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HYDROGEOLOGY OF THE SOUTHERN SACRAMENTO MOUNTAINS, NEW MEXICO

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ABSTRACT—The southern Sacramento Mountains between Cloudcroft and Mayhill are underlain by a complex system of multiple perched aquifers overlying a deeper regional aquifer. This system is characterized by numerous springs that discharge water to streams, followed by reinfiltration downslope. Analysis of multiple environmental tracers reveals mixing of young (mostly 15–25 years) and old (>50 years) groundwater and interactions with surface water. Major ion chemistry evolves largely by the process of dedolomitization, from the range crest east through the Pecos Slope to the Roswell Artesian Basin. Downgradient changes in isotopic composition, evolution of water chemistry, and progressive increase in residence time indicate that recharge is focused at high elevations, largely above ~ 8200 ft (2500 m), and is dominated by winter precipitation. The exceptions are extremely wet summers, such as 2006 and 2008, which produced significant water level rises in high elevation wells, and briefly shift the isotopic composition of groundwater. Such events may induce recharge over larger areas than winter precipitation typically does, but their long-term volumetric significance is unknown. The high elevations of the southern Sacramento Mountains are the primary source of recharge to the Pecos Slope aquifer and the Roswell Artesian Basin.

INTRODUCTION

Numerous small towns in the southern Sacramento Mountains rely on high-elevation watersheds that recharge aquifers and streams. Severe declines in water levels and reduction in stream and spring flow in the early 2000s prompted concern over the viability of local water supplies and recharge to the groundwater basins that surround the mountains (Fig. 1). This paper provides an overview of the results of recent hydrogeologic studies conducted by the New Mexico Bureau of Geology and Mineral Resources in the southern Sacramento Mountains (Land et al., 2012, Newton et al., 2012, Rawling, 2012). The goals of this work were to develop a conceptual model of interactions between aquifers and surface water, delineate areas of groundwater recharge, and determine directions and rates of groundwater movement. Elucidating hydrologic connections between the southern Sacramento Mountains and the Roswell Artesian Basin (RAB) were a particular focus (Fig. 1). The study area encompasses 2400 square miles (6216 km^2) between the western escarpment of the Sacramento Mountains near Alamogordo and the village of Hope, south and southeast of Mescalero Apache tribal lands (Fig. 1). Field methods, analytical procedures, background on geochemical methods, and all data collected during the geologic and hydrologic studies are described in detail in Newton et al. (2012).

Appendix data for this paper can be accessed at:
http://nmgs.nmt.edu/repository/index.cfm?rid=2014001

PREVIOUS WORK

Geology

Meinzer and Hare (1915) and Fiedler and Nye (1933) performed the first geologic and hydrologic studies of the western Sacramento Mountains and Tularosa Basin, and RAB respectively. Geologic maps covering the study area and environs include those of Pray (1961), Sloan and Garber (1971), Kelley

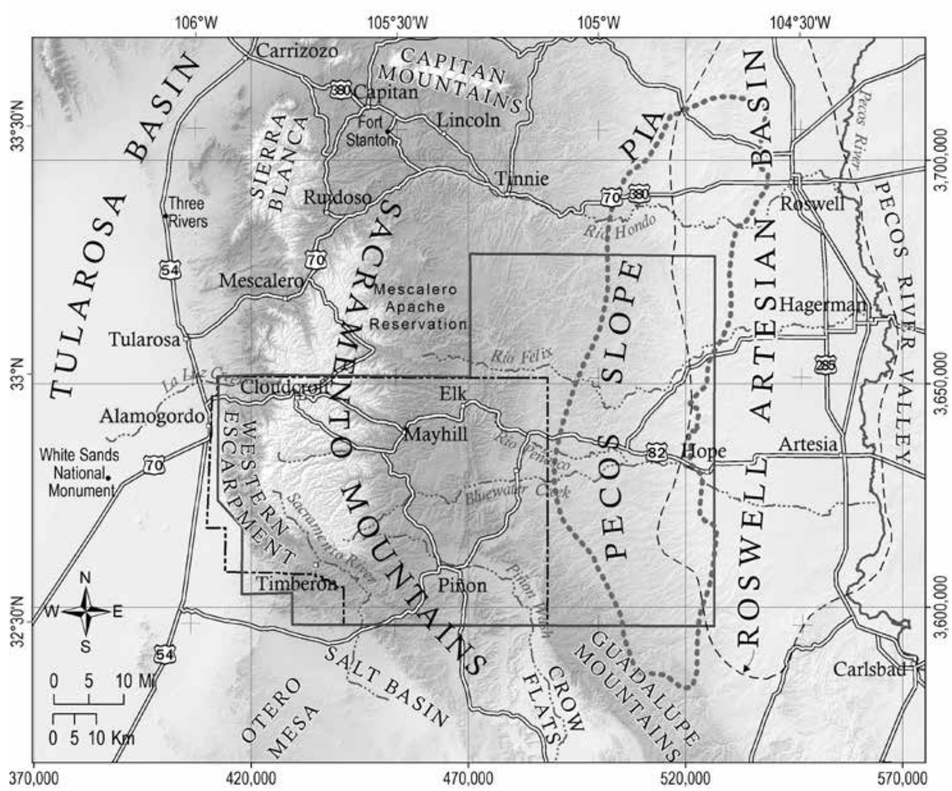

FIGURE 1. Study area outlined on map of the southern Sacramento Mountains and the Pecos Slope (solid black line). The principal intake area (PIA) defined by Fiedler and Nye (1933) is shown with a dotted line. Black dashed-dotted line shows extent of geologic map in Figure 2.

(1971), and Moore et al. (1988a and b). Portions of the maps of Pray (1961) and Black (1973) were incorporated into the geologic map produced for this study (Fig. 2).

Wasiolek and Gross (1983) investigated the Yeso Formation in James and Cox Canyons using logs of domestic water wells. Wasiolek (1991) presented lithologic logs of water wells up to 1200 ft deep in the Yeso Formation on the Mescalero Apache Reservation. Childers and Gross (1985) investigated the geology of the Yeso Formation aquifer on the western Pecos Slope using geophysical and lithologic logs of oil test wells. Walsh (2008) investigated the relationship of fracture orientations and topographic lineaments to the locations of springs.

Hydrology

Early hydrology studies include those of Meinzer and Hare (1915), Fiedler and Nye (1933), and Renick (1926). Hood (1960) reported the first chemical analyses of spring and well waters in the region. Mourant (1963) studied the Rio Hondo basin in the northern Sacramento Mountains.

Fiedler and Nye (1933) argued that most recharge to the RAB artesian aquifer occurs within a belt (the principal intake area, or PIA) on the Pecos Slope a few kilometers west of Roswell (Fig. 1), where the Rios Hondo, Felix, and Peñasco lose water through karst features in the San Andres Formation. They discounted the possibility of significant recharge to the RAB from the underlying Yeso Formation because of presumed low hydraulic conductivity and poor water quality.

Bean (1949) suggested that substantial recharge to the RAB may originate in the foothills of the Sacramento Mountains west of the PIA (Fig. 1). Gerardo Gross, colleagues, and students extensively investigated the hydrology of the artesian aquifer of the RAB and the adjacent Sacramento Mountains (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; Gross, 1985; Childers and Gross, 1985; Simcox and Gross, 1985). They concluded that much of the recharge to the RAB must be subsurface flow from the Yeso Formation, as leakage from losing streams in the PIA could not account for required recharge to the RAB. This was also required by the RAB groundwater model of Daniel B. Stephens and Associates (1995).

More recently, Eastoe and Rodney (2014) used stable isotopes and environmental tracers to investigate recharge in the Sacramento Mountains and adjacent groundwater basins. Their preliminary results were reported in Eastoe and Hibbs (2005), which was referenced in Newton et al. (2012). The results of Eastoe and Rodney (2014) are in agreement with the present work and the related study of Morse (2010) on the Pecos Slope.

METHODS

Field work was performed between 2005 and 2009. Data collection included 1:24,000 scale geologic mapping, measurement of fracture and aerial-photograph lineament orientations (Walsh, 2008), examination of well logs and cuttings, one-time and repeated depth-to-water measurements in wells, and one-time and repeated sampling of wells, springs, streams, and precipitation for major and trace-element chemistry, stable isotopes, and environmental tracers. Sampling methods and analytical procedures and uncertainties are described in Appendix A.

Regional Geology

Across the study area, the exposed rocks are gently east-dipping (2–3°) Permian Yeso and San Andres Formations (Figs. 2, 3). East of the range crest the land slopes more shallowly than the regional dip, thus the Yeso Formation is not exposed east of the longitude of Mayhill (Fig. 2). West of Mayhill, the Yeso Formation forms poor outcrop and is usually covered with colluvium or valley-bottom alluvium. It is composed of gray limestone with minor gray to tan dolomite, gray, buff, and reddish shale, yellow to tan siltstone and fine sandstone, and gypsum. Thickness ranges from 1200 to 1800 ft (365 to 548 m) in the western Sacramento Mountains (Pray, 1961; Kelley, 1971) due to stratigraphic heterogeneity and dissolution of evaporites. Intraformational dissolution-collapse features and chaotic bedding dips are common in outcrop and well-logs.

The overlying San Andres Formation is composed of light to dark gray and bluish-gray limestone and dolomite and contains abundant karst features including large cavernous fractures and sinkholes. It caps ridges west of Mayhill and forms the surface exposures east to Hope (Figs. 1, 2). Kelley (1971) estimated total thickness at 550 to 650 ft (168 to 198 m) based on mapping; results from this study indicate that the total thickness is ~1000 ft (305 m), based on mapping, cross-sections, and subsurface interpretation. Thickness variations of ±200 ft (61 m) are likely across the study area.

Joints are common in both San Andres and Yeso carbonates. Walsh (2008) measured 170 joints at 70 sites and identified two dominant, nearly perpendicular, sets oriented NE-SW and NW-SE. Solution-enlarged conduits are abundant in bedrock pavements exposed in stream channels. Walsh (2008) also documented the influence of regional fracture trends and topographic lineaments on stream valley orientations and spring locations.

HYDROLOGY

Precipitation

Average annual precipitation in the Sacramento Mountains ranges from 26.9 in/yr (68.3 cm/yr) in Cloudcroft (elevation 8810 ft, 2685 m) to 16.5 in/yr (41.9 cm/yr) in Elk (elevation 5710 ft, 1740 m), and is strongly correlated with elevation (Newton et al., 2012). About half of the yearly total occurs during the summer monsoon (July - September), usually as thunderstorms. Winter is the driest period, and April is typically the driest month (Malm, 2003). Tropical storms from the Gulf of Mexico or eastern Pacific can contribute 25% to 30% of seasonal rainfall totals (National Weather Service Climate Prediction

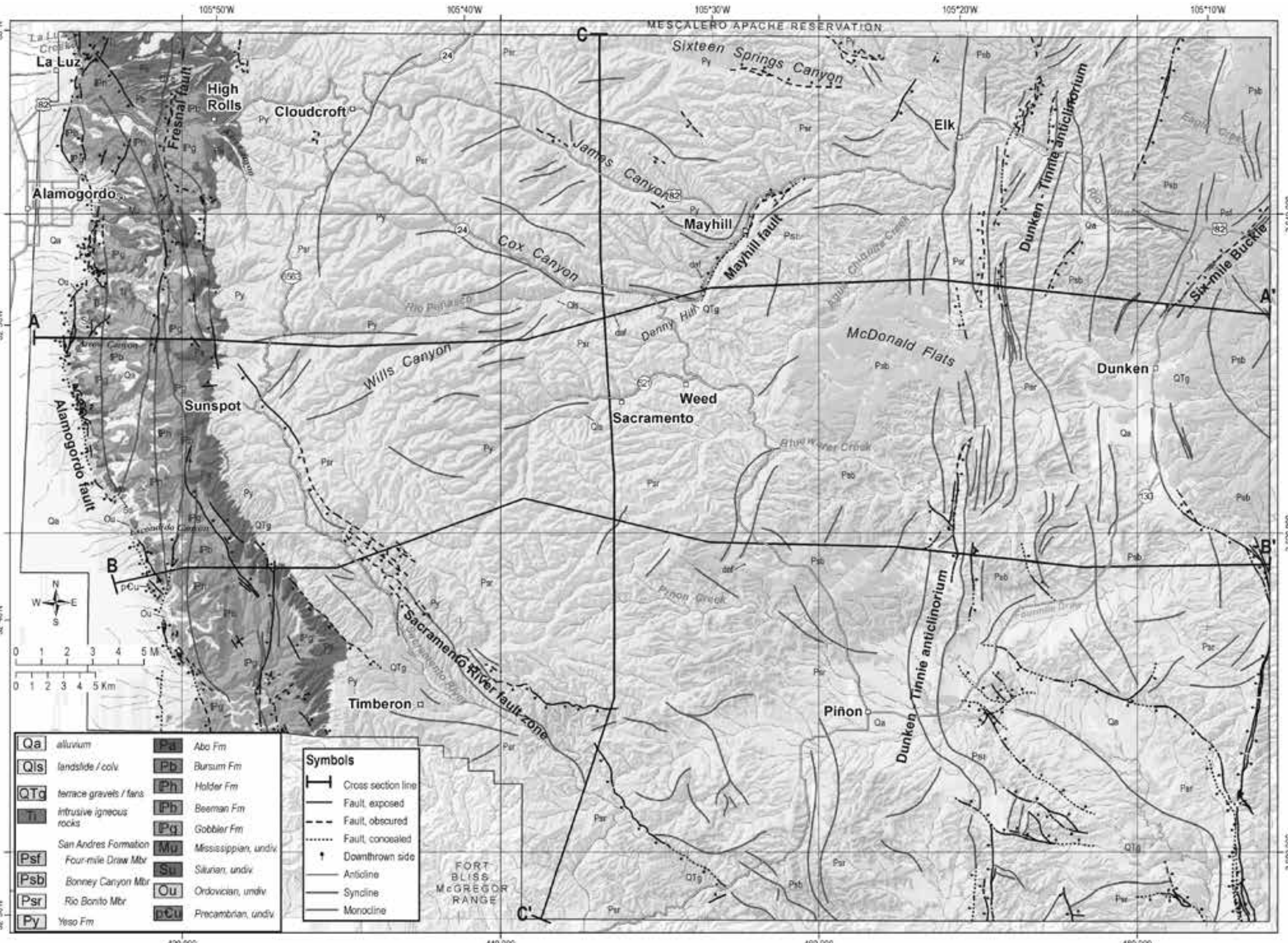

FIGURE 2. Geologic map of a portion of the study area. Simplified from Rawling (2012).

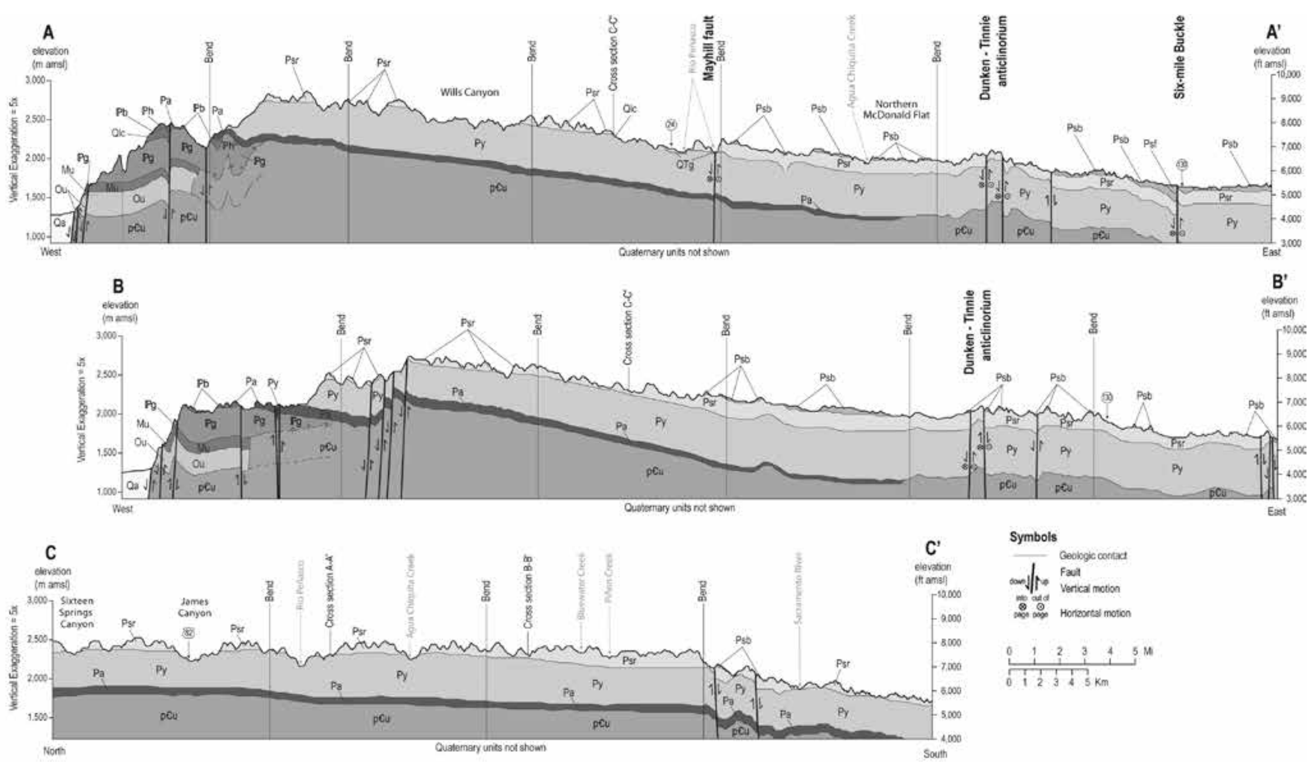

FIGURE 3. Geologic cross-sections; locations shown on Figure 2. (See also Color Plate 12 and 13)

Center, 2003; Ritchie et al., 2008). Significantly above-average summer precipitation occurred in 2006 and 2008 due to an exceptional monsoon season and the remnants of Hurricane Dolly, respectively (Pasch and Kimberlain, 2009). Prior to these years comparable summer precipitation, in terms of magnitude and fraction of the annual total, had not been seen since 1989 (Western Regional Climate Center, 2014).

Springs

Approximately 80% of the 93 inventoried springs lie above 7400 ft elevation (2255 m). Most discharge from fractured limestone beds overlying less permeable red mudstones in the upper 200–230 ft (60–70 meters) of the Yeso Formation. Springs are preferentially located along stream reaches parallel to the NE-SW and NW-SE regional fracture trends (Walsh, 2008). Many springs are located on large mounds, and are actively depositing calcareous tufa (Fig 4).

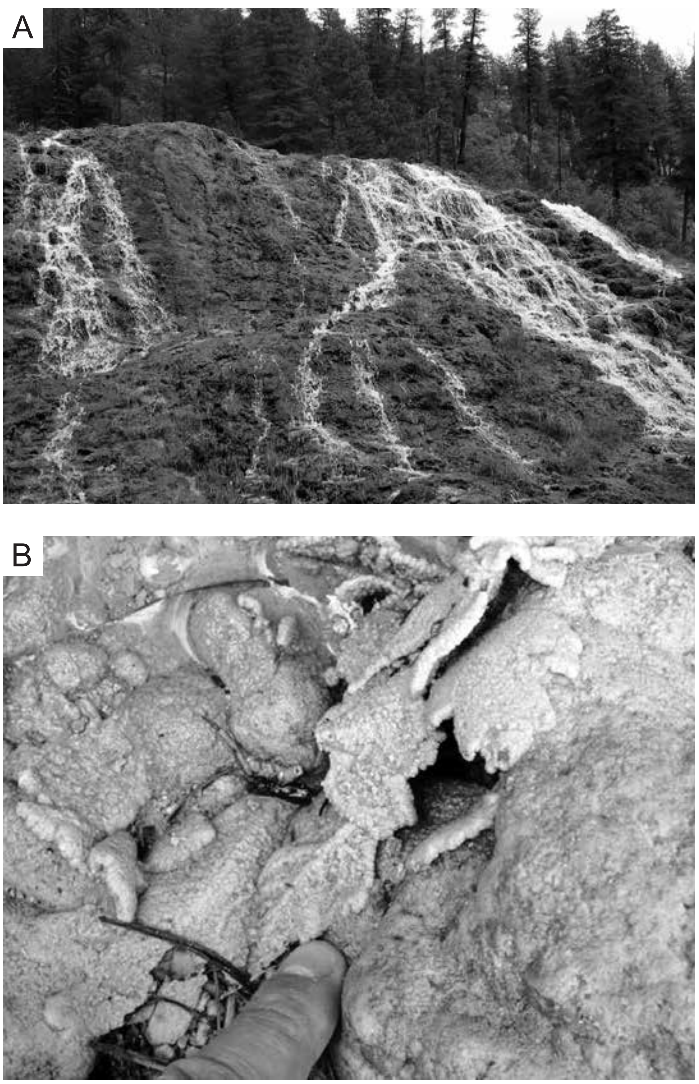

FIGURE 4. A. Large tufa mound at Monument Spring near Timberon. Mound is several meters high. B. Active precipitation of tufa on vegetation near a spring in Scott Able Canyon.

Streams

Perennial flow in streams usually only exists over short distances before infiltration to the shallow groundwater system. Small wetlands are common in the flat sections of stream valleys, especially around springs and at the heads of perennial reaches. These wetlands can evaporate more water than steeper, flowing stream channels because they have much larger surface area.

Groundwater

Based on well logs and spring locations, the Yeso Formation is the primary source of groundwater west of Mayhill (Figs. 1, 5). The water-producing intervals in most wells are either fractured limestone or collapse breccias. Wells in the Pecos Slope (Figs. 1, 5) are completed in both the Yeso and San Andres Formations. Here only the lowest San Andres formation is saturated, and is characterized by dissolution-enhanced fractures and conduits.

Water level elevations were hand-contoured based on well measurements (2005 to 2009), spring elevations, and perennial stream reaches (Fig. 5; Land et al., 2012). Perched and regional aquifers exist, but were not distinguished in contouring this regional-scale map. Water-level elevations mostly mimic topography (Fig. 5). Gradients are steepest, at 500 ft/mi (0.09), or about 5 degrees, along the western escarpment of the range, reflecting the topography. Between the range crest and Mayhill gradients are 150 to 220 ft/mi (0.03 to 0.04), and flatten to less than 50 ft/mi (0.009) near Hope. Stratigraphic dip is steeper than hydraulic gradients across much of the Pecos Slope, and the water table rises into the San Andres Formation there. The lowest gradients reflect topography and areas where groundwater flows through high-transmissivity limestone in the San Andres Formation (e.g., McDonald Flats, an area of known sinkholes).

Hydrographs

Continuous, monthly, and bimonthly hydrographs are plotted with daily precipitation in Figures 6A and B. The extremely wet summers of 2006 and 2008 correlate with significant water level rises, as did the winter of 2006–07 to a lesser degree (wells SM-22 and 49, Fig. 6A). Repeated precipitation rates on the order of 2 inches/day (5 cm/day) appear to be required to induce water level rises. In 2007, mild summer monsoon seasons did not have a significant effect on groundwater levels. Two trends are present: most wells with short-term response (STR) are less than 300 ft (91.4 m) deep and are located above 8000 ft (2438 m). Hydrographs show rapid rises that correlate with summer precipitation events during 2006 and 2008, and peak within one to three months (Fig. 6A). The falling limbs exhibit progressively declining slopes. Long-term response (LTR) wells are mostly greater than 300 ft (91.4 m) deep. Hydrographs show rises starting in late summer and fall 2006 that leveled off before increasing again during summer 2008. Water levels remained high at the end of monitoring in August 2009 (Fig. 6B).

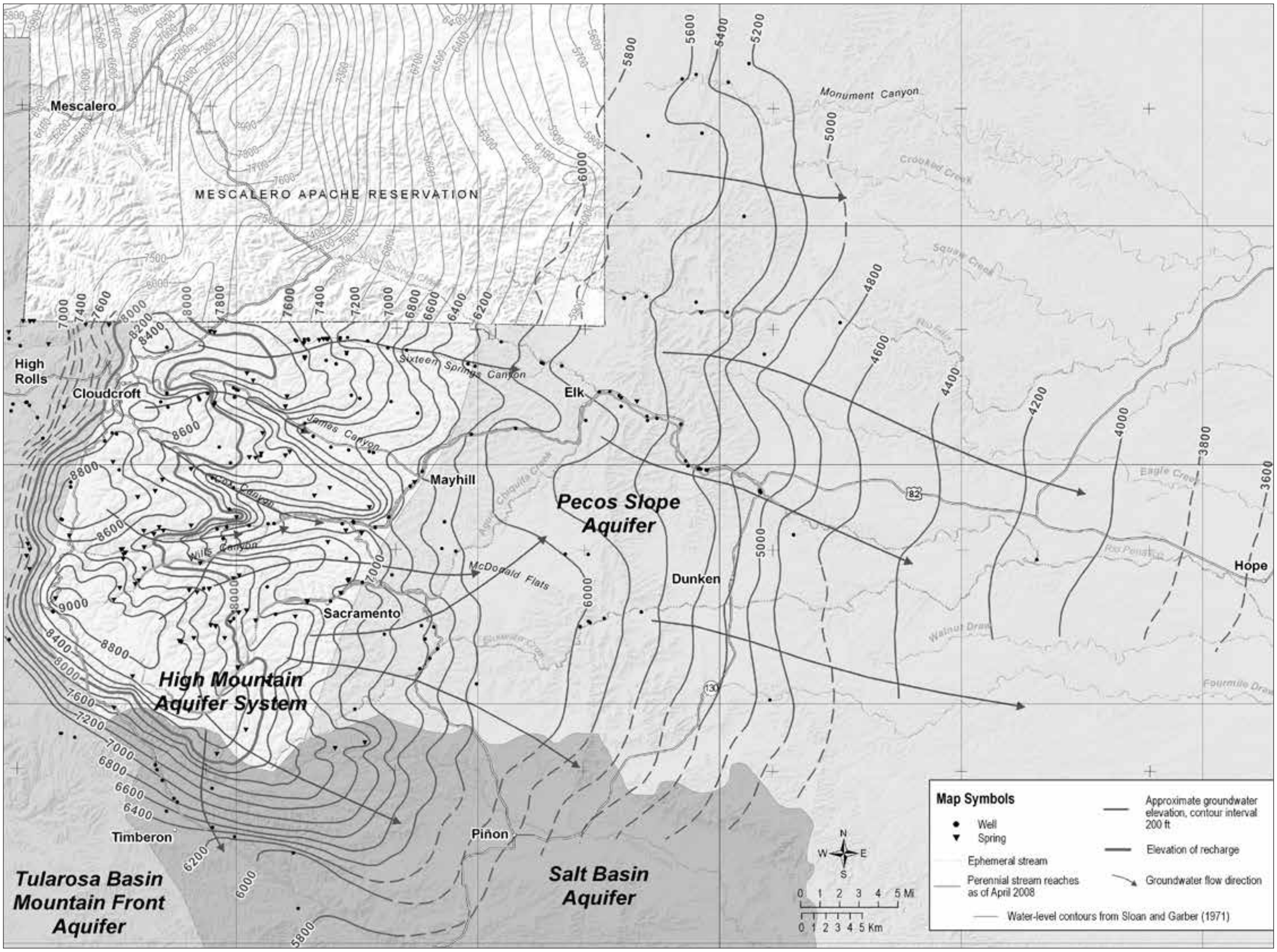

FIGURE 5. Water level elevation map of the study area with data sources (wells, springs, stream reaches), and extent of regional aquifers. Water levels are in feet above mean sea level. Data within the Mescalero Reservation are from Sloan and Garber (1971). 8000 ft (2438 m) water level contour (~ 8200 ft, 2500 m, surface elevation) bounds the predominant area of recharge (see text for discussion).

Rapid water-level rises, followed by progressively declining recessions (Fig. 6A), are common in spring hydrographs from karst aquifers, and reflect rapid infiltration and recharge through fractures and dissolution-enlarged conduits (Ford and Williams, 1989). The recession occurs when recharge becomes negligible, and indicates slow drainage from a saturated porous matrix into conduits and fractures. Hydrologically, the Yeso Formation can be idealized as consisting of three components with decreasing permeability, as follows: fractured carbonate beds, unfractured carbonate beds and/or siltstone, and mixed, thin-bedded carbonates ± siltstones, all with an original horizontally layered structure frequently disrupted by development of collapse breccias. Where fractures and conduits in the carbonate beds dominate the hydrology of the formation, well hydrographs resemble those of "classic" karst aquifers.

High water-levels persist following the rises in LTR wells (Fig. 6B), and are interpreted to represent conditions at deeper aquifer levels than the STR wells. LTR hydrographs in general are quite similar throughout the highlands west of Mayhill, suggesting regional hydraulic connections.

Hydrogeologic framework

Four regional aquifers or aquifer systems in the study area were identified based on drainage divides, geology, hydrogeologic character, depth to water, the regional water table surface, and hydrograph behavior (Newton et al., 2012; Fig. 5). This physical hydrogeologic framework is consistent with geochemical and tracer data, described below. Only the High Mountain aquifer system and Pecos Slope aquifer were investigated in detail in this study.

The High Mountain aquifer system occurs within the Yeso Formation and extends from the range crest to just east of Mayhill (Fig. 5). It is so named because it consists of multiple, discontinuous, shallow and/or perched aquifers (tapped by STR wells), largely in carbonate beds, that overlie a deeper, more continuous,

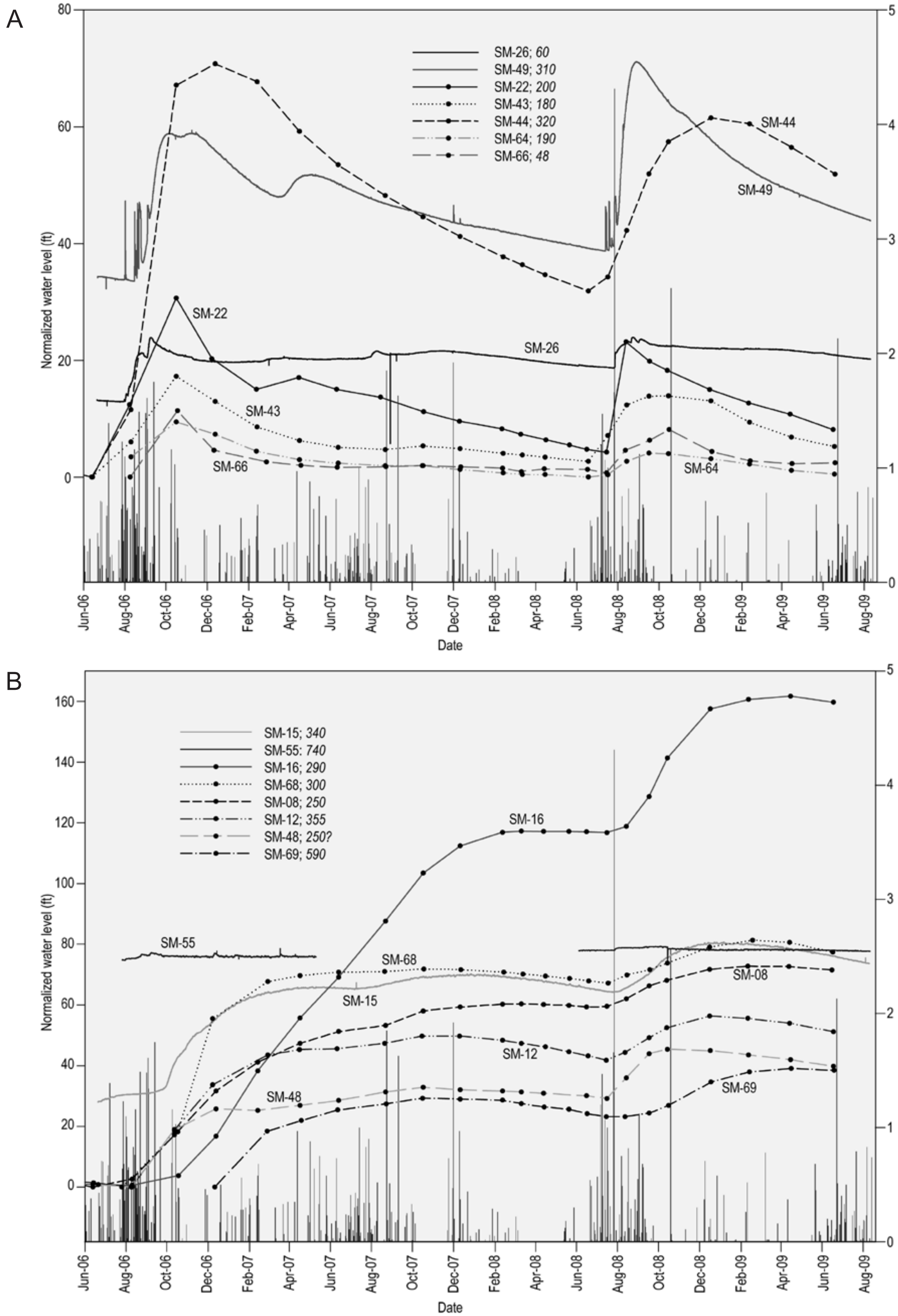

FIGURE 6. Representative hydrographs of wells in the High Mountain aquifer system, with daily precipitation (vertical bars) at Cloudcroft. Dots indicate monthly or bimonthly measurements, plain solid lines are continuous records. Well depth (feet below ground surface) in italics. A. Short-term response (STR) hydrographs. B. Long-term response (LTR) hydrographs.

regional aquifer (tapped by LTR wells). The shallow aquifers are interconnected by fractures, karst-collapse features, and surface water via springs and losing streams. These perched carbonate aquifers are similar to the "sandwich aquifer" concept of White (1969). They leak downward to a deeper, regional aquifer, which hosts the LTR wells. The system merges laterally with the Pecos Slope and Salt Basin aquifers.

The Pecos Slope aquifer is the regional aquifer beneath its namesake, east of the Mayhill fault. The west boundary ranges from 6300 to 7200 ft (1920–2095 m) in elevation (Figs. 2, 5). Well depth and depth-to-water are generally greater than in the High Mountains, and many wells produce from fractured and cavernous limestone in the San Andres, particularly east of the Dunken-Tinnie anticlinorium (Figs. 2, 5). Locally the lower San Andres Formation is saturated, causing flatter hydraulic gradients due to high transmissivity karst features, but the Yeso Formation is still the primary water-bearing formation. The Pecos Slope aquifer merges to the east with the confined San Andres Formation aquifer in the RAB.

WATER CHEMISTRY

Chemical and isotopic analyses of precipitation, stream, spring, and well waters provide insight into the flow paths of groundwater, where and how it is recharged, and its residence time in the subsurface. Waters were sampled for a number of analyses including major and trace element chemistry, hydrogen and oxygen isotopic composition, and several naturally occurring environmental tracers which provide estimates of groundwater age. Analysis procedures and uncertainties, sample location maps, and all data are presented in Appendices A, B, and C.

Major ions and water types

Ca, Mg, HCO_3, and SO_4 are the dominant ions in all water samples (Appendix B, Figs. 7, 8). SO_4 and Mg concentrations increase with declining elevation (down-gradient), opposite to HCO_3 (Fig. 7). Ca and Cl show little or no correlation with elevation (Fig. 7). Waters can be grouped into four types, and mapped spatially based on the dominant cations and anions present: (1) Ca-HCO_3, (2) Ca-Mg-HCO_3, (3) Ca-Mg-HCO_3-SO_4, and (4) Ca-Mg-SO_4-HCO_3 (Fig. 8). Type 1 spring and well waters are located near the range crest; water type progresses from type 1 to 4 downgradient to the east to the Pecos Slope.

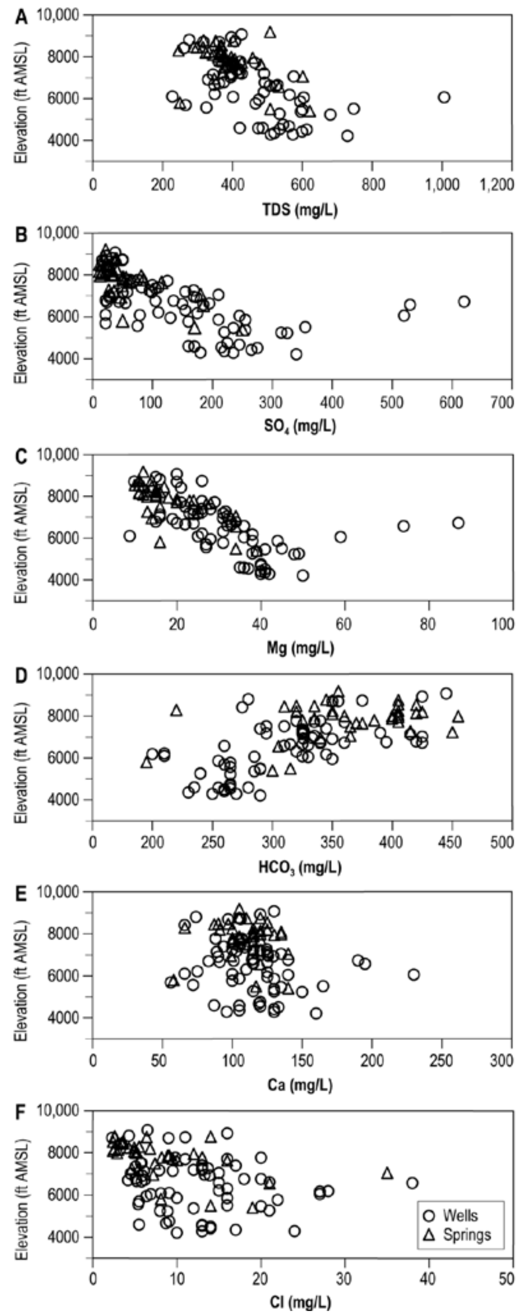

FIGURE 7. Total dissolved solids (TDS) and major ion concentrations plotted against elevation. Elevations decrease down-gradient to the east from the range crest. A. TDS, B. sulfate, C. magnesium, D. bicarbonate, E. calcium, F. chloride.

Stable isotopes of hydrogen and oxygen

Stable isotope data from precipitation samples form winter (October to March) and summer (April to September) fields and define a local meteoric water line (LMWL; Fig. 9). In general, seasonal variability is due to (1) temperature variations, (2) varying intensity of evapotranspiration, and (3) changing source areas of water vapor (Rozanski et al., 1993). Isotopically light precipitation from the remnants of Hurricane Dolly (Pasch and Kimberlain, 2009) is attributed to high condensation efficiency and long storm duration, which produces an extreme rain-out effect (Lawrence et al., 2002). Volume-weighted means of precipitation samples from 2007 plot within the range of summer values (Fig. 9), reflecting the dominance of summer precipitation to the annual total during that year; the variation amongst these is due to the different elevations of the four sampling stations. The Sacramento Mountain Trend (SMT) is a regional evaporation line defined

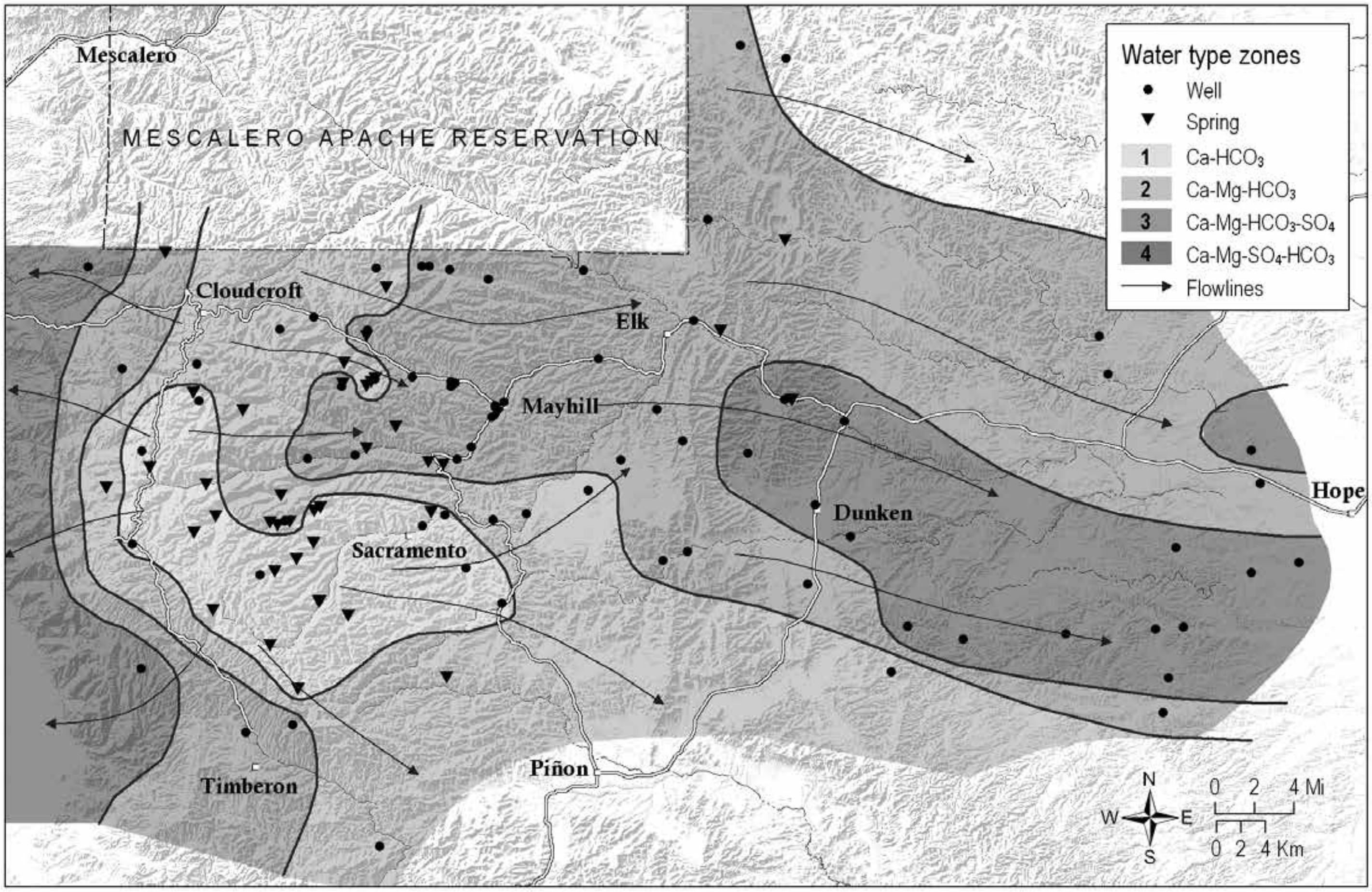

FIGURE 8. Water-type map based on major ion concentrations. Waters evolve from type 1 to type 4 during downgradient flow from the recharge area at the crest of the range.

by Eastoe and Rodney (2014) based on ground and surface water samples collected in 2003 from the Sacramento Mountains, Pecos Slope, and RAB. It projects to the winter field, indicating that winter precipitation is the dominant recharge source during years with average to below-average summer monsoon seasons, which was the case for the years 1997–2003 (Newton et al., 2012; Eastoe and Rodney, 2014, Western Regional Climate Center, 2014).

Stable isotope data for all spring, well and stream samples collected between 2006 and 2009 (with some repeat samples) plot along the SMT or between it and the LMWL (Fig. 10). Newton et al. (2012) discuss temporal isotopic trends in detail, wherein samples collected after the very wet summers of 2006 and 2008 plot closer to the LMWL than those collected at other times, which plot closer to the SMT.

Ratios of D become less depleted from west to east across the High Mountain aquifer system (Fig. 11; the trend is similar for ^{18}O values). Within the Pecos Slope aquifer, D values are similar to those at the eastern boundary of the High Mountain aquifer system (Fig. 11). Waters from High Mountain aquifer system springs plot further along the evaporation line (SMT) with decreasing elevation, indicating progressively greater degrees of evaporation (Fig. 12).

GROUNDWATER AGE AND RESIDENCE TIME

The residence time of groundwater may be inferred by its "isotopic age" determined from environmental tracers, and relates to the time elapsed between groundwater recharge and collection of the sample at a well or spring (Mazor and Nativ, 1992). Geological complexity in the aquifer system, mixing of waters of different ages, and multiple water sources can result in a range of ages and inferred groundwater velocities. Sample location maps and all age data are presented in Appendix B.

Tritium

Tritium (^{3}H) is a short-lived, naturally-occurring radioactive isotope of hydrogen with a half-life of 12.32 years, and is a commonly-used tracer for determining the relative age of groundwater less than fifty years old (Clark and Fritz, 1997). Waters with a concentration of 5 to 15 TU (tritium units; 1 TU indicates a tritium-hydrogen atomic abundance ratio of 10^{-18}) are considered to be modern groundwater, less than 5 – 10 years old. Tritium concentrations of 0.8 to 4 TU probably represent a mixture of recent and sub-modern recharge. Water samples containing less than 0.8 TU are assumed to be sub-modern,

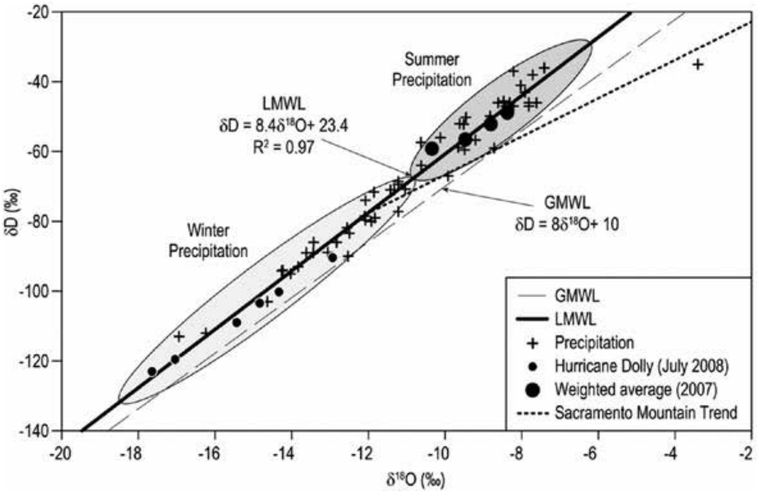

FIGURE 9. Stable isotopic compositions of precipitation collected during this study, and the local meteoric water line (LMWL) so defined. The LMWL differs from the global meteoric water line (GMWL) due to local climatic conditions. The Sacramento Mountain Trend (SMT) is a regional evaporation line determined by Eastoe and Rodney (2014) in 2003. The weighted average of 2007 precipitation (from four precipitation collectors) reflects the predominance of summer precipitation in that year. Hurricane Dolly samples plot in the winter field due to extreme isotopic depletion during heavy rains.

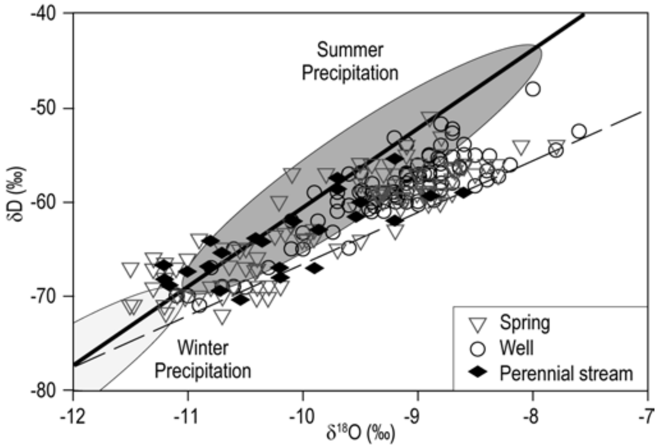

FIGURE 10. Stable isotopic compositions of groundwater and surface water collected during this study between 2006 and 2009, plotted with the LMWL (solid) and the regional evaporation line (SMT, dashed) of Eastoe and Rodney (2014).

recharged prior to 1952 (Clark and Fritz, 1997). Tritium levels in local precipitation range from 3 to 9 TU, reflecting seasonal variations (Eastoe et al., 2012). The highest tritium concentrations in groundwater occur near the range crest (Fig. 13), and decrease from west to east (down gradient and elevation), to less than about 1 TU, on the Pecos Slope (Fig. 13). Wells average 1.6 TU, springs 3.7 TU, implying that wells access deeper, older water than springs. The youngest waters in the Pecos Slope aquifer occur along the margins of the High Mountain aquifer east of Sacramento. Slightly elevated tritium concentrations are also found along the Rio Peñasco. Areas distal to these locations have the lowest tritium concentrations.

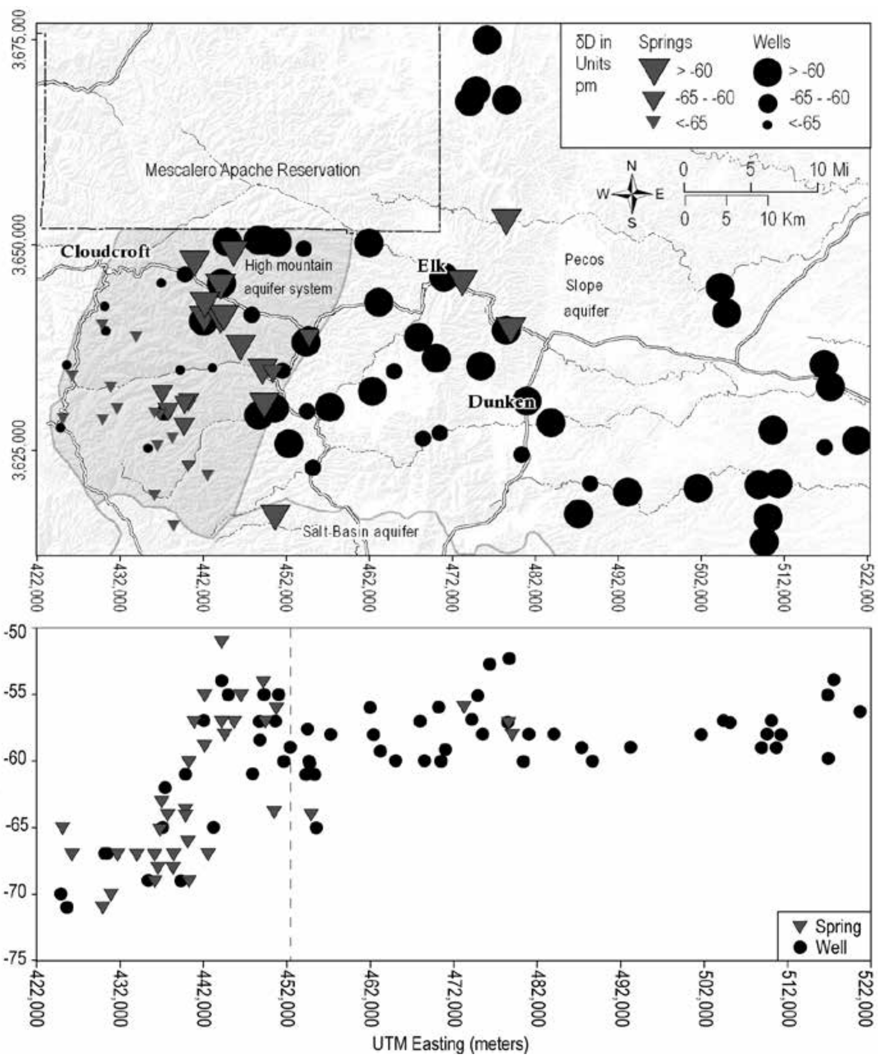

FIGURE 11. Stable isotopic compositions of well and spring waters as a function of easting coordinate. Compositions become less depleted (increase) as elevation decreases downgradient in the High Mountain aquifer system, and change little across the Pecos Slope. The dashed vertical line is the approximate boundary between the High Mountain aquifer system (west) and the Pecos Slope aquifer (east).

Tritium-helium

Tritium is subject to radioactive decay by beta emission to yield its daughter product, helium-3 (^3He). By measuring ^3H together with ^3He, a true radiometric

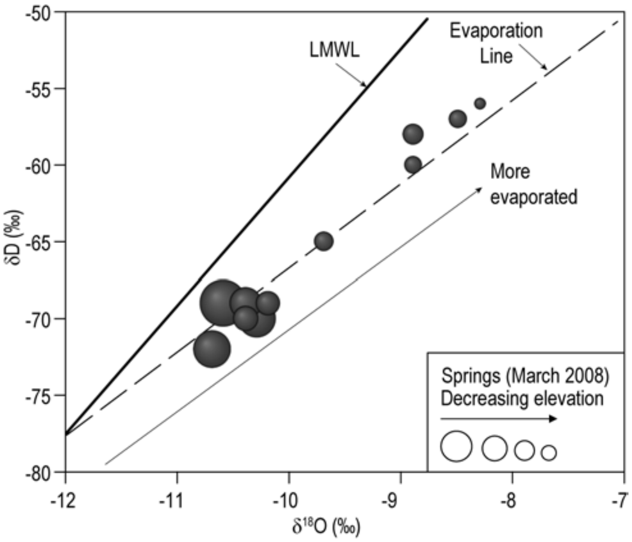

FIGURE 12. Springs sampled in March 2008 show decreasing depletion (increasing δD values) with decreasing elevation. This is due to repeated episodes of evaporation due to groundwater – surface water recycling

groundwater age can be determined (Solomon and Sudicky, 1991; Clark and Fritz, 1997; Kazemi et al., 2006). Other sources of ^3He include radioactive decay of U and Th in the crust, and atmospheric helium. An age greater than 50 years indicates that the true age of the groundwater sample is too old to be determined using this method (Clark and Fritz, 1997; Kazemi et al., 2006). Helium-4 (^4He) is also measured in the analyses and the $^3He/^4He$ ratio may be used to identify mantle-derived ^3He.

Twenty groundwater samples were analyzed with this method, yielding ages from zero (±3 years) to greater than 50 years, and averaging approximately 13 years, with several less than one year old. Well waters with $^3H/^3He$ ages >50 years also had very low tritium concentrations. Most $^3He/^4He$ ratios are low and similar to those of atmospheric gases, rendering contributions of mantle-derived ^3He unlikely. However, low $^3He/^4He$ ratios may result from elevated ^4He levels. ^4He is the most common atmospheric isotope of helium and is also a product of radioactive decay of U and Th. Two wells yielded $^3H/^3He$ ages >50 years and low $^3He/^4He$ ratios, indicating a possible deep crustal source of groundwater (Solomon, 2000). One was along the Mayhill fault and has anomalous warm temperatures and chemistry that is a more evolved water type than other nearby well-water samples.

Chlorofluorocarbons (CFCs)

Chlorofluorocarbons are volatile, synthetic compounds of carbon, chlorine and fluorine that have been used in refrigeration and other industrial applications since the 1930s (Plummer and Busenberg, 2000). The history of their atmospheric concentrations is well-known or has been reconstructed from production/release data. They enter the hydrologic cycle via dissolution in precipitation. Calculation of groundwater age using dissolved CFCs involves comparing measured water concentrations to historical atmospheric concentrations. It requires the elevation and temperature of recharge as inputs; errors in either will produce erroneous ages (Kazemi et al., 2006). In this study, recharge elevations were equated to the sample site elevation, and recharge temperatures were derived from a linear regression developed from noble gas concentrations in eight samples over a range of elevations (Stute and Schlosser, 2000; Newton et al., 2012).

CFC12 ages range from 20 to 64 years, with an average age of 28.4 years, while CFC113 ages average 25.1 years. There are discrepancies of 3 to 10 years between CFC12 and CFC113 ages. Groundwater apparent ages based on CFC113/CFC12 concentration ratios (method of Busenberg and Plummer, 2006) average 21.2 years, younger than those based on CFC12 alone. Such a discrepancy usually implies that mixing of waters of different ages has occurred (Han et al., 2001; Plummer et al., 2006).

If a water sample is a binary mixture of old (CFC-free) and young (CFC-bearing) waters, the CFC ratio age is the age of the younger fraction, and this fraction can be determined (Han et al., 2001; Plummer et al., 2006). The fraction of young water in this study averages 77%. The oldest samples, based on CFC12 apparent age, contain the smallest fraction of young water, indicating that a binary mixing model is valid (Long et al., 2008). The young groundwater components were recharged during the mid-to-late-1980s. The oldest waters include the well along the Mayhill fault with an old (>50 years) $^3H/^3He$ age, and anomalous temperatures and chemistry, and another well along the Dunken-Tinnie anticlinorium. This suggests that old, deep water is rising along these structures.

Carbon-14

Carbon-14 is a naturally-occurring radioactive isotope of carbon that is produced by cosmic radiation. ^{14}C radioactivity of inorganic carbon in water is expressed in units of percent modern carbon (pMC) relative to the abundance of ^{14}C in atmospheric CO_2. Once isolated from atmospheric and soil gases, the abundance of ^{14}C decreases at a rate governed by its half-life of 5730 years.

Waters in the High Mountain aquifer system are saturated with respect to calcite, show elevated levels of percent modern carbon (pMC), and many springs are actively precipitating tufa (Newton et al., 2012). The High Mountain aquifer system is an open system, allowing for re-equilibration between dissolved inorganic carbon and ^{14}C-active soil and atmospheric CO_2, limiting the utility of the ^{14}C age-dating method.

Both Morse (2010), in a companion study to the present work, and Eastoe and Rodney (2014) applied the ^{14}C method on sample traverses across the Pecos Slope, where the aquifer appears to be largely a closed system. Morse (2010) used measured ^{13}C data along with mass-transfer models of the dedolomitization process (Plummer et al., 1990; Back et al., 1983; see discussion below), and Eastoe and Rodney (2014) used assumed ^{13}C values for soil gas and Permian rock, to adjust ^{14}C ages so that they reflect the decrease in pMC values that are only due to radioactive decay. Both studies showed a systematic decrease in pMC ^{14}C from west to east, downgradient across the Pecos Slope. Data from both studies range from ~80% pMC along the west edge of the Pecos Slope aquifer to 50 – 70% pMC between Hope and

Artesia, with groundwater residence times ranging from near zero at the west edge of the Pecos Slope to 1300–5600 years east of Hope (Morse, 2010; Eastoe and Rodney, 2014).

DISCUSSION

Integration of field observations and physical and chemical hydrologic data from this study, together with the work of Morse (2010) and Eastoe and Rodney (2014), allows several important hydrogeologic processes occurring in the study area to be identified. These are discussed below, followed by the implications for groundwater recharge, and a conceptual model of the regional hydrogeology.

Chemical evolution via dedolomitization

The dominance of Ca, Mg, and HCO_3 ions is due to dissolution of limestone and dolomite. Waters in equilibrium with calcite and in the presence of gypsum and dolomite will become saturated with respect to calcite due to the addition of Ca ions from the dissolution of gypsum. As the dissolution of gypsum continues, the common ion effect causes calcite to precipitate, which removes carbonate from the system, and forces the dissolution of dolomite. This process is called dedolomitization and has been well documented in the Madison aquifer in Montana, Wyoming, and South Dakota (Plummer et al., 1990; Back et al., 1983).

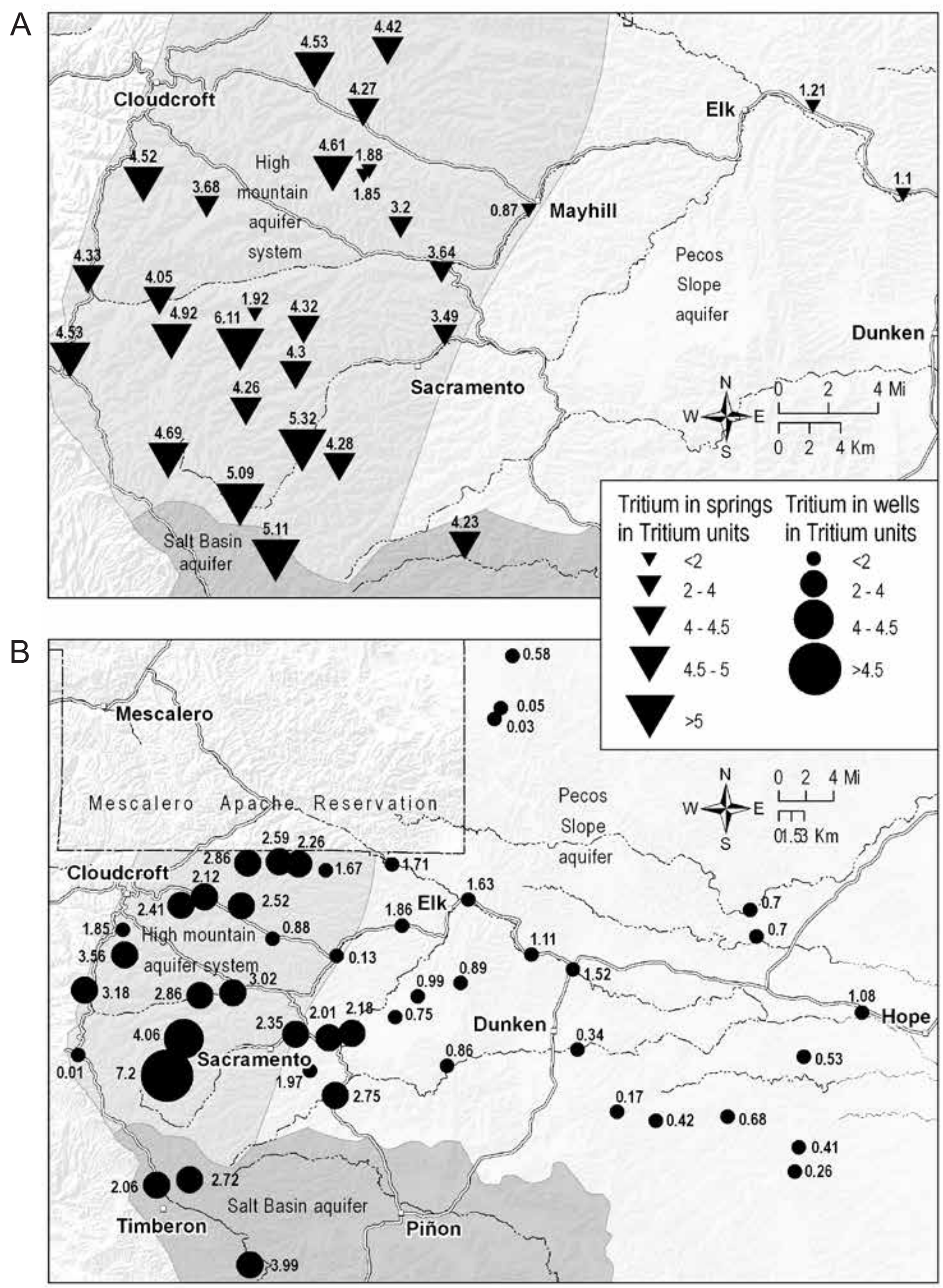

FIGURE 13. Spatial variation of tritium concentrations in A. springs and B. wells. The highest values are located at the crest of the range, in the proposed recharge area within the High Mountain aquifer system.

Downgradient increases in SO_4 and Mg concentrations (Fig. 7) and chemical evolution from Ca-HCO_3 to Ca-Mg-SO_4-HCO_3 type water (Fig. 8) are consistent with most groundwater recharge occurring at high elevations, where interactions with limestone and dolomite control the water chemistry, followed by progressive dedolomitization along the downgradient flow path and little additional recharge. Dedolomitization does not change HCO_3 concentrations, therefore, the down-gradient decrease of HCO_3 (Fig. 7) is likely a result of calcite precipitation driven by increasing water temperatures along deeper, longer flowpaths (Newton et al., 2012). The solubility of calcite decreases as water temperature increases (Hem, 1985).

Groundwater-surface water interactions and recycling

Field observations and isotopic compositions support a process of groundwater-surface water "recycling" in the High Mountain aquifer system. The many springs discharge groundwater, which becomes stream flow, and subsequently reinfiltrates into a shallow aquifer. This process may occur several times in a single canyon as water moves downslope (Newton et al., 2012). Progressively stronger evaporative isotopic signatures with decreasing elevation results from this process, as additional evaporation occurs with each surface exposure (Fig. 12).

Each time groundwater re-emerges from springs, at least partial re-equilibration with the atmosphere occurs, resulting in the CFC and $^3H/^3He$ "clocks" being completely or partially reset due to loss of dissolved gases. However, the tritium content is unaffected, as tritium is part of the water molecule. Recycling of groundwater is indicated by discrepancies between tritium content and $^3H/^3He$ or CFC ages of several samples. One sample, collected from a well adjacent to a spring-fed perennial stream yielded a tritium-helium age of less than one year and a tritium content of 2.72 TU. Land and Huff (2010) invoked such groundwater recycling to account for discrepancies between CFC apparent ages and tritium content in the Roswell Artesian Basin. Earman (2004) identified a similar process in the Chiricahua Mountains in Arizona.

Isotopic compositions change little across the Pecos Slope (Fig. 11), implying that this recycling process is not operative, and that Pecos Slope aquifer is largely a closed system receiving little local recharge. Most groundwater is sourced from the High Mountain aquifer system to the west, which is also suggested by the continuous evolution of the major-ion chemistry (Fig. 8).

Groundwater mixing

The Yeso Formation, with its fractures, conduits, karst-collapse structures, and interlayered clastic and carbonate rocks, facilitates mixing of waters with different ages, and chemical and isotopic compositions. Several mechanisms are operative, including inter-aquifer leakage, merging of multiple flowpaths, and in-stream mixing of spring water discharging from varied depths within the formation. Continuous downgradient trends in chemical and isotopic compositions indicate a continuity of geochemical processes along flowpaths, and that waters in the High Mountain aquifer system are well-mixed.

Most of the CFC data can be explained by binary mixing of "old", CFC-free water (pre-1940 recharge) and >50% younger CFC-bearing water, which is probably 15 to 25 years old. Water from some wells and springs appears to be a mix of young groundwater and significantly groundwater, probably upwelling along fault zones.

Thick unsaturated zone

Water-levels in many of the sampled wells are up to hundreds of feet below ground level, implying the existence of a widespread, thick unsaturated zone. Seepage though a thick unsaturated zone can produce conflicting, and opposed, results when using both CFC and tritium-helium dating methods. Only those ^3He atoms produced in the saturated zone are preserved in groundwater, which means that the $^3H/^3He$ age begins below the water table and does not account for travel time through the unsaturated zone (Kazemi et al. 2006). If infiltration is slow, and the unsaturated zone is thick, $^3H/^3He$ ages will be much younger than the true age of recharge.

A thick unsaturated zone has the opposite effect on CFCs, as they may partition into the gas phase or soil water, the net effect being an overestimation of groundwater age (Kazemi et al., 2006, Happell et al., 2006). Leakage of perched aquifers through an intermediate unsaturated zone, which is likely in the high-mountain aquifer system, can cause these same contrasting effects. Disparities between CFC and tritium-helium ages of 20 to 33 years seen in this study suggest that regionally, groundwater flow through unsaturated zones may be an important component of the total residence time. It is important to note, however, that flowpaths allowing rapid infiltration do exist, as shown by rapid water rises during extreme precipitation events (Fig. 6).

Recharge

The southern Sacramento Mountains are a recharge area, with almost all groundwater being derived from local precipitation. High-elevation groundwaters are of calcium-bicarbonate or calcium-magnesium-bicarbonate type. The downgradient geochemical trends (Fig. 8) caused by cumulative mineral-water interactions point to a common, high-elevation recharge area. Stable isotope data show progressive evaporative enrichment downslope (Fig. 12) within the High Mountain aquifer system. Multiple environmental tracers indicate mixing between recent recharge and resident water within the recharge area, but the highest tritium concentrations are at the crest of the range, and the lowest are along the Pecos Slope. The regional evaporation line (SMT) derived from surface and groundwater collected from the Sacramento Mountains, Pecos Slope, and RAB in 2003 projects to the field of winter precipitation for the Sacramento Mountains, specifically to an isotopic composition corresponding to average winter precipitation at ~9100 ft (2773 m, Eastoe and Rodney, 2014). As no summer rains comparable to the years of 2006 and 2008 had occurred since 1989, recharge is thus dominated by winter precipitation in years without exceptionally wet summers. This is in spite of the fact that, on average, there is more precipitation in summer than in winter (Newton et al., 2012; Eastoe and Rodney, 2014). Combined, the least evolved water chemistry, least evaporated isotopic compositions, and youngest tritium ages argue for recharge dominantly above about 8200 ft (2500 m, a water table elevation of ~8000 ft or 2438 m; Fig. 5), with the recognition that there is not a distinct elevation below which recharge ceases.

Morse (2010) showed that some recharge occurs on the Pecos slope, and in the PIA of Fiedler and Nye (1933). He documented subtle inflections in west-to-east trends in major ion chemistry and temperature, suggesting some recharge of fresh water, around the west boundary of the PIA. ^{14}C ages increase from zero near Mayhill (where the aquifer becomes a closed system with respect to ^{14}C) to greater than 1000 years easterly across the Pecos Slope; an inflection in ages at the western PIA indicates some recharge occurs there. Slightly higher tritium values near the Rio Peñasco (Fig. 13) suggest that some recharge occurs as leakage along its course. Low but detectable CFC concentrations in water samples across the Pecos Slope indicate that minor diffuse recharge occurs in the region (perhaps through karst features) and mixes with older water from the High Mountains to the west.

Exceptional summer rains in 2006 and 2008 clearly recharged aquifers (Fig. 6) and briefly shifted isotopic compositions of spring and well waters towards the LMWL. Newton et al. (2012) investigate this isotopic shift in detail, in terms of different spatial and temporal groundwater reservoirs in a multiple porosity model of the Yeso Formation. Such summer rain events probably contribute to diffuse recharge across the mountains and Pecos Slope, and flood flows in major drainages that may infiltrate in the PIA. Across the Pecos Slope, this summer recharge may be of sufficient volume to affect CFC, tritium, and ^{14}C trends, and cause the deflections in temperature and chemical concentration profiles observed by Morse (2010). It is not sufficient to change stable isotopic compositions (Eastoe and Rodney, 2014), which are relatively uniform and resemble evaporated winter precipitation at the east edge of the High Mountain aquifer system (Fig. 11).

Groundwater Flow Rates

Groundwater flow rates vary widely, as may be inferred by widely disparate residence times derived using different tracer methods. Numerical simulation of heat and mass transfer in groundwater flow in Hay Canyon in the High Mountain aquifer system, constrained by multiple tritium analyses, suggest an upper bound on groundwater flow rates of ~6 ft/day (~1.8 m/day; Newton et al., 2012). This implies that flow in fractures is dominant. Conversely, Morse (2010) used corrected ^{14}C data to calculate the travel time across the Pecos Slope along an inferred flowpath from the east edge of the High Mountain aquifer system. An age of 1300 years at the end of the flowpath yielded a flow rate of 0.24 ft/day (7.3 cm/day).

Regional hydrogeologic conceptual model

Figure 14 shows the conceptual model of regional hydrogeology. In years without exceptionally wet summers, recharge is dominated by winter precipitation infiltrating largely above 8200 ft (2500 m). Mixing of waters of different ages is promoted by the heterogeneity of the Yeso Formation, and at the surface by discharge from abundant springs into streams. Water flows downgradient from the recharge area though multiple perched carbonate aquifers (tapped by STR wells), springs and streams.

A progressively evaporative isotopic signature develops due to repeated exposure of water to the atmosphere. Dedolomitization causes the water chemistry to evolve from Ca and HCO_3-dominant to more SO_4-rich along flow paths from west to east. LTR hydrographs suggest the presence of a deeper, regional aquifer component to the High Mountain aquifer system. Most groundwater in the High Mountain aquifer system is a mixture of young water (15 to 25 years old) and older water (>50 years old). Groundwater and surface water in the High Mountain aquifer system ultimately recharges the Pecos Slope aquifer. Extremely wet summers such as 2006 and 2008 were significant recharge events, raising groundwater levels and affecting isotopic compositions.

The Pecos Slope is underlain by one regional aquifer whose stable isotopic composition reflects that of groundwater at the eastern edge of the High Mountain aquifer system and is fairly uniform throughout. This uniform isotopic composition, evolved water chemistry, and ^{14}C ages increasing smoothly eastward indicates that most groundwater in the Pecos Slope aquifer is sourced from the High Mountain aquifer system to the west. Tritium, CFCs and ^{14}C age-dates support a lesser quantity of recharge occurring across the Pecos Slope (Morse, 2010), as diffuse infiltration and/or streambed leakage. This may occur in years of intense, widespread summer precipitation such as 2006 and 2008. The Pecos Slope aquifer ultimately recharges the RAB aquifer to the east.

CONCLUSIONS AND IMPLICATIONS

When this study began, groundwater-levels were declining, springs were decreasing in flow, and the region was in a multi-year drought (e.g., National Climatic Data Center, 2013a). The data presented here, and that of Eastoe and Rodney (2014), suggest that snowmelt in the High Mountains has been the primary recharge input to the system. Matherne et al. (2010) examined stream discharge measurements in the Eagle Creek basin in Lincoln County, west of Ruidoso, and north of the present study area. From 1970 to 1980, streamflow was dominated by spring snowmelt, whereas from 1989 to 2008, streamflow was dominated by summer monsoon precipitation. Overall, stream discharge was lower during the latter period. Matherne et al. (2010) speculate that these changes could decrease the total amount of recharge, as peak flows during monsoon season are likely of higher magnitude and shorter duration as compared to spring runoff from snowmelt. The present work shows that the extremely wet summers of 2006 and 2008 indeed recharged groundwater in the southern Sacramento Mountains, and probably over a wider area than winter precipitation normally has. Since then,

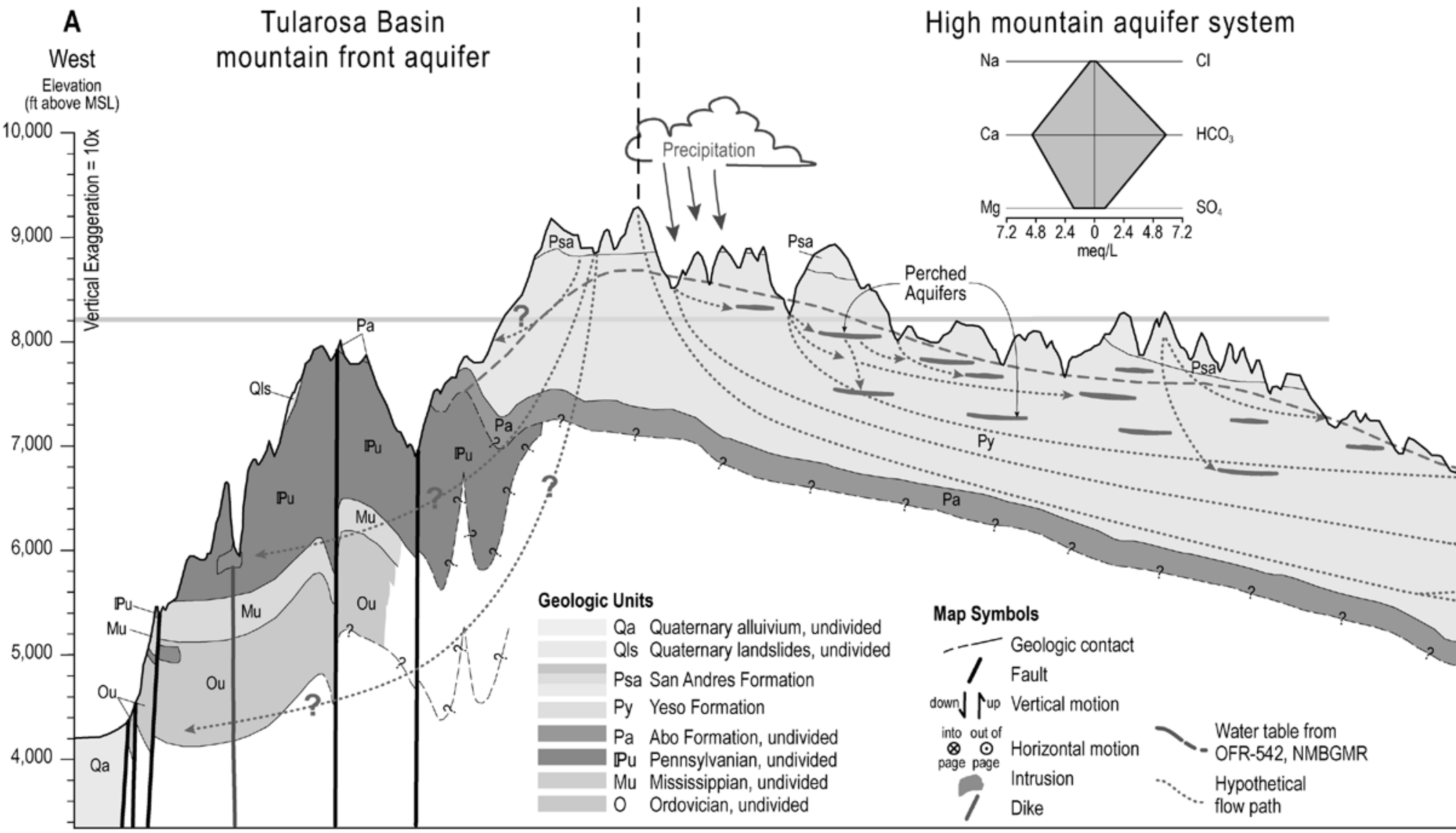

FIGURE 14. Hydrogeologic conceptual model extending across the southern Sacramento Mountains into the Pecos slope. Inset map shows location of section line. Stiff diagrams show representative chemical composition of waters from within the two main aquifer domains. Perched aquifers in the High Mountain aquifer system are tapped by STR wells, whereas LTR wells tap deeper levels. Faults and the Dunken-Tinnie structural zone may divert very old, deep water to the surface. Elevations above the 8200 ft (2500 m) line are where most recharge, dominated by winter precipitation, occurs. Occasional intense summer storm events can contribute additional recharge across the study area into the Pecos Slope.

July-September 2013 was the wettest such period on record in the southwest U.S. (National Climatic Data Center, 2013b). With changes in regional climate patterns, declines in winter precipitation may mean that such extreme monsoon seasons take on greater importance for recharge. However, the extent to which exceptionally wet summers can quantitatively replace declining winter snowpacks is unknown.

The results of this study are consistent with the conclusions of Eastoe and Rodney (2014) and the pioneering work of Gerardo Gross, colleagues, and students (see Previous Work), wherein the high elevations of the Sacramento Mountains are the ultimate source of groundwater that enters the Roswell Artesian Basin from the west. Although some recharge occurs on the Pecos Slope and in the PIA of Fiedler and Nye (1933), probably during intense summer precipitation events, the majority of the recharge to the RAB is derived from the high elevations of the Sacramento Mountains west of Mayhill, and flows through the Pecos Slope aquifer. Ongoing work at the NMBGMR aims to better quantify the annual recharge in the study area, over varied spatial and temporal scales, and relate this to previous estimates of recharge to the RAB.

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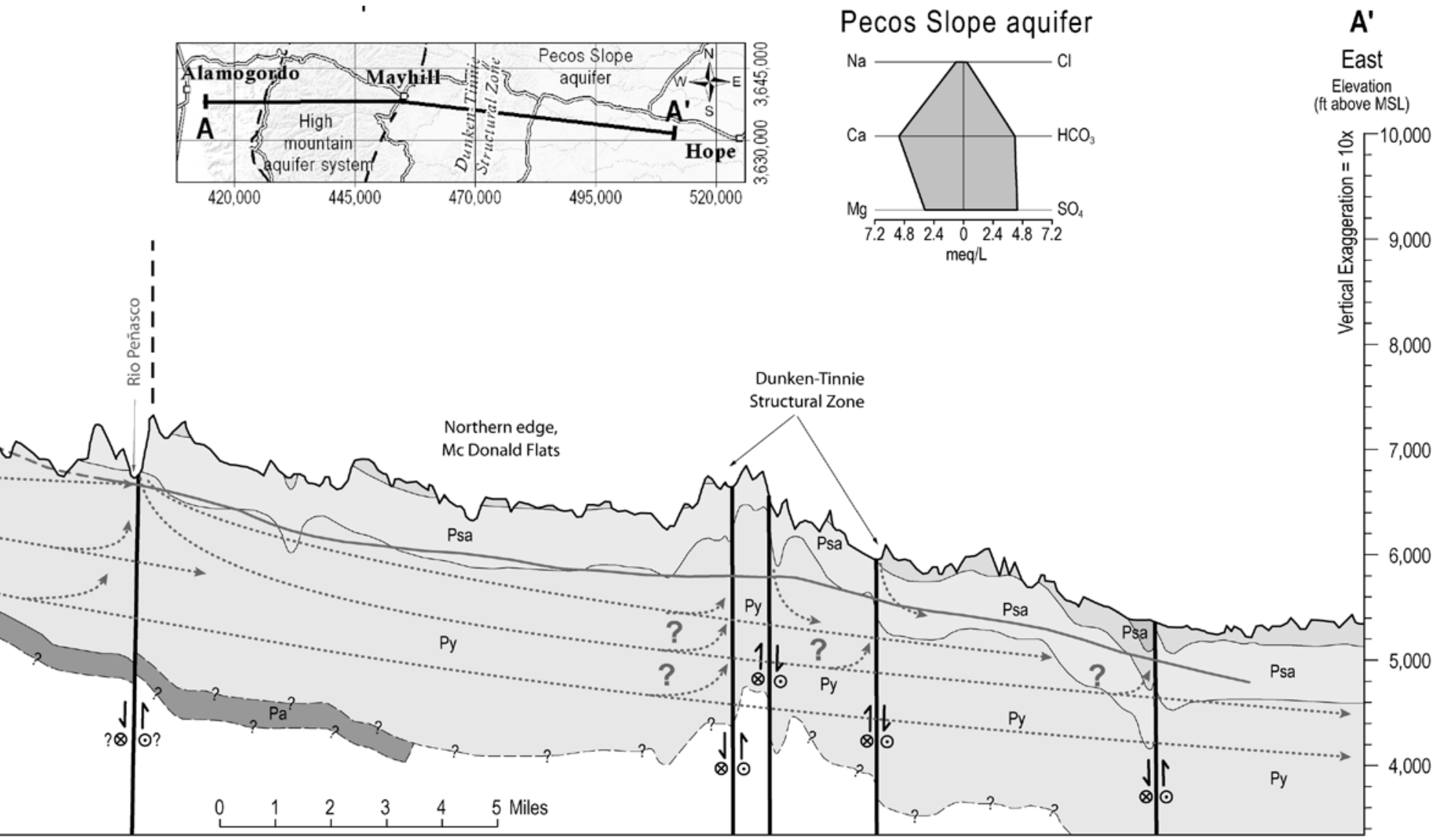

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