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HYDROGEOLOGY OF THE LA JENCIA AND SOCORRO BASINS: DATA SYNTHESIS AND PERSPECTIVES FOR FURTHER RESEARCH

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Abstract—The Socorro and La Jencia Basins are two adjacent, hydrologically connected groundwater basins located along the Rio Grande rift in central New Mexico. The groundwater flow system within and between these two basins is complex, and current understanding is limited by the absence of a high-resolution geologic framework. Geochemical studies provide a conceptual understanding of groundwater flow by identifying groundwater and spring waters of epigenic/meteoric, geothermal (circulation and heating of recharged waters), and endogenic (mantle- and crustal-derived) origins. This paper aims to expand on these groundwater flow and recharge source hypotheses. We integrate new stable isotope data collected from sites located along Socorro Canyon and the Rio Grande with legacy water quality, tracer, and water level data. Socorro Canyon is one of three east-west-trending canyons within the extensively faulted Socorro-Lemitar Mountains—a north-south-trending mountain range that bisects the La Jencia and Socorro Basins. Water quality in these canyons is controlled by water-rock interactions and contains a mix of young and old waters, indicating a series of nested, deep groundwater flow paths within the La Jencia Basin. The Socorro-Lemitar Mountains act generally as a barrier to flow between the basins, with a series of springs rising in through-cutting canyons. Nonetheless, the fractured nature of the Socorro-Lemitar Mountains suggests that interflow may occur over long periods of time. The majority of waters in the Socorro Basin are similar to Rio Grande waters, suggesting generally recent recharge of the shallow aquifer system. However, regional geochemistry of the Rio Grande and Low-Flow Conveyance Channel (LFCC) waters show that there are regions of upwelling, chloride-rich brines. Two sources are possible for these: (1) deep, axial basin gravity-driven circulation; and (2) lateral upwelling of waters recharged in the Magdalena Mountains. We believe that axial flow is more likely. Preliminary interpretations are consistent with findings from similarly structured surrounding rift basins; however, additional subsurface data is needed (geologic and hydrologic) for further understanding beyond the shallow flow system.

INTRODUCTION

The Socorro and La Jencia Basins are two adjacent, hydrologically connected groundwater basins located along the Rio Grande rift in central New Mexico. The groundwater flow system within and between these two basins is complex. Subsurface rift structure, variable stratigraphy, and geothermal fluids, combined with sparse, shallow well control complicate the understanding of groundwater sources and flow paths. A handful of studies have used general groundwater chemistry (Anderholm, 1983), tracers (Gross and Wilcox, 1983), water temperature trends and heat flow modeling (Barroll, 1989), or combinations thereof (Williams et al., 2013; Williams et al., 2015), to provide a conceptual understanding of the regional flow system in this area. Large-scale studies have investigated water chemistry patterns along the Rio Grande from its headwaters in Colorado to El Paso, Texas (Hogan et al., 2007; Moore and Anderholm, 2002; Phillips et al., 2003).

Neighboring Rio Grande rift groundwater basins (i.e., Albuquerque, Española) have been studied extensively in three-dimensions via geologic mapping and geophysical surveys and reveal the complexity of the rift basin framework and corresponding groundwater flow system (Grauch and Connell, 2013; Johnson et al., 2013). While geochemical studies have driven the current knowledge of potential groundwater flow paths and recharge sources in the Socorro and La Jencia Basins, these investigations are largely limited to 2-D cross-sectional frameworks based on a qualitative basin framework. This paper aims to expand on these groundwater-flow and recharge-source hypotheses by integrating water quality and tracer data with findings from previous studies.

LOCATION

The Socorro and La Jencia Basins are located along the Rio Grande Valley in central New Mexico (Fig. 1). The basins are bisected by the north-south-trending Socorro-Lemitar Mountains and are bounded by the Albuquerque Basin to the north, the Magdalena, Gallinas, and Bear Mountains to the west, the Loma de las Cañas region to the east, and the San Marcial Basin to the south (Figs. 1, 2). Elevation ranges from 10,783 feet above mean sea level (ft amsl) in the Magdalena Mountains to just below 4000 ft amsl in the Rio Grande Valley. Regional climate is classified as arid desert in the valley and semi-arid in the surrounding higher elevations (Kottek et al., 2006). The mean annual precipitation is 11 in., and mean annual snowfall is 10 in. (data averaged from years 1940–2021; Lawrimore et al., 2016). The region contains diverse terrain, vegetation, and wildlife. The west-bounding mountains contain pinon-juniper and ponderosa pine forest, whereas the east-bounding Loma de las Cañas include desert mountain ranges with sparse vegetation. The flanks of both basins are creosote and grassland dominated. The axis of the La Jencia Basin is filled with grassland. The Rio Grande flows along the axis of the Socorro Basin, supporting a narrow riparian forest and region of irrigated agriculture. The Sevilleta National Wildlife Refuge (SNWR) and the Bosque del Apache National Wildlife Refuge are located on the north and south ends of the study area, respectively.

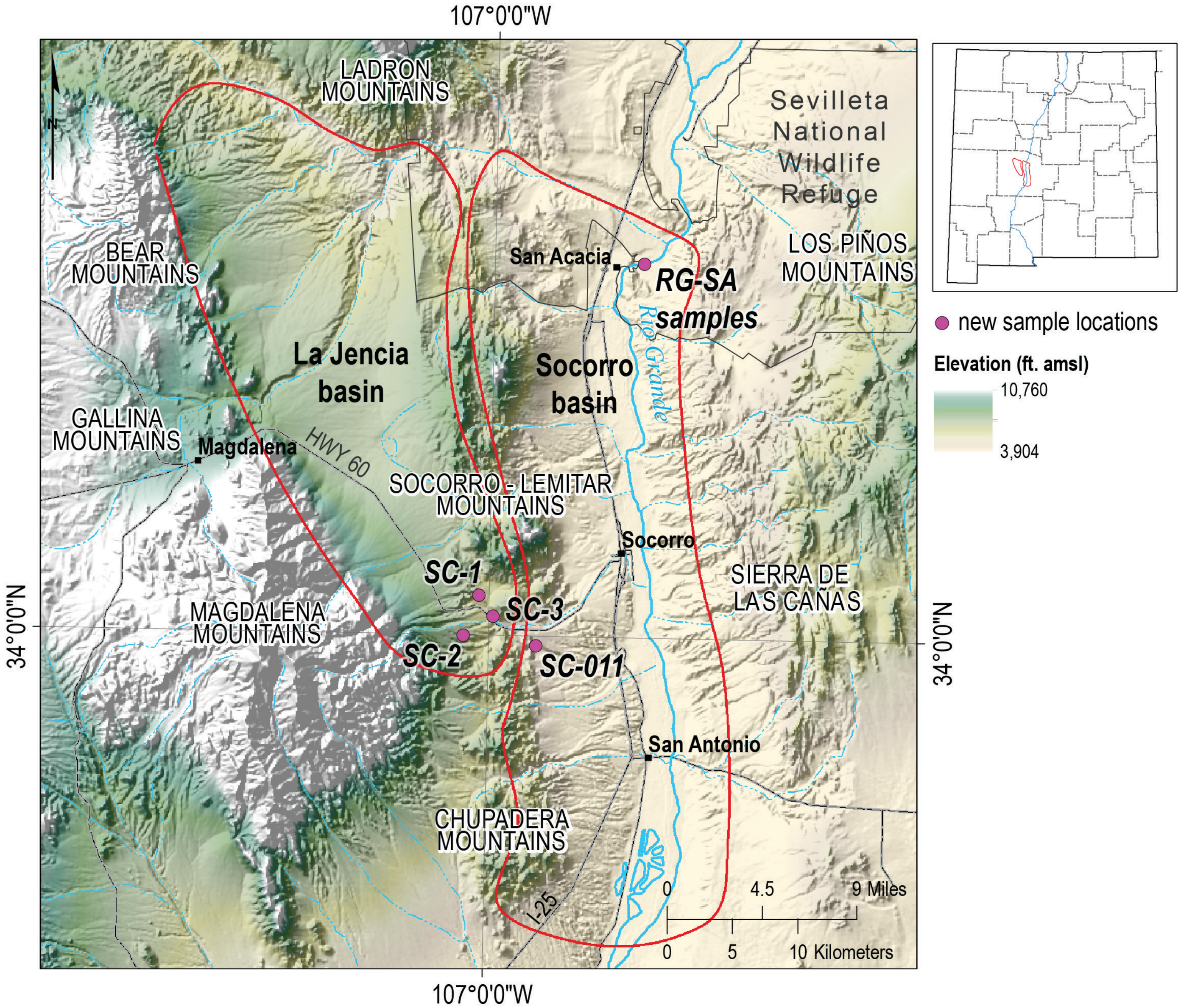

FIGURE 1. Location and physiography of La Jencia and Socorro Basins in central New Mexico. Elevation ranges from 10,700 feet above mean sea level (ft amsl) in the Magdalena Mountains to just under 4000 ft amsl in the Rio Grande Valley. SC-1, SC-2, SC-3, and SC-011 are locations of new water samples.

The city of Socorro, New Mexico, is the main population center of the region (pop. 8348; United States Census Bureau, 2021). Smaller towns located along the Rio Grande include San Acacia, Polvadera, Lemitar, and Escondida north of Socorro, and San Antonio to the south. The village of Magdalena (pop. 878) is located just north of the Magdalena Mountains on the flank of the La Jencia Basin. A handful of residential homes are located in canyons in the northeast Magdalena Mountains. The low-elevation grassland extending across the La Jencia Basin, referred to as the "Snake Ranch Flats," is sparsely populated.

GEOLOGIC SETTING

The regional geology is complex and has been studied by geologic mapping, geophysical surveys, and geochronological studies over the last 60 years (Cather et al., 1994; Chamberlin, 1983; Chamberlin et al., 2004; Chapin et al., 1978; Connell and Love, 2001; Balch et al., 1997; Sanford, 1968). Successive tectonic and volcanic events have resulted in a structurally controlled basin geometry and inter-/intra-basin fault networks. The relationship between structural features and anisotropic basin-fill units influences hydrologic interpretations.

The La Jencia and Socorro Basins are two parallel structural basins in the Rio Grande rift. The Rio Grande rift is a longitudinal north-south-oriented horst-and-graben valley extending from Colorado to Mexico that contains a series of half-graben basins with alternating tilt directions. Rift extension began in the late Cenozoic. The Socorro and La Jencia Basins were initially a single Popotosa basin, an early rift basin extending from the southern Albuquerque Basin to the Socorro accommodation zone (Chapin and Cather, 1994; Fig. 2; the Popotosa Basin boundary is the combined boundaries of the Socorro

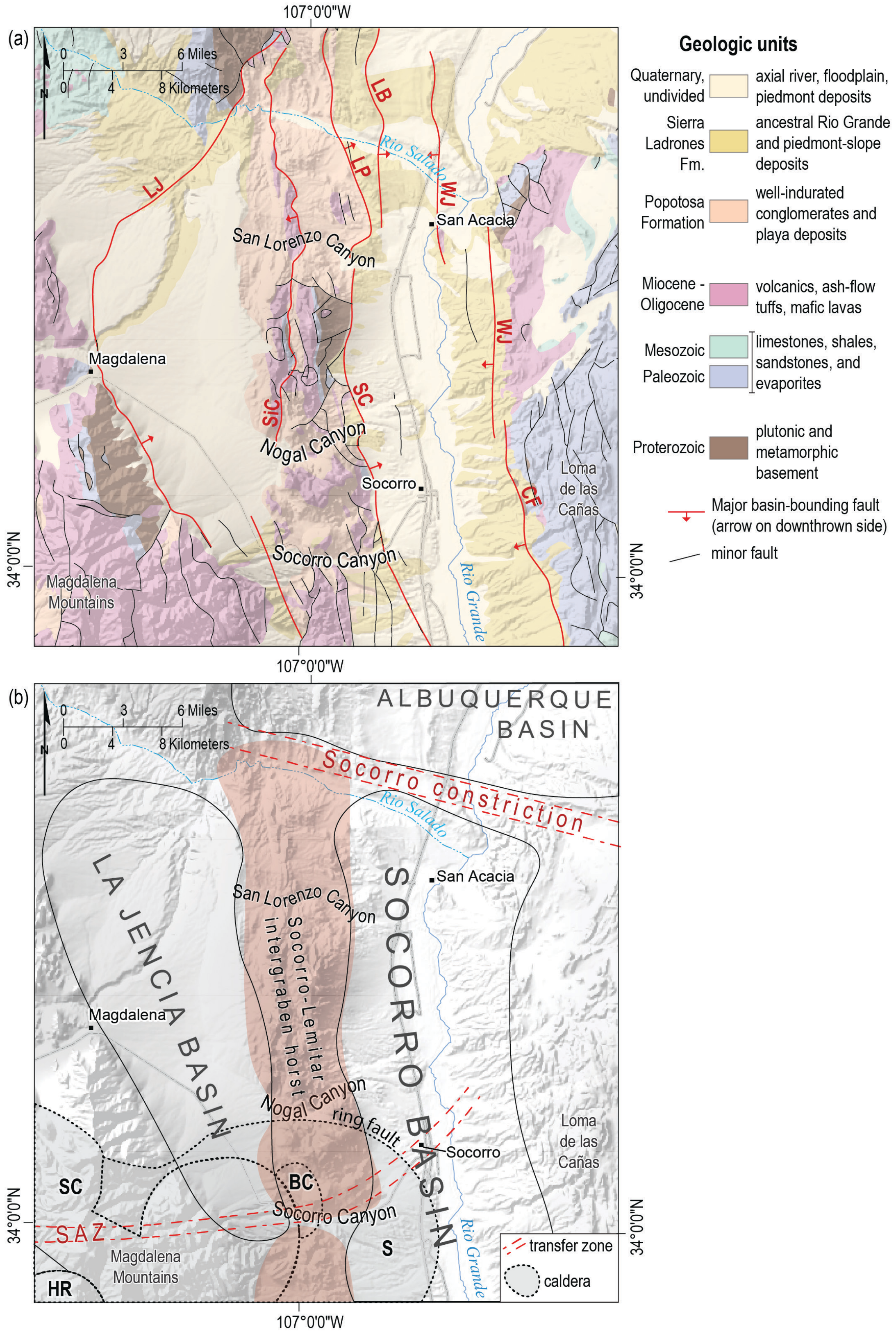

FIGURE 2. (a) Generalized geologic map including structural features that have the potential to influence groundwater flow (geology and faults simplified from Scholle, 2003). The north-south-trending Socorro-Lemitar intergraben horst bisects the basins. Major basin-bounding faults trend north-south at basin margins and juxtapose Miocene-Oligocene volcanic rocks with Cenozoic basin fill. Permeability in volcanic units is high along fracture zones at the surface, allowing rapid infiltration of precipitation. **LJ**: La Jencia fault; **SiC**: Silver Creek fault; **SC**: Socorro Canyon fault zone; **LP**: Loma Pelada fault; **LB**: Loma Blanca fault; **WJ**: West Joyita fault zone; **CF**: Cliff fault. (b) Basin boundaries, caldera boundaries, and east-west transfer zones. SAZ refers to the Socorro accommodation zone. Ignimbrite calderas in the study area include, from oldest to youngest: **S**: Socorro caldera (32.0 Ma); **BC**: Black Canyon caldera (30.0 Ma); **SC**: Sawmill Canyon caldera (28.7 Ma); **HR**: Hardy Ridge caldera (28.0 Ma; Chamberlin, 2006).

and La Jencia Basins). The Popotosa Basin experienced two major episodes of rapid extension, both associated with major volcanism. The first extensional event started roughly 25 Ma after the ignimbrite flare-up that formed the Mogollon-Datil Volcanic Field (MDVF; Ricketts et al., 2016), and the second extensional event occurred between 16 Ma and 10 Ma (Chapin and Cather, 1994). In the La Jencia and Socorro Basins, MDVF volcanism resulted in a cluster of caldera eruptions (24.3 to 32.0 Ma), of which the Socorro Caldera is the oldest (32.0 Ma; Chamberlin et al., 2004; Fig. 2). During this initial rapid extension, syntectonically deposited Santa Fe Group (Popotosa Formation) sediments filled the early closed basin, consisting primarily of alluvial fan deposits that grade basinward to fine-grained alluvial plain and playa deposits (Cather et al., 1994; Chapin and Cather, 1994; Figs. 2, 3). The second episode of major extension (16–10 Ma) resulted in the uplift of the Socorro-Lemitar intergraben horst, dividing the Popotosa Basin into the parallel Socorro and La Jencia subbasins (Cather et al., 1994; Chapin and Cather, 1994; Fig. 2). The uplift of this mountain block resulted in the juxtaposition of Paleozoic-Precambrian basement and Cenozoic volcanics with basin fill.

Continued syntectonic Santa Fe Group deposition occurred in the individual basins. However, the La Jencia Basin has remained a closed basin while the Socorro Basin was incorporated into the through-going Rio Grande drainage around 4.5 Ma (Repasch et al., 2017). Both basins contain, from oldest to youngest, (1) strongly tilted, well-indurated Popotosa Formation conglomerates and playa deposits, and (2) piedmont-slope deposits of the Sierra Ladrones Formation (Figs. 2, 3). In the Socorro Basin, the Sierra Ladrones Formation interfingers with axial river facies and floodplain deposits from the onset of Rio Grande incision around 0.8 Ma (Sion et al., 2020; Cather et al., 1994; Chapin and Cather, 1994; Chamberlin, 1983; Chapin, 1989; Chapin and Seager, 1975; Mack and Giles, 2004; Fig. 3). Basin fill is estimated to be up to 2 km thick in the La Jencia Basin (Chamberlin and Osburn, 2006) and 400–2000 m in the Socorro Basin (Chamberlin et al., 2001; Fig. 3). Basin fill thickness increases from basin margins toward the center.

Structural features with the potential to influence groundwater flow include: (1) major basin-bounding faults; (2) boundary faults between the Magdalena Mountains and La Jencia Basin; (3) boundary faults within the Socorro-Lemitar intergraben horst; and (4) major faults associated with calderas, including the Socorro Caldera ring fault (Chamberlin, 1999) and the east-northeast-striking Socorro accommodation zone (Chapin, 1989; Fig. 2). Stratigraphic features with the potential to influence groundwater flow include (1) tilted and rotated early Popotosa Basin sediments overlying tilted and rotated graben fault blocks at basin depth, and (2) intertonguing axial river, floodplain, and piedmont deposits in the Socorro Basin (Connell et al., 2012; Figs. 2, 3). In addition to complex structures and stratigraphy, high heat flow associated with rifting and the evolution of a shallow (~18 km depth) magma body (Balch et al., 1997) have potentially significant effects on the hydrologic system (Chapin et al., 1978; Barroll and Reiter, 1990).

REGIONAL HYDROGEOLOGY

The La Jencia and Socorro Basins are two basin-fill aquifers, connected via surface water and groundwater through structural features within the Socorro-Lemitar intergraben horst (Fig. 2). The primary aquifer unit in both basins is the Sierra Ladrones Formation, which overlies the Popotosa Formation; both formations fall within the Miocene-to-Quaternary Santa Fe Group (Fig. 3). Basin-fill hydrostratigraphic units include (from oldest to youngest): (1) the lower Popotosa Formation, which contains well-indurated mudflow deposits and fanglomerates; (2) the upper Popotosa Formation, a confining unit that contains low-permeability mudstones, sandstones, and conglomerates; and (3) the axial river, piedmont, and floodplain facies of the Sierra Ladrones Formation and piedmont, distal fan, and basin-floor facies in the La Jencia Basin (Fig. 3; Anderholm, 1983; Chapin et al., 1978; Connell et al., 2012; Hawley, 1978). Bedrock hydrostratigraphic units include middle Cenozoic volcanic and volcaniclastic rocks underlying basin-fill units and crop out at basin margins (Figs. 2, 3).

While the two basins are connected and contain similar hydrostratigraphic units (Fig. 3), key differences exist in the respective groundwater flow systems. The La Jencia Basin aquifer is recharged principally from precipitation in the Magdalena and Bear Mountains by focused mountain-block recharge (Anderholm, 1987). The perennial-to-intermittent Rio Grande and its system of irrigation works provides focused recharge to the Socorro Basin aquifer. Summer monsoon precipitation becomes diffuse recharge; however, this contribution is minor (Anderholm, 1987). Focused recharge from the Rio Grande and the associated floodplain is complicated by diversions and irrigation return flows. The Rio Grande between San Acacia and Elephant Butte is paralleled by the Low Flow Conveyance Channel (LFCC), the lowest elevation waterway in the basin. The LFCC was constructed in 1959 to aid in the delivery of Rio Grande Compact waters by reducing seepage losses from the main river channel. As the lowest topographic feature in the basin, the LFCC captures potential aquifer recharge from irrigation return flow and Rio Grande losses.

METHODS

Water data measured from wells and a spring along Socorro Canyon (stable isotopes $\delta^{18}O$ and δD, field parameters) is integrated with legacy water data (stable isotopes $\delta^{18}O$ and δD, major ions, water levels) to provide a hydrogeologic overview of the La Jencia and Socorro Basins. New data includes water isotopologues and field parameters measured from wells (SC-1, SC-2, SC-3) and Chupadera Spring (SC-011) located along Socorro Canyon, and from surface water samples from the Rio Grande at San Acacia (E. Williams, unpubl., 2022; Fig. 1, Table 1). Well and spring samples were collected in November of 2019. Surface water sampling was done in March, August, October, and December 2021. Sampling was done according to NMBGMR standard operating procedures for stable isotope sampling (Timmons et al., 2013). Analyses were conducted by the NMBGMR Analytical Chemistry Laboratory. Legacy

		La Jencia Basin			Socorro Basin		
Age	**Unit**	**Description**	**Hydro-stratigraphic Unit**	**Thickness (m)**	**Description**	**Hydro-stratigraphic Unit**	**Thickness (m)**
Holocene - Pleistocene	basin-fill	piedmont-slope, alluvial, playa deposits	sands, sandstones	0 - 100	intertonguing axial river, alluvial fan, piedmont and playa deposits	high heterogeneity; sandstones, mudstones	0 - 180
Lower Pleistocene to Pliocene	SANTA FE GROUP, Sierra Ladrones Formation, Upper	alluvial fan deposits and fine-grained eolian sands	sands, sandstones	340	piedmont, alluvial fan, conglomeratic sandstones, silty mudstones	high heterogeneity; sandstones, mudstones	340
Lower Pleistocene to Pliocene	SANTA FE GROUP, Sierra Ladrones Formation, Lower	piedmont-slope deposits, conglomerates, conglomeratic sandstones	conglomeratic sandstones	330	piedmont-slope conglomeratic sandstones, axial river sandstones	conglomeratic sandstones	800
Miocene	SANTA FE GROUP, Popotosa Formation, Upper	conglomeratic sandstones claystone, siltstones	playa	900	conglomeratic sandstones, alluvial fans claystone, siltstones	playa	900
Miocene	SANTA FE GROUP, Popotosa Formation, Lower	congomerates, conglomeratic sandstones	conglomerate	0 - 1000	conglomeratic sandstones, fanglomerates	conglomerate	0 - 1000
Miocene - Oligocene	Volcanics	ash-flow rhyolitic ignimbrite tuffs, basaltic andesite and andesite lavas	fractured volcanic tuffs	560 - 1460	ash-flow rhyolitic ignimbrite tuffs, basaltic andesite and andesite lavas	fractured volcanic tuffs	560 - 1460
Pennsylvanian	Madera Limestone; Sandia Formation	limestones interbedded with shales and fine-grained quartz arenite, intensely silicified	limestones and shales	>300	limestones interbedded with shales and fine-grained quartz arenite, intensely silicified	limestones and shales	>300
Precambrian	Pre-rift basement	Granitic plutonic rocks, exposed in northern Magdalena Mountains	basement	>1000	Meta-sedimentary rocks, intensely jointed, north-striking joints preferentially silicified	basement	> 1000

FIGURE 3. Generalized hydrostratigraphy for the La Jencia and Socorro Basins. Unit thicknesses estimated from Chamberlin (1999) and Chamberlin and Osburn (2006). Geologic units between basins are similar; differences are in the Sierra Ladrones Formation and the Holocene-Pleistocene basin-fill units. These units contain a higher degree of heterogeneity and anisotropy in the Socorro Basin.

data was compiled from agency databases and regional reports (Appendix 1). Legacy data sources include: New Mexico Bureau of Geology and Mineral Resources (NMBGMR); United States Geological Survey (USGS); Gross and Wilcox (1983); Williams et al. (2013); and the New Mexico Office of the State Engineer (NMOSE).

Groundwater levels and spring locations compiled from the NMBGMR, USGS, and NMOSE were used to construct a preliminary potentiometric surface map using ArcGIS (Fig. 4). Water level measurements include USGS water levels collected 1944–1995, NMBGMR water levels collected 2000–2021, and all available NMOSE static water levels. Major north-south-trending fault zones at the 1:500,000 scale (Scholle, 2003) were incorporated as discontinuities in the interpolation process.

Major element chemistry data (legacy) was compiled for 382 sites within the study area. Data includes analyses from NMBGMR, USGS, and Williams et al. (2013). Major element chemistry is displayed in a Piper Diagram (Piper, 1944; Fig. 5). Dominant hydrochemical facies were assigned to each sample based on dominant cations and anions (Figs. 5, 6).

Stable isotope ($\delta^{18}O$ and δD) measurements from three well samples and one spring sample in Socorro Canyon (Fig. 1, Table 1) are combined with data compiled from Gross and Wilcox (1983), Williams et al. (2013), USGS, and NMBGMR (Fig. 6, Appendix 1). The local meteoric water line (LMWL) was developed by performing an unweighted least squares regression on meteoric $\delta^{18}O$ and δD values measured in the central New Mexico region by NMBGMR staff. The global meteoric water line (GMWL; Craig, 1961) and the Albuquerque meteoric water line (AMWL; Plummer et al., 2012) are plotted for reference. The Socorro MWL plots with a relatively shallow slope of 7.33.

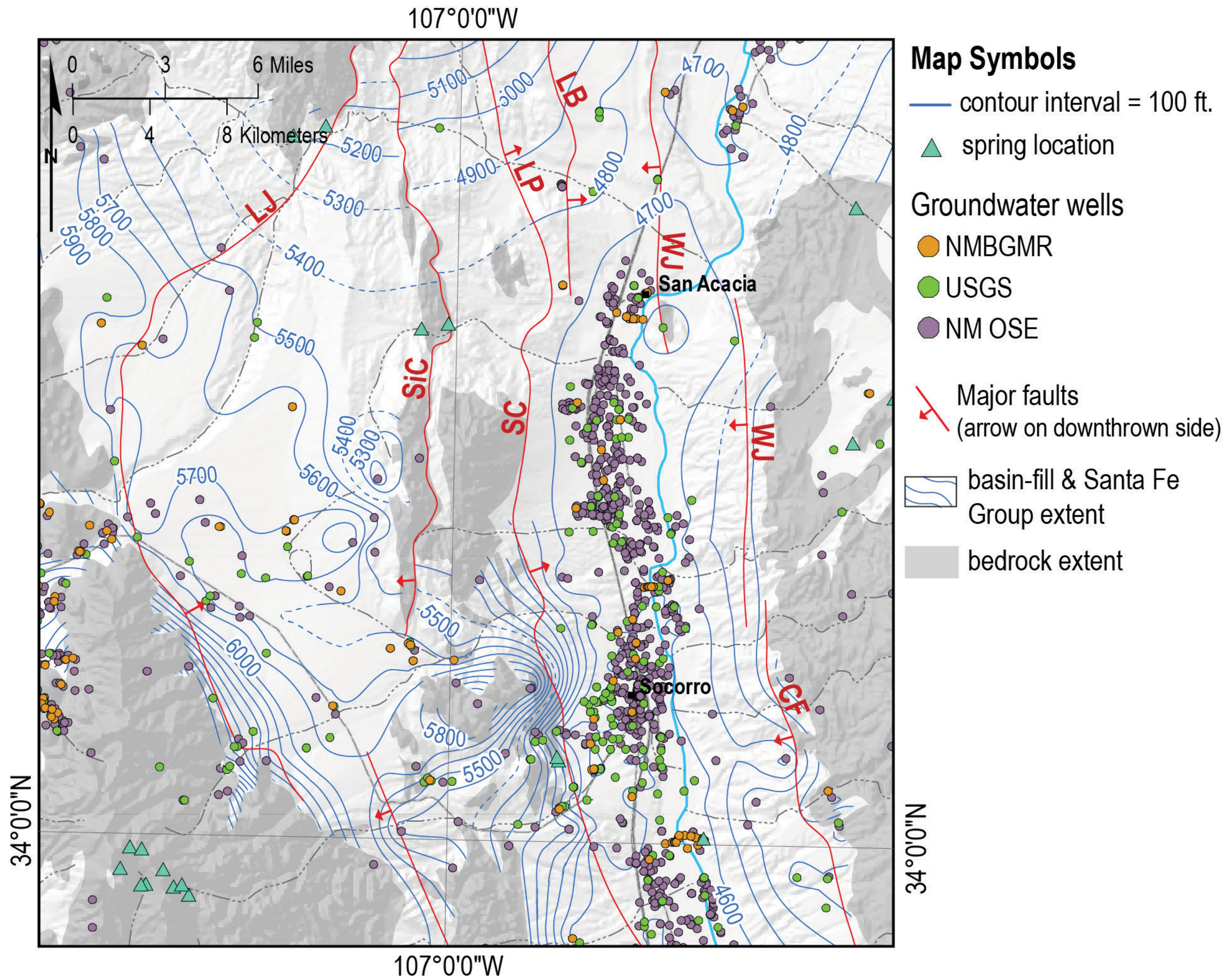

FIGURE 4. Potentiometric surface map of young basin fill and Santa Fe Group extent in the Socorro and La Jencia Basins. Static water level data compiled from USGS, NMBGMR, and NMOSE. Spring locations sourced from NMBGMR and USGS. Major structures (identified by initials in the caption for Fig. 2) were incorporated as discontinuities in the interpolation process. Most water levels are from shallow wells, therefore structural effects are not evident across all structures. La Jencia Basin: groundwater flows generally southwest to northeast across the basin, from the Bear and Magdalena Mountains toward the Rio Salado and Socorro Mountains, respectively. Socorro Basin: groundwater flows generally from the north, east, and west to the center of the basin into the Rio Grande. Contour units are in feet above mean sea level, contour interval is 100 ft; lines dashed where approximate.

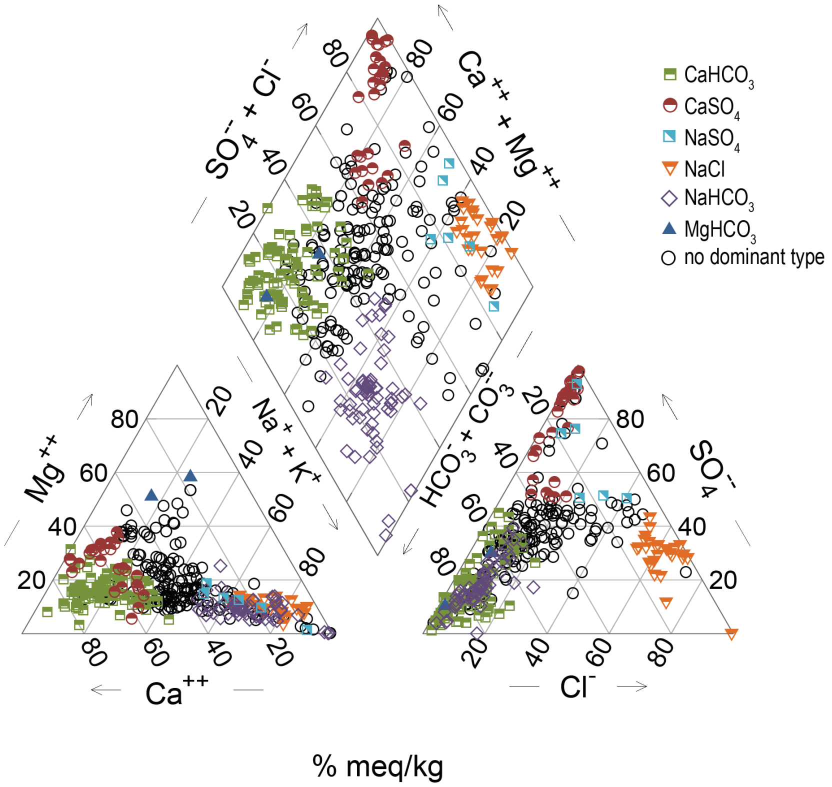

FIGURE 5. Piper diagram (Piper, 1944) displaying dominant water types of the Socorro-La Jencia Basin region.

PRELIMINARY SYNTHESIS OF WATER LEVEL, WATER QUALITY, AND TRACER DATA

Regional Groundwater Flow

The regional groundwater-flow gradient is southwest to northeast across the La Jencia Basin, and from high elevations to the Rio Grande in the Socorro Basin (west and east from the Socorro-Lemitar Mountains and Loma de las Cañas, respectively; Fig. 4). A groundwater divide is present in the La Jencia Basin; recharge from the Bear Mountains flows north toward the Rio Salado, whereas recharge from the Magdalena Mountains flows east-northeast toward the Socorro Mountains (Fig. 4). Isolines are continuous across most structures but are somewhat suspect given low data density. Water levels are from relatively shallow wells and likely represent the shallow aquifer groundwater head gradient. Structural effects on deep groundwater flow are less evident in Figure 4 as a result. Deep water levels from wells near/in the Socorro-Lemitar Mountains result in interesting flow patterns west of Silver Creek fault (Fig. 1). Additional data is needed in the northern half of the Socorro-Lemitar Mountains and La Jencia Basin to resolve flow patterns in this area. A groundwater high is present on Socorro Peak—an area with little consistent recharge in the form of precipitation. Multiple studies present evidence of upward movement of deep basin groundwater in this area (Anderholm, 1983; Barroll and Reiter, 1990; Gross and Wilcox, 1983; Mailloux et al., 1999). Most of this evidence is derived from hydrochemical and isotopic data measured from numerous fault-controlled thermal springs along the Socorro-Lemitar Mountains. The mechanism driving upward movement is thought to be gaps in regional confining units (hydrologic windows) allowing deep groundwater to flow upwards (Mailloux et al., 1999).

Major/Minor Element Chemistry

Major element chemistry shows the range of water quality types for the study area (Fig. 5). Dominant hydrochemical facies include (1) $CaHCO_3$ (calcium-bicarbonate), (2) $CaSO_4$ (calcium-sulfate), (3) $NaSO_4$ (sodium-sulfate), (4) NaCl (sodium-chloride), and (5) $NaHCO_3$ (sodium-bicarbonate; Fig. 5). Groundwater is generally $CaHCO_3$-type in the Magdalena Mountains and La Jencia Basin (Fig. 1), and total dissolved solids (TDS) concentration is low, averaging 235 mg/L. The Socorro-Lemitar Mountains (Fig. 1) have $NaHCO_3$-type water in the north, corresponding to San Lorenzo Canyon (Fig. 2), and south, corresponding to the Socorro Springs cluster (Fig. 6). Nogal Canyon (Fig. 6) wells and springs exhibit a mixture of all except NaCl water types. TDS concentration in the Socorro-Lemitar Mountains ranges from 108–2,500 mg/L. Groundwater in the Socorro Basin and Rio Grande Valley (Fig. 2) is mixed—NaCl- and $NaHCO_3$-type water is present near San Acacia, whereas the Socorro area exhibits more $CaHCO_3$-type water (Fig. 6). Socorro Basin TDS content ranges from 216 mg/L in well water near San Acacia to 26,400 mg/L in San Acacia spring water (Fig. 8; Williams et al., 2013). Samples in the Loma de las Cañas region are principally $CaSO_4$-type (Fig. 6)—TDS ranges from 174–3,800 mg/L with an average concentration of 1,532 mg/L.

Environmental Tracers

Stable isotope ($\delta^{18}O$ and δD) measurements from three well samples and one spring sample in Socorro Canyon (Fig. 1) are combined with data compiled from Gross and Wilcox (1983), Williams et al. (2013), USGS, and NMBGMR (Table 1, Fig. 7). The $\delta^{18}O$ and δD values range from -13.7‰ to -3.2‰ and -104.2‰ to -38.4‰ (SMOW, Standard Mean Ocean Water), respectively (Fig. 7). Meteoric data displays a large range of values. For reference, we show three meteoric water lines. We plot the local meteoric water line (LMWL) estimated from precipitation samples taken quarterly in the Socorro Basin, Magdalena Mountains, and San Mateo Mountains between 2011 and 2013; the samples from the 2012 water year had anomalously heavy δD values. We also show the Albuquerque meteoric line (AMWL) from Plummer et al. (2012) and the global meteoric water line (Fig. 7).

Many samples that plot to the left of the LMWL near the Magdalena Mountains fall within the range of δ-values seen in the LMWL data; they represent infiltration of precipitation from years with anomalously heavy δD values, perhaps indicating a shift in water source (Clark, 2015; Fig. 7). Measurements from Nogal Canyon springs and Socorro Canyon springs (Gross and Wilcox, 1983) are distributed close to the LMWL and to the left of the LMWL. These waters appear to be derived mostly from recharge in the local mountains and along the local mountain fronts.

Socorro Canyon sites (SC-1, SC-2, SC-3, SC-011), data from Williams et al. (2013), and USGS samples plot to the right of the LMWL (Fig. 7). The Socorro Canyon sites plot within the 'cloud' of meteoric waters. The data from Williams et al. (2013; Group 3) and the USGS samples in the Socorro Basin (Group 2) plot to the right of even the cloud around the LMWL, but along the AMWL. Some of the Williams et al. (2013) data fall within the LMWL data spread (Fig. 7).

Tritium (^3H, half-life = 12.3 years, Unterweger et al., 1980) is an excellent age tracer of young waters. Atmospheric tritium incorporated into precipitation is detectable in groundwater and spring discharge. Atmospheric tritium levels were drastically increased from nuclear testing between the years 1952 and 1964, with levels peaking 1963–1964 (Clark, 2015). Seasonal peaks of tritium activity also occur (Clark, 2015). Distribution of tritium activity from groundwater and springs in the La Jencia-Socorro Basin (1977–1978) was used by Gross and Wilcox (1983) to determine qualitative information regarding mixing of recharge contributions from different sources or recharge following different flow paths (Table 1). Tritium activity in springs in the Socorro-Lemitar Mountains indicated a mix of local and regional recharge components. The local recharge component was attributed to precipitation that falls on the Socorro Mountain complex and/or surface runoff following large thunderstorms. The regional component was attributed to be groundwater recharged in the Magdalena Mountains that flowed through the La Jencia Basin and discharged, mixed with shallow recharge, in the Middle Cenozoic volcanics of the Socorro-Lemitar inter-basin horst. The local recharge component had a residence time on the order of 4 years. The residence time of the regional recharge component could not be determined, only estimated to be substantially longer than the half-life of tritium (12.3 years).

The Rio Grande at San Acacia (Table 1, Fig. 6) shows a range of δ-values, with $\delta^{18}O$ values between

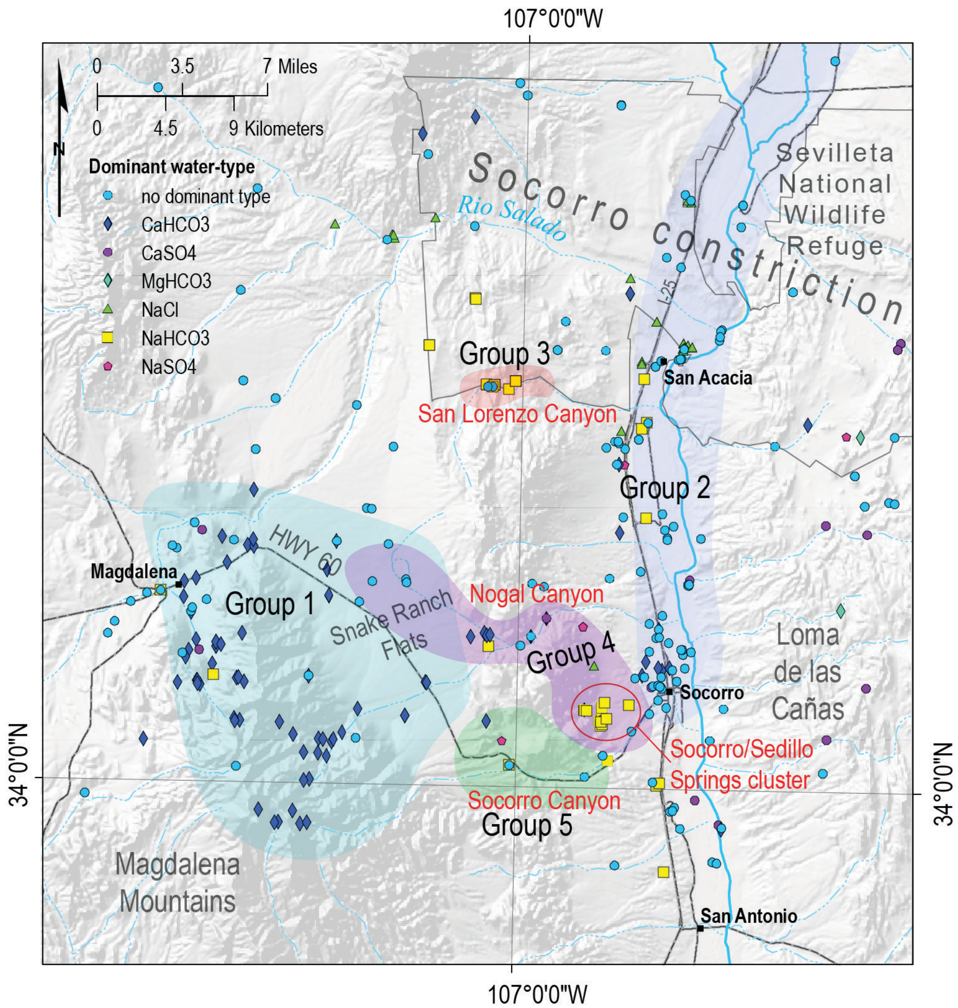

FIGURE 6. Spatial distribution of dominant water types from Figure 5. Groups are indicated with colored polygons and represent the following geographic regions: Group 1 – Magdalena Mountains and southern La Jencia Basin; Group 2 – Rio Grande Valley; Group 3 – San Lorenzo Canyon; Group 4 – Nogal Canyon, Socorro/Sedillo Springs cluster; Group 5 – Socorro Canyon. Major element chemistry is not available for new samples (Fig. 1); they are located within Group 5 for reference.

TABLE 1. Stable isotopes and field parameters of groundwater and Chupadera Spring in Socorro Canyon (SC) and the Rio Grande at San Acacia (RG-SA; Fig. 1).

Site ID	Site Type	Sample Date	Easting	Northing	$\delta^{18}O$ ‰ SMOW	δD ‰ SMOW	T (°C)	pH	EC μS/cm²	TDS mg/L	DO mg/L
SC-011	SP	11/23/2019	318720	3763543	-9.64	-65.52	15.5	8.14	1843	-	5.28
SC-1	GW	11/23/2019	314402	3767014	-9.94	-72.51	19.1	8.14	2202	-	1.05
SC-2	GW	11/23/2019	312984	3764538	-11.2	-79.07	15.3	8.54	2044	-	1.22
SC-3	GW	11/23/2019	315566	3765427	-10	-68.68	18.6	7.14	557.8	-	5.54
RG-SA1	SW	5/23/2021	326203	3792104	-12.0	-90.1	-	-	-	-	-
RG-SA2	SW	5/24/2021	326203	3792104	-12.0	-90.2	21.0	8	620.2	436	9.16
RG-SA3	SW	8/2/2021	326203	3792104	-8.4	-62.6	28.3	8.1	858.3	525	7.19
RG-SA4	SW	10/19/2021	326203	3792104	-11.0	-84.6	16.2	8.46	462.6	361	9.57
RG-SA5	SW	12/16/2021	326203	3792104	-11.6	-87.2	6.7	8.16	304.7	305	11.69

-12.0‰ to -8.4‰ (-11.0‰ average) and δD values between -90.1‰ and -62.6‰ (-83.0‰ average; Fig. 7). This is consistent with the AMWL. San Acacia Dam is the diversion structure for the Socorro Basin irrigation system, so this water is most likely to be similar to valley-wide recharge. The heaviest compositions occurred during large monsoonal flows of the Rio Salado in August 2022, which mixed with the Rio Grande water.

DISCUSSION

We discuss preliminary interpretations of major ion chemistry and environmental tracer results from groundwater and spring waters in the La Jencia-Socorro region within the context of the geologic framework. Interpretations are based largely on comparisons with other rift basins, including Plummer et al. (2012), Johnson et al., (2013), and Williams et al. (2013). Plummer et al. (2012) and Johnson et al., (2013) characterized hydrochemical processes in the Albuquerque and Española groundwater basins, respectively. The Española, Albuquerque, and La Jencia-Socorro Basins have stratigraphic and structural similarities, and geochemical findings from these studies have implications for the La Jencia-Socorro groundwater system. Williams et al. (2013) provided a three-dimensional perspective on sources contributing to surface and groundwaters at the Socorro Constriction (Fig. 2), focusing on groundwater within the Sevilleta National Wildlife Refuge (SNWR), and sites in the La Jencia and Socorro Basins, Sedillo/Socorro Springs, and the New Mexico Tech Geothermal Well.

La Jencia Basin

$CaHCO_3$-type water in the Magdalena Mountains and across the southern half of the La Jencia Basin is consistent with low TDS concentrations and stable isotope results indicating waters of near-meteoric composition near the recharge source, with no rock-water interaction or evaporation indicated (Fig. 7, Group 1). The northern half of the La Jencia Basin exhibits mixed type water (Fig. 5), and a few samples exhibit more depleted $\delta^{18}O$ values (Figs. 6, 7). Tritium results from Gross and Wilcox (1983) indicate that groundwater in this area is old relative to water in the Magdalena Mountains. The groundwater flow gradient is low across this portion of the basin (Fig. 4).

Groundwater and springs in San Lorenzo, Nogal, and Socorro Canyons have significant variability in chemical and isotopic composition (Figs. 5, 6). Many of these springs are fault-controlled (Chapin et al., 1978; Gross and Wilcox, 1983), and groundwater and spring discharge exhibit relatively high water temperatures (Appendix 1).

San Lorenzo Canyon is mostly $NaHCO_3$-type water, indicating ion exchange has taken place within the volcanic complex (Hall, 1963; Gross and Wilcox, 1983). Multiple isotopic measurements exist for this canyon (Fig. 6, Group 3). $\delta^{18}O$ and δD values range from between -6.5 to -8.5‰ and -53 to -67.2‰, respectively. The trend in isotopic measurements indicates waters that have undergone varying degrees of evaporation (Clark, 2015; Williams et al., 2013). Tritium values indicate mixing of more recent recharge relative to pre-1952 recharge (Williams et al., 2013). San Lorenzo Canyon springs occur along the N-S-striking Silver Creek fault and are roughly down-gradient of the rest of the inter-graben horst. It is also down-gradient of flow recharged in the Bear Mountains. The evaporated trend suggests that either the groundwater was evaporated as it flowed along the fault, or that it was more evaporated as it recharged at the Bear Mountains. Given the physical distance to the Bear Mountains and large offset from the LMWL, it seems likely that the San Lorenzo Canyon springs are sourced to the south within the inter-basin horst.

Nogal Canyon exhibits an array of water types. From the western canyon origin eastward, dominant water types are $CaHCO_3$, $NaHCO_3$, mixed, $CaSO_4$, and $NaSO_4$. The down-gradient trend from $CaHCO_3$ to $NaHCO_3$ suggests an evolution from meteoric through fractured volcanics. The transition from meteoric waters to $NaHCO_3$ waters, to undifferentiated waters, supports the hypothesis by Gross and Wilcox (1983) of mixing of different sources of water. The $CaSO_4$ to $NaSO_4$ evolution suggests a mixture of shallow groundwater from Mesozoic/Paleozoic aquifer units. $\delta^{18}O$ and δD values range from -8.6 to -11.66‰ and -52 to -65.18‰ and plot to the left of the MWL, although these values are still within the bounds of meteoric data (Fig. 7, Group 4). This suggests either (a) a different deuterium excess during recharge, or (b) low-temperature water-rock interactions (Jasechko, 2019). Variable water types and isotopic signatures in Nogal Canyon, combined with the mapped locations of numerous NW-SE-trending faults on the eastern side of the Socorro-Lemitar Mountains, suggest that waters (1) have a varied mixing ratio of regional (i.e., Magdalena Mountains) and local recharge (Socorro-Lemitar Mountains and focused recharge) within the canyon, and/or (2) flow through geologic units of different rock types. The differences in facies evolution on either side of the Socorro-Lemitar Mountains potentially indicates faults that act as barriers to flow directly across the mountain, and further suggests that groundwater is sourced from multiple deep flow paths.

Sedillo and Socorro Springs, located on the eastern Socorro-Lemitar Mountain front just north of Socorro Canyon, display similar isotopic signatures and water types to Nogal Canyon (Figs. 5–7, Group 4). $NaHCO_3$-type water in the Socorro Springs region suggests ion exchange has taken place (Hall, 1963). Additionally, helium isotope analysis results indicate these sites have "significant" and "high" mantle components best explained by mixing of deeply derived endogenic fluids, containing both mantle and crustal inputs, with shallow groundwater (Williams et al., 2013). Site proximity to the Socorro Caldera ring fault and the Socorro Canyon fault further support this interpretation (Fig. 2). The ring fault and basin-bounding faults will act as barriers to flow perpendicular to strike within bedrock, but as conduits to flow along the fractured dip plain, driving deep, regional flow to the surface.

Socorro Canyon exhibits mostly $NaSO_4$- and $NaHCO_3$-type waters (Fig. 5). Results from Gross and Wilcox (1983) suggested mixing of recent (<4-year-old) precipitation and older, regional groundwater flow at Nogal Canyon and perhaps at Socorro Canyon. Furthermore, the results indicate that groundwater in Socorro and Nogal Canyons consists of ~10–20% modern water mixed with 80–90% water that was >50 years old (Gross and Wilcox, 1983). Field parameters and stable isotope data measured along Socorro Canyon in 2019 (Table 1) support this local vs. regional groundwater recharge hypothesis. All wells sampled (SC-1, SC-2, SC-3) are interpreted to contain a mixture of regional and locally derived groundwater (Fig. 7, Group 5). However, this mixing ratio varies.

Compared to SC-1 and SC-2, well SC-3 (near Box Canyon) has low (558 $\mu S/cm^2$) specific conductivity, relatively high water temperature (65.5°F), high dissolved oxygen (5.54 ppm), and a lower pH (7.14 pH; Table 1). The lower pH and higher dissolved oxygen of SC-3 compared to SC-1 and SC-2 suggest that SC-3 contains a larger proportion of streamflow infiltration than SC-1 and SC-2. Compared to SC-3, wells SC-1 and SC-2 are interpreted to be less influenced by local stream infiltration. Wells SC-1 and SC-2 show high (>1000 $\mu S/cm^2$) specific conductivities and low dissolved oxygen (Table 1). Their pH values are also somewhat similar at 8.14 and 8.54.

The seep of Chupadera Spring (SC-011) has a high specific

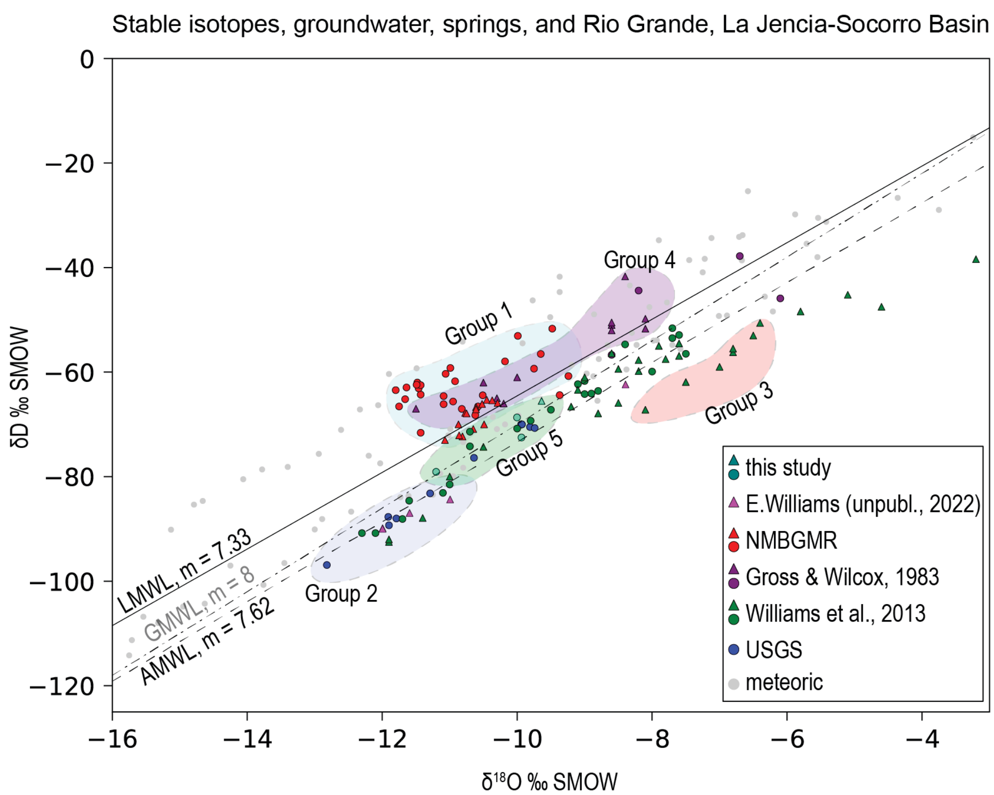

FIGURE 7. Stable isotopic composition of groundwater and spring waters in the Socorro and La Jencia Basins. Groundwater samples are represented by circles. Spring and/or surface water samples are represented by triangles. Points are color-coded by data source. Groups are indicated with colored polygons and represent the following: Group 1 – Magdalena Mountains and southern La Jencia Basin; Group 2 – Rio Grande Valley; Group 3 – San Lorenzo Canyon; Group 4 – Nogal Canyon, Socorro/Sedillo Springs cluster; Group 5 – Socorro Canyon. The local meteoric water line (LMWL) refers to the Socorro meteoric water line and was developed in this study. The Albuquerque meteoric water line (AMWL) is sourced from (Plummer et al., 2012). GMWL refers to the Global Meteoric Water Line (Craig, 1961).

conductivity (1843 μS/cm^2), high pH (8.14), cooler temperature (59.9°F), and relatively high dissolved oxygen (5.28 ppm; Table 1). The field parameters suggest that the water in the seep SC-11 is a mixture of regional water and local infiltration along Socorro Canyon. The $\delta^{18}O$ and δD values of the seep water (SC-011) were -9.6‰ and -66‰, respectively, and similar to that of nearby well SC-3 (-10‰ and -69‰; Table 1). Comparing SC-011 to the data in Gross and Wilcox (1983), SC-011 is most similar to the stable isotope composition of Lower Nogal Spring, Socorro Spring, and Sedillo Spring waters. Note that older measurements of δD are less accurate than modern measurements, but $\delta^{18}O$ values are generally comparable (Clark, 2015). While the exact flow path is impossible to determine, and knowing that the waters in SC-011 are a combination of young and old waters, the isotopic composition measurements suggest that SC-011 waters are 'evolved' waters from SC-03. Based on the conceptual model presented by Gross and Wilcox (1983), groundwater in SC-03 and SC-011 is a mixture of (1) deeper, recharged waters from Socorro Peak and possibly the local hills near Box Canyon (Fig. 1), and (2) rapid infiltration from summer-monsoonal flows in Socorro Canyon itself.

In summary, focused mountain-block recharge in the Magdalena Mountains infiltrates high-permeability faults and flows into the La Jencia Basin groundwater system. Shallow pathways are southwest to northeast from the Magdalena Mountains across the La Jencia Basin and west to east from the Magdalena Mountains through Socorro Canyon (Fig. 4). The Socorro-Lemitar Mountains are principally a discharge zone for groundwater sourced from a deeper groundwater flow path, presumably also southwest to northeast. There is evidence of flow from south-to-north in the Socorro-Lemitar Mountains. Groundwater flows beneath the Popotosa confining unit (Barroll and Reiter, 1990) and is forced upward through high-permeability fault zones. The Socorro-Lemitar Mountains are additionally a local recharge zone. Topographically driven flow from these local peaks contributes a small but significant component of recharge to surrounding canyons.

Socorro Basin

The Rio Grande Valley exhibits an expected variety of mixed-water types (Eastoe et al., 2010; Hogan et al., 2007; Phillips et al., 2003; Williams et al., 2013). Variable chemistry type waters along river corridors are often attributed to agricultural practices; however, water chemistry variations can also be explained by mixing of endogenic fluids with epigenic (dominated by meteoric recharge) water (Hogan et al., 2007; Phillips et al., 2003; Williams et al., 2013). Additionally, NaCl-dominant type water near the Socorro Constriction, where deep groundwater in the Albuquerque Basin is driven to the surface by the basin boundary, was found to have a significant mantle component (Williams et al., 2013). $\delta^{18}O$ and δD values from the Rio Grande Valley are depleted in both $\delta^{18}O$ and δD and fall near the AMWL (Plummer et al., 2012; Fig. 7, Group 2).

The Loma de las Cañas region exhibits $CaSO_4$-type waters. Williams et al. (2013) interprets this hydrochemical facies as shallow mixed groundwater from Mesozoic/Paleozoic aquifer units. This region is extremely structurally complicated with poor well coverage and also has a broad range of lithologies. In the bedrock terrain, lithologies range from the gypsum-poor Abo Formation to the extremely gypsiferous Yeso Formation, with a range of limestone, siltstone, and sandstone lithologies between (Fig. 3). It is likely that some of the spring waters and wells are sourced from confined aquifers, while other wells and springs are sourced in shallow alluvial aquifers. Between the structural complexity and the lithological heterogeneity, it is impossible to more specifically determine the source and nature of aquifers in this region without additional tracers.

The principal source of recharge in the Socorro Basin is focused recharge from the Rio Grande, which infiltrates into axial Rio Grande sediments. This is most clearly seen in the similarity between groundwater in the Socorro Basin and river water at San Acacia (Fig. 7, Group 2); this also falls along the AMWL trend (Fig. 7). Groundwater in the Socorro Basin along the riparian corridor does not, however, show depletion consistent with expected evaporation (Fig. 7; Clark, 2015). This raises several options. The Socorro Basin is also recharged by deep upwelling basin groundwater, which flows along conduits created by east-west-trending transfer zones (Socorro Constriction and Socorro accommodation zone; Fig. 2; Hogan et al., 2007; Phillips et al., 2003; Williams et al., 2013). We see potential evidence for deep upwelling flows by presence of occasional $NaHCO_3$ and $CaHCO_3$ waters; this could be local effects, or this could be mixing of shallow and deeper waters. The basin is narrow, and the basin-bounding mountains receive little precipitation; consequently, lateral shallow recharge to the basin is minimal. If there is a deeper groundwater signal, it is likely sourced from the La Jencia Basin by a deep flow path. Overall, Socorro Basin groundwater likely flows north to south down-gradient along high-conductivity axial river sediments. Hogan et al. (2007) found a large increase in chloride concentration at the Bosque del Apache National Wildlife Refuge at the southern edge of the Socorro Basin, consistent with deep axial flow interpreted in Williams et al. (2013) in the Albuquerque Basin, as well in the Española Basin (Johnson et al., 2013). The chloride increase is suggestive of deeper flows along the axis of the basin being driven up by underlying geologic structures.

SUMMARY

Our preliminary synthesis of previous work and our new isotopic data suggest that contributions to the groundwater system are (1) minimally evolved epigenic/meteoric, and (2) geothermal (circulation and heating of recharge). However, isotopically, all of the sampled waters are similar to local meteoric water and river water, with some evaporation trends. This argues for regional recharge in the Magdalena Mountains, small amounts of local recharge in the Socorro-Lemitar Mountains, and focused recharge from the Rio Grande. The pattern of flow paths is complicated. Water recharged in the Magdalena Mountains penetrates to different depths and then flows across the La Jencia Basin; the pattern of flow around the

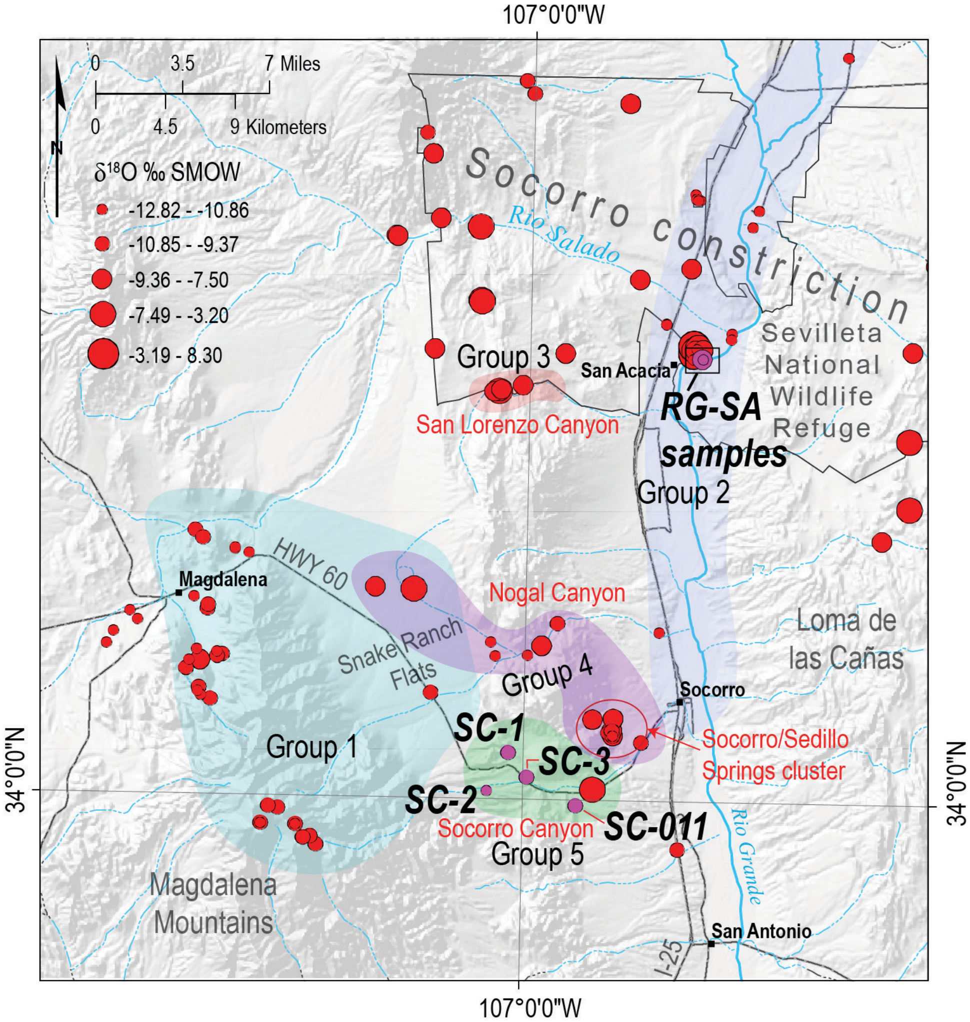

FIGURE 8. Spatial distribution of stable isotopic data displayed in Figure 7. Points are scaled in size by $\delta^{18}O$ value (‰ SMOW) as indicated in the legend. See Figure 6 caption for Group descriptions. Samples SC-1, SC-2, SC-3, and SC-011 are new Socorro Canyon samples.

lower-relief Bear Mountains to the north and the topographically low southern La Jencia Basin boundary are unknown. A significant amount of the groundwater flow in the La Jencia Basin is relatively shallow and discharges from springs along the Socorro-Lemitar interbasin horst. These springs are also more locally sourced by focused recharge in the Socorro-Lemitar interbasin horst. Other, deeper flow paths through the La Jencia Basin exist and flow out as isotopically depleted waters at springs and wells; the deepest flow paths come into the Socorro Basin as warm springs.

In the Socorro Basin, the shallow groundwater table shows a combination of lateral E-W flows toward the LFCC, but also more complicated patterns in the floodplain. The LFCC acts as a regional drain for the basin. Regional geochemistry of the Rio Grande and LFCC waters, however, shows that there are regions of upwelling chloride-rich brines. In the Albuquerque and Española Basins, these are associated with deep endogenic flows flowing up along EW-striking structures. We lack both the geophysical and physical constraints and the detailed geochemical data needed to support this hypothesis in the Socorro Basin, but it is reasonable, inasmuch as chloride-rich brines are present at the southern edge of the Socorro Basin (Hogan et al., 2007). Another source could be from deep flows recharged in the Magdalena Mountains, then released out of bedrock structures into the Socorro Basin aquifer. The details of the hydrogeologic plumbing of the basins in the vicinity of Socorro will remain enigmatic without further study.

From this synthesis, a few key perspectives on the current state of groundwater understanding in the La Jencia and Socorro Basins can be given. First, the overwhelming majority of groundwater studies in this area have focused on hydrochemical methods (Gross and Wilcox, 1983; Hall, 1963; Hogan et al., 2007; Phillips et al., 2003; Anderholm, 1983, 1987; Moore and Anderholm, 2002; Plummer et al., 2012; Williams et al., 2013; Williams et al., 2015; Johnson et al., 2013). Plummer et al. (2012), Johnson et al. (2013), and Williams et al. (2013) clearly demonstrate the advantages of using a robust and diverse set of geochemical data to characterize hydrochemical processes. The general chemistry and isotopic dataset presented here provides an excellent starting point for regional-scale interpretations regarding groundwater flow processes. The current coverage of stable isotope data has large gaps in the northern La Jencia Basin and along much of the Socorro Basin (Fig. 8). Even so, interpretations made from isotopic signatures combined with general chemistry data suggest that isotopic methods will be key to understanding the hydrogeology of these basins.

While there are many advantages to using geochemical data to understand groundwater flow processes, it is challenging to characterize groundwater flow paths in three dimensions with only shallow well data and without a 3D geologic framework, especially in geologically complex regions. In contrast to simple, horizontal, unconfined groundwater flow, topographically driven groundwater flow under spatially varying degrees of confinement consists of nests of groundwater flow paths, the distribution of which are highly dependent on stratigraphic heterogeneity and structural variations. To understand groundwater flow paths, we need geophysical and well data that can be used to constrain a 3D basin framework. As such, key future work includes the following: (1) collection of high-resolution potential field data (gravity and magnetic); (2) high-resolution water sampling for environmental tracers perpendicular and parallel to presumed flow paths in order to capture flow variability; and (3) integration of geophysical data with current/additional environmental tracer data using numerical methods to identify and quantify significant groundwater flow transitions within the hydrologic system. These methods should provide a quantitative estimate of the relative contributions of epigenic/meteoric, geothermal, and endogenic inputs to the Socorro-La Jencia Basin groundwater system, and they should further the general understanding of extensional basin hydrogeology.

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Appendices can be found at
https://nmgs.nmt.edu/repository/index.cfml?rid=2022008