Sacramento Mountains Hydrogeology Study

Open File Report - 518
October 2009

New Mexico Bureau
of Geology and
Mineral Resources

AQUIFER MAPPING PROGRAM

Talon Newton, Stacy Timmons, Geoffrey Rawling, Frederick Partey, Trevor Kludt, Lewis Land, Mike Timmons, and Patrick Walsh

DRAFT

This report is preliminary and will undergo revision. It is being distributed in this draft form to make the information available as quickly as possible, with the understanding that this work has not necessarily met the stringent peer review and editorial standards of more formal publications.

New Mexico Bureau of Geology and Mineral Resources

A division of New Mexico Institute of Mining and Technology

Socorro, NM 87801
(575) 835-5490
Fax (575) 835-6333
www.geoinfo.nmt.edu

Sacramento Mountains Hydrogeology Study

Progress Report
October 2009

Talon Newton, Stacy Timmons, Geoffrey Rawling, Frederick Partey, Trevor Kludt, Lewis Land, Mike Timmons, and Patrick Walsh

Graphic Design: Brigitte Felix

AQUIFER MAPPING PROGRAM

New Mexico Bureau of Geology and Mineral Resources

PROJECT FUNDING

Funding for this work came from the Otero Soil and Water Conservation District through legislative appropriation administered by the New Mexico State Department of Agriculture at New Mexico State University, Las Cruces, New Mexico. Additional funding for geologic mapping in the study area has been awarded through the National Cooperative Geologic Mapping Program (STATEMAP). Supplemental funding for the watershed study was provided by the New Mexico Interstate Stream Commission.

TABLE OF CONTENTS

TABLE

PLATES

APPENDICES ON CD

EXECUTIVE SUMMARY

The southern Sacramento Mountains are an important source of recharge to the Lower Pecos Valley, Roswell Artesian Basin, and Salt Basin aquifers. This study was initiated by the Otero Soil and Water Conservation District because of significant declines in water levels in wells, and spring and stream flow which have occurred in the past decade. The goals of the regional hydrogeology study are to delineate areas of ground water recharge, determine directions and rates of ground water movement, and to understand interactions between different aquifers and the ground water and surface water systems. This report describes progress to date of an ongoing, multi-scale study to understand the hydrogeology of the mountain aquifers, the relationship between surface water and ground water, and the effects of vegetation management and climatic variability on the local hydrologic balance.

The Yeso Formation, which consists of layers of limestone, dolomite, sandstone, and siltstone, is the primary aquifer in the study area. Fractured limestones and dolomites are the main source of water for most springs and wells in the southern Sacramento Mountains. Recharge primarily occurs in the high mountains west of Mayhill where the Yeso Formation is exposed at the surface. Stable isotope data suggest the snow melt usually contributes significantly more recharge to ground water recharge than summer precipitation. However, extreme summer precipitation events, such as those that occurred in 2006 and 2008 do recharge the ground water system, resulting in significant increases in water levels in wells and spring discharge.

The ground water system in the high mountains west of Mayhill is characterized by several fractured leaky perched aquifers that are interconnected by regional fracture networks and the surface water system. Snow melt in the high mountains recharges shallow perched aquifers that discharge at springs, which feed streams and ponds where evaporation occurs. Water in ponds and streams may then recharge another shallow perched aquifer, which again may discharge at a spring at a lower elevation. This cycle may occur several times until the water is deep enough to not interact with the surface water system. A deeper regional aquifer may exist in the high mountains. East of Mayhill along the Pecos Slope, regional ground water flow is dominantly to the east towards the Roswell Artesian Basin. Some ground water also flows to the southeast towards the Salt Basin and to the west into the Tularosa Basin.

The local watershed study aims to characterize the water budget of a single forested watershed and to understand the impacts of regional climatic variability and local tree thinning. Progress to date has consisted of installation of hydrologic monitoring equipment, initiation of baseline data collection, and surveys of soil and vegetation types. Base line data includes precipitation and weather data, spring discharge, stable isotope and water chemistry data, and soil moisture. Data collection will continue through and beyond tree thinning in the watershed, scheduled to start in 2010.

I. INTRODUCTION

Background

The southern Sacramento Mountains include the urban centers of Alamogordo, Cloudcroft, and Tularosa and numerous small rural population centers. High elevation watersheds in the Sacramento Mountains serve as sources of recharge to local aquifers and the major stream systems that drain the mountains and connect to the Lower Pecos River valley, the Roswell Artesian Basin aquifer, and the Salt Basin aquifers. Water managers and users across the region have observed declines in water levels and spring discharges in the past few decades. The Sacramento Mountain watersheds have undergone significant land use and hydrologic changes during the 20th century, including changes in vegetation patterns, increase in tree density, variable climatic conditions, localized and severe fire impacts, and new ground water and surface water diversions. This report describes the status and preliminary results of an ongoing study of the southern Sacramento Mountains that endeavors to understand the hydrogeology of the mountain aquifers, aquifer connections to streams and springs, and the effects of vegetation management and climatic variability on the local hydrologic balance.

Description of Study Area

The southern Sacramento Mountain study area (Figure 1) encompasses the region between the west face of the Sacramento Mountains eastward towards Hope. The northern boundary of the study area extends from the surface

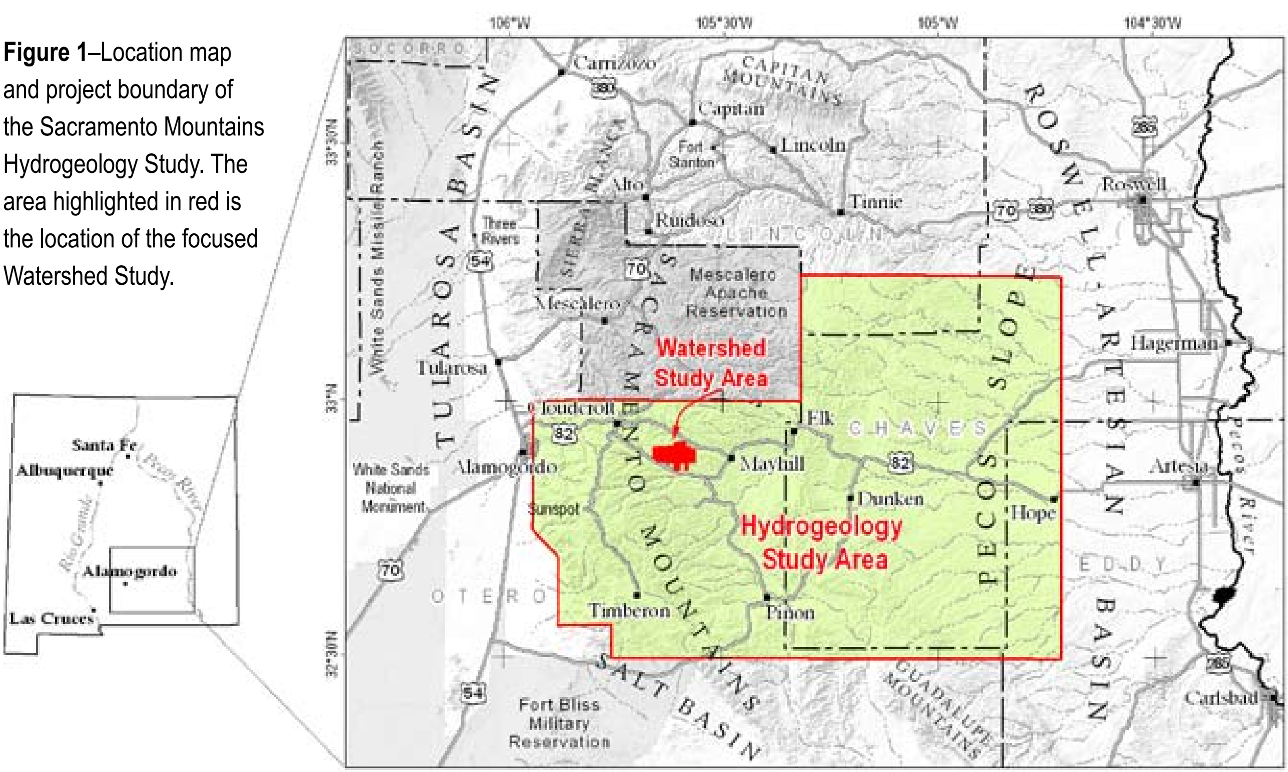


Figure 1–Location map and project boundary of the Sacramento Mountains Hydrogeology Study. The area highlighted in red is the location of the focused Watershed Study.

water divide separating the drainage basins of the Rio Peñasco and the Rio Hondo, around the southern boundary of the Mescalero Apache Reservation, and west to the Tularosa Basin. The southern boundary lies along the 32 degree, 30 minute line of latitude, and encloses the southern end of the mountain range and the village of Timberon. The study area covers the equivalent of 39 7.5-minute quadrangles, or approximately 2400 square miles, and includes numerous mountain villages and rural developments in Otero, Chavez, Eddy, and Lincoln Counties. Important adjacent physiographic features include the Tularosa Basin to the west, the Salt Basin to the south, the Roswell Artesian Basin and the lower Pecos River valley to the east, and Sierra Blanca and the Ruidoso highlands to the north.

Purpose and Scope of the Current Study

The Sacramento Mountains region is rather sparsely populated, with limited agricultural resources. For this reason, much of the previous work relevant to hydrology of the Sacramentos has focused on adjacent ground water basins – the Tularosa Basin to the west (e.g., McLean, 1970; 1975; Jennings, 1986, and many others), and to a much greater extent the Roswell Artesian Basin to the east, where more abundant water resources support a higher level of agricultural activity. In the first hydrogeologic investigations of the Roswell Artesian Basin (Fiedler and Nye, 1933), it was inferred that the Sacramento Mountains did not play a significant role in recharge to the Artesian Basin. Subsequent studies (Rabinowitz and Gross, 1972; Gross et al., 1976; Rabinowitz et al., 1977; Duffy et al., 1978; Davis et al., 1979; Gross et al., 1979; Gross and Hoy, 1980; Rehfeldt and Gross, 1981; Hoy and Gross, 1982; Gross et al., 1982; Gross, 1982; Wasiolek and Gross, 1983; Childers and Gross, 1985; Wasiolek, 1991), however, suggested that the Sacramento mountains might indeed play a significant role in recharging the Roswell Artesian Basin Aquifer. We now know that the southern Sacramento Mountains probably also provides recharge to the Salt Basin, and possibly the Tularosa Basin. Therefore, understanding the regional hydrogeologic system in the Sacramento Mountains is not only important for managing water resources in the region as the local population increases, but can also provide information relevant to adjacent hydrologic systems. Although a number of workers have published reports or maps on some aspects of the geology and hydrology in the Sacramento Mountains, there has been no comprehensive investigation of the ground water and surface water hydrology of the area.

Beginning in 2005, the New Mexico Bureau of Geology and Mineral Resources (NMBGMR), a division of New Mexico Tech, commenced a hydrogeology study of the southern Sacramento Mountains with the following primary goals:

- Delineating areas of ground water recharge
- Determining the direction and rates of ground water movement
- Elucidating the interconnectedness, if any, between various aquifers and between ground water and surface water

To characterize the regional hydrogeologic system, we utilized multiple geologic, hydrologic, and geochemical techniques including:

- Geologic mapping
- Statistical analyses
- Ground water level monitoring
- Water chemistry analyses
- Isotopic analyses
- Ground water age dating

As a part of this study, we are also conducting a focused watershed study to evaluate the effects of vegetation thinning on a local drainage scale water budget in the southern Sacramento Mountains. The study area is on a large private inholding within the Lincoln National Forest between Cloudcroft and Mayhill (Figure 1). The project consists of monitoring ground water levels, spring flows, ground and surface water chemistry, and soil moisture content within the study area. Local precipitation and weather data will be collected and detailed surface geologic and soil mapping will be conducted. These data will allow us to assess the impact of forest thinning on the water budget in the treated watershed.

Funding for this project was primarily provided by the State Legislature through the Otero Soil and Water Conservation District (SWCD). Additional funding was provided by from the U.S. Geological Survey under the STATEMAP component of the National Cooperative Geologic Mapping Program. Funding from the New Mexico Interstate Stream Commission was also provided to expand and improve the Watershed Study.

To date, data collection within the southern Sacramento Mountains study area, with the exception of the watershed study, has been completed. We are still working on analyzing the data for this part of the study, and we plan on completing the final report by 2012. We are presently beginning to collect data in the eastern portion of the Tularosa Basin between Alamogordo and Carrizozo. In this report we summarize our preliminary findings and plans for future data analysis.

II. GEOLOGY

Rationale for Geologic Mapping

Some of the most pressing challenges facing New Mexico stem from rapid population growth and the resulting competition for natural resources. Many of these problems can be addressed and evaluated by the use of modern geologic maps and their derivative products. Geologic maps are uniquely suited for solving problems involving Earth resources and hazards. Perhaps most importantly for the people of New Mexico, such maps help in the identification of aquifers and protection of ground water supplies, aid in locating water-supply wells, and are fundamental for all environmental studies and land-use plans. The primary objective of geologic mapping is to characterize the geology in sufficient detail to allow the information to be used in matters of practical economic and environmental concern to governments, communities, and planners, as well as to satisfy the goals of basic science. In addition, we continue to integrate the geology of individual quadrangles into an ever-expanding regional synthesis of New Mexico stratigraphy, structure, hydrogeology, and geologic hazards.

Geologic Mapping to Date and Future Work

The fundamentals of the geology of the southern Sacramento Mountains were well known prior to this study. The two essential references are the studies of Pray (1961), who focused on the western escarpment of the range, and Kelley (1971), who completed a reconnaissance geologic study of south central New Mexico. Our geologic mapping has been at a larger scale (1:24,000) than the maps in these studies and is intended to refine the geologic understanding to the level needed for a regional understanding of the hydrogeology.

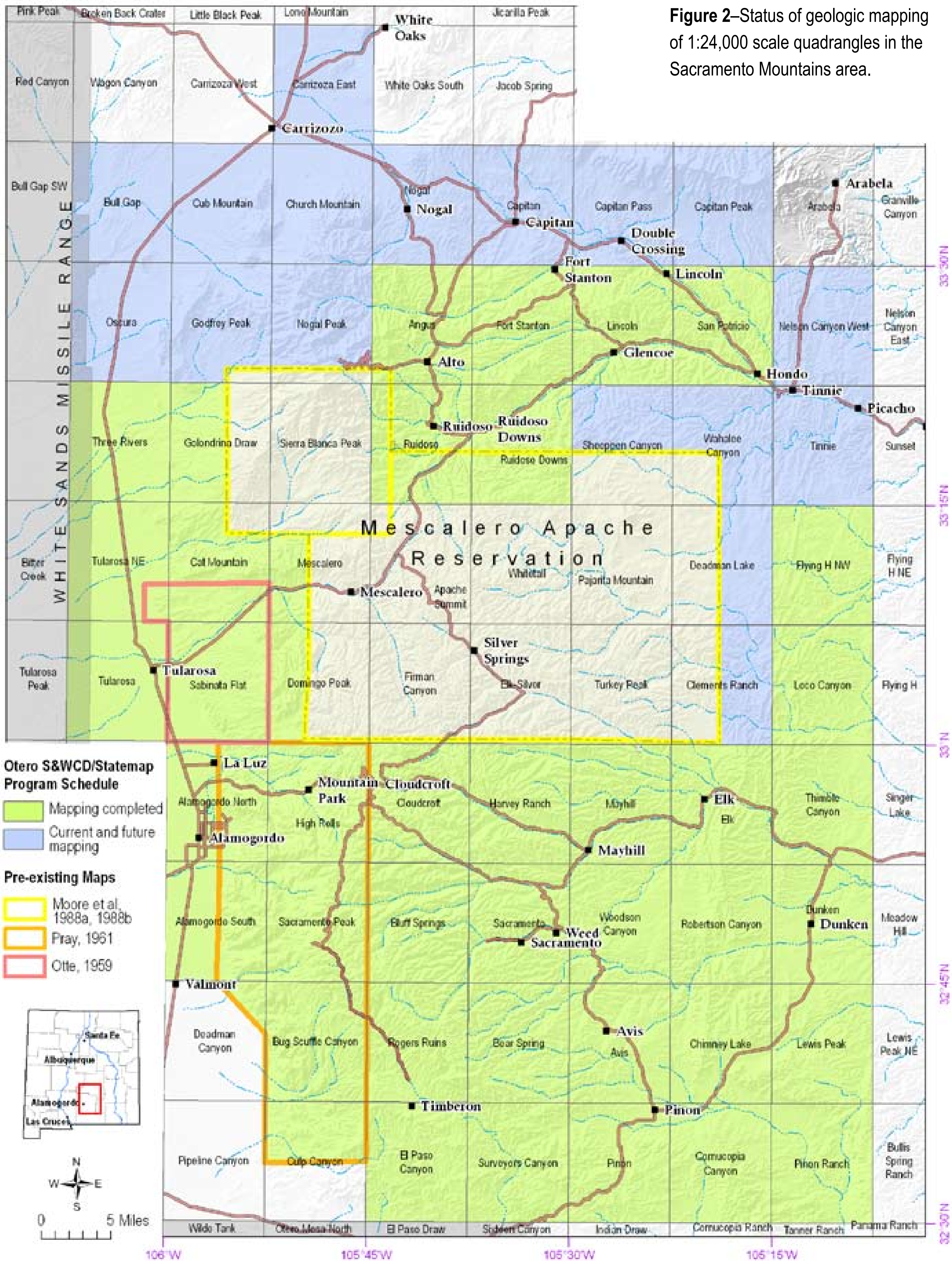
Geologic mapping is funded by the New Mexico legislative allocations through the Otero Soil and Water Conservation District which were used as matching funds to additional funding from the U.S. Geological Survey under the STATEMAP component of the National Cooperative Geologic Mapping Program. Geologic mapping was initiated in the Sacramento Mountains in 2005 and will continue at least into 2011. Mapping of approximately 42 quadrangles in the region of this study have been completed through the NMBGMR's mapping program (Figure 2), with an additional 12 quadrangles yet to be completed in the next few years. The completed individual geologic maps and cross-sections are available online at http://geoinfo.nmt.edu. Approximately 25 quadrangles have been combined for the southern Sacramento Mountains hydrogeology study as a compilation in this report. A preliminary partial compilation is included in this report as Figure 3, Plate 1.

Geology of the Sacramento Mountains

Introduction

East of a north-south line from High Rolls to Bug Scuffle Canyon (approximately following the West Side Road), to the crest of the range and east, the exposed rocks are the Permian Yeso and San Andres Formations, which dip shallowly (2-3°) to the east (Figure 3, Plate 1). East of the intersection of NM 24 and US 82, the topography is much more subdued towards the Pecos River. This area is referred to as the Pecos Slope. Along the west face of the mountains, the geology is more complex and is the focus of future

Figure 2–Status of geologic mapping of 1:24,000 scale quadrangles in the Sacramento Mountains area.



work. This area is dominated by steep cliffs composed of lower Paleozoic sedimentary rocks with some significant faults and folds.

Stratigraphy

The Yeso Formation is exposed in valley bottoms and the lower portions of valley side slopes, whereas the overlying San Andres Formation comprises the upper portions of valley slopes and caps the ridges (Figure 3, Plate 1). This pattern extends to a few miles east of longitude 105°30'0" west (a few miles east of Mayhill) where the easterly dip of the sedimentary rock layers causes the Yeso Formation to plunge beneath the ground surface. From this point east, the exposed bedrock is almost entirely the San Andres Formation. Furthermore, in this same vicinity it becomes possible to subdivide the San Andres Formation into the lower Rio Bonito member and the overlying Bonney Canyon member. As noted by Kelley (1971) and Black (1973), this subdivision is generally not possible further west because of tree cover and poor exposures. For example, it is likely that there is additional surface extent of the Bonney Canyon Member in the southwest portion of the study area, in the high elevation areas east of Timberon.

The Yeso Formation is composed of yellow to tan siltstone and fine sandstone, red to pink muddy siltstone and fine sandstone, gray to tan, often silty, carbonate rocks (limestone and dolomite, hereafter referred to generally as "carbonates"), and the evaporite minerals gypsum, anhydrite, and halite (Figure 4). Good, natural exposures of the Yeso Formation are rare, as it is less resistant than the overlying San Andres Formation and is usually covered with colluvium and valley bottom alluvium. A complete section is not exposed in the study area; Pray (1961) and Kelley (1971) measured one complete and two partial sections on the western escarpment, 11 miles north of the present study and at the extreme southwest corner of the present study. They estimated total thickness at 1300 – 1400 feet. The deep water well near Cloudcroft shown in Figure 4 penetrated 1650 feet of the Yeso formation. Anhydrite and/or gypsum is first observed at 930 feet below the top of the Yeso in this well, but at 260 feet depth in the southern surface section of Pray (1961). Anhydrite and minor halite were observed below 940 feet beneath the top of the Yeso in the Southern Production Co. #1 oil test well between Cloudcroft and the Rio Peñasco. No evaporites have been observed in surface exposures in the study area. In the upper portions of the Yeso Formation the evaporites have been dissolved, resulting in chaotic bedding dips. As a result, individual beds are not traceable laterally for more than a few tens of meters. In the area encompassing this study, Kelley (1971) and Pray (1961) noted that the gypsum content of the Yeso Formation increases to the north and the carbonate content increases to the south.

The San Andres Formation is composed of light to dark gray and bluish-gray carbonate rocks. Freshly broken surfaces are darker gray than weathered surfaces and often fetid. Subdivision of the San Andres into the lower dominantly thick-bedded Rio Bonito Member and overlying dominantly medium- to thin-bedded Bonney Canyon member (Kelley, 1971) was based largely on interpretation of aerial photographs. In most areas, the differences in the nature of the bedding are not reliably distinguishable on the ground. Kelley estimated thicknesses for the Rio Bonito Member at 250-350 feet and the Bonney Canyon Member at up to 300 feet. Based on our mapping, cross-sections, and well log interpretations, the thicknesses are ~580 and 400 feet, respectively. These differences are significant, but Kelley mapped at a much smaller scale (1:125,000) using a mix of air photo and topographic bases, and presented no cross-sections or well control to constrain his thickness estimates. Thickness variations on the order of ± 100 feet are likely in both members across the study area.

For the purposes of this study, younger geologic units have been generalized into Quaternary undivided alluvium, Quaternary landslide deposits and colluvium, and Quaternary and Tertiary terraces and gravels. The undivided alluvium includes unconsolidated alluvium in modern drainages, aeolian sand sheets, travertine

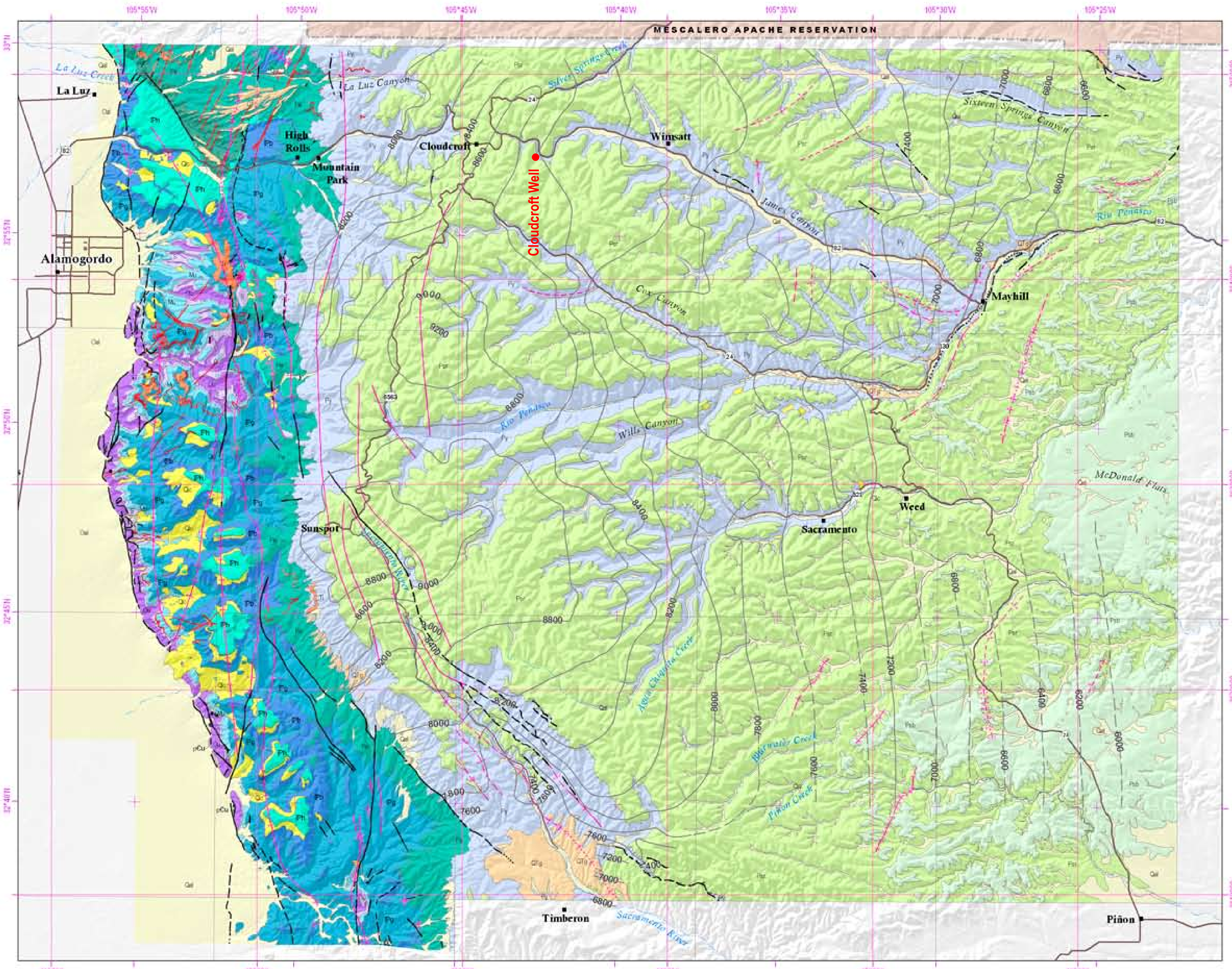


Figure 3–Generalized geologic map showing geologic units, faults and folds, and structural contours of the contact between the San Andres and Yeso Formations.

deposits around springs, and broad flat terraces and valley bottoms underlain by fine-grained sediment. The terrace and gravel unit includes coarse grained sediments and gravels that have been incised by modern drainages. Some of these gravels are well lithified and may be as old as Miocene.

Structural Geology

The shallowly east-dipping Yeso and San Andres beds are locally complicated by faulting and folding. The Sacramento River drainage extends southeast of Sunspot, through Timberon, and out of the study area into the Salt Basin. This drainage is structurally controlled as it follows a zone of west-side down normal faults and associated folds that form east-tilted structural blocks, or half-grabens (Figure 3, Plate 1).

The northeast–trending segment of the Rio Peñasco drainage that passes by Mayhill follows a fault with minor west-side down displacement (referred to in this report as the Mayhill fault zone). This fault and valley segment is aligned with the Border Buckle, a right-lateral strike-slip fault that extends for tens of miles to the northeast across the Pecos Slope (Kelley, 1971); thus the fault may be an extension of this regional structure and have some component of right-lateral slip. This fault appears to die out in the vicinity of Denny Hill north of Weed. There are several small folds extending to the southwest and northeast along the trend of this fault that are probably due to the distribution of displacement across a broad zone at the fault tip.

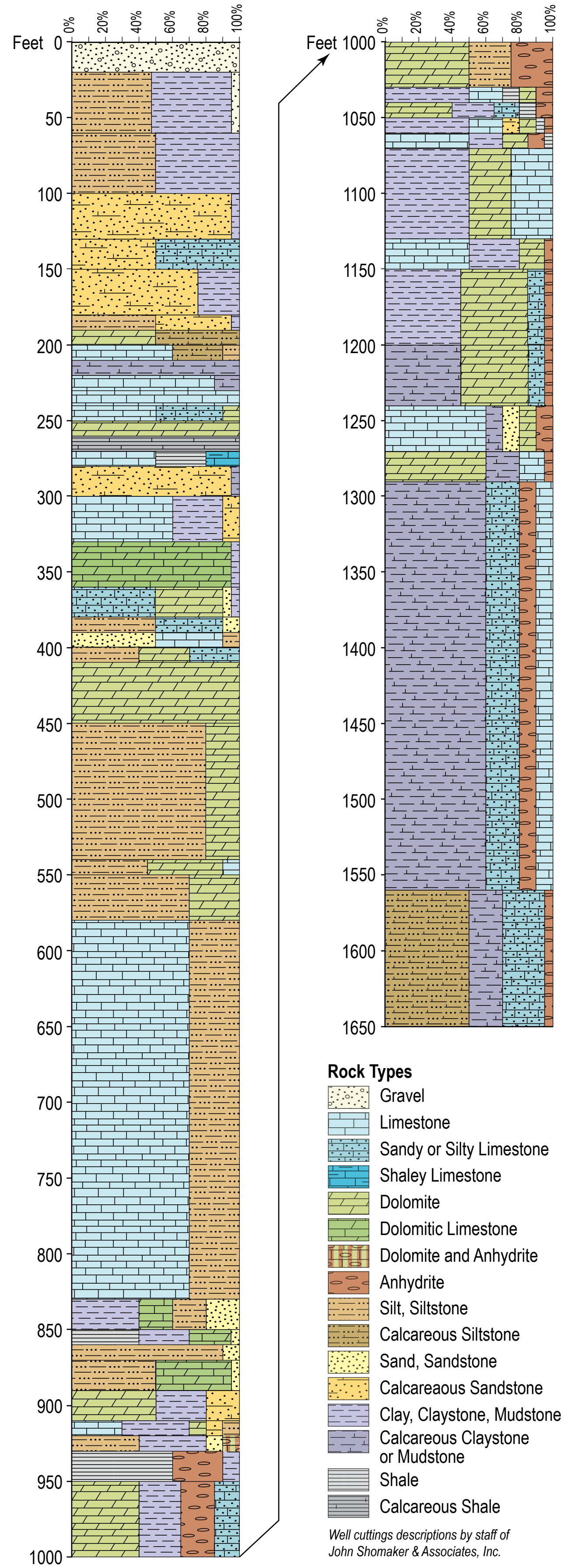
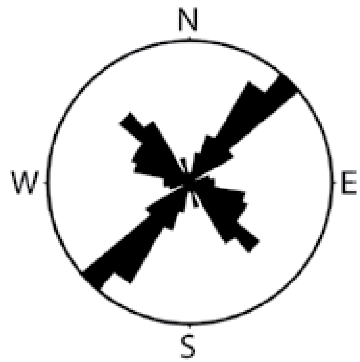


Figure 4–This simplified log of a deep water well (see Cloudcroft Well on Figure 3) illustrates the typical complexity of the geology in the upper portion of the Yeso Formation. Limestone, dolomite (commonly the water-producing units in wells) and claystone (which generally impedes ground water flow) are the most abundant rock types. Although the rock units were deposited as laterally continuous layers, now they are very discontinuous due to faulting, folding, and dissolution of limestone, dolomite, and anhydrite. Combined with the vertical variability, tracing rock units laterally from well to well throughout the study area is not possible.

Figure 5–Rose diagram of joint orientations in the Sacramento Mountains. Rose diagrams are like compasses that graph feature orientations. Each black triangle represents the number of joints within 10 degrees of an azimuth. The outer circle represents 16% of the total number of joints (27 of 170 joints). The two primary joint orientations observed are northeast-southwest and northwest-southeast.



Structural contours derived from elevation points along the mapped San Andres – Yeso geologic contact are illustrated in Figure 3 and Plate 1. The elevation of the surface defining the contact between these two units decreases from more than 9000 feet near the range crest to less than 6000 feet on the east side of the mapped area. The structure contours indicate that the strata dip gently to the east from a broad anticline (a down fold) at the range crest. The slight v-shaped contours along major drainages indicate broad folds that probably influenced the formation of the drainages and likely continue to influence ground water flow directions.

Carbonate rocks throughout the study area are deformed by joints, which are fractures that have small displacements perpendicular to the fracture surface, and negligible displacement in any other direction. We measured 170 joints at 70 sites. There are two predominant joint sets, northeast-southwest and northwest-southeast, consistently oriented throughout the study area (Figure 5). Most of the fractures have been widened by dissolution due to flowing ground water. Fractures and joints in the study area play an important role in the movement and recharge of ground water to wells, springs and streams.

Outcrops containing joints can be observed at road cuts, bedrock stream channels (Figure 6), and stream valley walls that are not covered with alluvium and/or vegetation. No consistent age relationship could be established between the joint sets. Many reaches of bedrock-floored streams have the same orientation as one of the joint sets.

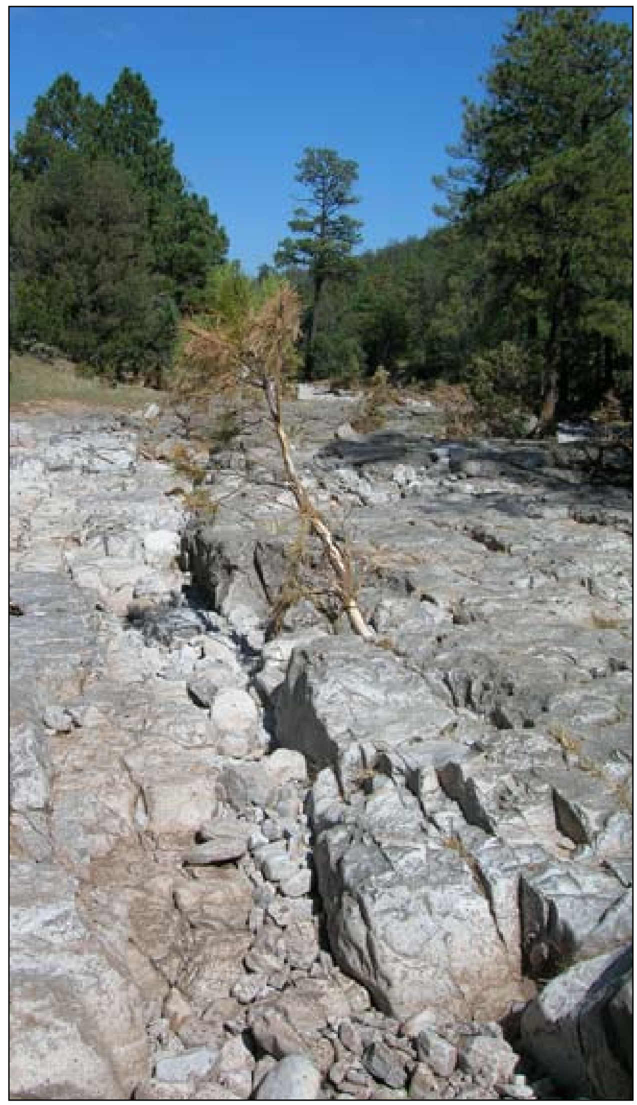


Figure 6–Photograph of joints in bedrock exposure in Piñon Creek. Joints are relatively closely spaced and the stream is parallel to them at this location. Bedrock stream beds are an indication of erosion.

III. HYDROGEOLOGY

Introduction

As shown in Figure 7, Plate 2, the study area has been divided into four regional aquifers. The boundaries are largely based on topography (surface water drainage basins) and the water table map that represents the average surface of the water table on a regional scale. The boundary between the high mountain aquifer system and the Pecos Slope aquifer is based on water chemistry and flow characteristics and is approximately where the Yeso Formation dips below the ground surface. In this section, we will discuss the different types of data for the various physical components of the hydrologic system, which include precipitation, perennial streams, springs, and the deeper ground water system that is accessed by wells. We will discuss how these data vary on a regional scale and within the different aquifers.

Precipitation

Regional Weather Patterns

Precipitation is the primary source of all ground water recharge in the study area. To accurately estimate this input, it is necessary to understand how precipitation in the area varies both

Hydrogeology Background

The ease with which water can move through a rock is a reflection of the rock's permeability. This in turn is controlled by the rock's porosity, or percentage of internal void space, and the degree of interconnectivity of the pores. Related to permeability is transmissivity, which incorporates the thickness of the water-bearing unit; this term is often used when neither the permeability nor thickness is known exactly.

Aquifers are bodies of rock that are permeable enough to conduct ground water and that yield economically significant quantities of said water to springs and wells. The distinction between confined and unconfined aquifers needs to be understood to interpret the water level data we have collected. Confined aquifers are those in which there is an impermeable or relatively low-permeability layer between the aquifer and the ground surface that prohibits or inhibits the upward movement of water. Often water within confined aquifers is at pressures greater than atmospheric. This pressure causes water levels in wells penetrating confined aquifers to rise above the top of the aquifer, and can result in naturally flowing (artesian) wells where the water reaches the land surface. Unconfined aquifers are those in which there is no low-permeability layer preventing easy movement of water between the aquifer and the ground surface. The water level in a well that penetrates an unconfined aquifer will coincide with the top of the aquifer or the water table. In reality aquifers can exhibit behavior between these two extreme types. If a zone of low permeability material overlies or is within higher permeability materials, for example a clay or shale bed surrounded by sandstone, a perched aquifer can develop.

An example relevant to the present study is valley alluvium of mixed clay and sand on top of limestone bedrock. Perched aquifers are almost always unconfined, and result from ground water moving downward and collecting on top of the low permeability layer. Few geologic materials are totally impermeable, and thus there is usually slow downward leakage through the low permeability layer, resulting in some hydrologic connection with the underlying, more widespread, regional aquifer. This leakage may become more abundant during especially wet periods. Because of the likelihood of this leakage, in this report we refer to leaky aquifers which overlie the regional aquifer.

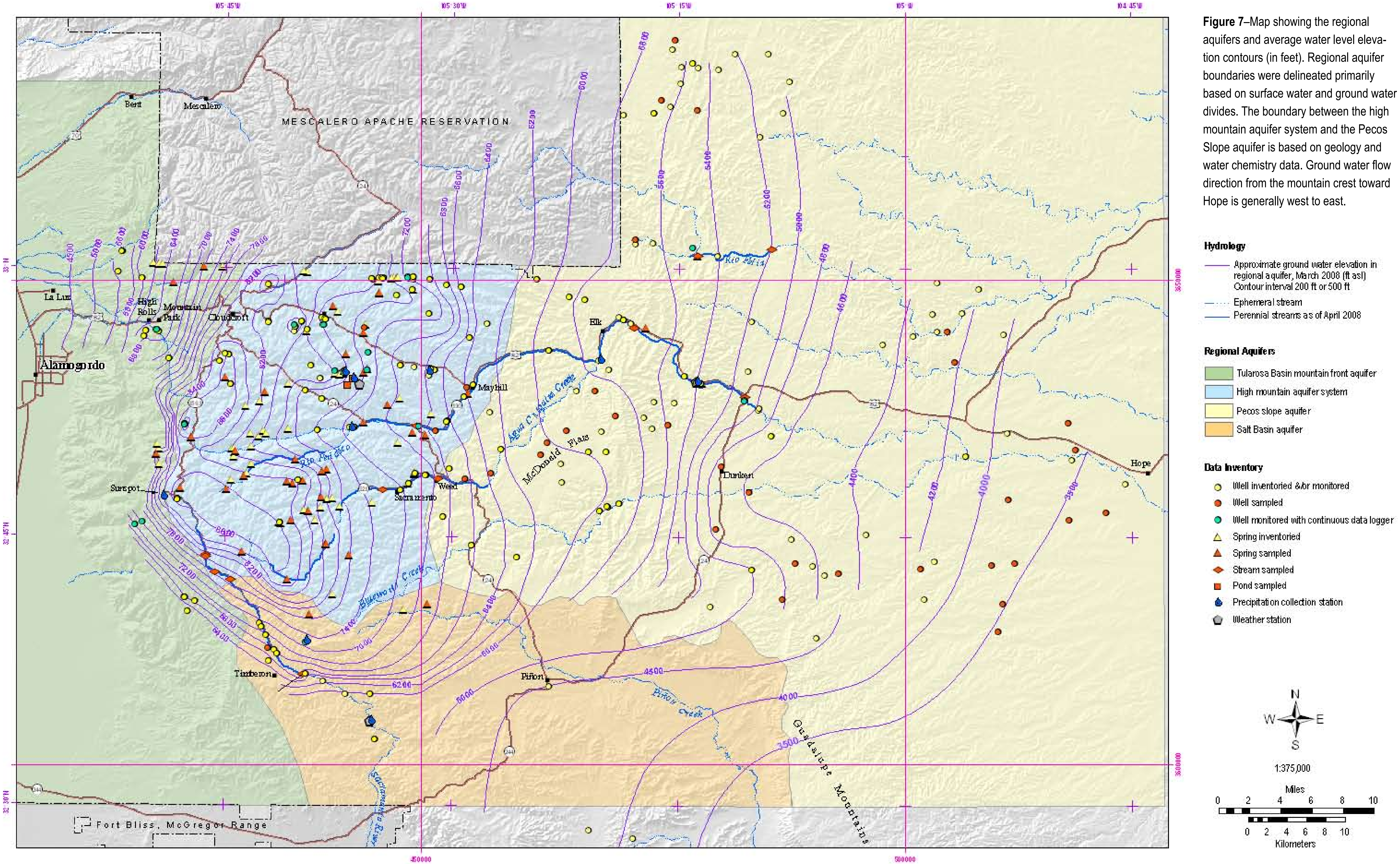


Figure 7–Map showing the regional aquifers and average water level elevation contours (in feet). Regional aquifer boundaries were delineated primarily based on surface water and ground water divides. The boundary between the high mountain aquifer system and the Pecos Slope aquifer is based on geology and water chemistry data. Ground water flow direction from the mountain crest toward Hope is generally west to east.

with space and time. In general, the summer months are the wettest. Winter precipitation is mainly produced by frontal storms that originate in the eastern Pacific and move from west to east across the country. Summer rainfall is generally produced by thunderstorms spawned by tropical moisture brought into the state by monsoonal air flows. Occasionally, tropical storms will be swept up into the greater southwest, providing additional summer rains.

The North American Monsoon (NAM) is the dominant source of warm season rainfall in the study area. Monsoon season generally runs from July through September, and upwards of 50% of total annual precipitation can fall during this time. As the earth's surface is heated in early summer, moisture from the eastern Pacific and the Gulf of California is advected into the region by the resulting low pressure at the surface. Moisture from the Gulf of Mexico is also drawn into the region at this time by easterly winds. (Liebmann et al., 2008; Stensrud et al., 1995; Gochis and Higgins, 2007; Ritchie et al., 2008; Ritchie and Szenasi, 2006; National Weather Service n.d. a, National Weather Service n.d. b, National Weather Service Southern Region Headquarters, 2006; National Weather Service Climate Prediction Center, 2004).

Tropical disturbances originating in the Gulf of Mexico or eastern Pacific can add significant amounts of rain to interior west. These disturbances include tropical depressions, tropical storms, and hurricanes, and can contribute 25% to 30% of seasonal rainfall totals. Occasionally, decaying tropical storms will be caught in weakening monsoonal flows, and get swept across the southwest at the end of the monsoon season.

During the winter, frontal storms are the primary source of precipitation in the state. Mid-latitude frontal storms occur throughout the year, as relatively warm subtropical air mixes with cooler air in the mid latitudes, generating areas of high and low pressure that move eastward from the Pacific Ocean across the continent. The track of these storms shifts northward during the summer and southward during the winter as the earth's surface heats then cools. During any given year, frontal storms lasting from 3 to 10 days move eastward from the Pacific and routinely cross New Mexico.

In addition to the annual movement of the prevailing storm tracks due to the heating of the land surface, large scale fluctuations in the heating and cooling of the Pacific Ocean can alter the prevailing storm track as well. During some

Hydrologic Cycle

The identification of the inputs and outputs of a hydrologic system requires an understanding the hydrologic cycle. Hydrologists attempt to quantify the different components of the hydrologic cycle by calculating a water balance of inputs, outputs, and storage for the aquifer system. Within the defined study area, precipitation is the primary input, while outputs include evapotranspiration (a combination of evaporation from soil and surface water bodies and transpiration from plants), ground water flow, and surface water flow across a defined boundary of the study area. Water can be stored in several different reservoirs including unsaturated soils, the saturated ground water system, stream channels, and the surfaces of vegetation.

Before many of the components of the water balance can be estimated, it is important to construct an accurate conceptual model of the hydrologic system. It is necessary to identify, characterize, and assess the interaction between the precipitation, vegetation, surface water systems, and ground water systems. The interaction between these components is controlled by climate, topography, and geology. For this study, we have utilized geologic, hydrologic and geochemical techniques to evaluate the different components of the hydrologic system.

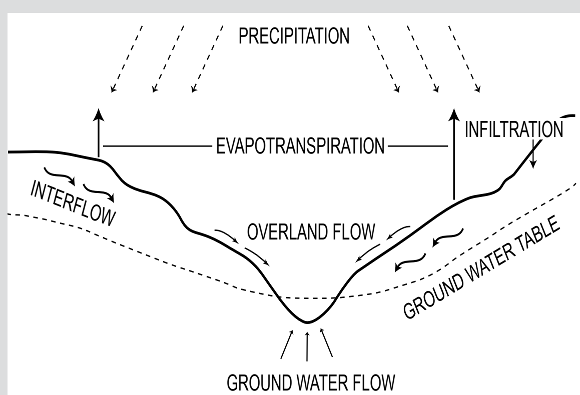


Table 1–Western Regional Climate Center (NOAA) weather stations used in discussion of historical precipitation record in the Sacramento Mountains.

Station	Station Number	Elev (ft)	Period of Record*
White Sands National Monument	299686	3990	1939 to 2007
Hope	294112	4100	1919 to 2007
Orogrande	296435	4180	1914 to 2007
Alamogordo	290199	4350	1914 to 2007
Tularosa	299165	4540	1914 to 2007
Elk	292865	5710	1895 to 2007
Mayhill Ranger Station	295502	6550	1917 to 1976
Mescalero	295657	6790	1914 to 1978
Mountain Park	295960	6790	1914 to 2007
Ruidoso	297649	6860	1942 to 2007
Cloudcroft**	291927/ 291931	8810	1914 to 2007

* = entire span may include gaps

** = combined record for Cloudcroft stations 291927 (1914 to 1987) and 292931(1987 to 2005).

years, unusually warm waters develop off the coast of South America, causing the dominant storm track to shift southward, increasing the contribution of winter storms to annual rainfall totals in the Southwest U.S. This warm phase is called an “El Niño” event. At other times, cool water develops along the coast, pushing the storm track northward, decreasing the contribution of frontal storm systems to precipitation totals in New Mexico. This cooler phase is called a “La Niña” event, and La Niña winters can be two to three times drier than El Niño winters in the Southwest (Ahrens, 2003).

In addition to the dominant patterns noted above, topography and elevation influence the amount of rainfall that will fall in a given location. As air is forced up and over topographic features such as the Sacramento Mountains, moisture within the air condenses and falls as precipitation. This is called the orographic effect and, all else being equal, results in increased rainfall with increased elevation.

Historical Precipitation Record

Daily precipitation amounts have been recorded in the Sacramento Mountains and vicinity for most of the past century, with some records dating back to 1895. These detailed records are available from the Western Regional Climate Center, National Oceanic and Atmospheric Administration (NOAA) (see http://www.wrcc.dri.edu/summary/climsmnm.html). Individual stations can be seen in Table 1.

Total annual precipitation, including snowfall, at each of the stations over the period of record is plotted against elevation in Figure 8. The correlation between elevation and average annual precipitation is quite strong, with an R^2 value of 0.92, indicating that elevation is a strong predictor of annual precipitation in the study area. Snowfall amounts alone are also influenced by elevation (data not shown). The correlation is not as strong (R^2 = 0.76) as that noted for total average annual precipitation but elevation is still a fairly robust predictor of total average annual snowfall.

Extreme rainfall events or seasons are of particular importance in terms of their potential impact on ground water recharge, especially when topography is taken into consideration. High elevation areas receive more rain and

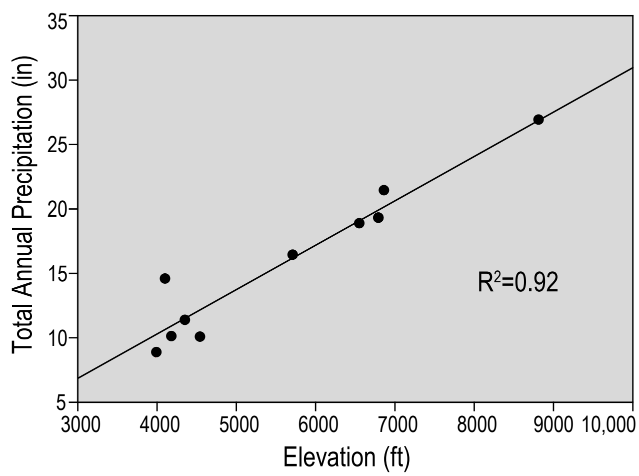


Figure 8–Average annual precipitation vs. elevation. The total annual precipitation (rain and snowfall) at weather stations listed in Table 1 shows a strong correlation with elevation, indicating that there is more precipitation at higher elevations than at lower elevations.

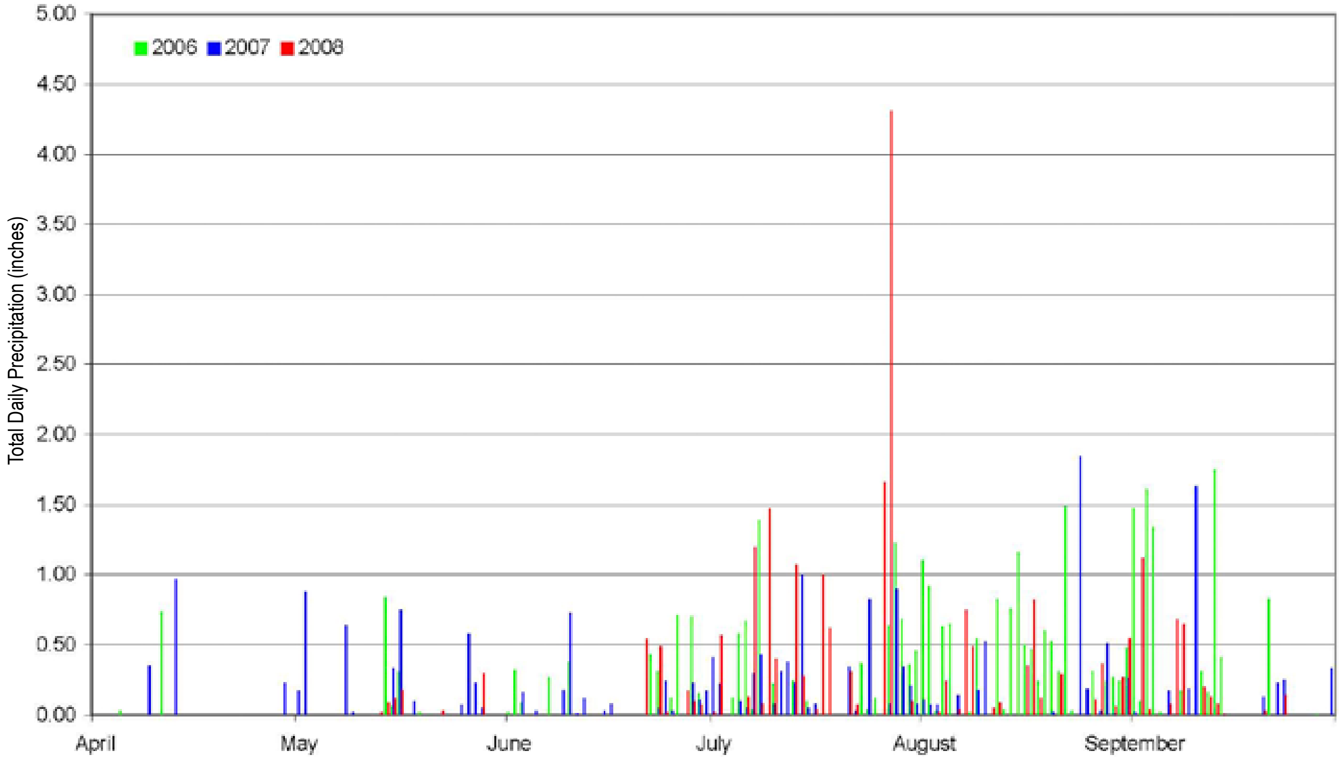


Figure 9–Warm season total daily precipitation in Cloudcroft: 2006 thru 2008

snowfall, and the lower temperatures characteristic of these locations increases the length of time that snow remains on the ground. During the summer, the lower temperatures found at higher elevations helps minimize evaporation of monsoon rainfall. Taken together, these factors suggest that high elevation areas are important to ground water recharge and that extreme rainfall events or seasons that impact high elevation portions of the study area will significantly influence ground water recharge and the local ground water table.

During the study, there were two discrete summer recharge events that resulted in an increase in water levels in most wells monitored in the study area. The recharge events were associated with above average precipitation during the summers of 2006 and 2008. There was no notable increase in water levels observed during the summer of 2007. Figure 9 shows daily precipitation amounts in Cloudcroft during summer months from 2006 to 2008. It can be seen that the wet monsoon season in 2006 is characterized by frequent small storms between July and October, while for 2008, approximately 55% of summer precipitation fell during the month of July. Probability of exceedance curves are plotted for annual and monthly precipitation in Cloudcroft between 1902 and 2008 (Figure 10). Figure 10a shows that there is a very small probability that the annual precipitation in Cloudcroft will exceed the amount measured in 2006 (recurrence interval ~36 years). The probability of exceedance for total annual precipitation in 2008 is higher than that for total annual precipitation in 2007 (Figure 10a). However, Figure 10b shows that July of 2008 was the wettest month on record (recurrence interval of 95 years), followed by August 2006. During July 2008, a remnant disturbance of Hurricane Dolly, which traveled over land in Southern Texas and Northern Mexico, produced heavy rainfall in the Sacramento Mountains (Pasch and Kimberlain, 2008). Cloudcroft received 13 inches of rain in July, 45% of which was contributed by this disturbance. The effect of these two above average wet periods on the hydrologic system will be discussed below.

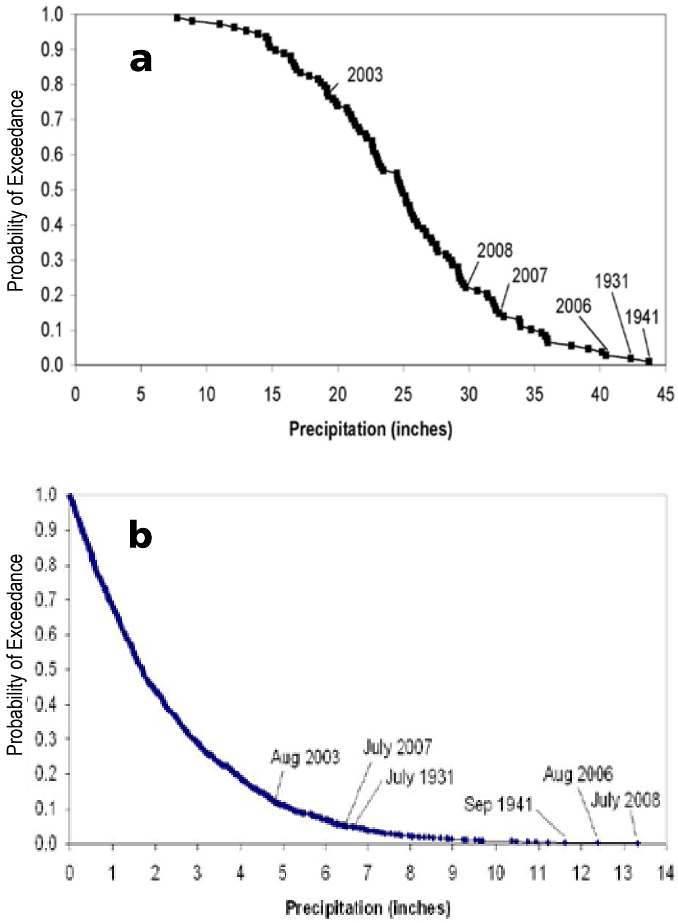


Figure 10a–Probability of exceedance curve for annual precipitation in Cloudcroft (1902-2008) shows the probability of the total annual precipitation exceeding a specific value. Selected years are labeled.

10b–Probability of exceedance curve for monthly precipitation in Cloudcroft (1902-2008) shows the probability of the total monthly precipitation exceeding a specific value. Selected months are labeled.

Stable Isotopes in Precipitation

We have collected precipitation in the Sacramento Mountains on a regular basis since 2006 for stable isotopic analysis. Figure 11 shows the location of the stations where precipitation is collected. We chose the locations of the precipitation collectors so that a range of elevations within the study area are represented. In general, samples were collected every three months (March, June, September, and December) in order to assess the seasonal variability of the average isotopic composition of precipitation. However, the time interval between sampling events sometimes varied due to the over-filling of the sample vessels during extreme precipitation events. For most precipitation samples, the total volume of water that accumulated in the sample vessel between sampling events was measured, and a sub-sample was collected to be analyzed for the stable isotopes of oxygen and hydrogen.

By determining a line that best fits this stable isotope data in δD vs. $\delta^{18}O$ space, we construct-ed a local meteoric water line (LMWL) (Figure 12 and see Stable Isotopes sidebar below). The linear equation for the LMWL is:

$$\delta D = 8.4\delta\ {}^{18}O + 23.4$$

We examined the seasonal variability of the isotopic composition of precipitation by categorizing precipitation samples as winter precipitation, summer precipitation, or mixed. For winter precipitation samples, at least 90% of the sample represents precipitation that fell between October and March. For summer precipitation, at least 90% of the sample represents precipitation that fell between April and September. Mixed precipitation samples are a mixture of winter and summer precipitation where both end members represent less than 90% of the mixture. For samples that were an accumulation of precipitation over a period of time that crossed the summer/winter boundary, the proportion of summer and winter precipitation was assumed to be the same as that observed at weather stations in the study area at similar elevations to those where precipitation was collected (http://www.wrcc.dri.edu/summary/Climsmnm.html).

The shaded areas in Figure 12 denote areas where the isotopic compositions of most winter precipitation (blue) and summer precipitation (red) plot along the LMWL. It should be noted that these shaded areas represent the average range of isotopic values for precipitation that falls at different times of the year based on our data. The isotopic composition of precipitation is controlled by many factors, and it is likely that an occasional individual storm event will result in precipitation with an isotopic composition that plots outside the expected range. This can be observed for precipitation associated Hurricane Dolly (Figure 12). These storms occurred in July 2008, but their isotopic composition plots with expected winter values. These samples will be discussed in more detail below.

Seasonal variations in the stable isotopic composition of precipitation are due to three factors (Rozanski et al., 1993): 1) seasonally changing temperature; 2) seasonally modulated evapotranspiration flux; and 3) seasonally changing source areas of vapor and/or different storm trajectories. All three of these factors play a role in the observed seasonal variability of the stable isotopic composition of precipitation in the Sacramento Mountains. Seasonal temperature fluctuations in the Sacramento Mountains average approximately 15 degrees C between sum-

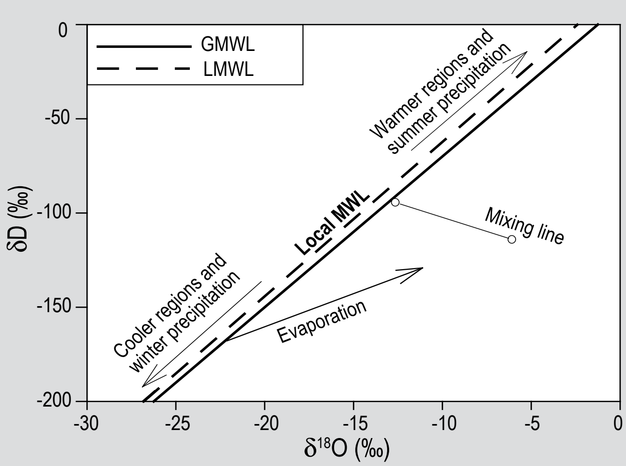
Stable Isotopes

Stable isotopes of hydrogen and oxygen are useful tools for tracking precipitation through a hydrologic system. The nucleus of most oxygen atoms contains 16 subatomic particles: 8 protons and 8 neutrons. A small fraction of all oxygen atoms (approximately 0.2%) contains 10 neutrons, for a total of 18 subatomic particles in the nucleus. This isotope of oxygen is referred to as oxygen-18, or ^{18}O. Most hydrogen atoms consist of a single proton in the nucleus orbited by a single electron. A very small fraction of hydrogen atoms (approximately 0.016%) also contain one neutron in the nucleus, for a total of two subatomic particles. This isotope of hydrogen is referred to as deuterium and abbreviated as D. Hydrologists refer to the ^{18}O and D varieties of oxygen and hydrogen as stable isotopes, because they are not subject to radioactive decay. The deviation of the ratio of the heavier isotope to the lighter isotope ($^{18}O/^{16}O$, D/H) in the water sample of interest from that of a standard, in parts per thousand (‰), is expressed as $\delta^{18}O$ and δD. A negative value of $\delta^{18}O$ or δD indicates that the water sample is depleted in the heavier isotopes (or lighter than) than the standard. For stable isotopes of hydrogen and oxygen, the standard is called Standard Mean Ocean Water (SMOW). Because these stable isotopes are actually part of the water molecule, small variations in these ratios act as labels that allow the tracking waters with different stable isotopic signatures.

Because a water molecule is made up of both hydrogen and oxygen, it is advantageous to evaluate δD and $\delta^{18}O$ data simultaneously. The figure to the right shows a graph with δD on the y-axis and $\delta^{18}O$ on the x-axis. On such a plot, the isotopic compositions of precipitation samples collected from around the Earth plot close to a line called the global meteoric water line (GMWL) due to the predictable effects of evaporation and condensation. In general, precipitation in warmer regions will plot towards the heavier end of the GMWL (less negative values), and precipitation from cooler regions will plot towards the lighter end (more negative values). At any given location, a seasonal trend is also evident with winter precipitation plotting on the GMWL towards the lighter end and summer precipitation towards the heavier end. The GMWL represents a global average variation in the isotopic composition of precipitation. In a study such as this, it is necessary to collect local precipitation and define a local meteoric water line (LMWL), whose slope and y-intercept may vary slightly from the GMWL due to local climatic conditions.

The effects of evaporation are illustrated below. As precipitation evaporates, the isotopic composition of the residual water evolves away from the meteoric water line (global or local) along an evaporation line, whose slope depends on the conditions under which evaporation has taken place.

The mixing of two water sources of different isotopic compositions can be evaluated by looking at a plot δD vs. $\delta^{18}O$. A water sample that is a mixture of two isotopically distinct waters will have an isotopic composition that plots on a straight line that connects the two end member water sources. The proportion of mixing can be quantified by evaluating the distance between the point that represents the mixed water and the points representing the two end members on the mixing line.



mer and winter. The Sacramento Mountains are heavily vegetated compared to surrounding areas, and during the summer a significant amount of water vapor is returned to the atmosphere due to an increase in evapotranspiration rates. This addition of water vapor to the atmosphere effectively reduces the extent of isotopic depletion of precipitation during the summer (Rozanski et al., 1993). As discussed above, the source area of winter frontal storms in most cases is different from that for storms associated with the North American Monsoon.

Stable isotope values for precipitation that fell in late July 2008, associated with Hurricane Dolly, plot along the LMWL within the range of expected winter values (Figure 12). This anomalously light isotopic composition of precipitation associated with hurricanes has been observed by other researchers (Lawrence et al, 2002) and is mainly attributed to a high condensation efficiency. At low condensation efficiencies where a small percentage of a given volume of water vapor condensates and rains out, the precipitation will be isotopically heavier than the water vapor (see stable isotope sidebar). As the condensation efficiency increases, the average isotopic composition of precipitation will decrease, approaching the isotopic composition of the water vapor.

The annual weighted average isotopic composition is the average of isotopic values of all samples collected at a single location over one year, weighted by the sample volumes. In other words the weighted average isotopic composition represents the isotopic value that would be measured if all samples collected at one location over a year were combined as one sample. Figure 12 shows the weighted average isotopic composition for samples collected in 2007. These values plot within the range of expected values for summer precipitation, which is indicative of the proportion of annual precipitation that

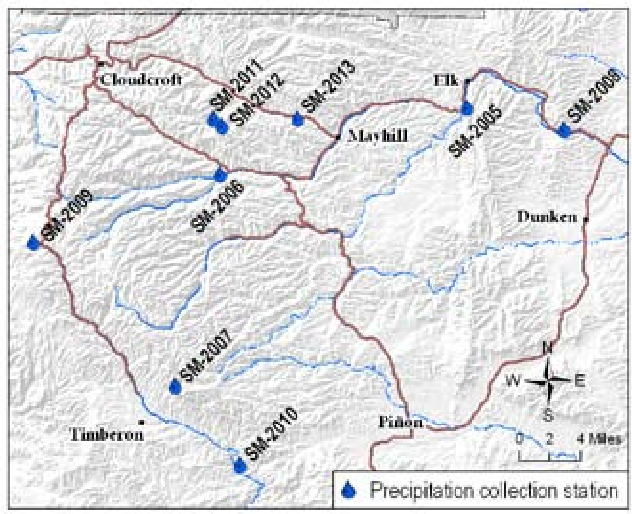


Figure 11–Map of precipitation collection stations.

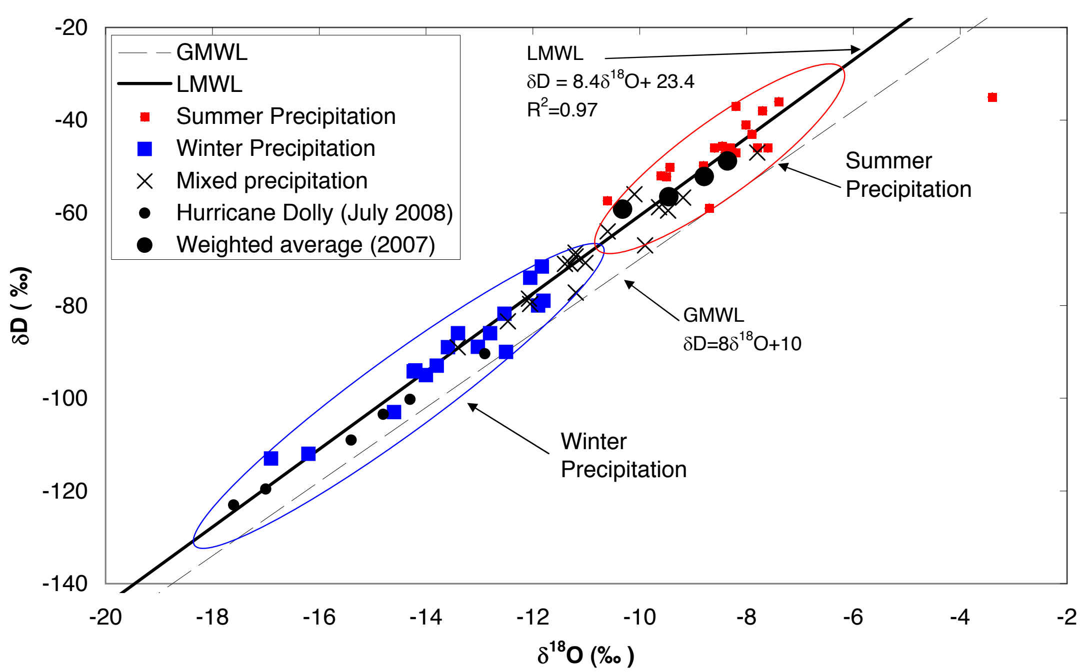


Figure 12–Local meteoric water line. The local meteoric water line (LMWL) is defined by the isotopic composition of precipitation sampled from several different elevations over the past two years. Summer precipitation plots at the heavier end along the LMWL while winter precipitation has isotopically lighter values.

falls in the summer (see historical precipitation discussion). The differences in the annual weighted average isotopic composition observed for different collection sites is due to the relative elevation of the collection site. Weighted average isotopic values for summer precipitation from 2007 become lighter with increasing elevation. This trend is also observed for precipitation in July and August 2008. The elevation effect is attributed to the progressive condensation of atmospheric vapor and rainout of the condensed phase as an air mass rises up along the slopes of mountains and cooling as a result of adiabatic expansion (Gonfiantini et al., 2001). Interestingly, we did not observe this elevation effect for winter precipitation. The fact that we see the elevation effect for summer precipitation, but not for winter precipitation reflects the different physical characteristic of the two primary weather patterns that contribute precipitation to the Sacramento Mountains: 1) Frontal storms in the winter and 2) The North American Monsoon in the summer.

Tritium in Precipitation

Tritium concentrations in precipitation (see sidebar on Environmental Tracers) samples collected in the southern Sacramento Mountains range from 2.97 to 10.4 TU, with a local average of 5.8 TU. As shown by the sampled precipitation tritium concentrations (Table 2), tritium varies seasonally in the Sacramento Mountains, with higher spring-summer values than winter values. In the northern hemisphere, it is typical for tritium levels to be highest during May through July (Solomon and Cook, 2000).

There is little variation in tritium concentrations in precipitation over the study area (Table 2). The observed variations are dominated by seasonal influences.

Table 2–Tritium concentrations measured in precipitation collected at various locations and dates in the southern Sacramento Mountains. All lab analyses were done at the Miami Tritium Laboratory. See Figure 11 for precipitation collection locations.

Point ID	Tritium (TU)	Sample Collection Date
SM-2006	10.1	22-May-07
SM-2007	10.4	22-May-07
SM-2008	9.4	22-May-07
SM-2009	3.37	05-Dec-07
SM-2010	2.97	05-Dec-07
SM-2006	4.43	04-Mar-08
SM-2009	4.68	05-Mar-08
SM-2009	2.93	29-Jul-08
SM-2009	4.02	06-Sep-08

Streams

General Description

East of the crest of the Sacramento Mountains, stream valleys drain generally eastward toward the Pecos River (Figure 7, Plate 2). Valley bottoms have approximately the same overall dip as the San Andres - Yeso geologic contact (2-3°). However, short stretches are steep, even approaching vertical, and others are nearly horizontal. Minor wetlands are common in the flat sections, especially around springs at the heads of perennial reaches of streams. These wetlands are characterized by saturated soil with single or multiple coalescing channels that drain the wetlands. These minor spring-fed wetlands are likely to evaporate more water than steeper, flowing stream channels because they have much larger surface area and nearly stagnant water. Wetlands are also likely to be sites of ground water recharge because they are permanently saturated. The headwaters of the Sacramento River, upper and lower Rio Peñasco, Wills Canyon, and Agua Chiquita all have these types of wetlands. Each of these drainages also has wetlands downstream of the headwater areas, but in developed watersheds, especially the Rio Peñasco, it is difficult to distinguish between natural wetlands and man-made irrigated fields.

Very few streams in the Sacramento Mountains are perennial (Figure 7, Plate 2). Perennial flow typically exists over relatively short distances before infiltration to shallow ground

Environmental Tracers and Ground Water Residence Time

Ground water residence time refers to the amount of time required for water derived from precipitation to travel from recharge areas to sites of discharge, such as springs or rivers. Ground water age refers to the amount of time water has spent in the hydrologic system between the time of recharge and when the sample was collected. If the sample is collected from a well, then we are estimating the ground water age, which is less than its residence time. If the sample is collected at a spring, the ground water age is equal to its residence time. Both ground water age and residence time are related to the length of the flow path and flow velocity. A variety of naturally-occurring and anthropogenic geochemical tracers are used to evaluate the residence time of ground water within an aquifer. Determining the residence time and/or age of ground water is not a straightforward process. Complex hydrologic systems such as the southern Sacramento Mountains may involve mixing of waters from several different sources, e.g., old deep waters that circulate upwards along faults, young shallow surface water that has recently recharged, or a mixture of water ages found in perched aquifers.

Most experts recommend using multiple tracer techniques to address these ambiguities instead of relying on a single method. The water ages from one method cannot be used alone but must be considered with other age tracers. Our results presented in this report are preliminary.

Tritium (^3H)

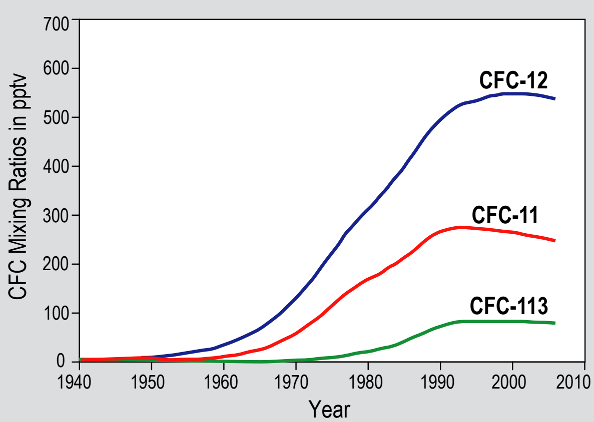
Tritium is a short-lived isotope of hydrogen with a half-life of 12.32 years. The vast majority of hydrogen atoms consist of a single, positively charged proton in the nucleus of the atom and a single, negatively charged electron orbiting the nucleus. The nucleus of the tritium version of hydrogen also includes two neutrons (neutral charge). Tritium (or ^3H) is produced naturally in the stratosphere by cosmic radiation. From 1952 to 1980 above-ground nuclear testing added large concentrations of tritium to the atmosphere. Tritium enters the hydrologic cycle via precipitation, with the tritium atoms directly incorporated into water molecules. Because the tritium in the water molecule is not a gas, as some of the other tracers discussed here are, it is not easily altered upon exposure to air. However, the amount of tritium decays by half every 12.32 years, so once it is in the ground water system the concentration begins to change.

Tritium concentrations are measured in Tritium Units (TU); one TU indicates one tritium atom per 10^{18} hydrogen atoms. Significant spatial and seasonal variations exist in the atmospheric concentration of tritium. The greatest natural increase in tritium concentrations in the atmosphere occurs during the spring months in mid-latitude zones due to displacement of the jet stream. Without knowing exactly what the tritium concentration was during recharge, the age of ground water cannot be precisely calculated using tritium alone. However, the tritium in ground water and spring water can be one of the most direct ways of determining the relative age of the ground water, even though it does not give an age in terms of years.

Chlorofluorocarbons (CFCs)

Chlorofluorocarbons, or CFCs, are synthetic gaseous compounds that were used in refrigeration systems, solvents, and as aerosol propellants from the 1940s through the 1990's. CFC compounds have different species, including CFC11, CFC12 and CFC113, which will be found in ground water if it has been exposed to the atmosphere at any time since the 1940's. CFC compounds increased in the atmosphere in a quasi-exponential fashion from the 1950s through late 1980s, at which time their abundance began to decline because of international agreements to limit their production.

CFC concentrations in precipitation are proportional to CFC content in the atmosphere when the precipitation forms. Therefore, if precipitation that recharges the saturated ground



water system maintains its CFC concentrations throughout the recharge process, the CFC concentrations in ground water can be compared to documented CFC levels in the atmosphere to estimate when that water fell as precipitation. CFCs in the atmosphere are relatively well known over time, and they can be compared with the results of a ground water sample to determine the apparent age (see figure). If waters of various ages are mixing in an aquifer, the measured CFC values will represent various proportions of different CFC concentrations from different recharge times. Therefore, the age calculated from the CFC concentrations is an apparent age, rather than an actual age.

The species most commonly used to date ground water are CFC11, CFC12 and CFC113. It should be noted that the ratios of the calculated atmospheric content for these different species (CFC11/CFC12, CFC11/113, CFC12/CFC113) can also be used to estimate ground water age. In a simple aquifer system where there is no mixing of older or younger water (called piston flow), the expected CFC apparent ages would be concordant with each other (±2 years). In general, greater than 2 year variations in ages among the different CFC species and their ratios imply there is significant mixing in the aquifer system. For example, if CFC113 ages are 10 years younger than CFC12 ages, then this is a qualitative method for determining that there is some degree of mixing in the aquifer system, but it does not provide ages of the actual water fractions. Also mixing is indicated by CFC113/12 ratio ages that are younger than the individual CFC age (Happell et al., 2006). Mixing water of different ages can occur, for example, as ground water and surface water interact, or as fractures and faults provide conduits for circulating deep old water with shallow younger ground water.

When using CFCs as an age dating tool, several important factors have been considered in the age calculations. The age results are dependent upon an input recharge elevation and recharge temperature. In general, these factors are difficult to determine and must be estimated. Recharge temperatures that are too cold will cause the CFC age to be too old, while samples that are given recharge temperatures that are too warm will appear too young. Likewise for elevation, if it is overestimated, samples will appear too young, and if elevation is underestimated, samples will appear too old.

Other potential problems with using CFCs as a ground water dating tool are due to CFCs being dissolved gases. Dissolved gas concentrations in the water are controlled by the relative abundance of gases in air it comes in contact with. Therefore, if, during or after the recharge process, ground water comes in contact with air that has different CFC concentrations than those of the atmosphere when that water was precipitation, CFC concentrations in the ground water will change and no longer give an accurate estimate of ground water age.

Lastly, CFC contamination can occur when CFC concentrations are measured above atmospheric levels. Contamination is often found in urban or industrial settings where refrigeration systems and solvents have been manufactured or dumped. CFC contamination can also come from seepage from septic tanks, and from materials in some pumps and sampling equipment (Cook, et al., 2006).

Tritium/Helium-3 ($^3H/^3He$)

As discussed previously, tritium has a half-life of 12.32 years, and decays by beta emission to become Helium-3 (^3He), a rare, stable isotope of helium. If the quantity of both tritium and the daughter product, ^3He, can be measured, the age of a water sample can be more precisely determined than with measurements of tritium alone. Under ideal circumstances, the tritium-helium method of dating ground water is remarkably accurate for waters less than 40 years old.

In addition to radioactive decay of tritium, there are several other sources of helium in ground water, including atmospheric gases, radioactive decay, and helium derived from the Earth's mantle. These other ^3He sources must be addressed before ages can be accurately calculated. It is also important to note that tritium begins to decay to ^3He in the unsaturated zone. Only those ^3He atoms produced in the saturated zone (i.e., below the water table) are preserved in ground water, which means that zero $^3H/^3He$ age begins at the water table. In areas where the unsaturated zone is especially thick, the $^3H/^3He$ age may be significantly younger than the true age of the water sample. Other errors can occur in $^3H/^3He$ dating if air bubbles remain in the sampling equipment when the sample is collected, or if air bubbles are produced by the submersible pump in the well (Solomon and Cook, 2000).

water. Base flow is the portion of stream flow that is attributable to ground water discharge. In the Southwest U.S. it is reasonable to expect perennial streams to approach base flow between late fall (after cessation of monsoons) and before snow melt runoff in late spring. This occurred during the extremely dry 2007-2008 winter and spring as stream flow rates and the extent of perennial flow reaches decreased throughout the Sacramento Mountains (Table 3).

Table 3–Repeat stream flow measurements and reduction in flow length of three perennial streams between November 2007 and April 2008. Measurements are made in cubic feet per second (cfs).

Stream	Flow rate (cfs) November, 2007	Flow rate (cfs) April, 2008	Reduction in stream length between Nov. and April (miles)
Wills Canyon	0.6	0.4	2
Agua Chiquita	4.1	2.0	>2
Sacramento River	2.17	0	3

Structural Control on Streams

We mapped stream valley segments in much of the study area with ArcGIS software. The stream courses were divided into short segments, and orientations were calculated for each. These oriented stream segments were used to study the relationship between streams, springs, and structural geology.

Stream locations, orientations, and interactions with ground water are influenced by structural features in the Sacramento Mountains. These structural features include faults, folds, joints, and the uplifted mountain block itself. Uplift of the Sacramento Mountains and the resulting eastward dip of both the geologic layers and the topographic surface cause streams to flow generally eastward toward the Pecos River. The crest forms a drainage divide between these streams and steep canyons that drain westward into the Tularosa Basin. The exception to this pattern is the Sacramento River, which drains southeast along a half-graben, out of the study area, and into the Salt Basin.

Faults influence stream flow in several areas, such as the segment of the Rio Peñasco just upstream and downstream of the Mayhill fault zone. Stream flow in this section of the Rio Peñasco increases significantly probably due to upwelling along the fault. Flow measurements in November 2007 showed an increase from 9.7 cubic feet per second (cfs) upstream of the fault, to 13.5 cfs about 1 mile upstream of Mayhill (along the fault zone), to 15.7 cfs approximately four miles downstream of Mayhill and the fault zone.

Streams valleys often follow joint orientations throughout the study area (Figure 6) due to preferential erosion along zones of fractured rock. Joints beneath stream valleys, whether floored by bedrock or alluvium, can provide flow paths for surface water to recharge ground water and for ground water to discharge back to streams. This recycling is likely to take place in much of the study area, as joints are prominent throughout. This hypothesis is confirmed by the isotopic data discussed below.

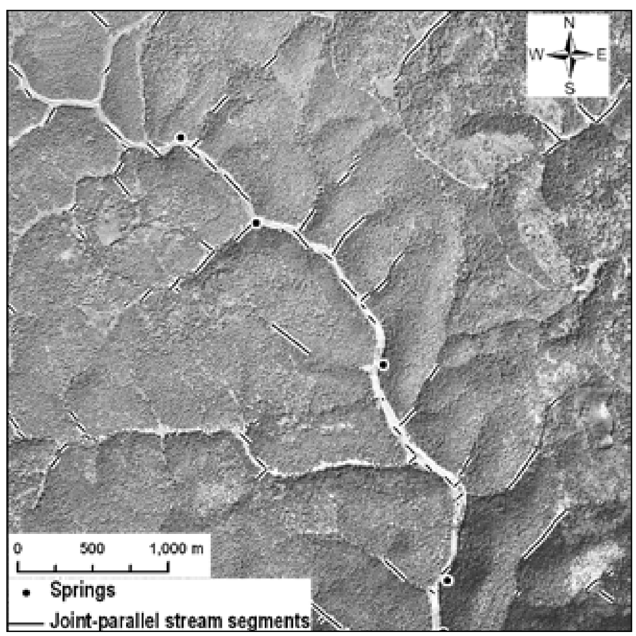


Figure 13–Aerial photograph near the head of the Sacramento River drainage with springs and joint parallel stream segments highlighted. The joint parallel streams correlate with spring locations, are likely to have increased joint density, and may result in higher well yields.

We developed a new method of regional lineament interpretation for this study by using ArcGIS software to identify portions of the surface drainage network parallel to regional joint trends (Figures 5 and 13). The joint-parallel stream segments most likely represent zones of high joint density in limestone beds (e.g., Figure 6). Higher joint density can focus ground water flow, resulting in increased bedrock dissolution in those areas. The high joint density in these stream valleys would also permit higher recharge rates, which may be quantified in future research.

Stable Isotopes in Streams

Several samples have been collected from four perennial streams in the study area at different times (Figure 14). Figure 15 shows stable isotope data on a δD vs. $\delta^{18}O$ graph. Over the time period that we collected the stream samples, the isotopic composition of streams change significantly. The isotopic composition of all samples collected in 2007 (green points) and during March 2008 (blue points) plot below the LMWL, which indicates that water in these streams has undergone evaporation to some degree. Conversely, the isotopic composition for all samples collected during September 2008 (black points) plot near the LMWL, indicating the water in streams is meteoric water that has not undergone evaporation. Of the samples collected during April 2009 (red points), some isotopic compositions plot beneath the LMWL, while others plot along the LMWL.

We can also see how the isotopic composition of a specific stream changes with time in Figure 15. For example, samples collected from the Sacramento River (round blue symbols) during March 2008 show an evaporative signature (plot significantly below the LMWL). Sacramento River samples collected during September

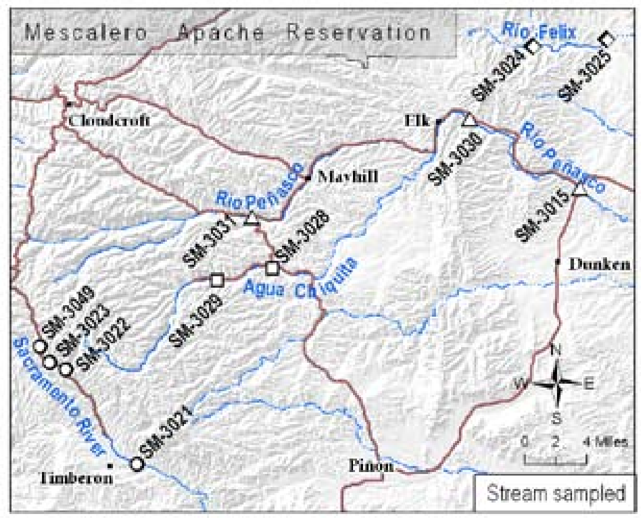


Figure 14–Map of sample locations of stable isotopes in streams.

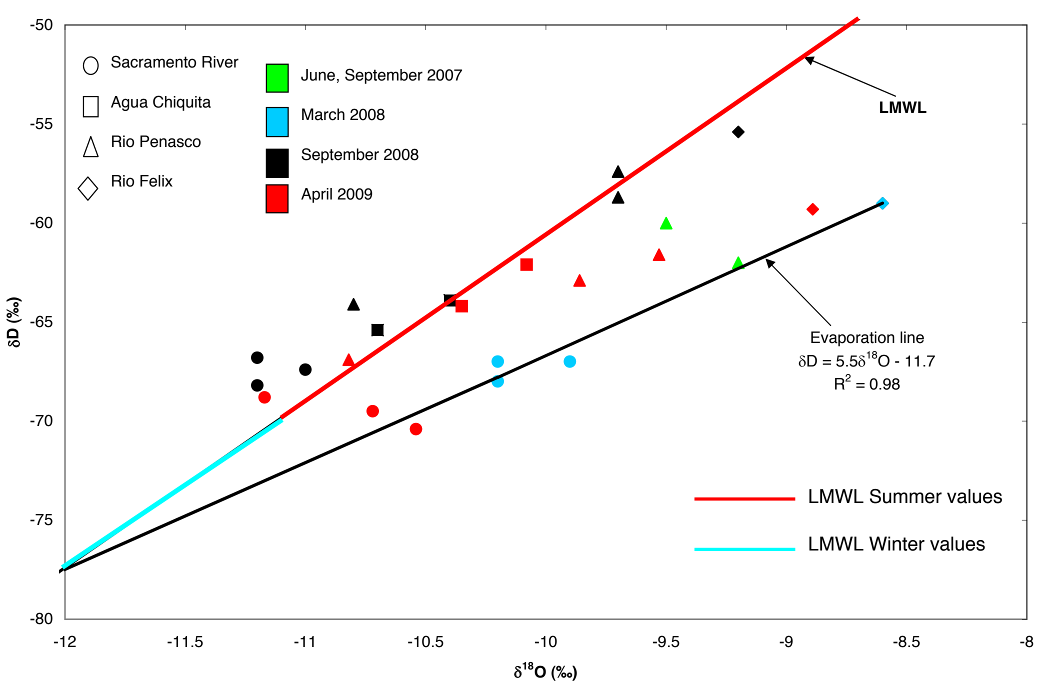


Figure 15–Stable isotopic composition of stream samples collected from different streams at different times between 2007 and 2009. The color of the points correlate to the time of sampling, and the shape of the point correlates to the stream that was sampled. The evaporation line is defined by the points that plot farthest from the LMWL.

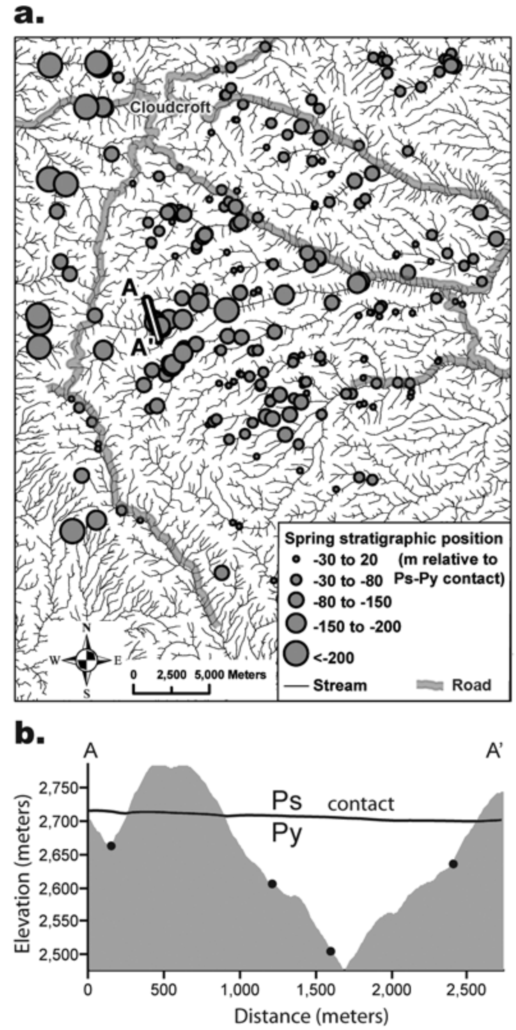
2008 (round black symbols) do not show an evaporative signature, as they plot close to the LMWL. From the three samples collected from the Sacramento River during April 2009 (round red symbols), one plots near the LMWL and the other two are beneath it. As will be discussed below in more detail, the temporal variability observed in the stable isotope data for streams, specifically in terms of whether or not an evaporation signature is observed, appears to be related to the timing of the two discrete recharge events from the heavy rains during the summers of 2006 and 2008. This observed trend has implications for recharge mechanisms that will be discussed in more detail below. Data points that show the most significant evaporative signature, including a sample from the Rio Peñasco collected in September 2007 and samples collected from the Sacramento River and the Rio Felix in March 2008, define an evaporation line with a slope of 5.5, which is indicative of open water evaporation. This evaporation line will also be discussed in more detail below.

Springs

Structural Control of Spring Locations

Springs are common throughout the southern Sacramento Mountains. The majority of springs in the study area discharge from the Yeso Formation (Figure 16), most commonly from fractured limestone beds immediately above a relatively impermeable clay or siltstone layer. We calculated the elevation difference between each spring and the surface representing the contact between the San Andres (Ps) and Yeso Formations (Py). The spring depth histogram (Figure 16c) calculated from the geologic contact surface shows a skewed distribution with a median around 150 feet (46 meters) depth below San Andres-Yeso contact, indicating that most springs are below (not at) this stratigraphic horizon (Figure 16b). In fact, fewer than 10% of the springs are within 30 vertical feet of the contact. The cross-section and spring histogram (Figures 16b and c) show several stratigraphic levels with numerous springs, indicating that ground water flows at several levels within the Yeso Formation.

Spring locations can also be controlled by joints and fractures. To analyze the effects of joints on springs, we evaluated stream valley segments that are parallel to the dominant joint orientations. Joint orientations cluster in two



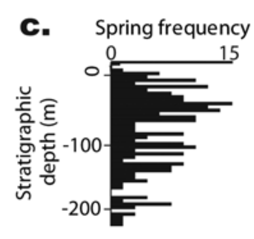


Figure 16a–Elevation of springs relative to San Andres (Ps) and Yeso (Py) contact in the western portion of the study area. Location of cross-section in Figure 16b is identified.
16b–Cross-section view where shaded area shows vertically exaggerated topography, black dots show spring locations, and Ps-Py contact indicates the stratigraphic surface.
16c–Spring histogram in 5-meter stratigraphic depth divisions and at the same vertical scale as (b).

groups, northeast-southwest and northwest-southeast (Figure 5). The number of springs decreases logarithmically away from joint-parallel stream segments (Figure 17). The orientations of the nearest stream segment to each spring are illustrated in Figure 18. On this rose diagram, structural dip orientation (east) is prominent, as are the joint orientations (northeast-southwest and northwest-southeast).

Joints affect both surface water and ground water flow, partially due to their pervasive nature. Stream segments that follow the predominant joint orientations may be associated with locally higher joint densities and preferential ground water flow. Joint-parallel stream segments may be used as guidance when drilling water wells because wells in these valleys are likely to have better yields.

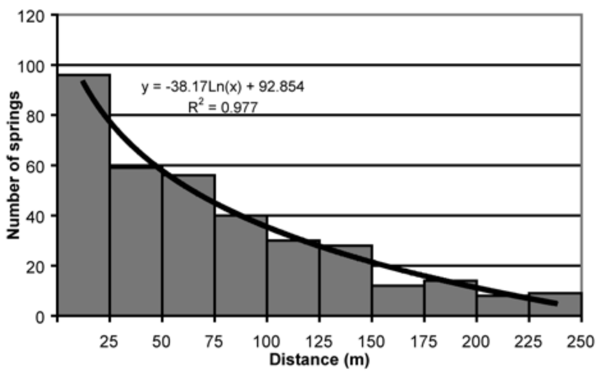
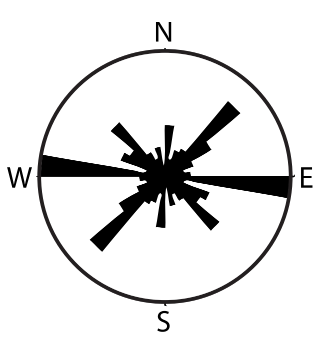


Figure 17–Relationship of springs to joint-parallel stream segments. This histogram represents the number of springs with distance away from joint-parallel stream segments. The implication of the logarithmic curve is that joints control spring locations, as well as surface water flow.

Figure 18–Rose diagram of orientation of the closest stream segment to each spring. Rose diagrams are like compasses that graph feature orientations. Each black triangle represents the number of closest stream segments to springs within 10 degrees of an azimuth. The east-west orientation correlates with the structural dip of the geologic units. The northeast-southwest and northwest-southeast orientations correlate with joint orientations.



Spring Water Chemistry

A total of 85 springs, most of which are located in the high mountains region, have been surveyed, with field parameters measured at most of these. Forty-two springs have been sampled for ion chemistry, trace elements, and stable isotopes. Most of these sampled springs have also been analyzed for tritium content and CFCs. The springs that have been sampled are identified in Figure 19. Spring chemistry results are tabulated in Appendix B.

Field Parameters

The temperature of spring water in the southern Sacramento Mountains varies between about 6.3 and 18.4 ºC with an average of 10 ºC (Figure 20). Average surface temperature in the southern Sacramento Mountains is 9.1 ºC (measured in Cox Canyon from 2002-2007). Spring waters cooler than the mean annual air temperature are likely recharged by snow melt, while springs with temperatures close to the mean annual temperature are likely part of a shallow ground water system (less than approximately 350 feet depth) (Mazor, 2004). However, mean annual air temperature varies across the mountain range, warming as elevation decreases, therefore this is an approximation. In general high mountain springs are cooler, while springs further east on the slope are warmer.

Ion Chemistry

Differences in chemical composition of springs are evident in a Piper diagram, which displays the relative concentrations of major ions within water samples (Figure 21). With the exception of SM-1025 and SM-1090, calcium and magnesium are the dominant cations (account for over 80% of total cations) and bicarbonate and sulfate are the dominant anions (account for over 80% of total anions). For cations, the approximate relative proportions observed for calcium and magnesium are 55-90% and 10-38% respectively. For anions, the approximate relative proportions observed for bicarbonate and sulfate are 55-95% and 5-50% respectively. In the diamond part of the piper diagram, we observe an increase in TDS as the relative proportion of sulfate increases. This increase in TDS may be a result of an increase in residence time and/or being in contact with rocks of higher solubility.

SM-1025 and SM-1090 are outliers, with significantly more sodium and chloride than other spring samples. SM-1025 is located on the west side of the Sacramento Mountains and discharges water from deep within the Yeso Formation. Spring SM-1090 is located at the top of the mountain range, near Sunspot. This spring is located along a fault which may circulate water from depth with relatively high concentrations of dissolved ions, especially sodium and chloride. Alternatively, there may be issues with shallow ground water contamination at this site.

"Water types" are a classification based on the dominant ions in the sample. The map of water types from springs (Figure 22) shows that most of the spring water samples (77%) are calcium bicarbonate (Ca-HCO_3) or calcium-magnesium bicarbonate (Ca-Mg-HCO_3) water types. This is typical of water that interacts with a carbonate aquifer (i.e. limestone or dolomite). Water types that include sulfate may have interacted with gypsum or anhydrite (Hem, 1985). Springs in the high mountains generally have calcium bicarbonate or calcium-magnesium bicarbonate water types.

Springs in the north have higher concentrations of sulfate than springs in the south, as shown in Figure 23. This north-south trend of decreasing concentration is also found with other constituents including chloride, strontium, sodium, magnesium, silicon, and TDS. This observed

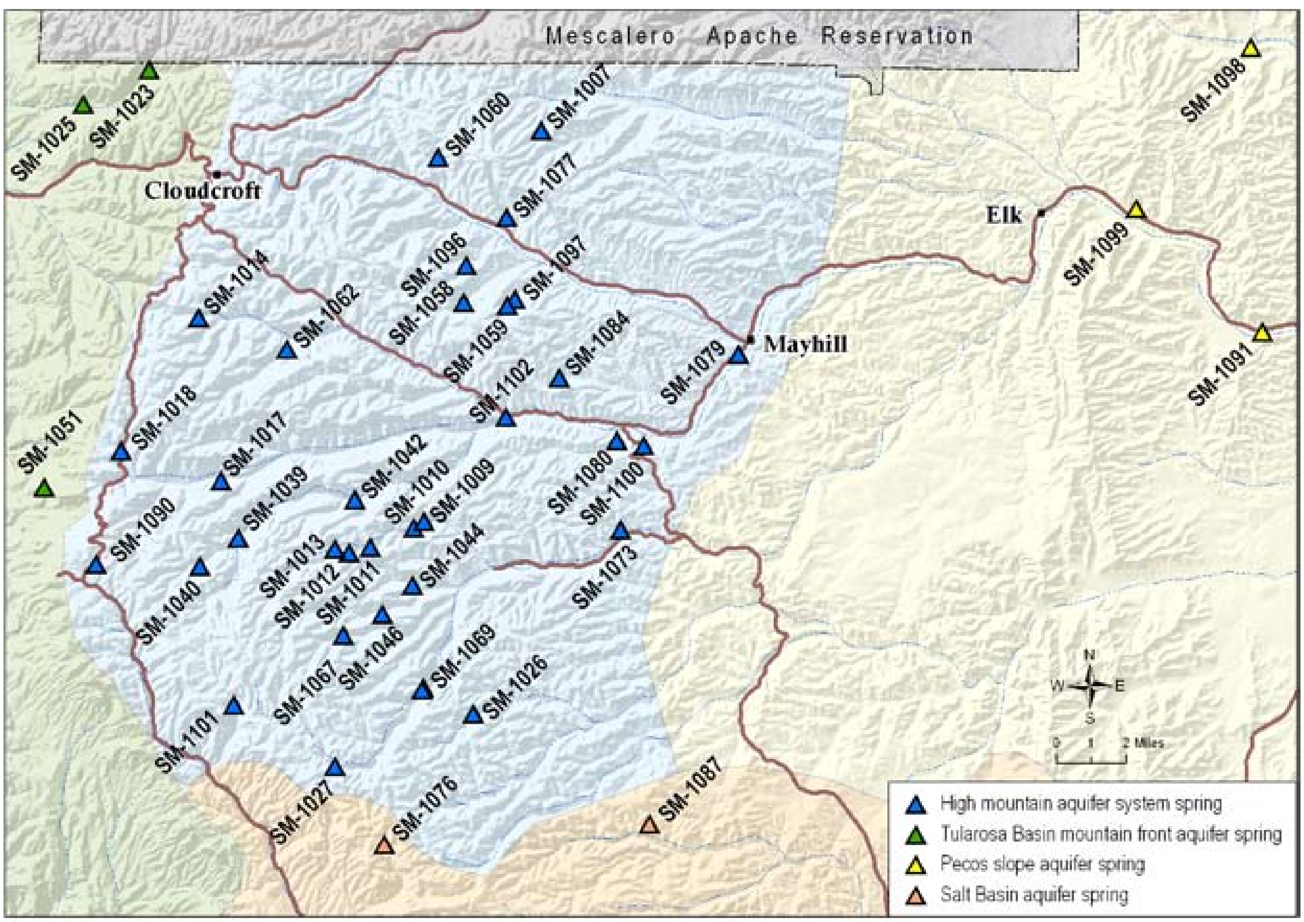


Figure 19–Sampled spring water locations referred to in text, where symbol color signifies the aquifer classification. The high mountain aquifer system has more springs than the surrounding areas.

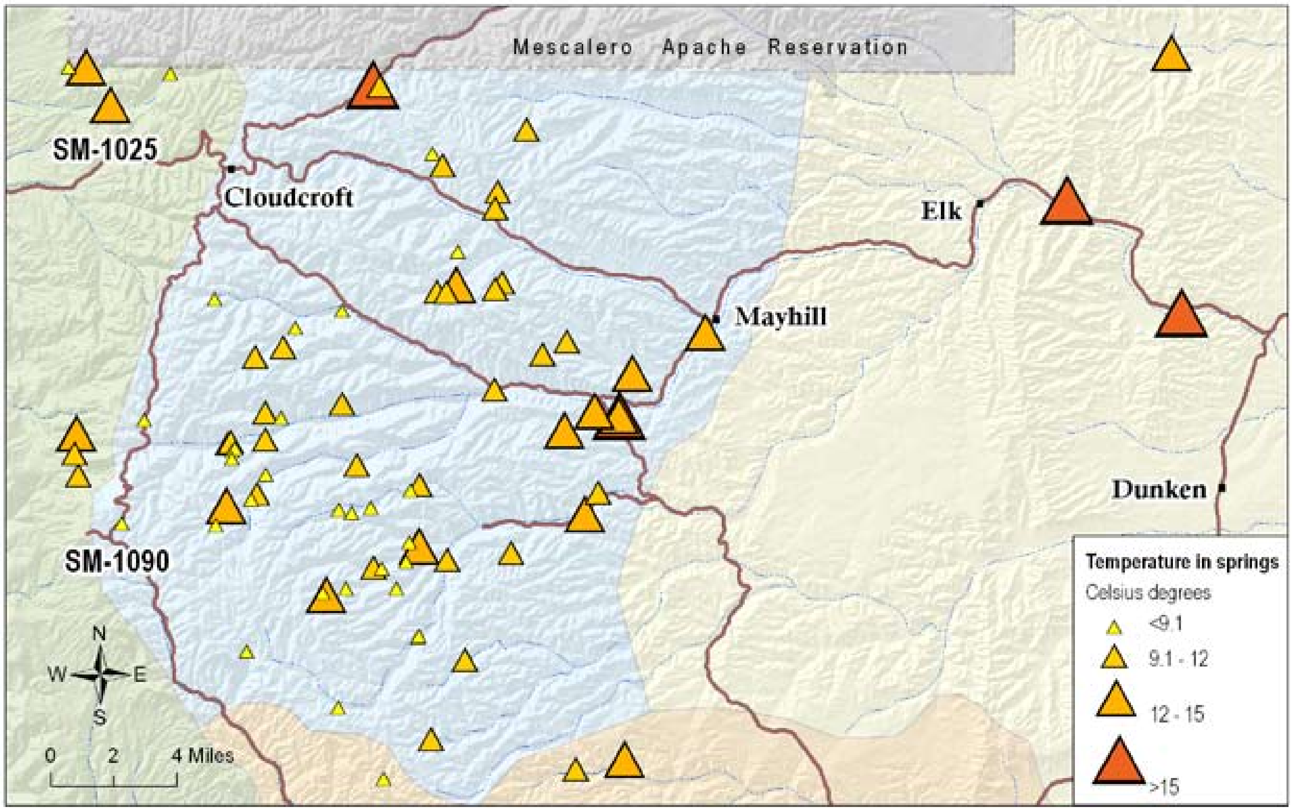
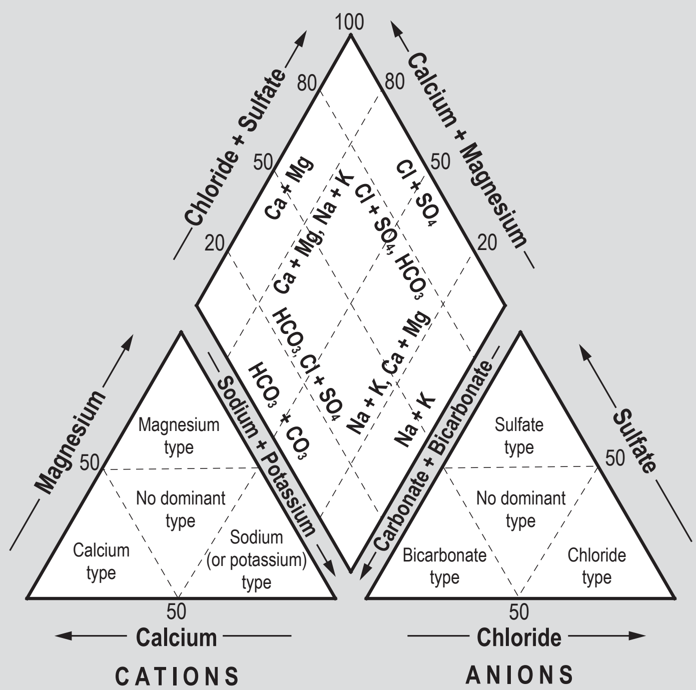


Figure 20–Map of temperature of spring waters. The symbol size is larger with warmer temperatures. Sampled springs are warmer on the west side of the mountains and a trend of warming to the north and east is also observed.

Ion Chemistry

All spring and well water samples collected were analyzed for major and minor ion chemistry (referred to as ion chemistry), as well as trace elements. Ions are elements that carry a positive or negative charge, and are found naturally in ground water. The ion chemistry of the water provides information about water-rock interactions that have taken place as the water travels through the aquifer, dissolving minerals in the rock.

Piper diagrams are often used to display the relative concentrations of cations (positively charged ions) and anions (negatively charged ions). The figure below shows schematically how Piper diagrams can be interpreted. Water chemistry concentrations are plotted on the anion triangle (bottom right), cation triangle (bottom left) and the combined ion diamond. These plots are used to help distinguish differences in groups of samples, because waters with similar origins should plot in the same regions on the Piper diagram.



Piper diagram

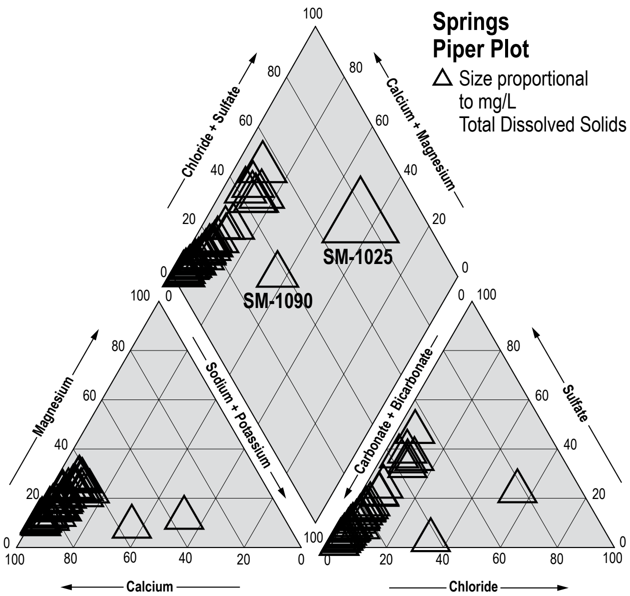


Figure 21–Piper diagram of spring waters. Most of the sampled springs cluster together, reflecting relatively high calcium, magnesium and bicarbonate concentrations typical of waters interacting with carbonate rocks. Springs plotting outside of this cluster (outliers) have higher total dissolved solids. Outliers are discussed in the text.

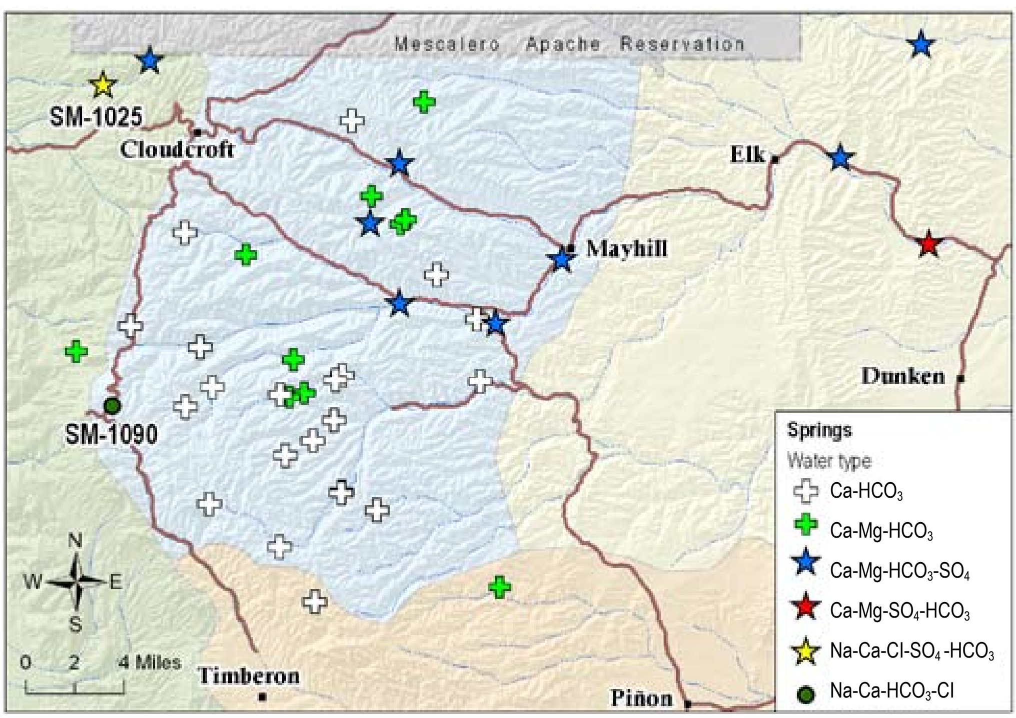
spatial trend in water chemistry may be due to spatial variability in gypsum and anhydrite content in the San Andres and Yeso Formations. Kelley (1971) and Pray (1961) noted that the gypsum content of the Yeso Formation increases to the north and the carbonate content increases to the south.

An alternate explanation for this spatial trend observed for springs would be a regional hydrologic connection between springs, where the increase in constituents to the north is a result of the evolution of water chemistry along an intermediate flow path. The southwest-northeast trending fracture systems (see discussion on structural geology) may control flow direction in the shallow perched hydrologic systems associated with the springs in the high mountains. It is likely that the observed spatial trend in water chemistry for springs is due to a combination of both of these hypotheses.

Stable Isotopes in Spring Water

Several springs throughout the study area were sampled multiple times during the duration of the study. Based on the stable isotopes of oxygen and hydrogen, the hydrogeologic system in

Figure 22–Map of spring water types. Most springs are categorized as calcium bicarbonate or calcium-magnesium bicarbonate waters, especially in the high mountain region.



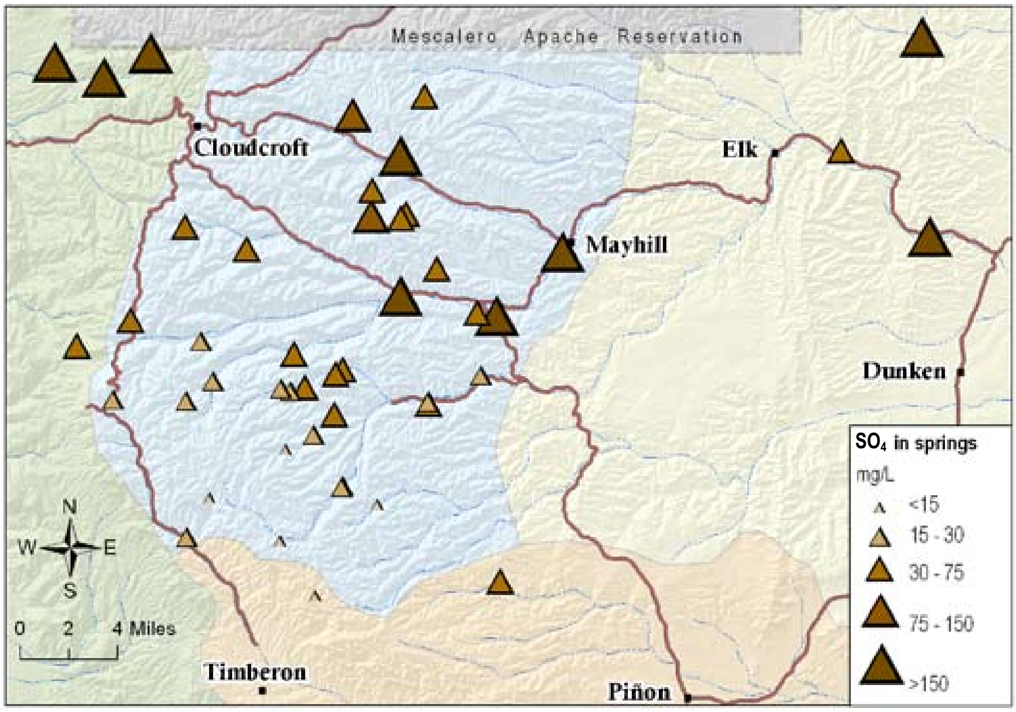


Figure 23–Map of sulfate in spring waters. The symbol size reflects the concentration of sulfate in the spring waters sampled, with larger symbols for higher concentrations. The trend of lower sulfate in more southern springs and higher sulfate in the north and east is apparent.

the study area appears to be very dynamic. The stable isotopic compositions of springs changed significantly over time during the study. The observed fluctuations of the isotope data appear to be related to the timing of two discrete recharge events: 1) The above average monsoon season in 2006, and 2) The summer of 2008, when a remnant disturbance of Hurricane Dolly produced large amounts of precipitation in the Sacramento Mountains. It appears that where the isotopic compositions of sampled springs plot in δD - $\delta^{18}O$ space relative to the LMWL depends on how much time has passed between the recharge events and when the water sample was collected.

Figure 24 shows the stable isotope data for springs sampled at different times. It can be seen that springs sampled in October and November 2006 (2-3 months after the 2006 monsoon season) group relatively tightly around the LMWL with some samples plotting slightly above the LMWL and other samples plotting slightly below it. The small number of springs sampled in 2007 also plot close to but beneath the LMWL. The isotopic compositions of springs sampled during January – May 2008 (17 to 21 months after 2006 monsoon season) all plot significantly below the LMWL and close to the evaporation line that was defined by stream samples during the same time period. Springs sampled during and shortly after July 2008 (the second recharge event) appear to have shifted away from the evaporation line and towards the LMWL, as do springs sampled in 2009.

To semi-quantitatively analyze these trends, we calculated the distance between each sample point and the LMWL, where negative values represent points that are above the LMWL and positive values represent points that fall beneath the LMWL. In general, it can be assumed that samples that plot significantly below the LMWL have probably undergone evaporation to some extent. Figure 25 shows how the distance between the stable isotope data points for springs and the LMWL vary with time. The 2006 and 2008 recharge events are also shown. This graph shows a similar trend where springs sampled shortly after the 2006 monsoon season plot closer to the LMWL. The distance from the data points to the LMWL increases with increasing time between the 2006 recharge event and when the samples were collected. Then immediately after the 2008 recharge event, the distance between

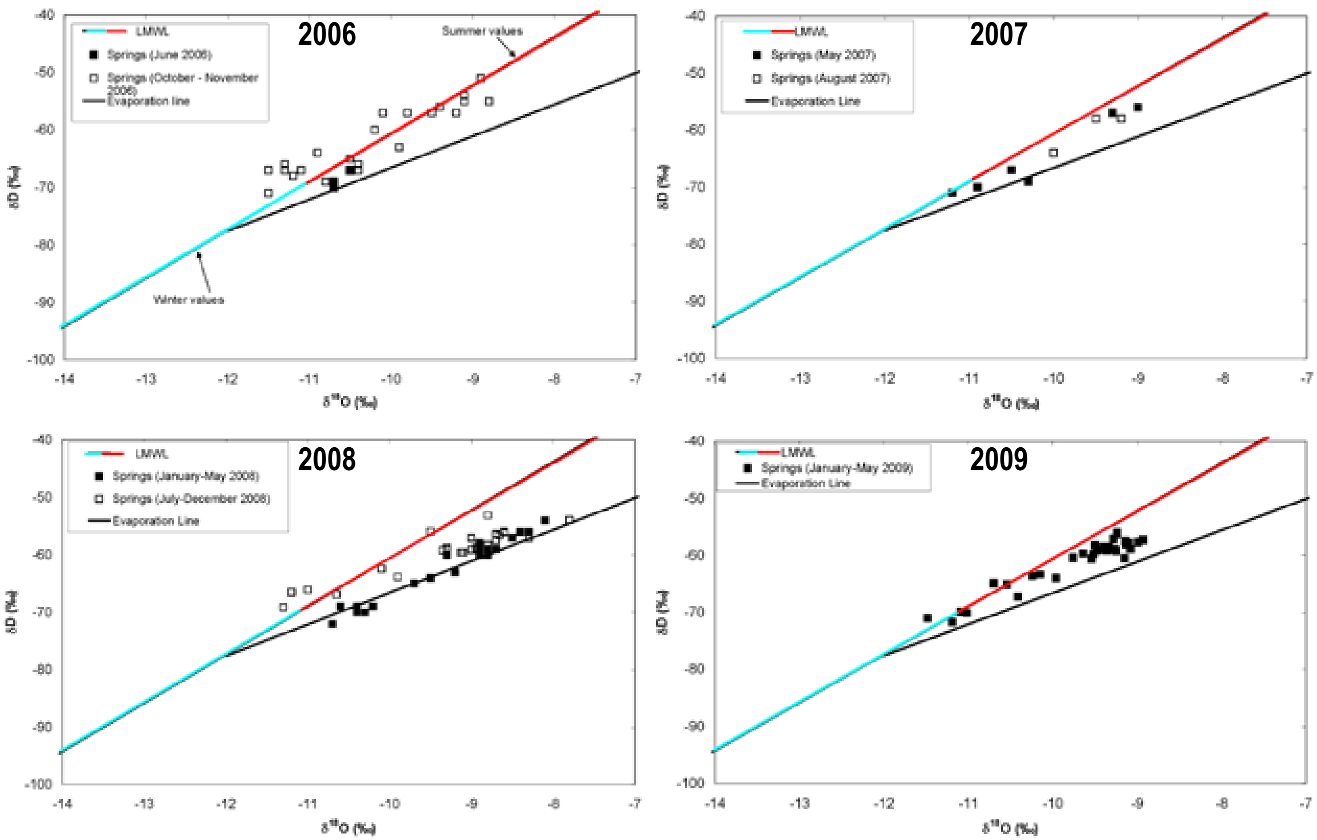


Figure 24–Stable isotopic compositions of spring water at different times. Isotope values fluctuate between the evaporation line and the LMWL. The isotopic shift towards the LMWL appears to be related to summer recharge events.

the data points and the LMWL begin to decrease. This trend suggests that during long time periods between discrete recharge events, most springs will have an evaporative signature. Water entering the hydrologic system as a result of these discrete recharge events appears to shift the isotopic composition of spring waters towards the LMWL. The fact that the isotopic composition of all springs sampled during March 2008 plot very close to a single evaporation line has important implications on recharge mechanisms in the Sacramento Mountains.

Researchers from the University of Arizona found that water samples collected in 2003 from springs and wells within the same study area plot along an evaporation line almost identical to the one defined in this study (Newton et al., 2008). It should be noted that historic precipitation records show that summer precipitation of the magnitude seen in 2006 and 2008 has not occurred since 1993. Therefore, it is likely that the stable isotopic composition of water samples collected in 2003 were not affected by summer recharge events. This supports the hypothesis that during long time periods between discrete summer recharge events, most springs will have an evaporative signature.

Assuming that these discrete summer recharge events are rare, this hypothesis suggests that isotopic data that plots along a single evaporation line is representative of the ground water system under long-term average climatic conditions. The isotopic compositions of water samples that plot along a single evaporation line can be explained by the evaporation of a single water source with an initial isotopic composition that plots at the intersection of the evaporation line and the LMWL. This initial isotopic composition represents a mixture of summer and winter precipitation that makes it past the root zone to recharge the ground water system. Figure 26 shows that in the southern Sacramento Mountains, the evaporation line intersects the LMWL within the range of expected values for winter precipitation. Therefore, for long-term average climatic conditions, the isotopic composition of springs can be explained by a mixture of dominantly snowmelt from the high mountains that has undergone evaporation in mountain streams and ponds.

As discussed above, the orientation of many streams appears to be controlled by regional fracture systems. It is not surprising that significant recharge would occur through fractures systems associated with streams. A single evaporation line also suggests that this is a well mixed system. A well mixed system is geologically plausible due to the heterogeneity with respect to hydraulic conductivity, and the presence of large fracture systems and karst features such as conduits. The presence of ground water flow paths with a large range of flow velocities can result in the mixing of waters of different ages.

Snow melt in the high mountains is the primary source of recharge in the Sacramento Mountains. However, it is apparent that extremely wet periods during summer months, such as those observed in 2006 and 2008, can contribute significant recharge to the ground water system. The change in isotopic compositions of spring waters caused by these recharge events has implications for the complex nature of this hydrologic system. Figure 26 shows isotopic shifts observed for individual springs that were sampled in November 2006, March 2008 and then again in September 2008. It can be seen in

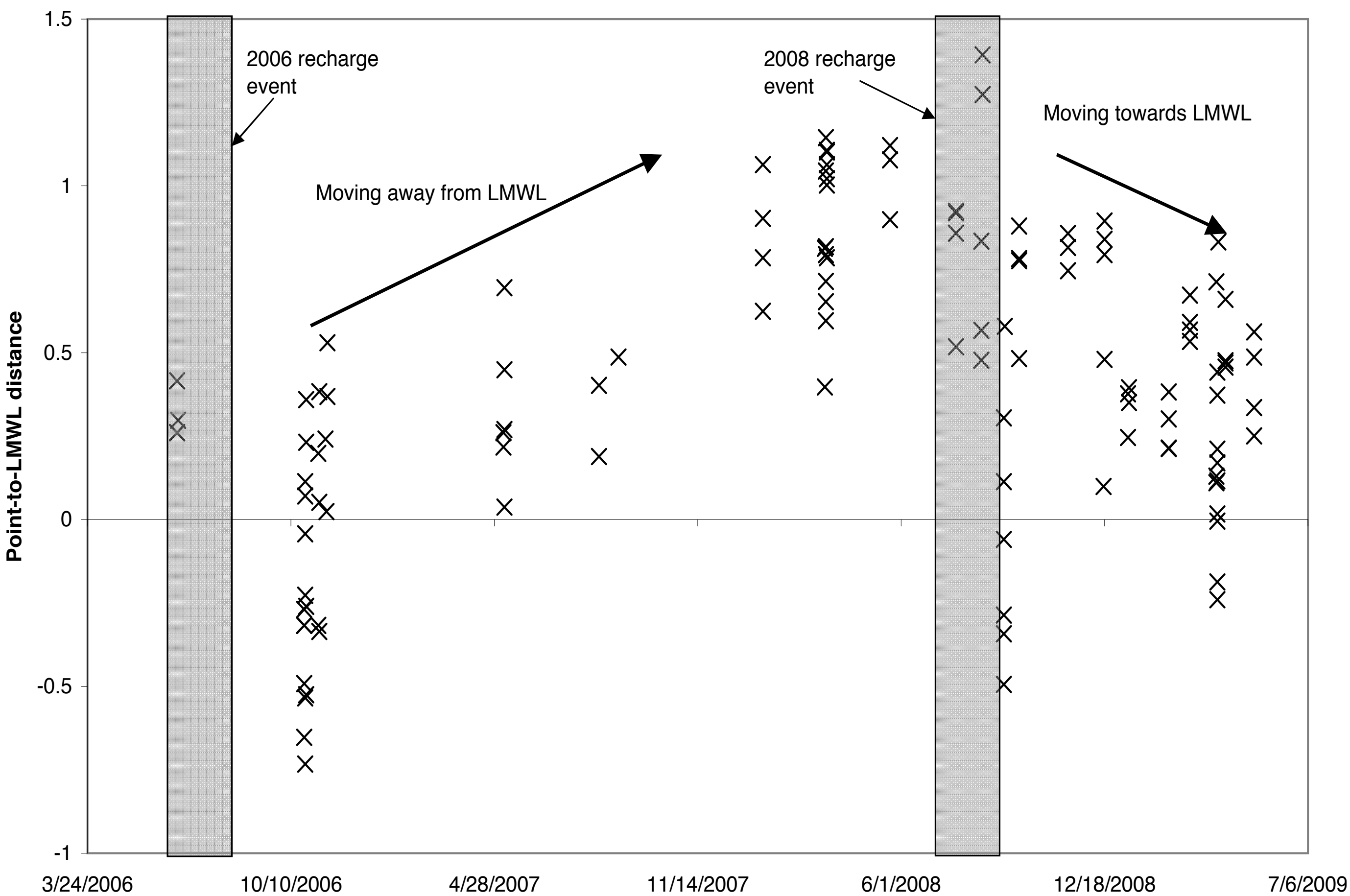


Figure 25–The distance between the isotopic compositions of springs (as plotted on δD vs. $\delta^{18}O$ graph) and the LMWL for samples collected at different times throughout the study. Points with positive values plot below the LMWL and generally have an evaporative signature. Points with negative values plot above the LMWL. The noted summer recharge events appear to cause the stable isotope composition of spring samples to plot closer to the LMWL.

Figure 26a that between November 2006 and March 2008, the stable isotopic composition of most springs sampled changed from plotting very close to the LMWL to plotting close to the evaporation line discussed above. Based on the above discussion, it appears that this observed change in isotope values is due to the stable isotopic composition of springs returning to long-term average values after being altered by the recharge event in 2006. Therefore, we hypothesize that the input of water associated with the 2006 recharge event generally caused stable isotope values to increase with respect to δD and decrease with respect to $\delta^{18}O$.

For spring samples collected after the 2008 recharge event, an isotopic shift towards the LMWL was observed (Figure 26b). In general, $\delta^{18}O$ values decreased and δD values increased, supporting the above hypothesis. Because the isotopic shift appears to be towards isotope values expected for summer precipitation, the simplest explanation for this isotopic shift towards

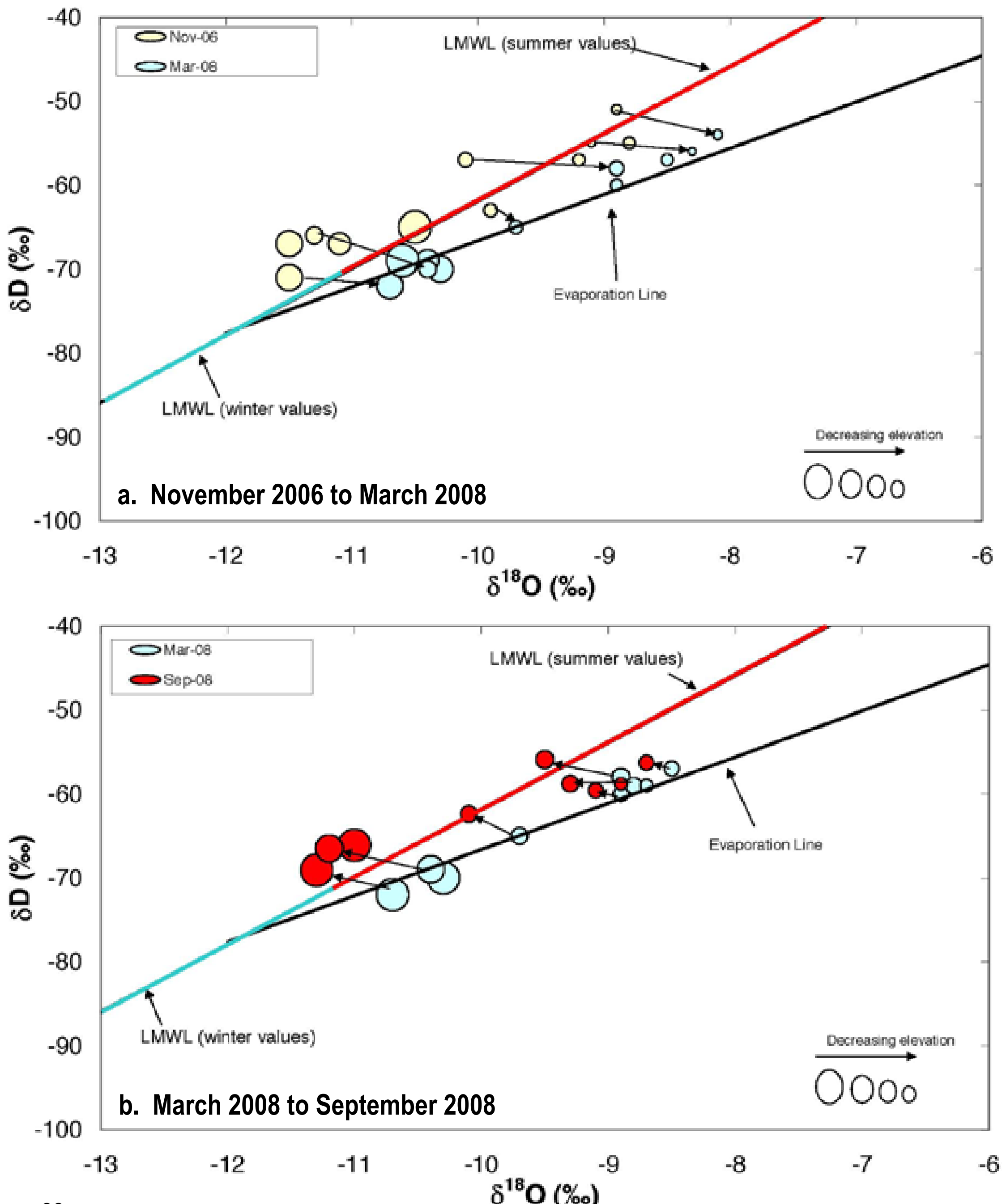


Figure 26a–Spring samples collected in March 2008 (blue points) shifted towards the evaporation line relative to the isotopic composition of samples collected from the same springs in November 2006 (yellow points). **26b**–Spring samples collected in September 2008 (red points) shifted towards the LMWL relative to the isotopic composition of samples collected from the same springs in March 2008 (blue points).

the LMWL is a direct input of non-evaporated precipitation that fell during the recharge event, resulting in a mixture of older water with an evaporative signature and very young water that has not undergone evaporation. The measured isotope values for summer precipitation sampled during the summer of 2006 did plot in the range of expected values for summer precipitation, which supports this hypothesis.

According to this hypothesis, springs sampled in November 2006 dominantly consisted of precipitation that fell during the summer of 2006. In a karstic system, it is feasible that summer precipitation, when available in quantity, can make its way through the hydrologic system very quickly. However, this explanation is not consistent with spring water chemistry and age dating (data not shown). Cation and anion concentrations in springs did not change significantly from one sample event to the next. Also, tritium content did not significantly change from one sampling event to the next. Furthermore, this hypothesis suggests that springs sampled shortly after the 2008 recharge event would show a shift towards the anomalously light isotope values observed for precipitation in July 2008 (~50% of July precipitation was associated with Hurricane Dolly), shown in Figure 12. In actuality, the stable isotopic shift associated with the 2008 recharge event was in the same direction as the apparent shift associated with the 2006 recharge event. Although, there probably is a small amount of recent precipitation in spring samples collected shortly after the recharge events, these observations suggest that the mixing of very young precipitation with older water within the system is not the main cause of the observed change in isotopic compositions of spring waters over time. Rather, these observations suggest that young meteoric water associated with these recharge events displaces and forces water that is stored in a relatively immobile reservoir into the main hydrologic system. This stored water then discharges from springs. In this complex hydrogeologic system, there are zones of relatively immobile water in both the saturated and unsaturated zones. However, it is unclear why these immobile waters would have isotopic compositions that differ from those of mobile waters. We are currently developing a conceptual model that will explain these observations.

Looking at springs sampled during March 2008 along the evaporation line (Figure 26, blue circles) we see that the sizes of the points, which are proportional to elevation, generally decrease with the extent of evaporation. In other words, springs at lower elevations appear to have undergone more evaporation that springs at higher elevations. When sampling springs, we made an effort to sample at the source so that any evaporative signature that was observed was not due to evaporation at the sampling site. Therefore, water discharging at a spring that shows an evaporative signature most likely underwent near surface evaporation (possibly in a mountain stream) before recharging the ground water system associated with the spring being sampled. Springs in the Sacramento Mountains are the source for most perennial stream reaches, many of which subsequently infiltrate back to shallow ground water. This observation along with the observed trend of increasing isotope values with decreasing elevation for springs implies a circular “recycling” relationship and interconnection between surface water, springs, and shallow ground water. Water that recharges a shallow perched aquifer may discharge at a spring that feeds a stream system, where it undergoes evaporation. This water that now has an evaporated signature can recharge another shallow aquifer and discharge at a spring at a lower elevation. This cycle may occur several times as the water flows down gradient. As water moves through this shallow hydrologic system, at any point along the way, there is potential for it to recharge a deeper aquifer that is deep enough that water will no longer interact with the surface water system.

Spring Water Ages

Tritium

Spring waters sampled in the southern Sacramento Mountains have tritium concentrations ranging from 0.87 to 6.11 TU, with an average

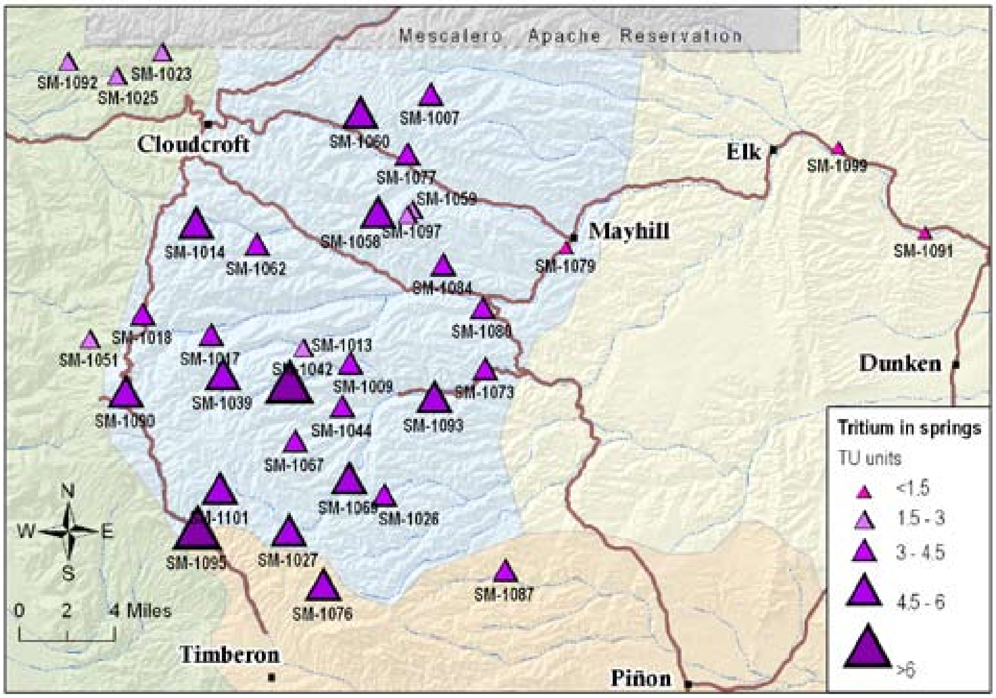


Figure 27–Map of tritium in spring waters. The symbol size reflects the concentration of tritium in the spring waters sampled, with larger symbols for higher concentrations. Generally, the higher the tritium concentration, the younger the water. Most springs in the high mountains have high tritium concentrations indicating that spring waters are fairly young. Outliers are discussed in the text.

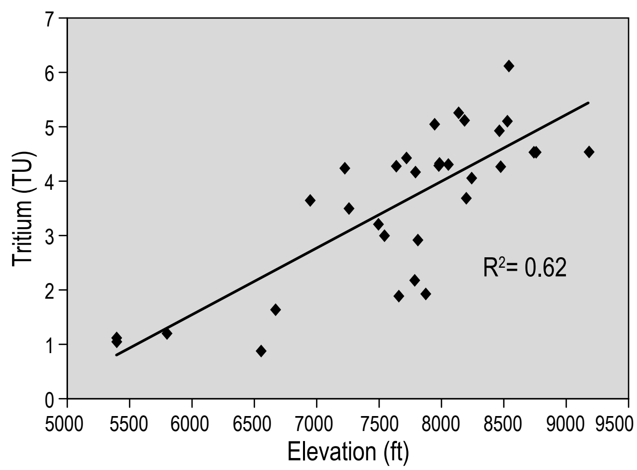


Figure 28–Tritium vs. elevation of sampled springs. Generally, the higher the tritium concentration, the younger the water. The relationship of tritium in springs with elevation indicates that spring water at higher elevations is younger than spring water at lower elevations.

of 3.63 TU (Figure 27). Compared with other areas studied, the springs sampled in the high mountains west of Mayhill generally have higher tritium values (fairly young water), with an average of 4 TU.

The spring with the oldest water in the high mountains is SM-1079 which is found along the Mayhill fault zone. It appears to circulate warm, old water up from depth, along with high concentrations of ions such as sulfate and magnesium. Two springs were sampled in the Pecos Slope region, SM-1091 and SM-1099, which had 1.04 and 1.21 TU, respectively. Three tritium samples from springs in the Tularosa Basin mountain front aquifer indicate that the spring water is older than in the high mountains region (average 2.51 TU). Lastly, two spring samples in the northern Salt Basin aquifer, SM-1076 and SM-1087, with 5.11 and 4.23 TU, respectively look very similar to springs in the high mountain aquifer system.

Spring waters show a trend of decreasing tritium concentrations to the east and at lower elevations (Figure 28). In other words, water discharging from springs at lower elevations and further along the regional ground water flow path, as depicted by the water elevation map (Figure 7, Plate 2), is relatively older than from springs at higher elevations. This spatial trend suggests a regional connection between springs. However, on a smaller scale within the high mountains, much of the observed spatial variability does not appear to correlate with the regional flow direction as shown in Figure 7 (Plate 2), which accounts for much of the scatter observed in Figure 28. There are several areas where a spring with a relatively high tritium concentration (young water) is located in close proximity to a spring that exhibits much lower tritium values (older water). The spatial variability at this smaller scale suggests the presence of multiple leaky perched ground water systems with different residence times.

A regional connection between springs is consistent with water being "recycled" as suggested by stable isotope data and the observed relationship between streams and regional fracture systems. It is likely that waters of different ages from fractured, perched aquifers discharge at springs and mix within streams and ponds before recharging the shallow aquifer system and discharging from springs at lower elevations.

Chlorofluorocarbons

CFC samples were collected at twenty-six springs in the study area (see Environmental Tracers sidebar and Figure 29). For this study, recharge elevations were estimated as the sample site elevation, for simplicity. We estimated recharge temperatures based on an empirical relationship between the water temperature measured during sampling and recharge temperatures that were estimated for 8 samples based on noble gas concentrations. In general, the recharge temperature was approximately 5°C below the measured water temperature.

The sample apparent ages from CFCs presented in this report have been pared down through several processes. For each sample location, there may be up to three samples collected, and therefore up to 18 different age possibilities from the different CFC species and their ratios. We have averaged the CFC concentrations for each CFC species and the derived an age from this concentration. In most samples the CFC11 species appears to be degraded (Happell et al, 2005). This makes CFC11 and ratios using CFC11 problematic to work with in this study area, and they will not be considered further. We only present the CFC12, CFC113 and CFC113/12 ratio apparent ages in this report. These values are reported in years, which indicate the apparent number of years before the sample date that the ground water was recharged.

Review of the CFC apparent ages from springs sampled in the study area shows that six of the locations had good age agreement among the different CFC varieties (highlighted in Table 4). There is quite a bit of variability in CFC ages

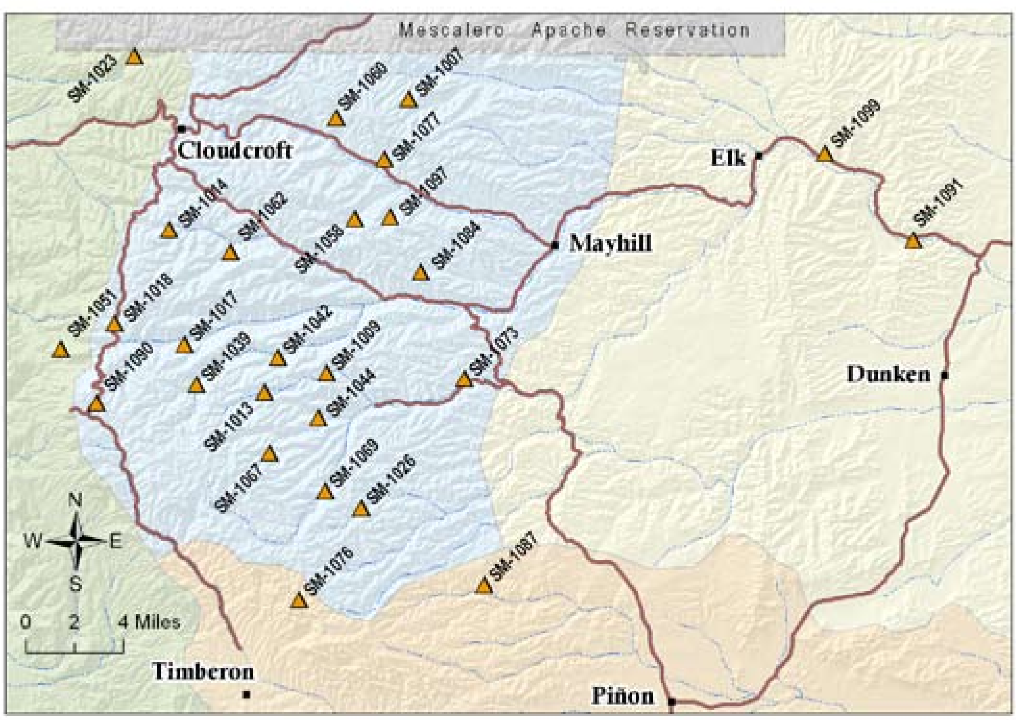


Figure 29–Map of CFC sampled locations in springs referred to in Table 4.

Table 4–This table shows the CFC age data for the sampled springs; highlighted springs are locations with approximate concordant CFC ages (± 2 years). The CFC apparent age (in years before sample collection date) shown here cannot be taken as an actual age of the ground water because of mixing of older and younger ground water in this system.

Spring Point ID	Collection Date	CFC113 (years)	CFC113/12 (years)	CFC12 (years)
SM-1007	24-Oct-06	21	19	25
SM-1009	23-Oct-06	20	18	24
SM-1013	20-Jun-06	20	17	24
SM-1014	25-Oct-06	21	19	24
SM-1017	20-Jun-06	21	19	25
SM-1018	24-Oct-06	23	21	26
SM-1023	13-Nov-06	21	21	22
SM-1026	20-Jun-06	28	21	34
SM-1039	07-Nov-06	22	21	25
SM-1042	07-Nov-06	21	20	24
SM-1044	23-Oct-06	20	19	23
SM-1051	06-Nov-06	21	20	22
SM-1058	15-Nov-06	20	19	22
SM-1060	25-Oct-06	19	18	20
SM-1062	25-Oct-06	22	20	26
SM-1067	23-Oct-06	21	20	25
SM-1069	23-Oct-06	21	20	24
SM-1073	24-Oct-06	24	21	28
SM-1076	24-Oct-06	24	22	27
SM-1077	24-Oct-06	21	17	26
SM-1084	25-Oct-06	24	23	25
SM-1087	07-Nov-06	23	21	26
SM-1090	14-Nov-06	21	19	25
SM-1091	12-Nov-08	23	23	24
SM-1097	28-Aug-07	24	21	27
SM-1099	19-Aug-08	23	22	24

in samples collected in the high mountains region indicating a great deal of mixing of different age waters (except for SM-1060 and SM-1084). The two spring samples collected in the Pecos Slope aquifer (SM-1091 and SM-1099) and two samples from the Tularosa basin mountain front aquifer (SM-1023 and SM-1051) have concordant CFC ages.

In general, most of the springs in the study area sampled for CFCs suggest that mixing of waters of varying ages is taking place. At locations where there is age agreement in the CFC varieties, we interpret these locations to have less mixing. In aquifer systems, such as the high mountains region, where water from multiple perched aquifers is mixed via fracture networks and surface water discharge/recharge processes, it is not surprising to find this variability.

One of the biggest difficulties with interpretation of CFC data for springs in the Sacramento Mountains is the occurrence of "recycled" ground waters. When springs discharge to a stream, which later recharges an aquifer, the CFC "clock" can be partially or completely reset. Because CFC's are gases, they are quickly exchanged with gases in the atmosphere upon exposure to the air. Therefore, if any samples have been exposed to the atmosphere along their flow path or during sample collection, we will likely see an apparent CFC age that is younger than the water may actually be. Additionally, in the southern Sacramento Mountains, processes of rapid, focused recharge (such as in fractures) can cause addition of excess air in the water, giving it a CFC age that is too young. Also in the Sacramento Mountains, the thickness of the unsaturated zone must also be considered. If it is greater than about 10 meters (33 feet), this can cause a significant lag effect on CFC ages making them appear too old (Cook, et al., 2006). In addition to mixing, the processes discussed above may also help to explain the large variability observed in the CFC data. We are currently working to identify samples that may have been affected by these processes.

Ground Water

Sources of Ground Water

Based on geologic mapping and inspection of water well logs, the Yeso Formation is the source of water for most wells in the study area west of Mayhill. This includes even those few wells drilled where the San Andres Formation is the exposed geologic unit at the ground surface. East of Mayhill few well logs are available, but some of the wells appear to be completed in the San Andres Formation.

The geologic and hydrologic data we have collected indicate that the aquifers are composed of numerous individual but variably interconnected water bearing zones. The water bearing zone in approximately 80 percent of the wells with available drillers' logs is composed of fractured limestone, collapse breccias formed by dissolution of gypsum and/or limestone, and less commonly, sandstone, all within the Yeso Formation. The remainder of the wells are completed in older, deeper units such as the Abo Formation on the west face of the mountains, in shallow valley-bottom alluvium, or spring deposits. The water–bearing zones in those wells east of Mayhill completed in the San Andres Formation are also probably fractured limestone.

Flow Direction

We combined water level measurements in wells from the spring of 2008 with the extents of perennial streams and valley floor elevations to contour the elevation of ground water throughout the Sacramento Mountains. In the locations where these data are not available, we used New Mexico State Engineer Office well records. No attempt was made to distinguish between perched and regional aquifers (see Hydrogeology Background sidebar). Figure 7 (Plate 2) shows these ground water elevation contours. A map that shows ground water level elevation contours is called a potentiometric surface map. For an unconfined aquifer, the potentiometric surface represented by the contours is the actual surface of the top of the aquifer or the water table. Water table maps are usually used to identify ground water flow direction and to quantify the regional hydraulic gradient.

It is important to note that in the case of the high mountain aquifer system, the ground water level elevation contours do not necessarily represent a continuous surface of a single unconfined aquifer. The high mountain aquifer system appears to be made up of several fractured, perched aquifers in carbonate layers within the Yeso Formation. As discussed previously (Figure 16), ground water flows at several levels within the Yeso Formation. If there is a deep, continuous regional aquifer in the high mountains, it is difficult to know which wells penetrate it. Therefore, the fact that water level elevation contours in the high mountains follow the topography may just indicate that there are shallow perched aquifers throughout the high mountains at several elevations. However, as suggested by stable isotope and tritium data for springs, these shallow aquifers do appear to be connected by the surface water system and by intersecting fracture networks. Therefore, ground water ultimately does flow from high elevations to low elevations, but not necessarily in the actual direction as suggested by the ground water level elevation contours.

Water chemistry and stable isotope data, which will be discussed below, suggest that the Pecos Slope aquifer behaves more as a single continuous aquifer within the San Andres and Yeso Formation. Therefore, for this aquifer, we interpret the ground water level elevation contours to represent the water table surface.

On a regional scale, ground water flow is controlled by topography, as ground water flows from high elevations to low elevations. Water level elevation contours range from 8800 feet near the range crest to 3500 feet near the east side of the study. Ground water in the Pecos Slope aquifer flows west to east. Water elevation contours also suggests that some ground water flows from the high mountains to the northern Salt Basin with possible minor ground water flow to the Tularosa Basin mountain front aquifer.

An important characteristic of the ground water contour map is the flow divide which separates regions of generally eastward flow from regions of generally westward flow. The divide runs along the crest of the mountains from Cloudcroft to Sunspot, bisecting the areas enclosed by the highest water level elevation contours (8400 and 8600 feet). From Sunspot the divide turns sharply southeast, again bisecting the 8600 foot ground water level contour, towards Agua Chiquita Creek.

The area of closed contours at the summit of the range (enclosed by the 8200 foot ground water contour) is a zone where recharge to the ground water system is likely to occur. Assuming that water is not flowing up from a deep regional aquifer (water chemistry, stable isotope, and tritium data support this assumption), the only way for ground water to enter the region of closed contours is via recharge from precipitation, either rain or snow. If recharge does not match the amount of water leaving the region, the water level elevation configuration will change with time, as water levels will drop. The configuration of the contours does not indicate how much recharge occurs above the 8200 foot contour, nor does it preclude some recharge occurring elsewhere in the study area.

From the western boundary of the Pecos Slope aquifer, to the eastern boundary of the study area, the average gradient of the ground water surface is shallow, approximately 100 feet per mile, or 1 degree. Ground water flow to the east is approximately parallel to bedding planes and permeable rock layers and is probably enhanced by joints. Variations in this eastward regional gradient can be correlated with geology. The gradient shallows to 40 feet/mile across McDonald Flats, a flat upland with abundant sinkholes, because the water table occurs in the San Andres Formation which is fractured and highly transmissive. East of McDonald Flats towards Dunken the gradient steepens again across the hills of the Dunken-Tinnie anticlinorium, a north-south trending uplift with faults and folds. Here the water table is again in the Yeso Formation and the flow direction is perpendicular to the faults and folds.

The ground water surface is significantly steeper to the west and southwest of the crest, with gradients close to 500 feet per mile, or about 5 degrees. These steeper gradients are associated with faults (which may be zones of low permeability), flow across bedding planes, and the steep topography of the west face of the mountains.

Well Classification and Hydrograph Interpretation

We used the changes of water level in each well with time, known as a well hydrograph, together with well depth, and the geologic setting (well-site topography and geology, and rock types encountered during well drilling) to classify the wells and their water level responses into groups. The well classifications are reflective of the nature of the aquifer in the vicinity of the well, and thus yield insight into the hydrogeology of the study area.

The large amount of precipitation in the summers of 2006 and 2008 resulted in significant ground water recharge and we observed a variety of water level responses in our monitored wells. We first defined well classifications based on the wells with continuous water level records (Figure 30). We found that one of the following four types encompassed all of the wells with sufficient data:

1. **Shallow perched**–(see Figure 30, SM-0026) Wells in this group are in or near drainages or springs and are less than 100 feet deep. They showed a water level rise in August-September 2006 and August 2008 in response to intense summer storm events, followed by a decrease within 2- 4 months back to near the original level. Water level changes since then have been smaller than this initial rise and quite variable. These wells tap unconfined, probably perched aquifers that respond directly to adjacent stream flow and/or local recharge along fractures. The shallow ground water often discharges at nearby springs.

2. **Fractured high-transmissivity**– (see Figure 30, SM-0049) The wells in this classification range from 80 to 400 feet deep. This classification includes all of the high elevation wells in the study area, those with well heads above 8500 feet. The distinguishing characteristic of the hydrographs is relatively rapid water level rises that are clearly correlated to precipitation events. Water levels in these wells began to rise in August 2006 in response to the abundant monsoon precipitation. All fell again after two or more months to their original level or less. Similar behav-

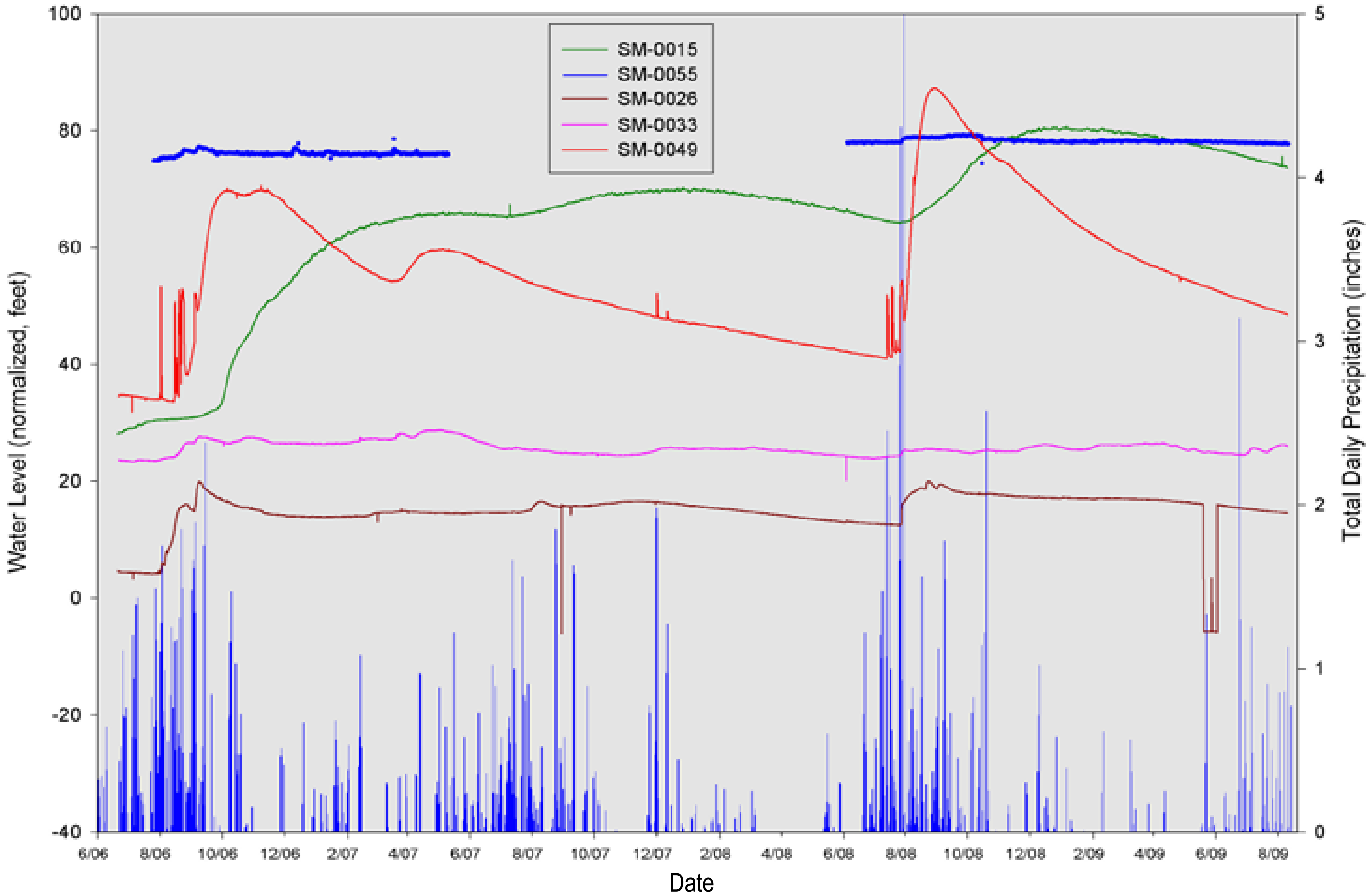
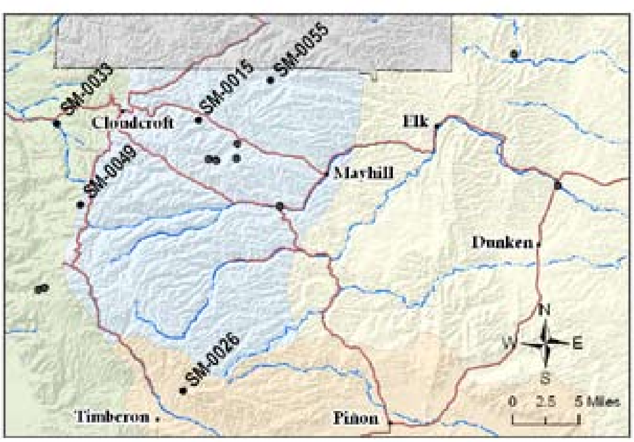


Figure 30a–Sacramento Mountains water level responses to precipitation. The hydrographs (curves) show water level responses to precipitation from five wells with continuous water level recorders (data loggers). The vertical bars below indicate total daily precipitation (in inches) as measured by five weather stations near Cloudcroft.
30b–Map of well locations with continuous data loggers.



ior was observed after the summer of 2008. Five wells above 8500 feet showed rises of 2-5 feet in the early summer of 2007; this timing suggests that the rise was due to infiltration of snow melt. All of these wells subsequently returned to previous levels within three months. We infer that the behavior of these wells is because they are completed in, or near, high-transmissivity limestone beds associated with well-developed fracture systems (composed of joints) that are regional in extent.

3. **Lower transmissivity–** (see Figure 30, SM-0015) Water levels in these wells began to rise at least one month later in 2006 than the wells in class 2. One well in upper Cox Canyon and three near Wimsatt in James Canyon rose 4-5 feet starting in early summer 2007. These changes are probably due to a pulse of ground water derived from snow melt recharge migrating east from the summit area

of the mountains. Summer precipitation in 2008 again induced water level rises in these wells, and since then levels have remained steady or slowly dropped less than those wells in class 2. We infer that these wells are not associated with fractured, highly transmissive limestone beds, and/or the associated fracture systems are not regional in extent.

4. **Deep confined–** (see Figure 30, SM-0055) Five wells 490 to 800 feet deep have shown little or no change throughout the period of monitoring. These wells may tap a deep confined portion of the regional aquifer. The very small water level changes observed may reflect attenuated ground water pressure pulses originating from shallower or up-gradient locations.

Implications for Recharge

Numerous discrete precipitation events are correlated to within a day or two with spikes, rises, or inflections in the water level records in wells SM-0026, SM-0033, and SM-0049 (Figure 30). Examples occur on August 2, 15, and 22 and September 3, 2006. In well SM-0049 the spikes are due to filling and draining of fractures by infiltration during storm events, until there had been enough regional precipitation and recharge to fill the available storage in the aquifer, resulting in a continuous water level rise. Snow melt recharge is evident in well SM-0049 in late spring 2007. Wells SM-0015 and SM-0055 show delayed and very small water rises respectively. SM-0015 may not have been responding to local precipitation, but rather to ground water that migrated down-gradient though the regional aquifer to the well, probably from recharge that occurred at higher elevations and/or to the west. The deep aquifer tapped by SM-0055 may receive attenuated pressure pulses from shallower, up-gradient recharge, but does not receive direct deep recharge, as the water levels changed very little.

After the first week of November 2006, small (approximately 5 cm or less) water level fluctuations superimposed on the hydrograph of well SM-0015 are inversely correlated with atmospheric pressure changes. This indicates that the aquifer changed from unconfined to confined behavior. In other words, when unconfined, the open void space in the fractured aquifer was filling with water. This continued until water levels in the aquifer rose to the elevation of some overlying confining bed of low permeability. Further recharge to the system resulted in the water pressure rising above atmospheric pressure, and the aquifer thus became confined.

The majority of the wells that can be classified are in classes 2 and 3 described above. The portions of the aquifer associated with class 2 wells are recharged rapidly during monsoon storms and spring snow melt periods and soon thereafter begin to drain as ground water flows down gradient to lower elevations. We infer that the rapid rise and subsequent fall in water levels in class 2 wells reflects ground water flow through well-developed, interconnected fracture networks. Water level rises from the summer 2006 and 2008 precipitation were lagged a month or more, on average, in class 3 wells and water levels in these wells have remained steady or decreased slightly as of August 2009. We infer that the flow in these portions of the aquifer is through poorly-connected fracture networks and/or less permeable sandstones and siltstones.

The summers of 2006 and 2008 and the winter of 2006-2007 show clearly in the hydrographs as recharge events. During and after the summer of 2006 the onset of water level rises in our monitored wells moved steadily east from the range crest with time: from August 2006 at the range crest, to late September and early October 2006 near Wimsatt in James Canyon and western 16 Springs Canyon, to February 2007 in central 16 Springs Canyon in the Mayhill quadrangle. There is little evidence in the hydrographs of recharge occurring from the monsoon season of 2007 and no evidence of recharge from the winter of 2007-2008 or the monsoon season of 2009.

Well Water Chemistry

We sampled 77 different wells across the study area for ion chemistry and trace elements; most were completed during the summer of 2007. The wells that have been surveyed, measured and sampled are identified on Figure 31 and Plate 2. Well chemistry results are tabulated in Appendix B. Sampled wells west of Mayhill are completed within the Yeso Formation; wells east of Mayhill produce water from the Yeso and San Andres Formations.

Field Parameters

Water temperature in wells ranges from 7.3 to 22.1°C (average temperature is 15.4). Well waters warm to the north, east, and south away from the high mountains (Figure 32). The coolest waters are found at the highest elevations. Water that is warmer than the mean annual air temperature by at least 6°C may indicate circulation to appreciable depths below land surface (Mazor, 2004). The mean annual air temperature in the study area ranges from 6.9°C in Cloudcroft (1971 to 2000), to 11.1°C in Mayhill (1971 to 2000), to 15.7°C in Hope (1919 to 2005). Wells SM-0076 and SM-0001 are rather warm for their locations at 17.5°C and 16°C, respectively. This may and may indicate upward circulation of deep ground water along a fault for SM-0076 or laterally through the Abo Formation in SM-0001.

Ion Chemistry

The chemical compositions of well samples are plotted on a Piper diagram, which displays the relative concentrations of major ions in the samples (Figure 33). With the exception of one location (SM-0032), calcium and magnesium are the dominant cations (account for over 80% of total cations) and bicarbonate and sulfate are the dominant anions (account for over 80% of total

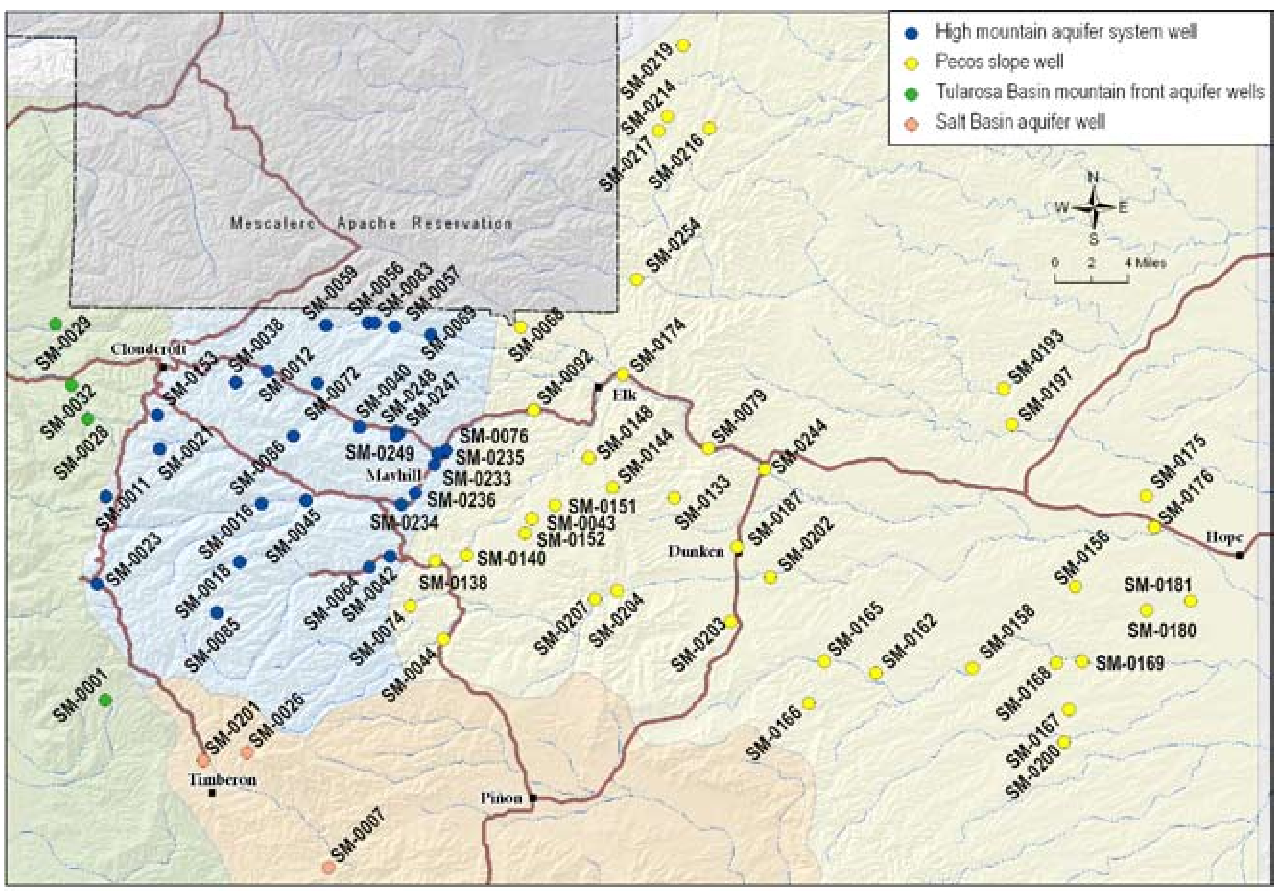


Figure 31–Sampled well water locations referred to in text where symbol color signifies the aquifer classification. Few samples were collected in the northern Salt Basin aquifer or Tularosa Basin mountain front aquifer.

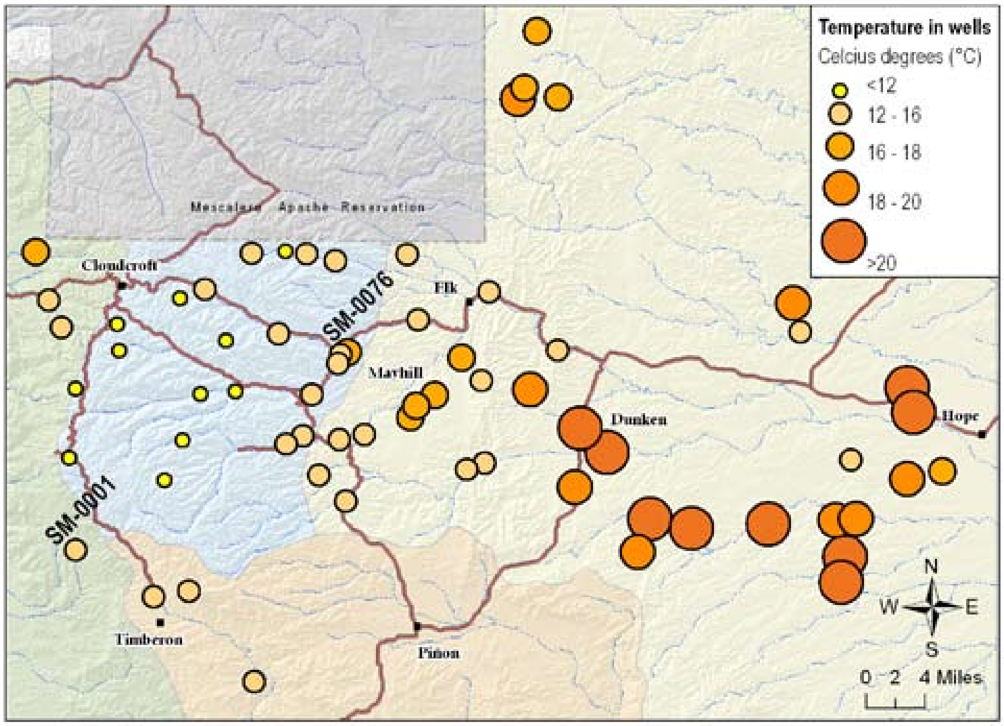


Figure 32–Map of temperature of well waters. The symbol size is larger with warmer temperatures. Temperatures of well waters increase towards the east.

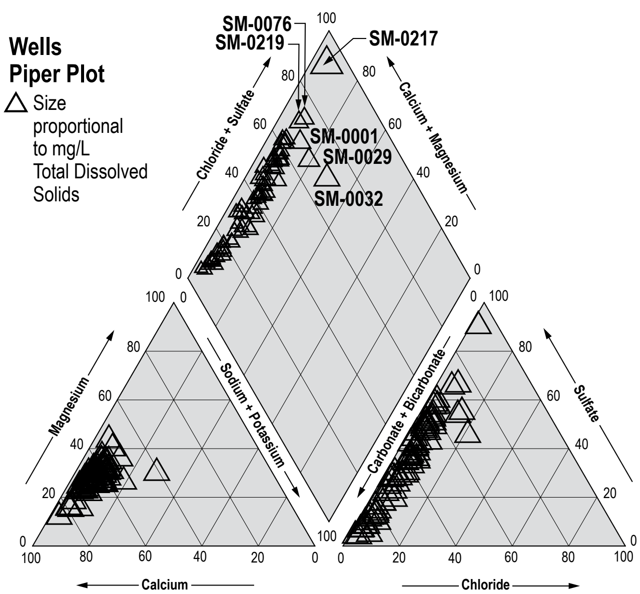


Figure 33–Piper diagram of well waters. The sampled well waters plot in a linear trend indicating increasingly sulfate-rich waters near the top of the plot. The well waters appear to have higher total dissolved solids at the upper end of the plot also.

anions). For cations, the approximate relative proportions observed for calcium is 40-85%, and for magnesium is 15-60%. For anions, excluding SM-0217, the approximate relative proportions observed for bicarbonate and sulfate are 25-95% and 5-75% respectively.

The uppermost point on the Piper diagram is well SM-0217 located along the eastern margin of the Mescalero-Apache Reservation (Figure 34). Nearby this point spatially and on the Piper plot is well SM-0219. Both of these well locations are along the northern extent of the Dunken-Tinnie structural zone, which may add water with higher ion concentrations from depth. Well SM-0076, along the Mayhill fault zone, is also one of the uppermost points on the Piper diagram. The water in this well is warm (17.5 °C), and has some of the highest measured concentrations of constituents such as sulfate, total dissolved solids, magnesium, sodium, chloride and strontium. Additional points, SM-0001, SM-0029 and SM-0032, are located on the western flank of the mountains. These wells may produce water from different geologic units, including the Abo Formation, which have different chemical signatures.

As with springs, well "water types" are defined based on the dominant ions in the water sample (Figure 34). Thirty-two percent of well water samples are calcium bicarbonate (Ca-HCO_3) or calcium-magnesium bicarbonate (Ca-Mg-HCO_3) water types; these dominate in the high mountains. This water type is expected from a carbonate aquifer (limestone and dolomite rocks). Wells sampled east of Mayhill are more commonly calcium-magnesium bicarbonate-sulfate (Ca-Mg-HCO_3-SO_4) or sulfate-bicarbonate (Ca-Mg- SO_4-HCO_3) water types (65%). Well water types that include sulfate may have interacted with gypsum or anhydrite, as well as with carbonates.

The ion chemistry of the well samples shows some interesting trends. Maps of concentrations of sulfate (SO_4), magnesium (Mg), and bicarbonate (HCO_3) are shown in Figures 35, 36, and 37. While spring water chemistry changes from north to south, well water chemistry changes are from west to east, with some north-south changes also. The concentration changes observed from west to east in the Pecos Slope aquifer follow the flow direction of ground water (Figure 7, Plate 2). Easterly increases in sulfate and magnesium concentration, and concomitant decreases in bicarbonate (Figure 38), suggest increased dissolution of anhydrite and/or gypsum, along with

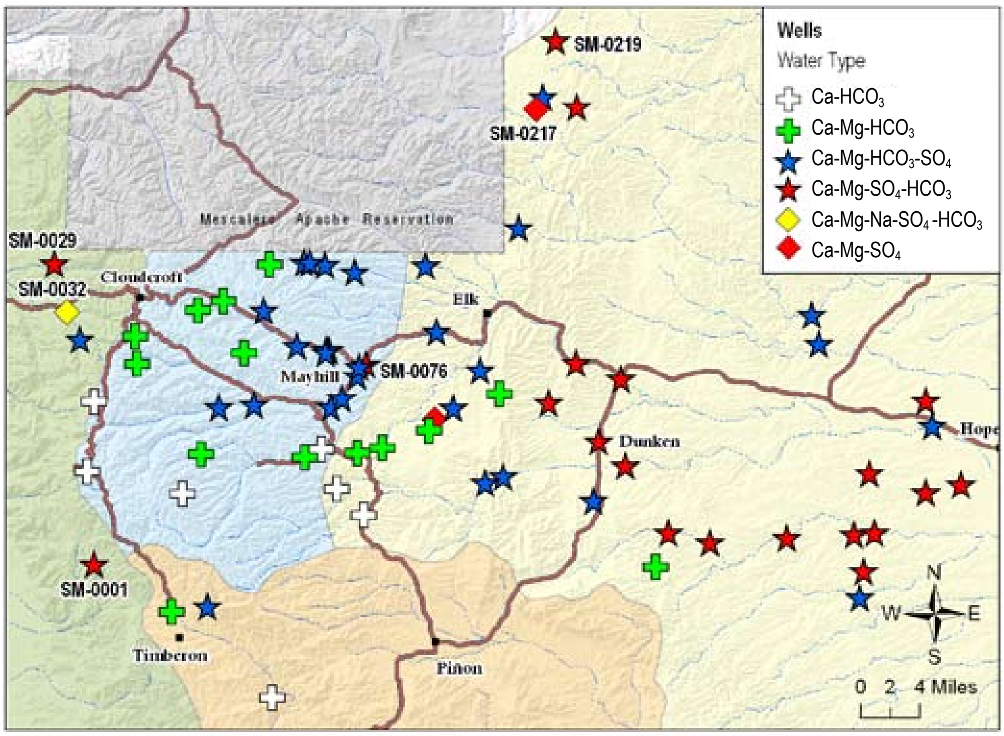


Figure 34–Map of well water types. Wells sampled in the high mountain region (west of Mayhill) are dominantly categorized as calcium bicarbonate or calcium-magnesium bicarbonate waters. Most well waters in the eastern region, and a few scattered in the high mountains, have higher concentrations of sulfate.

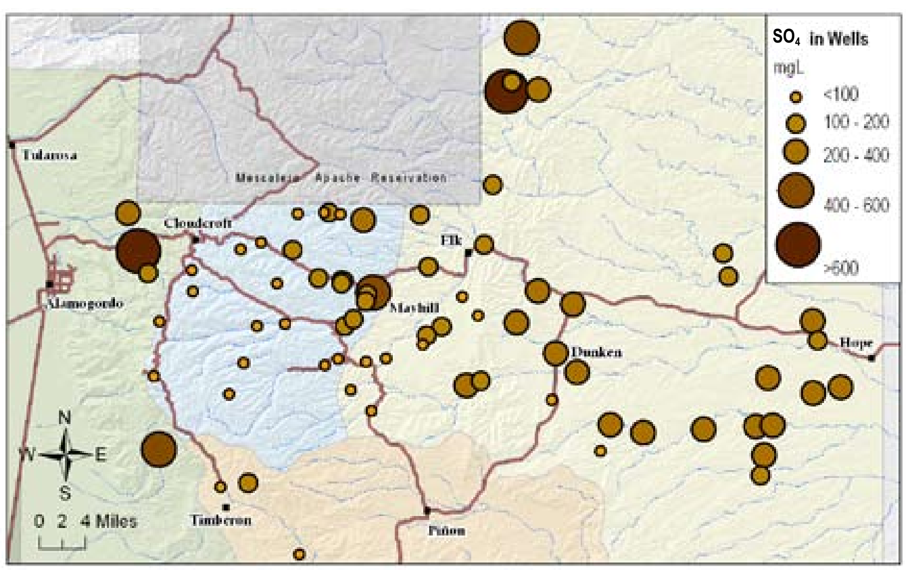


Figure 35–Map of sulfate in well waters. The symbol size reflects the concentration of sulfate in the sampled wells, with larger symbols for higher concentrations. The trend of higher sulfate concentrations towards the north and east is apparent.

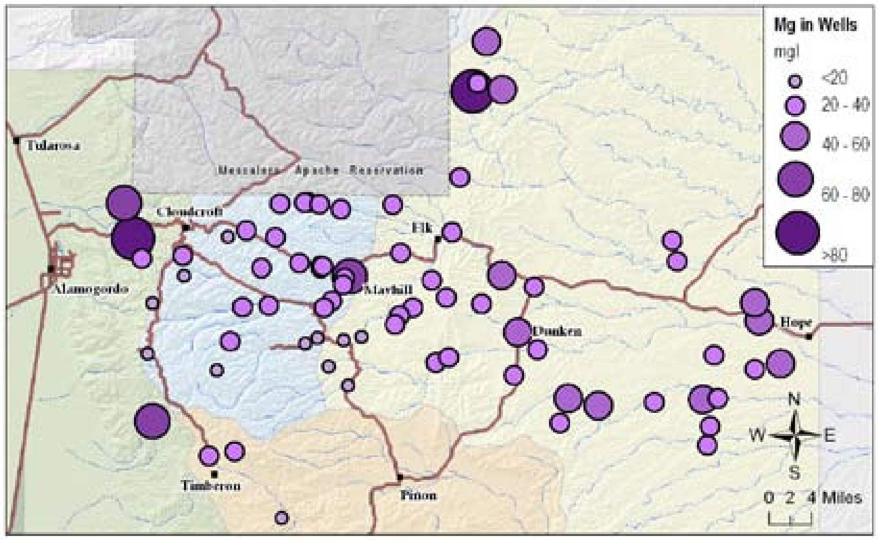


Figure 36–Map of magnesium in well waters. The symbol size reflects the concentration of magnesium in the sampled wells, with larger symbols for higher concentrations. The trend of higher magnesium concentrations towards the north and east is apparent.

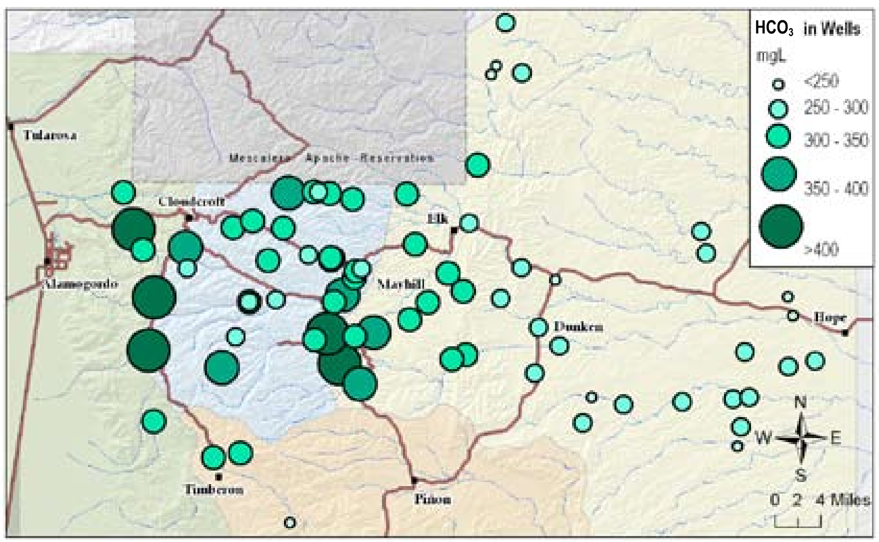


Figure 37–Map of bicarbonate in well waters. The symbol size reflects the concentration of bicarbonate in the sampled wells, with larger symbols for higher concentrations. The trend of lower bicarbonate concentrations towards the east is apparent.

dolomite, as the water moves east. These spatial trends suggest that a process known as "dedolomitization" is controlling the evolution of ground water chemistry. Dedolotimization is a process where the dissolution of gypsum or anhydrite (increase in sulfate) causes dolomite to be dissolved (increase in magnesium) and calcite to be precipitated. This west to east trend is consistent with the ground water becoming older as it moves eastward, further from sources of recharge.

For wells located in the high mountain aquifer system, in addition to the observed west-east trend, sulfate and magnesium both generally increase to the north. The north-south trends may reflect increases in the amount of evaporites in the Yeso Formation towards the north, similar to patterns observed in spring water chemistry. Alternatively, the north-south trend may be a result of the evolution of water chemistry due to dedolomitization as ground water flows through the high mountain aquifer system, suggesting the existence of some south-north regional flow paths within this system. Such a flow path may be a result of water flowing from one perched aquifer to another via the surface water system and southwest-northeast trending fractures.

Stable Isotopes in Well Water

Figure 39 shows stable isotope data for well water samples collected at different times.

Isotope values were variable and mostly plotted between the LMWL and the evaporation line, suggesting that most well samples were a mixture of water with an evaporative signature and non-evaporated water. Based on the stable isotope data for spring samples, the non-evaporated water end member is probably water that is primarily stored in immobile zones that was displaced and forced into the mobile hydrologic system due to the 2006 and/or the 2008 summer recharge events. With current data, we do not observe the same temporal variability for repeat well samples that we observed for repeat spring water samples. However, it can be seen in Figure 40 that the distances between the data points and the LMWL appear to decrease shortly after

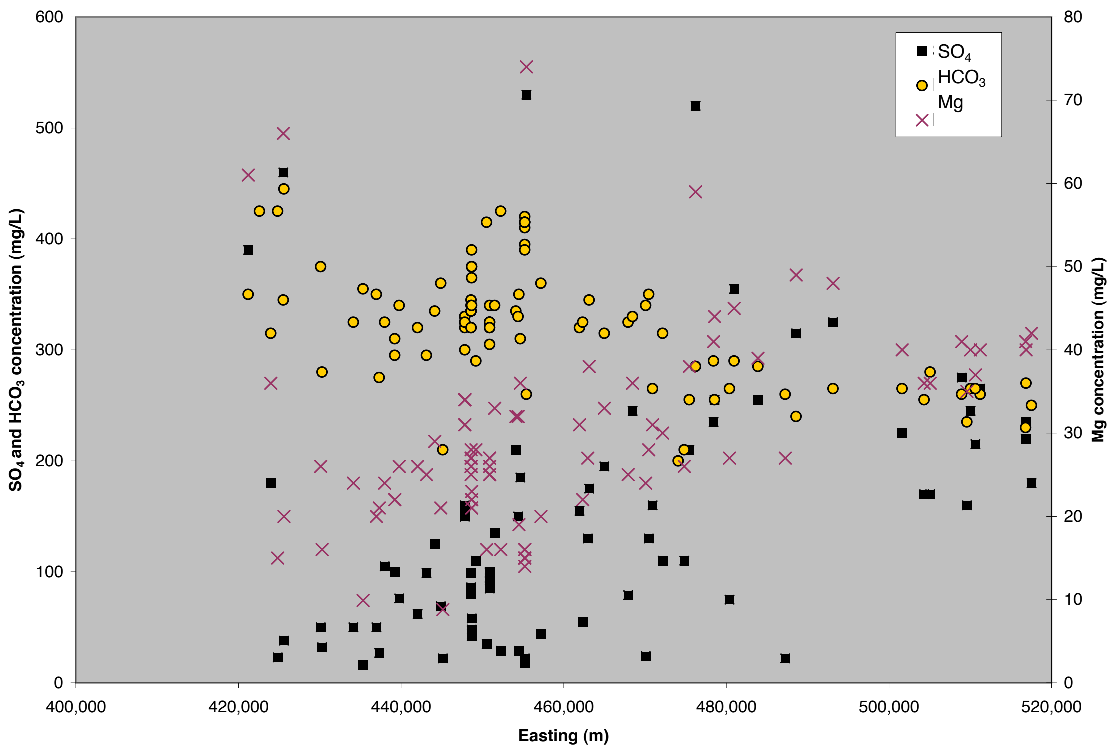


Figure 38–Sulfate, magnesium and bicarbonate vs. easting. This plot shows the trend from west to east of increasing SO_4 and Mg concentrations, along with decreasing HCO_3 concentration in water sampled from wells.

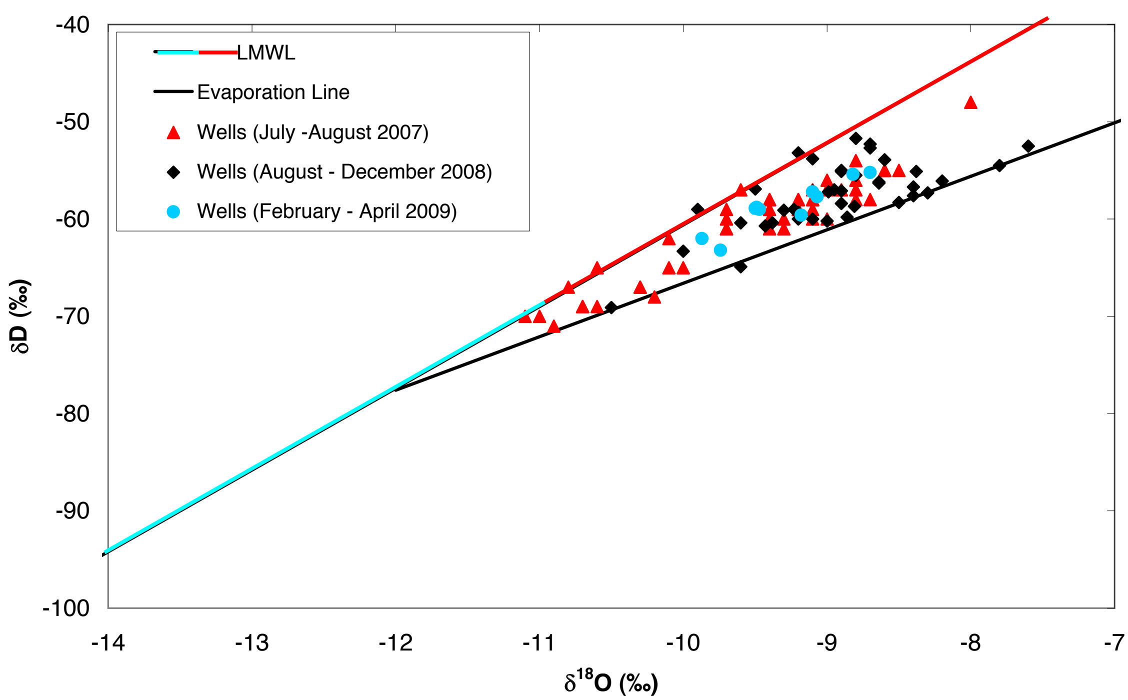


Figure 39–The isotopic composition of well samples collected in 2007, 2008, and 2009 vary both in space and time, with most samples plotting between the LMWL and the evaporation line.

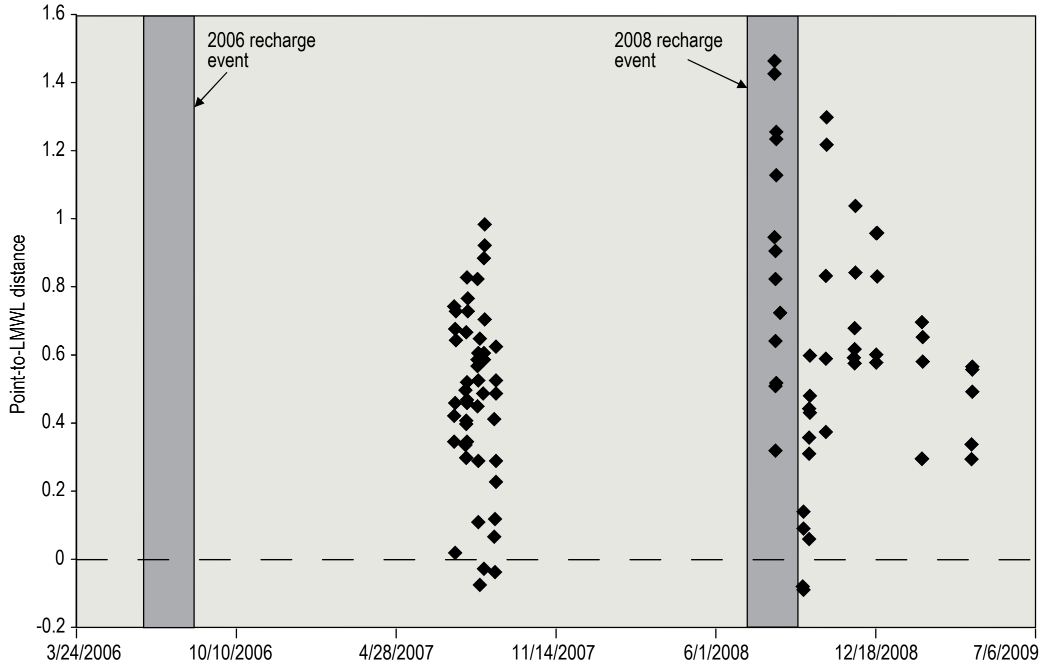


Figure 40–The distance between the stable isotopic composition of well samples (as plotted on δD vs. $\delta^{18}O$ graph) and the LMWL at different times. The isotopic composition of wells appears to shift towards the LMWL shortly after the 2008 recharge event.

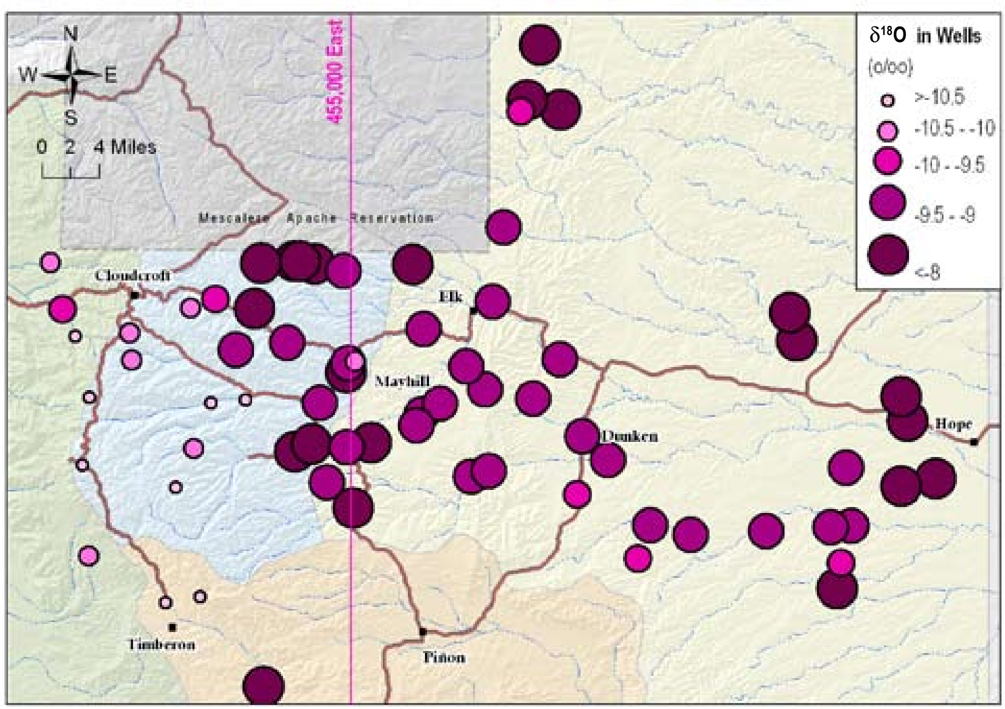


Figure 41–Map showing spatial variability of $\delta^{18}O$ values. Well samples are isotopically lightest to the west in the high mountains and get heavier to the east and northeast.

the 2008 recharge event, as was observed for springs. This trend again suggests that the 2008 recharge event is causing the isotopic composition of ground water to shift towards the LMWL

Figure 41 shows the spatial variation in $\delta^{18}O$ values for well waters. Within the high mountain aquifer system, $\delta^{18}O$ values increase to the north. This trend is similar to the spatial trend observed for springs in the high mountains (data not shown) and may be due to northeasterly flow paths within the high mountains. The isotopic compositions of well samples in the Pecos Slope aquifer are generally heavier and show less variation than those in the high mountains. A graph of $\delta^{18}O$ vs. easting (Figure 42) shows a trend of $\delta^{18}O$ increasing from west to east within the high mountain aquifer

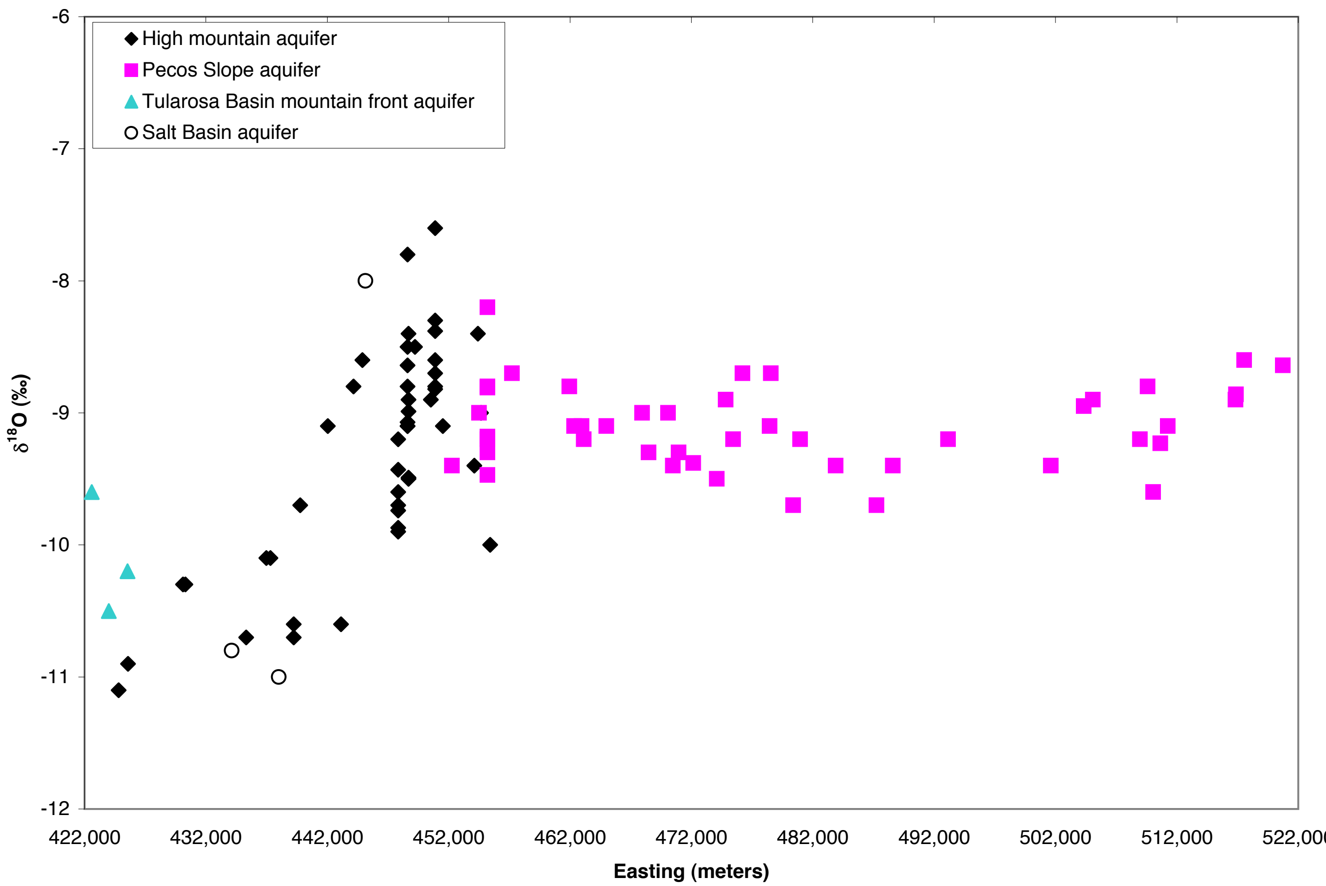


Figure 42–Oxygen isotopes in well waters vs. UTM Easting. $\delta^{18}O$ values for wells in the high mountain aquifer system increases from west to east. $\delta^{18}O$ values in the Pecos Slope aquifer are fairly constant with space and are similar to heaviest values observed in well waters in the high mountain aquifer system.

system. At an easting value of 455000 meters, approximately the longitude of Mayhill and the west boundary of the Pecos Slope aquifer, $\delta^{18}O$ values decrease and level off to between -9 and -9.5 ‰. The trend west of Mayhill (high mountain aquifer system) indicates that water with different isotopic compositions (that is primarily controlled by evaporation) is recharging the ground water system, most likely through seepage from streams and ponds. The termination of this spatial trend at Mayhill suggests that seepage from streams is not significant east of that point. Therefore, recharge to the Pecos Slope aquifer primarily comes from the high mountain aquifer system. The isotopic composition of ground waters in both the Tularosa Basin mountain front aquifer and the Salt Basin aquifer suggest that the high mountain aquifer system may provide some recharge to both of these aquifers.

Well Water Ages

Tritium

Water samples collected from wells in the Sacramento Mountains show a range in tritium values from 0 to 7.2 TU, with an average of 1.6 TU. Tritium concentration decreases to the east (Figure 43) and roughly with elevation (Figure 44). Compared with springs, wells on average are older. This is likely due to the fact that wells are accessing deeper, older water than springs. Wells located in the high mountains region are on average younger than wells located in other parts of the study area. The high mountains region wells have an average of 2.4 TU (n = 19), while the Pecos Slope wells average is 0.94 TU (n = 28). The three wells sampled in the northern Salt Basin had an average tritium concentration of 2.9 TU. The finding of younger water in the

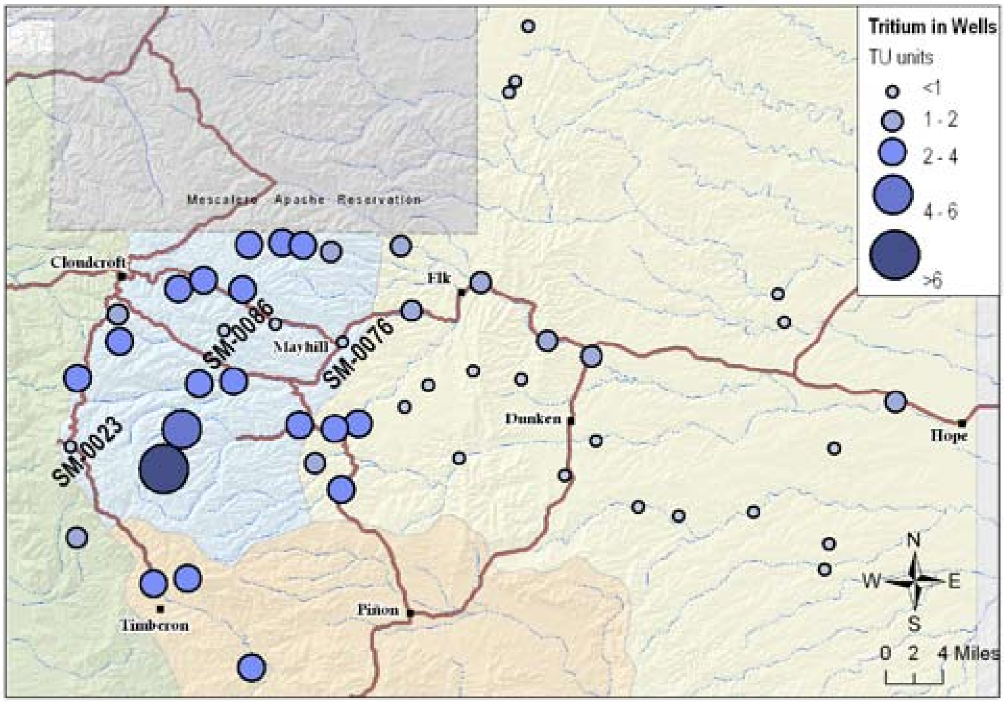


Figure 43–Map of tritium in well waters. The symbol size reflects the concentration of tritium in the well waters sampled, with larger symbols for higher concentrations. Generally, the higher the tritium concentration, the younger the water. Most wells in the high mountains have high tritium concentrations (younger water), while wells to the east have lower concentrations (older water). Outliers are discussed in the text.

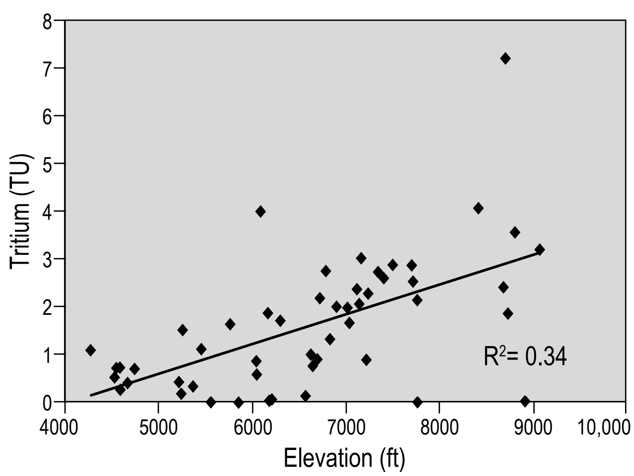


Figure 44–Tritium vs. elevation of sampled wells. Generally, the higher the tritium concentration, the younger the water. The relationship of tritium in well water samples with elevation generally indicates that well water at higher elevations is younger than well water at lower elevations.

wells in the high mountains supports the hypothesis that this is the primary region of recharge.

Wells with surprisingly low tritium concentrations include wells SM-0023, SM-0086, and SM-0076. SM-0023 is located at the top of the mountain range where we would expect young ground water, however, this well is along a fault which may influence the water age. Well SM-0086 is not near any known faults but the older water age may be due to circulation of deeper, older water along a particularly well-developed joint system. Well SM-0076 is located along the Mayhill fault zone, and also has anomalous water temperatures and chemical characteristics, which makes it likely that old water is circulated up from depth along the fault zone.

In the Pecos Slope region, the trend of young water along the margins of the high mountain aquifer indicates that this is the primary recharge zone for the Pecos Slope aquifer. Additional recharge likely also occurs proximal to the Rio Peñasco where slightly higher tritium concentrations are found. Well samples collected in areas distal to the high mountains margin and the Rio Peñasco are older water with lower concentrations of tritium. Presumably these areas with older water and low tritium concentrations are not receiving much recharge.

Chlorofluorocarbons

CFC samples were collected at thirty-one wells in the study area, however because of the complexity of the aquifer systems, in most cases the CFC ages cannot be taken as an actual age of the ground water (see Environmental Tracers sidebar). Mixing of water that has been recently recharged or recycled, with water that has been in the aquifer for some time will likely cause variability in the CFC ages from the different CFC species. Additionally, CFCs are gas analyses, and the results can be affected by many factors, such as air collection during sampling, excess air in the subsurface, and a thick unsaturated zone at the recharge location. The recharge temperature for each sample was determined by the same method as that used for spring samples, and the data were pared down to CFC113, CFC12 and CFC113/12 ratio apparent ages using the same methods described in the section on springs.

The fact that there is little age agreement (± two years) between the different varieties of CFCs indicates that there is significant mixing of older and younger ground water occurring in this aquifer system (Figure 45, Table 5). Review of the CFC apparent ages from wells sampled in the study area shows that six of the locations had good age agreement among the different CFC varieties (highlighted in Table 5). We see significant variability in CFC ages in samples collected in the high mountains region indicating a great deal of mixing is taking place (except for SM-0038, SM-0074, and SM-0085). Of the well samples collected in the Pecos Slope aquifer, only SM-0092, SM-0152, and SM-0202 have concordant CFC ages.

Well Point ID	Collection Date	CFC113 (years)	CFC113/12 (years)	CFC12 (years)
SM-0001	10-Jul-07	20	NA	Cont
SM-0007	23-Jul-07	19	17	22
SM-0011	23-Jul-07	30	26	34
SM-0018	28-Aug-07	23	20	26
SM-0021	10-Jul-07	20	19	22
SM-0023	10-Jul-07	29	NA	Cont
SM-0026	29-Aug-07	27	22	32
SM-0032	13-Aug-07	27	24	31
SM-0038	09-Jul-07	19	19	18
SM-0040	09-Jul-07	26	29	21
SM-0042	24-Jul-07	21	NA	Cont
SM-0044	09-Jul-07	23	22	25
SM-0045	10-Aug-07	27	NA	Cont
SM-0056	26-Jul-07	28	22	34
SM-0057	26-Jul-07	24	20	30
SM-0059	11-Jul-07	22	NA	Cont
SM-0068	10-Aug-07	31	24	36
SM-0074	24-Jul-07	22	22	22
SM-0076	25-Jul-07	38	17	47
SM-0085	24-Jul-07	21	21	23
SM-0086	25-Jul-07	23	21	26
SM-0092	13-Aug-08	26	26	26
SM-0152	07-Aug-07	38	38	38
SM-0153	25-Jul-07	24	22	27
SM-0158	08-Aug-07	27	30	23
SM-0174	25-Sep-08	23	25	17
SM-0193	20-Nov-08	22	NA	33
SM-0201	29-Aug-07	27	23	33
SM-0202	30-Aug-07	25	25	24
SM-0207	30-Aug-07	Cont	NA	29
SM-0217	24-Sep-08	40	NA	59

Table 5–This table shows the CFC age data for the sampled wells; highlighted wells are locations with approximate concordant CFC ages. The CFC apparent age (in years before sample collection date) shown here cannot be taken as an actual age of the ground water because of mixing of older and younger ground water in this system. “Cont” is noted for sites where water sample had higher than present day CFC concentrations. This may indicate contamination during the sample collection process or some local CFC contamination. “NA” is noted for sites where an age could not be derived from the ratio of CFC113/12.

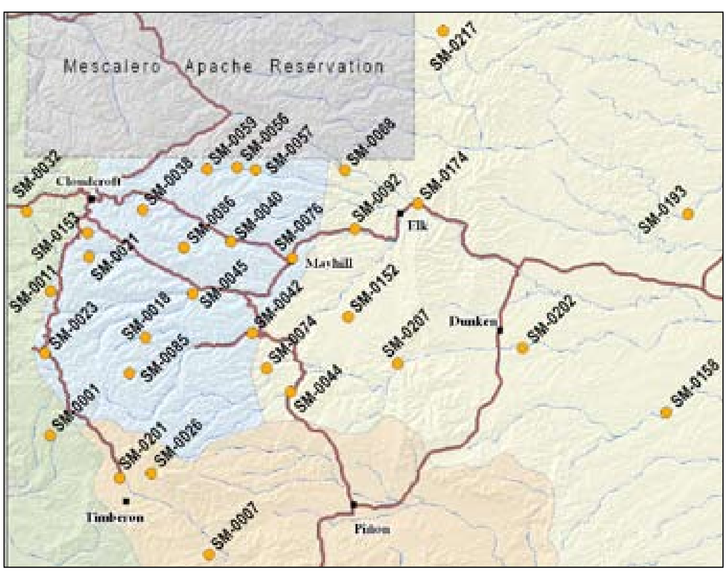


Figure 45–Map of CFC sample location in wells referred to in Table 5.

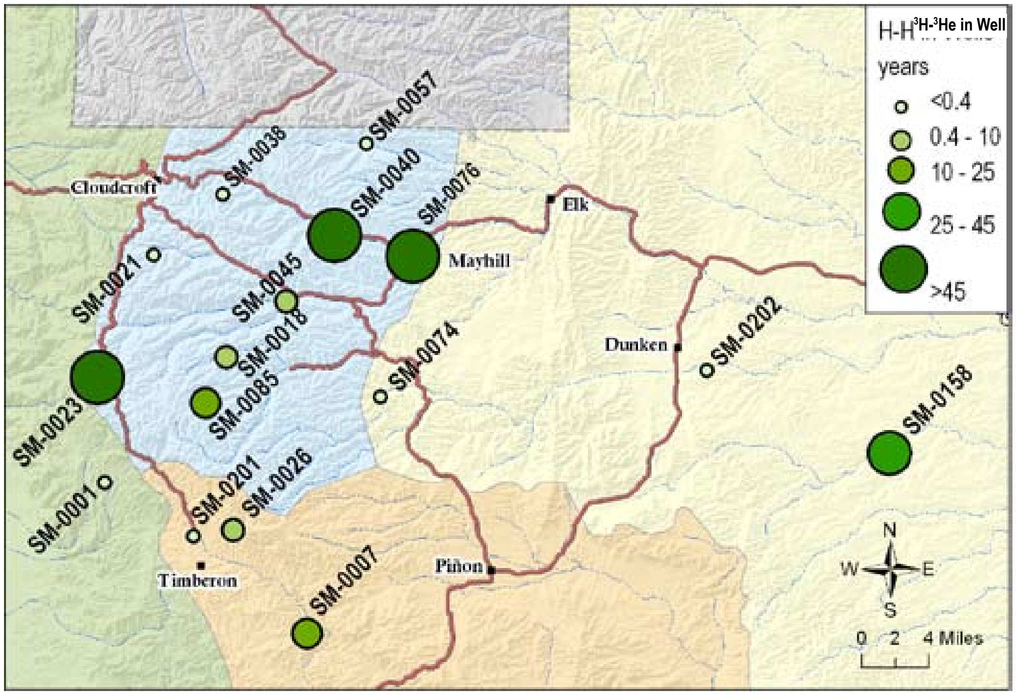


Figure 46–Map of ^{3}H-^{3}He ages of well waters. The symbol size represents the ^{3}H-^{3}He calculated recharge age of well waters, with larger symbols for older samples. There is a great deal of scatter in the data, with no strong spatial trends. Discussion of the issues with ^{3}H-^{3}He water ages is included in the text.

In general, most of the wells in the study area sampled for CFCs suggest that mixing of waters of varying ages is taking place. At locations where there is approximate age agreement in the CFC varieties, we interpret these locations to have less mixing. In aquifer systems, such as the high mountains region, where water from multiple perched aquifers is mixed via fracture networks and surface water discharge/ recharge processes, it is not surprising to find this variability.

Tritium-Helium (^{3}H-^{3}He)

^{3}H-^{3}He ages are available for 16 wells (Figure 46). Four of the wells sampled for ^{3}H-^{3}He show intermediate ground water ages, ranging from 1.9 to 14.9 years, while four wells, SM-0023, SM-0040, SM-0076, and SM-0158, yielded significantly older ground water ranging from 29.1 to >50 years. SM-0023 yielded >50 year old ground water, with tritium concentrations almost below detection limits. This well may be affected by circulation of water along a fault. SM-0076 in Mayhill has consistently old water with other dating techniques. Again, circulation of old, deep water up faults is proposed for these two wells. SM-0040 may have access older, deep water flowing through fractures, and possibly cavernous zones, in the Yeso Formation. SM-0158, located within the Pecos Slope aquifer, is probably producing water from a more confined, deeper aquifer than wells in the high mountains region to the west.

Eight of the well samples have near-modern ground water with ages of less than one year. In some cases, the ^{3}H-^{3}He results and the tritium measurements are not consistent. This can occur for several reasons. One scenario that may be common in the southern Sacramento Mountains is that recharge water must travel through a thick unsaturated zone or highly fractured bedrock before reaching the water table. If this is the case, erroneously young ^{3}H-^{3}He results can occur. ^{3}H-^{3}He measurements are extremely sensitive to tiny gas bubbles trapped within the unsaturated zone, referred to as “excess air”. Some sampling situations are not ideal for studying the ^{3}H-^{3}He ratios in ground water (e.g., the submersible pump cavitates and introduces air bubbles into samples, or the water degasses CO_2 upon sample collection).

IV. PRELIMINARY CONCEPTUAL MODEL

We have developed the following model of the hydrogeology of the southern Sacramento Mountains based on the geologic data, ground water levels, water chemistry data, stable isotope data, and ground water age data we have collected. We conceptualize the model in terms of the following regional aquifers shown in Figure 47 (cross-section):

1. The high mountain aquifer system
2. The Pecos Slope aquifer
3. Tularosa Basin mountain front aquifer

There is evidence that the ground water from the high mountain aquifer system does recharge the aquifer system in the northern Salt Basin. However, the small amount of data that we have acquired from the northern Salt Basin is not sufficient to fully characterize interactions between these two aquifer systems.

High Mountain Aquifer System

The aquifer system in the high mountains is complex and variable due to the surficial exposure of the Yeso Formation, the extreme heterogeneity, and the presence of regional fracture systems. There are many wells and springs in this region, therefore it is an area where we have abundant data. The complex geology of the Yeso Formation results in a complicated hydrologic system. Most water produced from wells and springs comes from fractured carbonate layers. Perched aquifers associated with the multitude of springs are connected to each other by regional fracture networks and local stream systems. It is probable that a deeper continuous aquifer exists in the eastern portion of the high mountains that connects to the Pecos Slope aquifer. The high mountain aquifer system recharges the Pecos Slope aquifer and the Salt Basin. The outcropping of the Yeso Formation, which is the primary aquifer in the study area, enables water to enter the ground water system.

Stable isotope data for springs and wells suggest a well mixed system and that water originates as local precipitation (primarily snow melt) and has undergone evaporation in mountain streams and ponds. Water discharging from perched aquifers and springs at higher elevations becomes part of the surface water system where it undergoes evaporation and then recharges another shallow ground water system and discharges at a spring at a lower elevation. This cycle may happen several times before the water is deep enough below the ground surface that it cannot interact with the surface water system.

The chemistry of this aquifer system indicates this water has spent less time in the subsurface than water in adjacent aquifers. Most water samples collected in this area are Ca-HCO_3 or Ca-Mg-HCO_3 water types. As water percolates below the surface and moves through the ground water system, it acquires its chemical signature by dissolving limestone and dolomite in the San Andres and Yeso Formations. Spatial variability in water chemistry is probably due a combination of the spatial distribution of gypsum and the evolution of water chemistry along ground water/surface water flow paths.

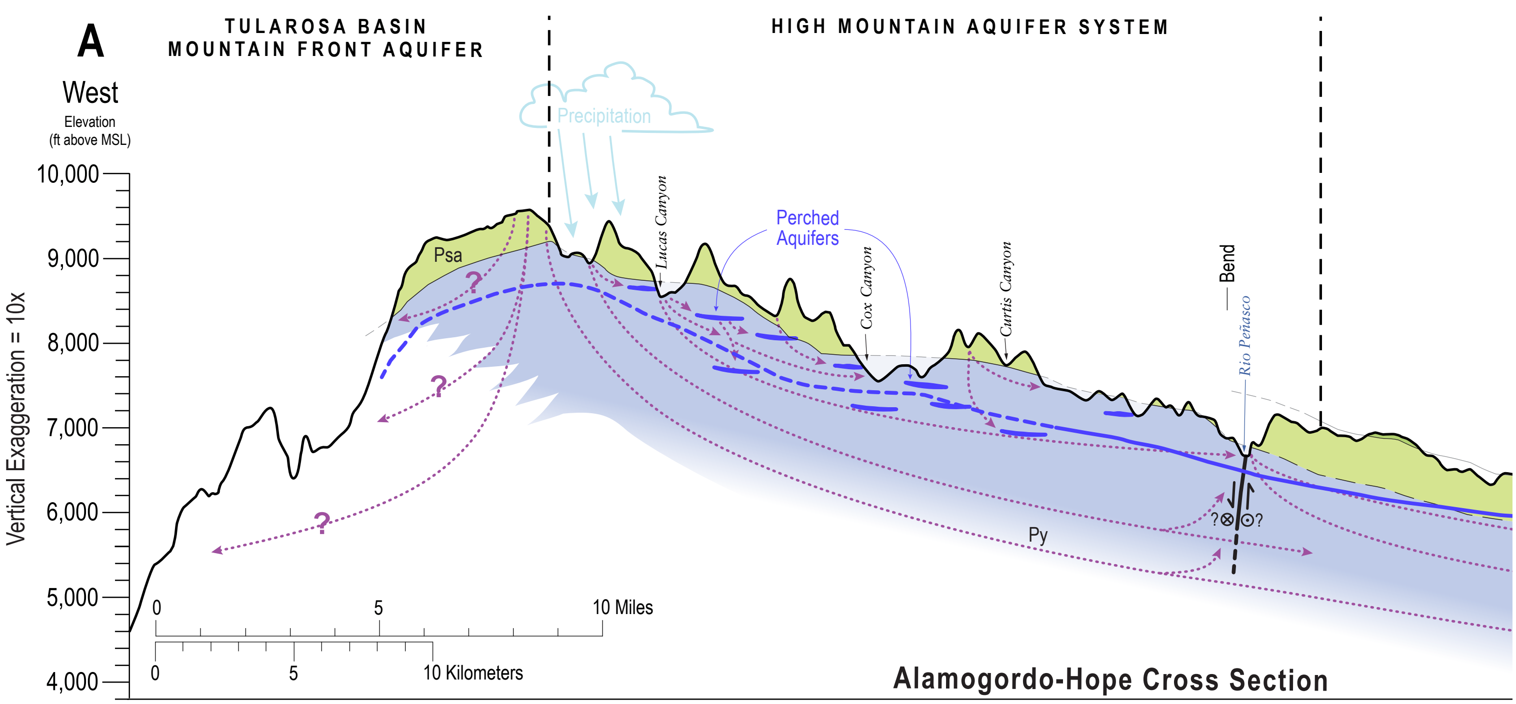
Age dating data also suggest that the high mountain aquifer system is a well mixed system. Water from multiple fractured, perched aquifers with varied flow velocities mix within the surface water system and where fracture systems intersect. Tritium data suggest that most ground water in this system is generally younger than water in adjacent aquifers (3.3 TU, from 44 spring and well samples), supporting the hypothesis that ground water in this system recharges adjacent aquifers.

Pecos Slope Aquifer

The aquifer from approximately Mayhill towards the eastern study boundary is geologically simple relative to the high mountain area, though there are several faults and structural zones which may influence the ground water. Wells are completed in both Yeso and San Andres Formations and a few springs discharge from the Yeso Formation. Recharge to this aquifer occurs primarily from the high mountain aquifer system to the west.

The stable isotopic composition of ground water in this aquifer is fairly constant over a large area and is similar to that of springs and wells sampled at the eastern edge of the high mountain aquifer system. This trend is consistent with the interpretation that recharge to the Pecos Slope aquifer comes primarily from the high mountain aquifer system.

Figure 47–The San Andres and Yeso Formations generally dip eastward, and the ground water table roughly mimics this pattern. Recharge to the ground water is from precipitation (primarily snow melt). Hypothetical ground water flow paths (in purple) illustrate recharge occurring in canyon bottoms, with some water going into deep flow paths and some following shallow flow paths. Perched aquifers in the high mountain aquifer system are connected via fractures and surface water. Many springs and wells discharge water which is a mixture of young, shallow water and deeper, older ground water. It is suspected that faulting in the region may cause vertical upwelling of ground water from deep flow paths.

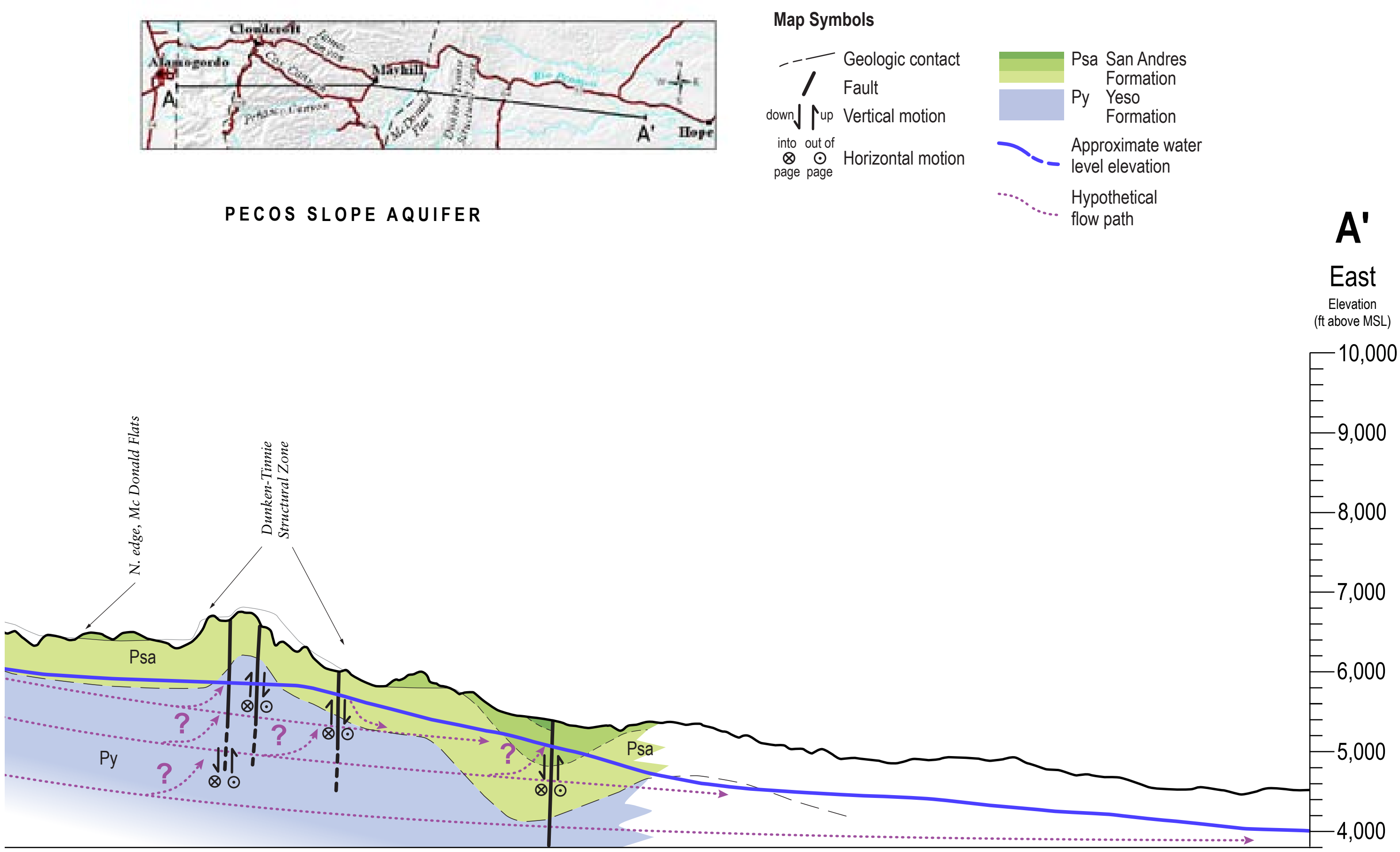


The chemistry of this aquifer indicates that ground water has been in the subsurface for a longer time period compared to the high mountain aquifer system. The observed water type of Ca-Mg-HCO_3-SO_4 indicates that the water chemistry is more evolved than that in the high mountain aquifer system, and therefore has been in the ground water system longer.

The relative age of the ground water in the Pecos Slope aquifer is also older than other areas, with an average tritium concentration of 0.95 TU (from 31 spring and well samples).

Tularosa Basin Mountain Front Aquifer

The steep west side of the study area has very different geology and hydrologic characteristics than areas east of the range crest. The geology is complicated by mountain-front parallel faulting. There are several springs that discharge along the steep mountain front, and many wells throughout the area. We have collected minimal data for this area, but it does indicate that water is different from the high mountain aquifer system and other areas encountered in this study. (Our studies will focus on the northern Tularosa Basin in the next few years.)



V. SACRAMENTO MOUNTAINS WATERSHED STUDY

Introduction

The Sacramento Mountain watershed study (SMWS) is a part of the Sacramento Mountain Hydrogeology Study that is focused on understanding the hydrologic system and the impacts of forest management at the watershed scale. The SMWS utilizes hydrologic, geochemical, and remote sensing techniques to examine how local precipitation is partitioned and distributed in the watershed and how this partitioning changes due to a change in vegetation density, type, and distribution as a result of thinning trees within the watershed. Researchers from NMBGMR, New Mexico State University College of Agriculture, the New Mexico Forest and Watershed Restoration Institute, and New Mexico Tech Department of Earth and Environmental Science are working to accomplish the following goals:

- Quantify the water balance at a watershed scale before and after the tree thinning treatment.
- Relate the observed changes in the water balance to the local hydrogeology.
- Construct a hydrologic model that can be used to predict how the ground water and surface water supply may be affected by tree thinning.

The work described above on the regional hydrogeology will help us to relate the observed changes in the water balance due to tree thinning in the watershed to the local hydrogeology. An understanding of the regional and local hydrogeology is also important in deciding how to model the system properly at a variety of scales. The watershed scale water balance established under the SMWS will be used to estimate a water balance on a larger scale for the regional study area.

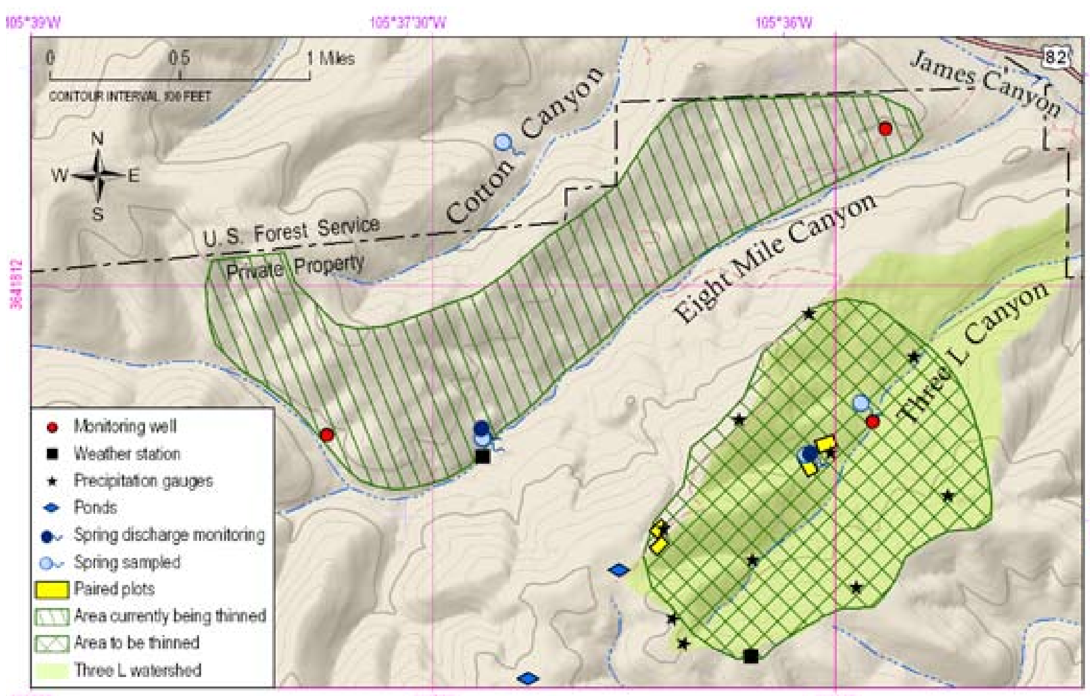


Figure 48–Watershed study area including area to be thinned, and locations of instrumentation.

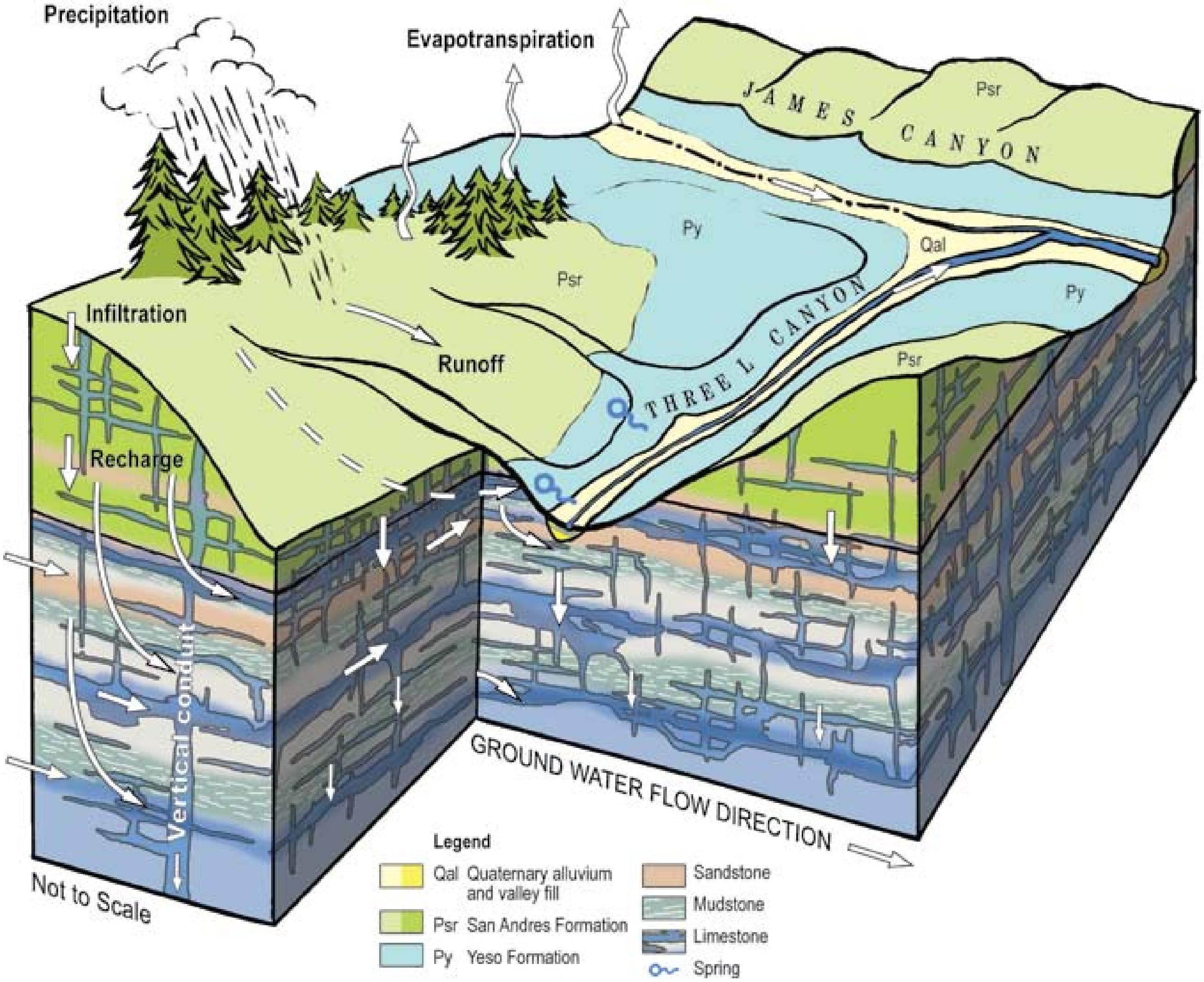


Figure 49–Conceptual model of hydrologic system in Three L Canyon showing components of the watershed water balance, including surficial hydrologic processes, schematic subsurface geology with fractures (in blue), and rock types labeled. Subsurface arrows illustrate hydrologic connections between aquifers. Some ground water comes in from outside the watershed. Local precipitation also recharges the ground water system through fractures. Water leaves the watershed via evapotraspiration, surface water runoff, and ground water leaving the local system. Water is stored in the watershed primarily in the soil, and within the ground water systems.

Study Description

Study Area

The main study area is located in Three L Canyon (Figure 48), which is on private property. Initially, thinning will take place on the northern slopes of the canyon. Data is being collected on these slopes and on the ridge between Three L and Eight Mile Canyons. Some data is being collected in Eight Mile Canyon where trees are currently being thinned. We are also monitoring spring discharge in the spring in Cotton Canyon, which is on U.S. Forest Service property and will not be thinned.

Tree Thinning

The goal of the tree thinning prescription is to restore a portion of the Three L Canyon watershed to historical tree densities. A pre-treatment tree density and ground cover density has been established by the NM Forest and Watershed Restoration Institute at Highlands University. The State Forestry Division Forest and Watershed Health Office (FWHO) will provide technical assistance to the Natural Resources Conservation Service and Otero Soil and Water Conservation District to develop a site-specific prescription for tree thinning.

Water Balance Method

Figure 49 shows a conceptual model of the hydrologic system in Three L Canyon based on geologic, hydrogeologic and geochemical techniques employed for the Sacramento Mountain Hydrogeology Study described in this report. We will use a water balance approach to evaluate how local precipitation is partitioned among the multiple components of the water balance. The water balance method is a simple concept based on the conservation of mass which is represented in the following equation:

$$I - O = \Delta S$$

where I is inputs, O is outputs and ΔS is change in storage. If inputs are greater than outputs, water will be put into storage. If we are considering storage in a ground water system, ground water levels will increase. If outputs are greater than inputs, water will be taken out of storage and ground water levels will decrease. If inputs equal outputs, storage will not change, and the system is considered to be in steady state. If we consider ground water and surface water systems together in the Three L watershed, inputs include:

- Local precipitation
- Ground water coming from outside the watershed

Outputs include:

- Evapotranspiration
- Surface water runoff leaving the watershed
- Ground water leaving the watershed

In this system, water is primarily stored in:

- Soil
- Shallow ground water system associated with springs
- Regional mountain aquifer system

The following sections discuss possible effects of tree thinning on the water balance.

Possible Effects of Tree Thinning on Inputs

The thinning of trees in the Three L watershed will not affect the amount of ground water flowing into the watershed, but it could have a significant effect on the amount of local precipitation that enters the system. A water balance can be used to assess how much precipitation might enter the hydrologic system (Figure 50). In this case we will consider a surface within the watershed, which includes a thin top layer of soil, forest litter, and vegetation (both understory and canopy). For this water balance, precipitation is the only input while outputs include:

- Canopy interception (water that gets intercepted by trees and evaporates)
- Understory interception (water that gets intercepted by understory and evaporates)
- Forest floor interception (water that gets intercepted by forest floor and litter, and then evaporates)
- Infiltration to ground water system
- Runoff to surface water system

The thinning of trees will obviously have an impact on canopy interception, which in conif-

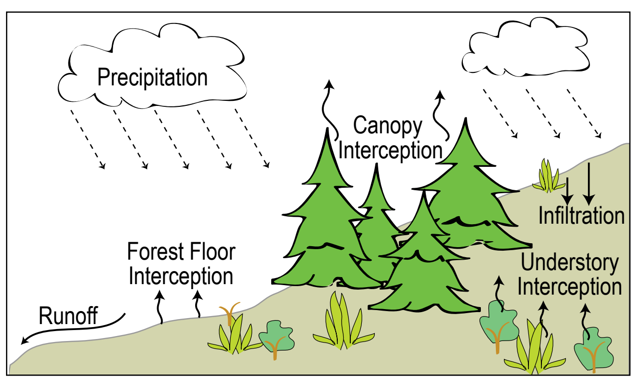


Figure 50–The different components of the hill slope scale water balance. Looking at the system in a smaller scale, the effects of individual processes such as canopy, understory, and forest floor interception, infiltration to ground water and surface runoff will be addressed. Many of these components will be measured before and after thinning

erous forests can account for up to 40% of the precipitation. A reduction in tree density will decrease canopy interception and therefore increase the amount of water that reaches the ground. Initially, understory interception will not change. However, the thinning of trees may result in a subsequent increase in understory vegetation and therefore an increase in understory interception. Because more water will reach the ground due to the thinning process, there is potential for infiltration to the ground water system to increase. The decrease in canopy interception may also potentially increase runoff to the surface water system. However, the change in texture of the forest floor due to the mastication of the slash may also potentially affect the amount of surface water runoff.

Because Three L Canyon is an ephemeral stream, water leaves the watershed as surface water only during flash floods. Much of the water that runs off hill slopes in Three L Canyon probably ends up infiltrating to the ground water system. Therefore an increase in surface runoff may result in an increase in infiltration to the ground water system. An increase in infiltration may possibly increase storage in soil and the saturated ground water systems.

Possible Effects of Tree Thinning on Outputs

Thinning trees in the forest may also affect the outputs from the watershed by changing the amount of water that leaves the system due to evapotranspiration, which includes water that is used by trees (transpiration). A decrease in transpiration from soil and the shallow saturated ground water system may result in an increase in the outflow of ground water from the watershed and a possible increase in spring discharge.

Hydrogeologic Characterization and Monitoring

Hydrogeologic monitoring entails collecting data that will enable us to estimate each component of the water balance and the change in storage in ground water system. For this study, the collection of baseline data is of utmost importance because it enables us to characterize the water balance under current conditions and to establish typical responses of the hydrologic system to different forcing mechanisms such as precipitation events and the melting of snow pack. The parameters monitored to obtain baseline characterization of the system will continue to be monitored during and after tree thinning.

We are currently collecting the following data:

- Water levels from shallow observation wells (time series)
- Water levels from ponds on ridge (time series)
- Discharge from springs in the study area (time series)
- Precipitation and weather data (time series)
- Hill slope runoff
- Canopy interception (time series)
- Water chemistry data from precipitation, ground water, and springs (time series)
- Oxygen and hydrogen isotope data for ground water, springs, and precipitation (time series)
- Soil moisture and chemical profiles in soil at several point locations
- In-situ soil moisture and matric potential at several locations (time series)
- Electromagnetic induction (EMI) surveys to assess spatial soil moisture variability in the study area (repeat measurements on a seasonal basis)
- Multiple remote sensing image analyses to estimate evapotranspiration (ET) rates in the study area
- Leaf area index
- Characterization of soil properties in the study area.

Time Line

The following tasks have been completed to date:

- Installation of 3 weirs with continuous data loggers to monitor discharge in springs in Three L Canyon and Cotton Canyon.
- Installation of a precipitation collector.
- Installation of weather stations.
- Installation of several rain gages.

- Several EMI surveys to assess the spatial variability of soil moisture
- Detailed description of soils in the study area
- Vegetation survey in Three L Canyon (tree density, tree height, wildlife pellet counts, etc.)
- Monthly spring water sampling. Samples are analyzed for general chemistry and stable isotopes.
- The first remote sensing image analysis to assess ET is underway.
- Soil samples have been collected at various depths at several different locations and analyzed for general chemistry, water content, and stable isotopic composition of soil water.
- Installation of three monitoring wells.
- Initiation of plot-scale experiments that compares water balances in thinned plots to those of non-thinned plots.

Present – August 2010
Collection of baseline data

Present - August 2010
Pre-treatment experiments

During this time period, all time series data listed above will continue to be monitored. The baseline data collected will be used to direct experiments such as hydrograph separations and/or tracer tests to get a more precise understanding of specific ground water flow paths. We will construct a preliminary hydrologic model for Three L Canyon.

August 2010 – October 2010 – Treatment

All time series data will continue to be collected during the vegetation thinning process.

November 2010 – December 2012
Post-treatment study

We will continue collecting data to estimated water balance after the thinning treatment, and complete the hydrologic model.

General Conclusions

The data collected thus far is not sufficient to come to any preliminary conclusions. Discharge in the upper spring in Three L Canyon has been relatively constant at around 30 gallons per minute over the last 6 months. Geophysical surveys (EMI) which measured apparent electrical conductivity of soil showed lower values for soils above the San Andres Formation and higher values for soils above the Yeso Formation. Plot-scale water balance experiments are under way and should provide some information about how vegetation affects the partitioning of rain into the different components of the water balance. We are currently compiling and analyzing data to begin to estimate different components of the water balance such as canopy interception, infiltration, and evapotranspiration.

Predicting how the hydrologic system might respond to the thinning of trees in the forest is not a simple task because the response is site specific. By estimating all the components of the water balance and changes in storage, we should be able to show how thinning trees in the Three L Canyon will affect the hydrologic system and the local ground water and surface water supply.

VI. FUTURE WORK

The Sacramento Mountains Hydrogeology Study is fully funded through summer 2012, and a final report will be delivered after that time. We will continue to issue short quarterly progress reports. Future tasks and a timeline for the watershed study are addressed in the previous section. Future tasks for the regional hydrogeology study include:

- Geologic mapping – All geologic mapping and compilation has been completed in the southern Sacramento Mountains. We are currently revising the regional cross-sections and working on cartographic layout work of the final map, which will be released with this Open File Report in 2010.
- Structure contour mapping – We will extend the structure contour mapping to the Bonney Canyon member – Rio Bonito member contact within the San Andres Formation, to provide a structural datum for the eastern portion of the study area.
- Joint analyses – We will continue analyses to assess the relationship between regional fracture systems and ground water flow characteristics.
- Subsurface geologic analysis – Construction of fence diagrams using surface geology and well records to identify stratigraphic units and water-bearing zones within the Yeso Formation.
- Spring watershed analysis – We will investigate local watersheds associated with sampled springs to identify possible zones of surface water – ground water "recycling" and to quantify this process.
- Age dating analysis – We will improve our interpretations of processes affecting age estimates so that we can better constrain residence times and/or ground water age within the study area.
- Quantification of recharge – We will use different methods of estimating the amount of precipitation that recharges the ground water system in the high mountain aquifer system.

PROJECT PERSONNEL AND ACKNOWLEDGEMENTS

Aquifer Mapping Program Manager

Peggy S. Johnson, M.S. Associate Director hydrogeologic programs, senior hydrogeologist and principal investigator, NMBGMR, peggy@gis.nmt.edu
Tasks: Project development and management, technical oversight, technical report.

Project Personnel

B. Talon Newton, M.S. Project hydrogeologist, NMBGMR, talon@gis.nmt.edu
Tasks: Task manager watershed studies, data collection, stable isotopes, hydrogeochemistry, data interpretation, technical report.

Frederick Partey, Ph.D., Geochemist, NMBGMR, parteyfk@nmt.edu
Tasks: Geochemical sample analysis, water chemistry data interpretation, technical report.

Geoffrey C. Rawling, Ph.D., Field geologist, NMBGMR, geoff@gis.nmt.edu
Tasks: Task manager geologic mapping, hydrologic data collection, map and data compilation and interpretation, technical report, public outreach

J. Michael Timmons, Ph.D., Manager Geologic Mapping Program, NMBGMR, mtimmons@gis.nmt.edu
Tasks: Project development and management, data compilation and interpretation, geologic mapping, technical report.

Stacy Timmons, M.S., Senior geologic research associate, NMBGMR, stacyt@gis.nmt.edu
Tasks: Site inventory and network data maintenance, water level measurements, water quality sampling, data compilation and interpretation, technical report, public outreach.

Support Personnel

Brigitte Felix, GIS Specialist/Geologic illustrator, NMBGMR, bfk@gis.nmt.edu
Tasks: ARC GIS, cartography, drafting, report design, layout and production.

Sam Fernald, Ph.D., Assistant Professor of Watershed Management, NM State University, fernald@nmsu.edu
Tasks: Technical assistance on watershed study.

Bonnie Frey, M.S., Chemistry Lab Manager / Geochemist, NMBGMR, bfrey@nmt.edu
Tasks: Geochemical sample analysis, hydrologic data collection.

Trevor Kludt, Ph.D., Hydrogeologic lab associate, NMBGMR, tkludt@nmt.edu
Tasks: Field instrumentation and monitoring, data collection, map and data compilation, data analysis, ARC GIS, cartography.

Lewis Land, Ph.D., Cave and karst hydrogeologist, NMBGMR, lland@gis.nmt.edu
Tasks: Karst hydrology, water chemistry sampling, hydrogeochemistry and environmental tracers, data interpretation, technical report.

Shannon Williams, B.S., Lab associate, NMBGMR, swilliams@gis.nmt.edu
Tasks: Assistance with hydrologic data collection.

Geologic Mappers

Bruce Allen, Ph.D., Field geologist, NMBGMR, allenb@gis.nmt.edu
Tasks: Geologic mapping and data compilation.

Shari Kelley, Ph.D., Field geologist, NMBGMR, sakelley@ix.netcom.com
Tasks: Geologic mapping and data compilation.

Dan Koning, M.S., Field geologist, NMBGMR, dkoning@nmt.edu
Tasks: Geologic mapping and data compilation.

Students

David Burkhard, New Mexico Tech B.S. student,
Tasks: Field and laboratory assistance.

Robin Lynch, New Mexico Tech B.S. student,
Tasks: Field and laboratory assistance.

Jeremiah Morse, New Mexico Tech M.S. student
Tasks: hydrology sampling and studies related to M.S. degree.

Hector Ramirez, M.S., Ph.D. student, New Mexico State University
Tasks: Assistance and data collection for watershed studies.

Other

Patrick Walsh, M.S., Subsurface fluids geologist, NMBGMR
Tasks: Geologic mapping and lineament analysis, ground water hydrology, surface water/ground water interaction, technical report.

Lewis Gillard, GIS technician, NMBGMR
Tasks: ARC GIS; cartography.

Contractors

Ben Hallet, M.S., University of Idaho
Giovanni Romero, M.S., NM State University
Amy Luther, M.S., University of New Mexico
Colin Shaw, Ph.D., University of New Mexico
Jedidiah Frechette, M.S., University of NM
Kate Zeigler, Ph.D., University of New Mexico
Steve Skotnicki, Ph.D., Arizona State University
Katherine Giles, Ph.D., NM State University
Randy Goossen, B.S., Harvey Mudd College

Acknowledgments

This project would not be possible without the kind cooperation of the many residents and land owners of the Sacramento Mountains who have granted access to their property, wells, and springs. Mr. Michael Coleman has granted us permission to conduct the watershed study on his property. Jan Hendrickx, Sungho Hong, Ken Smith, and Anna Szynkiewicz have assisted with analytical work, data analysis and interpretation. Lab analyses and assistance in interpretation were performed at the Stable Isotope Laboratory of New Mexico Tech, the New Mexico Bureau of Geology and Mineral Resources Chemistry Laboratory, the University of Utah Dissolved Gas Service Center, the University of Miami Tritium Laboratory, Indiana University and Beta Analytic Inc.

REFERENCES

Hem, J. D., 1985, Study and Interpretation of the Chemical Characteristics of Natural Water, U. S. Geological Survey Water-Supply Paper 2254, 264 p.

Black, B. A., 1973, Geology of the northern and eastern parts of the Otero platform, Otero and Chavez counties, New Mexico, Ph.D. dissertation University of New Mexico, 158 p.

Childers, A. and Gross, G. W., 1985, The Yeso aquifer of the middle Pecos basin, analysis and interpretation: New Mexico Tech, Geophysical Research Center, Report H-16, 162 p.

Cook, P. G., Plummer, L. N., Solomon, D. K., Buesenberg, E., and Han, L. F., 2006, Effects that can modify apparent CFC age, in Use of chlorofluorocarbons in hydrology: A guidebook: International Atomic Energy Agency, Vienna, p. 31-58.

Davis, P., Wilcox, R., and Gross, G. W., 1979, Spring characteristics of the western Roswell Artesian Basin: New Mexico Water Resources Research Institute Report 116, 93 p.

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

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

Gochis, D. J. Higgins, W.R., 2007,The Path to Improving Predictions of the North American Monsoon: U.S. Clivar, v. 5, no. 1.

Gonfiantini, R., Roche, M. A., Olivry, J.C., Fontes, J. C., and Zuppi, G.M., 2001, The altitude effect on the isotopic composition of tropical rains: Chemical Geology, v. 181, p. 147-167.

Gross, G. W., 1982, Recharge in semiarid mountain environments: New Mexico Water Resources Research Institute Report 153, 36 p.

Gross, G. W. and Hoy, R. N., 1980, A geochemical and hydrological investigation of ground water recharge in the Roswell Basin of New Mexico: Summary of results and updated listing of tritium determinations: New Mexico Water Resources Research Institute Report 122, 141 p.

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 Institute Report 080, 212 p.

Gross, G. W., Davis, P., and Rehfeldt, K. R., 1979, Paul Spring: An investigation of recharge in the Roswell (NM) Artesian Basin: New Mexico Water Resources Research Institute Report 113, 135 p.

Gross, G. W., Hoy, R. N., Duffy, C. J., and Rehfeldt, K. R., 1982, Isotope studies of recharge in the Roswell Basin, in Perry, Jr., E.C. and Montgomery, C.W. (eds.), Isotope Studies of Hydrologic Processes: DeKalb, Northern Illinois University Press, p. 25-33.

Happell, James D., Stephen Opsahl, Zafer Top, and Jeffery P. Chanton, 2006, Apparent CFC and 3H/3He age differences in water from Floridan Aquifer springs, Journal of Hydrology, v. 319, p. 410-426.

Hem, J. D., 1985, Study and Interpretation of theChemical Characteristics of Natural Water, U. S. Geological Survey, Water-Supply Paper 2254, 264 p.

Hoy, R. N. and Gross, G. W., 1982, A baseline study of oxygen 18 and deuterium in the Roswell, New Mexico, ground water basin: New Mexico Water Resources Research Institute Report 144, 94 p.

Jennings, J., 1986, The hydrogeology of the Sacramento Mountains between Cloudcroft and Alamogordo, Otero County, New Mexico: New Mexico Tech, Geophysical Research Center, Report H-17, 123 p.

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

Lawrence, J.R., Gedzelman, S.D., Gamache, J., and Black, M., 2002. Stable Isotope Ratios: Hurricane Olivia: Journal of Atmospheric Chemistry, v.41, p.67-82.

Liebmann, B., Blade, I., Bond, N. A., Gochis, D., Allured, D., and Bates, G. T., 2008, Characteristics of North American Summertime Rainfall with Emphasis on the Monsoon: Journal of Climate v. 21, p.1277-1294

Mazor, E. 2004, Chemical and Isotopic Ground water Hydrology, Third Edition, Marcel Dekker, Inc. Publisher, New York, 453 p.

McLean, J. S., 1970, Saline ground-water resources of the Tularosa Basin, New Mexico: U.S. Dept. of the Interior, Office of Saline Water Research and Development Progress Report 561, 128 p.

McLean, J. S., 1975, Saline ground water in the Tularosa Basin, New Mexico, in Seager, W. R., Clemons, R. E., and Callender, J. F., eds., Las Cruces Country: New Mexico Geological Society, Guidebook 26, p. 237-238.

Moore, S. L., Foord, E. E., and Meyer, G. A., 1988a, Geologic and aeromagnetic map of a part of the Mescalero Apache Indian Reservation, Otero County, New Mexico: U. S. Geological Survey Miscellaneous Investigations Series Map I-1775, scale 1:50,000.

Moore, S. L., Foord, E. E., Meyer, G. A., and Smith, G. W., 1988b, Geological Map of the northwestern part of the Mescalero Apache Indian Reservation, Otero County, New Mexico: U. S. Geological Survey Miscellaneous Investigations Series Map I-1895, scale 1:24,000.

National Weather Service Forecast Office, n.d. a The North American Monsoon. http://www.wrh.noaa.gov/twc/monsoon/monsoon_info.php

National Weather Service Forecast Office, n.d. b Monsoon Inter-annual Variability. http://www.wrh.noaa.gov/twc/monsoon/monsoon_info.php

National Weather Service Climate Prediction Center, 2003, "Reports to the Nation: The North American Monsoon", http://www.cpc.noaa.gov/products/outreach/Report-to-the-Nation- Monsoon_aug04.pdf

National Weather Service Southern Region Headquarters, 2006, Special Feature: The North American Monsoon. http://www.srh.noaa.gov/abq/climate/Monthlyreports/July/nams.htm.

Newton, B. T., Timmons, S. S., Rawling, G. C., Kludt, T., Eastoe, C. J., 2008, The use of Stable Isotopes to Assess Climatic Controls on Ground water Recharge in the Southern Sacramento Mountains, New Mexico. Eos Trans. AGU, 89(53), Fall Meeting, Abstract A23-0303.

Otte, Carel, Jr., 1959, Late Pennsylvanian and Early Permian stratigraphy of the northern Sacramento Mountains, Otero County, New Mexico, New Mexico Bureau of Geology and Mineral Resources, Bulletin 50, 111 pp.

Pasch, R. J. and Kimberlain, T. B.,2008, Tropical Cyclone Report, Hurricane Dolly (AL042008), 20-25 July 2008, National Hurricane Center.

Pray, Lloyd D., 1961, Geology of the Sacramento Mountains escarpment, Otero County, New Mexico, New Mexico Bureau of Geology and Mineral Resources, Bulletin 35, 144 p.

Rabinowitz, D. and Gross, G. W., 1972, Environmental tritium as a hydrometeorologic tool in the Roswell Basin, New Mexico: New Mexico Water Resources Research Institute Report 016, 268 p.

Rabinowitz, D., Gross, G. W, and Holmes, C., 1977, Environmental tritium as a hydrometeorological tool in the Roswell Basin, New Mexico, I, II, III: Journal of Hydrology, v. 32, p. 3-46.

Ritchie, E., Wood, K., White, S., and Gutzler, D.,2006, The Impact of Tropical Cyclone Remnants on the Rainfall of the North American Southwest Region. Paper presented at the 28th Conference on Hurricanes and Tropical Meterology, Orlando, Fl.

Ritchie, E. and Szenasi, D., 2006, The Impact of Tropical Cyclone Remnants on the Rainfall of the North American Southwest Region. Paper presented at the 27th Conference on Hurricanes and Tropical Meterology, Monterey, Ca.

Rehfeldt, K. R. and Gross, G. W., 1981, The carbonate aquifer of the central Roswell Basin: Recharge estimation by numerical modeling: New Mexico Water Resources Research Institute Report 142, 136 p.

Rozanski, K., Araguas, L., and Gonfiantini, R., 1993, Isotopic Patterns in Modern Global Precipitation, in Swart, P. K., Lohmann, K. C., McKenzie, J., Savin, S. (eds.), Climate Change in Continental Isotopic Records: American Geophyxical Union, Geophysical Monograph 78, p.1-36.

Solomon, D. Kip, and Peter G. Cook, 2000, ^{3}H and ^{3}He, in Environmental tracers in subsurface hydrology, editors Peter Cook and Andrew L. Herczeg, p.397-424.

Stensrud, D. J., Gall, R.L., Mullen, S.L., and Howard, K. W., 1995, Model Climatology of the Mexican Monsoon: Journal of Climate v. 8, p.1775-1794.

Wasiolek, M., 1991, The hydrogeology of the Permian Yeso Formation within the upper Rio Hondo Basin and the eastern Mescalero Apache Indian Reservation, Lincoln and Otero Counties, New Mexico, in Barker, J. M., Kues, B. S., Austin, G. S., and Lucas, S. G. (eds.), Geology of the Sierra Blanca, Sacramento, and Capitan Ranges, New Mexico: New Mexico Geological Society, Guidebook 42, p. 343-351.

Wasiolek, M. and Gross, G. W., 1983, Hydrogeology of the upper Rio Peñasco drainage basin between James and Cox Canyons, Otero County, New Mexico: New Mexico Tech, Geophysical Research Center, Report H-13, 122 p.

New Mexico Bureau of Geology and Mineral Resources

A Division of New Mexico Institute of Mining and Technology

Socorro, NM 87801
(575) 835-5490
Fax (575) 835-6333
www.geoinfo.nmt.edu