59	4	41	112	13	111	352	872	6		19	1632
1981	149	34	55	179	154	33	412	594	300	103	0	0	2013
1982	44	22	2	34	260	145	505	193	122	152	101	137	1717
1983	39	45	36	68	29	79	111	66	419	365	119	21	1397
1984	29	1	20	2	242	774	108	707	98	298	84	85	2448
1985	45	81	60	187	251	60	98	45	516	323	80	0	1746
1986	1	44	7	0	225	1693	65	203	378	342	162	181	3301
1987	15	244	85	95	467	508	89	203	492	47	35	82	2362
1988	1	80	9	34	42	68	419	519	434	5	12	5	1628
1989	0	65	4	13	19	133	52	383	261	0	0	36	966
1990	11	17	18	60	58	10	270	182	201	5		11	843
1991	106	23	0	0	97	176	454	261		8	40	356	1521
1992	71	88	14	83	493	230	176	86	158	22	18	23	1462
1993	101	13	2	69	104	76	246	172	68	138	41	26	1056
1994	27	0	37	50	231	151	5	168	112	213		17	1011
1995	34	84	26	7	128	388	7	214	513	0	0	20	1421
1996	23	0	4	73	8	410	263	690	452	3	48	15	1989
1997	34		19	170	279	162	285	198	352	141	62	215	1917

Carlsbad Caverns City, NM. Gauge no. 291475.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1942									383	134	0	218	735
1943	4	0	2	9									15
1948							90	35	28	91	0	13	257
1949	293	0	10	41	150	426	105	229	533	65	0	19	1871
1950	2	25	1	27	35	83	449	54	344	320	0	0	1340
1951	11	30	131	15	120	9	147	121	4	10	8	0	606
1952	7	23	12	50	46	81	189	17	67	0	59	2	553
1953	7	14	2	34	94	39	92	18	70	284	2	76	732
1954	0	0	0	68	104	6	15	346	4	275	0	14	832
1955	47	0	8	73	23	40	316	117	193	181	43	3	1044
1956	27	132	0	4	107	132	66	86	0	17	0	5	576
1957	6	40	55	8	85	30	60	148	2	297	69	0	800
1958	163	102	101	95	21	61	129	304	545	272	56	2	1851
1959	2	17	31	10	345	26	135	126	29	65	3	36	825
1960	35	38	18	0	19	100	506	266	28	316	0	158	1484
1961	87	12	38	0	52	110	40	6	29	168	95	11	648
1962	69	2	13	63	88	102	413	6	201	99	38	11	1105
1963	10	21	87	43	114	38	66	252	24	3	0	24	682
1964	0	3	23	0	66	35	13	124	315	9	1	0	589
1965	0	22	4	2	176	106	75	145	234	0	64	49	877
1966	35	0	7	183	78	71	0	802	108	23	0	0	1307
1967	0	1	17	9	13	191	178	16	119	1	11	27	583
1968	150	80	120	33	135	5	471	175	0	18	157	2	1346
1969	10	36	33	40	17	56	66	123	236	399	49	49	1114
1970	1	84	106	0	23	184	0	81	277	78	0	3	837
1971	5	2	1	24	13	0	370	534	190	24	34	91	1288
1972	14	0	0	0	154	204	219	398	332	136	56	7	1520
1973	97	177	27	0	131	57	301	52	166	58	1	0	1067
1974	54	8	20	46	15	27	79	496	923	343	18	76	2105
1975	31	100	17	4	13	22	346	87	156	4	0	18	798
1976	18	1	5	66	71	4	231	73	474	76	91	0	1110
1977	42	8	104	218	147	54	87	158	99	145	14	0	1076
1978	22	34	16	21	140	233	36	101	844	157	342	32	1978
1979	20	46	3	11	274	90	449	253	62	0	7	58	1273
1980	45	13	0	80	100	10	9	208	761	9	107	20	1362
1981	77	32	62	123	191	35	347	280	248	66			1461
1982			4	126	176	10	206	82	201	146	125	186	1262
1983	47	31	27	106	31	53	58	255	205	190	54	34	1091

Measurements are in hundredths of inches.

Carlsbad Caverns City, NM. Continued.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1984	35	3	12	9	250	312	198	641	147	270	91	46	2014
1985	35	34	23	35	106	111	57	69	299	230	11	2	1012
1986	31	45	11	0	175	898	179	151	255	276	275	252	2548
1987	29	102	36	28	468	491	35	438	56	78	41	146	1948
1988	2	49	2	72	181	179	531	381	499	1	0	44	1941
1989	3	93	52	16	42	211	83	122	251	6	0	21	900
1990	41	6	32	116	29	0	217	251	531	131	70	4	1428
1991	143	41	0	11	151	32	541	201	876	8	64	360	2428
1992	102	140	11	48	533	503	48	336	19	15	37	64	1856
1993	100	39	7	51	58	143	336	213	14	118	29		1108
1994	38	0	11	49	256	137	14	296	61	72	82	17	1033
1995	32	40	13	6	122	100	1	79	345	16	1	24	779
1996	36	0	1	71	19	187	89	494	220	20	44	0	1181
1997	47	191	8	179	185	151	64	183	332	303	42	284	1969

Carlsbad, NM. Gauge no. 291469.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1931	93	100	5	399	57	30	81	307	60	10	61	185	1388
1932	66	193	21	27	200	139	109	111	736	100	0	111	1813
1933	15	119	0	3	47	41	109	266	254	70	37	0	961
1934	0	0	67	20	185	35	105	121	18	117	8	3	679
1935	1	44	11	81	146	110	98	137	526	92	111	44	1401
1936	69	0	17	4	338	30	187	114	267	74	72	27	1199
1937	0	22	159	0	360	0	108	159	58	251	38	36	1191
1938	95	35	16	67	41	237	277	1	336	118	13	24	1260
1939	43	20	38	28	91	33	214	118	37	115	27	25	789
1940	10	40	0	131	305	197	62	158	26	231	69	1	1230
1941	67	74	427	144	1228	153	65	148	681	327	20	60	3394
1942	53	17	0	176	105	85	252	393	168	289	0	212	1750
1943	0	0	8	34	82	422	194	5	72	0	75	192	1084
1944	90	98	0	0	36	308	109	218	416	20	155	36	1486
1945	63	0	0	0	46	11	176	227	134	613	0	3	1273
1946	84	0	36	33	87	110	172	199	113	237	46	55	1172
1947	77	0	63	24	66	4	13	113	22	97	61	56	596
1948	9	41	4	12	91								157
1948						624	126	4	47	88	0	27	916
1949	231	5	20	38	146	481	157	46	581	124	0	19	1848
1950	2	25	1	49	157	134	548	115	268	320	0	0	1619
1951	14	34	105	67	117	5	96	178	5	22	0	0	643
1952	15	17	10	42	51	221		16	61	0	73	0	506
1953	2	1	44	35	105	43	169	47	16	93	0	42	597
1954	0	0	0	62	265	5	0	441	26	199	0	20	1018
1955	39	0	4	11	71	128	159	34	113	180	47	0	786
1956	0	70	0	0	55	11	95	165	0	28	0	16	440
1957	14		77	5	182	55	26	144	102	386	59	0	1050
1958	137	110	205	112	18	84	121	319	620	308	62	0	2096
1959	4		28	9	555	92	165	205	10	77	2	19	1166
1960	36	17	21	0	39	148	476	293	41	376	0	209	1656
1961	106	37	80	0	40	119	79	27	28	41	189	12	758
1962	51	16	13	66	94	237	436	4	258	99	1	31	1306
1963	15	38	4	193	150	29	45	476	35	8	0	23	1016
1964	2	12	26	0	31		31	71	189	10	13	10	395
1965	0	64	3	58	308	95	62	169	159	2	36	91	1047
1966	51	0	45	150	67	54	70	762	173	11	0	0	1383
1967	0	3	22	5	34	317	97	75	80	0	27	37	697

Carlsbad, NM. Gauge no. 291469.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1968		93	126	13	197	59	489	186	0	41	153	0	1357
1969	9	32	57	91	23	122	157	179	132	340	37	61	1240
1970	0	72	95	0	97	119	63	23	265	75	0	0	809
1971	13	8	3	37	1	2	250	397	226	24	54	100	1115
1972	4	8	0	0	169	493	208	202	532	186	68	4	1874
1973	86	183		0	64	83	288	3	272	84	0	0	1063
1974	52	10	11	9	29	61	15	443	1005	578	18	80	2311
1975	15	180		7	1	19	537	29	150	8	0	58	1004
1976	27	10	9	17	274	2	182	93	294	112	106	0	1126
1977	30	13	117	233	96	202	65	221	71	206	25		1279
1978		91	25	33	182	197	192	116	798	211	451	37	2333
1979	34	48	4	15	283	244	250	210	67	0	3	91	1249
1980	83	59	0	118	69	91	52	90	1227	30	103	20	1942
1981	59	18	43	355		153	363	208	208	76	0	0	1483
1982		24	0	35	226	19	208	63	96	234	106	238	1249
1983	35	57	33	139	42	61	53	127	189	264	47	20	1067
1984	30	0	20	0	336	226	330	770	204	314	100	93	2423
1985	61	19	34	69	170	300	30	74	310	184	4	1	1256
1986	26	56	5	0	150	569	56	110	175	182	251	232	1812
1987	31	85	35	63	130	536	25	398	157	63	45		1568
1988	2	48	1	42	82	225	241	374	474	0	0	5	1494
1989	2	100	43	22	20	80		127	161	12	0	27	594
1990	69	5	59	86	14	3	413	211	63	123	87	11	1144
1991	142	19	1	0	61	68	748	77	829	2	40	379	2366
1992	80	157	16	51	421	257		114	278	12	30	45	1461
1993	122	42	2	63	14	89	131	200	7	93	38	0	801
1994	13	7	6	18	236	39	20	162	31	70	109	9	720
1995	34	36	25	0	135	116	14	47	297	11	0	30	745
1996	62	0	0	84	0	228	97	670	200	13	44	0	1398
1997		226	13	178	141	101	57	311	215	495	49	247	2033

Lake Avalon, NM. Gauge no. 294736.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1931	104	90	10	367	11	28	124	216	60	38	85	195	1328
1932	72	209	40	23	155	270	106	47	631	79	0	104	1736
1933	12	87	0	0	61	19	96	247	290	16	59	0	887
1934	0	7	90	27	155	0	18	46	10	163	13	4	533
1935	0	38	25	71	156	182	228	47	349	100	110	46	1352
1936	75	5	0	5	578	20	172	46	503	90	105	18	1617
1937	0	20	179	0	378	41	38	234	44	182	0	38	1154
1938	63	52	21	74	30	252	242	8	280	43	5	18	1088
1939	38	13	38	28	114	255	212	80	135	80	53	5	1051
1940	36	36	9	103	206	95	78	112	0	287	45	7	1014
1941	68	58	312	77	1224	278	279	226	760	255	18	72	3627
1942	45	44	12	160	61	43	143	261	168	270	0	201	1408
1943	0	0	10	3	191	241	102	0	52	27	37	117	780
1944	75	78	0	2	8	247	80	193	373	14	162	25	1257
1945	51	7	11	0	2	7	214	187	73	477	0	12	1041
1946	37	25	30	119	75	36	146	110	130	206	34	41	989
1947	80	0	52	15	235	2	18	198	19	18	36	11	684
1948						648	119	46	0	48	0	21	882
1948	12	49	2	7	108								178
1949	201	2	5	32	58	207	40	101	360	62	0	8	1076
1950	2	22	0	13	95	174	380	41	217	191	0	0	1135
1951	8	2	52	16	267	1	97	190	1	29	8	0	671
1952	12	0	3	24	46	240	146	22	62	0	64	1	620
1953	10	4	8	31	173	54	132	58	1	71	0	15	557
1954	0	0	0	81	324	9	12	442	5	292	0	6	1171
1955	39	0	0	6	99	77	309	11	239	303	22	0	1105
1956	2	27	0	7	67	132	91	226	4	53	0	20	629
1957	4	35	75	1	330	2	86	127	5	406	94	0	1165
1958	135	82	95	105	40	58	111	403	597	298	83	0	2007
1959	4	8	15	17	447	65	266	125	19	79	0	29	1074
1960	25	0	13	0	55	163	328	169	19	452	0	184	1408
1961	99	29	71	0	24	116	5	8	46	5	190	12	605
1962	74	12	13	79	88	154	358	0	235	72	0	26	1111
1963	9	24	0	149	109	18	20	344	22	27	0	18	740
1964	3	9	24	0	29	27	84	58	214	0	10	35	493
1965	0	63	10	30	204	39	46	115	138	0	10	81	736
1966	34	0	76	137	16	33	47	665	126	0	0	0	1134
1967	0	0	17	0	56	200	100	106	182	0		28	689
1968	137	98	124	6	196	10	643	251	8	32	189	15	1709

Lake Avalon, NM. Continued.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1969	9	46	142	89	37	84	170	197		505	14		1293
1970	0	71	92	0	16	116	102	44	302	103	0	0	846
1971		0	0	44	0	20	192	438	212	49	71	59	1085
1972		6	0	0	88	346	134	152	485	464	123	4	1802
1973	94	159	100	27	70	115	367	0	455	130		0	1517
1974	38	13	29	41	0	50	70	381	831	545	19	80	2097
1975	33	213	19	15	64	0	356	29	319	60	0	52	1160
1976	90	0	20	10	202	0	177	67	465	109	50	0	1190
1977		14	92	151	72	127	7	234	44	148	0	0	889
1978		62	37	30	140	272	63	79	854	193	352		2082
1979	71												

Queen RS, NM. Gauge no. 297176

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1963	24	15	10	107	19	211	2	184	298	84	29	35	1018
1964	1	83	4	6	97		75	180	222	21	2	49	740
1965	0	76		2	127	240	60	470	417	0	11	102	1505
1966	57	11	10	167	55	342	79	1003	209	5	0	22	1960
1967	0	20	0	0	11	482	334	431	65				1343
1968	340	95	167		0	0	706	400	0	30	268	70	2076
1969	0	7	30	41	70	50	258	1088	447	225	160	260	2636
1970	38	221	270	0	75	180	177	309	478	180	0	0	1928
1971			0	55	27	13	112	470	196	68	50		991
1972		13	0	0	10	374	128	401	615	106	157	82	1886
1973	242	371	231	10	55	141	218	224	395		52	0	1939
1974	192	47	27	20	0	0	290	264	1100	610	35		2585
1975	56	197	80										

Brantley Dam, NM, Gauge no. 291153.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1987								105	33	51	0	226	415
1988	5	38	1	59	52	192	380	288	435	0	0	44	1494
1989	15	100	26	5	28	97	44	282	75	1	0	12	685
1990	21	0	58	102	16	37	318	334	305	86	90	11	1378
1991	111	17	0	9	120	130	547	242		20	79	303	1578
1992	61	135	23	73	538	232	331	86	72	28	38	20	1637
1993	85	34	2	50	67	76	71	173	58	92	41	2	751
1994	12	0	33	14	469	44	25	228	25	32	96	9	987
1995	27	29	8	6	141	196	66	85	339	7	0	23	927
1996	43	0	0	83	0	215	80	353	169	11	31	0	985
1997	35	114	5	193	164	263	77	81	281	239	43	206	1701

Red Bluff Dam, TX. Gauge no. 417481.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1939											14	38	52
1940	17					320	13	155	0	180		10	695
1941	60	136	90	226	971	193	29	28	557	310	10	20	2630
1942	3			59	60	3	134	42	194	76	21	231	823
1943	12	0	18	3	103	285	160	0	38	61	18		698
1944	57	44	0	0	4	216	135	322	452	3	171	58	1462
1945	55		82	9	61	6	281	266	82	178	0	0	1020
1946	179	0	0	66	26	124	125	119	164	241	13	75	1132
1947	63		79	31	147	20			0	0	69	26	435
1950										120	0		120
1951	0		76										76
1952	6	44	0	48	51	25	197	40	9	0	48	13	481
1953	0	8	26	27	5	9	170	107	0	250	0	11	613
1954	5	0	4	166	75	87	45	336	0	42	0	3	763
1955	73	0	4	0	128	30	92	12	112	212	36	0	699
1956		4	0	71	76	8	43	39	14	29	0	20	304
1957	14	149	47	26	73	4	30	44	37	366	63	1	854
1958	175	92	71	58	50	210	201	235	366	202	23	0	1683
1959	2	8	0	11	207	154	158	106	61	139	22	29	897
1960	19	6	10	1	85	75	610	296	28	291	4	190	1615
1961	64	2	51	0	82	254	86	115	85	0	90	18	847
1962	14	8	13	24	67	50	141	17	142	140	0	18	634
1963	7	8	0	32	125	73	4	370	102	6	20	7	754
1964	0	0	36	0	152	229	62	33	105	11	0	15	643
1965	3	12	2	0	200	218	171	39	94	0	54	34	827
1966	30	0	13	76	106	301	3	356	58	8	0	0	951
1967	0	2	22	26	56	160	141	25	98	0	50	40	620
1968	45	64	116	14	100	47	150	230	112	36	160	0	1074
1969	3	33		41	84	256	96	2	370	445	50	17	1397
1970	0	90	158	0	0	218	112	44	415	80	0	8	1125
1971	6	0	0	10	0	71	259	471	369	63	0	37	1286
1972	22	0	0	0	86						37		145
1973	99		29	0	37	45	285	10	132	98	7	0	742
1974	138	0	18										156
1975			15	0	120	11	107	134	175	28	18	58	666
1976	10	5	45	16	195	0	144	0	389	173		0	977
1977	53	6	37	90	21	209	44	62	46	184	22	17	791
1978	9	66	22	7	134	321	325	107	834	190	327	34	2376

Red Bluff Dam, TX. Continued.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1979		55	2	0	95	222	371	291	49	0	0	74	1159
1980	61	14	0	30	68	18	0	75	776	30	105		1177
1981	130	35	114	407	71	428	315	164	253	171	0	0	2088
1982	11	2	0	99	113	52	306	46	68	0	126	333	1156
1983	136	10	9	90				0	84	59			388
1984			0	0	219	780	20	320	153	211	66	96	1865
1985	46	71	41	0	60		136	21	214	194	56	0	839
1986	24	59	16	0	137	848	23	242	244	211	100	390	2294
1987	19	142		30	206	386	0	416	67	55	21	87	1429
1988	0	18	0	18	117	24	420	220	306	0	0	22	1145
1989	18	122	4	0	35	92	30	457	86	0	0	23	867
1990	81	24	28	118	5	0	535	169	569				1529
1992							140	45	0	0	0	0	185
1993		16	38	39	9	12	265	75	9	53	13	12	541
1994	32	2	11	0	176	209	69	0	141	50	19	46	755
1995	18	13	20	31	148	197	37	12	410	117	0	37	1040
1996	25	0	0	99	0	276	400	308	175	10	48	0	1341
1997	16	43	12	184	42	189	130	62	95	29	40	122	964

Pine Springs 1 NE, TX. Gauge no. 417044.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1939	98	10	114	18	70	20	216	512	0	105	153	45	1361
1940	132	81	48	40	103	144	141	240	0	244			1173
1941	32	212	252	193	304	359	522	439	1474	346	19	95	4247
1942	13	83	5	266	17	192	319	678	91	184	10	244	2102
1943	54	0	28	15	139	559	230	13	249	0	95	254	1636
1944	133	212	1	0	33	153	293	388	492	30	56	101	1892
1945	95	0	112	16	0	8	365	483	70	370	0	20	1539
1987		170	176	72	271	396	193	234	126	52	126	91	1907
1988	26	63	10	168	102	31	527	296	140	30	58	18	1469
1989	22	122	28	0	101	80	303	379	126	5	0	48	1214
1990	12	61	102	22	22	0	418	513	749	397		63	2359
1991						82	525	786	652	34	184	287	2550
1992	295	23	50	105	398	94	247	376	66	68	47	28	1797
1993	94	83	17	27	26	93	476	118	77	94	77	28	1210
1994		50	60	41	192	72	197	78	200	175	204	108	1377
1995	127	142	98	7	41	281	181	344	304	4	12	163	1704
1996	18	71	0	84	0	597	148	612	323	41	83	40	2017
1997	62		28	87	123	132	139	213	215	208	150	338	1695