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Analyses of Permeability Proxies, Total Dissolved Solids, and Groundwater Flow in the Santa Fe Group Aquifer of the Northwestern Albuquerque Basin, New Mexico

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ANALYSES OF PERMEABILITY PROXIES, TOTAL DISSOLVED SOLIDS, AND GROUNDWATER FLOW IN THE SANTA FE GROUP AQUIFER OF THE NORTHWESTERN ALBUQUERQUE BASIN, NEW MEXICO

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Abstract—Rio Rancho and adjoining areas to the west in the northwestern Albuquerque Basin are entirely reliant on groundwater from the Santa Fe Group for their water supply. This paper summarizes a component of a larger hydrogeologic study that assesses permeability differences between and within hydrostratigraphic units of the northwestern Albuquerque Basin. An ancillary goal is to conduct a preliminary analysis of total dissolved solids (TDS) spatial variation and groundwater flow. Four hydrostratigraphic units (HSUs) were identified: Upper, Middle, and Lower Rio Rancho HSUs and the Zia HSU.

Analyses of permeability differences between and within the HSUs were conducted using sand vs. clay lithologic proxies constrained by various well data, porosity analyses from wireline logs, and comparison of hydraulic conductivities (K) derived from pumping tests. In terms of groundwater resources, the Upper Rio Rancho HSU is the most favorable of the four HSUs. Compared to the underlying Middle Rio Rancho HSU, it has less clay, is coarser, and has higher K values (median of 9.25 ft/day vs. 3.25 ft/day). Seventy-five percent of pumping test K values for the Upper Rio Rancho HSU exceed the 75th percentile (5.35 ft/day) of the Middle Rio Rancho HSU. The Upper Rio Rancho HSU also tends to exhibit higher density-porosity log values, probably reflecting lesser compaction, and lies closest to the surface. Even if somewhat less permeable, the Middle Rio Rancho HSU is also an important aquifer because of its larger extent and greater thickness. The Middle Rio Rancho HSU generally does not exhibit lateral trends in permeability proxies, except possibly along its northern margin and in the southwestern corner of the study area.

We make three interpretations based on analyses of a 3D hydrostratigraphic model, approximate potentiometric surface map, TDS data, and ^{14}C ages. First, the Ziana horst, a north-south structural high between Bernalillo and the intersection of Unser and Northern Boulevards, is associated with higher-TDS water and a higher potentiometric surface. Groundwater flows south in the Santa Fe Group between faults bounding the horst, but this water is likely affected by upwelling of salty water from shallow, fractured, and faulted bedrock. Second, south of the faulted southern end of this horst, groundwater derived from the Rio Grande flows west-southwest into the Santa Fe Group aquifer, bringing relatively fresh and young groundwater (<10 ka). Third, to the west of these two areas lies older groundwater (31–15 ka) underlying a north-south "trough" of the potentiometric surface. This trough and corresponding older groundwater are probably due to faults and possible dikes acting as groundwater barriers.

INTRODUCTION

Residents in the northwestern part of the Albuquerque Basin, west of Corrales and north of Paseo del Norte Boulevard, rely on groundwater for their water supply. Most people here live in Rio Rancho, a city whose population has grown from ~10,000 in 1980 to 104,046 in 2020 (United States Census Bureau, 2025). Because of the importance of groundwater to the city of Rio Rancho, in 2018 the city funded a three-year project with the New Mexico Bureau of Geology and Mineral Resources (NMBGMR) to provide the city with a water-related database, hydrogeologic assessment, and visualizations to better understand the local Santa Fe Group aquifer system. To fulfill the latter two objectives, the NMBGMR built a 3D hydrostratigraphic model of the Santa Fe Group aquifer in the northwestern Albuquerque Basin and assessed permeability differences within and among aquifer units, hereafter referred to as hydrostratigraphic units (HSUs), that compose the model. Other products included construction of an approximate potentiometric-surface map and compilation of groundwater TDS and age data.

A companion paper presents the 3D hydrostratigraphic model, describes the methods used to construct it, and relates the geometries of the HSUs to geologic structure (Koning et al., 2026a). The paper presented here focuses on permeability differences and trends within and among hydrostratigraphic units. We describe two approaches used to assess permeability: lithologic proxies (i.e., proportion of clay) and hydraulic conductivities from pumping tests. Permeability differences within and among hydrostratigraphic units are then evaluated. We also present a preliminary analysis of groundwater flow based on a potentiometric-surface map, groundwater ^{14}C data and TDS values. We argue that these data can be used to distinguish three groundwater zones. We then analyze the combined datasets to evaluate the groundwater resource of the northwestern Albuquerque Basin.

Study Area

The study area focuses on Rio Rancho and surrounding areas (Fig. 1) in the northwestern Albuquerque Basin. The landscape of the area is characterized by a gently eastward-sloping,

mesa-like feature called Llano de Albuquerque. The Llano is bounded on its west and north sides by eroding escarpments called La Ceja del Puerco and La Ceja, respectively.

This region is underlain by the Santa Fe Group aquifer. The Santa Fe Group consists of all clastic sediment filling the Rio Grande rift and includes tongues of syn-rift volcanic rocks

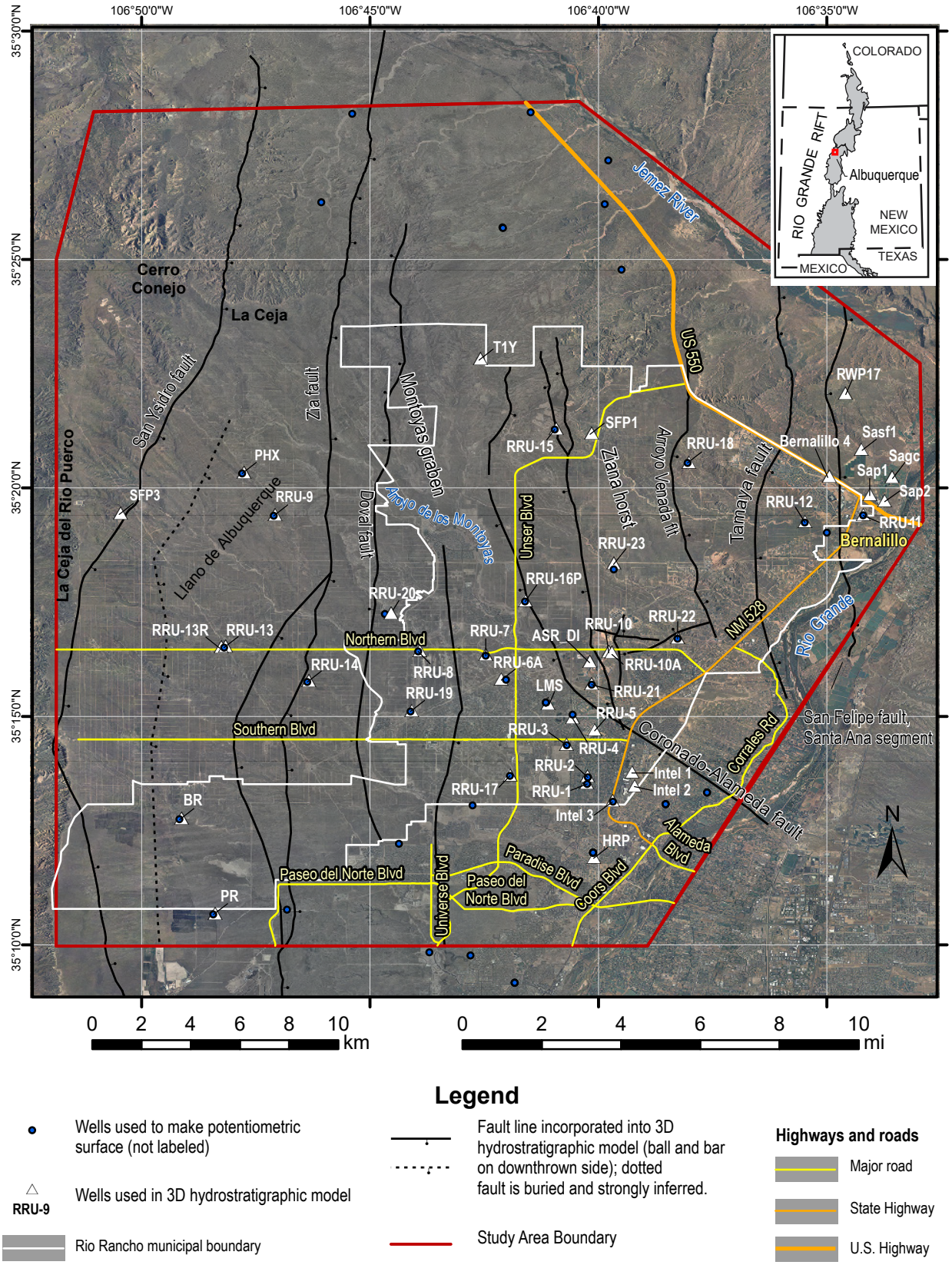


FIGURE 1. Map of study area with a satellite imagery background. Select highways and roads are shown in addition to wells and faults germane to this study.

(Spiegel and Baldwin, 1963; Chapin and Cather, 1994). In the study area, the Santa Fe Group consists of sand bodies interstratified with variable, but typically subordinate, layers of clay, silt, and gravel (Kelley, 1977; Connell, 2004, 2008a, 2008b). This clastic sequence was deposited between approximately 25 and 1 Ma years during Rio Grande rifting, concurrent with basin subsidence along extensional faults (Kelley, 1977; Chapin and Cather, 1994; Connell, 2004; Connell et al., 2013). These strata are amenable to detailed stratigraphic study because of good exposure in the aforementioned escarpments in addition to data from at least 37 deep wells (Koning et al., 2026a, 2026b).

Previous Work

Detailed groundwater investigations in the northwestern Albuquerque Basin generally began in conjunction with accelerated growth of Rio Rancho during the early 1990s. Most of these investigations involved evaluating newly drilled wells or planning new wells for the city (Appendices 1 and 2) and for northwestern Albuquerque (Allen et al., 1998; Connell et al., 1998). Comprehensive investigations of the hydrogeologic framework of the Albuquerque Basin were initiated by Hawley and Haase (1992), Thorn et al. (1993), Hawley et al. (1995), and Hawley (1996).

The U.S. Geological Survey conducted many noteworthy hydrogeologic studies in the Albuquerque Basin during the 1990s and 2000s. These efforts included early groundwater flow modeling in the Albuquerque Basin (Kernodle and Scott, 1986; Kernodle et al., 1987, 1995; and Kernodle, 1998). The U.S. Geological Survey also spearheaded several geochemistry investigations: Sanford et al. (2004a, 2004b), Plummer et al. (2001, 2004a, 2004b, and 2004c), Bexfield and Plummer (2003), and Bexfield et al. (1999). Plummer et al. (2004a, 2004b, and 2004c) used a variety of geochemical data to identify various groundwater hydrochemical zones for the upper 2,000 ft (610 m) of the Santa Fe Group aquifer system. Groundwater-level maps were produced by Bexfield and Anderholm (2000, 2002), which indicated a curious north-south-trending groundwater low ("trough") feature west of the Rio Grande. These studies were used to make updated groundwater flow models relevant to our study area (McAda and Barroll, 2002; Bexfield et al., 2004) and an assessment of groundwater resources (Bartolino and Cole, 2002). Riesterer et al. (2004) concluded that the most important factors influencing well production were well depth and total screen length, regardless of geologic unit or proximity to faults. Minor and Hudson (2006) investigated how faults in the northwestern Albuquerque Basin affect groundwater flow.

Hydrostratigraphic Units (HSUs)

An important part of the larger hydrogeologic study requested by Rio Rancho was mapping hydrostratigraphic units (HSUs) in the subsurface and integrating them into a hydrostratigraphic model defined by four GIS raster surfaces. See Koning et al. (2026a, 2026b) for methodology on how a lithostratigraphic scheme was converted into a hydrostratigraphic classification, how boundaries separating the HSUs were mapped using structural contouring, and how these structural contours were converted into XYZ raster files.

The four HSUs comprising the hydrostratigraphic model are the Upper, Middle, and Lower Rio Rancho HSUs and the Zia HSU. The boundary of each HSU corresponds to a lithologic boundary, and each HSU includes saturated and unsaturated strata. Figure 2 shows a 3D visualization of the model and HSU components. The saturated extents and thicknesses of the Upper and Middle Rio Rancho units are germane to this paper and shown in Figure 3. See Koning et al. (2026a, 2026b) for a discussion of the geologic structures in the context of the HSUs in addition to a complete set of maps and plates depicting the HSUs.

METHODS

We used two approaches to assess permeability differences between HSUs. The first approach uses lithologic proxies for permeability based on the proportion of clay. The second approach compiles pumping test data reflective of permeability, namely hydraulic conductivities and specific capacities, for wells screened in specific HSUs. Here, we describe the methods used in the two approaches.

Lithologic proxies for permeability

Well analyses

Rio Rancho has at least 37 wells with detailed well records (Appendices 1 and 2; Koning et al., 2026b). These well records include archived cuttings and wireline geophysical logs. The wireline logs commonly contain induction (or electric resistivity), spontaneous potential (SP), gamma ray, neutron porosity, and density porosity data (Koning et al., 2026b, appendix 4). Some wells have formation-analysis logs that use the previously listed wireline data to calculate sand vs. shale vs. calcium carbonate content, as well as effective porosity, as a function of depth. These data were supplemented by detailed descriptions of well cuttings from 14 wells archived in the Subsurface Cuttings Library of the New Mexico Bureau of Geology and Mineral Resources (Koning et al., 2026b, appendix 3). Cuttings descriptions from consultant reports listed in Appendix 1 were also used. Utilizing these wireline data and available cuttings data, we delineated sand, clay, and muddy sand intervals for 22 of these wells using standard wireline interpretation methods (Appendix 3; Asquith and Krygowski, 2004; Koning et al., 2026b, appendix 5). The proportions of clay, muddy sand, and sand were then calculated and compiled for each hydrostratigraphic unit (Appendix 3).

Note that this lithologic differentiation was conducted from the water table to the bottom of the well. Thus, the lithologic summaries only pertain to the saturated zones of an HSU; in the case of the Middle Rio Rancho HSU, which coarsens upward (Koning et al., 2026b), this will result in an underestimation of sand content compared to using the entire HSU (including the saturated and unsaturated zones). Also, we only

delineated lithologies to the bottom of the Cerro Conejo Formation, corresponding to the upper part of the Zia HSU, in the case of deep oil-exploration wells (Appendix 2, well labels T1Y, SFP1, SFP3).

Vshale analyses

To assess subsurface lithology, we also calculated Vshale and net-to-gross ratios of sand bodies. The net-to-gross ratio represents the percentage of sand bodies relative to the saturated HSU thickness in a given well.

Vshale is calculated using Kingdom software from downhole gamma-ray logs. The gamma-ray response at a given depth is compared to that of pure sand and pure clay. The corresponding equation (Tearpock and Bischke, 2002) is:

$$Vshale = (GR-GRCLN)/(GRSHL-GRCLN)$$

where:

GR is gamma-ray log value at a measured depth

GRCLN is minimum gamma-ray value (clean sand) along the studied depth of the well

GRSHL is maximum gamma-ray value (clay or shale) along the studied depth of the well

For this study, sand bodies were recognized as such where the Kingdom Vshale value was 0.25 or less.

Compilation of pumping test data

Three approaches were used to measure vertical and lateral changes in permeability in the hydrogeologic study of Koning et al. (2026b): compilation of hydraulic conductivity and specific capacity from pumping tests, the Kozeny-Carman model, and the Berg model. However, the results of the latter two methods were not considered reliable, primarily due to the lack of effective porosity values, overly thick sampling intervals for sand grain-size data, and the fact that sand grain sizes were derived from cuttings rather than intact core samples. We therefore present only hydraulic conductivity and specific capacity data.

We compiled hydraulic conductivity and specific capacity measurements (Table 1) from pumping tests contained in the consultant reports listed in Appendix 1. These data were available for the Rio Rancho production wells (except RRU-18 and RRU-20), the Bernalillo No. 4 well, and the three Intel production wells. Pumping test data were also available from the extreme southwest of the study area and include the Black Ranch test hole and the Soil Amendment Facility well (Table 1, BR and SAF-1), the latter located 1 mile (1.6 km) south of the southern boundary of the study area. Where more than one pumping test was conducted on a well, corresponding to different depth-intervals of a particular HSU, the average of the hydraulic conductivities was used. This averaging was done for the Black Ranch test hole (BR), which had hydraulic conductivities of 12 ft/day and 5.4 ft/day in the Middle Rio Rancho HSU, and in well RRU-13R, which had values of 1.2 and 0.8 ft/day in the Middle Rio Rancho HSU (Table 1). We selected the pumping tests for wells whose screened intervals corresponded uniquely to a given HSU or were >80% within a given HSU. In the case of the Intel wells, we attributed the pumping test data as being from the Upper Rio Rancho HSU, even though 20–30% of the screens were in the Middle Rio Rancho HSU. This is because the Middle Rio Rancho HSU was notably finer grained than the Upper HSU in the well logs, so we assumed that the pumping test mostly reflected the Upper Rio Rancho HSU. We could not use wells RRU-10A, RRU-12, RRU-16P, RRU-22, and NM Util 4 because their screens extended significantly across multiple HSUs. Only one well, RRU-23, had a pumping test from a screened interval wholly within the Lower Rio Rancho HSU.

RESULTS

Well Analyses of Clayey vs Sandy Sediment

The lithologic results of the wireline analyses provide an indirect proxy for permeability because they reflect the proportion of clay in a stratigraphic interval. They are indirect because other properties influence permeability, including degree of cementation and compaction. The proportions of sand, muddy sand, and clay are tabulated in Appendix 3. Figure 4 summarizes the results of these analyses.

These data show that the Lower Rio Rancho HSU has the most favorable lithologic permeability proxies, followed by the Upper Rio Rancho HSU. The sand-to-clay ratio in the Lower Rio Rancho HSU is 17.1 compared to 4.4 in the Upper Rio Rancho HSU, 2.9 in the Middle Rio Rancho HSU, and 1.6 in the upper Zia HSU (Fig. 4). The proportion of clay and muddy sand in the Lower Rio Rancho HSU is at most half that of the other three HSUs. The proportion of clay and sand (relative to total) in the Upper Rio Rancho HSU (Appendix 3) is 11% and 51%, respectively, while that of the Middle Rio Rancho HSU is 16% and 47%.

For the saturated part of the Upper and Middle Rio Rancho HSUs, the proportion of clay, muddy sand, and sand are plotted as pie charts on a map of the central study area (Fig. 5). Where a well penetrates the saturated parts of both units (i.e., wells RRU-12 and RRU-22), the proportion of sand vs. clay in the saturated Upper Rio Rancho HSU is equal to or greater than that in the Middle Rio Rancho HSU. This is consistent with a general coarsening-upward trend from the Middle to Upper Rio Rancho HSU interpreted from wireline logs (Koning et al., 2026a, 2026b). Assuming this coarsening-upward trend mimics permeability trends and given that compaction decreases up-section, then the Upper Rio Rancho HSU is likely more permeable than the Middle Rio Rancho HSU.

Determining sand vs. clay for HSUs using Vshale

Where adequate gamma-ray logs were available, net-to-gross ratios of sand bodies were calculated for each saturated HSU (Appendix 4; Figs. 6 and 7), where sand bodies were delineated using a Vshale threshold of ≤ 0.25. A net-to-gross value of 1.0 indicates that the entire interval thickness is sand, whereas lower values represent the fraction of sand within the interval. For example, a net-to-gross ratio of 0.2 indicates that 20% of the interval consists of sand.

Net-to-gross sand values of saturated sand bodies in the Middle Rio Rancho HSU show a moderate correlation with pumping test-derived hydraulic conductivities (tabulated in the next section), with $R^2 = 0.0.46$ (Fig. 8). This correlation supports the use of net-to-gross ratios of sand bodies as a proxy for relative permeability variations, particularly in areas lacking pumping test data.

Where both the MRR and LRR HSUs are penetrated by a well, the proportion of sand is greater in the Lower Rio Rancho HSU compared to the Middle Rio Rancho HSU (Fig. 7). The average value of net-to-gross ratios (Appendix 4) is greater in the Lower Rio Rancho HSU (0.52 ± 0.20) compared to the stratigraphically higher Middle Rio Rancho HSU (0.29 ± 0.16) and Upper Rio Rancho HSU (0.34 ± 0.24) (errors correspond to one standard deviation; note the overlap between HSUs). This is consistent with data presented above that show the Lower Rio Rancho HSU has greater sand proportions than the Middle Rio Rancho HSU.

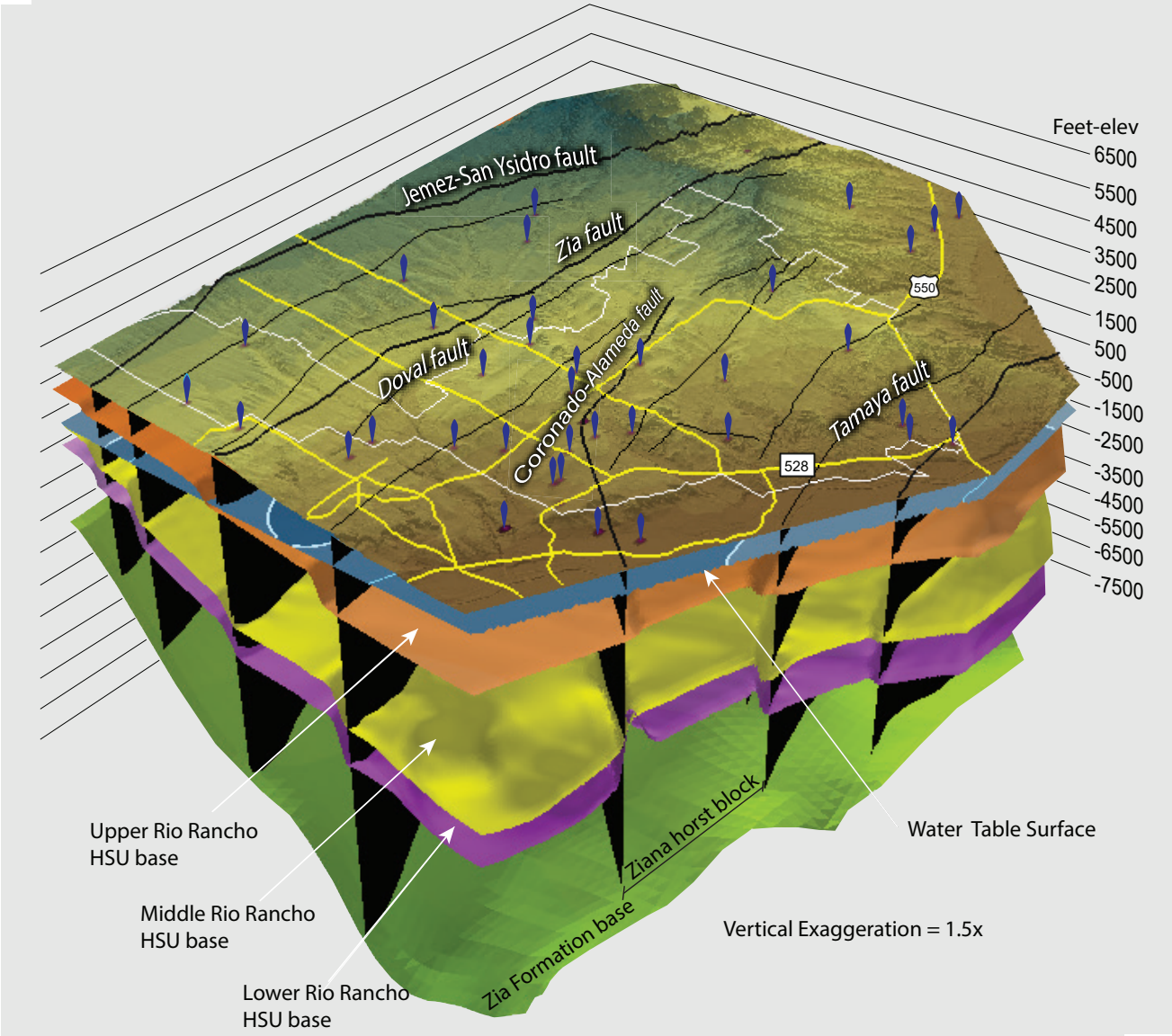


FIGURE 2. Three-dimensional depiction of the HSU surfaces under the northwestern Albuquerque Basin. The uppermost surface is a shaded-relief map of surface topography on which the following features are shown: roads (yellow lines), Rio Rancho municipal boundary (white line), and faults (black lines). The underlying HSU surfaces are color-coded and labeled. Subsurface fault planes are depicted by black, vertical to very steeply dipping panels (planes). The sloping water table surface is shown in blue.

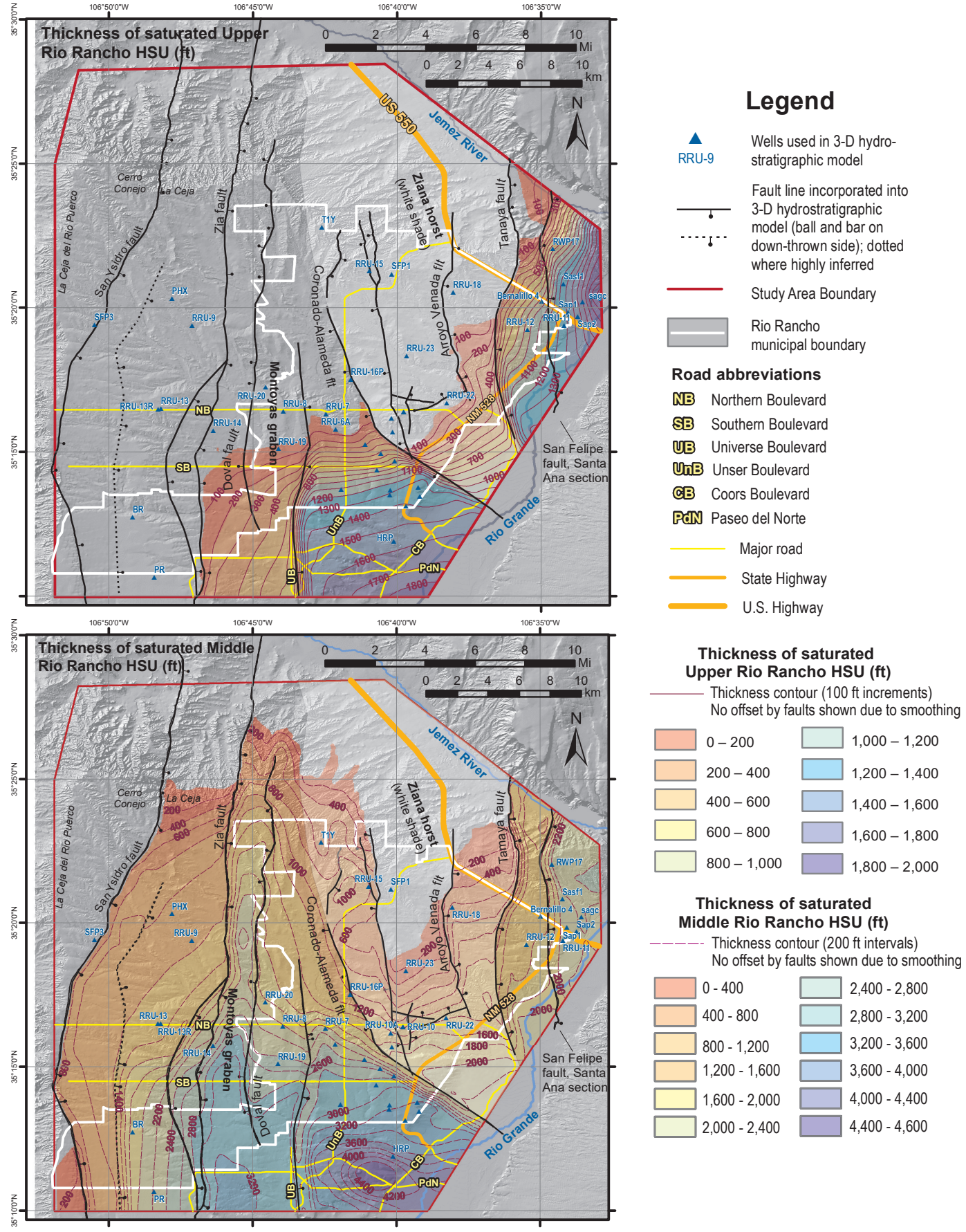


FIGURE 3. Thickness (in feet) of the saturated part of the Upper Rio Rancho HSU (top) and the Middle Rio Rancho HSU (bottom).

Density porosity analyses

Density porosity was calculated using Kingdom software and wireline data. Arithmetic means were compiled for (1) saturated strata within an HSU, (2) the sand fraction alone in the saturated zone (defined by intervals where Vshale ≤ 0.25), and (3) sand fraction in both saturated and unsaturated zones within an HSU (Appendix 4, columns 5–7). The data all lie within one standard deviation, although the mean values suggest slightly higher porosities for the Upper and Lower Rio Rancho HSUs than the Middle Rio Rancho HSU. When density porosities are compiled for the sand bodies in both the saturated and unsaturated zones in a given well, the difference between the Upper and Middle Rio Rancho HSUs becomes more pronounced (Fig. 9). Since the proportion of sand relative to clayey sediment is only slightly higher (~5% in the saturated zone) in the Upper Rio Rancho HSU vs. the Middle Rio Rancho HSU (Fig. 4; Appendix 3), we infer that the difference in density-porosity values is largely due to differences in compaction and cementation (e.g., Haneberg, 1996; Busch et al., 2022). Collectively, the lower clay content, lesser compaction, and reduced cementation in the Upper Rio Rancho HSU compared to the Middle Rio Rancho HSU explain the generally higher hydraulic conductivity values observed in the Upper Rio Rancho HSU, as discussed below.

Compilation of Pumping test Data

Hydraulic conductivities at a given well per HSU unit are depicted as bubble plots in Figure 10, where the width of the circle is scaled to the value of hydraulic conductivity. Note how the Upper Rio Rancho HSU data are notably larger than the Middle Rio Rancho HSU data, indicating higher hydraulic conductivity values for the Upper Rio Rancho HSU. Both hydraulic conductivity and specific capacity data derived from pumping tests are shown in the box-and-whisker plots of Figure 11. For the Upper Rio Rancho HSU, the median value is 9.25 ft/day and the first quartile (25 percentile) is 7 ft/day. The median hydraulic conductivity for the Middle Rio Rancho HSU is 3.25 ft/day, and 75% of the values are ≤ 5.35 ft/day, which is below the 25th percentile of the Upper Rio Rancho HSU (Fig. 11). Although there is some overlap in the distribution of standard deviations (cf., Riesterer et al., 2004), the data indicate a higher probability of encountering higher-permeability strata in the Upper Rio Rancho HSU than in the Middle Rio Rancho HSU. There is more overlap in the specific capacity data, where the median value is 10.5 gpm/ft for the Upper Rio Rancho HSU and 8.45 gpm/ft for the Middle Rio Rancho HSU (Fig. 11).

PRELIMINARY EVALUATION OF GROUNDWATER FLOW

Potentiometric Surface Map

A map of the approximate potentiometric surface elevation is presented in Figure 12. See Koning et al. (2026a, 2026b) for details on its construction and associated groundwater-depth data. Note that the input data for this map were not as rigorously screened as the U.S. Geological Survey's potentiometric maps produced for the neighboring city of Albuquerque (e.g., Galanter and Curry, 2019), as exemplified in the inclusion of water levels collected over multiple decades (see details in Koning et al., 2026a, 2026b). Therefore, this map should be

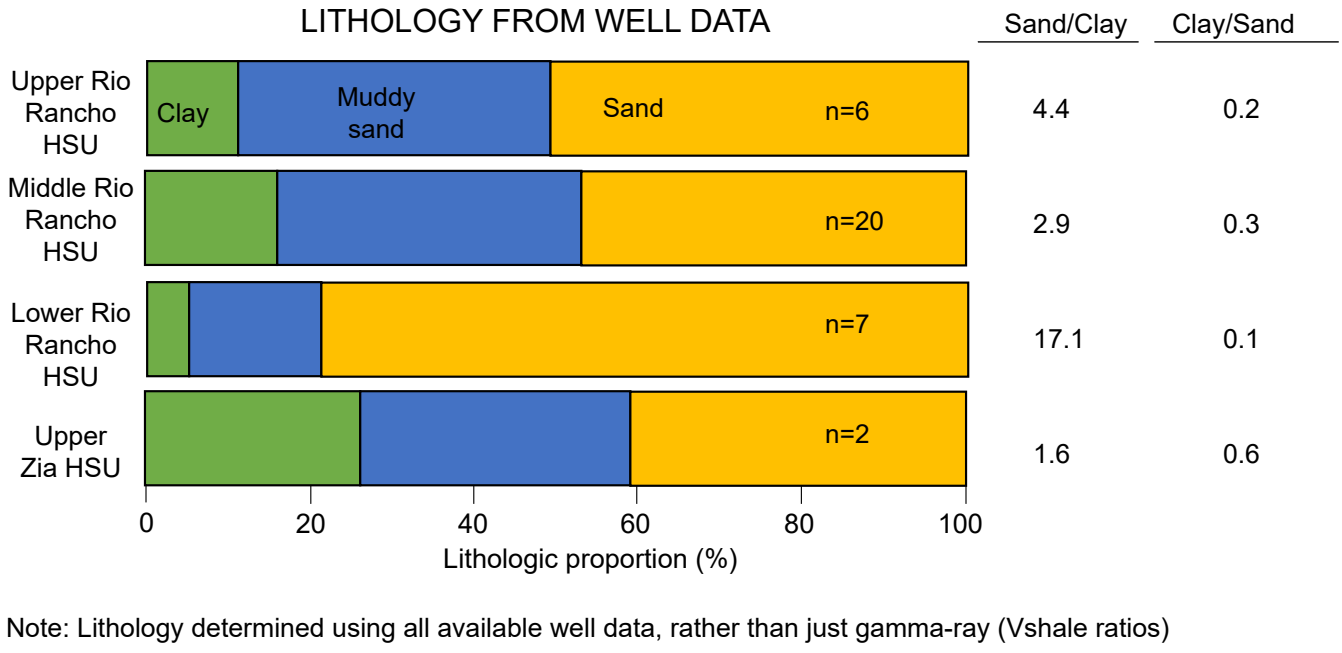


FIGURE 4. Results of lithologic analyses for 22 wells in the study area, determined manually using all available well data. The bar plot enables a comparison of the proportions of clay, muddy sand, and sand for the four HSUs. The sand versus clay and clay versus sand ratios (excluding "muddy sand") are shown to the right of the bar plot. Associated data (i.e., subsurface picks of clayey vs. sandy intervals per well) are in Appendix 3 and Koning et al. (2026b, appendix 5) and restricted to the saturated zone in an HSU.

TABLE 1. Well hydraulic conductivity (K), TDS, and age data

Well Label	Well name	HSU	K from pumping texts (ft/day)[1]	Specific capacity (gpm/ft)[1]	Storativity	TDS (ppm)[2]	C-14 age (ka)[3]
RRU-1	Rio Rancho Utilities 1	URR	21.2	3.7		412	
RRU-2	Rio Rancho Utilities 2	URR	3.2	5.7		360	2.8
RRU-3	Rio Rancho Utilities 3	URR	10.7	10.5		300	
RRU-4	Rio Rancho Utilities 4	URR	6.3	8.3		376	14.8
RRU-5	Rio Rancho Utilities 5	URR	9.4	7.5			
RRU-6A	Rio Rancho Utilities 6A	MRR	4.9	11	0.00002	274	
RRU-7	Rio Rancho Utilities 7	MRR	2.1	2.5		190	
RRU-8	Rio Rancho Utilities 8	MRR	5.2	13.3		260	18.2
RRU-9	Rio Rancho Utilities 9	MRR	1.1	4.6		322	23.1
RRU-10	Rio Rancho Utilities 10	MRR	2.0	5.9		388	19.3
RRU-10A	Rio Rancho Utilities 10A	MRR-LRR	2.5	14.4		900	
RRU-11	Rio Rancho Utilities 11	URR	20.7	5		1100	
RRU-12	Rio Rancho Utilities 12	URR-MRR	3.9	11.94	0.0008	461	11.9
RRU-13	Rio Rancho Utilities 13	MRR	1.9	11		282	30.9
RRU-13R	Rio Rancho Utilities 13R	MRR	1.0[7]	2.5		291[1]	
RRU-14	Rio Rancho Utilities 14	MRR	29	13.3	0.0013	274	
RRU-15	Rio Rancho Utilities 15	MRR	5.4	4.6	0.00004	530	14.2
RRU-16P	Rio Rancho Utilities 16P	MRR		5.9			
RRU-16P	Rio Rancho Utilities 16P	MRR-LRR	1.8		0.0001	466	
RRU-17	Rio Rancho Utilities 17	URR	9.1	39.5	0.00001	330	
RRU-18	Rio Rancho Utilities 18	MRR-LRR				1248	
RRU-19	Rio Rancho Utilities 19	MRR	2.8	11.9	0.00001	462	
RRU-21	Rio Rancho Utilities 21	MRR	3.6	16.2	0.0001	412	
RRU-22	Rio Rancho Utilities 22	LRR-Zia				5207	
RRU-23	Rio Rancho Utilities 23	LRR	21[4]	18.7	0.0017	1400[4]	
BR	Black Ranch test well	MRR	8.7[7]			370	
ASR_Di[5]	Rio Rancho ASR direct injection well	MRR				405[8]	
Bern 4	Bernalillo 4 well	URR	2.6	13.3			
HRP	Hunter Ridge piezometer	URR					5.7
NM Util 4	NM Utilities 4	URR	2.8	14.5			23.9
Intel 1	Intel Production Well 1	URR	8.4	26.5	0.001	280[1]	
Intel 2	Intel Production Well 2	URR	9.3	22		299	4.8[6]
Intel 2B	Intel Monitoring Well 2B	URR					
Intel 3	Intel Production Well 3	URR	10	26.6	0.0013	260[1]	
LMS	Lincoln Middle School piezometer	URR				205[9]	15.4
NMU-1	New Mexico Utilities 1	URR?				326[11]	18.8
NMU-2	New Mexico Utilities 2	URR				376[11]	6.0
NMU-3	New Mexico Utilities 3	URR				414[11]	17.2
NMU-4	New Mexico Utilities 4	URR-MRR	2.8			351[11]	23.9
SAF-1	Soil Amendment Facility	MRR	7			624[11]	28.1
SWAB	SWAB test holes 1 and 2	MRR					21.3
MP-MW1	Mariposa MW1[10]	LRR				680	
MP-MW3	Mariposa MW3[10]	LRR				478	

TABLE 1. Footnotes

Gray shades were not included in box-and-whisker plots because <80% of screen length is from a single HSU. In the case of the Intel wells, we attributed the pumping test data as all being from the Upper Rio Rancho HSU, even though 20–30% of the screens were in the Middle Rio Rancho HSU, because the MRR was notably finer-grained than the URR.

[1] Data from reports listed in Appendix 1; NMU-4 is from Riesterer et al. (2004).

[2] TDS data are from Riesterer et al. (2004) unless noted otherwise.

[3] Groundwater ages from table 10 of Plummer (2004c): "adjusted 14C calendar years (ka)." ka = thousands of years. For HRP, SWAB, and LMS, all sampled depths (n=3 for each) were averaged.

[4] Table 8 of Riesterer and Drakos (2008).

[5] Data from Marley, B., July 21, 2009, Biannual Report for OSE Permit No. USR 3 - Rio Rancho Direct Injection Aquifer Recharge Demo Project: unpublished consultant report to the NM Office of the State Engineer by Daniel B. Stephens and Associates.

[6] Data from Riesterer et al. (2004).

[7] Pumping test is the average of two screened intervals: 1.2 and 0.8 ft/day for the RRU-13R well 12 and 5.4 ft/day for the BR well.

[8] Average TDS of these values: 410, 460, 400, 360, 410, and 390 ppm.

[9] Average TDS from three depth intervals: 189, 203, 222 feet.

[10] Location of MP-MW1: 349033 m E, 3915713 m N; location of MP-MW3: 348863 m E, 3915644 m N. Data from Marley, B., January 30, 2009, USR 1 Biannual report 2009 to 2017: unpublished consultant report to the NM Office of the State Engineer.

[11] Calculated from Plummer (2004c) using major ions and SiO2, NO3, and F.

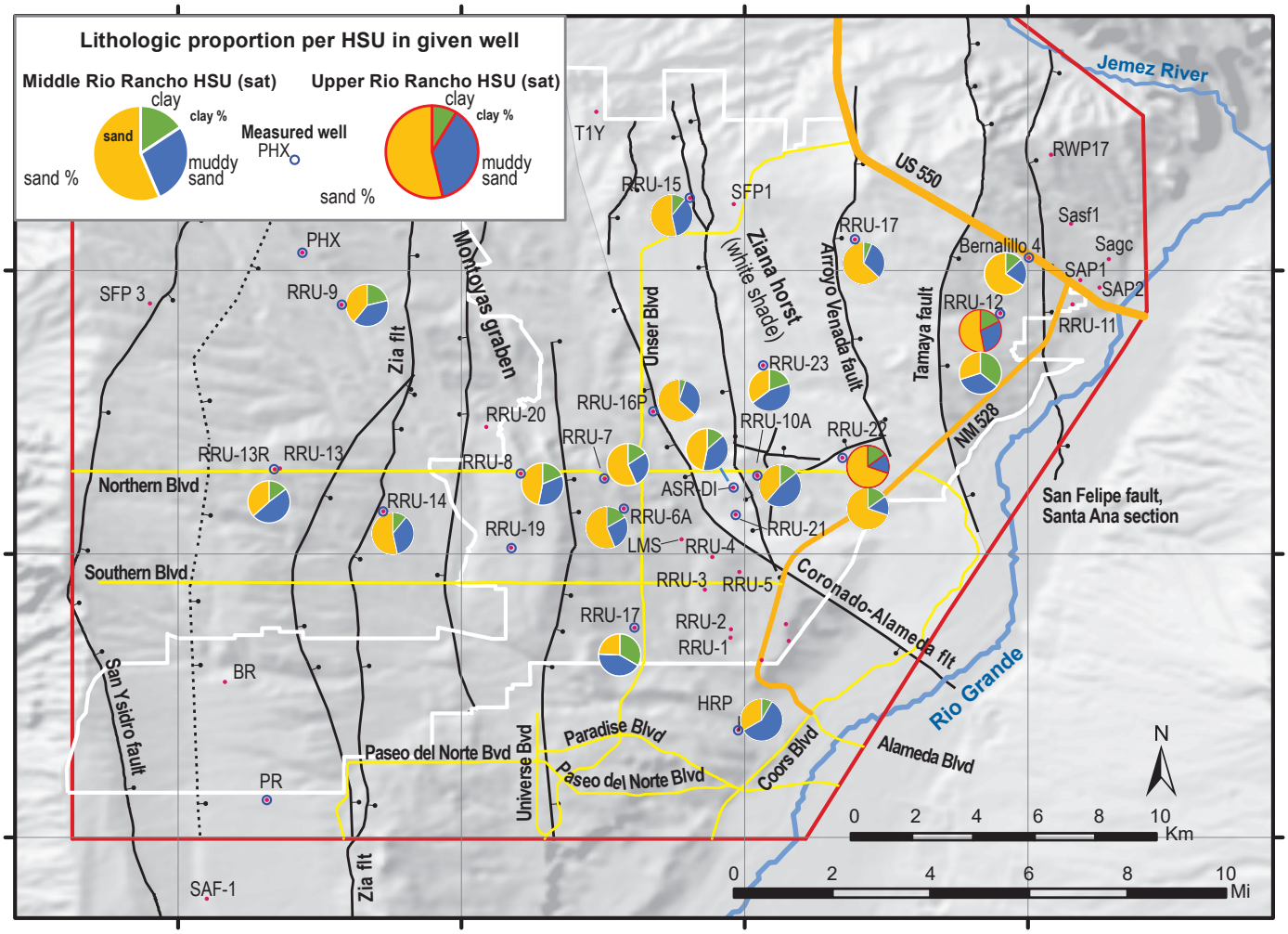


FIGURE 5. Pie graphs on map showing the proportion of clay, muddy sand, and sand per HSU in a given well. The approximate average paleoflow direction is to the southeast (Cather et al., 1997; Koning et al., 1998; Connell, 2008a, 2008b; Koning and Jochems, 2014; Koning and Rawling, 2017). Associated data (i.e., subsurface picks of muddy vs. sandy intervals per well) are compiled in Koning et al. (2026b, appendix 5) and restricted to the saturated zone in an HSU.

considered an approximation of the potentiometric surface and may locally contain 10–100 ft (3–30 m) of inferred vertical error, especially toward the northwest corner of the study area (i.e., where elevation-contour lines are dashed in Fig. 12). This map indicates recharge from the Rio Grande into the southeastern part of the study area. Over most of the central and northern parts of the study area, groundwater flow is to the south. A prominent groundwater trough, previously noted and discussed in Bexfield and Anderholm (2000) and Plummer et al. (2004a, 2004c), is present west of the north-south fault that projects northward from the vicinity of Universe Boulevard.

Total Dissolved Solids Data

In addition to being a proxy for groundwater quality, the spatial variation in TDS data can aid in evaluating groundwater flow and potential compartmentalization. We compiled water-quality data from chemistry analyses of samples from Rio Rancho's wells, particularly the city's main pumping wells (Table 1, Fig. 12). Note that the Coronado-Alameda fault delineates two TDS zones. Southwest of the fault, TDS values are quite low, ranging from 205 to 462 ppm (Table 1), and were obtained from wells screened in either the Upper or Middle Rio Rancho HSUs. TDS values are higher on the northeast side of the Coronado-Alameda fault, corresponding to the Ziana horst, where they range from 388 to 1,400 ppm (Fig. 12; Table 1). Due to the northward pinch-out of the saturated Upper Rio Rancho HSU (Fig. 3) and the southward dip of the HSUs in the southern part of the horst (Koning et al., 2026a, 2026b), sampled aquifers in this area consist of the Middle and Lower Rio Rancho HSUs and the Zia HSU (Fig. 12). Water samples east of the Ziana horst (i.e., east of the Tamaya fault) returned variable concentrations of TDS. These data indicate a spatial association between higher-TDS groundwater and areas on or near the Ziana horst, particularly north of Northern Boulevard. Even the shallower aquifers in the northern part of the horst (such as the Middle RRU sampled in RRU-15) have relatively high TDS (530 ppm) compared with values elsewhere in the study area (Table 1; Fig. 12).

Groundwater implications from radiocarbon ages

Groundwater radiocarbon data compiled from fourteen wells (Table 1) are plotted in Figure 12. Radiocarbon ages provide approximations of the true groundwater age, being subject to complications due to dissolution of older carbon in calcium carbonate cements or mixing of waters from sources with different ages. Still, when used in a relative sense, these ages can support or discredit hypotheses regarding groundwater flow paths and source areas. The youngest groundwater ages (2.8

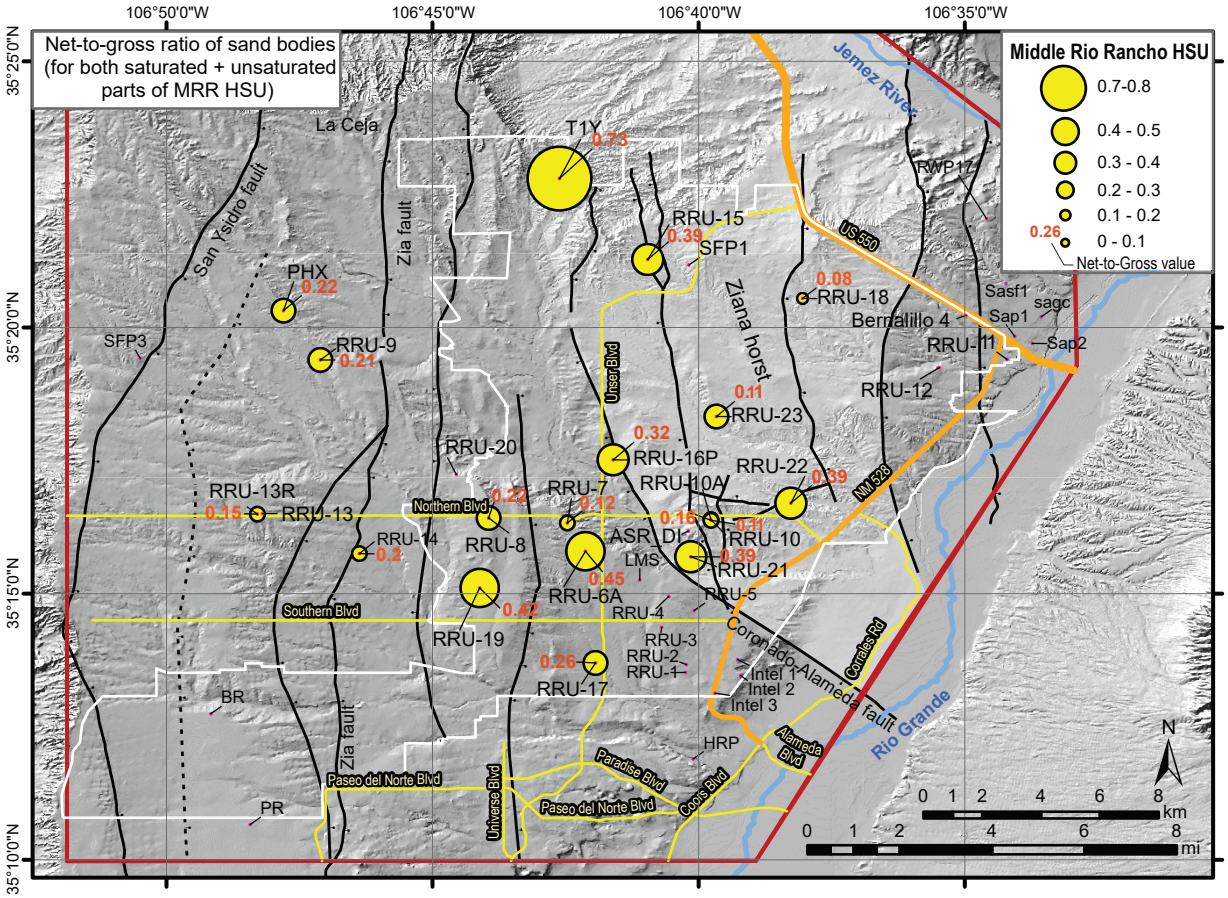


FIGURE 6. Bubble plot of net-to-gross of sand bodies in both the saturated and unsaturated zones for the Middle Rio Rancho HSU. Values are depicted using scaled yellow circles. This analysis is conceptually equivalent to calculating the proportion of sand bodies in the penetrated HSU. Note that "sand" is defined by a Vshale ≤ 0.25. Input data given in Appendix 4.

to 15.4 ka) are associated with the Upper Rio Rancho HSU in the southeastern study area, southwest of the Coronado-Alameda fault. Groundwater ages from the Middle Rio Rancho HSU range from 14.2 to 30.9 ka. The oldest groundwater ages occur west of the Coronado-Alameda fault and include samples from RRU-9 (23.1 ka), RRU-13 (30.9 ka), NMU-1 (18.8 ka), NMU-4 (23.9 ka), and SWAB (21.3 ka). These values are from the Middle Rio Rancho HSU except for well NMU-1 (sampling the Upper Rio Rancho HSU) and NMU-4 (likely sampling a mix of the Upper and Middle Rio Rancho HSUs). These data suggest long groundwater flow paths in the Santa Fe Group aquifer southwest of the Ziana horst and west of the longitude approximating Universe Boulevard.

DISCUSSION

Vertical and Lateral Trends in Permeability

Compilations of lithologic proxy data indicate that the Upper Rio Rancho HSU is slightly coarser and less clayey than the Middle Rio Rancho HSU, and thus more likely to have higher permeability. The first compilation utilized wireline data plus well cuttings (Figs. 4 and 5) and the second used net-to-gross ratios calculated from gamma-ray data (Figs. 6 and 7). Density-porosity data are higher in the Upper Rio Rancho HSU compared to the Middle Rio Rancho HSU (Fig. 9), probably reflecting less compaction and cementation in the upper unit.

A southeast decrease in coarseness (and increase in fine-grained sediment) and a corresponding decrease in hydraulic conductivity in the Middle Rio Rancho HSU could be expected based on southeastward paleoflow data in the Arroyo Ojito Formation (latter given in Connell 2008a, 2008b; Koning et al., 1998; Cather et al., 1997; Koning and Personius, 2002; Koning and Jochems, 2014; Koning and Rawling, 2017). However, in the Middle Rio Rancho HSU, there are no obvious southeastward trends in the lithologic and hydraulic conductivity data (Figs. 6 and 10). This possibly may be attributed to the fact that specific stratigraphic layers that are saturated vary from well to well. This variability is due to the sloping potentiometric surface (Fig. 12), variable well depths, and faulting. Alternatively, the portion of the paleodrainage within the study area may be too limited (compared to the total length of the paleodrainage) to exhibit such a trend (Koning et al., 2026b).

For the Middle Rio Rancho HSU, there are suggestions of increased lateral permeability near the southwest corner and northern boundary of the study area. Visual inspection of the mapped hydraulic conductivity data indicates that two wells in the southwestern corner of the study area yielded relatively higher hydraulic conductivities for the Middle Rio Rancho HSU: 8.7 ft/day for the Black Ranch well and 7 ft/day for well

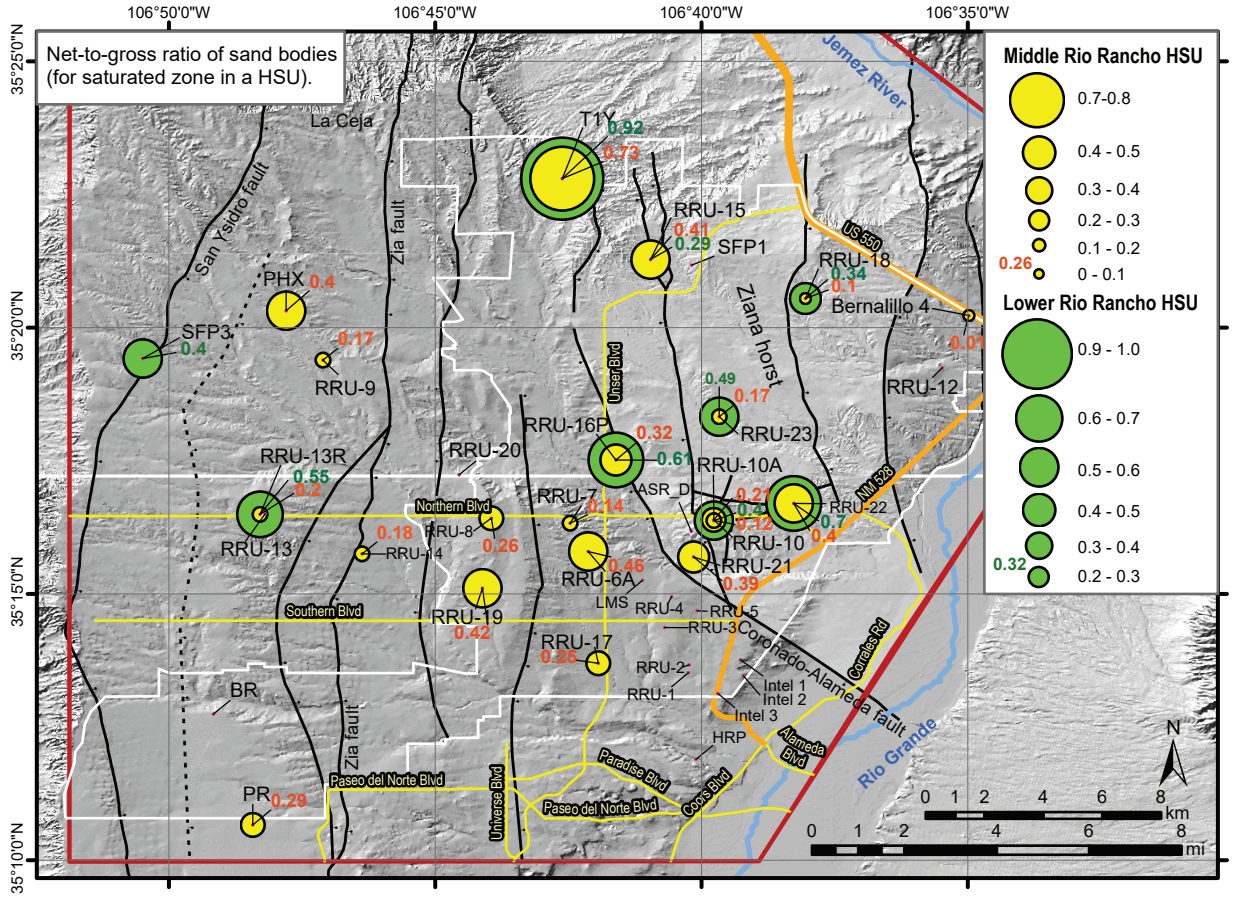


FIGURE 7. Bubble plot of net-to-gross ratios of sand bodies in the saturated zone for the Middle and Lower Rio Rancho HSUs, for the portion of the HSU penetrated by a given well. Values are depicted using scaled yellow and green circles (for the Middle and Lower Rio Rancho HSUs, respectively). Note that "sand" is defined by a Vshale ≤0.25. Input data are given in Appendix 4.

SAF-1 (Fig. 10). This may be due to coarse-grained tongues associated with the Benavidez lithologic unit (piedmont sediment sourced from the southeastern Colorado Plateau; Koning et al., 2021, 2026c). Net-to-gross values of sand bodies are variable across the study area, but there is a suggestion that the northernmost part of the saturated Middle Rio Rancho HSU, (corresponding to the area around wells PHX, T1Y, and RRU-15), is slightly more permeable. This interpretation is based on northward increases in sand body net-to-gross values (Figs. 6 and 7) and the moderate correlation between NGR values and pumping test hydraulic conductivities (Fig. 8). Perhaps the change north of the latitude N35°, 19–20' reflects the approximate toe of a paleofan. North of this inferred toe was relatively steeper slopes of a distal fan, whereas downstream (to the south-southeast) the paleodepositional environment consisted of a gently sloping bajada or basin floor.

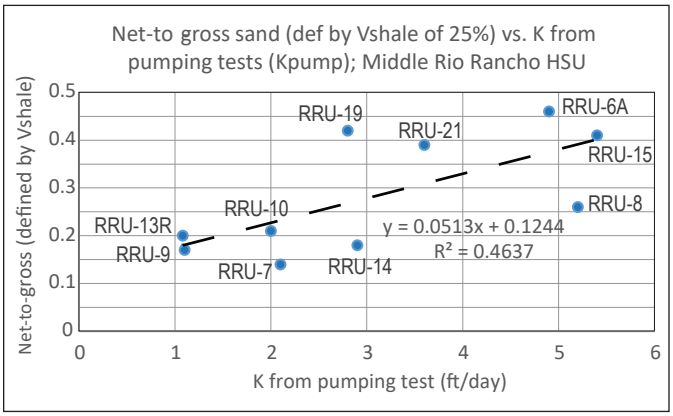


FIGURE 8. Net-to-gross ratios of sand are plotted against hydraulic conductivity data derived from pumping tests. There is a moderate correlation with pumping test data (K_pump; R^2 of 0.46). The percentage of sand bodies was calculated using the Vshale curve in Kingdom software, where "sand" is defined by a Vshale ≤0.25. All data are from the Middle Rio Rancho HSU.

Groundwater Resource Considerations

Most favorable HSU

Although there is some overlap in hydraulic conductivity values between the Upper and Middle Rio Rancho HSUs, the Upper Rio Rancho HSU contains considerably higher values, and its median hydraulic conductivity is 3 times greater than that of the Middle Rio Rancho HSU. (Fig. 11; Table 1). The Upper Rio Rancho HSU also contains groundwater with the lowest TDS values (Fig. 12; Table 1), excluding the anomalous data at well RRU-11, and is the shallowest HSU. Therefore, the Upper Rio Rancho HSU can be considered as the most favorable HSU for groundwater-production potential. However,

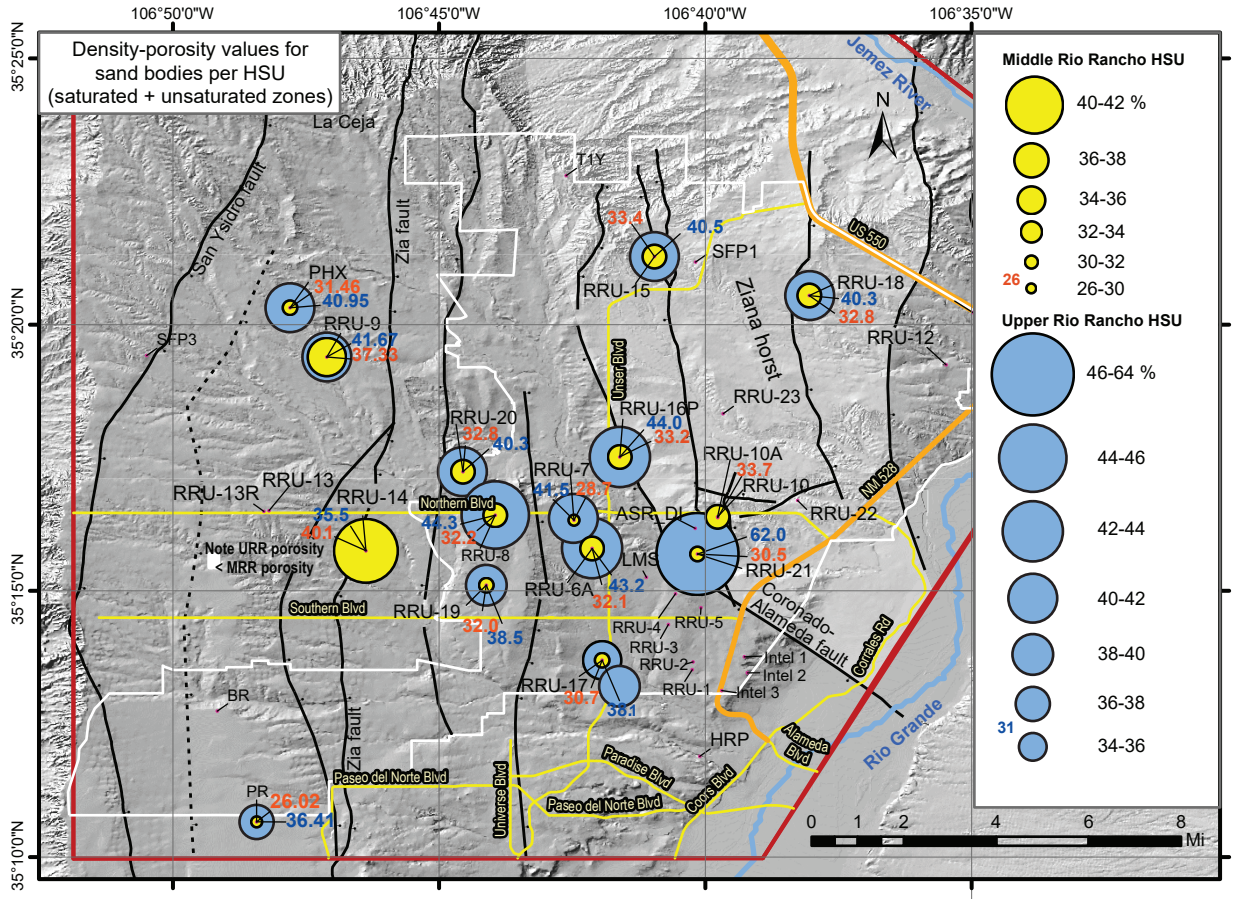


FIGURE 9. Bubble plots illustrating arithmetic means of density-porosity data for sand intervals in wells penetrating the Middle and Upper Rio Rancho HSUs (scaled yellow and blue circles, respectively). Sand intervals are defined using Vshale ratios ≤0.25. Except for well RRU-14, the Upper Rio Rancho HSU has consistently higher values than the Middle Rio Rancho HSU. Input data given in Appendix 4.

most of the Upper Rio Rancho HSU is unsaturated, with saturated zones restricted to the southeastern corner of the study area and along the eastern boundary (Fig. 3). Additional discussion of the saturated thickness trends of the Upper Rio Rancho HSU is given in the companion paper (Koning et al., 2026a).

Most favorable area

Areas where the saturated Upper Rio Rancho HSU is thickest, in the eastern and southeastern parts of the study area (Fig. 3), correspond to locations where groundwater flow paths and radiocarbon ages indicate recharge from the lower Jemez River and the Rio Grande (Fig. 12). TDS values are low in these areas, except locally near faults (e.g., RRU-11). Young (<15,000 years old) radiocarbon ages and groundwater flow directed away from rivers suggest a component of recharge from relatively young surface waters. In terms of hydrogeologic properties, this area may be viewed as favorable for groundwater extraction.

Middle Rio Rancho HSU

The extent and thickness variations of the saturated portion of the Middle Rio Rancho HSU are shown in Figure 3. Note that it extends notably farther northwest than the Upper Rio Rancho HSU, reaching the San Ysidro fault. Full discussion of Middle Rio Rancho HSU thickness variations is presented in Koning et al. (2026a).

Our sand vs. clay permeability proxies, obtained from well data, suggest that the Middle Rio Rancho HSU generally has lower permeability at a given site than the Lower and Upper Rio Rancho HSUs (Figs. 4 and 5). Compilation of hydraulic conductivity and specific capacity data from pumping tests indicates that, in general, the Middle Rio Rancho HSU is likely to be less permeable than the Upper Rio Rancho HSU (Figs. 10 and 11), although there is overlap in these datasets (especially for specific capacity). However, the relatively high saturated thickness of the Middle Rio Rancho HSU (>1,000 ft) promotes high transmissivities (T = hydraulic conductivity x saturated thickness), and the TDS values for this unit are <500 ppm west and southwest of the Ziana horst. Therefore, the Middle Rio Rancho HSU is an important component of groundwater management for the northwestern Albuquerque Basin.

Groundwater zones

Synthesis of the potentiometric surface map, TDS values, and radiocarbon ages indicate three broad zones where these groundwater features have relatively distinct properties. These informal zones approximately coincide with the hydrochemical

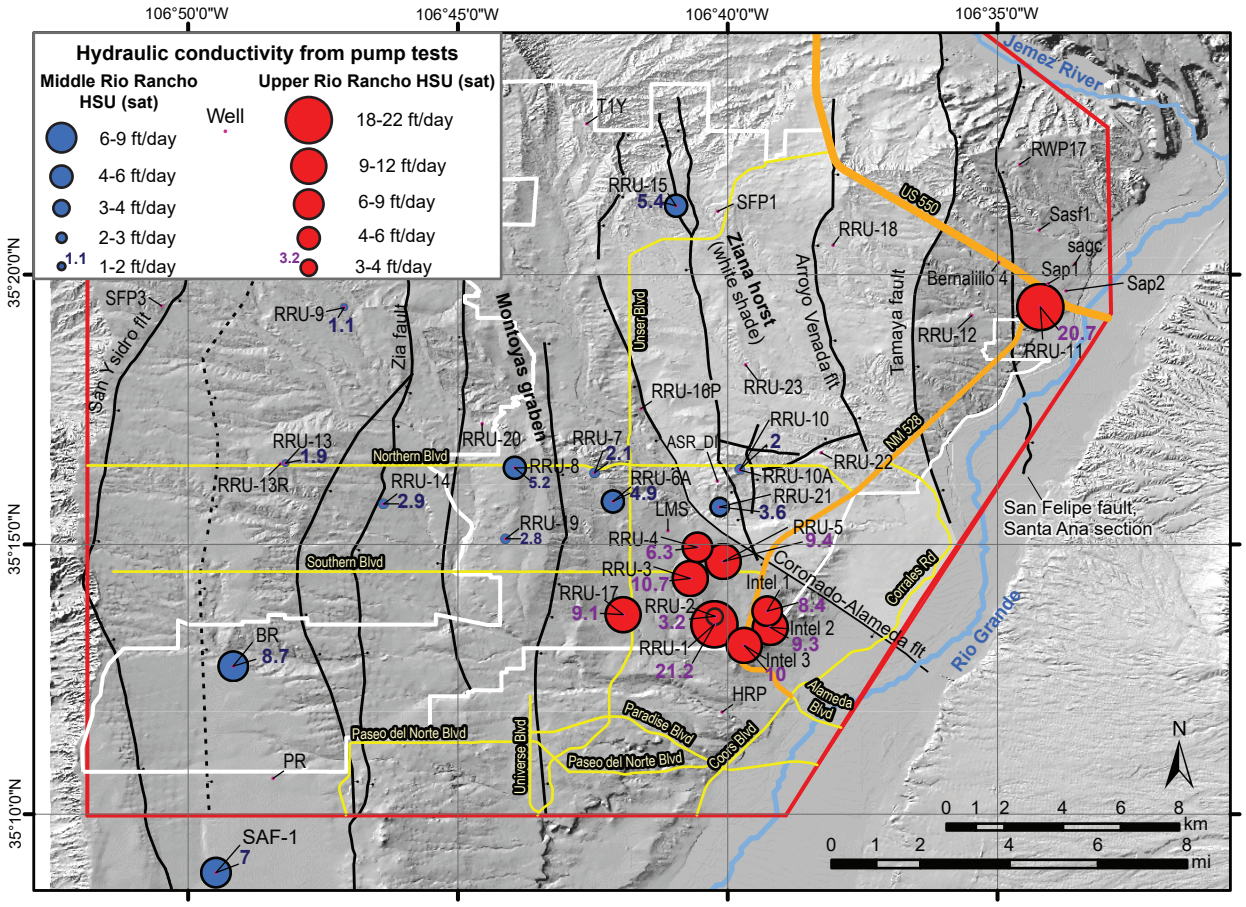


FIGURE 10. Map showing spatial distribution of hydraulic conductivities calculated from pumping tests (Table 1). Pumping tests in the Upper Rio Rancho HSU vs. Middle Rio Rancho HSU are shown in red and blue shades and fonts, respectively.

zones of Plummer et al. (2004a, 2004c). Our zones are labeled A, B, and C in Figure 12. Zone A coincides with the west-central hydrochemical zone of Plummer et al. (2004a, 2004c), has relatively old radiocarbon ages, and corresponds spatially to the aforementioned groundwater trough. TDS values are relatively low, but various chemical parameters indicate that groundwater flowed via long paths through bedrock (Plummer et al., 2004a, 2004c). Zone B coincides with the Ziana horst and is separated from Zone A by the Coronado-Alameda fault. It shares the northwestern and northern mountain front hydrochemical zones of Plummer et al. (2004c). Groundwater flow is to the south and TDS values are relatively high there, perhaps due to upwelling of salty water from fractured, shallow bedrock near faults. Zone C corresponds to low-TDS groundwater recharged from the Rio Grande. This area lies in the central hydrochemical zone of Plummer et al. (2004a, 2004c), who also interpreted young recharge from the Rio Grande. The fault along Universe Boulevard and continuing northward is interpreted as a groundwater barrier separating older (west, Zone A) from younger (east, Zone C) groundwater. Such a barrier, either this fault or perhaps subsurface basaltic dikes, would also explain the position of the eastern margin of the groundwater trough in Zone A.

Brackish water resources

The middle and northern parts of the Ziana horst, particularly north of Northern Boulevard, is spatially associated with high TDS and poorer-quality groundwater (Fig. 12). This is exemplified at well RRU-23 by the groundwater quality problems documented in Riesterer and Drakos (2008) and the lack of current pumping. The Ziana horst corresponds to the Zone B groundwater zone, where groundwater flows southward and TDS values are relatively high (Fig. 12). The salty water likely results from upwelling of deep water from the relatively high (structurally elevated) and faulted (and presumably fractured at depth) horst block. Deep groundwater sourced from the Jemez Mountains may also flow southward in the lower Zia HSU between north-striking faults. Future water-well drilling in this zone probably has the best chances for success to the south, since the Upper and Middle Rio Rancho HSUs thicken southward (Fig. 3), and TDS values also lessen in that direction (Fig. 12).

Two relatively deep, sandstone-dominated intervals that likely contain brackish water are the Lower Rio Rancho HSU (especially on the Ziana horst) and the lower-middle Zia HSU (Koning et al., 2026b). The Lower Rio Rancho HSU is deemed to be permeable based on its relatively higher sand content (Fig. 4) and high hydraulic conductivity value from a single pumping test (Table 1, well RRU-23). The lower–middle Zia HSU lacks pumping test data, but it is notably sandy where encountered in wells (e.g., well SFP1 in Koning et al., 2026b). It also likely correlates to the Piedra Parada Member of the Zia Formation, which shows relatively low amounts of strong cementation in outcrops and is inferred to be relatively permeable (Koning et al., 1998; Koning and Jochems, 2014; Koning and Rawling, 2017). The TDS content of the Lower Rio Rancho HSU is relatively high on the Ziana horst (Fig. 12), and water from the lower–middle Zia HSU is also likely brackish to saline. Therefore, these two stratigraphic intervals may have moderate permeabilities, but associated groundwater is expected to be brackish. If extracted for municipal use, this water would likely need to be desalinated or blended to meet water quality standards. Whether such treatment or blending is practical or economically feasible warrants further study.

CONCLUSIONS

This study assesses permeability differences and trends between and within hydrostratigraphic units (HSUs) in the northwestern Albuquerque Basin. It also uses an approximate potentiometric surface map, radiocarbon data, and TDS values to refine interpretations of groundwater flow and potential compartmentalization. Although there is overlap in the datasets, the Upper Rio Rancho HSU generally exhibits higher hydraulic conductivity values (compiled from pumping tests) compared to the Middle Rio Rancho HSU, consistent with its higher sand/clay ratio inferred from well data and its higher density-porosity values. Furthermore, the TDS values of the Upper Rio Rancho HSU are relatively low, typically 200–400 ppm. However, the thick saturated portions of the Upper Rio Rancho HSU are only found east of the Tamaya fault and in the southeastern part of the study area, south of Southern Boulevard and southwest of the Coronado-Alameda fault. The saturated Middle Rio Rancho HSU is over 1,000 ft thick across

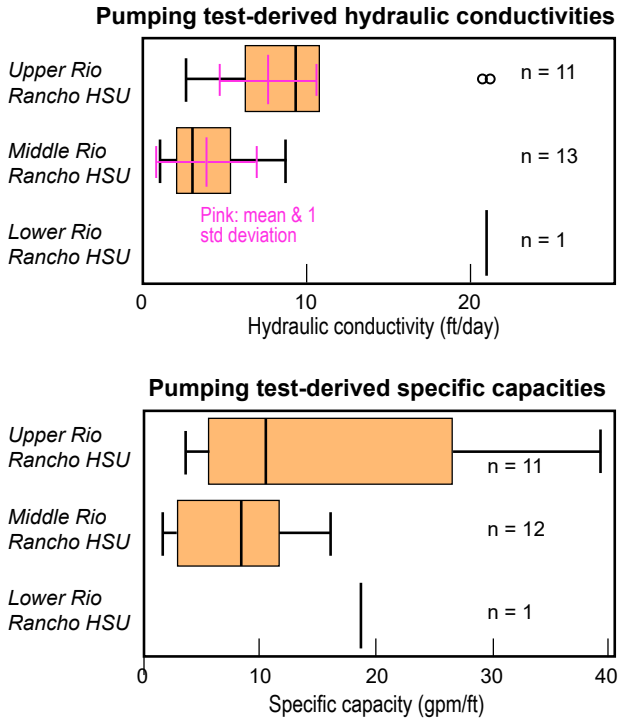


FIGURE 11. Box and Whisker plots of hydraulic conductivity and specific capacity data for the Upper, Middle, and Lower Rio Rancho HSUs. Outliers are plotted as circles and are defined as being more than 1.5 times the interquartile distance (i.e., the distance between the 25th and 75th percentiles) relative to the 75th percentile. The pink lines show the standard deviation relative to the mean of the data (note the mean is plotted as the longer, pink bar).

most of the study area, including a northward prong extending between the Ziana horst and the Zia fault. Several wells indicate a coarsening-upward trend in this HSU (e.g., fig. 4 of Koning et al., 2026a), so areas where its upper part is saturated are more favorable than where only its lower part is saturated. There are no strong lateral permeability trends across most of the saturated Middle Rio Rancho HSU, but hydraulic conductivities compiled from pumping tests do indicate higher

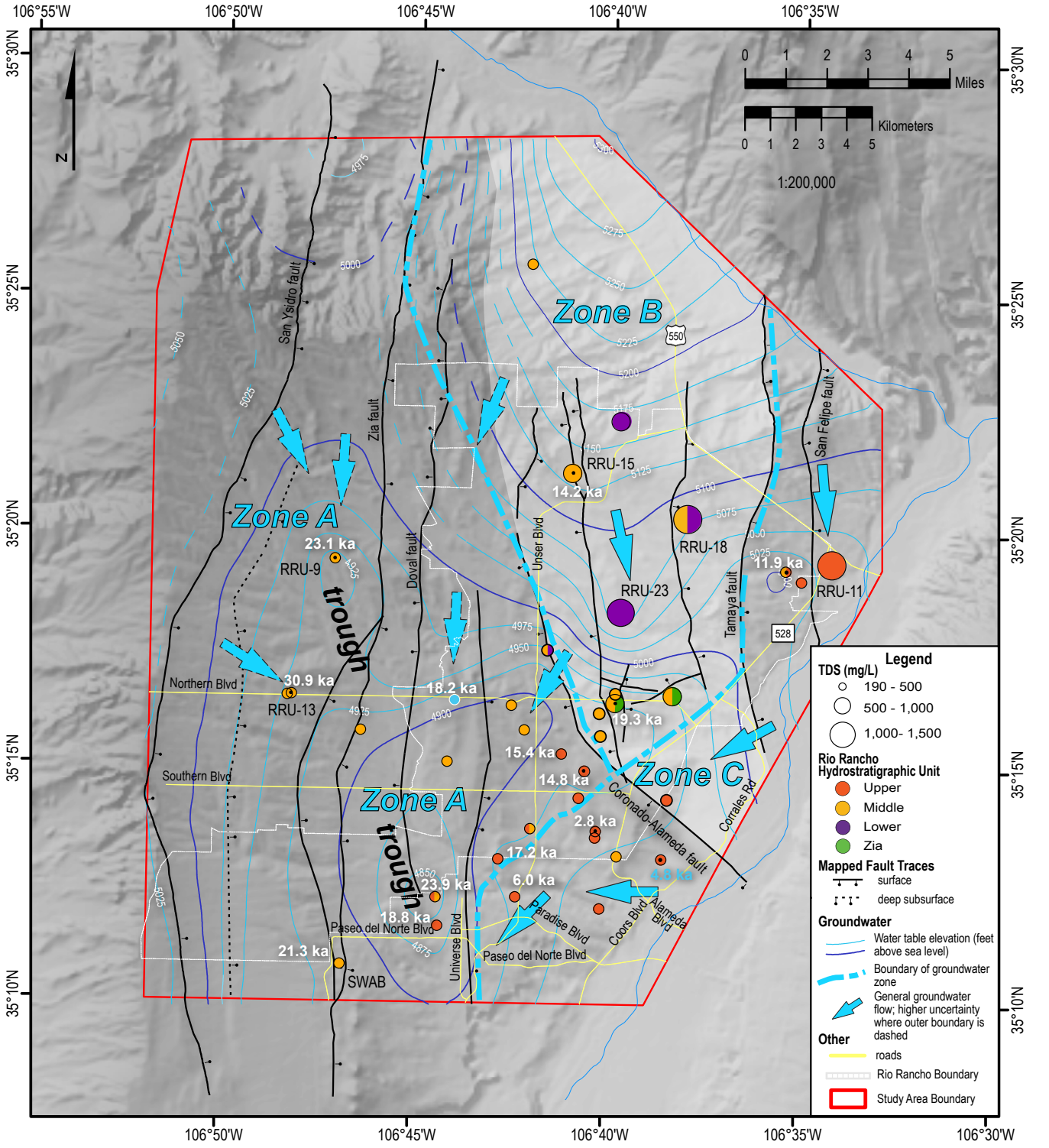


FIGURE 12. Map of groundwater flow, TDS values, radiocarbon ages, and inferred groundwater zones where these properties are relatively similar (Table 1). Locations of wells are shown via colored circles, where the colors are coded according to the HSU (e.g., Upper, Middle, Lower Rio Rancho HSU) and the circles are scaled according to the TDS value. Note that two colors within a circle means a TDS value is interpreted to reflect two HSUs, based on comparison of screen depths with the depths of HSU boundaries in a given well. Groundwater radiocarbon ages are shown by the white text (Table 1) and are in ka (thousands of years before present). Groundwater-elevation contours are dashed where highly approximate. Groundwater flow is denoted by arrows, whose margins are dashed where uncertain. Names given for select wells (see Figure 1 for full listing).

permeability values of the study area, about 5 miles (8 km) northwest and southwest of the western end of Paseo del Norte Boulevard. A slight northwest increase in sand proportions also occurs north of the approximate latitude of RRU-9 (N35°20'), suggesting a possible increase in permeability that remains to be confirmed by pumping test data.

We recognize three general zones (zones A through C) where groundwater TDS values, flow, and ages are distinct. Groundwater in Zone A, to the southwest, exhibits a trough in the potentiometric surface and contains the oldest groundwater. Zone B corresponds to the Ziana horst and its groundwater has relatively high TDS values in its northern half. Zone C contains the freshest and youngest groundwater, probably due to recharge from the Rio Grande.

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Appendices can be found at
https://nmgs.nmt.edu/repository/index.cfml?rid=2026008



View to SSE towards Tunnel Springs, located near the golden cottonwood trees, framed by the northern Sandia Mountains. This spring was named for a mine adit (now collapsed) that fortuitously encountered a branch of the Pomecerro fault and associated fractures that yielded 20 gpm (in 1962), enough to supply a fish hatchery (W.E. White and G.E. Kues, 1992, USGS OFR 92-118). Photograph courtesy of Daniel Koning.