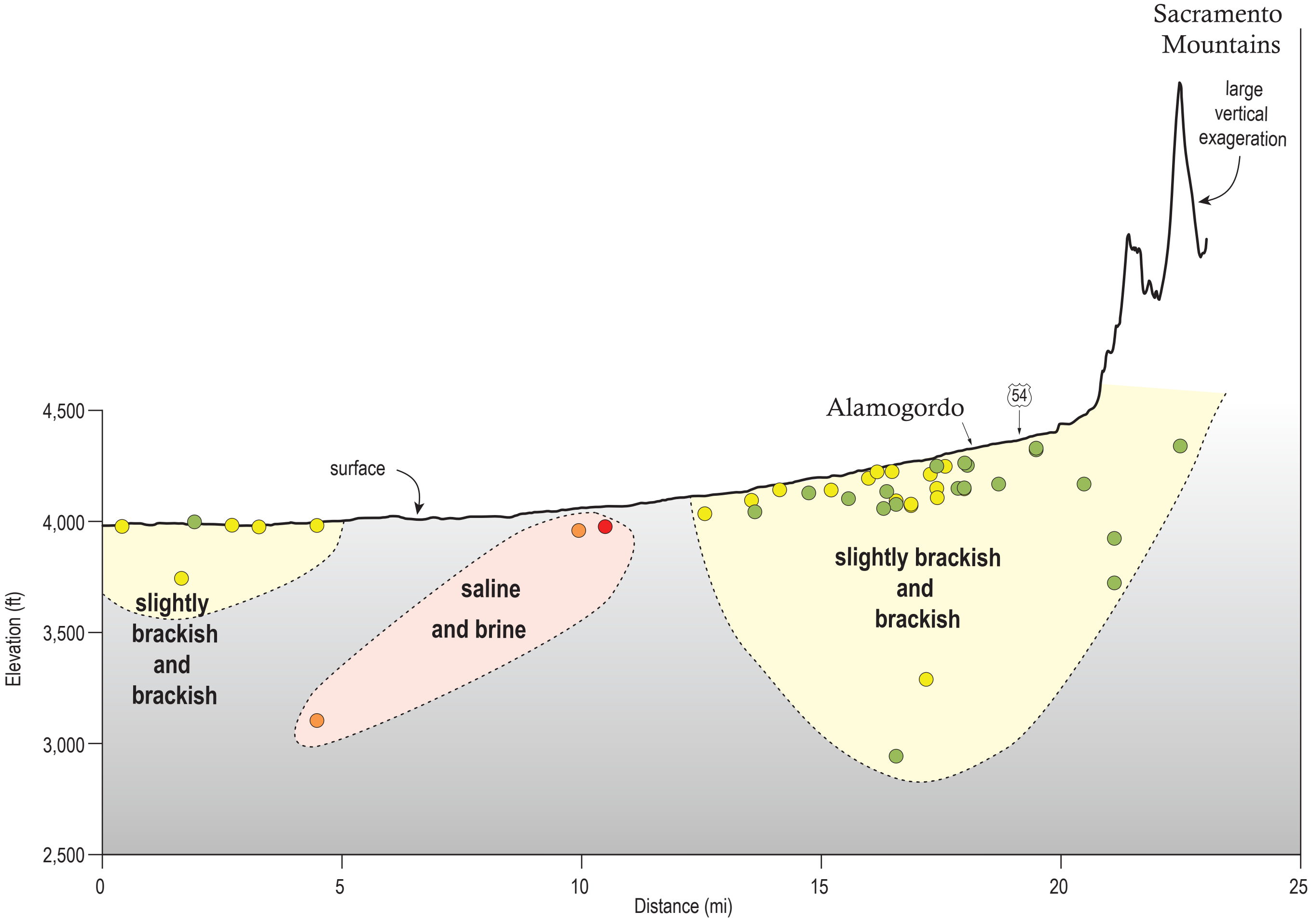
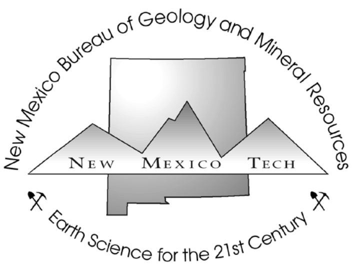
NEW MEXICO BUREAU OF GEOLOGY AND MINERAL RESOURCES

Brackish Water Assessment in the Eastern Tularosa Basin, New Mexico

B. Talon Newton
Lewis Land

Open-file Report 582
June 2016





New Mexico Bureau of Geology and Mineral Resources

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AQUIFER
MAPPING
PROGRAM

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PROJECT FUNDING

Funding for this project is from the New Mexico Environment Department, Drinking Water Bureau, MOU 16 667 3000 0006, Project 4.

CONTENTS

Figures

Tables

EXECUTIVE SUMMARY

Communities in the Tularosa Basin, including Tularosa and Alamogordo, face serious challenges related to water resources, both in terms of water quantity and quality. An arid climate, limited surface water as streams or rivers, variable groundwater quality, and projected population increases make water resource management in the Tularosa Basin challenging. Groundwater accounts for approximately 70% of all water use in the area, including irrigation, domestic use, and public supply. It has been estimated that less than four percent of groundwater in the Tularosa Basin is fresh with total dissolved solids (TDS) of less than 1,000 milligrams per liter (mg/L). Most public supply wells pump relatively fresh water from very localized zones located on the eastern margin of the basin at the base of the Sacramento Mountains.

Plans to pump and desalinate brackish water (1,000–10,000 mg/L TDS) for public water supply for Alamogordo are in development. There are concerns about the effect of pumping large quantities of brackish water on the water quality for multiple other users. To evaluate the potential impacts of pumping brackish water on existing water resources, it is necessary to know the spatial distribution of groundwater salinity. This report describes recent efforts by the New Mexico Bureau of Geology and Mineral Resources (NMBGMR) to assess the spatial distribution of groundwater salinity in the Tularosa Basin. The objectives of this study were to:

1) Compile and review existing water chemistry data in the area to assess the spatial distribution of groundwater salinity
2) Collect up to 30 water quality samples to address spatial and temporal data gaps
3) Using all data, provide an assessment of fresh and brackish water resources
4) Suggest future research to improve understanding of groundwater salinity in the Tularosa Basin

The study area of interest focuses on the east-central portion of the Tularosa Basin, specifically around the communities of Tularosa and Alamogordo. The Tularosa Basin is a fault-bounded basin with the San Andres Mountains to the west and the Sacramento Mountains to the east. The basin is filled with 3,000–4,000 feet of sediment as a result of millions of years of erosion.

Surface water from a few perennial and ephemeral streams that drain the Sacramento Mountains provide a portion of the water for public water supply and agriculture. These surface water resources are vulnerable to drought.

Existing water chemistry data from historical reports, the NMBGMR, the United States Geologic Survey (USGS), and the New Mexico Environment Department (NMED) were compiled to identify spatial trends and data gaps. The data include water chemistry results from the last 100 years from research projects and monitoring programs. The NMED data are results from water quality testing and protection of public health. As part of this study, samples were collected from twenty-one domestic wells and analyzed for major cations and anions, trace metals, and stable isotopes of oxygen and hydrogen.

Compiled data show that the freshest water in the study area is located south of Alamogordo on the eastern margin of the basin, where many public supply wells are located. To the north, along the eastern margin of the basin, groundwater tends to be slightly brackish (1,000–3,000 mg/L TDS). In general, groundwater salinity increases toward the west. Samples collected in February 2016 exhibited the same trends as described above. On a large scale, the spatial distribution of groundwater salinity appears to be controlled by locations of groundwater recharge, as it mixes with more saline groundwater, and water/rock interactions. Groundwater recharge to the basin fill aquifer primarily occurs at the eastern margin of the basin, resulting in fresher water in this area. The westward increase in TDS concentrations is likely due to mixing of this fresher recharge water with saline water to the west and the dissolution of minerals in the basin fill aquifer as it flows to the west.

However, on a scale of hundreds to thousands of feet groundwater salinity is highly variable. This complexity is due in part to variations in porosity and permeability of sediments in the basin-fill aquifer, and the localized nature of groundwater recharge processes in the Tularosa Basin. For example, groundwater near La Luz Creek exhibits slightly lower TDS values due to local recharge from the creek. However, this trend was not observed for other streams, such as Rio Tularosa, which may reflect lithologic differences. Repeat TDS measurements for a few wells showed that TDS concentrations can change significantly over a few months and over the course of several years.

The available data are insufficient to conclusively assess the possible effects of pumping brackish water upon existing water resources. However, the potential for deterioration of groundwater quality on both a short-term local scale and on a long-term regional scale exists. Increases in the pumping of brackish water may mobilize water in localized zones of different salinities, resulting in the deterioration of water quality in nearby wells. Prolonged pumping of brackish water may significantly affect the regional groundwater flow regime, and could cause encroachment of more saline water.

Most wells are located in and around the local communities. The total population in the basin is relatively small and communities are separated by large expanses of ranches and federally-owned land where no wells exist. Therefore, we cannot determine the salinity distribution in groundwater for a large proportion of the study area. This bias is also seen in the vertical salinity distribution. Most wells are less than 400 feet deep, which represents a very small proportion of the entire basin fill aquifer. We propose that future work includes the installation of monitoring wells and the use of geophysical techniques, such as measurements of the electrical resistivity of the subsurface, to better characterize the three-dimensional distribution of groundwater salinity.

I. INTRODUCTION

Water resources in the Tularosa Basin are greatly limited due to the arid climate, scarce surface water and poor groundwater quality. In general, groundwater in the Tularosa Basin is characterized by a high total dissolved solids (TDS) content. It has been estimated that within the basin-fill aquifer, which covers an approximate area of 6,500 square miles and is thousands of feet deep in areas, less than four percent of stored groundwater is fresh with a TDS value of less than 1000 milligrams per liter (mg/L) (Orr and Myers, 1986).

Local communities, including Alamogordo and Tularosa heavily rely on groundwater for public water supply, agriculture, and domestic use. For the entire basin, groundwater accounts for about 70% of all water diversions in 2010 (Longworth et al., 2013); it accounts for approximately 57% of the public water supply, 79% of irrigation diversions, and 100% of domestic water use.

The quality of groundwater is suitable for some types of agriculture, but any deterioration in water quality will have significant negative impacts on crops in the Tularosa Basin. Residents of the areas surrounding Alamogordo and Tularosa are greatly impacted by the poor groundwater quality. Many residents with private wells rely on bottled water for drinking and use a water softener to treat well water for other uses including washing dishes and bathing.

Currently, public water supplies for local communities barely meet demands, and some communities periodically need to supplement the water supply with groundwater of poor quality (>1,000 mg/L), which must be blended with surface water to dilute the concentrations of dissolved minerals (New Mexico Office of the State Engineer, 2016). Water demand was projected to increase by 30% between the years 2000 and 2040 (Livingston and JS&A, 2002), mainly due to population growth. While poor water quality has largely been seen as a significant limitation in terms of water resources, the option of desalination of these brackish waters may significantly supplement the public water supply in the Tularosa Basin in the near future.

The 2016 draft of the Tularosa, Great Salt and Sacramento River Basins Regional Water Plan states that much of the groundwater in the region is brackish with TDS concentrations greater than 1,000 milligrams per liter and that the development of brackish groundwater resources can be an additional source of water supply for this region. The Alamogordo Regional Water Supply Project is a plan to develop 4,000 acre-feet of brackish groundwater from the Tularosa Basin as a new source of water for the city of Alamogordo (BLM, 2012). This project will be discussed in more detail below.

Most groundwater is produced from the basin fill aquifer, which is composed of gravel, sand, silt and clay. Previous studies (Mamer et al., 2014) have suggested that much of the groundwater in the Tularosa Basin is thousands of years old and that groundwater recharge is limited. Therefore, there is concern about the depletion of potable water and the resulting deterioration of the quality of groundwater being pumped. In addition, there is also concern about how the future pumping of brackish water for public water supply may affect the quality of existing groundwater resources, including public water supply, irrigation, domestic, and others. Variations in water quality within the basin-fill aquifer depend on many factors, including the location of the recharge area, the spatial arrangement of the different sediment types that make up the aquifer, and the density of the water; water with high TDS concentrations is more dense than water with low TDS concentrations. In order to understand how the pumping of brackish water may affect groundwater quality near the communities of Tularosa and Alamogordo, it is necessary to know the characteristics of fresh and brackish waters in the aquifer.

In the subsequent sections of this report, the terminology that describes different ranges in groundwater salinity is defined in Table 1. For context, the average salinity of seawater is 35,000 mg/L.

Table 1. Catagories of different groundwater salinities based on TDS concentrations.

Total dissolved solids (mg/L)	**Water type**
0–1,000	Fresh water
1,000–3,000	Slightly brackish water
3,000–10,000	Brackish water
10,000–35,000	Saline water
>35,000	Brine

Scope of Work

This report describes recent efforts by the New Mexico Bureau of Geology and Mineral Resources to assess the spatial distribution of groundwater salinity in the eastern Tularosa Basin, with the intent to gain an understanding of how pumping brackish water may affect the current water supply in local communities. The objectives of this study were to:

1. Compile and review existing water chemistry data in the area to assess the spatial distribution of groundwater salinity
2. Collect up to 30 water quality samples to address spatial and temporal data gaps
3. Using all data, provide an assessment of fresh and brackish water resources
4. Suggest future research to improve understanding of groundwater salinity in the Tularosa Basin

II. STUDY AREA

The study area of interest focuses on the east-central portion of the Tularosa Basin, specifically around the communities of Tularosa and Alamogordo (Figure 1). The Tularosa Basin is a topographically closed basin with internal drainage that covers approximately 6,500 square miles and extends from Chupadera Mesa in the north to a gentle topographic rise in Texas that separates the Tularosa Basin and the Hueco Bolson. The basin is bounded on the west by the Oscura, San Andres and Franklin Mountains and on the east by the Sacramento Mountains and Otero Mesa. Alamogordo is the largest city in the Tularosa Basin, with a population of over 30,000. Other communities include La Luz, Tularosa, Oscuro, and Carrizozo. A large proportion of the basin is rangeland, much of which is occupied by military installations, including Fort Bliss Military Reservation, Holloman Airforce Base, and White Sands Missile Range. Although agriculture is limited due to an inadequate fresh water supply, common crops include forage for livestock, pecans, pistachios, apples, and cherries.

Geology

The present day landscape in the Tularosa Basin is primarily a result of tectonic forces associated with the Rio Grande rift, combined with extensive erosion over the past 25 million years. The Tularosa Basin is a fault-bounded basin (Figure 2, Figure 3) with two half-grabens (Figure 3). The eastern half-graben is bounded on the east by the west-down Alamogordo fault zone and on the west by the west-down Jarilla fault zone. The San Andres Fault defines the western edge of the basin.

The surrounding mountains are mainly composed of volcanic and Paleozoic sedimentary rocks (Figure 2). The most current geologic descriptions of the western side of the Sacramento Mountains is provided by Koning et al. (2014) and Kelley et al. (2014) and is summarized by Mamer et al. (2014). The geology along the steep western escarpment of the mountains varies considerably from north to south. These geologic variations significantly affect the groundwater chemistry.

North of Three Rivers, the high mountain geology is dominated by upper Eocene and lower Oligocene volcanic rocks and igneous intrusives that effectively fill a structural low, called the Sierra Blanca Basin. To the immediate west, exposed rocks include highly faulted Cretaceous sandstones and shales. Another prominent feature in the norther portion of the basin is the basalt lava flow near Carrizozo. In the high mountains and west facing slopes to the south, the geology is characterized by highly faulted and fractured Paleozoic sedimentary rocks, including the San Andres, Yeso and Abo Formations. These rocks contain significant amounts of carbonates and evaporites (salts), which affect the water chemistry in this area.

Since rifting began approximately thirty million years ago, the basin has filled with thousands of feet of alluvial-fan, piedmont-slope, alluvial-flat and playa deposits. Basin fill includes weakly to well consolidated sediment. The basin fill thickness is 3,000–4,000 feet thick near Tularosa (Mamer et al., 2014). The basin fill becomes finer grained with increasing distance from the mountain front. Alluvial fan deposits on the edge of the basin margin and alluvial deposits in the basin consist of sand, gravel, silt and clay. In these areas channelization of sediments has resulted in zones of higher permeability, through which water can move more easily. In the central/western part of the basin, lacustrine deposits are predominantly clay with some fine sand layers.

A unique feature of the western Tularosa Basin is the White Sands gypsum dune field. Underlying the dune field are recrystallized gypsum deposits and lacrustrine (lake) deposits, which are primarily clay (Orr and Myers, 1986). Orr and Myers (1986) describe a well log from a test well that was drilled to evaluate the availability of water from the deeper section of the basin fill deposits. The test well is located in the southern part of the basin and is almost 6,000 feet deep. The top 180 feet consists of coarse grained sand, silt, clay and gravel. The interval from 180 to approximately 3,620 feet below the surface consists primarily of clay with thin beds of fine and medium grained sand. At depths greater than 3,620 feet, the sediments consist of mostly sand with

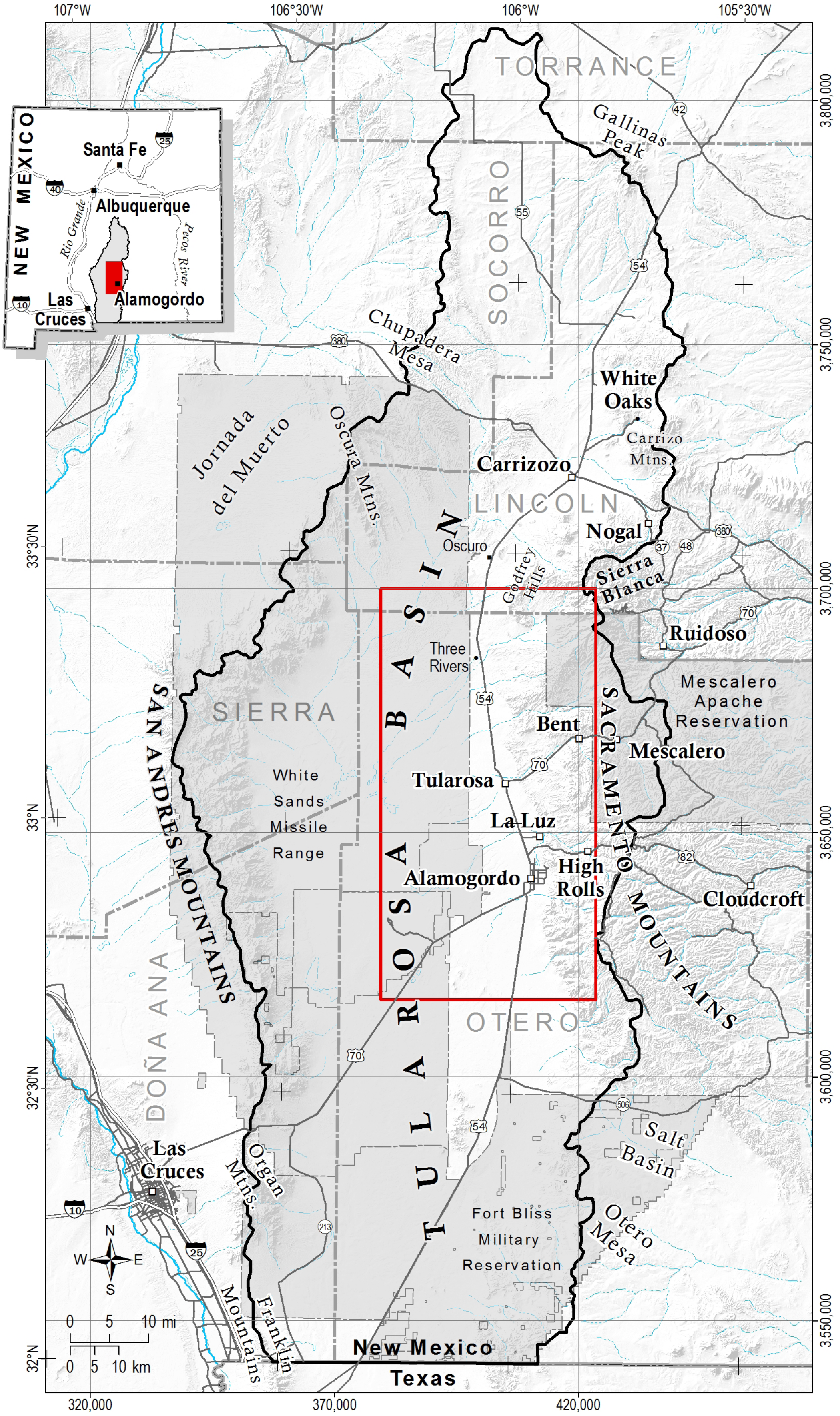


Figure 1. Tularosa Basin and surrounding features. The red outline indicates the area of focus for this study.

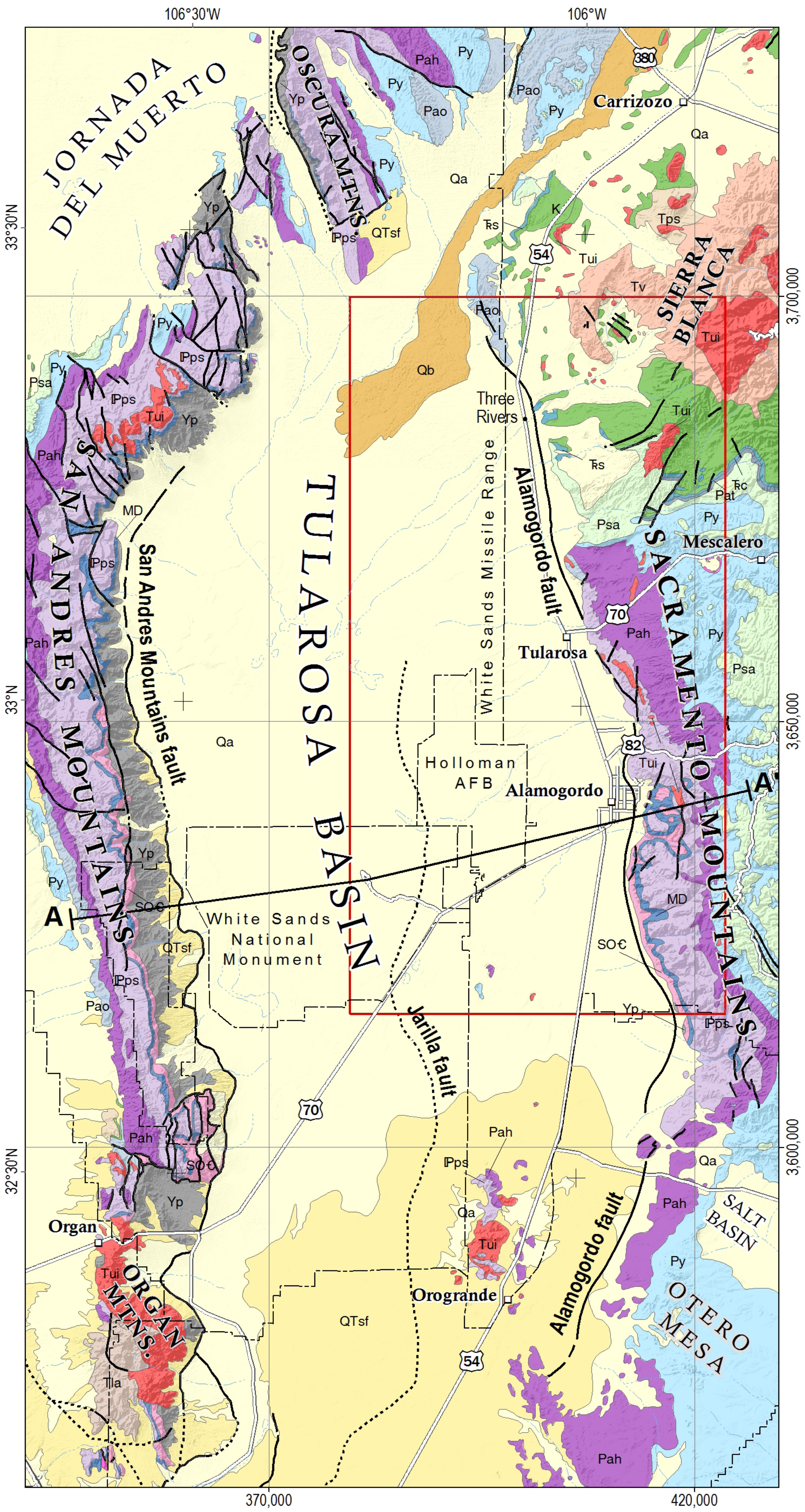


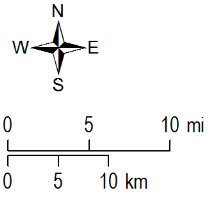
Figure 2. Generalized geologic map of the Tularosa Basin. A-A' denotes cross-section line shown in Figure 3.

Geologic Units

🟨	Qa	*Alluvium, piedmont and playa deposits (Quaternary)*
🟧	Qb	*Basalt lava flows (Quaternary)*
🟨	QTsf	*Sedimentary rocks (Quaternary/Tertiary)*
⬜	Tps	*Sedimentary rocks (Eocene - Paleocene)*
🟧	Tv	*Volcanic rocks (Tertiary-Upper Createous)*
🟥	Tui	*Igneous Intrusions (Tertiary)*
🟫	Tla	*Andesite and basaltic flows (Lower Tertiary)*
🟦	TRc	*Chinle Group (Upper and Middle Triassic)*
🟩	K	*Sedimentary rocks (Upper Createous)*
🟩	Psa	*San Andres Formation (middle Permian)*
🟦	Pao	*Sedimentary rocks (middle and upper Permian)*
🟦	Pat	*Artesia Group (middle Permian)*
🟦	Py	*Yeso Formation (Lower Permian)*
🟪	Pah	*Abo and Hueco Formations (Lower Permian)*
🟪	IPps	*Sedimentary rocks (Pennsylvanian)*
🟦	MD	*Sedimentary rocks (Mississippian-Devonian undivided)*
🟪	SOꞒ	*Sedimentary rocks (Silurian-Cambrian)*
⬛	Yp	*Granitic rocks (Precambrian)*

Map Symbols

———	Fault, exposed
— —	Fault, intermittent-obscured
⋯⋯	Fault, concealed



thin clay layers. It is difficult to correlate specific units from this well log to data from wells in other parts of the basin. However, it is reasonable to assume that the vertical distribution of sediments in much of the eastern margin of the basin can be characterized similarly with coarse sediments at shallow depths (top few hundred feet), mostly clays at intermediate depths (~1,000–3,000 feet), and coarser sediments at depths greater that ~3,000 feet (Personal communication, Dan Koning, 2016). Toward the center of the basin, the vertical distribution of sediments is probably dominated by finer grained units (Orr and Myers, 1986)

The characterization of sediments that make up the basin fill aquifer is important for understanding the hydrogeology of the Tularosa Basin, because water moves through different sediments at different rates. Fresh water that is moving from the adjacent mountains will preferentially flow through sediments of higher permeability, such as sands and gravels, while older groundwater, with higher TDS concentrations, may reside in finer sediments, such as silts and clays. Therefore the spatial arrangement of these sediments in the subsurface largely controls the spatial distribution of groundwater salinity.

Hydrogeology

Surface Water

The study area is characterized by a semi-arid climate with a mean annual rainfall ranging from 10 in/yr in the central parts of the basin to ~30 in/yr in the adjacent Sacramento Mountains. No major rivers flow through the Tularosa Basin, and the only available surface water supplies are from springs, small streams, and artificial reservoirs in the Sacramento Mountains. There are four major stream systems that drain the western slopes of the Sacramento Mountains: Nogal Creek, Three Rivers, Rio Tularosa, and La Luz Creek (Figure 4). Three Rivers and Rio Tularosa are perennial, while the other streams are ephemeral, flowing primarily during the monsoon season (July through September). These drainages are important features because most groundwater recharge to the basin fill aquifer occurs along these streams (Mamer et al., 2014; Waltemeyer, 2001). Springs are the primary source for many streams in the area that drain into the Tularosa Basin. Spring discharge rates are generally low, less than 6 gallons per minute (gpm) (Mamer et al., 2014).

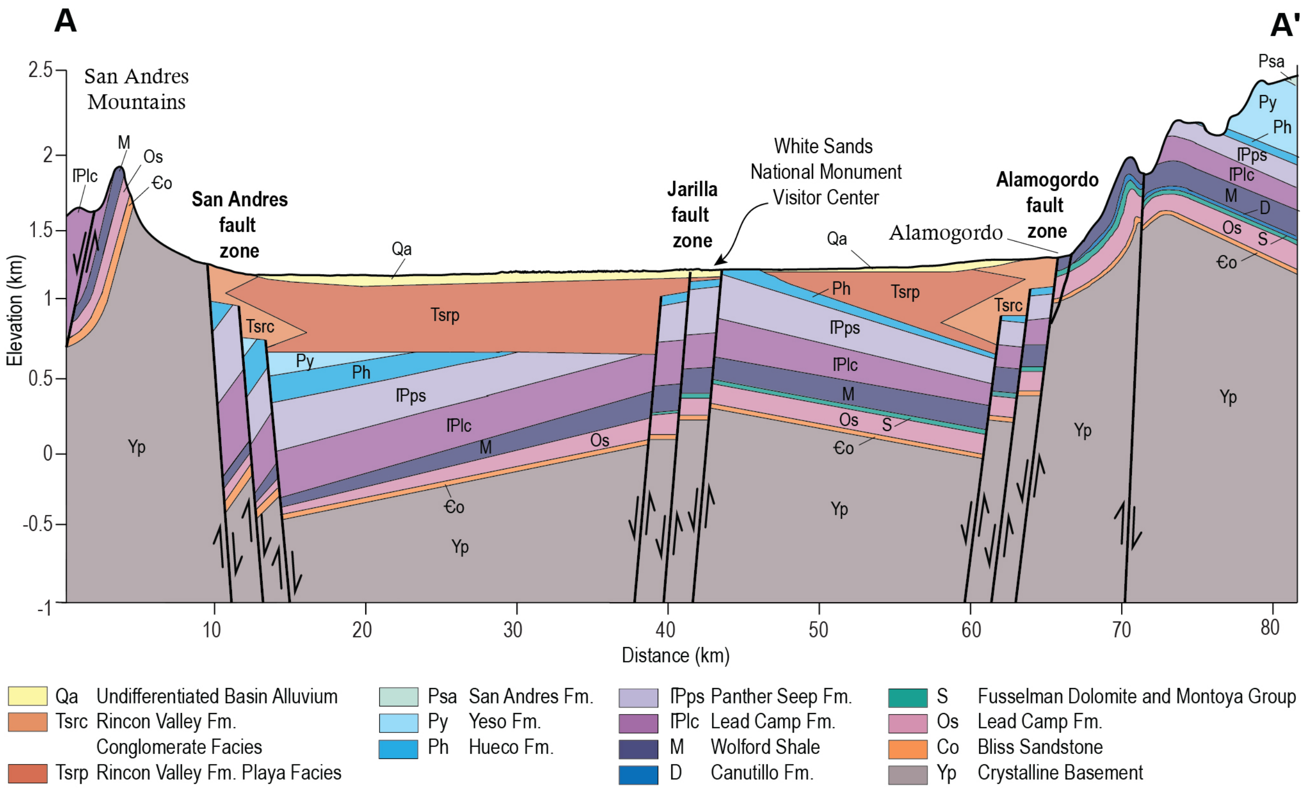


Figure 3. Geologic cross section of the Tularosa Basin.

In the year 2000, approximately 25% of water diversions for all uses in the basin, including public water systems, domestic use, livestock, agriculture, etc., came from surface water (Livingston and JS&A, 2002). Currently, surface water makes up approximately 70% of Alamogordo's public water supply. Because surface water is ultimately derived from snow melt and monsoon rains in the Sacramento Mountains, as a water supply it is very vulnerable to drought. Bonito Lake, located in the northern Sacramento Mountains, historically supplied many communities in the basin, including Alamogordo, with a significant amount of water via a pipeline. In 2012, the Little Bear fire damaged Bonito Lake, and it is not currently (presumably temporarily) supplying water to local communities.

Groundwater

Within the Sacramento Mountains domestic, irrigation, and stock wells produce water from a variety of sedimentary and volcanic geologic units. Mamer et al. (2014) describe how water moves from streams and aquifers in the mountains to the basin fill aquifer, which provides most groundwater resources for communities in the Tularosa Basin. It has been estimated that 8.9% of precipitation on the western slopes of the Sacramento Mountains provides recharge to the basin fill aquifer (~67,900 AFY) (Mamer et al. (2014). Although some of this recharge does move through the mountain block as groundwater, most recharge to the basin fill aquifer occurs at mouths of surface water drainages, where stream water infiltrates into porous alluvial fan material.

Most groundwater used in the Tularosa Basin resides in the basin fill aquifer. Figure 5 shows the water table map for this aquifer. The water level elevation contours represent the surface of the top of the aquifer (water table). In general, groundwater flows from high groundwater level elevations to low water level elevations. The water table map shows that groundwater flows from the north and east to the south and west, and supports the conclusions of Mamer et al. (2014) and other researchers' (e.g., Meinzer and Hare, 1915; Orr and Myers, 1986; Waltemeyer, 2001) that the basin fill aquifer is recharged by precipitation in the Sacramento Mountains to the east. However, it appears that some groundwater is also flowing from the north. The semi-closed 3900 ft contour suggests that the area near Lake Lucero, an ephemeral playa, is a discharge area. Researchers have shown that groundwater leaves the groundwater system in this area

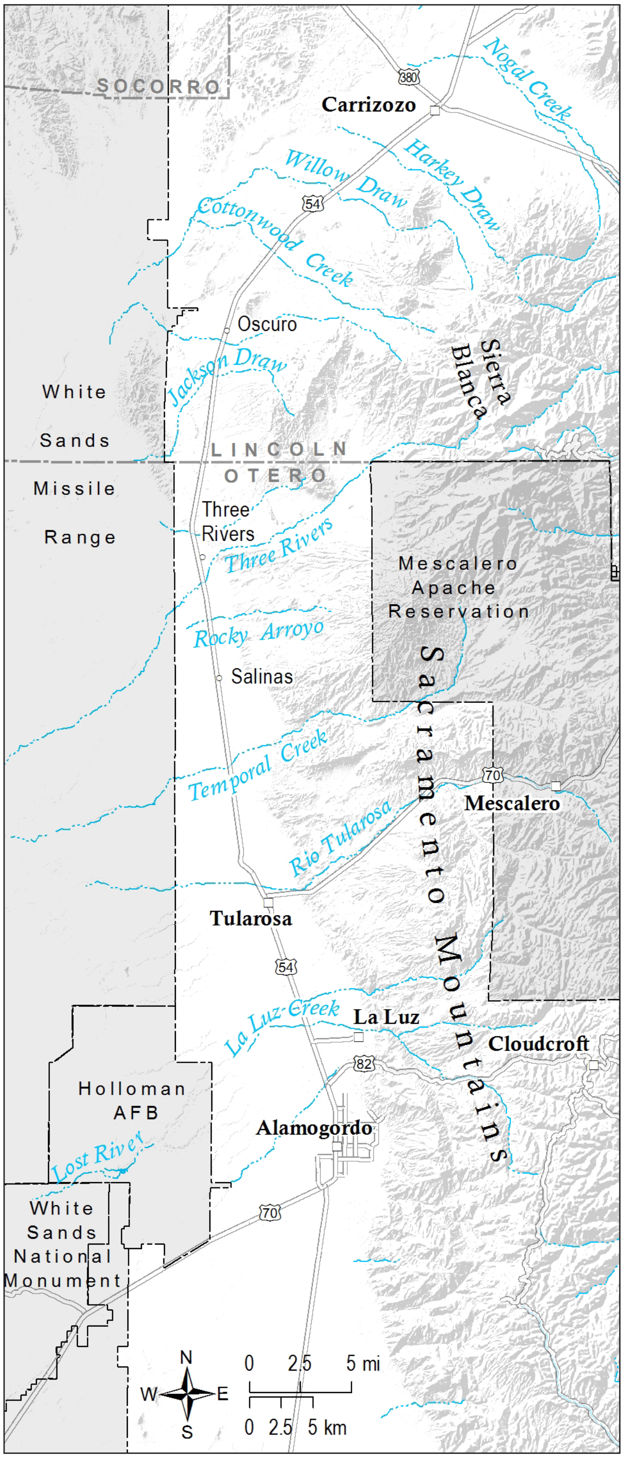


Figure 4. Perennial and ephemeral streams in the Tularosa Basin.

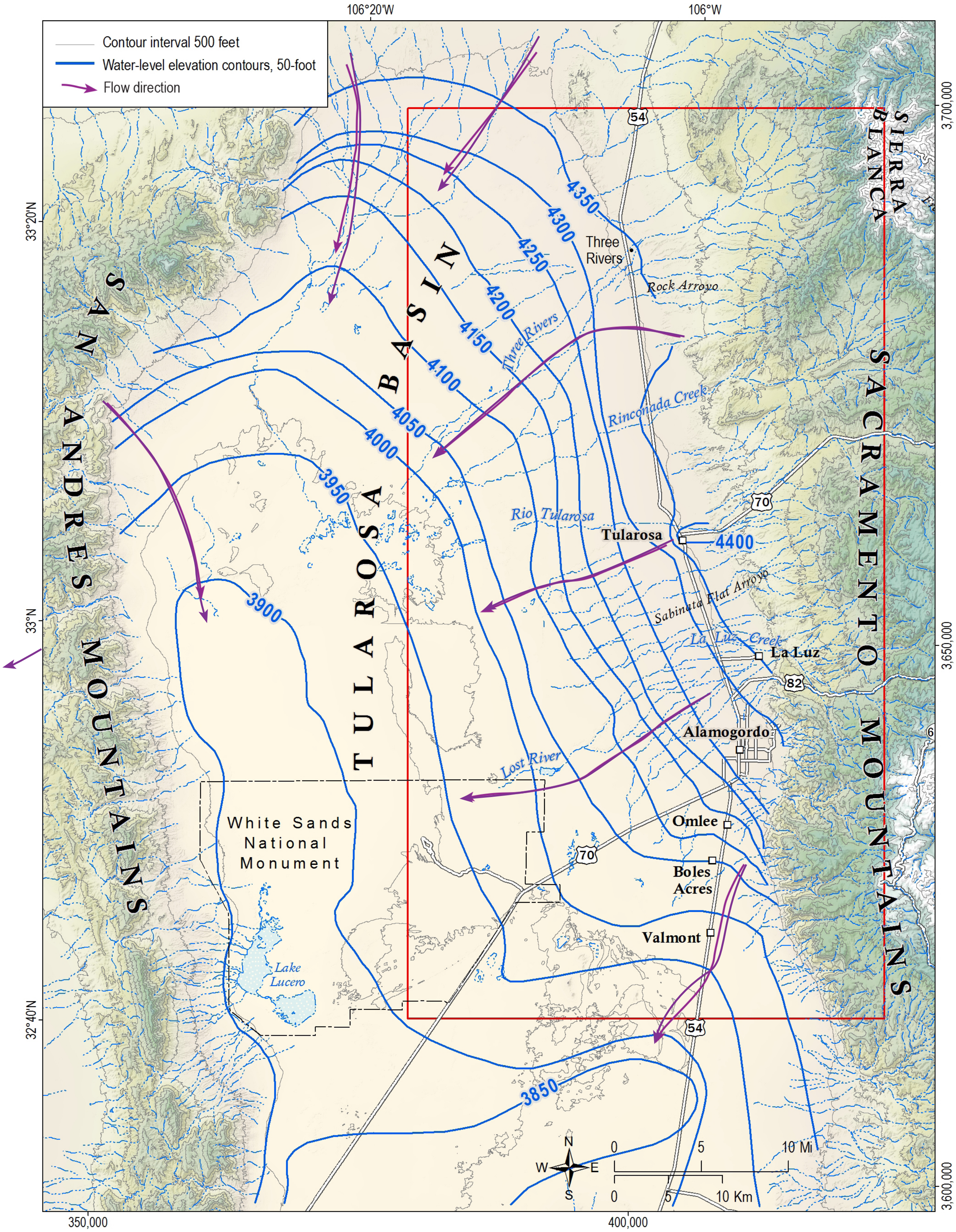


Figure 5. Water table map of the Tularosa Basin (modified from Embid and Finch, 2011).

and throughout the gypsum dune field and Alkali Flat area via evaporation (Newton and Allen, 2014; Allmedinger and Titus, 1973). The depth to groundwater in this area is very shallow (0–3 feet below the surface). Capillary forces pull up groundwater through pores in the sediments to the surface, where it evaporates. While this is a discharge area, water level elevation contours show that much of the groundwater continues to flow to the south. It should be noted that groundwater in the study area moves very slowly. Groundwater ages in the basin fill aquifer have been estimated to be tens of thousands of years old (Mamer et al., 2014; Newton and Allen, 2014).

Water Quality

Water quality in the Tularosa Basin has been studied by many researchers (e.g., Meinzer and Hare, 1915; McLean, 1970; Garza and McLean, 1977; Orr and Myers, 1986; Basabilvazo et al., 1994; Mamer et al., 2014, Newton and Allen, 2014). Most fresh groundwater (TDS <1,000 mg/L) in the basin fill aquifer is located south of Alamogordo in alluvial fan deposits at the base of the Sacramento Mountains. This is the primary source area for water used by Holloman Airforce Base (Figure 6). Alamogordo gets much of its public water supply from the La Luz well field and other public supply wells. Figure 6 shows permitted wells listed in the Office of the State Engineer (NMOSE) designated as public supply wells. Alamogordo, Tularosa and other communities generally pump slightly brackish water and then mix it with surface water to decrease the TDS to desirable levels. Fresh groundwater can also be found in some localized zones in bedrock aquifers at higher elevations in the mountains. Most other wells, which including irrigation, domestic, and stock wells, produce slightly brackish water. Garza and McLean (1977) concluded that much of the slightly brackish groundwater near Tularosa appeared to be suitable for many of the crops grown in the basin. However, there was evidence that some crop yields may be slightly reduced due to high salt content of the water. Garza and McLean (1997) voiced concern about the encroachment of chemically inferior water (TDS >4,000 mg/L) from the west into the large irrigated area near Tularosa. In the center of the basin beneath Alkali Flats and White Sands dune field, the groundwater is brine with TDS values greater than 100,000 mg/L in some areas (Newton and Allen, 2014).

Orr and Myers (1986) conducted electrical resistivity surveys to assess fresh and slightly brackish water resources in the basin. For these surveys,

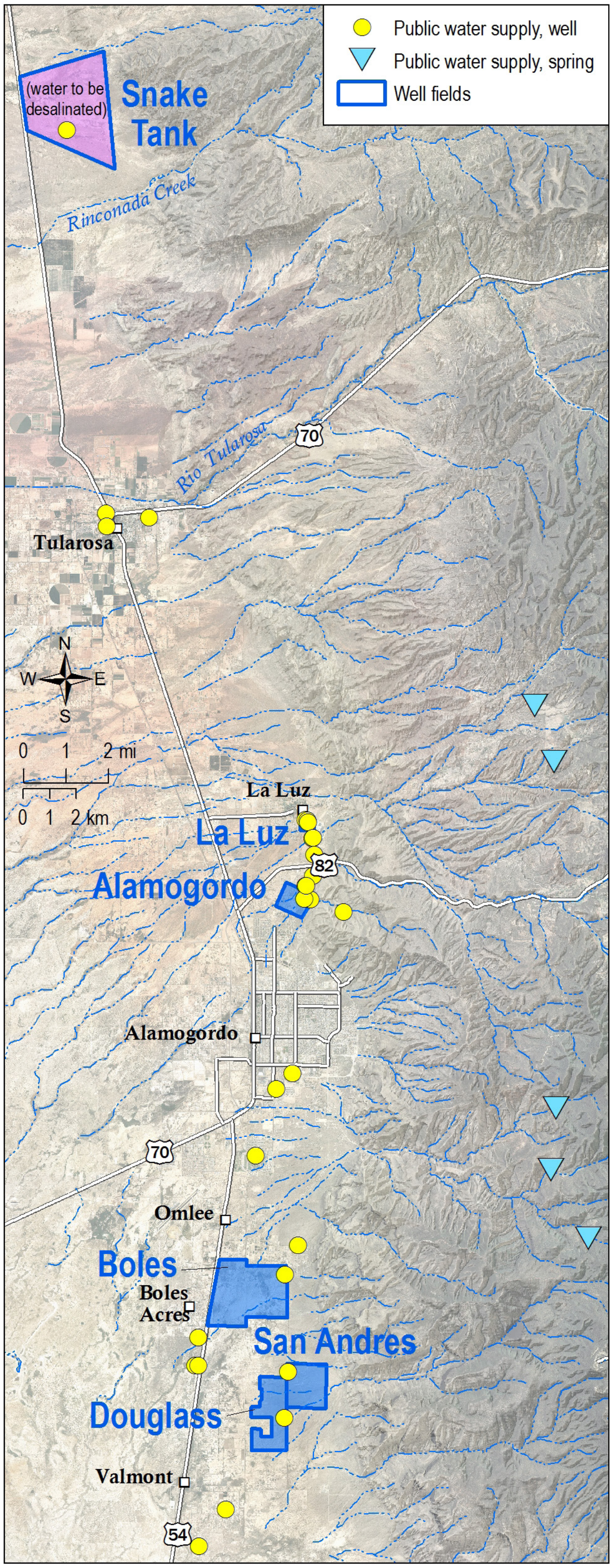


Figure 6. Location of well fields. The Boles, San Andres, and Douglass well fields supply water to Holloman Airforce Base. Alamogordo pumps groundwater from the La Luz well field and other wells north of town. The Snake Tank well field will pump brackish water that will be piped to Alamogordo, where it will be treated for public supply (BLM, 2012).

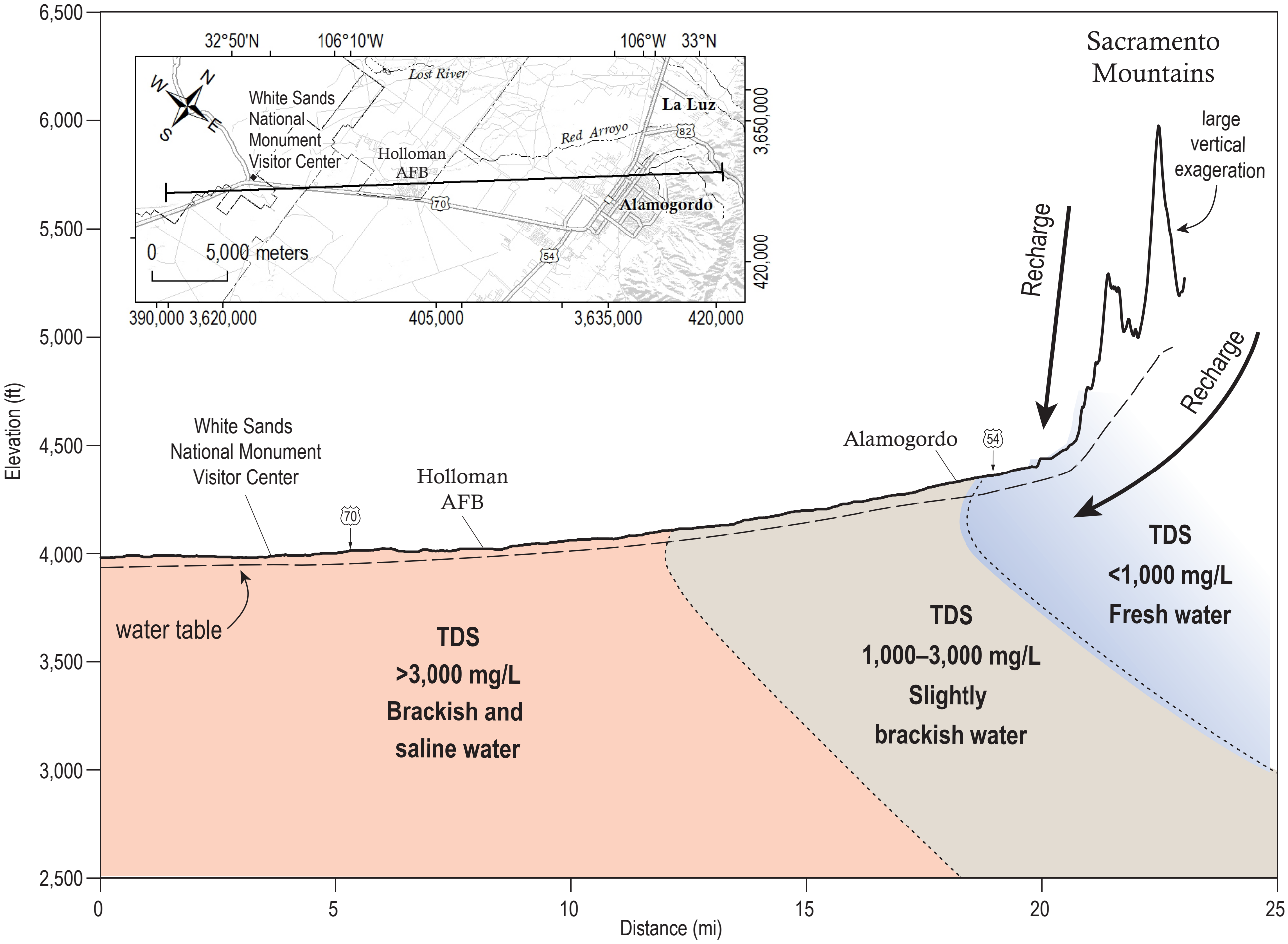


Figure 7. Conceptual model of groundwater salinity distribution along an east-west transect.

electrical resistivity was measured in the subsurface at several depths at different positions along many transects that usually ran from the eastern margin of the basin to the west for a few miles. These types of geophysical techniques are advantageous for looking at the distribution of groundwater salinity.

Most resistivity profiles completed by Orr and Myers (1986) show fresh or slightly brackish water on the far eastern margin of the Tularosa Basin at shallow depths and higher salinities with depth and towards the central/western part of the basin. Figure 7 shows a conceptual model that explains these observations. The interpretation of Orr and Myers (1986) is that precipitation in the Sacramento Mountains recharges the basin fill aquifer as fresh water and as it slowly moves to the west it mixes with brine in the basin fill.

III. METHODS

Existing water chemistry data from the NMBGMR, USGS, and NMED were extracted and compiled to identify spatial trends and data gaps. For the study area, there are 307, 188, and 77 wells from the NMBGMR, USGS, and NMED datasets, respectively. Each agency includes water chemistry collected over the last 100 years from different research projects and monitoring programs. The NMED data has been collected specifically for water quality testing for the protection of public health. For wells in the study area, the NMBGMR database includes data from Mamer et al. (2014), Newton et al. (2012), McLean (1970), Huff (1996), John Shomaker & Associates, Inc. (2006) and the Brackish Groundwater National Desalination Research Facility (BGNDRF). The procedure used to compile these datasets is described in Timmons (2016). Due to data issues such as uncertainties of locations and different naming conventions, there are undoubtedly wells that are represented in more than one of these datasets. Therefore, these data sets were not combined into one dataset for statistical analyses. All datasets had several repeat samples at different times. For the statistical analyses, results from the most recent sample were used. In analyses that group the three data sets, it is important to note that many of the data points may be duplicated. Data gap analyses were primarily conducted by visual inspection on a GIS map and statistical analyses. Spatial analyses were conducted using ArcGIS.

Samples were collected from twenty-one domestic wells and analyzed for major cations and anions, trace metals, and stable isotopes of oxygen and hydrogen. Sample locations were focused on the center of the study area near Tularosa and chosen to observe groundwater salinity along a north-south and east-west transect. The data are provided in Appendix A and will be discussed in more detail below. Standard sampling and analytical procedures used are described in Timmons et al. (2013).

IV. RESULTS AND DISCUSSION

This section describes analyses performed for general water chemistry from all datasets described above, including chemistry results for samples collected in February of 2016 by NMBGMR personnel. There are thousands of wells in the Tularosa basin, including municipal, irrigation, stock, and domestic wells. Figure 8 shows locations of all wells in the study area that are documented by the New Mexico Office of the State Engineer (NMOSE). The distribution of wells is correlated to population density. Most wells are located in clusters around local communities. Domestic and irrigation wells account for over 50% and 16% of these wells, respectively. The spatial distribution of wells results in a bias in the chemistry data because there are large areas where groundwater cannot be sampled.

Figure 9 shows wells from all three data sets that have water chemistry data associated with them, including wells that were sampled in February of 2016 by the NMBGMR. While the wells with chemistry data associated with them represent a very small proportion of the total number of wells in the study area, they are clustered around the same population centers where the majority of wells are found. Large areas where there are no groundwater chemistry data are primarily due to the fact that there are very few or no wells present in these areas.

A survey of the total depth of these wells showed that most of them are less than 400 ft deep (Figure 10). The fact that most of the wells produce water in the top 400 ft of an aquifer system that is thousands of feet deep in some areas exposes a depth bias in the chemistry data.

The water chemistry data sets are extremely variable in terms of constituents that were analyzed in the water samples. Some samples were tested for a full suite of major cations, anions, and trace metals, while many other samples were only tested for one or two constituents. For this study, the principal goal was to identify general spatial trends in salinity; therefore, TDS was the analyte of choice. However, all three data sets do not consistently have TDS calculations or measurements for every sample. A survey of the data reveals that SO_4 is the most commonly populated constituent. Figure 11 shows TDS as a function of SO_4 along with a linear regression with a very high correlation coefficient (R^2=0.99). We utilize this relationship between TDS and SO_4 to maximize the amount of available data by using SO_4 as a proxy for TDS. Table 2 shows the range in SO_4 concentrations that correlates to the different categories of salinity. TDS values calculated with the equation shown in Figure 11 were compared to measured TDS values. In general, the proxy-estimated TDS values match the measured values reasonably well, especially for lower TDS waters (data not shown). However, for fresh and slightly brackish water, the predicted values may still differ from measured TDS concentrations by several hundreds of mg/L. For waters of higher salinity, the predicted values may differ by up to 2,000 mg/l. It is important to note that the water categorized into different salinities based on SO_4 concentrations is somewhat imprecise. However, with such a large range of TDS values, the categorizations based on SO_4 concentrations still exhibit relative salinity differences adequately. The analyses discussed below utilize TDS values for samples which have measured or calculated values and SO_4 values for waters that do not have TDS data available. Figure 12A shows the wells classified as fresh, slightly brackish, brackish, saline, and brine.

Table 2. Groundwater salinity classifications correlated to SO_4 concentrations.

Total dissolved solids (mg/L)	**Water type**	**SO_4 proxy** (mg/L)
0–1,000	Fresh water	0–527
1,000–3,000	Slightly brackish water	527–1,327
3,000–10,000	Brackish water	1,327–4,127
10,000–35,000	Saline water	4,127–12,127
>35,000	Brine	>12,127

Based on the data we have compiled, we find that most of the fresh water on the eastern margin of the basin is located south of Alamogordo (Figure 12C), where wellfields that supply water for Holloman Air Force Base are located. With a few exceptions, throughout the study area the remaining wells producing fresh water are located at higher elevations in the Sacramento Mountains. Most wells

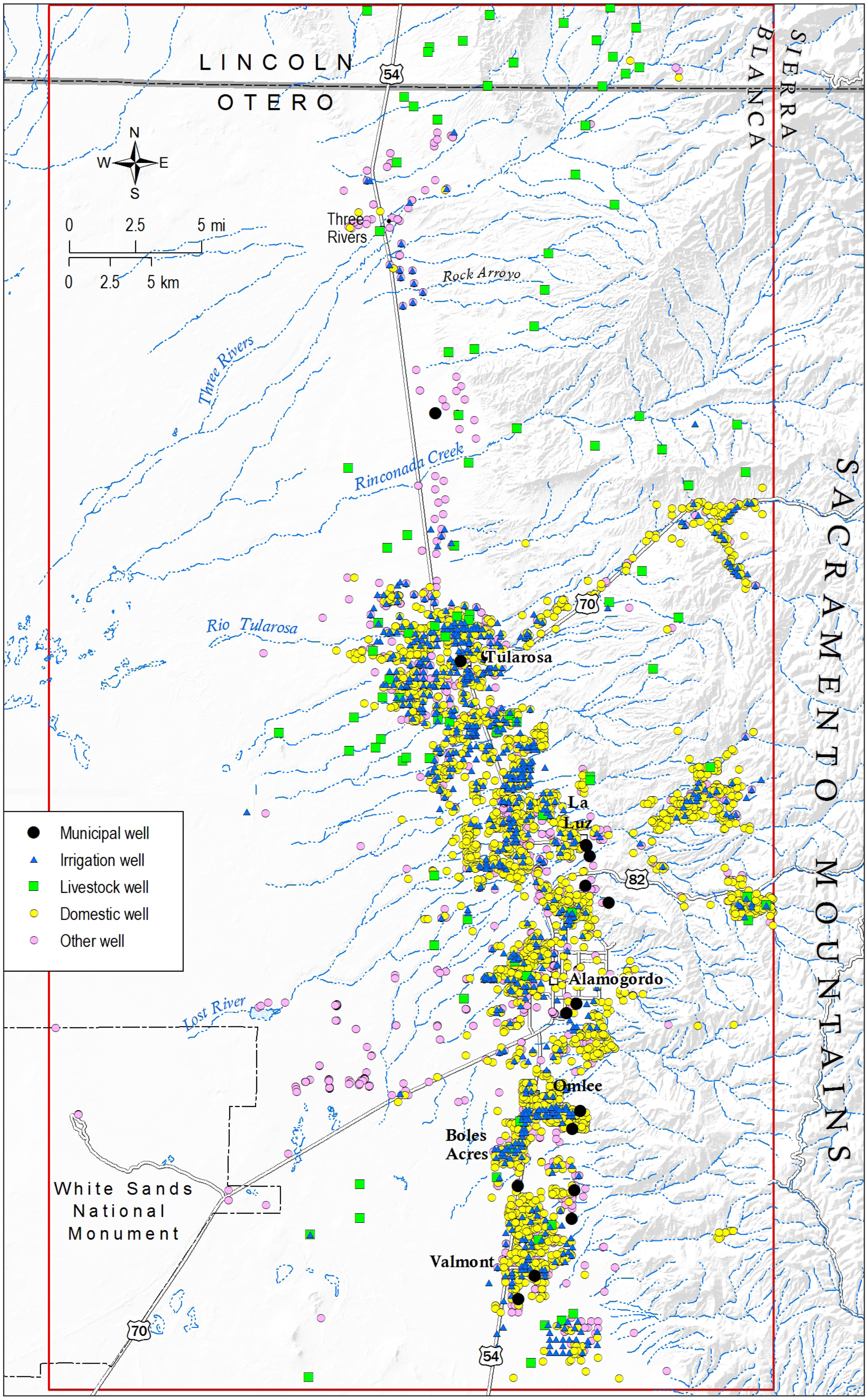


Figure 8. All wells that are permitted and documented by the NM Office of the State Engineer.

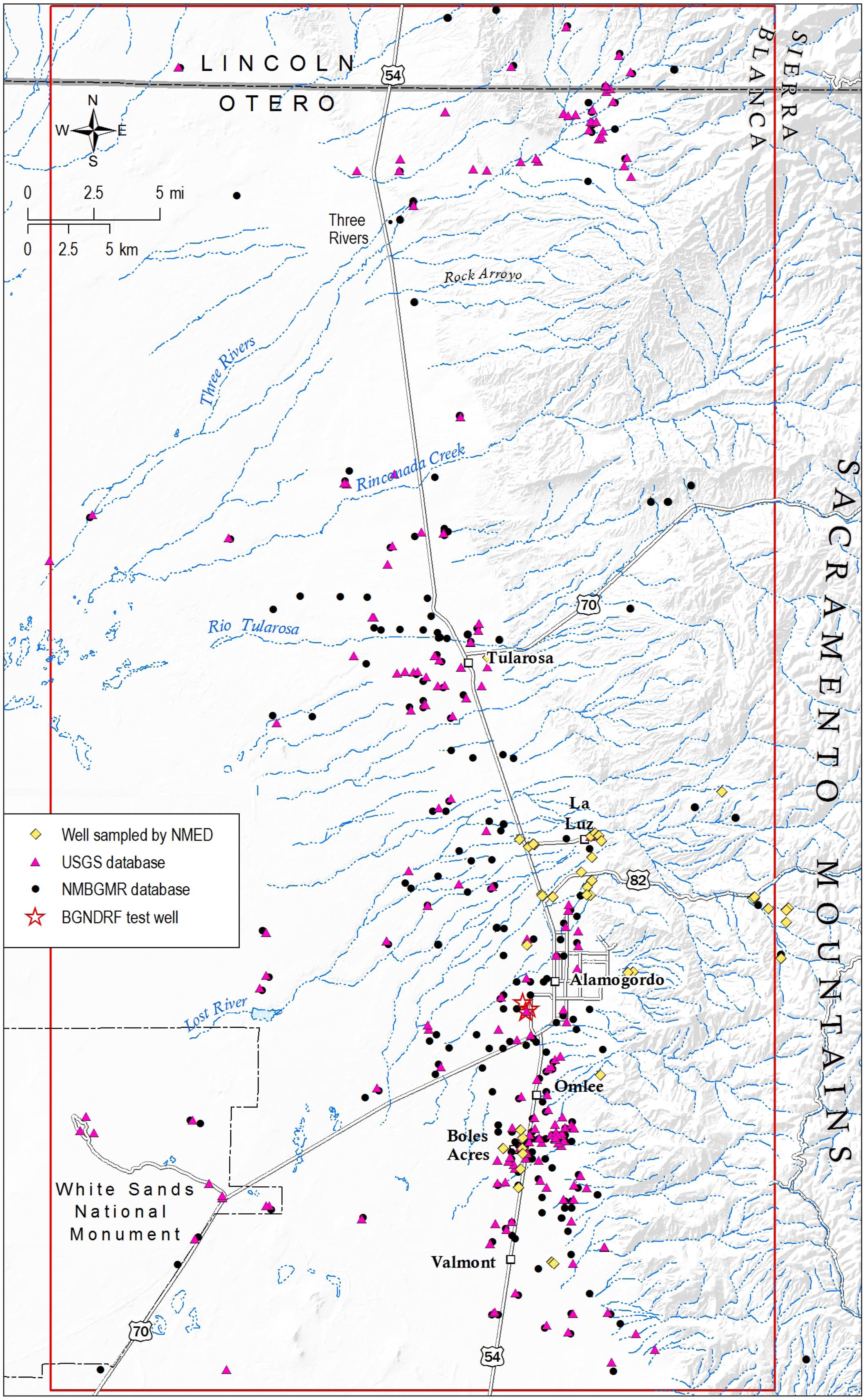


Figure 9. Locations for wells from NMBGMR, USGS, and NMED databases that have water chemistry associated with them. Test wells at the Brackish Groundwater National Desalination Research Facility (BGNDRF) are also shown.

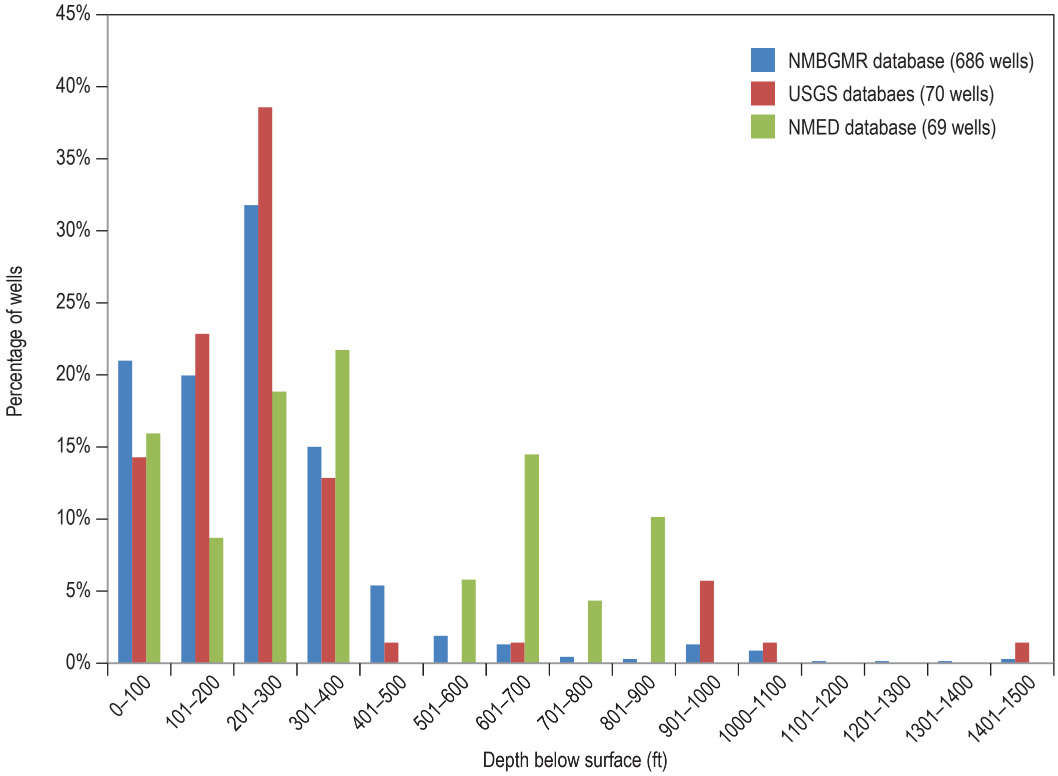


Figure 10. Histogram showing well depth distribution for wells with chemistry data. Most wells are less than 400 feet deep.

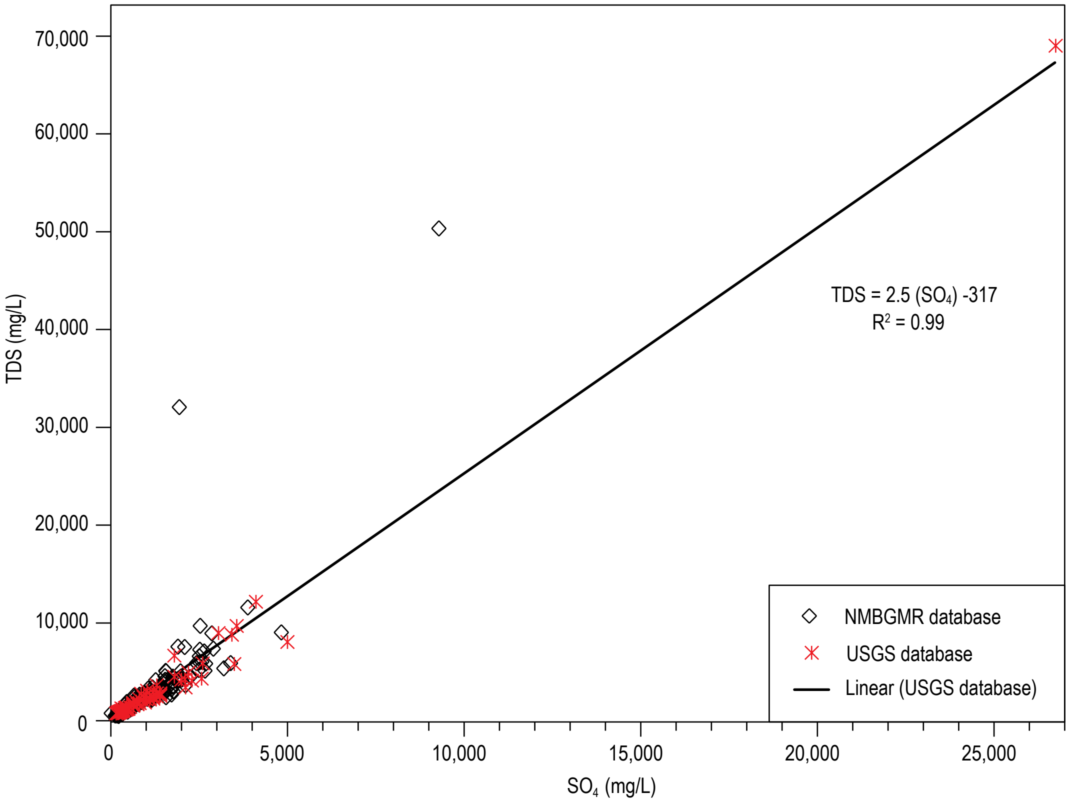


Figure 11. Total dissolved solids as a function of SO_4. The strong correlation allows us to use SO_4 as a proxy for TDS. This is advantageous because there are more SO_4 data than TDS data.

in Alamogordo produce slightly brackish to brackish water. To the southwest, along HWY 70 groundwater is mostly brackish with some saline water and brines in some areas. Wells near La Luz Creek produce mostly slightly brackish water (Figure 12C). North of La Luz Creek, groundwater quality appears to deteriorate. Wells in the vicinity of Tularosa dominantly produce slightly brackish and brackish water. Most saline groundwater and brines in the study area are located in the western region.

The conceptual model presented in Figure 7 shows zones of different TDS concentrations along a cross-section on the eastern edge of the basin. The model suggests that because groundwater recharge occurs at the interface between the mountains and the basin fill, groundwater in this area is the freshest.

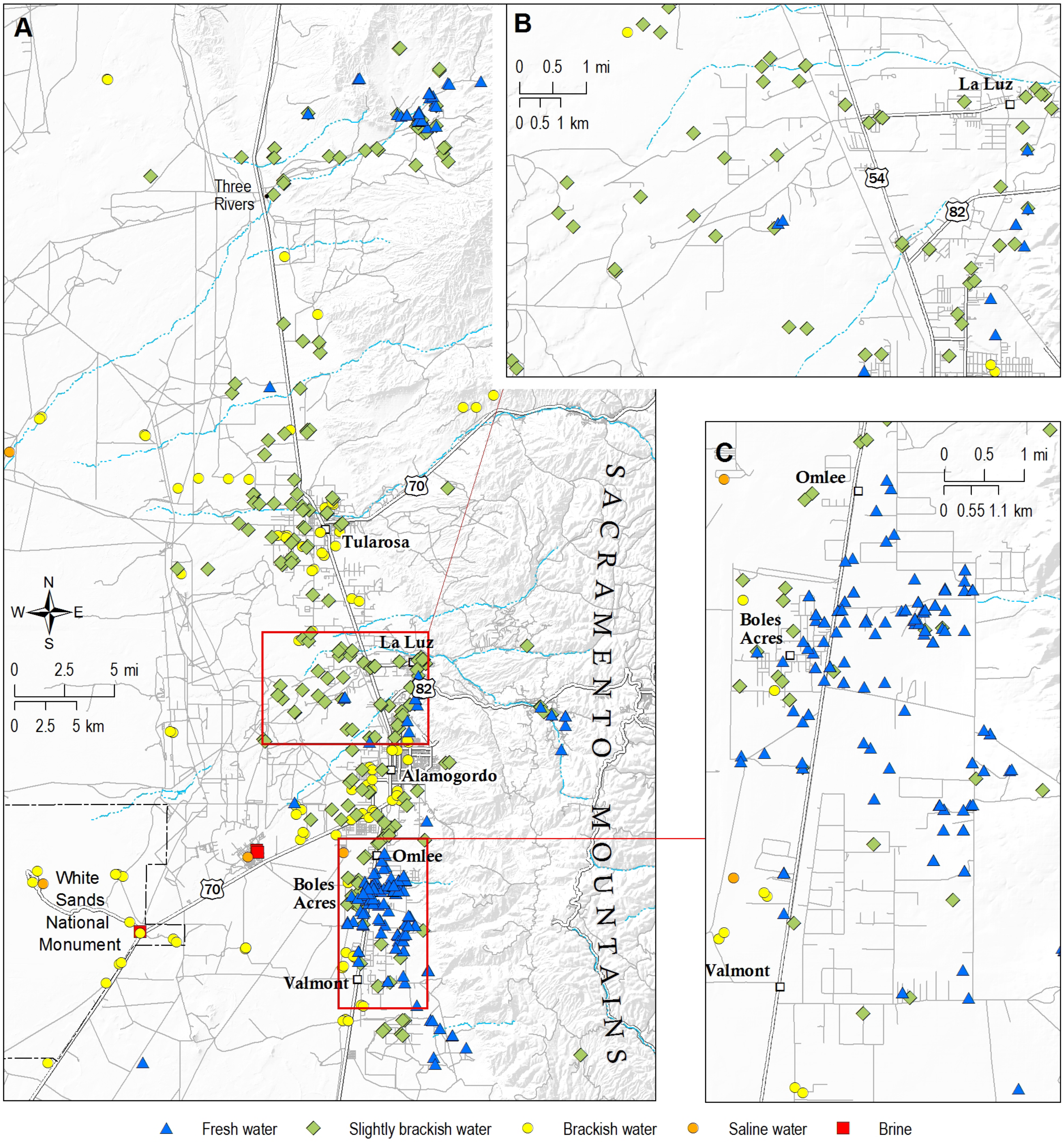


Figure 12. Groundwater samples classified as "fresh," "slightly brackish," "brackish," "saline," or "brine." For samples with no TDS data, classifications were determined based on SO_4 concentrations.

From the limited data shown above (Figure 12), it appears TDS values in groundwater generally increase to the west, consistent with the conceptual model. This trend is probably due to mixing of relatively fresh groundwater coming in from the east and high TDS brines to the west and water-mineral interactions. Figure 13 also provides evidence for these processes. Sulfate is shown as a function of the ratio of SO_4 to bicarbonate (HCO_3). HCO_3 in groundwater is primarily derived from limestone in the subsurface. Paleozoic rocks in the Sacramento Mountains contain limestones, and groundwater in the Sacramento Mountains near Alamogordo and Tularosa generally has a chemical signature indicative of the dissolution of limestone (Mamer et al., 2014). In these waters, HCO_3 is the dominant anion (negative ion), and therefore the samples are characterized by a small SO_4/HCO_3 ratio. SO_4 in groundwater is usually the result of the dissolution of gypsum. As discussed above, recrystallized gypsum deposits and lacrustrine deposits are present in the subsurface farther toward the center of the basin (Orr and Myers, 1986). Figure 13 shows that as SO_4 concentrations increase, the SO_4/HCO_3 ratios also increase. This observation can be explained by the mixing of incoming fresh water from the mountains with brines in the basin fill aquifer, and the continual evolution of water chemistry due to water-mineral interactions. In addition, at higher TDS concentrations the relationship between SO_4 and SO_4/HCO_3 ratios becomes increasingly non-linear (Figure 13). This phenomenon may reflect variations in water-mineral reaction rates at higher salinities, and the diminishing role of freshwater recharge at greater distances from recharge areas along the basin margin.

Orr and Myers' (1986) electrical resistivity surveys and the data discussed above suggest a relatively uniform progression of increasing salinity from the eastern margin of the basin in a westward direction following the general direction of groundwater flow (east to west/ southwest). However, the large spatial variability of salinity shown in Figure 12A and the actual data shown along a transect near Alamogordo (Figure 14) suggest a more complex system. While the lowest TDS values are at the eastern margin of the basin (between twenty and twenty-five miles on the transect) there are no water samples with TDS values less than 1,000 mg/L. Rather, these waters are slightly brackish. Figure 12 shows that this is typical of most areas along the eastern margin of the basin, with the exception of very localized areas south of Alamogordo. Moving to the west along the transect shown in Figure 14, between miles fifteen and twenty, there is a mixture of slightly brackish and brackish waters. Then, at approximately the eleven mile mark, there are two relatively shallow wells that produce

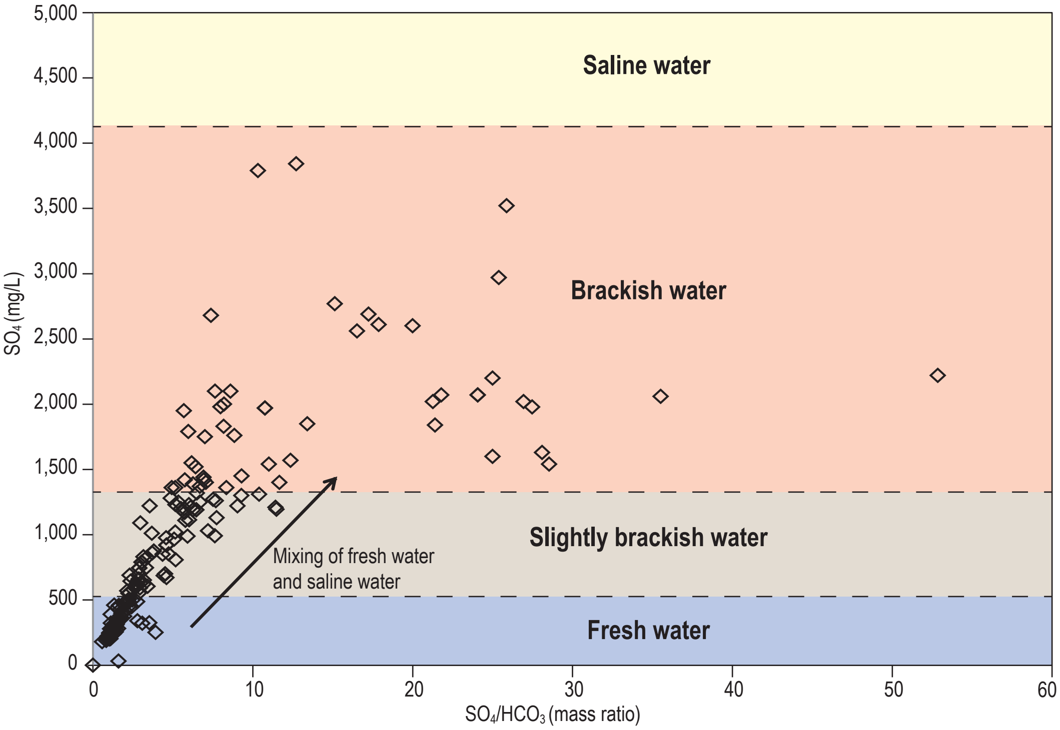


Figure 13. SO_4 concentration as a function of SO_4/HCO_3 ratio. The direct correlation between these two parameters is a result of the mixing of relatively fresh recharge with saline water.

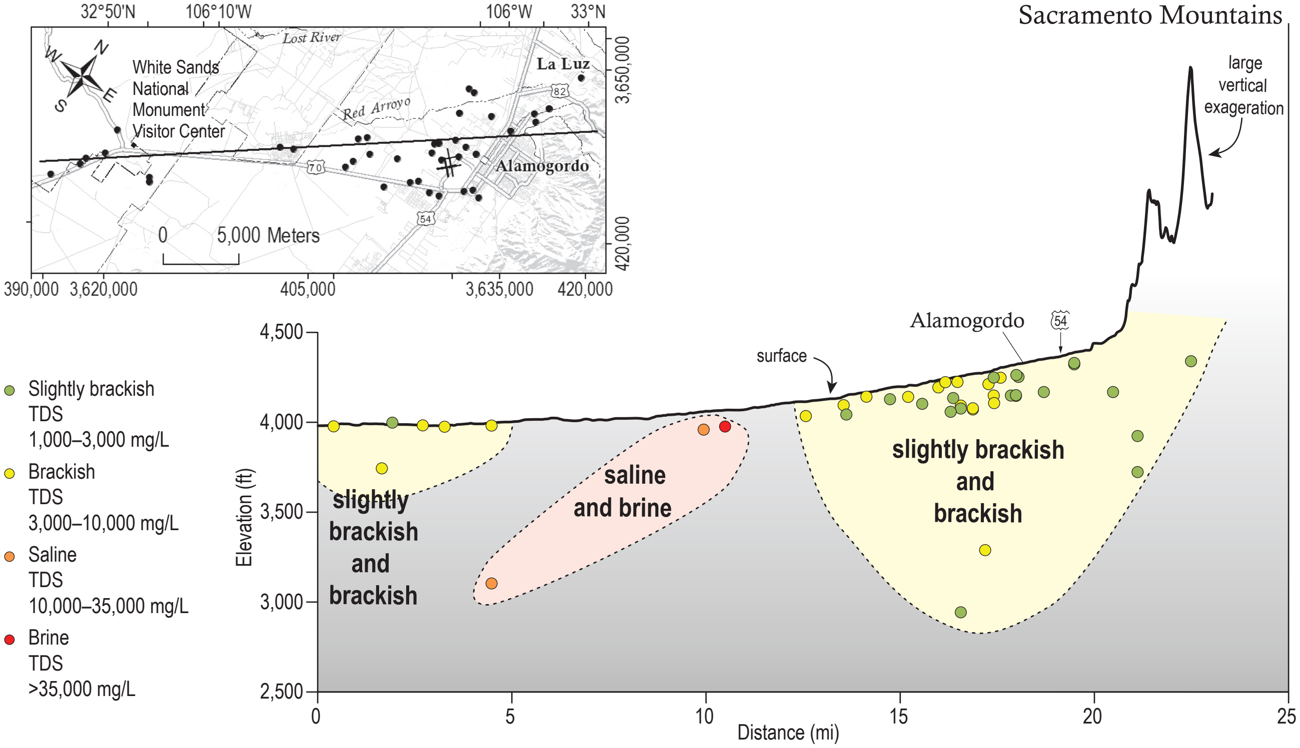


Figure 14. Updated conceptual model of TDS variability along a transect near Alamogordo. TDS data indicate a more complicated system with a large range of TDS values in the different zones.

saline water and brine. Further to the west, between zero and five miles, most wells produce brackish water. One deeper well in this area produces saline water. It is also apparent that water chemistry from existing wells provides information about only a very small proportion of the basin fill aquifer, in the shallowest groundwater.

Previous work using geophysical methods such as that performed by Orr and Myers (1986) has helped to assess the spatial variability of groundwater salinity in the Tularosa Basin. It should be noted that there were large distances between resistivity measurements made by Orr and Myers (1986) along each transect, which required considerable interpolation between measurement points to define different zones of different ranges in salinity. The water chemistry data discussed above shows that the salinity of groundwater in the study area is highly variable on a fairly small spatial scale. This variability is probably due to the spatial distribution of the different sediments that make up the aquifer and the different rates of recharge in different areas.

Chemistry data for well samples collected by NMBGMR in February, 2016 (Table 3, Figure 15) exhibit similar trends to those observed for other compiled chemistry data that has been collected over the last 100 years. All samples except one have TDS values between 1,000 and 3,000 mg/L, and therefore are classified as slightly brackish water. The lowest TDS waters were observed near La Luz Creek (Figure 15), with values ranging from 1,230 to 1,890 mg/L. These values are consistent with other TDS values in the area as seen on Figure 12B. The relatively low TDS values in this area are due to local recharge from La Luz Creek. Interestingly, this apparent effect of a local stream on the nearby groundwater chemistry is not nearly as pronounced for the area around the Rio Tularosa (Figure 15) for reasons that are unknown. There is one domestic well, located just north of the Rio Tularosa that exhibits a TDS value less than 2,000 mg/L. Other wells along the Rio Tularosa have similar TDS concentrations that range from 2,360 to 2,790 mg/L. These observations, again, demonstrate the high spatial variability of groundwater salinity.

One of the principal motivations for this study is a concern about how pumping brackish water may affect water utilized by existing public supply, irrigation, and domestic wells. There is anecdotal evidence reported by some land owners and irrigators of water quality changes in water from some wells during a prolonged period of pumping, such as irrigation season. As an example, Figure 16 shows the change in TDS for four test wells at the Brackish Groundwater National Desalination Research Facility

Table 3. Water chemistry data collect in February 2016

Point ID	Well depth (ft)	Collection date	Calcium Ca (mg/L)	Chloride Cl (mg/L)	Bicarbonate HCO_3 (mg/L)	Potassium K (mg/L)	Magnesium Mg (mg/L)	Sodium Na (mg/L)	Sulfate SO_4 (mg/L)	TDS (mg/L)
TB-0311	300	02/09/16	420	368	247	3.07	156	254	1,420.00	2790
TB-0319	260	02/09/16	170	228	216	1.81	62.4	151	485	1230
TB-0318		02/09/16	205	269	224	1.78	76.5	167	593	1450
TB-0316	340	02/08/16	189	257	177	2.27	76.5	166	604	1410
TB-0313	280	02/08/16	351	173	367	2.38	128	138	1,090.00	2100
TB-0314	200	02/08/16	530	568	237	3.17	214	202	1,520.00	3230
TB-0315		02/08/16	337	437	192	4.54	141	234	1,110.00	2400
TB-0317		02/08/16	271	268	200	1.87	95.6	204	921	1890
TB-0309	215	02/07/16	445	338	198	2.93	157	174	1,400.00	2670
TB-0305	200	02/07/16	455	241	208	3.57	139	161	1,440.00	2590
TB-0312	185	02/07/16	386	340	234	2.82	138	223	1,250.00	2500
TB-0308	170	02/07/16	404	264	205	3.27	140	205	1,370.00	2540
TB-0310	160	02/07/16	306	130	263	1.77	77.4	83.4	830	1590
TB-0304	250	02/06/16	432	162	164	3.51	115	92	1,260.00	2190
TB-0307	165	02/06/16	427	352	203	2.63	157	170	1,320.00	2580
TB-0303		02/06/16	437	146	169	3.08	112	72.7	1,270.00	2160
TB-0306		02/06/16	415	313	198	2.63	144	128	1,210.00	2360
TB-0302	527	02/05/16	431	151	135	3.55	98.1	68.4	1,220.00	2080
TB-0300	258	02/05/16	527	315	156	3.85	134	127	1,450.00	2710
TB-0301	43	02/05/16	488	222	127	3.46	127	200	1,570.00	2740

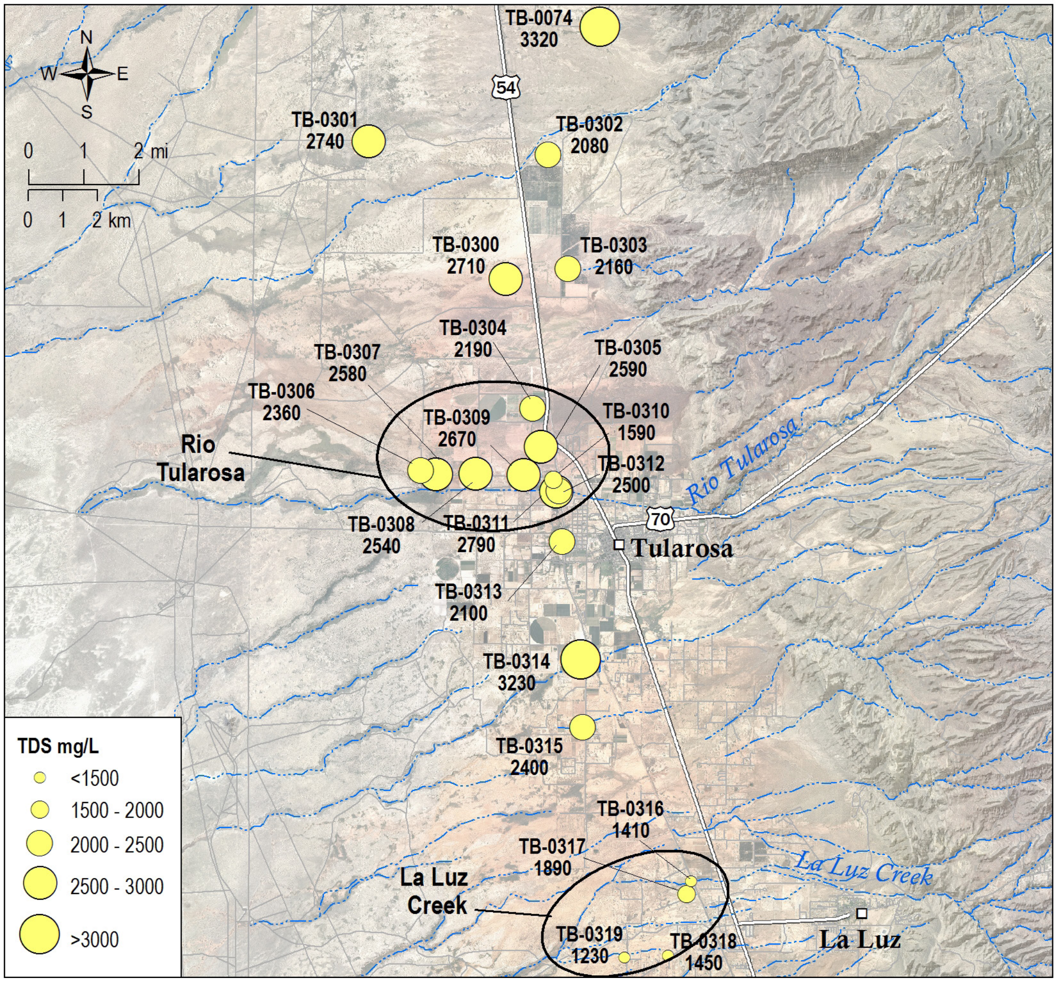


Figure 15. TDS concentrations for 2016 NMBGMR samples. Note that grey-green patches are irrigated fields. Circled areas are discussed in text.

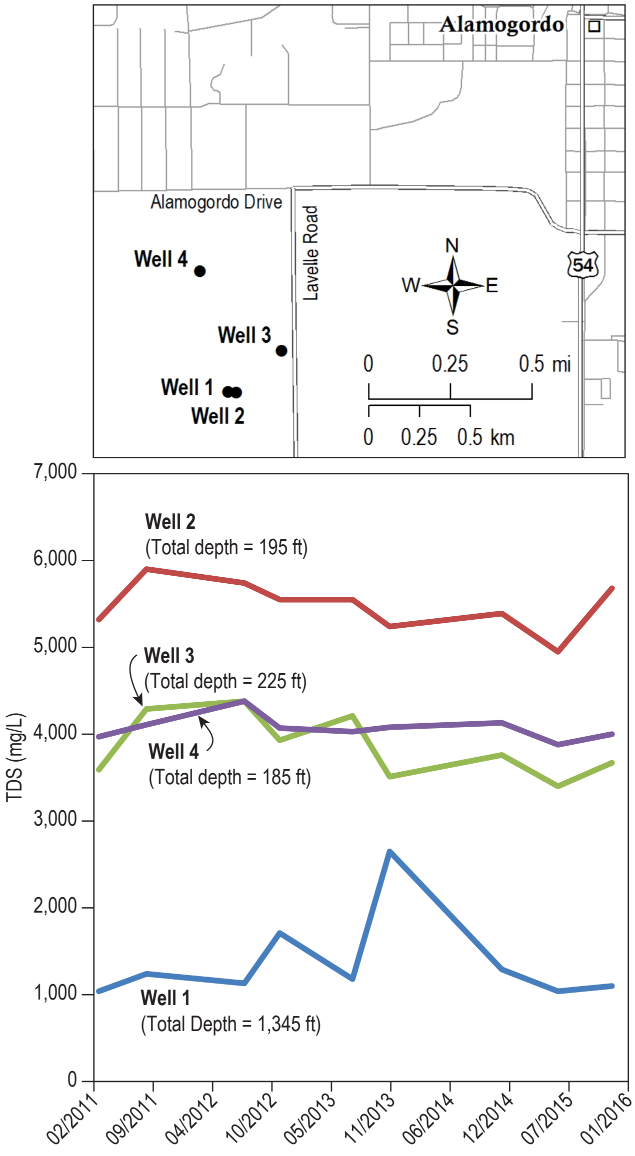


Figure 16. Wells described by McLean (1970) that were sampled repeatedly during the 1950s and 60s.

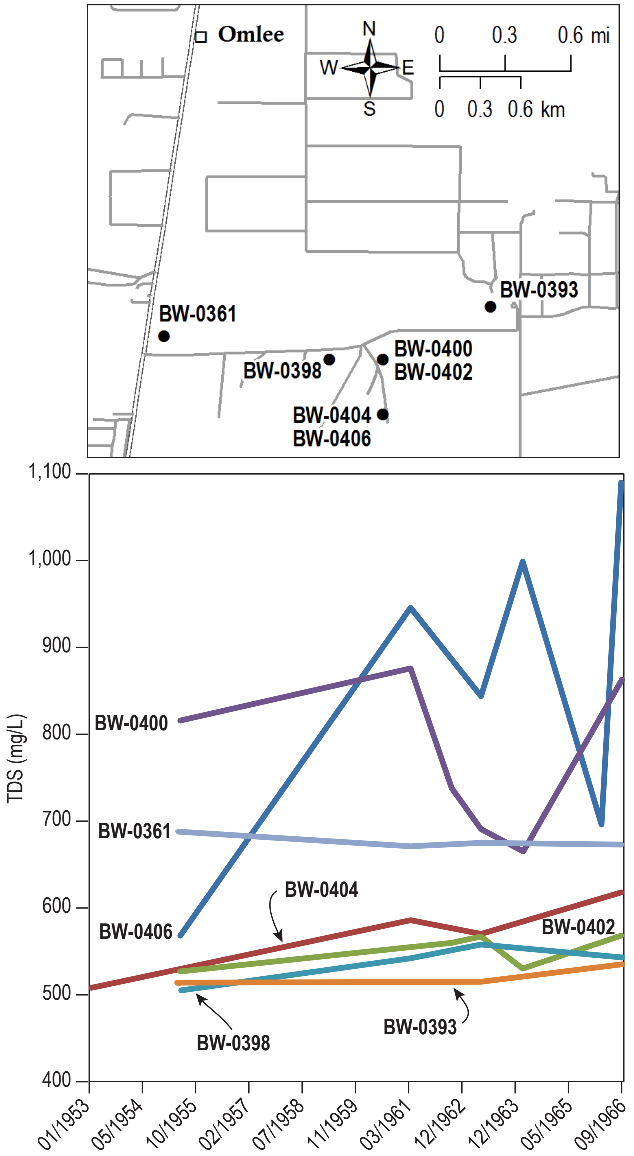


Figure 17. Wells described by McLean (1970) that were sampled repeatedly during the 1950s and 60s.

in Alamogordo. Wells 2, 3, and 4, which are completed to similar total depths (185–225 ft.), show fluctuations in TDS of up to 1,000 mg/L between March of 2011 and December of 2015. The observed TDS value for Well 1, which has a total depth of 1,345 ft., increased from 1,180 mg/L in July 2013 to 2,650 mg/L in November 2013 and then decreased to 1,290 mg/L by December 2014.

There are several wells that were sampled by the USGS multiple times during the 1950s and 60s. Figure 17 shows data and locations for selected wells that were described by McLean (1970). These wells were all supply wells for Holloman Airforce Base, located within 1.5 miles of each other, and have total depths between 175 and 370 feet below the surface. The TDS concentrations for five of the seven wells were rather constant over time, while water produced by two wells, BW-0400 and BW-0406, fluctuate substantially over the eleven year period. BW-0400 and BW-0406 have total depths of 260 and 205 ft, respectively. Interestingly, BW-0402 is 240 ft deep and does not show significant fluctuations of TDS concentration. The northernmost well sampled by NMBGMR in 2016 (Figure 15) showed an increase in TDS from 2,802 mg/L in August 2010 to 3,320 mg/L in February 2016. There is thus evidence that TDS values of groundwater at a specific location can change significantly over time.

V. CONCLUSIONS

Over the last 100 years, various researchers have sampled hundreds of wells in the eastern Tularosa Basin and have managed to obtain water chemistry data in most areas where wells are present. With a goal to assess the spatial variability of groundwater salinity in the eastern Tularosa Basin, focusing on areas around Tularosa and Alamogordo, it immediately became clear that analyzing the data from these public, domestic, and irrigation wells introduces bias. Wells are located mostly in and around population centers and lack spatial distribution across the entire study area. Therefore, we cannot determine the salinity distribution in groundwater for a large proportion of the study area without additional well coverage. This bias is also apparent for the vertical salinity distribution. Most wells are less than 400 feet deep, which represents a very small proportion of the entire basin fill aquifer, which in some areas can be thousands of feet thick.

Much work has been done in this area with respect to water quality and availability (Orr and Myers, 1986; Mamer et al., 2014; Garza and McLean, 1977; McLean, 1970), and now much of these data are compiled electronically. A review of groundwater chemistry data that was obtained from the USGS, NMED, and NMBGMR databases confirms many observations made by other researchers.

1. Most of the fresh water is located in alluvial fan deposits south of Alamogordo, where several public supply wells are located.
2. Most groundwater in and around Tularosa is slightly brackish to brackish.
3. In general, shallow groundwater near the eastern margin of the basin is fresh or slightly brackish due to incoming recharge from the Sacramento Mountains.
4. In general, TDS concentrations increase towards the west and with depth as a result of fresh recharge mixing with saline water and brines.

The spatial trends in groundwater salinity described above exist on a large scale (miles). On a scale of hundreds to thousands of feet, TDS values vary considerably. Factors that control the spatial distribution of groundwater salinity include the physical arrangement of different sediment types in the aquifer, proximity to ephemeral and perennial streams, and the rate of recharge in different areas.

The variability in groundwater salinity has implications for the effects of pumping brackish water as a resource on the water quality of current fresh or slightly brackish water that is being used. On a large scale (years), prolonged pumping of brackish water in the area of Tularosa may cause groundwater with much higher TDS concentrations to the west to encroach on water resources being used for agriculture in local communities. This concern has been voiced by other researchers (e.g., Garza and McLean, 1977). Bourret (2015) constructed a groundwater model of the Tularosa Basin and simulated groundwater flow under different pumping scenarios, including pumping from the Snake Tank Well Field as is proposed for the Alamogordo Regional Water Supply Project. Under some scenarios, the simulated cone of depression was quite large and did significantly change the flow direction of groundwater in the surrounding area.

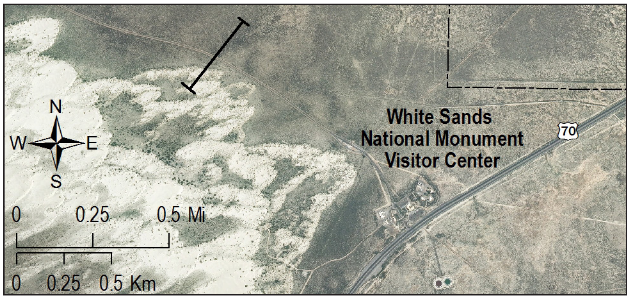
On a smaller spatial scale, the presence of localized zones of variable salinity (Figure 12) suggests that seasonal pumping may have an effect on water chemistry in existing wells. Most residents with domestic wells are already impacted by water of poor quality and do not drink their well water. A slight deterioration of their water quality would probably have a limited impact on them. However, ranchers and farmers may be severely impacted by a slight deterioration in the quality of their water.

VI. FUTURE WORK RECOMMENDATIONS

There is evidence that water quality in a well can change significantly with time. More research is needed to understand the mechanisms behind this temporal variability in water chemistry.

In order to accurately determine or predict possible changes to water quality that may result from large scale pumping, more detailed, depth-specific water quality data would be required. The use of water chemistry from existing well samples alone is inadequate for the assessment of the spatial variability of groundwater salinity due to bias in existing well locations. Large data gaps exist in areas with no wells. We suggest the installation of additional wells to fill in some of these spatial and vertical data gaps, along with geophysical surveys. New geophysical surveys could improve upon the work of Orr and Myers (1986), who used older technology in electrical resistivity in conjunction with well data to examine the distribution of fresh and slightly brackish water in the Eastern Tularosa Basin with much success.

Currently, there are many electromagnetic (EM) methods that are used to image the electrical conductivity (or resistivity) of rocks and fluids in the subsurface. Different methods provide data at different scales. Figure 18 shows an electrical resistivity survey that was conducted at White Sands National Monument (Newton and Allen, 2014). The image shows a moderately resistive zone in green overlying a low resistivity zone (blue). The moderately resistive zone represents fresh to slightly brackish water in sand which is sitting on top of brines that reside in low permeability clays below the dune field. We highly recommend to include these types of methodologies, along with the installation of additional wells for control points to better understand the spatial distribution of fresh and brackish water resources in the Tularosa Basin.



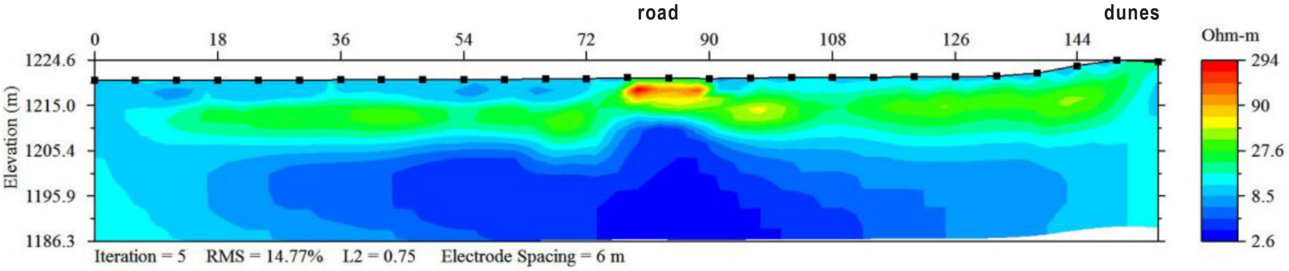


Figure 18. Electrical resistivity profile at White Sands National Monument. The transect crosses the road that going into the monument from the Visitor's Center. Relatively fresh to slightly brackish groundwater (green) can be seen flowing from the dune field . The dark blue represents low resistivity brines.

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