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ORIGINAL ARTICLE

Geochemical indicators of interbasin groundwater flow within the southern Rio Grande Valley, southwestern USA

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Abstract Increased groundwater withdrawals for the growing population in the Rio Grande Valley and likely alteration of recharge to local aquifers with climate change necessitates an understanding of the groundwater connection between the Jornada del Muerto Basin and the adjoining and more heavily used aquifer in the Mesilla Basin. Separating the Jornada and Mesilla aquifers is a buried bedrock high from Tertiary intrusions. This bedrock high or divide restricts and/or retards interbasin flow from the Jornada aquifer into the Mesilla aquifer. The potentiometric surface of the southern Jornada aquifer near part of the bedrock high indicates a flow direction away from the divide because of a previously identified damming effect, but a groundwater outlet from the southern Jornada aquifer is necessary to balance inputs from the overall Jornada aquifer. Differences in geochemical constituents (major ions, δD, δ^{18}O, δ^{34}S, and ^{87}Sr/^{86}Sr) indicate a deeper connection between the two aquifers through the Tertiary intrusions where Jornada water is geochemically altered because of a geothermal influence. Jornada groundwater likely is migrating through the bedrock high in deeper pathways formed by faults of the Jornada Fault Zone, in addition to Jornada water that overtops the bedrock high as previously identified as the only connection between the two aquifers. Increased groundwater withdrawals and lowering of the potentiometric surface of the Jornada aquifer may alter this contribution ratio with less overtopping of the bedrock high and a continued deeper flowpath contribution that could potentially increase salinity values in the Mesilla Basin near the divide.

Keywords Jornada · Mesilla · Rio Grande · Geothermal influence · δD · δ^{18}O · δ^{34}S

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Introduction

Freshwater resources in arid and semiarid areas are highly vulnerable to drought and climate change (Kundzewicz et al. 2007), and aquifers in these regions, such as the southwestern USA, can be stressed because of large groundwater withdrawals to sustain human development in these climates (Alcamo et al. 2003a, b). In the southwestern USA, the shallow aquifer within the Jornada del Muerto (Jornada) Basin (Fig. 1) within the Rio Grande Valley has received increasing attention as an additional water source for human development in the southern reach of the Jornada and adjacent transnational Mesilla Basin. With the possibility of increased withdrawals from the Jornada and Mesilla aquifers and a possible change in form, timing, and amount of precipitation that will decrease recharge with climate change (Field et al. 2007), an understanding of the connection between the aquifers is necessary to evaluate any potential effects on either of the aquifers.

A buried bedrock high from Tertiary intrusions (Oligocene to Miocene) divides the Jornada and Mesilla aquifers and likely restricts and (or) retards groundwater contributions from the Jornada aquifer into the Mesilla aquifer. Woodward and Myers (1997) suggested that little to no water is transmitted through the bedrock high separating these basins, but the overlying Santa Fe Group deposits are saturated and likely allow some groundwater flow between

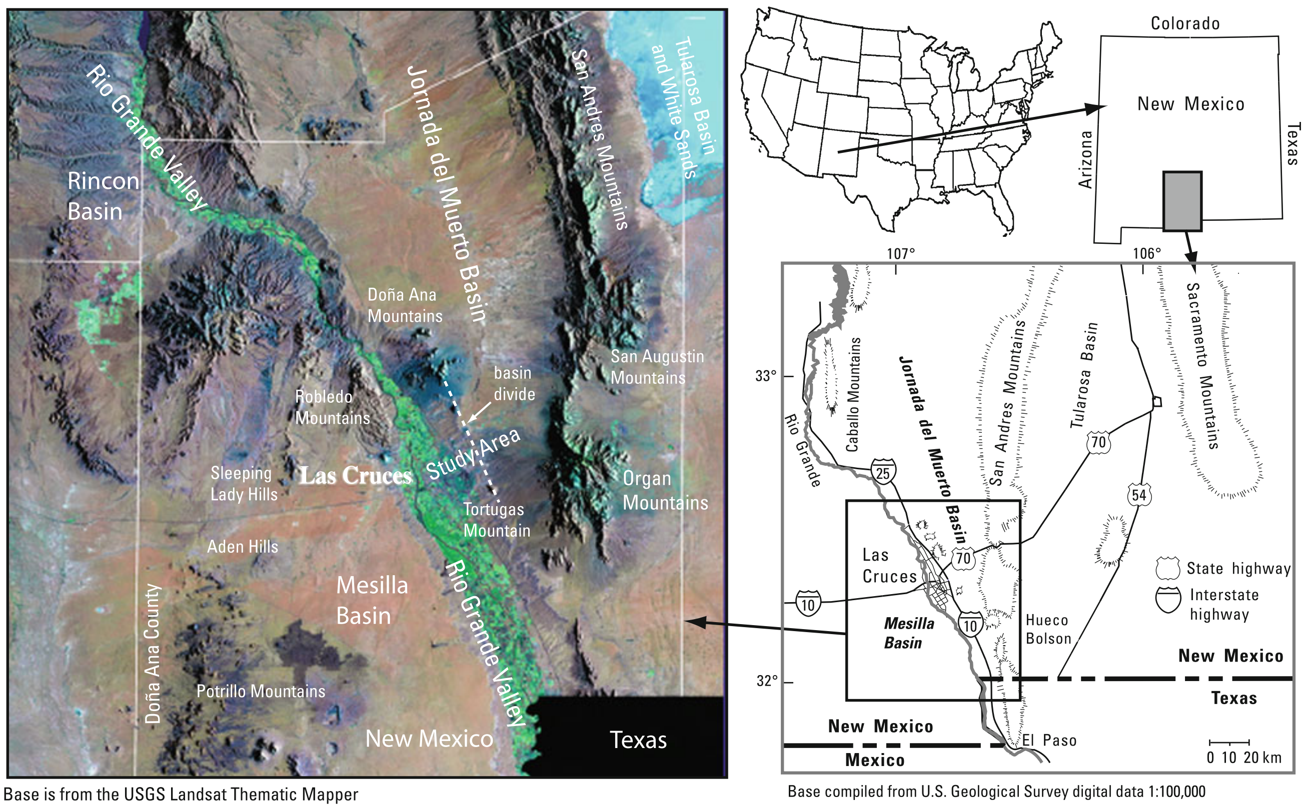


Fig. 1 Mesilla and Jornada del Muerto basins along the Rio Grande in southern New Mexico, USA

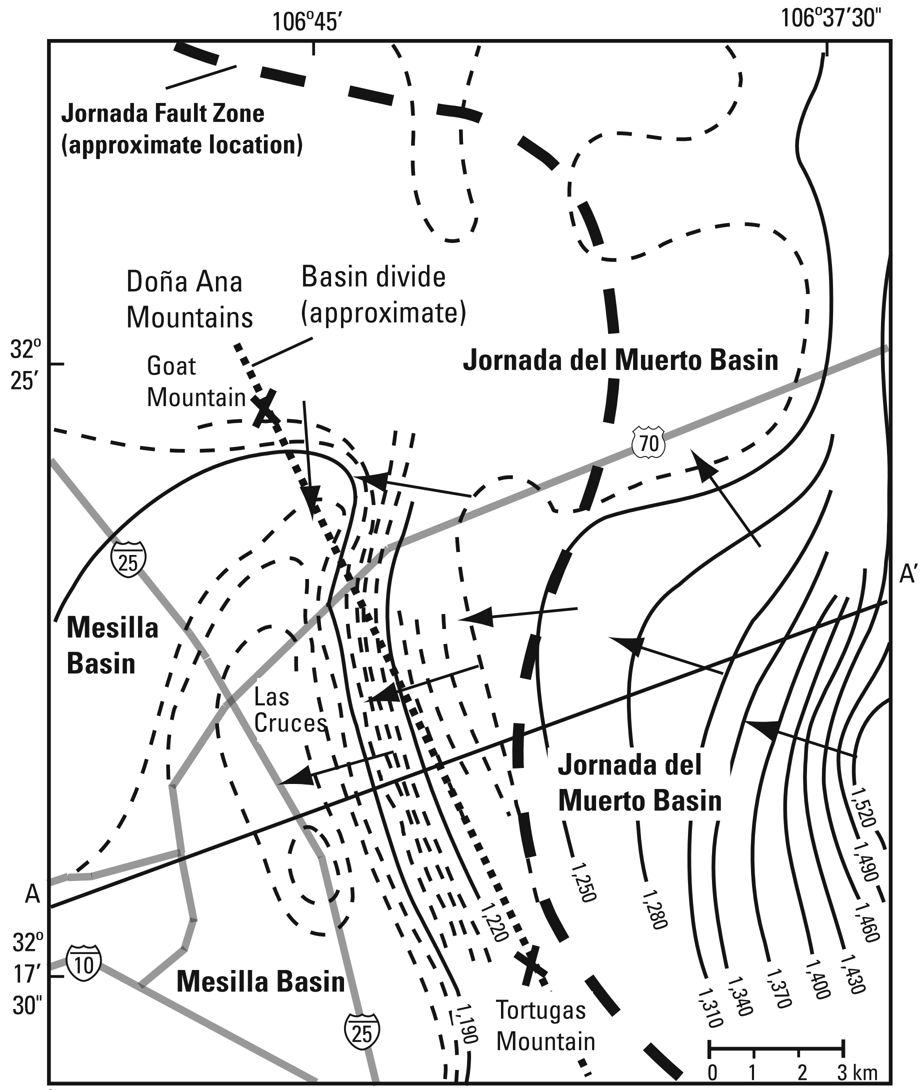
the basins. This possible transfer of groundwater between the aquifers through the sediments overlying the buried horst composing the divide generally has been accepted as the only pathway between the aquifers, as no studies have closely examined the issue of interbasin transfer through the Tertiary intrusions. Woodward and Myers (1997) and Witcher et al. (2004) suggested that deeper water migrates upward around the divide, but the source of this water has not been identified.

Witcher et al. (2004) described the geologic and geochemical characteristics of the Mesilla aquifer and noted a geothermal influence in the northern and eastern Mesilla along the divide with the Jornada that helps to shape the groundwater composition in this area. For this study, the geothermal influence is described as the "geothermal effect", and this effect represents the influence of residual heat associated with Tertiary intrusions that has an influence on groundwater composition through enhanced dissolution of minerals and increased solubility of certain elements in solution. The data from Witcher et al. (2004) was compared with data collected in 2009 from the southern Jornada aquifer near the Jornada–Mesilla divide to examine possible geochemical correlations and to better understand the connection between the Jornada and Mesilla aquifers. This study presents a multi-solute (major ions and select trace elements) and multi-isotope (δD, δ^{18}O, δ^{34}S, and ^{87}Sr/^{86}Sr) approach to help resolve the possible interbasin transfer in an area where multiple surface-recharge points, a lack of identified flowpaths, and a geothermal effect influence groundwater flow and composition.

Hydrogeological setting

The Mesilla and Jornada basins are north–south trending, contiguous basins located in the southern Rio Grande Rift structural province within the larger Mexican Highland section of the Basin and Range physiographic province (Fenneman 1931; Hawley 1986). The Jornada Basin is a Neogene intermontane, synclinal basin with about 1.4–3.6 km of basin fill along its axis (Gilmer et al. 1986; Harder et al. 1986). The Oscura, San Andres, and San Augustin Mountains are located along the basin's eastern margin and various small peaks, including the Doña Ana and Tortugas Mountains, compose its western margin, which separates it from the Mesilla Basin (Fig. 1). The transition from the Jornada Basin to the Mesilla Basin is not distinctly identifiable at the surface, but is present as a low topographic rise near Highway 70 and east of Interstate Highway 25. The basin divide includes the Jornada Fault Zone and a bedrock high (mostly buried horst) that includes Goat Mountain in the Doña Ana Mountains and Tortugas

Fig. 2 Estimated groundwater flow patterns in the Mesilla and southern Jornada del Muerto basins (modified from Wilson et al. (1981), courtesy of the New Mexico State Engineer; fault zone from Woodward and Myers (1997), courtesy of the US Geological Survey)



Mountain (northwest to southeast alignment, Figs. 1, 2). The Mesilla Basin is bounded on the east by the Organ and Franklin Mountains and on the west by fault-block and volcanic uplands that include the Robledo and Potrillo mountains and the Sleeping Lady and Aden hills. The primary aquifer matrix of the Mesilla and Jornada basins is the Santa Fe Group, which is composed of alluvial, eolian, and playa lake sediments (Hawley and Kennedy 2004). The Santa Fe Group can be subdivided into upper, middle, and lower hydrostratigraphic units with sandy to clayey basin-floor deposits in the upper unit, coarser fluvial deposits in the middle unit, and finer deposits in the lower unit that also include lake and playa deposits (Hawley and Kennedy 2004; Hawley et al. 2009). The Santa Fe Group overlies Tertiary volcanic and associated sedimentary rocks that compose the buried horst, and Quaternary alluvium deposited following initiation of the Rio Grande Valley overlies the Santa Fe Group (Hawley et al. 1969; Hawley and Lozinsky 1992).

The majority of recharge in the Jornada Basin occurs through precipitation along the mountain fronts (Hibbs 1999). Except for a few perennial springs and seeps and short reaches of intermittent mountain streams, there are no permanent surface-water bodies. The Jornada Basin is an enclosed basin with no drainage outlets such as the Rio Grande in the adjacent Mesilla Basin. Existing water users in the Jornada Basin withdraw water from the aquifer in the southern part of the basin where the City of Las Cruces is locating new municipal supply wells. Substantially larger water use is present in the Mesilla Basin where the through-flowing Rio Grande is heavily used for agriculture along with smaller uses for municipal and industrial uses in addition to groundwater from wells located throughout the

Mesilla Basin in New Mexico, Texas, and Mexico. Mesilla groundwater is the primary municipal supply of the area, and recharge to the Mesilla is primarily through infiltration of Rio Grande water (Frenzel et al. 1992).

Jornada–Mesilla divide

The structures of the Jornada and Mesilla basins are a result of the compressional Laramide environment during the late Cretaceous to mid-Cenozoic followed by widespread Oligocene volcanism and the Neogene extensional environment associated with the Rio Grande Rift (Keller et al. 1990). This area is typical Basin and Range morphology that contains strongly tilted mountain blocks and a tendency toward half-graben morphology and listric boundary faults (Seager 1995; Seager et al. 1987; Mack and Seager 1990; Seager and Mack 1994; Leeder et al. 1996). The Jornada–Mesilla divide consists of a buried horst, the Doña Ana-Tortugas Uplift (King et al. 1971; Hawley 1984; Mack 1985; Woodward and Myers 1997), which is primarily composed of volcanic and volcaniclastic rocks overlying Permian sedimentary rocks (Woodward and Myers 1997). The divide is heavily faulted (Jornada Fault Zone), and these faults are mainly Pleistocene normal faults (Fig. 3). Goat Mountain and Tortugas Mountain are the only distinct surface expressions of the eroded bedrock high that separates the Mesilla and Jornada basins (Hawley and Kennedy 2004).

Groundwater has been hypothesized to move from the Jornada aquifer to the Mesilla aquifer through the Santa Fe Group that overlies the bedrock high (Woodward and Myers 1997; Hawley and Kennedy 2004), but little evidence has been found to support this conclusion (Woodward and Myers 1997). Woodward and Myers' (1997) investigation of groundwater flow between the aquifers showed that some test holes along the aquifer boundary contained little or no groundwater, and some test holes contained some groundwater flowing through the Santa Fe Group deposits above the bedrock high. Woodward and Myers (1997) interpreted the gross geometry of the horst, but examination of seismic-reflection data was unable to identify the presence or absence of channels incised into the horst. It was hypothesized that incised, buried channels atop or within the horst could provide pathways for inter-basin transfer of groundwater across this divide. Interpretation of the seismic-reflection data by Wilson et al. (1981) and Woodward and Myers (1997) did indicate that the water table was estimated to lie above the altitude of the buried horst from Highway 70 to Tortugas Mountain (southward direction), but the horst altitude likely is above the water table north of Highway 70. With the southward flow of water in the Jornada Basin, the horst causes a rise and steepening of the potentiometric surface along the divide (Peterson et al. 1984). It was hypothesized that groundwater in the Jornada likely accumulates until it

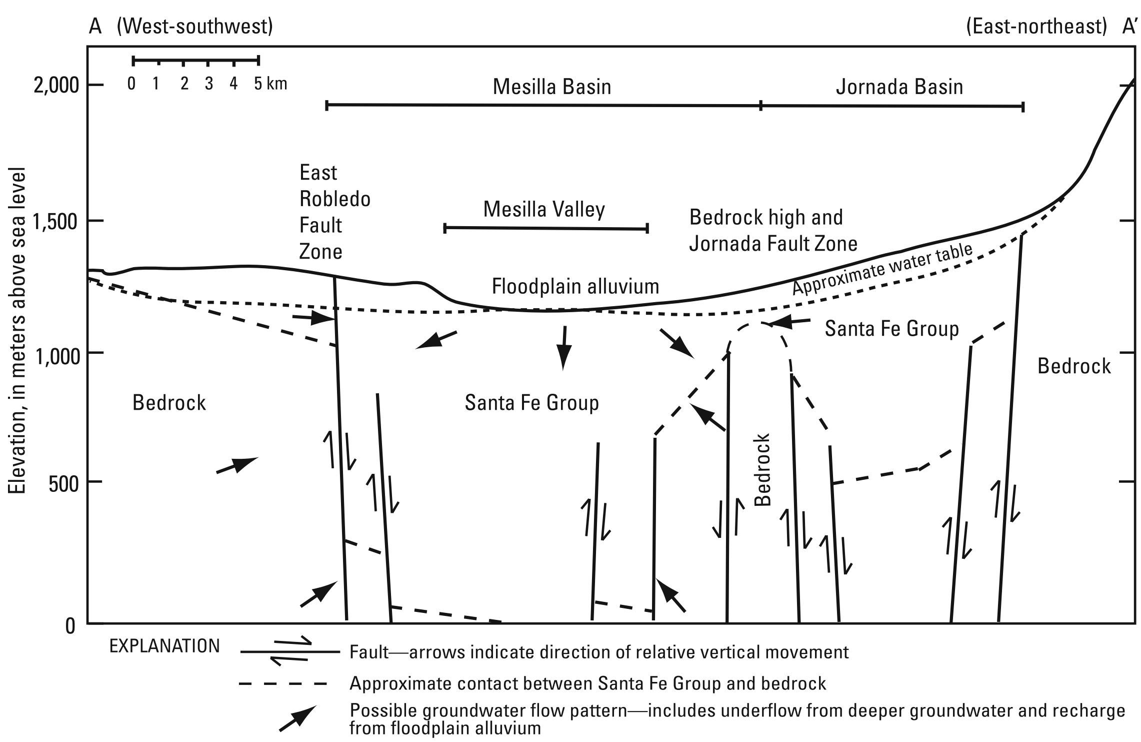


Fig. 3 Generalized structural cross section of the Mesilla Basin and the Jornada del Muerto Basin (modified from Woodward and Myers 1997, courtesy of the US Geological Survey)

reaches a permeable path that allows groundwater to overtop the eroded horst (Peterson et al. 1984; Woodward and Myers 1997; Hawley and Kennedy 2004), thereby providing an outlet for Jornada groundwater that moves southward in this enclosed basin. Additionally, geothermal waters of unknown source(s) are migrating into the Mesilla aquifer near the Jornada Fault Zone (Swanberg 1975; Frenzel et al. 1992; Witcher et al. 2004).

The current conceptual model of flow between the Jornada and Mesilla basins only considers flow through permeable paths in the Santa Fe Group overlying the horst (Wilson et al. 1981; Peterson et al. 1984; Frenzel et al. 1992; Woodward and Myers 1997; Hawley and Kennedy 2004). The groundwater moving through these Santa Fe Group flowpaths likely is a minor contribution to the Mesilla Basin (Woodward and Myers 1997; Hawley and Kennedy 2004). Deeper inflow to the Mesilla Basin near the divide is attributed to the geothermal effect that causes an upwelling of groundwater into the shallower part of the aquifer. The source of the geothermal water is speculated to be deep basinal water of possible intrabasinal origin (Phillips et al. 2003; Hibbs and Merino 2006; Witcher et al. 2004; Hogan et al. 2007; Moore et al. 2008). This conceptual model is understandable because of the likely low permeability of the Tertiary intrusion compared to the likely much higher permeability of the unconsolidated Santa Fe Group sediments separating the Jornada and Mesilla basins. The lack of investigation of possible flowpaths through the horst from the Jornada to the Mesilla has limited the inclusion of such pathways as a possible connection between these basins, and the geothermal water along the divide in the Mesilla Basin has simply been identified as deeper basinal water without a discrete source.

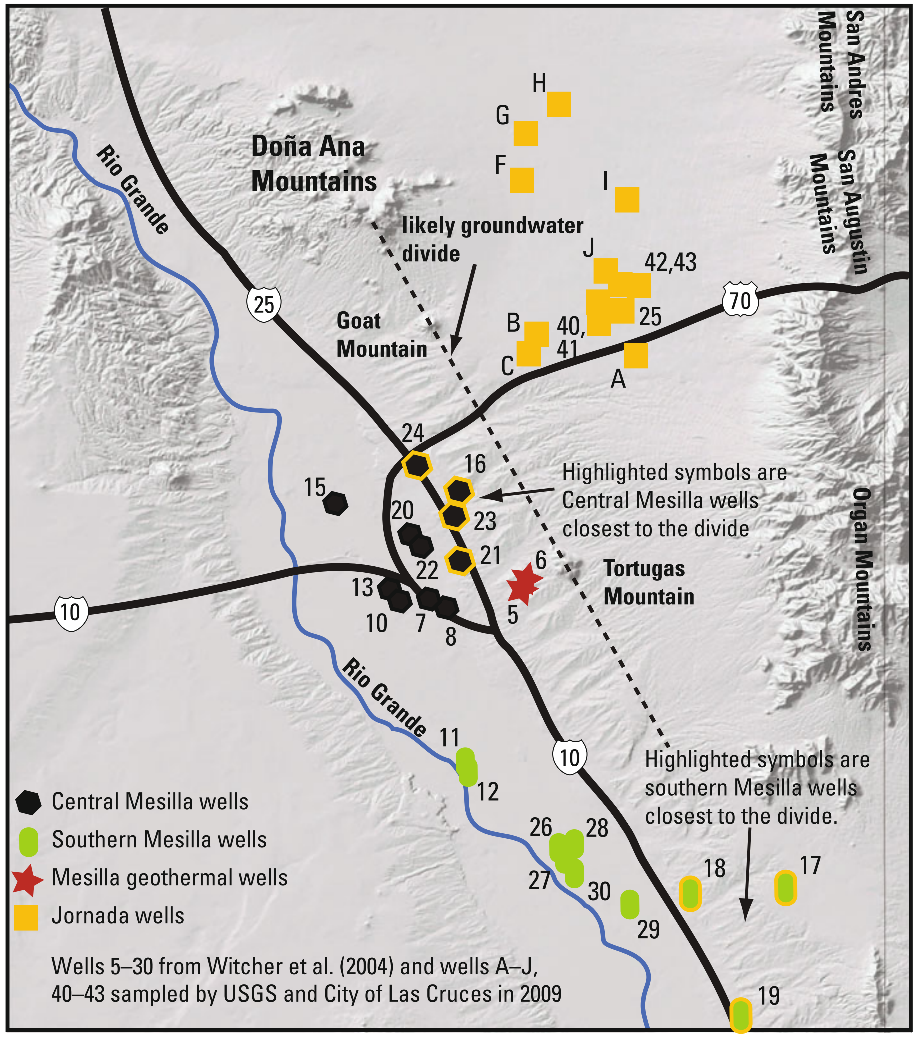
Methods

Jornada groundwater samples were collected in July 2009 as part of a monitoring project overseen by the USGS, and the data are freely available through the USGS National Water Information System. Various wells comprise the monitoring network (Fig. 4)—ten wells that are privately owned, measured for water level and water quality by the USGS, and four wells that are municipal production wells, measured for water level and water quality by the City of Las Cruces. The Witcher et al. (2004) data (Table 1) were collected as part of a larger geologic and geochemical investigation of salinity in the Mesilla Basin, and the data are publicly available through the New Mexico Water Resources Research Institute. All wells have their screens set in the Santa Fe Group. Within the individual basins, the hydrostratigraphic units of the Santa Fe Group should be hydraulically connected (vertically and horizontally) because of the relatively coarse nature of the unconsolidated sediments. All USGS project samples were collected as 0.45 µm-filtered water for analysis of all constituents listed in Table 2. During well purging by the USGS, field values of specific conductance, water temperature, and pH were monitored in a flowthrough chamber and allowed to stabilize prior to sample collection. Sequential-replicate samples were collected at randomly selected wells to evaluate laboratory precision and all replicate values were within 10 % of each other. Environmental samples were collected for laboratory matrix-spike analysis to ascertain matrix interference through standard additions of the analytes, and no matrix interference issues were identified. Samples collected by the City of Las Cruces in 2009 were measured for the same field properties, and the samples were measured for the same major ion and trace element constituents, although as total concentrations (unfiltered) instead of dissolved concentrations. These results should be comparable to the USGS and Witcher et al. (2004) dissolved concentrations, because of the well-developed screen and filter packs at the municipal wells that produce very low turbidity measurements (<0.20 NTU for all city well samples). Results from the City of Las Cruces wells did not indicate any substantial inputs of particulates and subsequent release of elements because of digestion during sample preparation (comparable major ion and SiO_2 values to the dissolved concentrations from the other wells). Isotope results are not available for the groundwater samples collected from the City of Las Cruces municipal wells. All major ion, trace element, δD, $\delta^{18}O$, and $\delta^{34}S$ of SO_4 data from 2009 were obtained through analysis of groundwater samples according to established and published procedures (Table 2), and $^{87}Sr/^{86}Sr$ data were obtained through analysis of groundwater samples according to accepted procedures. Ratios of $^{87}Sr/^{86}Sr$ were measured on a Finnigan Mat 261 thermal ionization mass spectrometer. Following purification through ion exchange, the Sr was mixed with phosphoric acid and loaded on degassed, zone-refined tantalum filaments. The resulting $^{87}Sr/^{86}Sr$ ratios were normalized to $^{86}Sr/^{88}Sr$ of 0.1194.

Some of the isotopic data (δD and $\delta^{18}O$ of water and $\delta^{34}S$ of SO_4) were used to inversely calculate the possible contributions of Jornada groundwater to the southeastern Mesilla Basin. End members were the median values of the Jornada data and median values of wells 26–30 representing the southern Mesilla that contributed to the resulting mixture represented by groundwater in the southeastern Mesilla (wells 17–19). To estimate fractional contributions of source waters, isotope data were inserted into a binary, isotope-mixing equation:

$$R_M = R_A f_A + R_B(1 - f_A),$$

where R = isotopic ratio, M = mixture, A = component 1, B = component 2, and f = compositional fraction of mixture.



Base from U.S. Geological Survey, National Elevation Dataset, shaded relief, 1 arc second

Fig. 4 Well locations in the study area

Microsoft Excel Solver (what-if-analysis tool) was used to perform the inverse calculations (precision equal to 0.00001, convergence set at 0.0001). The inverse calculator varied the possible fractional contribution of each end member that had a known isotopic signal to minimize the residual of the calculated output compared to the known isotopic signal of the mixture. Each constituent was assumed to behave conservatively to compare the fractional contribution differences between constituents that should behave conservatively (δD and δ^{18}O of water) and those that likely do not behave conservatively (δ^{34}S of SO_4 and ^{87}Sr/^{86}Sr) because of the geothermal effect.

Conceptual model

Previous studies provide an initial conceptual model of the possible flowpaths at the study site. Given what is known about the altitude of the potentiometric surface and the eroded bedrock of the Jornada–Mesilla divide, it is possible for Jornada water to enter the Mesilla Basin where the potentiometric surface overtops the bedrock high (more likely southward of Highway 70), and greater interbasin transfer may occur where eroded channels in the bedrock are present. The Jornada and Mesilla aquifers should be influenced by similar local recharge sources, such as precipitation along the San Andres and Organ mountains, but the Mesilla Basin is highly influenced by recharge from the Rio Grande (Witcher et al. 2004; Szynkiewicz et al. 2011). Comparison of the Jornada and Mesilla datasets tests whether a geochemical signal can be established for Jornada groundwater that is different from groundwater in the Mesilla Basin and whether the influence of Jornada water is visible in the central or southern Mesilla Basin. Geochemical data from Witcher et al. (2004) and the more recent (2009) data collected by the USGS and City of Las Cruces are listed in Tables 3 and 4.

Table 1 Study area wells in the Jornada del Muerto Basin and wells from Witcher et al. (2004) in the Mesilla Basin

Well number	Longitude (NAD83)	Latitude (NAD83)	Elevation (m)	Total depth (m)	Productive interval (m)
Jornada del Muerto wells, USGS and City of Las Cruces monitoring					
C	32.4031	106.7090	1,339.6	149.4	NA
B	32.4106	106.7052	1,339.3	137.2	107–137
A	32.4036	106.6558	1,393.9	243.8	NA
I	32.4696	106.6595	1,372.8	170.7	NA
H	32.5101	106.6944	1,324.7	121.9	NA
G	32.4981	106.7116	1,313.4	97.5	91–98
J	32.4390	106.6703	1,364.3	157.0	151–157
F	32.4774	106.7124	1,311.2	101.5	92–101
25	32.4172	106.6734	1,361.8	304.8	NA
40	32.4174	106.6740	1,364.9	356.6	201–221, 236–286, 331–351
41	32.4247	106.6742	1,362.2	396.2	198–292
42	32.4325	106.6604	1,381.4	356.6	213–351
43	32.4325	106.6549	1,390.5	350.5	223–344
Witcher et al. (2004) wells in the Mesilla Basin					
Central Mesilla wells (5 and 6 are geothermal wells)					
5	106.7170	32.2842	NA	262.1	NA
6	106.7144	32.2881	NA	309.4	NA
7	106.7618	32.2807	1,183.2	217.0	98–141, 167–203
8	106.7534	32.2744	1,192.4	233.5	96–233
9	106.7763	32.2777	1,184.1	46.9	NA
10	106.7752	32.2777	1,184.1	24.4	NA
13	106.7798	32.2841	1,184.1	213.4	NA
15	106.8076	32.3259	1,189.6	188.1	142–188
16	106.7517	32.3299	1,277.1	146.3	84–146
20	106.7508	32.3199	NA	212.4	139–168, 180–212
21	106.7467	32.2967	1,217.4	189.0	122–183
22	106.7663	32.3057	1,200.9	213.4	NA
23	106.7509	32.3199	1,243.6	207.3	NA
24	106.7688	32.3445	1,242.1	181.7	139–182
Southern Mesilla wells					
11	106.7426	32.2031	NA	152.4	NA
12	106.7418	32.1991	NA	61.0	NA
17	106.5903	32.1441	NA	161.5	144–162
18	106.6371	32.1419	NA	124.4	73–106, 92–124
19	106.6075	32.0717	NA	144.8	122–145
26	106.6983	32.1640	1168.9	117.3	85–116
27	106.6982	32.1625	NA	79.2	NA
28	106.6926	32.1652	1168.9	173.7	132–169
29	106.6649	32.1399	NA	NA	NA
30	106.6899	32.1529	NA	88.4	85–88

Groundwater flow directions

The potentiometric surface of the southern Jornada aquifer in 2009 had highly variable flow directions (Fig. 5) similar to the water-level contouring by Wilson et al. (1981) as shown in Fig. 2. The westward flow direction in the northeastern part of the Jornada likely is related to recharge in the San Andres Mountains, and the southward flow direction in the northern part is regional flow moving southward in the overall Jornada aquifer (typical of the intermontane, alluvial aquifers within the Rio Grande Rift). It is critical to note the northward flow direction away from

Table 2 Sample analytes and laboratory analysis methods for groundwater samples collected in the Jornada del Muerto Basin

Constituent	Description	Instrument or method	Medium	Laboratory	Analytical precision
Field values	Water temperature, pH, conductance	Orion 130A, Orion 250A+	Water	Field collection	±0.1 °C, ±0.02 pH, +0.5 % µS/cm
Alkalinity	Alkalinity as $CaCO_3$	MCAWW 310.1	Water	TestAmerica, Denver	1.1 mg/L
Major anions	Br, Cl, F, SO_4	MCAWW 300.0A	Water	TestAmerica, Denver	0.06–1.2 mg/L
Major cations	Ca, Mg, Na, K	SW846 6010B	Water	TestAmerica, Denver	0.034–1.1 mg/L
Trace elements	SiO_2, Sr	SW846 6010B4, SW846 60204	Water	TestAmerica, Denver	0.01–2 µg/L
Water isotopes	$^2H/^1H$, $^{18}O/^{16}O$	Révész and Coplen (2008a, b)	Water	USGS Reston Stable Isotope Laboratory	±2 ‰ as δD and ±0.2 ‰ as $\delta^{18}O$
Sulfate isotopes	$^{34}S/^{32}S$ of SO_4	Révész and Qi (2006)	Water	USGS Reston Stable Isotope Laboratory	±0.2 ‰ $\delta^{34}S$
Strontium isotopes	$^{87}Sr/^{86}Sr$	Positive thermal ionization mass spectrometry	Water	USGS Menlo Park Regional Research Laboratory	±0.00002 as $^{87}Sr/^{86}Sr$

°C degrees Celsius, *µS/cm* microsiemens per centimeter at 25 °C, *mg/L* milligrams per liter, *µg/L* micrograms per liter, *USGS* US geological survey, *mmol/L* millimoles per liter, $\delta^x X$ (‰) = $(\text{Ratio}_{sample}/\text{Ratio}_{standard} - 1) \times 1{,}000$ of specified isotope ratio; ‰, per mil

the Jornada–Mesilla divide (Fig. 5). The damming effect of the divide, as discussed by Peterson et al. (1984) and Woodward and Myers (1997), creates a potentiometric surface that can move water away from this location. The accumulation of groundwater because of the damming effect would allow an overtopping of the buried horst and flow into the Mesilla somewhere along the Jornada–Mesilla divide as hypothesized by Peterson et al. (1984). Overtopping of the divide and groundwater flow through the Santa Fe Group sediments has been accepted as a likely flowpath because of the necessity to lessen the accumulating water in the southern Jornada.

Groundwater chemical environments

The Mesilla aquifer is primarily recharged by the Rio Grande, including associated agricultural canals and drains, with local inputs from mountain-front recharge in the higher elevations along the eastern and western boundaries of the basin (Frenzel et al. 1992; Nickerson and Myers 1993; Anderholm 2000). The Jornada aquifer receives recharge from precipitation along the San Andres Mountains and probably some central basin recharge because of playa lake accumulations (Anderholm 2000). There is no agricultural irrigation in the Jornada except for a minor amount to sustain a few hectares of nut trees. Field properties of water collected from the Jornada and Mesilla basins indicate similar neutral to alkaline chemical environments. Water temperatures were mostly between 15 and 35 °C, although there is a small subset of Mesilla wells that contains groundwater above 55 °C. These wells are strongly influenced by the geothermal effect, which also produces slightly acidic water (Table 3). Groundwater in the Jornada was generally warmer than groundwater in the Mesilla (excluding the geothermal wells) except for the southeastern Mesilla wells along the Mesilla–Jornada divide that had higher water temperatures and slightly lower pH. Central Mesilla wells near the Jornada–Mesilla divide (wells 16, 21, 23, and 24) contained groundwater similar in pH and temperature to water within the Jornada aquifer (Table 3).

Major ion concentrations were different for water from the Jornada and Mesilla basins and between the central and southern parts of the Mesilla Basin (Table 3; Fig. 6). Jornada groundwater contains a greater amount of Mg and SO_4 than Mesilla groundwater, and Jornada water fluctuates in its anion dominance with a mixture of HCO_3 and SO_4 dominance among the wells. Within the Mesilla, Cl-rich, geothermal water is present in the central Mesilla (wells 5 and 6, which are noted geothermal wells) and a similar effect appears to influence southern Mesilla groundwater wells with the largest influence apparent in water from the most southeastern wells (17, 18, and 19) along the Mesilla–Jornada divide. The geothermal water has a NaCl signal indicative of the dissolution of halite. The Rio Grande in the Mesilla Basin has shown a similar increase in Cl with downgradient flow (Bexfield and Anderholm 1997). A deep water input to the Mesilla Basin that increases its influence in the downgradient direction has been suggested as the source of increased salinity in the basin (Moore and Anderholm 2002; Witcher et al. 2004; Hogan et al. 2007), although agriculture inputs also have been identified as a contributing factor to this salinity increase and changes in SO_4 concentrations (Szynkiewicz et al. 2011). This alteration of major ion composition from

Table 3 Groundwater properties in the southern Jornada aquifer, July 2009, and groundwater properties in the Mesilla aquifer reported by Witcher et al. (2004)

Well ID	Water-level altitude (m)	Temp (°C)	pH	Specific cond. (µS/cm)	TDS (mg/L)	Ca (mg/L)	Mg (mg/L)	K (mg/L)	Na (mg/L)	HCO_3 (mg/L)	SO_4 (mg/L)	Cl (mg/L)	F (mg/L)	SiO_2 (mg/L)	Sr (µg/L)
Jornada aquifer															
C	1,228.6	26.9	7.87	369	200	27	8	2.0	31	134	38	7	1.2	32.1	610
B	1,227.8	25.4	7.80	353	280	29	10	2.2	28	146	45	9	1.0	34.2	730
A	1,220.9	25.4	7.33	660	460	79	21	3.4	25	171	170	19	0.8	32.1	1,254
I	1,233.9	26.9	7.96	727	460	32	32	3.5	64	105	210	38	0.7	14.8	1,560
H	1,236.1	25.3	7.69	609	460	33	28	3.4	64	195	140	20	1.1	23.5	1,930
G	1,238.3	22.7	7.73	1,404	1,000	130	43	6.1	120	113	640	21	1.6	29.9	9,306
J	1,230.3	27.2	8.14	535	380	35	28	3.6	32	134	130	20	0.8	36.4	1,250
F	1,239.6	24.2	7.69	804	610	43	23	6.5	88	134	270	17	1.2	47.1	11,600
25	NA	29.9	7.64	508	329	59	16	2.7	35	150	103	14	0.6	54.3	103
40[a]	1,224.2	29.8	7.30	643	420	63	13	2.9	41	167	130	13	0.5	39.0	–
41[a]	1,224.5	29.5	7.49	553	350	48	13	2.7	37	161	98	11	0.6	38.0	–
42[a]	1,236.0	28.8	7.48	603	380	43	16	6.2	40	157	119	15	0.6	40.0	–
43[a]	1,168.7	30.0	7.52	656	410	52	16	5.5	43	156	136	15	0.5	39.0	–
Median values (all Jornada wells)		26.9	7.69	609	410	43	16	3.4	40	150	130	15	0.8	36.4	1,254
Mesilla aquifer															
Central Mesilla wells (wells 5 and 6 are previously identified geothermal wells)															
5	NA	58.7	6.90	3,420	1,960	162	21	53.1	470	510	228	554	1.1	78.3	466
6	NA	63.4	6.59	3,250	1,907	168	24	57.6	452	465	236	578	1.8	52.8	491
7	NA	19.9	7.71	655	435	74	10	4.7	55	170	93	63	0.4	25.5	86
8	NA	21.1	7.69	546	371	55	9	5.4	53	158	69	53	0.5	27.2	72
10	NA	19.3	7.92	467	305	51	6	2.6	39	145	47	38	0.4	24.6	54
13	NA	19.7	7.92	533	365	54	8	4.7	62	170	61	50	0.5	27.4	64
15	NA	20.2	7.83	390	351	56	8	6.5	53	155	55	52	0.5	29.1	62
16	NA	24.0	7.56	924	622	80	17	8.0	97	175	157	114	0.7	33.6	147
20	NA	21.8	7.88	562	389	36	7	7.5	79	160	65	59	0.8	25.5	56
21	NA	26.0	7.71	763	497	88	14	5.6	61	145	97	104	0.6	29.3	114
22	NA	20.4	7.38	1,222	810	159	27	9.7	66	240	212	158	0.2	28.4	223
23	NA	24.8	7.37	1,169	832	128	28	10.1	87	170	228	184	0.5	29.1	240
24	NA	23.1	7.40	1,239	846	93	23	6.9	154	200	172	209	0.6	35.5	243
Southern Mesilla wells															
11	NA	19.7	7.7	728	566	93	12	3.5	57	183	120	69	0.3	26.7	1,030
12	NA	19.0	7.69	814	646	102	12	4.2	68	195	161	76	0.4	25.7	1,150
17	NA	29.6	6.82	2,170	1,622	150	18	37.5	299	528	185	362	0.6	35.9	4,220
18	NA	32.2	7.10	2,220	1,611	139	17	42.7	309	508	190	351	1.4	47.1	3,840
19	NA	30.9	7.43	1,945	1,335	62	11	20.9	337	335	169	360	1.4	34.4	2,460
Median values (wells 17–19)		30.9	7.10	2,170	1,611	139	17	37.5	309	508	185	360	1.4	35.9	3,840
26	NA	20.5	7.62	784	517	82	16	22.9	60	160	111	93	1.1	38.9	1,170
27	NA	20.7	7.71	616	401	53	11	15.6	66	175	65	55	2.0	42.1	713
28	NA	22.7	7.82	544	367	31	7	15.2	69	175	56	44	12.0	38.7	550
29	NA	33.6	7.85	854	556	26	6	16.4	144	255	97	70	2.4	38.3	744
30	NA	20.6	7.81	565	379	47	7	19.1	61	178	60	46	2.1	40.2	814
Median values (wells 26–30)		20.7	7.81	616	401	47	7	16.4	66	175	65	55	2.1	38.9	744

[a] Unfiltered samples: these were collected as unfiltered samples from screen areas with substantial filter packs. Turbidity was less than 0.20 NTU for all samples. Solute concentrations in the unfiltered samples do not indicate substantial input of solutes from the digestion of particulates. All other well samples were collected as filtered samples, and the listed concentrations are dissolved concentrations

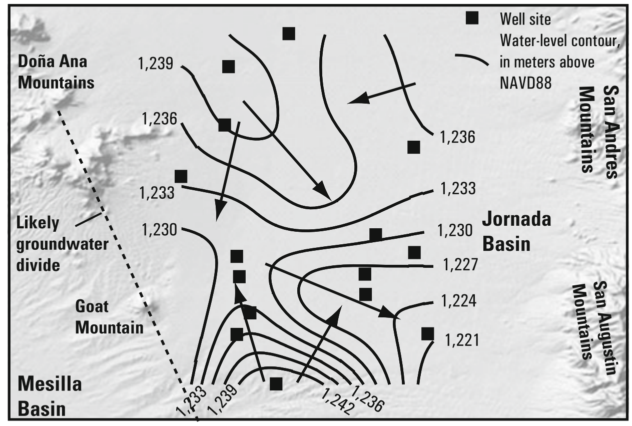
Water-level altitude in meters above NAVD88

°C degrees Celsius, *cond*. conductance, *µS/cm* microsiemens per centimeter at 25 °C, *mg/L* milligrams per liter, *µg/L* micrograms per liter

Table 4 Groundwater isotope properties in the southern Jornada aquifer, July 2009, and groundwater isotope properties in the Mesilla aquifer reported by Witcher et al. (2004)

Well ID	δD (‰)	δ^{18}O (‰)	δ^{34}S of SO_4 (‰)	^{87}Sr/^{86}Sr
Jornada aquifer				
C	−61.34	−9.07	8.07	0.70847
B	−60.14	−8.87	7.81	0.70874
A	−65.98	−9.63	9.56	0.70902
I	−66.22	−9.37	5.98	0.70891
H	−70.71	−9.99	5.37	0.70839
G	−66.02	−9.40	8.10	0.70953
J	−63.78	−9.43	5.74	0.70881
F	−64.54	−9.22	7.72	0.70952
25	−71.39	−9.21	8.70	0.70888
40	–	–	–	–
41	–	–	–	–
42	–	–	–	–
43	–	–	–	–
Median (all)	−65.26	−9.385	7.765	0.70886
Mesilla aquifer				
Central Mesilla wells (wells 5 and 6 are geothermal wells)				
5	−82.40	−10.13	7.80	0.71395
6	−76.67	−9.74	8.40	0.71394
7	−94.19	−11.19	4.40	0.70981
8	−85.48	−11.36	7.60	0.71007
10	−93.93	−11.46	8.00	0.70943
13	−91.28	−11.42	9.40	0.70978
15	−93.15	−11.40	7.70	0.71033
16	−89.55	−11.11	3.70	0.71022
20	−89.63	−11.29	7.30	0.71069
21	−89.68	−11.32	5.70	0.71029
22	−87.86	−9.73	3.00	0.71071
23	−88.08	−10.87	2.90	0.71020
24	−90.85	−11.38	5.70	0.70901
Southern Mesilla wells				
11	−86.45	−10.75	3.90	0.70934
12	−82.61	−10.01	1.10	0.70949
17	−73.69	−9.75	8.10	0.71344
18	−85.92	−10.48	7.70	0.71344
19	−78.63	−10.30	7.30	0.71136
Median (17–19)	−78.63	−10.30	7.70	0.71344
26	−91.57	−11.43	5.40	0.70920
27	−87.77	−11.49	7.60	0.70922
28	−91.07	−11.45	7.10	0.71055
29	−93.89	−11.30	5.60	0.71181
30	−90.94	−11.29	7.70	0.71337
Median (26–30)	−91.07	−11.43	7.10	0.71055

δ^xX (‰) = (Ratio$_{sample}$/Ratio$_{standard}$ − 1) × 1,000 of specified isotope ratio; ‰, per mil



Base from U.S. Geological Survey, National Elevation Dataset, shaded relief, 1 arc second

Fig. 5 Groundwater flow directions in the southern Jornada del Muerto Basin, July 2009

smaller TDS and a Ca–Mg–HCO_3 water type to larger TDS and Na–SO_4–Cl water type is common with dissolution of soluble salts such as NaCl and $CaSO_4$ (Vengosh 2003).

Principal components analysis (Spotfire S+ (Tibco Software, Inc.)), PCA, was used as a tool to quantitatively identify linear combinations of data (mole units) that largely explain groundwater composition variation among the data groups. Results of the PCA indicate strong contrasts in major ion variation and likely changes in source waters between the Jornada and Mesilla basins and within the Mesilla Basin (Table 5). Likely dissolution of NaCl (represented by Cl variation) is strongly influential in the geothermal waters of the Mesilla Basin, and this influence is present in the central and southern Mesilla but not in the Jornada. The geothermal effect only influences groundwater downgradient of the divide separating the basins. Variations in SO_4 are strongly visible in the Jornada PCA results, and this variation likely is from dissolution of evaporite minerals deposited from the drying of Lake Jornada (Gile 2002). A similar variation is visible in the central part of the Mesilla Basin compared to the southern part. Schulze-Makuch et al. (2003) found a decreasing SO_4 concentration in a flowpath from the San Augustin Mountains through the southern Jornada to the Mesilla along Highway 70 and suggested the decrease may be precipitation of $CaSO_4$.

The relations of the major cations and anions were analyzed from a stoichiometric perspective by assuming inputs from common mineral dissolution because of the geothermal effect or possibly outputs through mineral precipitation (i.e., $CaSO_4$) as suggested by Schulze-Makuch et al. (2003). Given the increases in Na and Cl in the Mesilla and the HCO_3 and SO_4 variation in the Jornada, the assumed inputs are from dissolution of NaCl and $CaSO_4$ (possibly $CaCO_3$ depending on the evolution of HCO_3 and

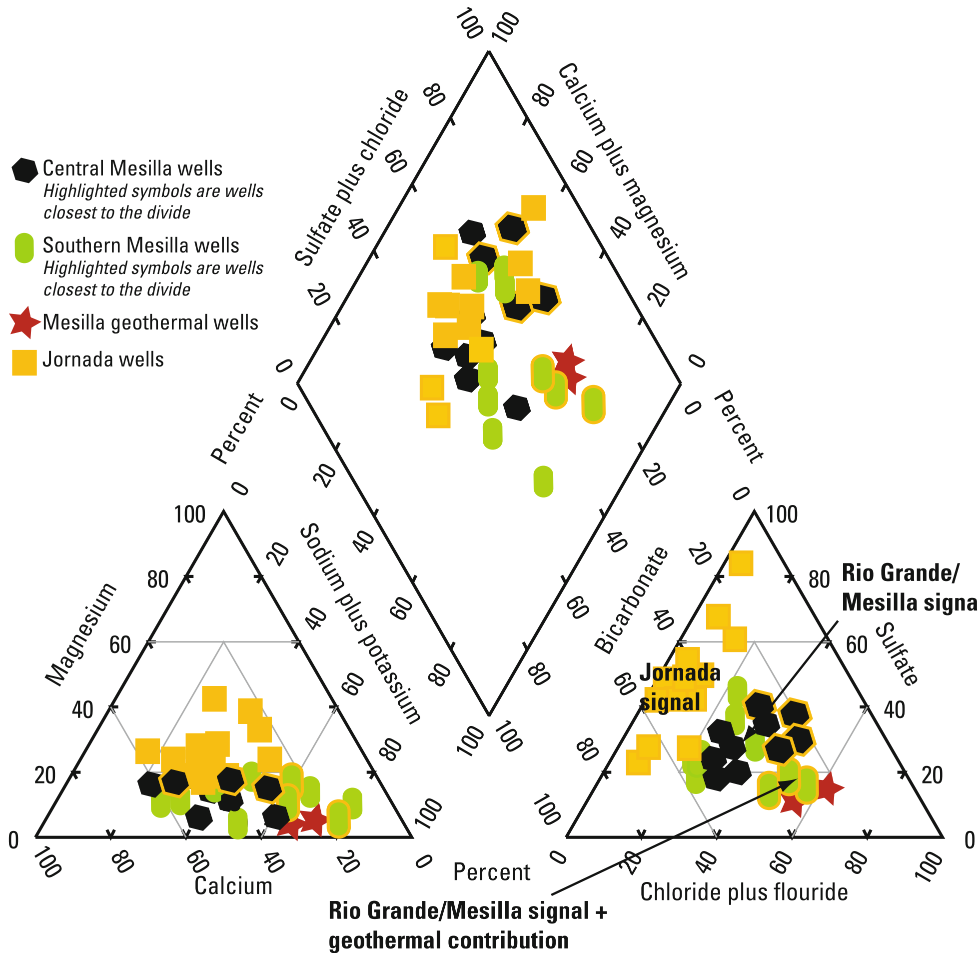


Fig. 6 Piper diagram of major ion concentrations for groundwater from the Mesilla Basin and Jornada del Muerto Basin

Table 5 Results of principal components analysis for groundwater data collected from the Jornada aquifer in June 2009 and groundwater data collected from the Mesilla aquifer as reported by Witcher et al. (2004)

Loadings 1	Witcher et al. (2004)			USGS/Las Cruces Jornada
	Geothermal	Central Mesilla	Southern Mesilla	
Ca	0.116	−0.301		0.262
Mg	0.101	−0.138		0.166
K				
Na	−0.604	−0.5	−0.746	0.548
HCO_3	−0.573	−0.132	−0.313	
SO_4		−0.273		0.771
Cl	0.519	−0.74	−0.576	
F				
Proportion of variance	1	0.81	0.95	0.87

Loadings 1, coefficient of the principal components transformation or summary of the influence of the original variables on the principal components that are related to the original values by orthogonal transformation

SO_4 as the dominant anion), with the possible dissolution of $CaMg(CO_3)_2$ given the presence of these minerals in the basin and region. These minerals are not common within the Jornada and Mesilla basins, but are present in the region—marine carbonates at Tortugas Mountain, gypsite at the south end of the Organ Mountains, and carbonate and gypsum deposits associated with Pleistocene Lake Jornada (southern Jornada Basin east of the Jornada Fault Zone). Dissolution features are observable in the exposed and buried carbonate and gypsiferous rocks of the area (Gile 2002; Witcher et al. 2004). The upwelling of deep brines to the Mesilla aquifer is assumed to be a result of local evaporite dissolution (Witcher et al. 2004; Hogan et al. 2007). Figure 7a and b shows the correlation of increasing dissolved solids with Na and a larger enrichment of Na compared to Cl, which indicates NaCl and general silicate weathering associated with the geothermal effect and the influence of this effect on water chemistry near the southeastern part of the divide (wells 17–19). Figure 7c suggests a greater increase in SO_4 and (or) HCO_3 than congruent addition of Ca from $CaSO_4$ and (or) $CaCO_3$

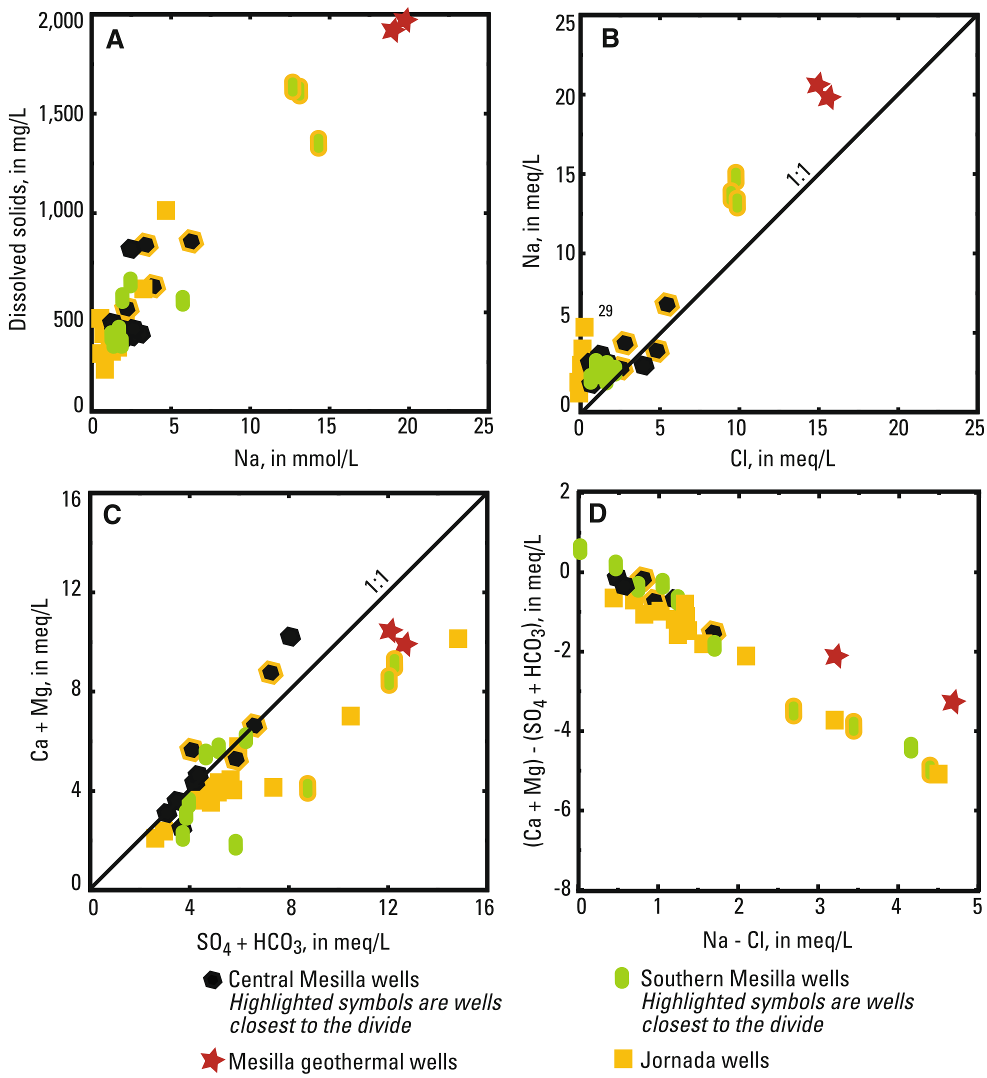


Fig. 7 **a–d** Major ion and dissolved solids relations for groundwater from the Mesilla Basin and Jornada del Muerto Basin

indicating another S and (or) C source. The oxidation of reduced S minerals such as pyrite is a possible contributor to the variable SO_4 concentrations in the Jornada aquifer (Schulze-Makuch et al. 2003). The evolution of groundwater from a Ca–HCO_3 to Na–SO_4 water type is common for aquifers in the larger region because of these evaporite mineral dissolution reactions (Fisher and Mullican 1997; Witcher et al. 2004). The comparison of the possible addition of elements from $CaSO_4$ and $CaCO_3$ dissolution versus NaCl dissolution (Fig. 7d) indicates greater Na addition and greater SO_4 or CO_3 addition, and not from dissolution Ca or Mg minerals in areas near the divide. These results support the idea of evaporite and silicate mineral dissolution in the basins and an input of mineral-laden, geothermal water that influences groundwater composition in the Mesilla aquifer along the southern Jornada–Mesilla divide, defined by the Tertiary intrusions and the Jornada Fault Zone.

Groundwater isotopic signals

The major ion concentrations indicate regional and local influences on groundwater composition, and the stable isotopes of water indicate similar influences with greater discrimination between the aquifers. The heavier δD and $\delta^{18}O$ values for the Jornada (Fig. 8) likely represent recharge from the San Andres and San Augustin mountains where mountain-front recharge does not experience substantial evaporation that would shift the water isotope values away from the Global Meteoric Water Line (GMWL, from Craig 1961). Jornada values are similar to those found by Gross (1988) for springs discharging from the Organ Mountains, which should represent recent mountain-front recharge. Most water from wells within the Mesilla Basin indicate a relatively lighter water isotope signal (Rio Grande recharge) with water from the geothermal wells and water from the most southeasterly wells

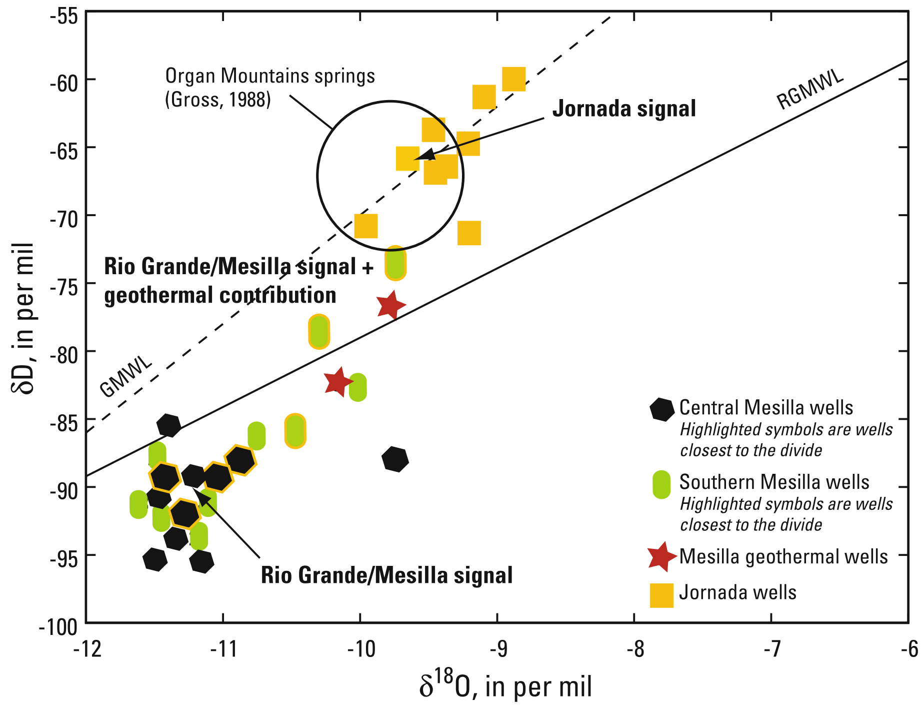


Fig. 8 Groundwater values of δD and $\delta^{18}O$ for the Mesilla Basin and Jornada del Muerto Basin. GMWL is the Global Meteoric Water Line of Craig (1961) and RGMWL is the Rio Grande Meteoric Water Line of Phillips et al. (2003)

indicating relatively heavier ratios (possibly local recharge water). The similar δD and $\delta^{18}O$ values and major ion distributions in the Mesilla's southeastern wells compared to the geothermal wells indicates a likely geothermal influence or deeper groundwater influence and not just Rio Grande recharge in the southeastern Mesilla aquifer. Water from the geothermal wells and the southeastern Mesilla wells appear similar to the relation developed by Phillips et al. (2003) for the Rio Grande that represents an increase in mineral input from deeper, more saline water in the downgradient direction.

With no corresponding water isotope indication of Jornada water contribution to the central Mesilla Basin (Fig. 8) as indicated in the major ion relations, there is no substantive contribution of groundwater from the Jornada Basin directly to the central Mesilla Basin over the eroded Tertiary intrusions separating the aquifers. This conclusion is in agreement with the potentiometric surfaces of the Jornada derived by Wilson et al. (1981) and this study (Fig. 5) where the damming effect of the buried horst routes Jornada groundwater northward near Highway 70. Given this scenario, groundwater in the southern Jornada must still exit the basin, either horizontally or vertically, because a convergence of flow in the center of the southern Jornada Basin is not sustainable without a corresponding loss somewhere to relieve the accumulating mass of water.

Various rock types develop different $^{87}Sr/^{86}Sr$ ratios because of the chemical fractionation of Sr and Rb during mineral formation and the influence of mineral age where radiogenic ^{87}Sr increases from the β-decay of ^{87}Rb (Nimz 1998). Water–rock interaction imparts an $^{87}Sr/^{86}Sr$ signature on through-flowing water because of Sr mineral dissolution (Stewart et al. 1998; Bullen and Kendall 1998). Groundwater from the Jornada has an Sr signal slightly greater in Sr concentration and slightly less in $^{87}Sr/^{86}Sr$ ratios compared to the Mesilla/Rio Grande signal of the central Mesilla Basin (Fig. 9). The geothermal effect has a strong influence on Sr with substantial increases in Sr concentration and $^{87}Sr/^{86}Sr$ ratios as seen in groundwater from the geothermal wells. This effect is apparent in the southeastern Mesilla and also in a few other southern Mesilla wells, indicating a possibly wider influence of the geothermal effect on water in the southern Mesilla. The Sr results support the idea of very limited contribution of Jornada water to the central Mesilla Basin and a possible Jornada connection with the southern Mesilla Basin. It appears that migration of groundwater from the Jornada to the Mesilla may be more tortuous than previously hypothesized, and Jornada water only contributes a significant amount to the southeastern Mesilla Basin following alteration of the Sr signal because of the geothermal effect.

The $\delta^{34}S$ and SO_4 values (Fig. 10) also suggest no connection between the Jornada aquifer and central Mesilla aquifer. Mesilla groundwater shares an isotopic signal with the Rio Grande but not with the Jornada aquifer, which is much more variable (possibly from the effects of pedogenic $CaSO_4$ from the drying of Lake Jornada). Groundwater from the geothermal wells and southeastern Mesilla wells closest to the divide have similar $\delta^{34}S$ and SO_4 values

Fig. 9 Strontium concentration and $^{87}Sr/^{86}Sr$ ratio of groundwater from Mesilla Basin and Jornada del Muerto Basin

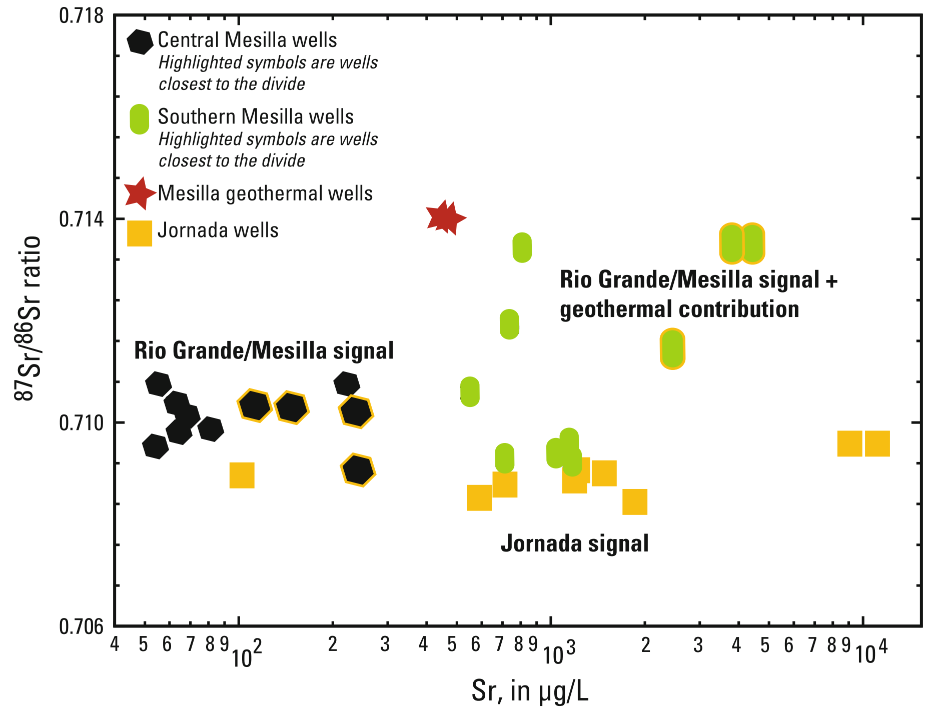
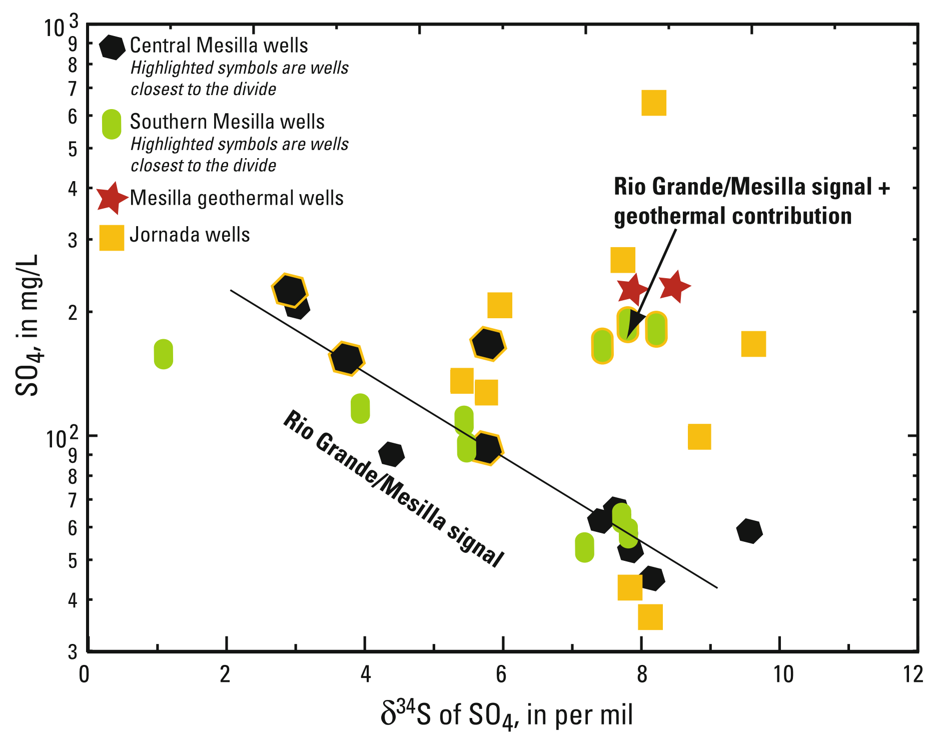


Fig. 10 Sulfate concentrations and $\delta^{34}S$ values of groundwater from the Mesilla Basin and Jornada del Muerto Basin



compared to some of the groundwater from the Jornada aquifer. These values support the idea of a more tortuous flowpath from the Jornada through the divide and discharge to the Mesilla aquifer at locations farther south than the divide between Goat Mountain and the Tortugas Mountains (central Mesilla Basin). A deeper connection between the two aquifers allows the geothermal influence to alter the composition of Jornada water flowing into the Mesilla, and this altered-composition water enters the Mesilla aquifer at points in the southeastern Mesilla Basin. Such a connection appears more likely in comparison with the $\delta^{34}S$ and $\delta^{18}O$ values (Fig. 11). Jornada values are similar to the

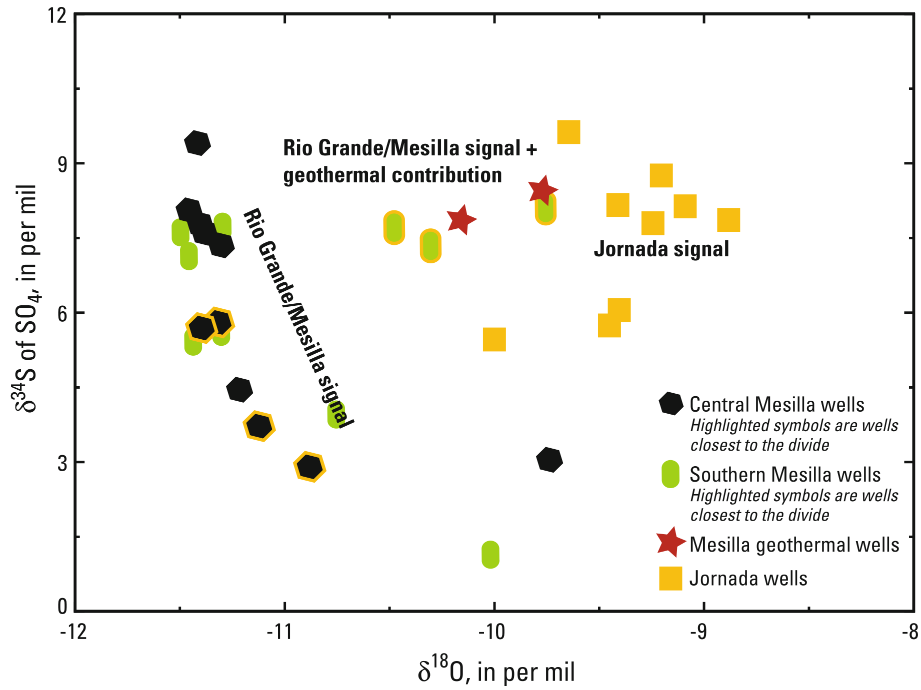


Fig. 11 Sulfate δ^{34}S and water δ^{18}O values of groundwater from the Mesilla Basin and Jornada del Muerto Basin

geothermal signal and the southeastern Mesilla wells. These three waters appear to share similar geochemical traits that are likely a result of recharge along the eastern part of the Jornada Basin (San Andres, San Augustin, and Organ Mountains) with a geothermal influence as a result of migration through the Tertiary intrusions and reappearance at shallower depths at lower altitudes downgradient of the divide. Such a scenario would alleviate some of the groundwater accumulation problem in the southern Jornada.

Groundwater mineral phases and mixing

Median values for major ion and trace element concentrations and isotopic ratios of groundwater from the geothermal wells, central Mesilla, southern Mesilla, and Jornada were entered into PHREEQ (Parkhurst and Appelo 1999) using PHREEQCI (Charlton and Parkhurst 2002) to determine saturation indices (log of the ratio of the ion activity product (IAP) and the solubility product (K_{sp})) for each of the waters (Table 6). Median values for these waters were chosen to examine each as possible source water that could assist in understanding the deeper flowpath from the Jornada into the Mesilla. The selected mineral phases represent likely minerals available for dissolution or precipitation that can account for the change in dissolved concentrations, but are not meant to indicate the only minerals likely to dissolve or precipitate. The saturation indices of the median values appear to reinforce the idea of Jornada water traveling a more tortuous path through the Tertiary intrusions and a subsequent contribution to the southeastern Mesilla aquifer (Table 6). The saturation indices for groundwater from the Jornada and groundwater from the geothermal wells share similar mineral phases and saturation indices that are strongly different from those for groundwater from the central or southern Mesilla Basin. Given the dominance of Rio Grande recharge to the Mesilla aquifer, the Jornada/geothermal water does not have a strong effect on Mesilla water, because the central and southern Mesilla saturation indices are similar. This agrees with Figs. 7, 8, 9, and 10 that show only the southeastern wells in the Mesilla showing similar geochemical traits as the Jornada and (or) geothermal wells.

The deeper flowpath scenario allows some water from the Jornada to enter the Mesilla, but at locations further south than the expected Santa Fe Group flowpaths along the transition between Goat Mountain and the Tortugas Mountains in the central Mesilla Basin. The deeper flowpath contribution is limited in scope as its signal is masked further into the southern Mesilla aquifer because of the influence of the Rio Grande. The addition of altered Jornada water in this more southerly area fits Witcher et al.'s (2004) discussion of a strong geothermal upflow zone from Tortugas Mountain southward (Las Cruces East Mesa Geothermal System). Under this study's proposed conceptual model, the geothermal system is fed by Jornada water that migrates through the Tertiary intrusions with mixing occurring along the southernmost part of the Jornada–Mesilla divide. This mixing scenario is visible in the ^{87}Sr/^{86}Sr data and Sr/Na ratios (Fig. 12) that show the influence of inputs from mountain-front recharge (dilution

Table 6 Results of mineral phase saturation indices for Jornada groundwater data collected in June 2009 and Mesilla groundwater data reported by Witcher et al. (2004)

Mineral phases	Mineral chemical composition	Witcher et al. (2004)			USGS/Las Cruces Jornada
		Geothermal	Central Mesilla	Southern Mesilla	
Anhydrite	$CaSO_4$	−1.15	0.46	0.52	−1.91
Aragonite	$CaCO_3$	0.30	2.49	2.54	−0.15
Calcite	$CaCO_3$	0.42	2.64	2.69	0.00
Celestite	$SrSO_4$	−1.96	−0.10	0.98	−1.47
Chalcedony	SiO_2	0.22	2.09	2.22	0.59
Chrysotile	$Mg_3Si_2O_5(OH)_4$	−3.92	2.11	2.22	−1.97
Dolomite	$CaMg(CO_3)_2$	0.47	4.63	4.68	−0.02
Fluorite	CaF_2	−0.91	1.49	2.36	−1.45
Gypsum	$CaSO_4{:}2H_2O$	−1.18	0.69	0.75	−1.69
Halite	NaCl	−5.31	−4.35	−4.25	−7.76
Quartz	SiO_2	0.55	2.53	2.66	1.02
Sepiolite	$Mg_4Si_6O_{15}(OH)_2{:}6H_2O$	−3.66	4.80	5.08	−0.55
Silica	SiO_2 (amorphous)	−0.51	1.23	1.37	−0.25
Strontianite	$SrCO_3$	−1.82	0.60	1.68	−1.04
Talc	$Mg_3Si_4O_{10}(OH)_2$	0.63	9.94	10.31	2.90

Mineral phases were determined by assuming equilibrium conditions, and saturation indices are the log of the ratio of the ion activity product (IAP) and the solubility product (K_{sp}) as determined by inputing into the PHREEQC program (Parkhurst and Appelo 1999)

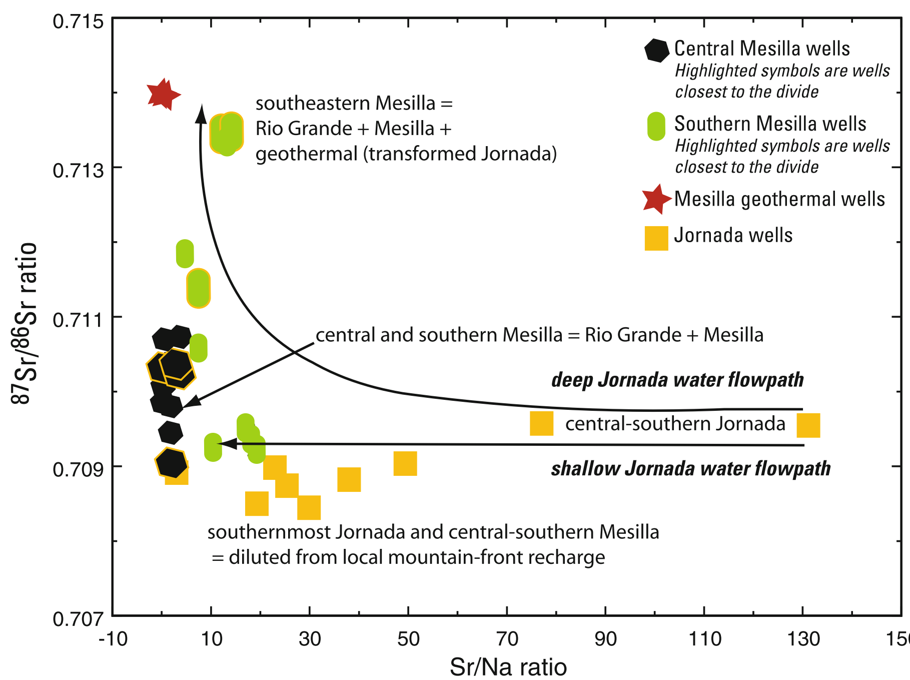


Fig. 12 $^{87}Sr/^{86}Sr$ ratio and Sr/Na ratio of groundwater from the Mesilla Basin and Jornada del Muerto Basin

in the Jornada with local recharge) and the geothermal effect that influences Sr isotopes and mineral inputs from weathering of the evaporites and aluminosilicates in the aquifers' matrices. Distinct mixing paths are visible in the geochemical relations as Jornada water enters the Mesilla.

To test the proposed conceptual model of a deeper Jornada contribution to the southeastern Mesilla, inverse calculations were performed to estimate the contributions of Jornada groundwater to the southeastern Mesilla through mixing with southern Mesilla groundwater (Table 7). Isotope median values (Table 4) were determined for Jornada (all Jornada wells) and southern Mesilla (wells 26–30) groundwater, and these values were mixed to produce the groundwater found along the southeastern Mesilla Basin (wells 17–19). Results of the inverse calculations for the conservative isotope data (δD and δ^{18}O of water) indicate nearly equal contributions of Jornada and southern Mesilla water to the southeastern Mesilla groundwater. Expected

Table 7 Calculated fractional contributions of Jornada and southern Mesilla groundwater to groundwater found in the southeastern Mesilla Basin

Modeled constituent	Jornada signal	S. Mesilla signal	Modeled signal compared to known value
	End member 1	End member 2	Residual
δD of water	0.48	0.52	<0.00001
δ^{18}O of water	0.55	0.45	<0.00001
δ^{34}S of SO_4	0.90	0.10	<0.00001

Median values of Jornada (wells A, B, C, F, G, H, I, J, and 25) and southern Mesilla (wells 26–30) groundwater were used as end members to determine fractional contributions of the resulting mixture that is southern Mesilla groundwater (median values of wells 17–19). Median values are shown in Table 4

non-conservative isotope data (δ^{34}S of SO_4) because of water–rock interactions indicate nearly all Jornada water comprising the southeastern Mesilla groundwater, which is highly unlikely because of the substantial influence of the Rio Grande in the Mesilla Basin. The alteration of SO_4 composition near the divide because of the geothermal effect causes a substantial error in the δ^{34}S of SO_4 inverse calculation as compared to the conservative isotope data. The ^{87}Sr/^{86}Sr ratios were not used for the inverse calculations, because the southeastern Mesilla ^{87}Sr/^{86}Sr median value is larger than either of the end members' median values. This larger ratio indicates a third contribution, which is dissolution of Sr-bearing minerals at the divide because of the geothermal effect. This enhanced water–rock interaction is apparent with all the solutes, as nearly all median solute concentrations for the southeastern Mesilla wells are greater than the median values for groundwater from the Jornada wells and the southern Mesilla wells (26–30) as shown in Table 3. The geothermal effect produces a substantial input of solutes to the Jornada water as it passes through the divide and enters the Mesilla along the southern portion of the divide.

Conclusions

Hydraulically, a connection between the southern Jornada and Mesilla appears necessary, but wells in relatively close proximity to the central part of the divide separating these basins do not share similar geochemical traits that would indicate a substantive flow from the Jornada into the central Mesilla. The previously hypothesized flowpaths in the Santa Fe Group sediments overlying the bedrock high is still possible, but it is likely that some Jornada water enters the Mesilla Basin through deeper and more tortuous flowpaths within the Tertiary intrusions that form the buried horst dividing the two basins. These deeper flowpaths likely are present because of the prevalent faults in the Jornada Fault Zone. In these deeper flowpaths, the composition of Jornada groundwater is altered because of the local geothermal effect. This flow of Jornada water through the divide provides a substantial geothermal water contribution that can be seen in the southeastern Mesilla aquifer, but not deeper into the Mesilla Valley because of the dominant Rio Grande influence. The geothermal effect is not simply a chemical environmental change that is seen with changes in temperature and pH, but also a substantial solute change where major ion relations are significantly altered and an NaCl signal is introduced that was not present in Jornada groundwater within its southern portion. It is likely that some Jornada water enters the Mesilla Basin through the shallower flowpaths in the Santa Fe Group sediments atop the buried horst as proposed by earlier studies, but there likely is an equal or greater contribution of Jornada water that appears as deeper, geothermal water entering the Mesilla Basin along the southern part of the divide. Increased groundwater withdrawals and lowering of the potentiometric surface of the Jornada aquifer may alter this contribution ratio with less overtopping of the bedrock high between the basins and continued deeper flowpath contribution that could potentially increase salinity values in the Mesilla Basin along the southern divide with the Jornada Basin.

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