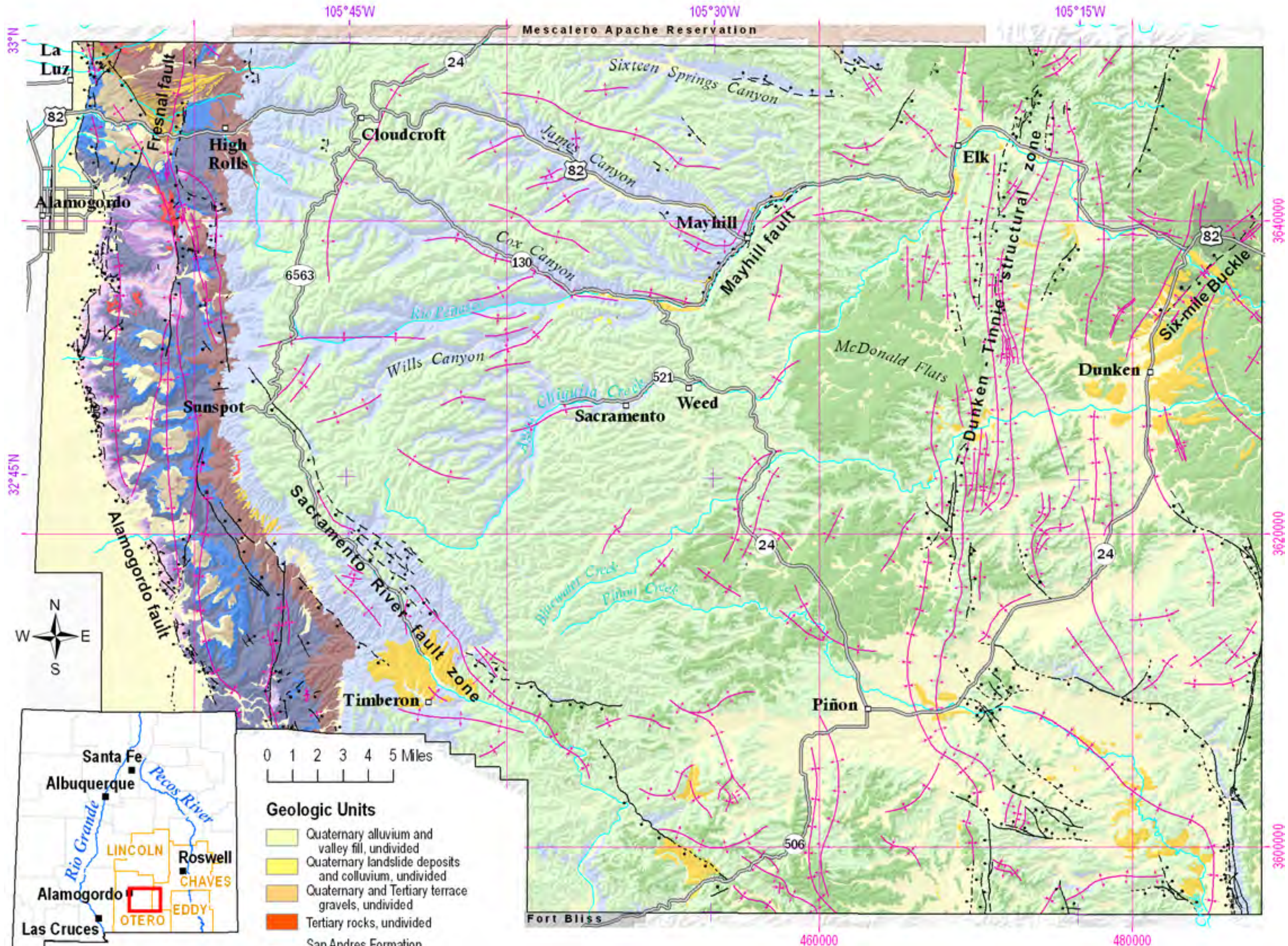
SACRAMENTO MOUNTAINS HYDROGEOLOGY STUDY

AQUIFER MAPPING PROGRAM
New Mexico Bureau of Geology and Mineral Resources

June 2010



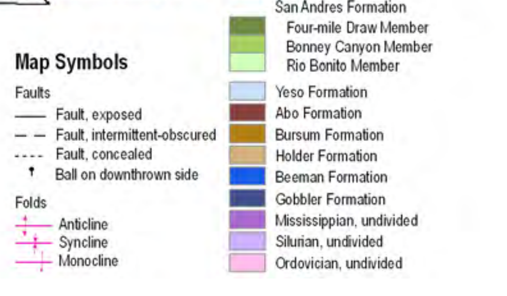


Figure 1—Generalized geologic map of the southern Sacramento Mountains. The geologic formations of interest are the Yeso Formation (pale blue) and members of the San Andres Formation (shades of green). The Yeso Formation is the primary aquifer and is the geologic unit where most recharge takes place, even though it is only exposed along lower valley walls and valley bottoms in the high mountains west of Mayhill.

The high-elevation watersheds in the southern Sacramento Mountains are sources of water for 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 aquifer. This is an overview of the 2005 to 2009 hydrogeologic study in the southern Sacramento Mountains that was initiated by the Otero Soil and Water Conservation District. The goals were to define and characterize the groundwater and surface water systems, determine areas and timing of recharge, and determine the geologic controls on the movement of groundwater and surface water. Our interpretations of data are currently being finalized as we complete our report for this project (New Mexico Bureau of Geology and Mineral Resources Open File Report 518 available at www.geoinfo.nmt.edu).

HYDROGEOLOGY

The main water-bearing units in the southern Sacramento Mountains are the Yeso and San Andres Formations. The Yeso Formation, a highly variable geologic unit composed of siltstone, sandstone, dolomite, and limestone, is the primary aquifer in much of the study area. The main recharge area is west of Mayhill where the Yeso Formation is exposed at the surface. As the Yeso Formation plunges beneath the surface east of Mayhill, recharge to aquifers decreases significantly. Groundwater is stored within the small pores and fractures in the rocks of this formation. The fractures and conduits, particularly within the limestone and dolomite layers, are the primary zones that produce water in springs and wells. Although the rock units may have been deposited as laterally continuous layers, now they are very discontinuous due to faulting, folding, and the dissolution of limestone, dolomite, gypsum, and anhydrite (Figures 2 and 3).

A regional aquifer is a large, laterally extensive geologic unit or group of units that conveys water from a recharge area (usually at higher elevation) to a discharge area (lower elevations). A perched aquifer is smaller in size and is found above and disconnected from a regional system. In the high mountains region of the southern Sacramento Mountains, we do not see a large, regional aquifer in the classic sense. Rather, the aquifer system, with multiple perched aquifers connected by fractures, reflects the discontinuity and heterogeneity of the geologic layers.

The San Andres Formation is more homogeneous than the Yeso Formation, and is composed primarily of gray limestone and dolomite. It is found on ridge tops and upper hill slopes in the high mountain region. It is a dominant water-bearing unit only in the eastern parts of the Pecos Slope region, where it is a regional aquifer.

Figure 4 is a rose diagram that shows two main fracture orientations in the region (NE-SW and NW-SE). Canyons and streams with these same orientations show that these regional fracture systems significantly affect the direction of surface water flow in the high mountains. Statistical analyses suggest that the fracture systems also play a role in controlling groundwater flow associated with the multiple springs found in the high mountains. The presence of a variety of different rock types, in addition to the regional fracture system, significantly affects groundwater flow characteristics (flow direction and velocity) in the high mountains.

Figure 2—Typical example of folding and collapse in the Yeso Formation caused by dissolution of soluble rocks by groundwater over geologic time. This broad fold is found along NM 24 in Cox Canyon, but folds like this are common throughout the Yeso Formation.

Figure 3—Dissolution of soluble rocks by groundwater has caused these Yeso limestone beds to collapse and fracture, forming a chaotic breccia. This photo was taken along Highway 82, just west of Mayhill. This type of feature commonly occurs in the Yeso Formation and can disrupt the flow of groundwater along rock layers.

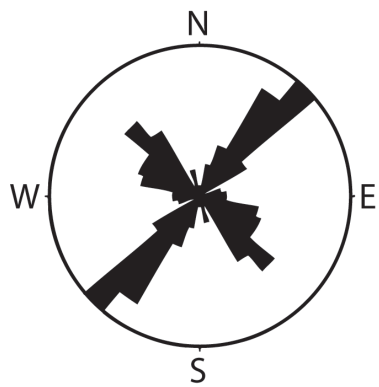


Figure 4—Rose diagram of fracture orientations in the Sacramento Mountains. Rose diagrams are like compasses that graph the orientation of structural features. The two primary fracture orientations are northeast-southwest and northwest-southeast. The length of the black bars is proportional to the number of measured fractures in that orientation. A total of 170 fractures were measured.

GROUNDWATER FLOW CONDITIONS

Aquifer boundaries—We have divided the study area into four aquifer regions (Figure 5). The boundaries are based on topography (surface water drainage basins), spring locations, water level data, geologic contacts, water chemistry, and groundwater age. The boundary between the high mountain aquifer system and the Pecos Slope aquifer is based on water chemistry and flow characteristics. It is also approximately where the Yeso Formation dips below the ground surface. Our interpretations, described below, of the southern Sacramento Mountains groundwater systems are also depicted on the cross section (Figure 6).

Water table map—We have prepared a map of the regional water table surface in the southern Sacramento Mountains based on measurements made in water wells in 2008 and elevations of flowing springs and perennial streams. In general, contours represent average groundwater level elevations. On a regional scale, groundwater flow from the Sacramento Mountains (recharge area) to the Pecos Valley (discharge area) is driven by topography, flowing from high elevations to low elevations, as can be seen in Figure 5. Along this regional flow path, smaller-scale phenomena such as groundwater flow velocity and direction are influenced by the local geology (e.g., rock type, bedding dip, and geologic

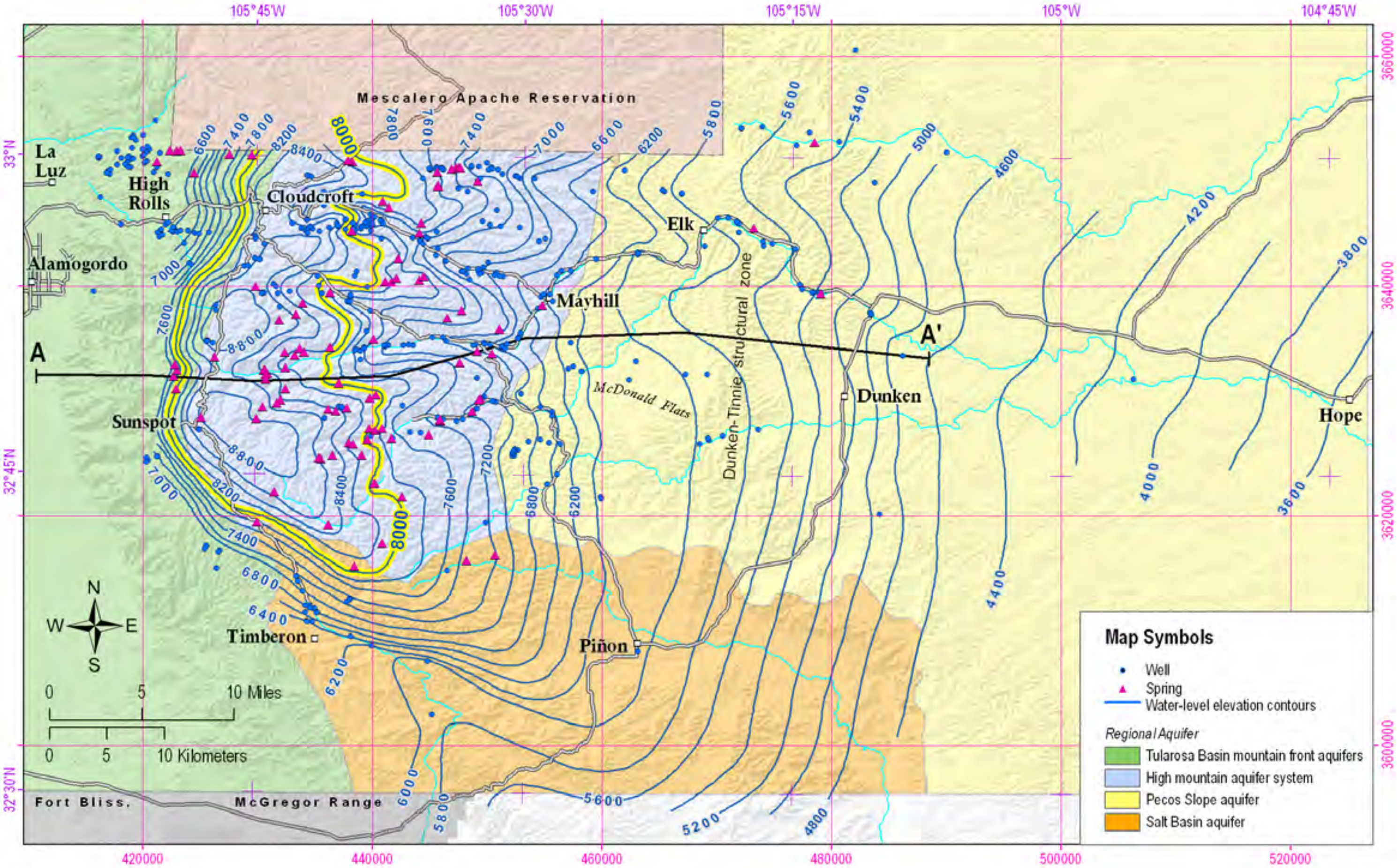


Figure 5—Groundwater elevation contours for the southern Sacramento Mountains. The map represents the approximate surface of the water table on a regional scale. In general, most of the groundwater flows eastward from the crest of the mountains towards the Pecos River Valley. Some water also flows southward into the Salt Basin. Most groundwater recharge occurs within the area of the 8,000 ft water level contour (highlighted). The cross section line for Figure 6 is shown from A to A'.

structures) and by hydrologic characteristics such as porosity, permeability, and aquifer thickness.

Most groundwater recharge occurs near the crest of the Sacramentos (above the 8,000 ft water level elevation contour in Figure 5), where high mountain springs discharge from small, perched aquifers. The hydrology of the high mountain aquifer system is very complex due to the large topographic relief observed in individual canyons and local watersheds, the presence of local and regional fracture systems, and the lateral and vertical distribution of different rock types in the Yeso Formation. Water-bearing zones are distributed throughout the Yeso Formation, and the distinction between perched and regional aquifers is ambiguous and in most cases difficult to determine. Because of these complicating factors, local groundwater flow directions within the high mountain aquifer system may differ from that indicated by the regional water table map (Figure 5). By contrast, within the Pecos Slope and Salt Basin aquifers, the water table is a subdued reflection of the regional topography. Most groundwater flows east toward the Pecos Valley, and southeast toward Otero Mesa and the Salt Basin.

The spacing of the groundwater elevation contours defines the hydraulic gradient, which is the vertical change in water table elevation over a lateral distance. Hydraulic gradients are steepest (contours closer together) along the western escarpment of the Sacramentos. On the eastern flank of the mountains, gradients range from ~150 to 220 feet/mile at higher elevations (high mountain aquifer system). East of Mayhill within the Pecos Slope aquifer, there is a pronounced flattening of the hydraulic gradient (contours are farther apart). This is particularly noticeable across McDonald Flats, where the slope of the water table is less than 48 feet/mile. The flattening of the hydraulic gradient across McDonald Flats is most likely due to the presence of large fractures and conduits, which transmit groundwater easily. Geologic structures such as the Dunken-Tinnie structural zone also influence groundwater flow, causing a local steepening of the hydraulic gradient east of McDonald Flats.

REGIONAL AQUIFERS

High mountain aquifer system—In the high mountain aquifer system perched aquifers associated with the multitude of springs are connected to each other by regional fracture networks and local stream systems. There are many wells and springs in the high mountain region, therefore it is an area where we have abundant data. The primary recharge source in this aquifer system is recent, local precipitation. Stable isotope data for springs and wells suggest that water originates primarily as snow melt and has undergone evaporation in mountain streams. Water discharging from perched aquifers and springs at higher elevations becomes part of the surface water system where it undergoes evaporation, but then recharges another shallow groundwater 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. This "recycling" of surface water and groundwater shows the importance of the connection between these two water systems, but also complicates some interpretations of the age of the water as discussed below.

The chemistry of this aquifer system indicates this water has spent less time in the subsurface than water in adjacent aquifers. As water percolates below the surface and moves through the groundwater system, its chemical signature is modified by dissolving limestone and dolomite in the San Andres and Yeso Formations. Dissolution of these rock types adds small amounts of calcium, magnesium, and bicarbonate to the water. This makes a diamond shaped Stiff diagram that is representative of most water sampled in the high mountain aquifer system (as seen above the cross section, Figure 6).

The relative age of this water compared with that of adjacent aquifers supports the chemistry findings. On average, the water in the high mountains has the most tritium (3.3 TU, from 44 samples), suggesting it is younger water than the surrounding aquifers. This finding suggests that the high mountain aquifer system is the primary recharge area for the Pecos Slope, southern Roswell Artesian Basin, and the Salt Basin.

Because of the recycling of spring water to surface water to groundwater, determination of well-constrained groundwater ages is extremely difficult. When water is exposed to air or fresh precipitation on the surface, or through shallow, open fractures in the rock, many of the commonly used water age-dating "clocks" can be reset or show a mixed age result. Our data suggest that many of the locations within the high mountain aquifer system have a mixture of water that ranges in age from as young as 1–2 years old to greater than 80 years old. A few groundwater ages from samples along faults, such as the Mayhill Fault (Figure 1), indicate the groundwater in this system can be fairly old (greater than 80 years old). These data suggest that some geologic structures permit upwelling of older, deeper water.

Overall, groundwater found in the high mountain aquifer system is fairly young, with extremely variable flow velocities among the different rock types, perched aquifers, fracture networks, and streams. According to fluid and heat flow modeling the maximum potential flow velocity in the high mountains is approximately 10 ft/day. This linear flow velocity estimate is very high for most groundwater systems. However, for fracture flow in a mountainous terrain with large topographic gradients, 10 ft/day is realistic.

Pecos Slope aquifer—The aquifer from approximately Mayhill towards the eastern study boundary is geologically and

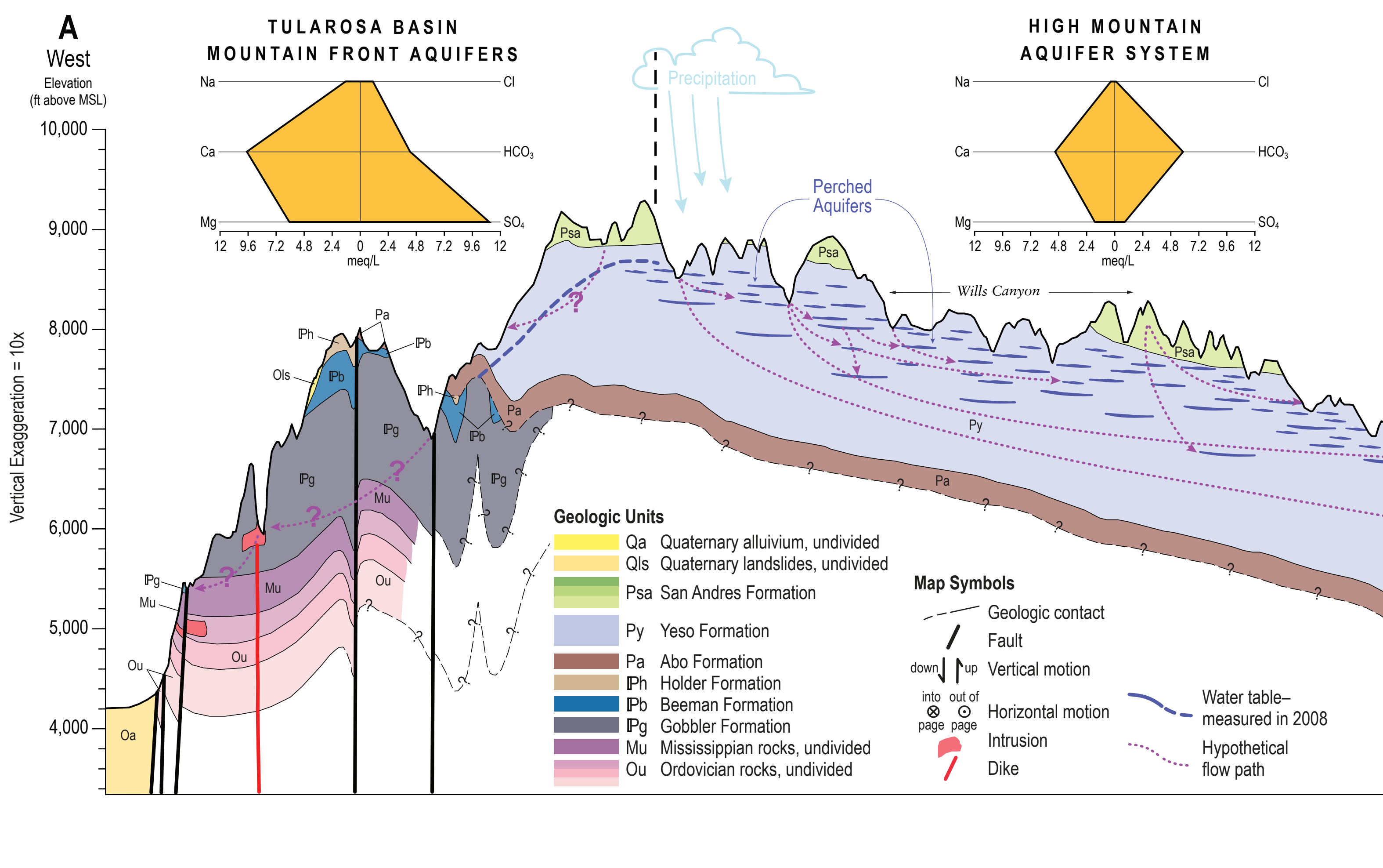


Figure 6—Hydrogeologic cross section. The San Andres and Yeso Formations generally dip eastward, and the groundwater table roughly mimics this pattern. Recharge to groundwater is from precipitation (primarily snow melt). Hypothetical groundwater flow paths (in purple) illustrate recharge occurring in 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 groundwater. It is suspected that faulting in the region may cause vertical upwelling of groundwater from deep flow paths.

topographically simple relative to the high mountain area, although there are several faults and structural zones which may influence the groundwater flow. 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, with very minor additional recharge along drainages, such as the Rio Peñasco.

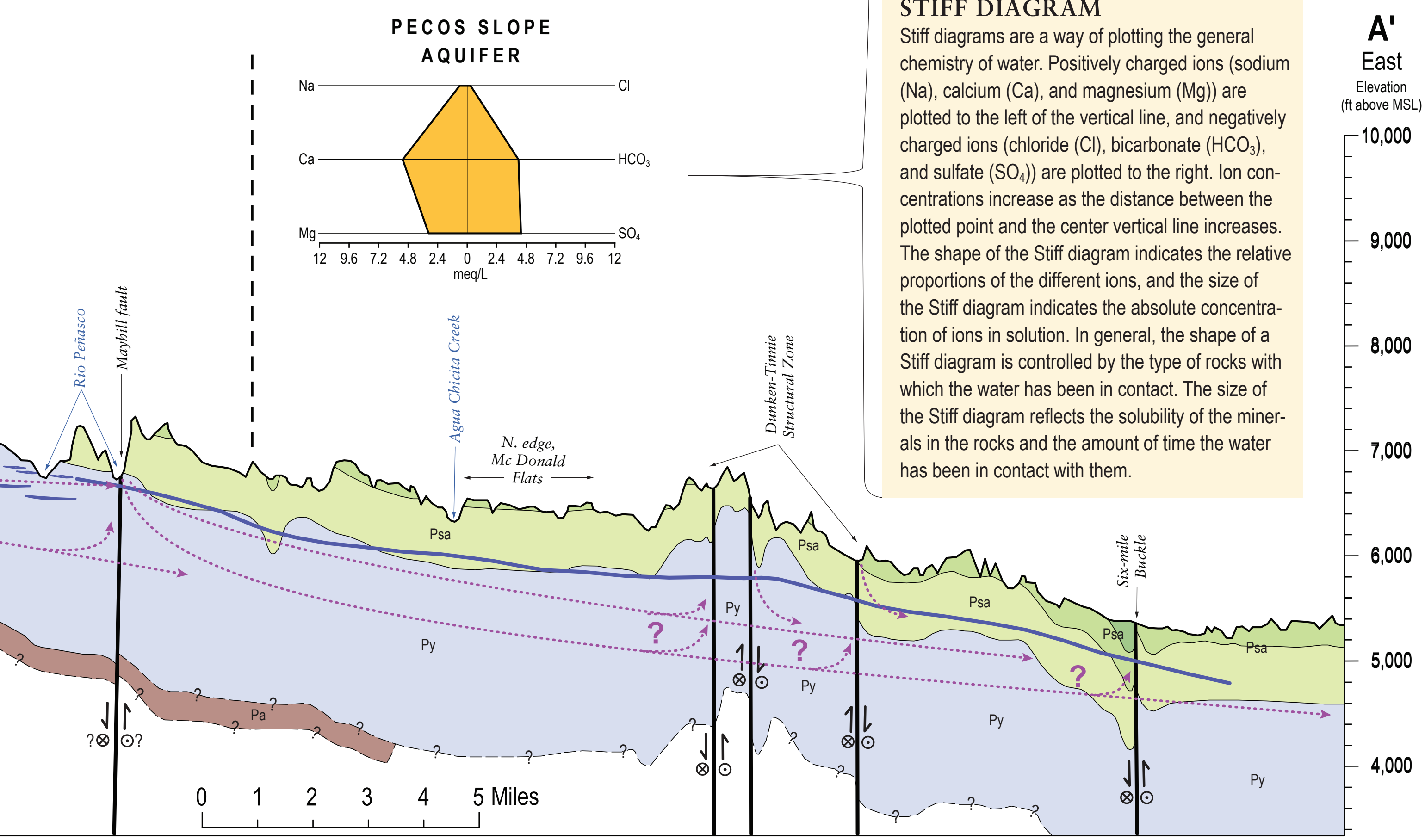
The stable isotope composition of groundwater in this aquifer is fairly constant over a large area and is similar to that of springs and wells sampled at the eastern edge of the high mountain aquifer system. This trend is consistent with the interpretation that recharge to the Pecos Slope aquifer comes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

The chemistry of this aquifer indicates that groundwater has been in the subsurface for a longer time compared to the high mountain aquifer system. The Stiff diagram (Figure 6) shows elevated sodium, magnesium, and sulfate concentrations compared to groundwater in the high mountain aquifer system. The significant increase in sulfate in the Pecos Slope aquifer is a result of groundwater dissolving gypsum in the Yeso Formation. This observed increase in ion concentrations in the groundwater support our interpretation that this water is older. In general, the groundwater found in the Pecos Slope aquifer has had more time to interact with the rocks, which contributes additional ions to the groundwater.

The relative age of groundwater in the Pecos Slope aquifer is also older than groundwater in the high mountain aquifer system, with a low average tritium concentration of 0.95 TU (from 31 samples). Groundwater that has moved from the western boundary of this aquifer to the far eastern boundary of the study area can be upwards of 1,000 years old, with low groundwater flow velocities in the range of 0.06 ft/day (about 6.5 ft/year). We also see evidence of a small amount of young water mixing with this old water in the east, as a result of local recharge from ephemeral streams in the area.

Tularosa Basin mountain front aquifers—The steep west side of the study area has very different geology and hydrologic characteristics than areas east of the range crest. The geology, with rocks that are older than in the high mountains, is complicated by mountain-front parallel faulting, folding, and igneous intrusions (dikes and sills). 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 they do indicate that groundwater has significant chemical differences from the high mountain aquifer system and other areas encountered in this study. The most striking observed difference when comparing average Stiff diagrams is the size (Figure 6). The measured concentrations for most major ions are at least twice that of those measured for the other two aquifer systems. The shape of the Stiff diagram also indicates high sulfate waters, which probably reflects the different rock types that are present in this system.

We do not have enough information to characterize this aquifer system in the same detail as we did for the east side of the mountain range. However, given the complexity of the geology, the groundwater system is unlikely to occur as a laterally continuous single aquifer. Rather, it is probably highly compartmentalized due to faulting and the presence different rock types.



STIFF DIAGRAM

Stiff diagrams are a way of plotting the general chemistry of water. Positively charged ions (sodium (Na), calcium (Ca), and magnesium (Mg)) are plotted to the left of the vertical line, and negatively charged ions (chloride (Cl), bicarbonate (HCO_3), and sulfate (SO_4)) are plotted to the right. Ion concentrations increase as the distance between the plotted point and the center vertical line increases. The shape of the Stiff diagram indicates the relative proportions of the different ions, and the size of the Stiff diagram indicates the absolute concentration of ions in solution. In general, the shape of a Stiff diagram is controlled by the type of rocks with which the water has been in contact. The size of the Stiff diagram reflects the solubility of the minerals in the rocks and the amount of time the water has been in contact with them.

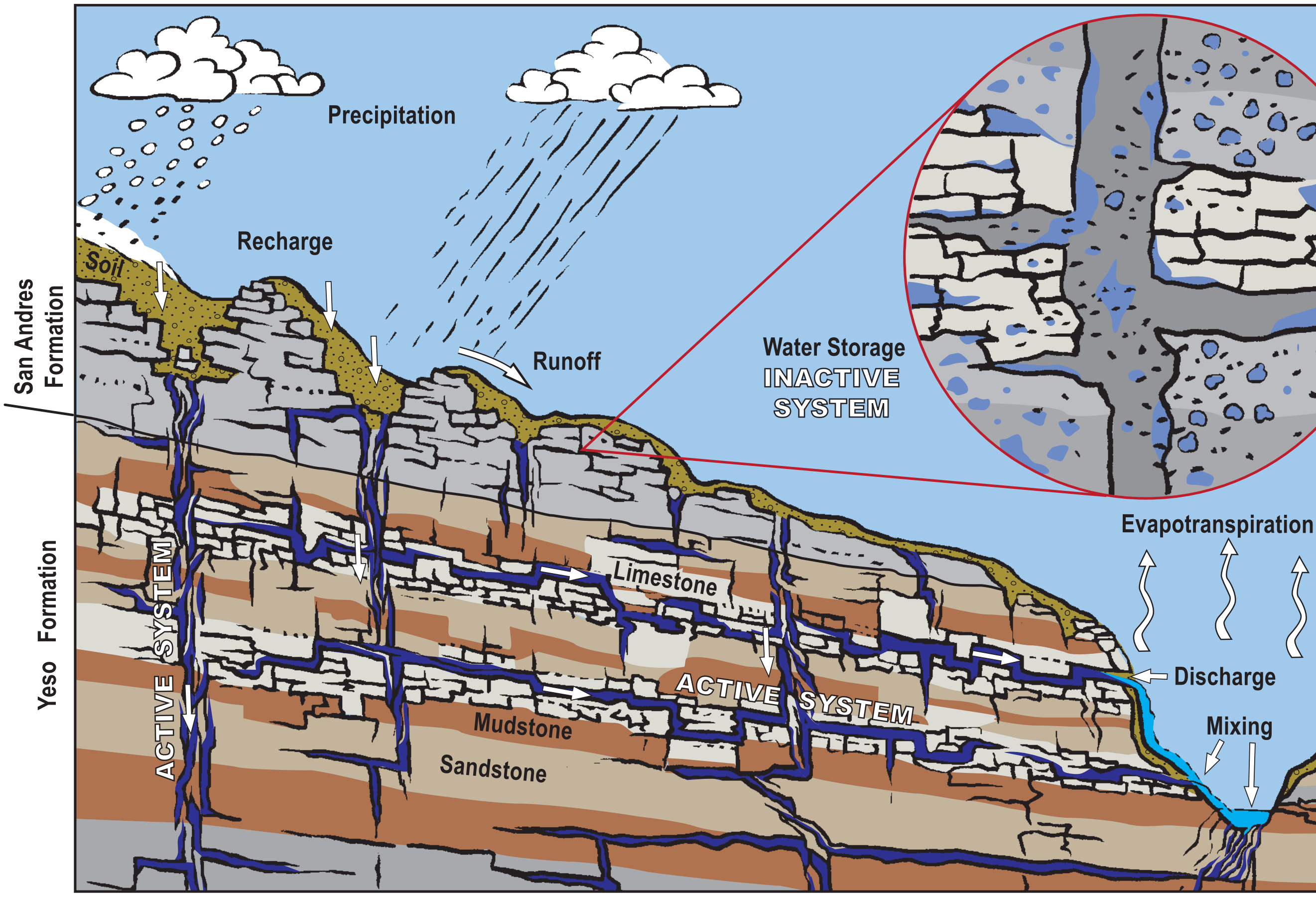


Figure 7—Groundwater storage within rocks. Vertical fracture zones and fractured limestone units make up the active hydrologic system from which most springs and wells produce water (dark blue areas). Fractures connect surface water to the perched limestone aquifers and allow for mixing of recharge from different areas. The inactive hydrologic system consists of saturated and unsaturated zones of low permeability and fractures that are not connected to the active system (depicted in the circle). Water stored in the inactive zone probably interacts and contributes to the active system slowly, except during extreme wet periods (e.g., summers of 2006 and 2008) when inactive waters are quickly flushed into the active system.

Salt Basin aquifer—The Salt Basin aquifer (Figure 5) is defined by the surface water divide where streams begin to flow south and east from the high mountains and Pecos Slope regions. Only a few wells and springs were studied in the northern Salt Basin aquifer, which are not enough to characterize the region. However, it appears that the northern Salt Basin is chemically very similar to the high mountain aquifer system.

RECHARGE AND GROUNDWATER MOVEMENT

Most recharge occurs within the area of the high mountains, largely above the 8,000 ft elevation water level contour (Figure 5). What little recharge occurs outside of the high mountain aquifer system appears to be limited to streambed infiltration along major drainages such as the Rio Peñasco. The amount of groundwater that flows from the high mountain aquifer system to adjacent aquifers depends on the amount of precipitation within the high mountains, the rate at which water leaves the system by evapotranspiration (water evaporated and used by vegetation), the amount of water that can be stored, and the rate at which water moves through the system.

Average annual precipitation in the high Sacramento Mountains ranges from 19 to 29 inches, which is high compared to most other areas in New Mexico. Evapotranspiration is very difficult to estimate, but we are currently attempting this in an ongoing small-scale watershed study discussed below. It should be noted that the presence of shallow perched aquifers throughout the high mountains makes water readily available to vegetation, which may result in high evapotranspiration rates.

The amount of storage and rate at which water moves through the high mountain aquifer system is controlled by the hydrogeology. The combination of regional fracture systems and the different rock types within the Yeso Formation results in the development of areas of high permeability that easily transmit water and areas of low permeability that reduce groundwater flow. Water moves most quickly within the high mountain aquifer system through highly permeable fractured limestone beds that are connected to each other by fractures and the surface water system (active system) (Figure 7). However, groundwater is also present in zones of low permeability and in fractures that are not connected to the active system (inactive system). The inactive system includes water stored in areas that are saturated and unsaturated. Water in this inactive system moves through the system very slowly compared to water in the active system. However, there is probably significantly more water stored in the inactive system than in the active system.

Recharge during "average" years appears to be dominated by snowmelt at the higher elevations, which is redistributed down slope through the active system of shallow groundwater and streams. However, exceptionally wet summers such as 2006 and 2008 (Figure 8), are very important as shown by water level increases in wells (Figure 9), increased spring discharge, and isotopic effects. The various responses to the 2006 and 2008 summer recharge events by each of the different wells (Figure 9) demonstrate the complexity of the hydrogeologic system. A change in the isotopic composition of water in springs and wells associated with summer recharge events in 2006 and 2008 indicates that during unusually wet periods, water in the inactive system may be flushed into the active system. Under more normal climatic conditions, interactions between the active and inactive zones take place at a much slower rate.

We have estimated the amount of recharge that enters the groundwater system using two methods. The first, based on physical interpretation of a hydrograph, estimates recharge from a single storm in a single basin and results in estimates of 1% to 14% of precipitation recharging the groundwater system. This range of values is most likely due to the characteristics of the different storms, such as precipitation amount, and the durations of the individual storms. The second is based on water chemistry and is valid over the whole study area over time scales of several years or more. This method results in estimates of about 2% to 15% of precipitation recharging the groundwater system. This range of values mainly reflects the spatial variability of water chemistry due to the highly variable flow rates in the high mountain aquifer system.

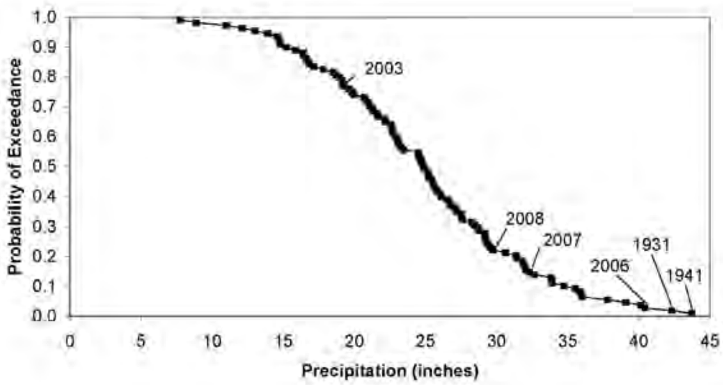


Figure 8a—Probability of exceedance curve for annual precipitation in Cloudcroft (1902–2008) shows the probability of the total annual precipitation exceeding a specific value. Selected years are labeled. This shows that there is a very small probability that the annual precipitation in Cloudcroft will exceed the amount measured (approximately 41 inches) in 2006.

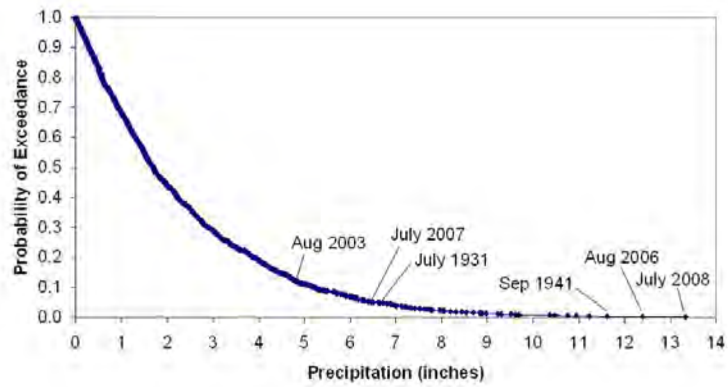


Figure 8b—Probability of exceedance curve for monthly precipitation in Cloudcroft (1902–2008) shows the probability of the total monthly precipitation exceeding a specific value. Selected months are labeled. This plot indicates that the month of July 2008 was the wettest month ever recorded in the Cloudcroft area, with more than 13 inches of precipitation.

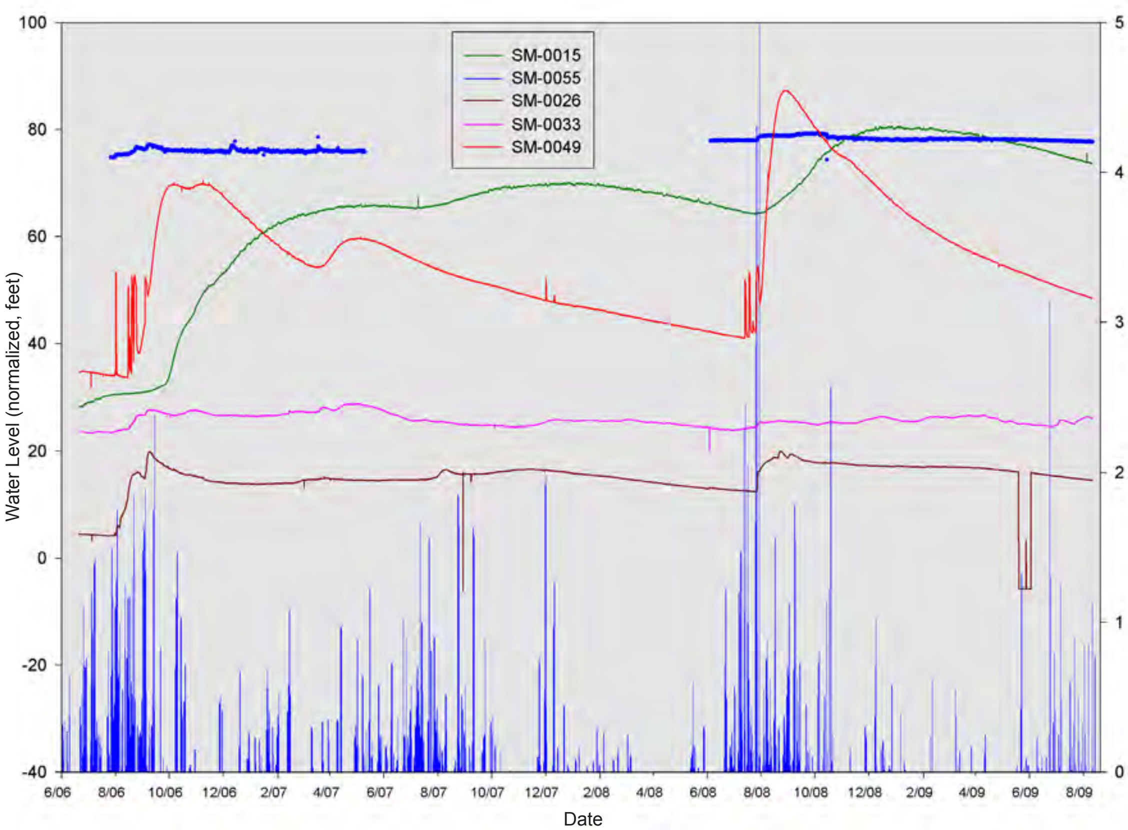
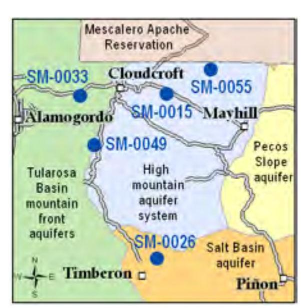


Figure 9—Continuous hydrographs of five different wells (curves) with daily precipitation (bars) from June 2006 to August 2009. The bar graph timeline on the x-axis and right side y-axis show the large precipitation events which occurred in August 2006 and July 2008 (Figure 8). The hydrograph curves illustrate significant, but varied, water level increases and fluctuations in response to the precipitation events. The red hydrograph was used to calculate recharge percentages from individual storm events. It should be noted that 2007 and 2009 monsoon rains did not affect water levels.



SUMMARY

The goals of this study were to delineate areas of groundwater recharge, determine directions and rates of groundwater movement, and better understand the interactions between different aquifers and between the groundwater and surface water systems. Data collected from 2005 to 2009 include geologic mapping, frequent water level measurements in wells, single time and repeated well and spring sampling, precipitation measurement and sampling, fracture orientation measurements, and stream flow measurements. This data collection was initially focused on the high mountain region from Cloudcroft to Mayhill, and south to Timberon. In later years the focus moved to the Pecos Slope region between Mayhill and Hope, and south towards Piñon. The large regional coverage of our hydrogeologic data (approximately 2,400 square miles), in an area with rather complex, heterogeneous geologic units, during a time period with extreme precipitation events and weather conditions, provides a unique and useful dataset to interpret the hydrogeology of this region.

Water level measurements over the study area provide the basis for our water table map compilation, which indicates that groundwater in the southern Sacramento Mountains generally follows topography. Average groundwater elevation contours show that most of the groundwater moves from the crest of the Sacramento Mountains eastward toward the Pecos Slope and southern Roswell Artesian Basin. Some groundwater also flows southward toward the Salt Basin. Through this study, we have defined four major aquifer regions. These include the high mountain aquifer system, the Pecos Slope aquifer, the Salt Basin aquifer, and the Tularosa Basin mountain front aquifers.

Data from spring, well, and precipitation samples, along with water level measurements, suggest that the primary area of recharge for aquifers in and surrounding the southern Sacramento Mountains is in what we have delineated as the high mountain aquifer system. Recharge normally occurs from infiltration of snowmelt or surface water that has undergone some evaporation. Above average summer rains can also supplement recharge to this area, however it is not the dominant water source to this groundwater system, especially during drought years. After precipitation recharges the groundwater in the high mountain aquifer system, it is subsequently recycled through springs and streams.

Groundwater in the high mountain aquifer system is fairly young, fresh water. In some high mountain springs and wells, water that is very recent (less than 1–2 years old) can be found, while further down gradient in the Pecos Slope aquifer, water is much older, by hundreds of years. Our studies indicate that in the high mountains, most water discharging from wells and springs travels relatively quickly through an active system, which is primarily made up of fractured limestone and dolomite. Inactive water is found in pores within the rocks and fractures that are not connected to the active system, and moves much more slowly through the system. Under very wet conditions, such as the summer rains in 2006 and 2008, the large amount of recharge water that is forced through the aquifer system causes some of the inactive, stored water in the rock pores to mix into the active water system. This situation, in addition to the recycling effect, makes it difficult to quantify exact ages of the groundwater in the high mountain region.

Geologic mapping and fracture orientation measurements have highlighted the importance of the fracture network on the connectivity of the groundwater systems and surface water. Because of the extreme heterogeneity and lateral discontinuity in the Yeso Formation, perched groundwater is found at various depths throughout the high mountains region. Multiple perched aquifers are likely connected to each other and to the surface water system via fractures.

This study has found that as little as 1% to as much as 15% of annual precipitation potentially recharges the aquifer system in the high mountains region. The amount of recharge is difficult to determine due to the complex hydrogeology that results in variable flow conditions throughout the study area.

LOCAL ONGOING STUDIES

A watershed-scale study to assess the effects of tree thinning on the local water balance is currently under way. This study is taking place in a watershed (~800 acres) on private land near James Canyon between Cloudcroft and Mayhill. To calculate a water balance, we need to know how much water enters the system and how much water leaves the system. In general, precipitation is the main input. Outputs include evapotranspiration (water used by vegetation), evaporation, and out-flowing groundwater. We are collecting data to quantify these different components of the local water balance. The data we are collecting includes precipitation and climate data, groundwater levels, spring discharge, vegetation type and density, leaf area index, and soil moisture. We have been collecting baseline data over the past 2 years, and will begin to thin trees this year (2010). We plan to continue collecting data over the next 2 years.

Hydrogeologic studies continue in the northern Tularosa Basin from approximately Carrizozo and Nogal south to Alamogordo. A similar, albeit smaller, dataset is being collected for this region including bimonthly and continuous water level measurements, spring and well water sampling, precipitation sampling, and weather monitoring. The goals of this hydrogeologic study are also similar, as we plan to determine locations and timing of recharge, direction and rate of groundwater movement, and examine the connections of different aquifers and surface water systems.

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.

Authors
Talon Newton,
Stacy Timmons,
Geoffrey Rawling,
and Lewis Land

Graphic Design
Brigitte Felix

New Mexico Bureau of
Geology and Mineral Resources

A Division of New Mexico Institute
of Mining and Technology

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

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