NEW MEXICO BUREAU OF GEOLOGY AND MINERAL RESOURCES

Hydrogeologic Framework of the Village of Peña Blanca, New Mexico

Alex J. Rinehart

Open-file Report 586
Final Report
September 2016

New Mexico Bureau of Geology and Mineral Resources

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AQUIFER
MAPPING
PROGRAM

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PROJECT FUNDING

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Cover photo: Looking due west at the water table exposed in a trench near the East Drain (berm seen in background) in Peña Blanca, NM.
Photo by Alex Rinehart.

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EXECUTIVE SUMMARY

The New Mexico Bureau of Geology and Mineral Resources serves as the state's geologic survey, and has been working in Peña Blanca since March 2016 at the request of the NM Environment Department (NMED). The goal was to understand the local hydrogeology of Peña Blanca in order to make a recommendation for an area to place a new well. The need for a new well was highlighted by the discovery of solid waste, a hydraulic fluid tank and a diesel tank immediately adjacent to but on different property than the current municipal well. We met our goal by reviewing the existing literature on the local and regional geology, historical studies of groundwater levels, and regional groundwater chemistry studies. We also collected measurements of groundwater levels and sampled water chemistry in 25 municipal and domestic wells in and around Peña Blanca.

Peña Blanca is a small municipality in the Rio Grande valley surrounded by Cochiti and Santo Domingo Pueblos in north-central New Mexico. The village is built on the eastern margin of the Rio Grande floodplain and river terraces. Peña Blanca stretches west from the valley edge across agricultural fields to the East Drain east of the Rio Grande channel. The fields are flood irrigated using Rio Grande surface water. The village is bounded on the north by the Santa Fe River and to the south by the Galisteo River. The Santa Fe River is impounded by Cochiti Dam to the east of Peña Blanca. Cochiti Dam also impounds the Rio Grande, forming the Cochiti Reservoir north of Peña Blanca. Much of Peña Blanca uses domestic water wells. Both these wells and the larger public water supply wells are generally screened in either recent Rio Grande sands or in older-than-11,500 yrs (Pleistocene-aged), deeper Rio Grande sands and gravels. The older Rio Grande sands and gravels form a continuous aquifer to the east underneath the uplands.

We measured water levels and sampled water chemistry in domestic and public supply wells in and around Peña Blaca. A summary of the hydrogeology of the Peña Blanca follows.

- The wells sampled all had good water quality based on the major ions and trace metals in the water (below recommendations by U.S. Environmental Protection Agency (USEPA) or NMED for drinking water limits). One well had high iron concentrations. We did not test for any biological contaminants.
- The primary aquifer is formed from old deposits of the Rio Grande, mainly sand and gravel.
- This reach of the Rio Grande is gaining water from groundwater, leading to shallow groundwater levels near the river.
- In Peña Blanca, groundwater is moving west-southwest from the uplands in the east to the East Drain and the Rio Grande.

- Water chemistry, isotopes and water levels indicate the groundwater is regional groundwater from the nearby uplands, is from local recharge from Rio Grande-sourced irrigation and the ditches, or a combination of both.

Based on the groundwater data available, we recommend siting a new well in the shaded zone shown in Figure 1 on the southeast edge of Peña Blanca between the existing municipal well and the arroyo flowing east-west along the southern boundary of Peña Blanca. This region is up-gradient of known land surface contamination (arrows show current groundwater flow direction and known contamination sites are labeled). Also, this region is outside of the populated valley, decreasing the potential for groundwater contamination both because of fewer potential sources and having deeper depths-to-water than in the valley.

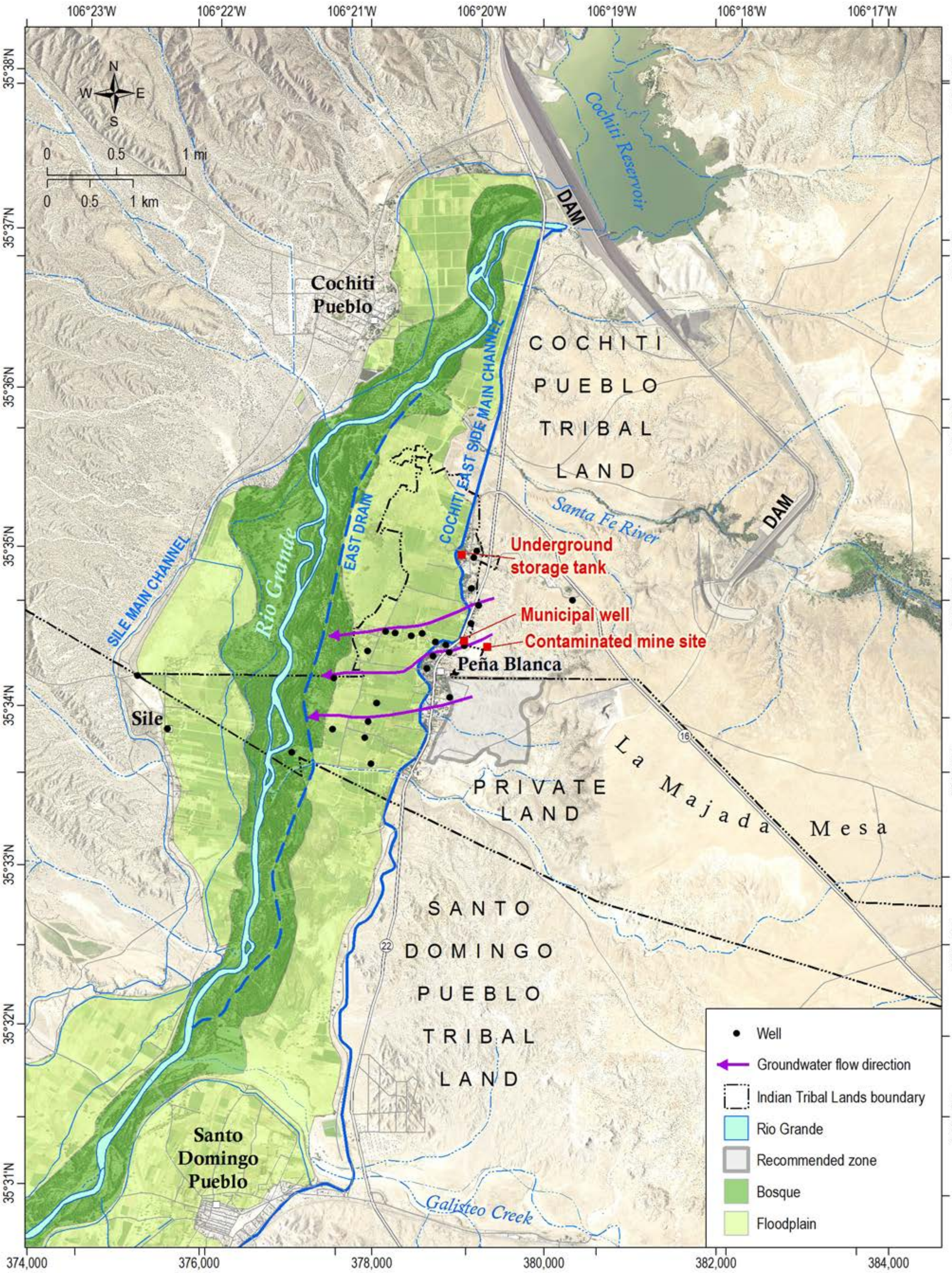

Figure 1. Summary figure of possible zone for a new municipal water well and major groundwater flow direction.

Looking northwest at well housing (culvert in foreground) and across field in Peña Blanca, NM. *Photo by Alex Rinehart.*

I. INTRODUCTION

We present a brief hydrogeologic overview of the town of Peña Blanca in north-central New Mexico (Fig. 1 and 2) to aid in siting a new municipal well. In order to have greater water security, it is necessary to have more than one source of drinking water in a municipality. In much of New Mexico, this is generally done by having multiple municipal drinking water wells. Currently, Peña Blanca has a single municipal drinking water well that supplies much of the town. Many households continue to use domestic water wells, either as a supplemental source or because it has proven difficult to connect portions of the town to the municipal water supply. Recently, a mined area immediately adjacent to the Peña Blanca municipal water supply well was found to contain solid waste, diesel and hydraulic fluid tanks and possibly other liquid waste (Peña Blanca Water and Sanitation District, 2014). This discovery has raised awareness of the vulnerability of the Peña Blanca municipality water supply. This project was initiated upon the request of the New Mexico Environment Department, Drinking Water Bureau, Source Water Protection Program. They provided funding for this review, field data collection and sample analyses.

Drilling new production wells can be very costly. Therefore, before drilling it is important to gather as much information as possible about the region. Information about the region may include local water quality, depth-to-water, and productivity of the aquifer. It is necessary to understand the local geology, geologic and man-made controls on water quality, and the direction of groundwater flow. In this study, we have combined existing knowledge of the region with new water chemistry and water level measurements to understand the controls on groundwater character and provide a recommended zone for a new municipal well.

We begin by providing a review of the geology and the hydrogeology of the region surrounding Peña Blanca (Background). Then, we summarize the methods used for field sampling and laboratory analysis (Methods) and present the results of our sampling and measurements (Results). At the end, we present our conceptual model of the Peña Blanca hydrogeology, and discuss our recommended area for a new municipal well (Discussion and Recommendations).

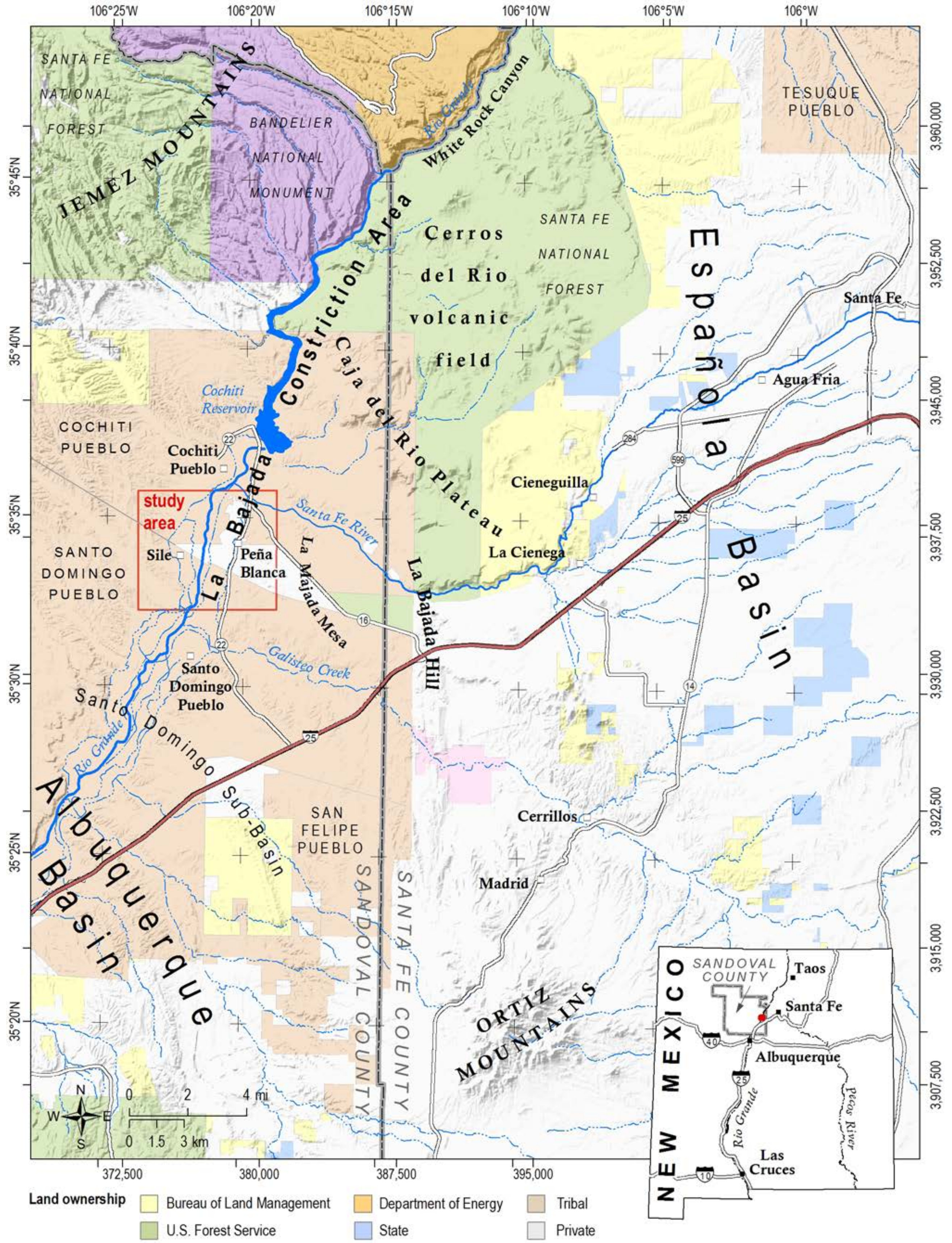

Figure 2. Overview of region surrounding Peña Blanca, including major landmarks, hydrography and roads.

II. BACKGROUND

The town of Peña Blanca is in the Rio Grande valley in north-central New Mexico between the Cochiti Pueblo to the north and east, and Santo Domingo Pueblo to the south (Fig. 2). The majority of the town is found on the eastern edge of the Rio Grande valley with houses and agricultural fields extending west across the floodplain to the bosque. On the west side of the river, the village of Silé is similarly positioned on the western edge of the Rio Grande valley. The major tributary streams on the east side of the river are the Santa Fe River to the north and the Galisteo Creek to the south, with a number of smaller arroyos cutting the eastern uplands and spilling out into the main valley. East from Peña Blanca are La Majada Mesa and then La Bajada Hill (Fig. 2). To the northeast is Caja del Rio Plateau, which is a volcanic-capped mesa hosting the Cerro del Rio Volcanic Field.

The Rio Grande is a large perennial river flowing from its headwaters in southern Colorado through New Mexico and Mexico to the Gulf of Mexico. It flows through a sequence of geologic basins, or lows, formed by the east-west opening and deepening Rio Grande rift (Connell, 2004). The river has been flowing through from Colorado through New Mexico and into the Gulf of Mexico for about 5 million years (Connell, 2004). Peña Blanca is in a narrow portion of the rift valley called the La Bajada Constriction Area between the Santo Domingo Sub-Basin of the northern Albuquerque Basin and the southern Espanola Basin (Sawyer and Minor, 2006).

Detailed Geologic History

In the discussion below, we provide detail of the geologic history around Peña Blanca. This discussion has bearing on water quality in the basin, aquifer characteristics and possible impediments to groundwater flow. To summarize, the region around Peña Blanca is in the Rio Grande rift, a roughly north-south oriented series of basins. Around Peña Blanca, most of the aquifer froming sediments filling the basin are with gravels and sands deposited by the Rio Grande more than 800,000 years ago; these form the major aquifer of the region. To the east, sediments from tributaries and the Rio Grande are either at the surface, are buried by wind-blown sand, or are capped by volcanic rocks. In the floodplain, the coarse sediment is capped by finer grained recent (less than 11,500 years old) muds and sands. To the west, sediments from the volcanic Jemez Mountains spill into the valley. The presence of volcanic rocks at the surface to the east implies their presence in the aquifer—this may increase sulfates, uranium and arsenic in the groundwater. No major faults cross Peña Blanca, so there is little chance of compartmentalized aquifers or deep brines being driven to the surface here.

As the river flowed through the different basins over the last 5 million years, it has deposited hundreds to thousands of feet of sediments of mostly sands and gravels (Sawyer and Minor, 2006a,b; Dethier and Sawyer, 2006, and Smith and Kuhle, 2000; Fig. 3, units QTsl and QTsls) while sediments spilled in along the sides of the valley from the surrounding highlands (ref; Fig 3, unit QTslp). The Rio Grande valley in much of New Mexico filled until approximately 800,000 years ago (Connell et al., 2013). It seems likely this maximum level of aggradation was marked by the La Majada Mesa surface (Fig. 3, unit Qalm), but the La Majada Mesa surface is on a graben that was subsiding until 500,000 years ago (Minor et al., 2006); the top of its Rio Grande sediments has been covered by alluvial fans and eolian sediments (Smith and Kuhle, 2000; and Dethier and Sawyer, 2006). After this, the Rio Grande began to cyclically cut and fill, leaving a suite of terraces (benches) inset against the older basin fill (Smith and Kuhle, 2000; Fig. 3, units Qtg, Qtgp4, and Qoa) with a roughly 100 ft thick layer of modern sandy and finer grained sediment capped by floodplain muds near the river (Fig. 3, unit Qf). Interlayered and overtopping the Rio Grande sediments are thin (less than 30 ft) layers of sediment filling tributary valleys and spilling onto the recent Rio Grande valley floor as alluvial fans (Fig. 3, Qal; Dethier et al., 2006). The area also has small sand sheets and dunes in places (Fig. 3, unit Qe; Smith and Kuhle, 2000).

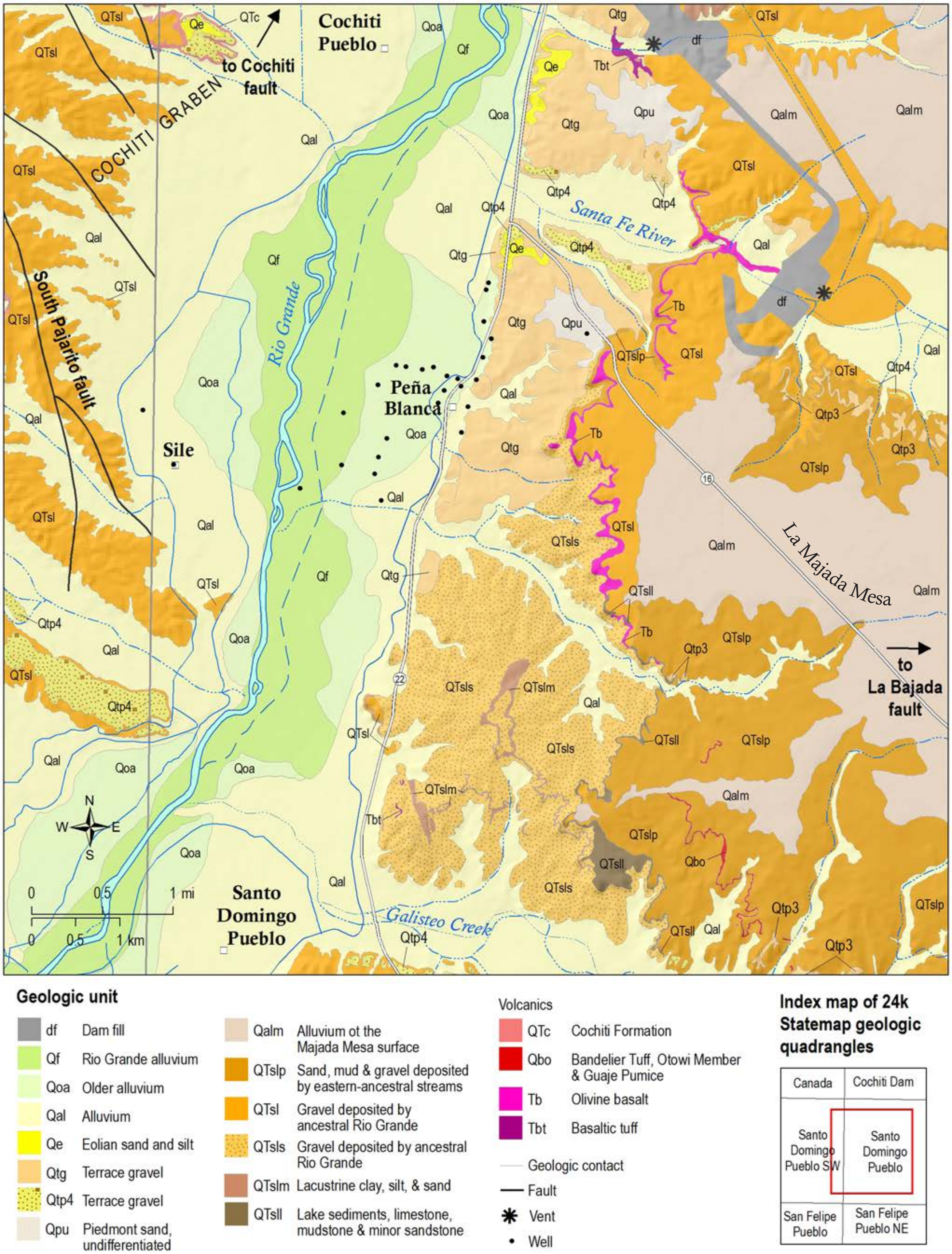

Figure 3. Geologic map (1:24,000) adapted from Smith and Kuhle (2000).

Volcanic eruptions have occurred along the margins of the Rio Grande rift from the beginning of its opening through recent times (3000 years ago; Minor and Sawyer, 2006a). The area around Peña Blanca is no exception. The Jemez Mountains are to the north and west of Peña Blanca. These mountains are the result of a series of volcanic eruptions beginning 14–13 million years ago (Fig. 3 unit QTc) with the largest eruptions at from 1.6 to 1.2 million years ago (Goff and Gardner, 2004; Fig. 3., unit Qbo). Eroded volcanic sediments (Cochiti Formation, Smith and Kuhle, 2000) interfinger with the axial Rio Grande sediments on the west side of the valley. In addition, the sedimentation from the Jemez eruptions occasionally blocked the Rio Grande, forming lakes and leaving lacustrine sediments (Smith and Kuhle, 2000).

The Cerro del Rio Volcanic Field northeast of Peña Blanca was erupted between 2.7 and 2.2 million years ago (Minor and Sawyer, 2006a). Volcanic rocks from these eruptions are on top of mostly Rio Grande-sourced sediments to the east of Peña Blanca (Minor and Sawyer, 2006a). Volcanic rocks often are associated with high arsenic, sulfide minerals, uranium and other radioactive minerals, and mercury. The dikes, sills and volcanic necks that were the source of the Cerro del Rio Volcanic Field flows must cut the buried Rio Grande sediments, but no exposure exists (Minor and Sawyer, 2006a).

A number of geologic faults cut roughly northwest-southeast through the La Bajada Constriction Area and near Peña Blanca (Minor et al., 2006). These can act as barriers or conduits to groundwater flow and, when cross cutting volcanic rocks and intrusive rocks, faults can cause deep, saline waters to be driven up near the surface. The major faults near Peña Blanca are the La Bajada fault to the north and east, the Sanchez fault to the north and east (not shown), and the Cochiti fault to the west (Minor et al., 2006). Peña Blanca is on the southern end of the Cochiti Graben between the down-to-the-west Cochiti fault and the down-to-the-east Pajarito fault (Minor et al., 2006). The La Bajada fault is the current basin bounding fault and forms the eastern boundary of the La Majada Mesa surface (Minor et al., 2006).

Hydrogeology

The regional hydrogeology around Peña Blanca has been characterized in a sequence of U.S. Geological Survey (USGS) reports (Blanchard, 1993; Anderholm, 1994; Plummer et al., 2004; and Minor and Sawyer, 2006a,b). These studies have been spurred by the local effects of the emplacement of Cochiti Dam for flood control purposes (Blanchard, 1993) and the need to understand the water resources of the northern Albuquerque Basin and southern Española Basin in the face of growing water needs (Anderholm, 1994, Plummer et al., 2004; and Minor and Sawyer, 2006a).

After the completion of Cochiti Dam in 1973, water levels in Peña Blanca and north began to rise (Blanchard, 1993). Cochiti Dam blocks both the Rio Grande, which forms the primary reservoir, and the Santa Fe River to the east. A level canal connects the two reservoirs, which allows transfers of water if water levels in one reservoir are raised above the other (Blanchard, 1993). It is thought that the coarse Rio Grande gravels in the subsurface beneath the lake behind Cochiti Dam provided a ‘fast-path’ for groundwater coming south around Cochiti Pueblo and Peña Blanca (Minor and Sawyer, 2006b). The coupling of lake water levels and down-gradient groundwater levels was documented in Blanchard (1993), where, with short time lags, higher lake levels caused high groundwater levels. In response to this, drains were cut on either side of the river to help drain the groundwater from the floodplain (Blanchard, 1993). During this time, groundwater flow on the east side of the river was still mostly moving west-southwest to the Rio Grande throughout the year (Fig. 4; Blanchard, 1993). Cutting drains and the incision of the Rio Grande lowered groundwater levels by decreasing the lowest elevations in the valley where groundwater can discharge.

More regionally, groundwater is flowing from the recharge area in the highlands and possibly from the Española Basin to the east toward the Rio Grande (Minor and Sawyer, 2006b). Minor and Sawyer (2006b) summarizes the hydrogeology of the La Bajada Constriction Area, which, on its southern end, includes Peña Blanca. They report that individual faulted blocks show good permeability and that the Rio Grande sediments below the Cerro del Rio Volcanic Field appear to have moderate permeability. This allows transfer of water from the neighboring Española Basin (Minor and Sawyer, 2006b). To the south in the Cerrillos Hills, impermeable sedimentary rocks provide an aquitard (layer impeding groundwater flow) between the Española and Albuquerque Basins. On the west side of the river, there appear to be perched aquifers (local aquifer from the regional aquifer by a unsaturated layer) in the Jemez Mountains and a complex of stacked aquifers recharging the Rio Grande valley aquifers

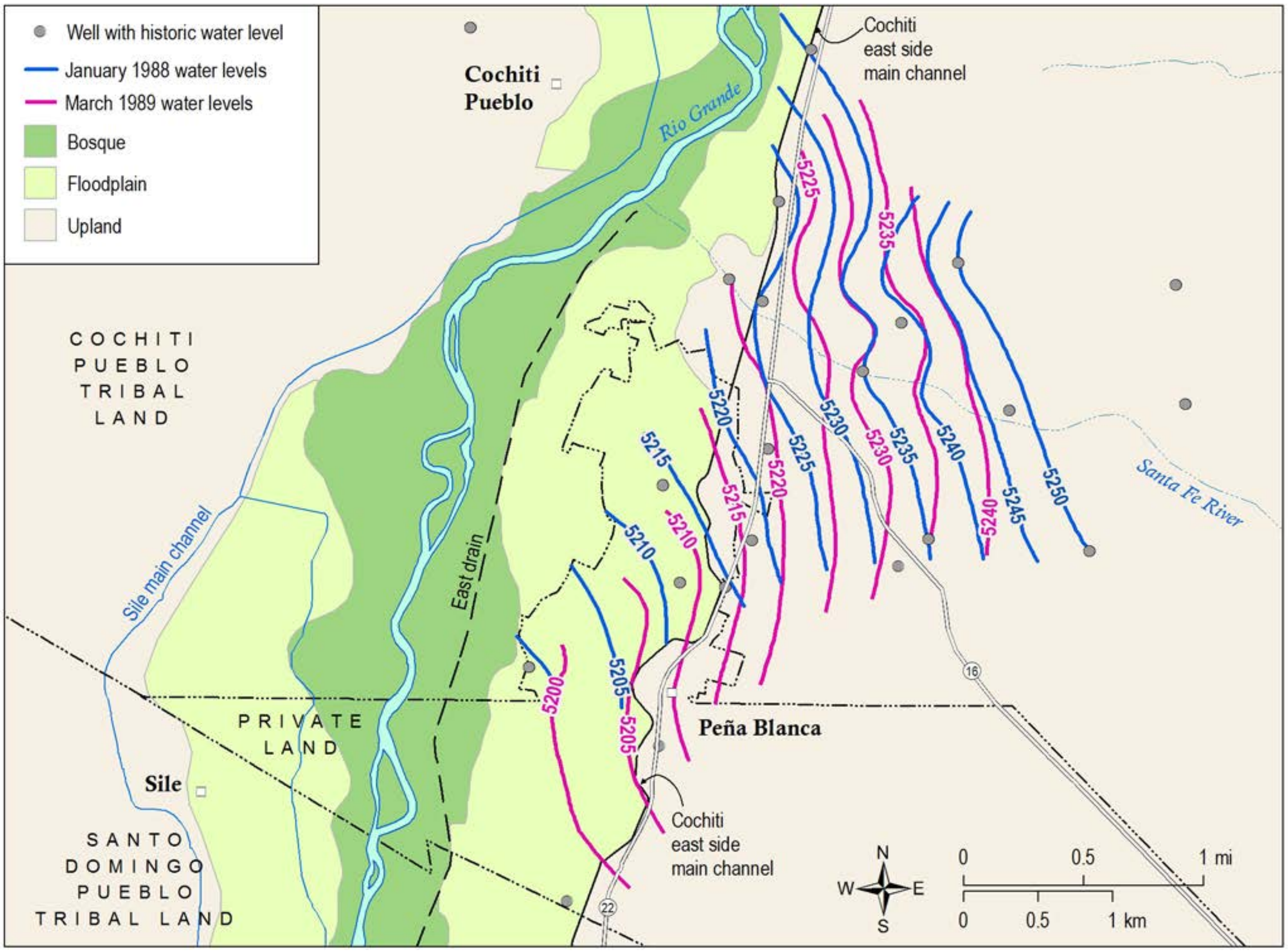

Figure 4. Historical groundwater levels from January 1988 and March 1989 (from Blanchard, 1993).

across faults (Minor and Sawyer, 2006b). Under the La Majada Mesa surface, Minor and Sawyer (2006b) posited that groundwater was mostly flowing through highly permeable unconsolidated Rio Grande sandy gravels with some flow through moderately permeable sands and muds from eastern tributaries.

In their review of the groundwater quality (i.e., chemistry) of the Albuquerque basin as a whole, Plummer et al. (2004) included Peña Blanca on the boundary of their Northern Mountain Front Region. The Northern Mountain Front Region water qualities, which include groundwater in the Rio Grande basin sediments and recharge in the Jemez Mountains, fall mostly in the calcium carbonate water type (Drever, 1997; and Plummer et al., 2004). This implies that Northern Mountain Front waters, conversely, likely have relatively fast travel times through relatively unweathered bedrock and sediment (Plummer, et al. 2004). The wells closest to Peña Blanca from Plummer et al. (2004) have major ion chemistry that are calcium-carbonate water type, with over 70% total of both Ca and CO3-HCO3 over other cation and anions, respectively. In much of the basin and in the Northern Mountain Front, groundwater is close to saturation with calcite and quartz (Plummer, 2004). The high silica concentrations are likely indicative of interaction with weathering volcanic rocks (Plummer et al., 2004).

III. METHODS

We measured water levels and sampled water for chemical analysis from over 25 domestic and municipal wells in and around Peña Blanca on 28–29 March 2016, 12–13 April 2016, and 22 April 2016. This was approximately 1 to 2 months after the beginning of the irrigation season. Not all wells had both water level measurements and water quality sampling, depending on the site specific plumbing and access. At each well, we completed a well inventory including pictures of the well and the area around the well, measurement of the height of the casing above the land surface, location of the well using the UTM Zone 13 N projection with the NAD 1983 datum, contact information, and any available well construction information such as total depth, pump type, static water level, and screened interval. We did find well depth or other well construction information for some of the wells though most of this information was anectoded from the land owner. A unique identifier was assigned to each well. Land surface elevations for each well were taken from a 4.5 m resolution gridded digital elevation model (DEM; U.S. Army Corp of Engineers, 2015). Table 1 summarizes the well location information, well depth, if a well had a water level measurement, and if a well had a water quality sample taken.

The water level measurements were taken before water quality sampling. This was to minimize the effect on the water level from pumping. The time since last pumping and any other possible effects on groundwater, such as other wells nearby being pumped or very close surface water, were noted. A specialized steel tape measure with 0.01 ft demarcations on the last 20 ft was used to take the depth-to-water measurements (Fig. 5a and b). The tape was sanitized before measurements using anti-bacterial wipes and then was coated with chalk (Fig. 5a). The chalked tape was lowered into well, the length of tape lowered is held at to a foot measurement point (Fig. 5a), and then the tape is withdrawn. The wetted length (shown by wet chalk) is then measured. The difference between the depth lowered and the wetted length is the depth-to-water from the measuring point. This process was repeated until two measurements were within 0.01 ft of each other. Then, the height of the measurement point from land surface is subtracted from the depth to measurement point to find the depth-to-water below ground surface (bgs).

For water quality sampling, water was taken from the outlet closest to the well. Field parameter and water sampling was done as outlined in Timmons

Table 1. Summary of well locations, surface elevation, well depth, measurement or sampling date, and if well was included in water level measurements or water quality sampling.

Site ID	UTM easting NAD 83	UTM northing NAD 83	Elevation (ft als)	Well depth (ft bls)	Date measured	Water level	Water sample
PB-0001	379214	3938580	5246	60.00	5/28/16	X	
PB-0002	378057	3936808	5206	200.00	5/28/16	X	X
PB-0003	380331	3938003	5370		5/28/16		X
PB-0004	378459	3937592	5216		5/28/16	X	X
PB-0005	377559	3937101	5198	12.00	4/12/16	X	
PB-0006	378583	3937621	5221		5/28/16	X	X
PB-0007	378896	3937401	5239		5/28/16		X
PB-0008	377541	3936509	5199		5/28/16	X	X
PB-0009	377068	3936240	5191	50.00	5/28/16	X	X
PB-0010	378639	3937210	5226	165.00	5/28/16	X	X
PB-0011	375629	3936512	5223	80.00	5/28/16	X	X
PB-0012	375279	3937132	5209		5/28/16	X	X
PB-0013	378709	3937354	5228		4/12/16	X	X
PB-0014	378739	3937519	5226		4/12/16	X	X
PB-0015	378860	3937486	5226		4/12/16	X	
PB-0016	379241	3937943	5251	170.00	4/12/16	X	X
PB-0017	378905	3936877	5241		4/12/16	X	X
PB-0018	379156	3938142	5236		4/12/16	X	X
PB-0019	377952	3937418	5207		4/12/16	X	X
PB-0020	379073	3937477	5272	195.00	4/12/16	X	X
PB-0021	379149	3937735	5238	64.00	4/13/16	X	X
PB-0022	378976	3937170	5250		4/13/16	X	X
PB-0023	378270	3937626	5209	24.00	4/13/16	X	X
PB-0024	377918	3936408	5207	38.00	4/22/16		X
PB-0025	377957	3936598	5205	38.00	4/22/16		X
PB-0026	379183	3938500	5240		4/22/16		X
PB-0027	378161	3937643	5209	155.00	4/22/16	X	X
PB-0028	377990	3936106	5217	90.00	4/22/16	X	X

amsl–above mean sea level; bgs–below ground surface

Figure 5. Images of (a) water level measurement taken to measurement point, (b) raising the steel tape, (c) measuring water quality field parameters to ensure a characteristic groundwater sample, and (d) taking a filtered groundwater quality sample.

et al. (2013). Whether the sample was taken before or after a pressure tank was noted, and we took unchlorinated samples. Before sampling, the well was pumped until field parameters including temperature (°C), oxidation-reduction potential (ORP; mV), pH (-), dissolved oxygen (DO; ppm), and specific conductance (μs/cm) stabilized. The field parameters above were measured using a YSI 556 mulitpara-meter probe with a temperature and specific conductance probe, a pH and ORP probe and a DO probe, (Fig. 5c). The probes were calibrated before measurement. Excess water was split off before reaching the probe (Fig. 5d). The flow rate was noted by measuring the time required to fill a five gallon bucket.

We followed the sampling protocol of Timmons et al. (2013), with a slight modification to analyze for nitrite/nitrate concentrations. At each of the wells, four samples were taken after field parameters stabilized: a 250 mL sample of raw water for general chemistry; a 25 mL sample of raw water for stable isotope analysis; a 125 mL sample for trace metals that was filtered with a 0.45 μm filter that was acidified with 10 drops of nitric acid for trace metals; and a 125 mL sample of raw water that had approximately 20 drops of chloroform added to prevent bacterial activity for anion concentrations, (Fig. 5d). Samples were kept in a cooler with ice or in a refrigerator until analyzed. Samples were delivered to the laboratory for analysis within 48 hours of being taken.

All water samples were analyzed as outlined in Timmons et al. (2013) at the New Mexico Bureau of Geology and Mineral Resources Chemistry Laboratory.

IV. RESULTS

Water Levels and Groundwater Flow Direction

Table 2 and Figure 6 summarize the water level measurements, showing the measured well locations (Fig. 6, blue dots), depth-to-water (ft bgs; Fig. 6 black labels), water table elevation (ft amsl; Fig. 6 blue labels), water elevation contours from the current study (blue contours) and water elevation contours from March 1989 (red contours). Water level contours were drawn based on water elevations at wells and on topographic (land surface) contours. We assumed that the water levels intersect both the East Drain and the Rio Grande, given observed groundwater discharging, or adding to the drain. Although we did not measure the water level in the East Drain and the Rio Grande, we roughly extrapolate water elevation contours to the drain and the river based on the neighboring land surface elevation. In general, water levels became shallower from the upland area to the floodplain to the bosque, with depth-to-water ranging from 71 ft below-ground-surface (bgs) on the high terrace to 1.7 ft bgs near the East Drain. Groundwater elevation contours where perpendicular to the direction of groundwater flow in the subsurface. Water elevations decrease from northeast to southwest, showing the direction of groundwater flow is toward the southwest. This is similar to the flow direction from December 1988 (Fig. 4) and March 1989 (Figs. 4 and 6). In the current water elevations, there appears to be a small area of lower water levels, called a cone of depression, around the current municipal well (Fig. 6, depth-to-water 71 ft bgs). This water level measurement was rising about 1 ft in 30 minutes when measured. On the northeastern portion of the floodplain, there may be a slight groundwater mound (isolated area with higher groundwater elevations than those around it; like a small hill of water), likely caused by the neighboring Cochiti East Side Main Channel (i.e., the main irrigation ditch), wetlands to the north and flood irrigated fields overlying it. Water elevations have decreased between 3 ft and 10 ft since March 1989. There is a broad, low slope region on the southern end of the floodplain. Further south from the study area, the floodplain widens and becomes a wetland. It is likely that the low-gradient region is caused by a buffering source of water in the wetland to the south. One well (PB-0002) had a surprisingly low elevation, which we excluded from the contouring.

Water Quality Analysis

Tables 3 and 4, and Figure 7 summarize the primary water quality parameters for the Peña Blanca area. In Figure 7, we use a Piper diagram to visualize variations and trends in major ion concentrations. The different symbols in Figure 7 indicate regional groundwater and Rio Grande-sourced water, as

Table 2. Summary of water level measurements.

Site ID	Depth-to-water (ft bgs)	Water elevation (ft amsl)
PB-0001	33.90	5212.10
PB-0002	21.08	5184.92
PB-0004	5.09	5210.91
PB-0005	1.71	5196.29
PB-0006	8.40	5212.60
PB-0008	3.65	5195.35
PB-0009	4.95	5186.05
PB-0010	26.29	5199.71
PB-0011	27.02	5195.98
PB-0012	8.15	5200.85
PB-0013	23.86	5204.14
PB-0014	21.06	5204.94
PB-0015	19.39	5206.61
PB-0016	37.57	5213.43
PB-0017	36.19	5204.81
PB-0018	29.45	5206.55
PB-0019	7.97	5199.03
PB-0020	71.01	5200.99
PB-0021	29.49	5208.51
PB-0022	42.69	5208.01
PB-0023	6.89	5202.11
PB-0027	6.28	5202.71
PB-0028	20.65	5195.98

bgs–below ground surface; amsl–above mean sea level

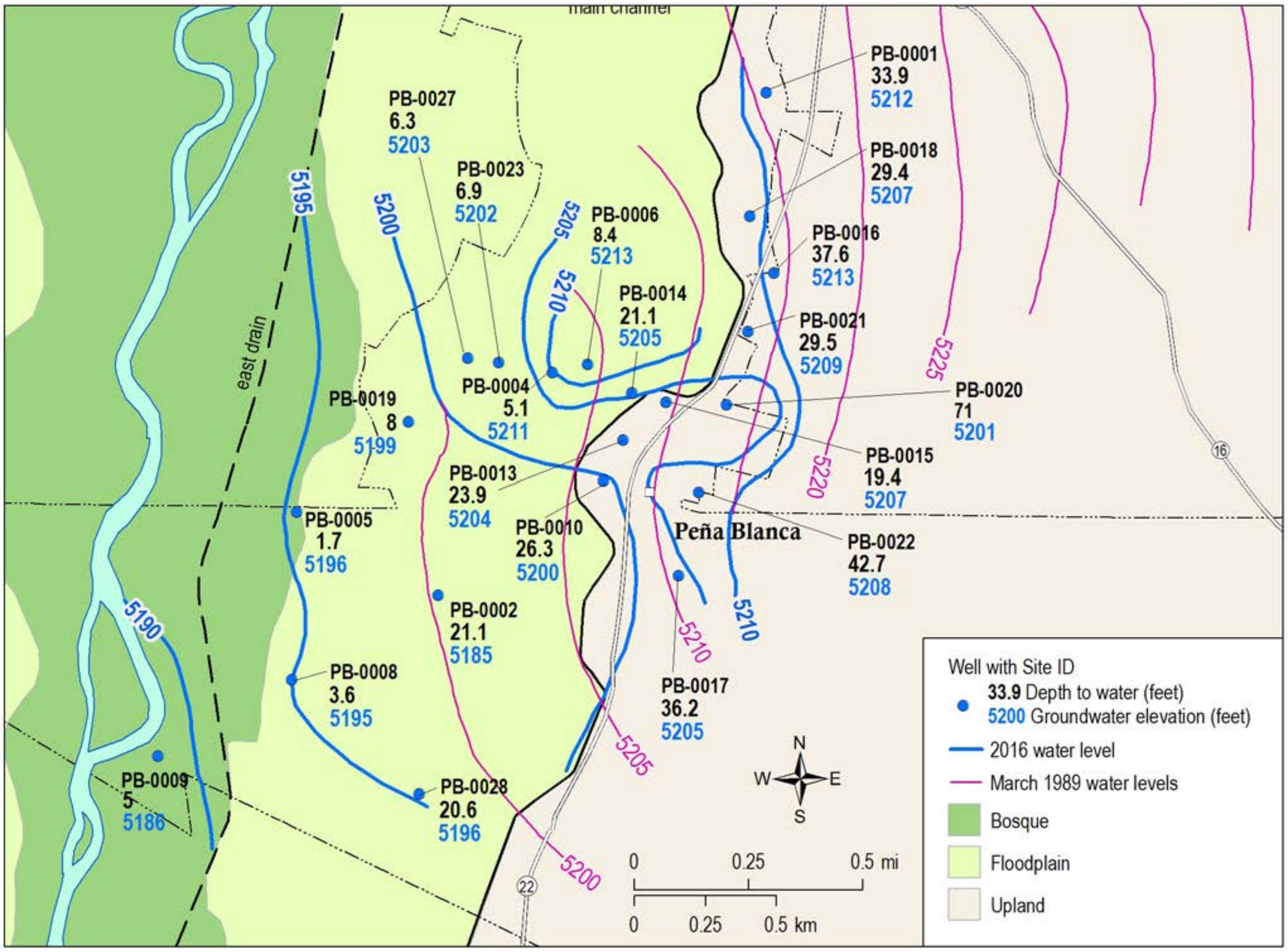

Figure 6. Map of measured water elevations and manually estimated water elevation contours.

defined using stable isotopes below. The waters sampled are all in the calcium carbonate water type (Drever, 1997). From the isotopic analysis that follows, the red squares are interpreted as being a mix of Rio Grande-sourced irrigation water and regional groundwater, while the blue circles are interpreted as primarily groundwater with a local precipitation ("meteoric") source (i.e, the regional groundwater). The diamond part of the Piper diagram shows two clusters of data, one with slightly higher sulfate concentrations than the other grouping (Fig. 7). These wells in the upper cluster fall primarily in the northeastern area of Peña Blanca near or in the uplands. The Piper diagram shows that the major ion chemistry of the waters in Peña Blanca was very consistent and similar to each other.

In Figures 8 and 9, we present the maps of temperature, specific conductance, the chloride/bromide ratios, and sulfate concentration. Symbol size is proportional to the value. In all the maps, it is important to note well PB-0003, on the east side of

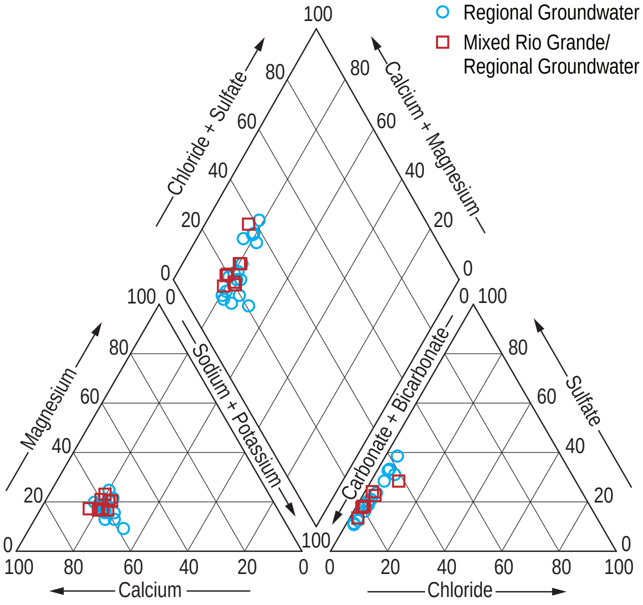

Figure 7. Piper diagram summarizing variations in major ion concentrations, with waters isotopically similar to local meteoric water (blue circles) and similar to evaporated Rio Grande waters (red squares).

Table 3. Summary of field parameters, and major and minor ion concentrations.

Site ID	pH	Temperature (°C, celsius)	ORP (mV)	Spec. Cond. (µs/cm)	Bicarbonate (HCO_3, ppm)	Calcium (ppm)	Carbonate (CO_3, ppm)	Chloride (ppm)	Magnesium (ppm)	Potassium (ppm)	Sodium (ppm)	Sulfate (ppm)
PB-0002	7.9	16.6	65.7	274	151	35.8	<5	3.07	6.12	2.75	12.9	15.4
PB-0003	7.58	14.88	-	345	187	43.8	<5	4.38	6.98	2.66	21.1	21.5
PB-0004	7.01	13.86	52.3	720	398	92.6	<5	7.04	24.5	5.47	34.8	68.4
PB-0006	7.21	15.00	153.7	537	255	71.8	<5	9.46	11.9	3.24	26.9	61.2
PB-0007	7.42	14.26	114.6	744	291	106	<5	13.4	18.9	4.73	34.7	151
PB-0008	7.17	15.01	148.9	567	302	75.2	<5	5.92	12.4	5.84	30.2	54.4
PB-0009	7.4	17.73	153.6	284	143	35.6	<5	4.08	4.66	4.15	16.4	22.7
PB-0010	7.52	15.55	64.6	420	198	53.4	<5	6.09	9.36	3.62	20.6	42.3
PB-0011	7.49	17.23	139.6	312	151	37.9	<5	2.98	3.46	2.95	22.6	28.2
PB-0012	7.55	17.86	140.5	307	148	42	<5	3.56	5.03	2.62	17.2	30.9
PB-0013	7.41	15.78	143.6	549	226	73.8	<5	8.71	13	3.69	25.1	92.6
PB-0014	7.2	14.98	136.7	676	302	97.6	<5	12.5	18.4	4.05	28.8	100
PB-0016	7.37	15.41	177.4	285	146	38	<5	2.94	6.03	2.22	12.6	18.3
PB-0017	7.32	16.49	174.8	578	239	69.8	<5	8.97	16.1	4.31	30.2	95.4
PB-0018	7.18	15.44	123.3	518	190	68.6	<5	12.2	10.7	3.19	22.7	73.7
PB-0019	7.16	14.59	160.2	469	234	61.3	<5	6.05	12.0	4.35	22.2	46.6
PB-0020	7.44	15.53	166.2	312	167	41.2	<5	3.55	6.45	2.88	15.9	16.3
PB-0021	7.48	15.64	190.8	403	198	52.7	<5	5.88	8.06	2.86	21.1	37.3
PB-0022	7.26	15.64	160	526	250	65.4	<5	8.76	13.7	4.38	26.3	63.3
PB-0023	7.05	13.92	105	590	318	78.3	<5	5.75	16.2	3.66	26.3	53.6
PB-0024	6.95	14.89	168	491	258	61.9	<5	5.56	13.2	4.11	26.1	45.7
PB-0025	6.98	15.84	158.2	575	310	74.8	<5	5.21	17.9	4.36	25.5	54.7
PB-0026	7.28	15.49	144.8	487	193	68.4	<5	17.8	10.5	2.93	18.3	68.5
PB-0027	7.21	16.14	162.6	242	125	30.4	<5	2.59	5.65	3.52	10.9	15.5
PB-0028	7.07	16.59	175.7	549	265	71	<5	6.2	15.0	4.56	27.8	68.7

mV–measured in millivolts; µs/cm–Siemens per meter; ppm–Parts per million

Table 4. Summary of minor ion and trace metal concentrations (ppm), and water isotope deviations (‰).

Site ID	Arsenic (ppm)	Bromide (ppm)	Flouride (ppm)	Iron (ppm)	Nitrate (ppm)	Uranium (ppm)	Zinc (ppm)	δD (‰)	$\delta^{18}O$ (‰)
PB-0002	0.0014	0.013	0.35	<0.02	3.46	0.0024	0.109	-86.5	-12.35
PB-0003	0.0019	0.10055	0.35	<0.02	4.52	0.0038	0.005	-77.5	-11.13
PB-0004	0.0046	0.059	0.56	0.088	0.78	0.0102	0.0185	-83.4	-11.61
PB-0006	0.002	0.112	0.36	<0.02	2.76	0.0087	0.0185	-80.7	-11.62
PB-0007	0.0015	0.17974	0.23	<0.02	1.65	0.0157	0.0554	-81	-11.68
PB-0008	0.0022	0.043	0.44	<0.02	2.54	0.0086	0.0025	-87.8	-12.25
PB-0009	0.0032	<0.01	0.33	<0.02	2.89	0.0019	0.0058	-91.7	-13.08
PB-0010	0.0015	0.098	0.3	<0.02	3.09	0.0059	0.002	-84.7	-12.15
PB-0011	0.006	0.049	0.2	<0.02	1.67	0.0008	0.0043	-84.3	-11.95
PB-0012	0.0024	0.051	0.15	<0.02	1.36	0.0009	0.0083	-84.9	-11.91
PB-0013	0.0016	0.072	0.27	<0.02	2.59	0.0102	0.0027	-82.5	-11.62
PB-0014	0.0023	0.18	0.3	<0.02	2.3	0.0146	0.012	-83.2	-11.54
PB-0016	0.0018	0.064	0.23	<0.02	6.58	0.003	0.0055	-85	-11.92
PB-0017	0.0021	0.133	0.26	<0.02	1.4	0.008	0.0029	-81.3	-11.46
PB-0018	0.0015	0.14	0.27	<0.02	23.1	0.005	0.0018	-78.3	-11.02
PB-0019	0.0023	0.14	0.3	<0.02	2.61	0.0086	0.0089	-87.8	-12.17
PB-0020	0.0014	0.042	0.24	<0.02	3.99	0.0039	0.006	-82.5	-11.58
PB-0021	0.0019	0.06	0.25	<0.02	3.61	0.0052	0.0021	-79.2	-11.18
PB-0022	0.0017	0.13	0.25	<0.02	1.13	0.0097	0.0095	-84.9	-12.02
PB-0023	0.0021	0.24	0.32	<0.02	0.32	0.0089	0.0136	-84.5	-11.52
PB-0024	0.0035	0.066	0.5	<0.02	2	0.0052	0.0093	-89.3	-12.42
PB-0025	0.0025	0.089	0.58	<0.02	2.36	0.0066	0.004	-86.9	-11.96
PB-0026	0.0017	0.14	0.23	<0.02	4.71	0.0055	0.0186	-89.3	-12.31
PB-0027	0.0023	0.028	0.31	<0.02	2.57	0.0028	0.0031	-94.2	-13.12
PB-0028	0.0023	0.064	0.42	<0.02	2.13	0.0097	0.0045	-87.7	-12.16

the study area, near NM-16. This well is in the non-agricultural area and is up-gradient of the other wells (Figs. 6 and 8). It provides a possible background water quality composition for the regional groundwater. We also sampled two wells in Silé. The groundwater chemistry of these wells is similar to that in Peña Blanca, but they are part of a different hydrologic system draining out of the Jemez Mountains and will not be discussed.

Throughout Peña Blanca, there were modest groundwater temperature variations, ranging from 13.9 °C to 17.7 °C (Fig. 8a). PB-0003 had a temperature of 14.9 °C. The waters along the eastern edge of Peña Blanca were mostly 0.5 °C warmer than PB-003. In the floodplain, temperatures vary from well to well, with some wells 1.0 °C cooler than PB-0003 (PB-0023 and PB-0004), most wells close to 15 °C, and some 1 °C or more warmer than PB-0003. Interestingly, PB-0009 had a temperature of 17.7 °C, the warmest well east of the Rio Grande even though it is immediately between the East Drain and the Rio Grande. Generally, temperature had a negative correlation with ion concentrations. In other words, warmer waters had lower dissolved ion concentrations (Tables 2 and 3). We did not have enough reliable well depth records to correlate temperature with well depth, which is a possible control.

The specific conductance (indicative of the amount of dissolved ions) of waters in Peña Blanca (Fig. 8b) showed some variation (242 µs/cm to 744 µs/cm) and had a positive correlation with major ion concentrations, total dissolved solids, minor ion concentrations and some trace metal concentrations including uranium (Tables 2 and 3). The conductance

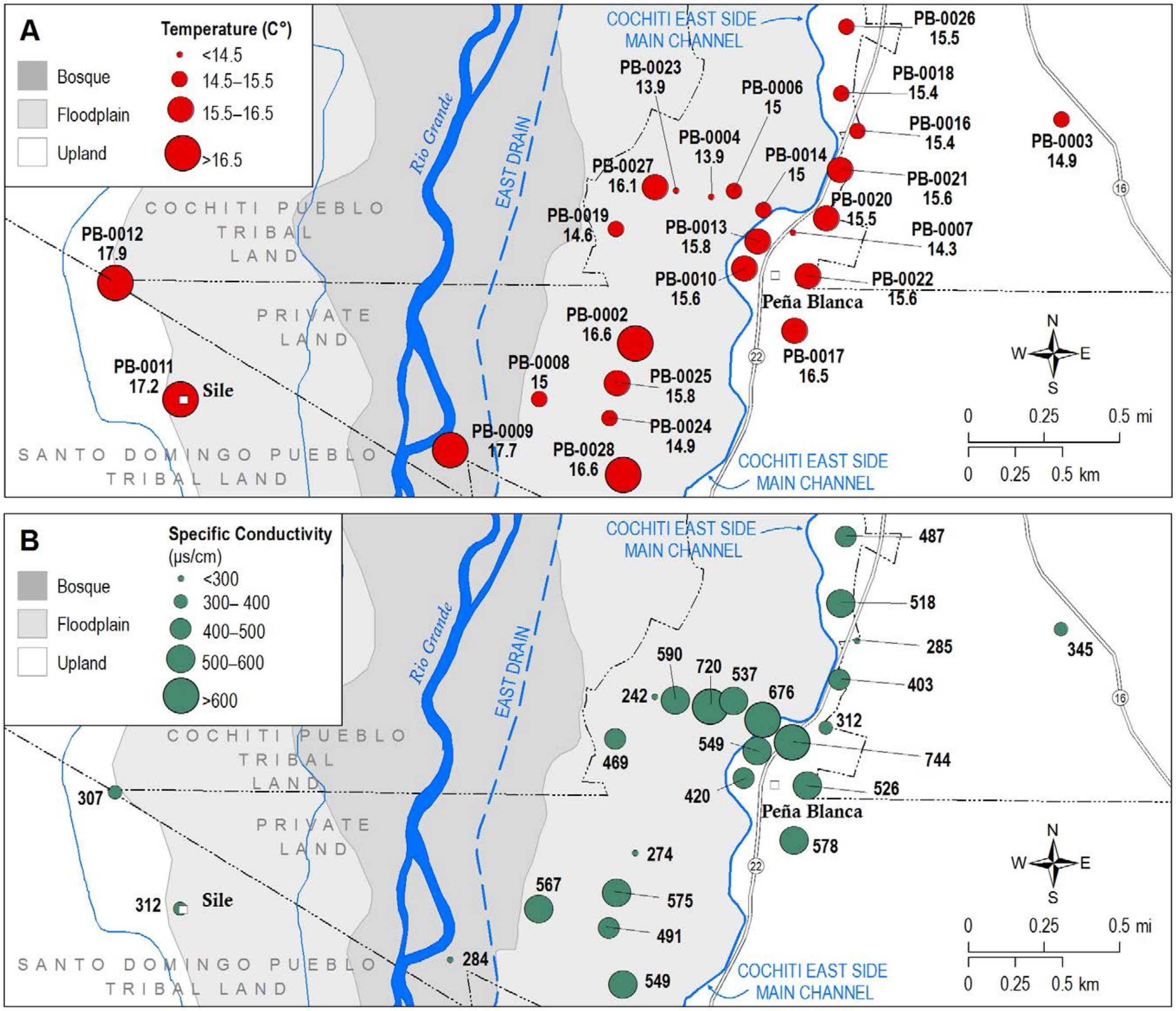

Figure 8. Maps of (a) temperature (°C); and (b) specific conductance (µS/cm).

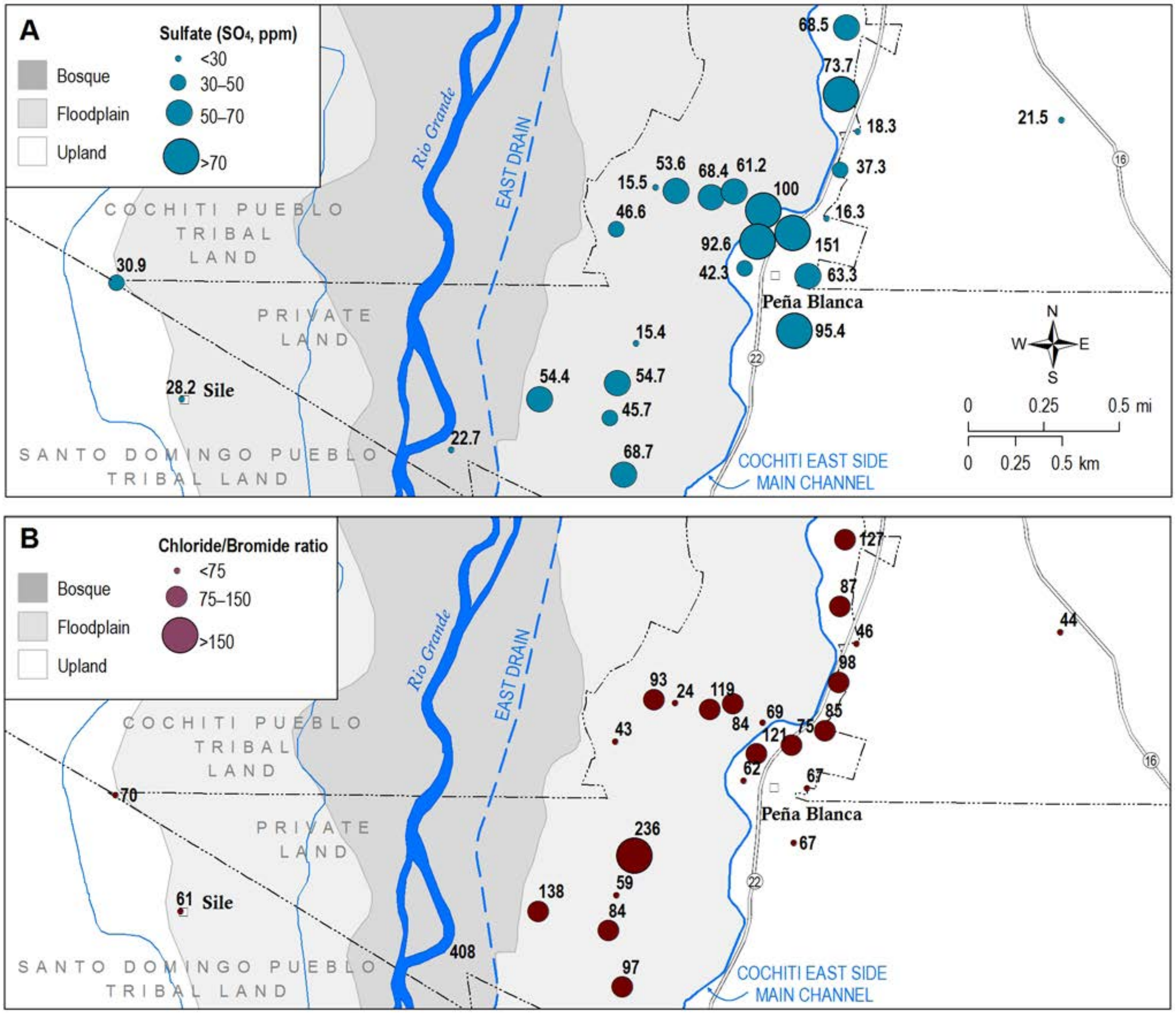

Figure 9. Maps of (a) SO_4 concentration (ppm); and (b) Cl/Br ratio (-).

of PB-0003, PB-0009 and PB-0002 were all very low (less than 300 ppm). The highest conductivities were found in wells with low temperatures, generally in irrigated regions. However, some of the wells along the eastern margin of the valley show higher conductivities also.

Throughout Peña Blanca, sampled waters had low sulfate concentrations (Fig. 9a), ranging from 15.4 to 151 mg/L. Some of the wells sampled along the eastern margin had the highest sulfate concentrations sampled, while PB-0003, the Peña Blanca municipal well (PB-0020) and other wells that showed warmer temperatures and lower conductivities showed remarkably low sulfate concentrations.

All of the wells sampled had chloride/bromide (Cl/Br) ratios consistent with natural waters (Fig. 9b; Davis et al., 1998). Because of the high concentrations of Cl in industrial and animal wastes, and the lack of Br in these wastes, Cl/Br ratios can be used to help identify the presence of human-caused contaminants in water. In natural waters, both Cl and Br generally have low but similar concentrations. In other words, high (greater than 300) Cl/Br values suggest the presence of human-caused contaminants, while low Cl/Br values suggest natural waters (Davis et al., 1998). Some wells in irrigated lands had higher Cl/Br ratios that, while still consistent with natural waters, may warrant a more detailed investigation to explore possible contamination (Fig. 9b).

Using the measured concentrations and field parameters, we estimated the saturation of the water with respect to various minerals using PhreeqC v. 3

(Parkhurst and Appelo, 2013). For the one well with a detectable iron concentration (PB-0004), there was enough iron in solution to precipitate both hematite (SI = 8.19, SI is the saturation index) and goethite (SI = 3.12). Other wells had non-detectable amounts of dissolved iron (Table 2), though there may be colloidal iron filtered out of the analysis. All wells were sligthly undersaturated (SI = -0.07 to -0.52) with respect to calcite and oversaturated with respect to quartz (SI = 0.47 to 0.81). This is consistent with the regional waters measured in Plummer et al. (2004). The level of saturation of the waters with respect to calcite and quartz indicates that regional groundwater has been interacting with rock for a significant time, likely greater than 1,000 yrs.

Stable Isotope Analysis

The variations of stable hydrogen and oxygen isotopes in water provide a means of identifying the sources and flow paths of groundwater (Clark and Fritz, 1997; and Sharp, 2007). In general terms, most elements have stable atoms that have a range of atomic masses. We are interested in variations in the hydrogen and oxygen atoms that make up water. For example, the most common form of hydrogen has one proton and one electron (^{1}H), while a rare but stable isotope of hydrogen, deuterium, has one proton, one electron and one neutron (^{2}H or D). For oxygen, the stable isotopes of interest are ^{16}O and ^{18}O. We report variations in isotopic concentrations as a per mil difference from a standard. As in most labs, we use the Vienna Standard Mean Ocean Water, or VSMOW (Sharp, 2007). Because the heavier isotopes also are held more strongly by other water molecules, they are harder to evaporate or sublimate (Sharp, 2007). For example, a $^{1}H^{16}O^{18}O$ molecule is less (more) likely to evaporate (condense) under the same conditions than a $^{1}H^{16}O_2$ molecule.

This leads to some general trends. First, there are consistent trends for the isotopic composition of rainfall and snow fall. These trends form local and global meteoric water lines (Craig, 1961). Along this line, winter precipitation tends to be isotopically lighter (fewer D and ^{18}O atoms, and more negative) than summer precipitation (higher or less negative). Second, water that originated as precipitation from the last Ice Age (older than 10,000 years) is generally isotopically lighter because temperatures were cooler, making it harder to move heavier water into the atmosphere. (Sharp, 2007). Lastly, when meteoric water is evaporated, the residual water becomes isotopically heavier (less negative) (Clark and Fritz, 1997). If the same reservoir (i.e., lake or stream) of water keeps evaporating under the same conditions, the remaining reservoir becomes enriched on a roughly linear trend with a slope lower than the meteoric water line. The exact slope of that line depends on local conditions such as relative humidity and temperature (Sharp, 2007).

Figure 10 shows a plot of measured δD against δ^{18}O as well as the local meteoric water line of Anderholm (1994; $\delta D=8.0\ \delta^{18}O + 11.1$; solid line) and the trend documented by Mills (2003; $\delta D=4.7\ \delta^{18}O - 31.3$) in Rio Grande water isotopic composition from Colorado to Fort Quitman, Texas (dashed line). Anderholm (1994) collected precipitation from around Santa Fe, NM, including in the Sangre de Cristos Mountains which are the headwaters of Santa Fe River; his isotopic results are consistent with a local meteoric water line derived for the Jemez Mountains (Vuatez and Goff, 1986). The trend from Mills (2003) shows that the Rio Grande is evaporating water from upstream (more negative) to downstream (more positive). The majority of samples

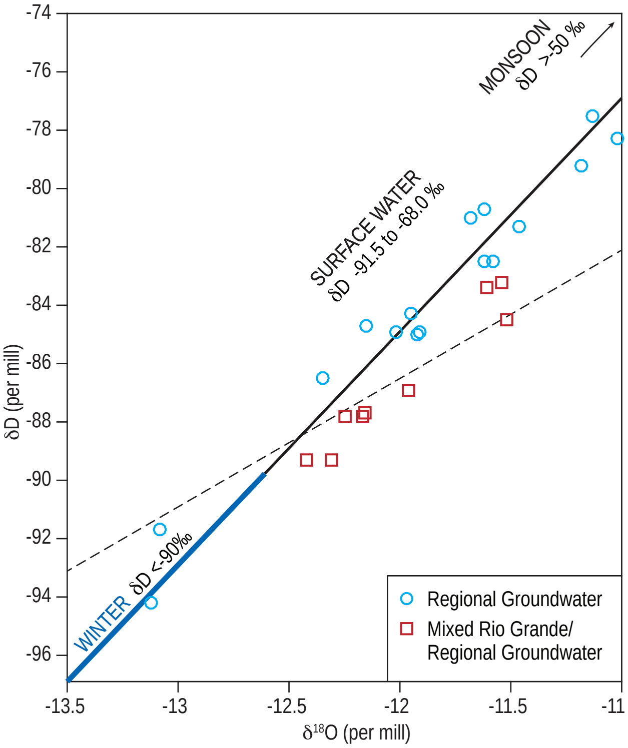

Figure 10. Plot of δD (‰, VSMOW) against δ^{18}O (‰, VSMOW), showing measured values (circles), the local meteoric water line (LMWL) and correlation of season and source with isotopic composition from Anderholm (1994; solid), and Rio Grande water evaporative trend of Mills (2003; dashed). The 'winter' portion of the LMWL is shown in blue and the 'surface water' range of the LMWL is in black.

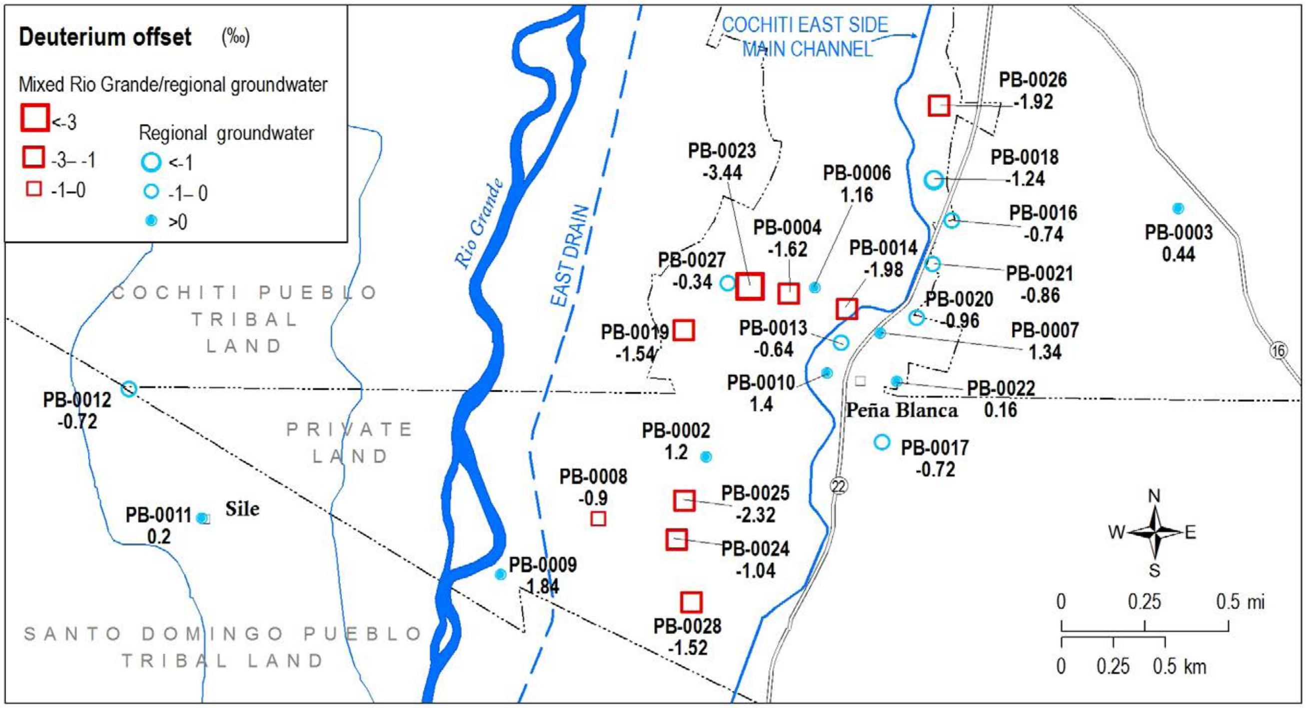

Figure 11. Map of deuterium offset (‰) with evaporated (red square) or regional groundwater (blue circle) indicated.

collected in the Peña Blanca region plot near the local meteoric water line, while a subset of samples plot around the evaporative trend. For reference, the isotopic composition of water in Cochiti Reservoir by Anderholm (1994) and Mills (2003) is within 1‰ for δD and 0.5‰ for δ^{18}O of the intersection of the meteoric water line and the evaporative trend (Anderholm, 1994; and Mills, 2003).

We interpret this plot a few ways. First, it suggests that some of the groundwater in Peña Blanca is sourced primarily from Rio Grande water, likely from return flows from irrigation or from leakage from irrigation canals. The other water, what we are calling regional groundwater, is mostly unmixed and unaltered precipitation that has recharged groundwater somewhere upgradient, such as in an arroyo in the uplands area. On Figure 10, the Peña Blanca groundwater isotopic compositions plot between winter precipitation and summer precipitation from Anderholm (1994; Fig. 10). In particular, the regional groundwater is more similar to summer precipitation values (Anderholm, 1994). The Rio Grande waters close to the meteoric water line are more similar to winter precipitation ranges (Anderholm, 1994). In terms of groundwater source, this suggests that the regional groundwater is a mixture of monsoonal and winter meteoric isotopic water compositions, while the Rio Grande water is mostly sourced from winter snowmelt with limited, though present, monsoonal runoff. Additionally, it suggests that the regional groundwater is less than 10,000 years old and probably much younger.

Figure 11 shows a map of the deuterium offset from the local meteoric water line (‰) with different symbols for Rio Grande water and regional groundwater. These symbols are also used on the Piper diagram of Figure 6. The deuterium offset is the difference in value of the meteoric water line's δD at a measured δ^{18}O, and the measured δD. If the δD value is negative, then the water has possibly undergone significant evaporation. If it is positive or close to the meteoric water line, then it most likely has not experienced significant evaporation. The majority of evaporated points have a large deuterium offset and are found either near the irrigation canal or around flood irrigated fields. The regional groundwater samples are mostly from the eastern margin of the valley away from irrigated lands, or from deeply drilled wells.

Looking east over a well house across fields and the bosque from Silé to Peña Blanca, NM. Bluff seen in background is made up of Rio Grande terrace gravels and the La Majada surface. *Photo by Alex Rinehart.*

V. DISCUSSION AND RECOMMENDATIONS

Our conceptual model for the groundwater flow in Peña Blanca is that there is a mixture of deeper groundwater moving southwest from the Santa Fe River and Cochiti Dam, and the southern Española Basin; and shallow return flow and infiltration from Rio Grande surface water irrigation (Fig. 12).

Blanchard (1993) documented a rapid response (weeks to months) of groundwater levels in Peña Blanca to changes in water levels behind Cochiti Dam. This is direct evidence that the relatively shallow (less than 200 feet) aquifer is well connected with the Santa Fe River, which is dammed by Cochiti Dam. Our study, Blanchard (1993) and Minor and Sawyer (2006b) all show a southwesterly flow of groundwater with Peña Blanca downgradient of the Santa Fe River portion of Cochiti Dam.

Groundwater contribution from the Santa Fe River and Cochiti Dam is supported by the isotopic and geochemical evidence. The Santa Fe River above Cochiti Dam is a small perennial stream with peak flows either from snowmelt in May and early June, or during monsoon-driven floods in August (USGS Surface Water Gage 08317200, accessed via http://waterdata.usgs.gov/nm/nwis/uv). The water in the Santa Fe River is a mixture of winter snowmelt and summer monsoon runoff from the Sangre de Cristo Mountains, and from upwelling groundwater from the southern Española Basin near La Cienega, NM (Johnson et al., 2016). While we do not have direct isotopic samples of the Santa Fe River, this mixture of summer and winter precipitation is consistent with our measured groundwater isotopes. Additionally, the Santa Fe River's short flow path, narrow and sheltered streambed, and perennial flows all support recharge of non-evaporated water.

There appear to be two populations of regional groundwater, given the distinct clusters seen in the Piper diagram (Fig. 7) and seen in map view. In the northern area of the study area, regional groundwater is higher in sulfate and has higher specific conductivity than further south. We hypothesize that the northern waters pass through a more volcanic clast-rich aquifer than further south. Nonetheless, the two populations of regional groundwater are very similar. They likely flow through slightly different rocks, with more volcanic (sulfate-mineral rich) rocks present in the north than toward the south.

The primary line of evidence we have for shallow recharge return flows from flood irrigation into the shallow groundwater is isotopic—wells near the ditch and irrigated fields had isotopically similar water to the evaporated Rio Grande water. This is further supported by the groundwater mound outlined in the groundwater elevation contours in northeast Peña Blanca, with groundwater sourced from the main east canal and near irrigated lands.

Figure 12 summarizes our conceptual model for groundwater flow around Peña Blanca. Flow is coming from the east and, for the shallow aquifer (less than 200 ft depth), is likely sourced from the Santa Fe River and the southern portion of Cochiti Dam. Water levels under La Majada Mesa are likely moderately deep (greater than 80 ft). In the floodplain, the water levels are shallow (less than 20 feet)

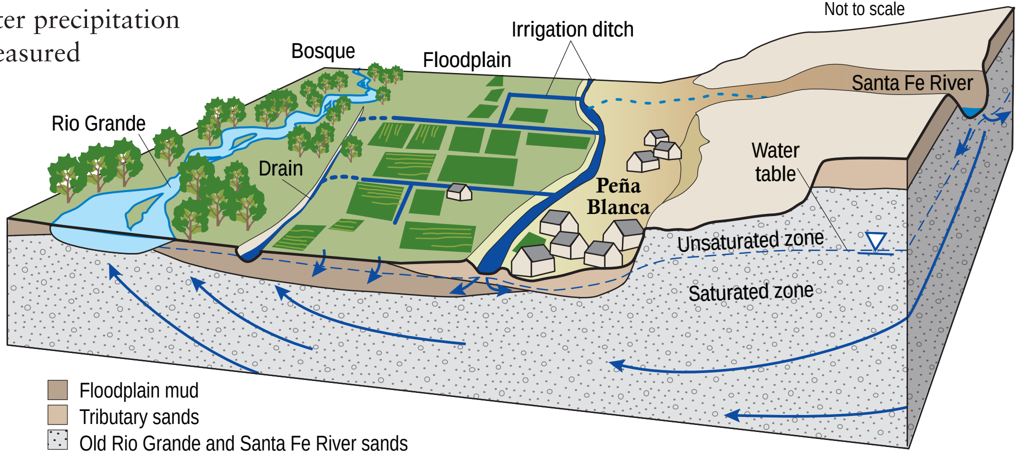

Figure 12. Conceptual model for groundwater flow around Peña Blanca.

and approach the land surface closer to the river. On the irrigated flood plain, there are return flows to the groundwater from flood irrigation and possibly from unlined ditches. This irrigation-type water appears to be isotopically and chemically similar to Rio Grande water. Nonetheless, there are pockets of upwelling regional groundwater, or wells that are screened deeply enough to penetrate the regional system. The deep screened wells access thermally, chemically and isotopically distinct water to appear next to Rio Grande-like waters sourced from return flows.

The regional groundwater is very similar to local meteoric water isotopically. This suggests that the regional shallow groundwater is recent (1,000s years). However, climatic patterns, and temperatures, in New Mexico have been roughly stable for the last 10,000 years old. Given the low dissolved solids of most of the waters, we suggest that the more recent bound (more then a 1,000 years) is more reasonable.

As a site for a new municipal well, we recommend an area to the south and east of the current municipal well (Fig. 13). This places the new well up-gradient from and to the side of the path of possible contaminants coming from the waste dump and fuel storage site in the mined area to the east of the current municipal well. The outlined area in Fig. 13 also avoids existing gravel pits and other known man-made disturbances. However, the recommended area does have small check dams and tanks that should be avoided during drilling. On 28 August, 2016, we examined the NMED map of known hazard and waste locations, and there did not appear to be any identified contaminant sites near the proposed drilling area. The deeper water levels beneath the uplands and the La Majada Mesa to the east of Peña Blanca also helps protect the proposed municipal well from contamination in the future. Simply having a greater depth-to-water and a deep screened interval in the well, reduces the potential for contamination of the future drinking water well. The water quality throughout the valley is relatively uniform and of good quality. Based on this, with respect to drilling a new well, we believe that most locations in this region will also have good drinking water quality. Based on geologic mapping constrained by well logs and outcrops, the aquifer material under the terrace the current well is on, and the proposed well would be on, is old Rio Grande sediments, which consist of coarse gravels and sands that form a productive aquifer in other parts of the valley. The further east the well is placed, the more likely finer grained eastern tributary sourced sediments will be, potentially decreasing transmissivity and well production.

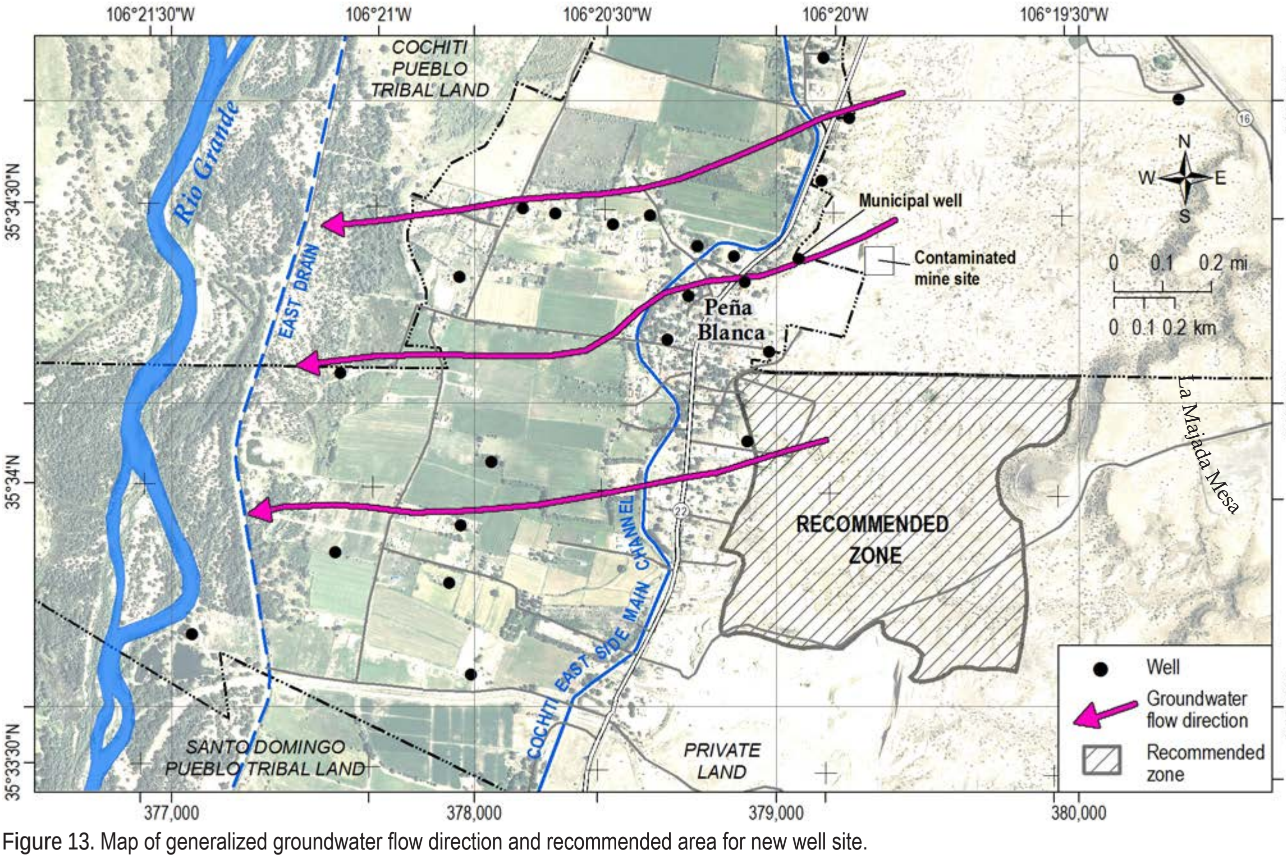

Figure 13. Map of generalized groundwater flow direction and recommended area for new well site.

VI. ELECTRONIC SUPPLEMENT

At http://geoinfo.nmt.edu/resources/water/amp/projects/Pena_Blanca.html, the complete tables of water level and information (e1_waterlevel.xlsx), and water quality (e2_waterquality.xlsx); and a geodatabase (e3_spatial.gdb) including the groundwater contours, water level, water quality values, groundwater flow directions, approximate bosque, floodplain and upland boundaries, and study area boundary.

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In the communities of Peña Blanca and Silé, we thank the individual well owners for giving us access to their wells and letting us onto their properties. We also thank Cochiti Pueblo for allowing us to sample the well at their elementary and middle school. This sample provided the background groundwater quality immediately up-gradient of Peña Blanca.

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