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Aquifer Storage and Recovery Feasibility Analysis for Middle Rio Grande Conservancy District

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OPEN-FILE REPORT

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New Mexico Bureau of Geology and Mineral Resources
A research and service division of New Mexico Institute of Mining and Technology

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CONTENTS

Figures

Tables

INTRODUCTION

The Middle Rio Grande Conservancy District (MRGCD) is exploring options for aquifer storage and recovery (ASR) in the middle Rio Grande valley and approached the New Mexico Bureau of Geology and Mineral Resources (NMBGMR) for assistance in reviewing potential sites. Aquifer storage and recovery is the process by which surface water is stored underground in natural formations that can retain water for future recovery and use. Agriculture in the middle Rio Grande valley relies predominantly on surface water diversions and flood irrigation, apart from some groundwater pumping in Valencia and Socorro Counties. The MRGCD is responsible for delivering much of the irrigation water that is used on an annual basis in the middle Rio Grande valley. The MRGCD is looking for alternatives to traditional water management and delivery that will allow them greater ability to provide water to their customers, especially in dry years. Specifically, the MRGCD is interested in determining whether there are sites feasible for ASR within its middle Rio Grande valley service area.

Aquifer storage and recovery is commonly more economical than building aboveground storage facilities and minimizes water loss due to evaporation. However, care must be taken to select sites that have favorable parameters. These parameters include (1) adequate permeability to transmit and store inputted water, (2) a water table that is not too deep, so extracting the water via pumping is not overly expensive, (3) the water table is not too shallow, creating the potential for mounding of groundwater, and (4) the inputted (recharged) groundwater flows in the desired direction so it can stay in the MRGCD boundaries and be recovered effectively. Groundwater mounding is most common when the groundwater table is relatively high and the sedimentary substrate has relatively lower permeability.

This document describes a preliminary assessment of seven potential ASR sites (Fig. 1) that the NMBGMR undertook using a scoring scheme incorporating the aforementioned parameters as well as possible next steps for future studies.

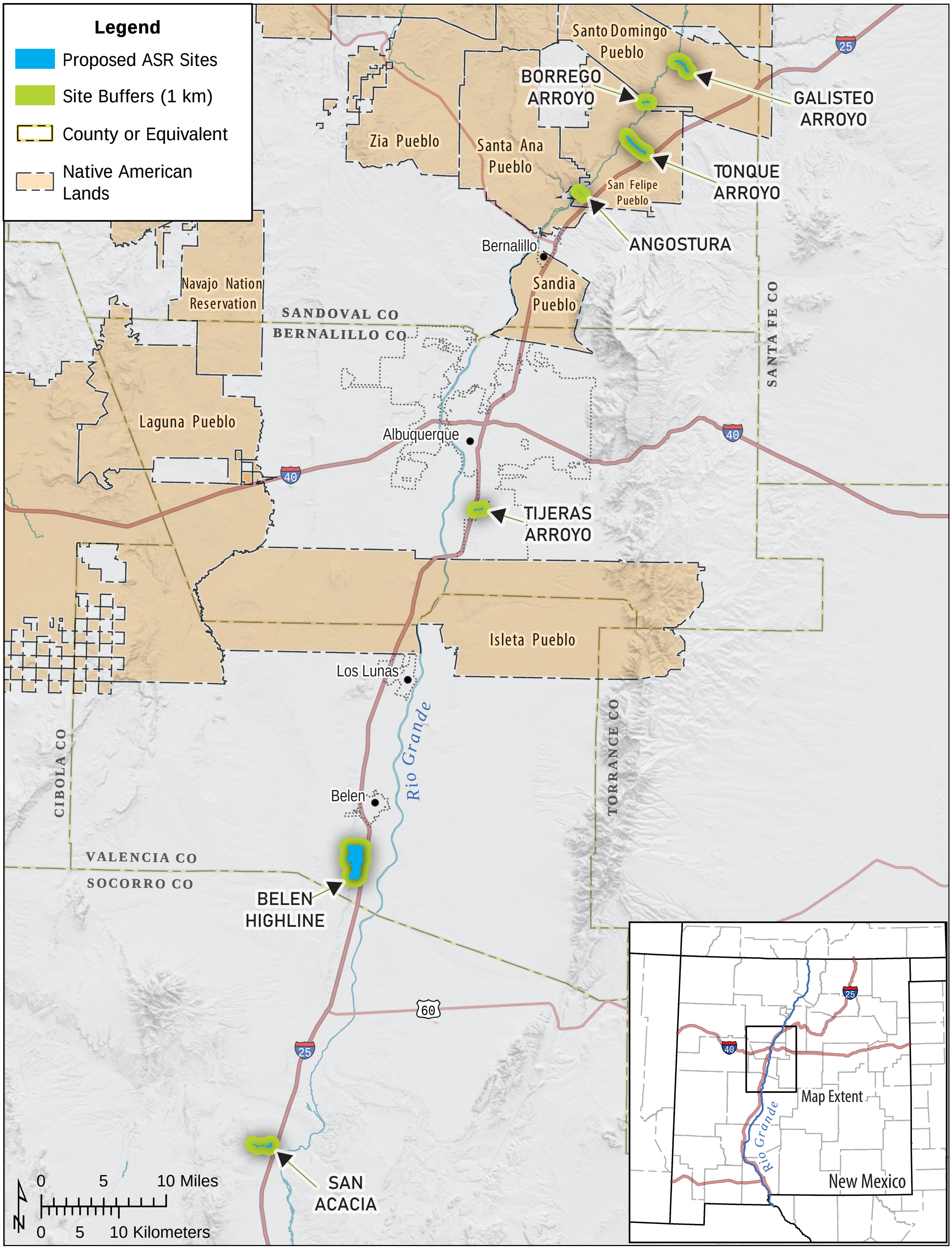

Figure 1. Location map of the seven selected study areas within the middle Rio Grande service area.

GEOLOGIC SETTING

The geologic substrate underlying the MRGCD has high potential for ASR due to its generally sandy and permeable character (e.g., Daniel B. Stephens & Associates, 2009, 2010, 2018). Figure 2 schematically illustrates the geologic character of the near-surface strata at the mouth of a side-stream arroyo, which is typical for the seven potential ASR sites. These side-stream arroyos form alluvial fans at the margin of the Rio Grande floodplain. The fans generally contain 50–100 ft of unconsolidated, sandy sediment (sand, gravelly sand, minor silt-clay) that was deposited during the Holocene epoch and possibly the latest Pleistocene epoch (the past about 11,000 years of Earth's history). This Holocene alluvium is underlain by various units of the Santa Fe Group, which is a term applied to 25- to 1-million-year-old strata deposited in the larger Rio Grande valley in a geologic structure extending north–south across New Mexico called the Rio Grande rift. Compared to Holocene alluvium, Santa Fe Group sediment is more compacted and cemented. However, the compaction and cementation are notably less than that seen in older "bedrock" units (such as Mesozoic or Paleozoic sedimentary rocks or granitic rocks), and the corresponding permeability for the Santa Fe Group is notably higher than that of these older bedrock units. Nevertheless, the proportion and geometry of low-permeability sediments such as clay layers in the Santa Fe Group would impact local permeability, so knowledge of such low-permeability strata is important for assessing the suitability of a local area for ASR. Fault lines are found in the Santa Fe Group and can impact groundwater flow, relative groundwater levels, and permeability (e.g., Sigda and Wilson, 2003; Caine and Minor, 2009; Johnson, 2009; Johnson et al., 2013).

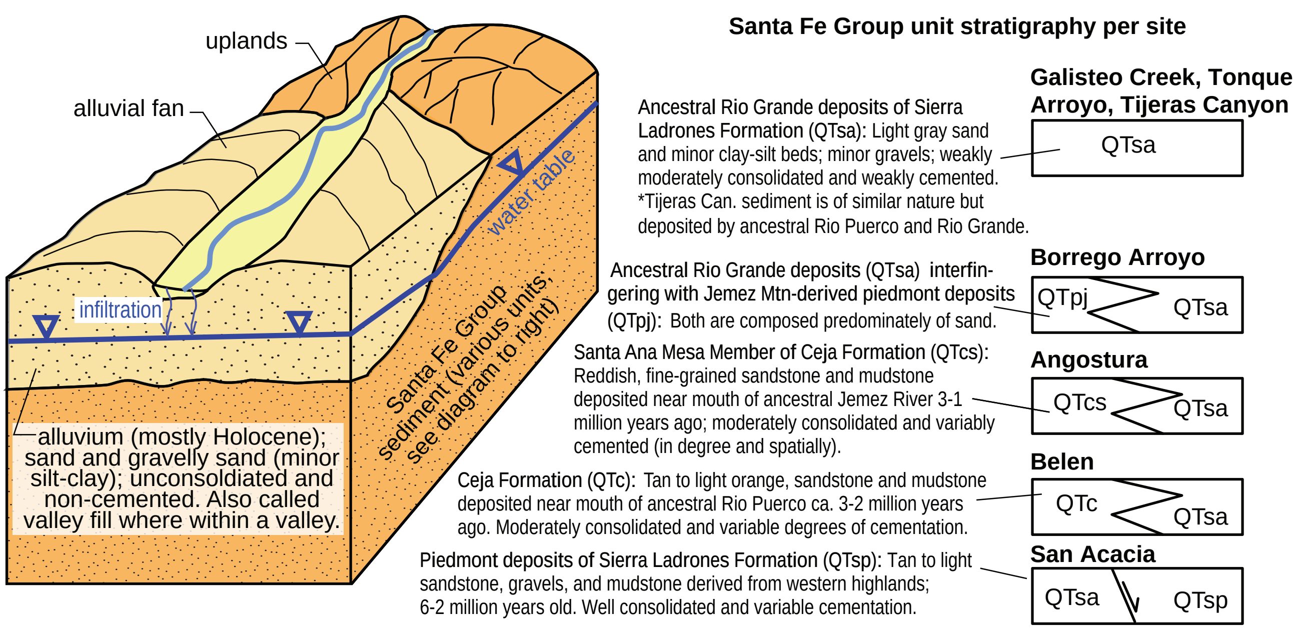

Figure 2. Conceptual model of the Santa Fe Group stratigraphy in the middle Rio Grande valley.

PREVIOUS WORK

The NMBGMR has previously worked with the Albuquerque Bernalillo County Water Utility Authority to assess the potential for managed aquifer storage and recovery within their service area (Koning et al., 2019). The result of this work is two maps showing suitability for deep injection recharge (i.e., pumping water directly into the water table) and another map for shallow recharge (by spreading water in basins and arroyos or by injecting water in shallow wells above the water table). Factors for site suitability included aquifer transmissivity, thickness of sand- and clay-rich zones, water-table depth and gradient, soil characteristics, and distances to infrastructure. This analysis capitalized on extensive well logs and records in the Albuquerque region, allowing the creation of a three-dimensional digital subsurface model of the multiple stacked geologic units and faults of the region.

The Albuquerque Bernalillo County Water Utility Authority aquifer recharge study was fortunate to have access to abundant subsurface well data, allowing for suitability ranking for both shallow and deep zones across most of the Albuquerque area. Unfortunately, the MRGCD service area, which incorporates agricultural land along about 140 mi of the Rio Grande and encompasses 438 mi^2, contains lesser amounts of (variable quality) data on subsurface geology, depth to water, and infiltration rates. Due to the lack of site-specific data, the NMBGMR team turned to a method developed at the University of California–Davis (O'Geen et al., 2015) that uses a Python coding script to calculate a suitability index for groundwater recharge on agricultural lands. Named the Soil Agricultural Banking Index (SAGBI), this code uses data that include root zone residence times (to account for drainage times of active agricultural lands), topography, soil percolation or hydraulic conductivity rates, soil salinity, and other inherent soil properties (such as soil crusting based on sodium adsorption ratios and soil erosion factors). This SAGBI method was modified to fit the needs and data available for this study; for example, the SAGBI module accounting for clay layers impacting deep percolation was replaced with a new module accounting for the depth to groundwater. The details of the rank-based assessment of each site are described in the following sections.

PROJECT DESCRIPTION

Seven sites within the middle Rio Grande valley service area were selected by MRGCD staff for analysis. These sites are located between Santo Domingo (Kewa) Pueblo north of Albuquerque and the Sevilleta National Wildlife Refuge north of Socorro (Fig. 1). The selected sites range in size from 8 to 1,723 acres and consist primarily of arroyo tributaries to the Rio Grande with gentle slopes and visibly sandy arroyo floors. Sites were also selected for their proximity to MRGCD service canals and are generally located upstream of areas with higher water demand. To evaluate the feasibility of ASR at these sites, the project was broken into three components, which are discussed below: data compilation and creation of water-table maps; a quantitative ranking based on soil characteristics, depth to water, slope, and potential for contamination; and a final, qualitative, site-specific ranking based on geologic knowledge of the area.

DATA COMPILATION

The first component of this project was a compilation of available information for the seven potential ASR sites (Table 1). The information included land ownership, geologic publications (e.g., geologic maps and cross sections), depth to water and geologic logs from New Mexico Office of the State Engineer drilling permits, and environmental data such as protected wildlife habitat. Data on known contamination sites were obtained from the New Mexico Environment Department (NMED) to assess possible water quality concerns near the potential ASR sites. Contamination locations within 5 km of a proposed ASR site were included in the ranking criteria. We reached out to local geohydrologic consulting firms and the U.S. Bureau of Indian Affairs for any possible data relating to the sites, but they either had none or did not reply.

Table 1. Description of the datasets included in the ASR analysis. These datasets are available at the source listed in the right column or from the University of New Mexico Resource Geographic Information System (RGIS) Program.

Dataset	Data Included	Data Source
Topography	1 m lidar (3DEP) for individual sites, 10 m DEM (1/3 arc second) for producing a map of the entire MRGCD district	U.S. Geological Survey National Map
Soil data	Saturated hydraulic conductivity (K_{sat}), soil erodibility factor (K_w), sodium adsorption ration (SAR), and electrical conductivity (EC)	Natural Resources Conservation Service Soil Survey Geographic Database (SSURGO)
Land status	Land surface ownership and/or land use. A nationwide dataset from the Bureau of Land Management was supplemented with the boundaries of the seven districts composing the New Mexico Council of Governments, which contains more accurate tribal data than the Bureau of Land Management dataset.	Bureau of Land Management and New Mexico Council of Governments
Geologic maps	Surface geology, faults, and cross sections	New Mexico Bureau of Geology and Mineral Resources
Wells	Depth to water and geologic well logs from permitted points of diversion; data used for clay/sand ratios and water-table analysis	New Mexico Office of the State Engineer
Critical habitat	Designated habitat for endangered species	U.S. Fish and Wildlife Service
Contamination	Brownfields, state cleanup programs, voluntary remediation programs, Superfund sites, hazardous waste facilities, landfills, leaking tank sites, National Pollutant Discharge Elimination System permits, and impaired waters	New Mexico Environment Department
Wetlands	Extent and approximate location of wetlands, riparian, deepwater, and related aquatic habitats across the United States	U.S. Fish and Wildlife Service
Irrigation infrastructure	Middle Rio Grande Conservancy District service lines, canals, and ditches	Middle Rio Grande Conservancy District

Groundwater-level measurements were used to construct water-table elevation maps that can help determine the direction of groundwater flow and hydraulic gradient. A shallow water-table map was created for prospective recharge locations. The well locations and groundwater-level measurements were collected from a combination of resources, including the New Mexico Office of the State Engineer, the U.S. Geological Survey (USGS), and the NMBGMR.

It was assumed that the Rio Grande, which flows near all of the sites, is hydrologically linked to the water table and shallow aquifer. As a result, the surface elevation of the Rio Grande was treated as the elevation of the water table where it flows near the study sites.

Water tables were initially created using the Topo to Raster toolbox in ArcGIS. Inputs to the toolbox included water-level measurements and the elevations of the river surface. A contour map was created from the resulting digital elevation raster. The contours were then manually adjusted to remove anomalous water-level measurements and to create a dataset that more accurately represents real-world conditions.

QUANTITATIVE ANALYSIS

The second component to evaluate the ASR sites was a quantitative ranking of the sites broken into four modules (Fig. 3, Table 2). These four modules include a modified SAGBI script, the estimated clay percentage in middle to late Quaternary fans, the estimated clay percentage in the underlying Santa Fe Group, and a qualitative geological assessment that is described in the following section (Table 3). Each of these four modules resulted in a ranking from 0 to 5, with 5 being the best; a weighted average of these scores was then calculated for a final result (out of 5, with 5 being the most favorable).

Table 2. Logic and weighting scheme used in the MRGABI module, listed in descending order from the highest-weighted module. Fuzzy logic linearly scales real-world values into the range 0–1. Crisp reclassification is a binning procedure that assigns user-defined, binary scores (commonly 0, 1) to real-world values.

Component of SAGBI or MRGABI Calculations	SAGBI		MRGABI		
	Logic	Weight	Logic	Ranking Criteria	Weight
Depth to groundwater Shallow groundwater (<30 ft) can cause mounding of water at the surface. Deep groundwater (>500 ft) is difficult to extract.	Not included in SAGBI		Hybrid fuzzy. 30–140 ft is ideal.	<30 ft = 0 30–140 ft = more is better 140–500 ft = less is better >500 ft = 0	0.3
Distance to contamination sites The farther in linear distance from known contamination, the more favorable the site.	Not included in SAGBI		Fuzzy. More is better.	min = 0 m max = 2,000 m	0.25
Root zone residence (K_{hm} = harmonic mean of K_{sat}) A high average soil column conductivity (K_{hm}) indicates the site will drain quickly.	Fuzzy. Higher K_{hm} is better.	0.275		min = 1 µm s-1 max = 30 µm s-1	0.15
Topography The flatter the site, the easier it will be to spread water over the surface for infiltration.	Crisp. Less slope is better.	0.2	Fuzzy. Less slope is better.	0–250% rise = 100 250–500% rise = 75 500–750% rise = 50 750–1,000% rise = 25 1,000–1,000,000% rise = 0	0.15
Electrical conductivity High conductivity can indicate high salt concentrations or large clay percentages in the soil.	Fuzzy. Less electrical conductivity is better.	0.2	Fuzzy. Less electrical conductivity is better.	min = 16 dS m-1 max = 4 dS m-1	0.05
Surface condition Soils with high erodibility factor (K_w) and high sodium adsorption ratios (SAR) are prone to crusting and compaction.	Fuzzy. Lower K_w and SAR are better.	0.05	Fuzzy. Lower K_w and SAR are better.	K_w <0.2 is ideal SAR <13	0.05
Deep percolation (lowest K_{sat}) A clay layer (low K_{sat}) can impede percolation even within soils that have a high average K_{sat}.	Fuzzy. Higher K_{sat} is better.	0.275	Clay layer thickness was determined from well logs and is included in a separate module; see Figure 3.		

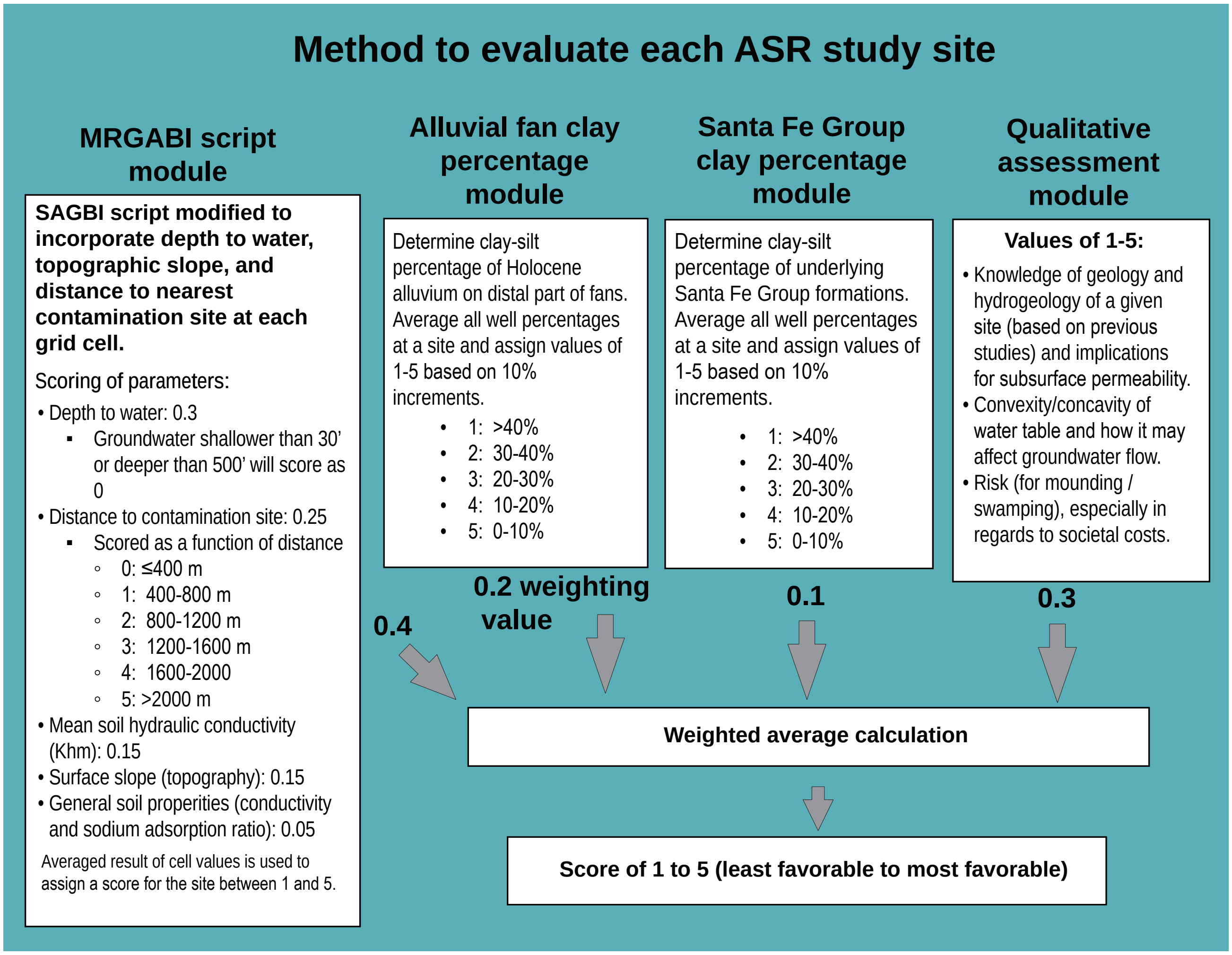

Figure 3. Flowchart illustrating the ranking procedure used to evaluate each of the seven potential ASR sites along with the final weighted values for each of the four modules.

Data amenable for raster (grid cell) calculations are included in the first module and consist of a modified SAGBI script, which we have named the Middle Rio Grande Groundwater Aquifer Banking Index (MRGABI). The original SAGBI code focused on data pertaining to the upper 1–2 m of sediment underlying the topographic surface, which are tabulated and readily extractible from SSURGO databases on the Natural Resources Conservation Service website. These data are available for the entire MRGCD. However, for the detailed analyses of the seven ASR sites, characteristics of deeper sedimentary layers, depth and geometry of the water table, and distance to contamination sites were also important factors to include in the site evaluation.

The MRGABI incorporates four of the five parameters from the original SAGBI script (listed below) plus two new parameters: groundwater-table depth and elevation (with lower scores for shallow water and deep water) and distance to contamination sites (with lower scores for closer sites). The four components of the original SAGBI script, applicable to the upper 1–2 m of the vadose zone, are (1) the harmonic mean of the saturated hydraulic conductivity of soil horizons in a given soil map unit (K_{hm}), (2) the soil erodibility factor (K_w), (3) the sodium adsorption ratio (SAR), and (4) electrical conductivity (EC). These parameters are explained in detail in the original SAGBI report (O'Geen et al., 2015) and in corresponding data downloaded from the SSURGO database accessed through the Natural Resources Conservation Service website (Table 1). Slope data (in percent rise) were extracted from a 1-m digital elevation map (DEM; created from lidar data). The GIS raster (spatial grid) files for depth to water and distance to contamination sites were created for each proposed site. Reclassification logic and weighting factors for these components are shown in Table 2. After all components were reclassified and weighted, they were mosaicked together to create a summary score raster for the first module at each proposed site (note that the other three modules have separate scores).

Notably, the reclassification logic for depth to water forces a score of 0 on any region in the study area with a depth to water less than 30 ft or greater than 500 ft, regardless of the soil or topographic characteristics at that point. This is the source of large zero-score regions in some study areas and was put in place to disqualify areas where redirected surface waters either were likely to mound or would not efficiently recharge the water table.

The second and third modules incorporated sedimentologic data (i.e., clay proportion) that serve as a proxy for estimating the permeability of the sediment below the upper 2 m of soil. These deeper data were obtained from analyses of available driller well log data and are not conducive for raster analyses due to the general paucity of well data (only Tijeras Arroyo had a satisfactory density of wells). Thus, we generalized the permeability of the upper two geologic layers by compiling the proportion of sandy versus clayey sediment listed in available wells at a site, averaging those values, and then applying that average to the whole site. The upper geologic layer was assessed in the alluvial fan clay percentage module (second module; Fig. 3). At all seven sites, this upper layer consists of relatively coarse-grained, weakly consolidated, sandy alluvium (mainly Holocene age) with subordinate clayey layers; note that analyzed alluvium at the San Acacia site includes both alluvial fan and Rio Grande valley-floor sediment. The underlying geologic layer is assessed in the Santa Fe Group clay percentage module (third module; Fig. 3). The deeper Santa Fe Group layer at a given site corresponds to one of four Santa Fe Group units: (1) sandy sediment of the ancestral Rio Grande (axial-fluvial facies of the Sierra Ladrones Formation), (2) distal alluvial fan sediment of the Rio Jemez (Santa Ana Mesa Member of the Ceja Formation), (3) fluvial sediment of the intertonguing Rio Puerco and Rio Grande (Ceja Formation at the Belen site), and (4) alluvial fan (piedmont) deposits shed from the flanks of the Rio Grande valley near the San Acacia site (Sierra Ladrones Formation piedmont deposits). These Santa Fe Group units have higher proportions of clayey layers compared to the upper geologic layer (ranging from 37 to 50%; Table 4) and are more consolidated, translating to relatively lower permeabilities.

QUALITATIVE ASSESSMENT

The third and final component in determining site suitability was an expert-based, qualitative assessment of the hydrogeologic characteristics of each site, especially of items not specifically addressed in the other modules. The ultimate result of this qualitative assessment was a ranking from 1 to 5 for each site, which was then included in the site's overall weighted score (fourth module; Fig. 3).

The features considered in the qualitative assessment include the convexity/concavity of the groundwater table, which determines whether the applied recharge flows away from or toward the river valley, and the potential societal impact if mounding were to occur at the downstream ends of the individual study site tributary valleys. Also included was expert-based judgment of the influence of stratigraphic architecture in the subsurface, particularly the potential presence of laterally extensive clays or cementation. This judgment was based on Daniel Koning's observations and mapping of the exposed portions of the aforementioned stratigraphic units during his 20-year career. Land ownership was included in the maps of the ASR sites but was not considered part of the ranking criteria.

RESULTS

A total of seven sites were examined for ASR potential along the middle Rio Grande. A summary for each of these sites is presented below, starting with the northernmost site, Galisteo Arroyo, and working south to the San Acacia site. The results presented here are limited by the available data, and future studies could change these preliminary evaluations. In particular, the sites at Borrego, Tonque, and Angostura Arroyos were very data-poor and did not receive a final score.

Subsurface data from well drilling logs were reasonably sufficient for the Tijeras Arroyo site but were limited at the other six sites. The lack of well data for the Borrego Arroyo site resulted in no water-table map development.

In the following sections, three maps are shown for each site. The first shows land ownership, wetland sites, and critical habitat areas. The second shows surface geology and fault lines (which can act as subsurface barriers). Note that fault lines very likely do not extend upward into the upper geologic layer (Holocene alluvium), so the barrier effect is limited to deeper (Santa Fe Group) strata. The final map shows the results of water-table elevation contouring, known contamination locations, and the MRGABI analyses, in which red colors are less favorable and blue colors are more favorable.

Table 3 summarizes land ownership, rates the quantity and quality of data available from New Mexico Office of the State Engineer well logs, and lists the generalized depth to alluvium determined from those logs. Table 4 summarizes the final scoring results for each of the four modules used to rank the ASR sites.

Table 3. Land ownership, data availability, and alluvium depth for each site.

		Data Availability	Alluvium Depth**		
Site	Land Ownership	Quantity and Quality of Subsurface Data*	Mean (ft)	Standard Deviation (ft)	n (number of wells)
Galisteo Arroyo	Tribal	2			0
Borrego Arroyo	Tribal	1			0
Tonque Arroyo	Tribal	2			0
Angostura Arroyo	Tribal	4	74	16	6
Tijeras Arroyo	Private	5	104	18	11
Belen Highline	Private	4	75	36	24
San Acacia	U.S. Fish and Wildlife Service, private	5	59	22	9

* Features considered include well density across the study area, level of detail in the well logs, and proximity to a published geologic cross section.

** For each well, the depth of the upper layer (alluvium) was picked from drillers' well logs obtained from the New Mexico Office of the State Engineer. This depth was averaged using well picks across an entire site, and the standard deviation was calculated.

Table 4. Numerical scoring for the four modules used to rank sites for ASR suitability. Each module and the final score are a 0–5 ranking, with 5 being the most favorable for ASR and 0 being the least favorable.

	MRGABI Module		Clay % Alluvium			Clay % Santa Fe Group					
Site	Mean Individual Score (%)	Rating	Sand	Clay	Rating	Unit	Sand	Clay	Rating	Qualitative Assessment*	FINAL SCORE (0 to 5)**
Galisteo Arroyo	9.92	1								4	
Borrego Arroyo	0	0								5	
Tonque Arroyo	62.12	4								4	
Angostura Arroyo	0	0	94%	6%	5	QTcsa	63%	37%	2	4	2.4
Tijeras Arroyo	82.24	5	69%	31%	2	QTsa	64%	36%	2	1	2.9
Belen Highline	66.75	4	81%	19%	4	QTc	50%	50%	1	2	3.1
San Acacia	31.48	2	80%	20%	4	QTsp	58%	42%	1	4	2.9
Weighting		0.4			0.2				0.1	0.3	

* Considers groundwater flow paths, stratigraphy and related permeability, and mounding risks (especially regarding societal impact).
** 0 is least favorable, 5 is most favorable

GALISTEO ARROYO

Size: 153 acres

Land ownership: Santo Domingo (Kewa) Pueblo

Land use: Galisteo Arroyo is a tributary to the Rio Grande that flows in from the southeast. Analysis of Google Earth satellite imagery shows homes and businesses along the southern edge of site boundary and agricultural fields approximately 200–300 m north of the site. The U.S. Fish and Wildlife Service (USFWS) spatial data identify the main site as riverine habitat, while the surrounding area includes freshwater emergent wetlands and a freshwater pond 45 m east of the proposed site boundary.

Contamination: Contamination locations from the NMED include a brownfield site 2 km upstream of the recharge site.

Geologic information: NMBGMR Open File Geologic Map 15: Geology of the Santo Domingo Pueblo and Santo Domingo Pueblo SW Quadrangles, Sandoval County, New Mexico (Smith and Kuhle, 1998). This work has a geologic cross section (B–B´) drawn about 0.5 km north of the site.

Stratigraphy: Holocene fan alluvium of Galisteo Creek (50–100 ft thick) is called Qal on the map of Smith and Kuhle (1998). The correlative unit in the Albuquerque managed aquifer recharge study (Koning et al., 2019) is Qaya_cs, with a horizontal conductivity (K_{hor}) of 26 ft/day.

Pleistocene alluvium (20–30 ft thick) is called Qoa on Smith and Kuhle's map. It consists of sand, gravel, and silt that are late Pleistocene(?) to Holocene. The correlative unit in the Albuquerque managed aquifer recharge study (Koning et al., 2019) is Qtr, with a K_{hor} of 13 ft/day.

The Santa Fe Group unit consists of >150 ft of QTslg, a gravelly alluvium deposited by the ancestral Rio Grande (Smith and Kuhle, 1998). The correlative unit in the Albuquerque managed aquifer recharge study (Koning et al., 2019) is QTsa, with a mean K_{hor} of 64 ft/day.

Structure: The Siles fault passes through the middle of the site.

Groundwater considerations: A total of 19 water wells were within a 5-km buffer of the proposed site and were used in the water-table interpolation. These wells were supplemented with 13 artificial 0-ft depth to water points along the Rio Grande to achieve better interpolations. Water-table interpolation shows a hydraulic gradient approximately pointing to the southwest. The water table underlying the proposed site is <30 ft below ground surface for approximately the lower half of the arroyo reach in the study area.

Quantitative assessment: The average MRGABI score for this site is 9.92%, or 1 out of 5. This low score is primarily due to the shallow groundwater across the site. Unfortunately, there were not enough site-specific soil data to evaluate the clay and sand percentages of the alluvium or Santa Fe Group.

Qualitative assessment: The qualitative assessment of this site is 4 out of 5, primarily due to the ideal sandy stratigraphic sequence at this location. In the Santa Fe Group at depth (below 50–100 ft), the Siles fault may create a hydrologic barrier, preventing groundwater from reaching the Rio Grande floodplain. There is a high impact (risk) if mounding occurs due to the many agricultural fields just north of the Santo Domingo (Kewa) Pueblo townsite. Groundwater flow is to the southwest, relatively parallel to the Rio Grande valley.

Overall score: This site did not receive an overall score due to the lack of site-specific clay and sand percentage data (Table 5).

Next steps: Site-specific subsurface and groundwater data would greatly help in evaluating this site. Subsurface data can be obtained by boreholes combined with electrical resistivity or electromagnetic surveys, which can be used to analyze the proportion and geometry of low-permeability clays. The majority of the wells used to generate water-table surfaces were far outside the site; additional water-level data at or near the site should be considered. Nearby existing land use and ownership are sources of potential permitting and site access concerns and should be considered during further evaluation.

Table 5. Module ratings for Galisteo Arroyo and overall score (out of 5, with 5 being best).

MRGABI Module (40%)	Clay/Sand Ratio Alluvium (20%)	Clay/Sand Ratio Santa Fe Group (10%)	Qualitative Score (30%)	Overall Score
1	NA	NA	4	NA

NA = not available due to inadequate data availability

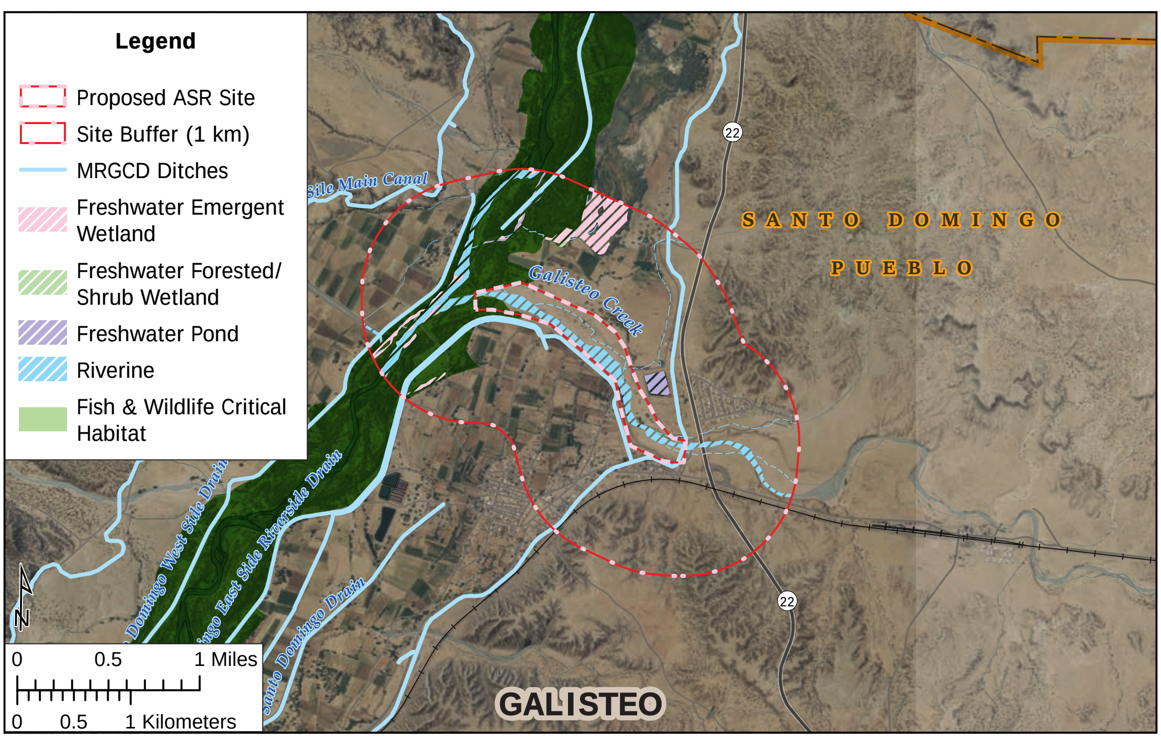

Figure 4a. Galisteo Arroyo. Surface land ownership and land uses, including wildlife habitat.

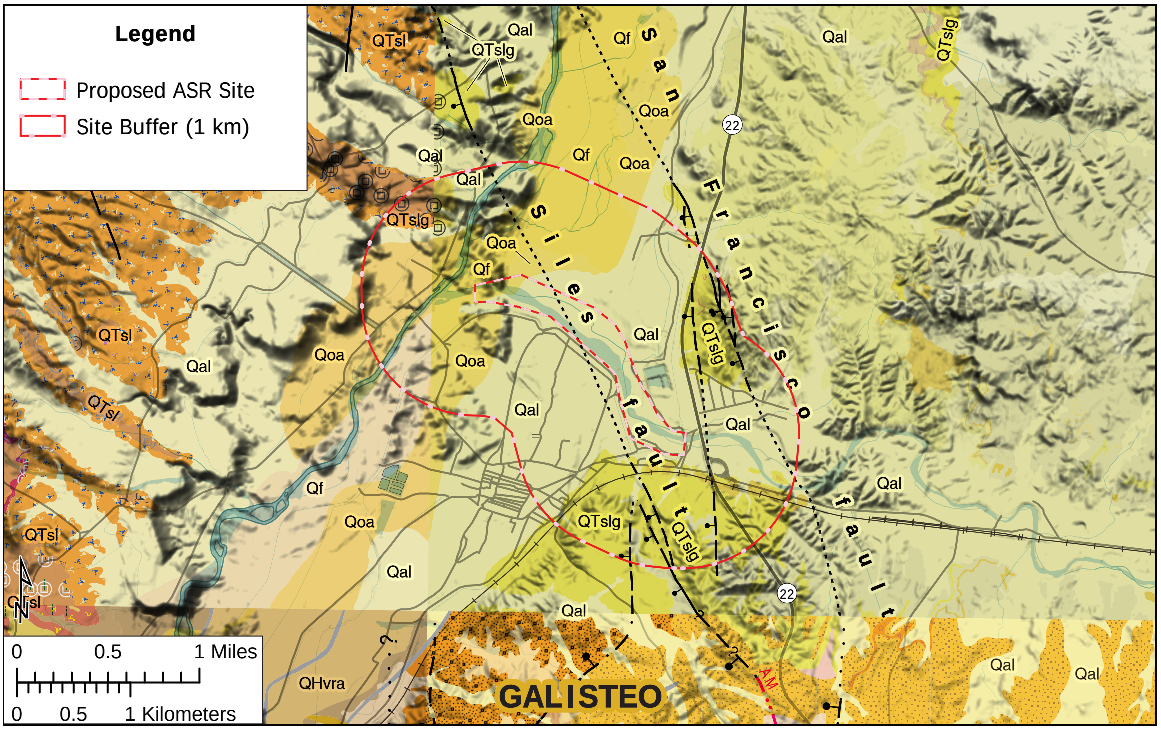

Figure 4b. Galisteo Arroyo surface geology. Map includes geologic features from these mosaicked 1:24,000-scale quadrangles: Smith and Kuhle (1998), Cather and Connell (1998), and Black et al. (2000). Note that map units vary per these three maps, and each should be consulted for full legends and geologic unit descriptions. Site-relevant geologic units include Qf – modern Rio Grande channel and floodplain; Qal – Holocene fan alluvium; Qoa – late Pleistocene and Holocene alluvium; and QTslg – Sierra Ladrones Formation (Santa Fe Group), older Rio Grande gravel, and sand.

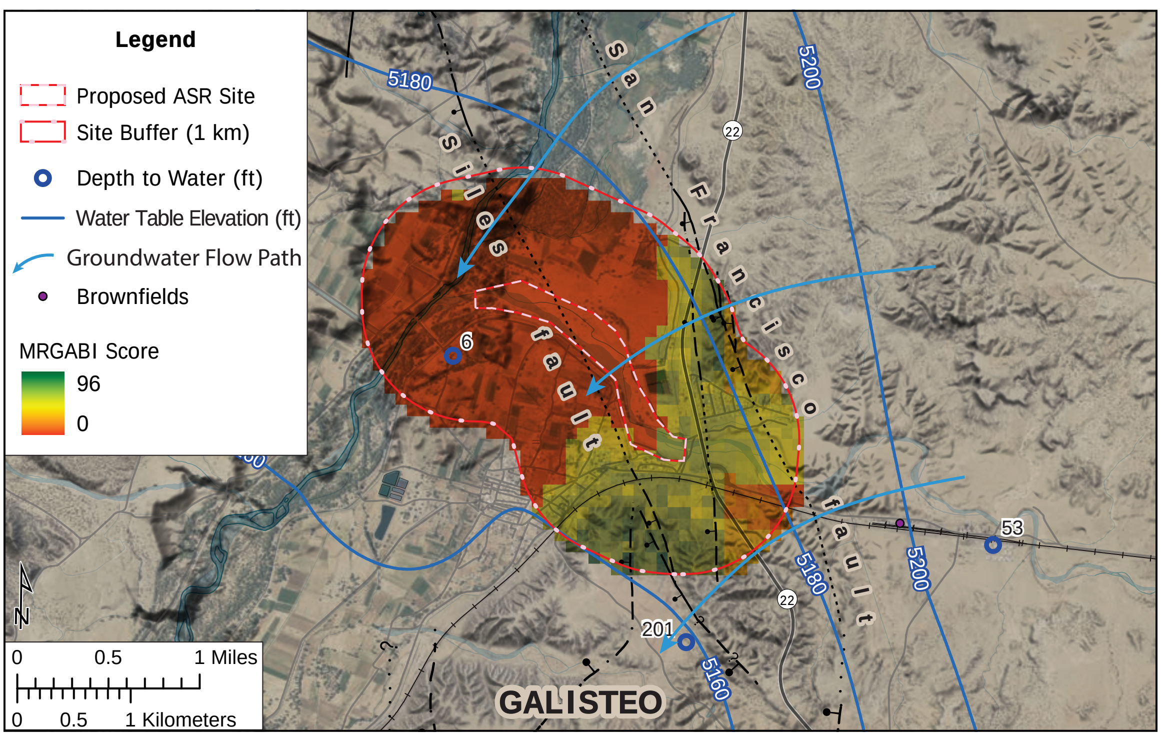

Figure 4c. Galisteo Arroyo. MRGABI ranking results, water-table contours, and well locations. Faults are shown here and in Figure 4b following Federal Geographic Data Committee Standards. Solid black lines represent where a fault is mapped with certainty; the ball and bar show the downthrown side of the fault. Dashed lines and question marks indicate where the exact fault location is uncertain. Readers should refer to the location-specific geologic map for more details.

BORREGO ARROYO

Size: 47.4 acres

Land ownership: San Felipe Pueblo and Santo Domingo Pueblo Joint Use Area

Land use: This site sits at the mouth of Borrego Arroyo. No human residences or businesses are within a 5-km buffer of the site; however, there are agricultural fields at least 100 m north of the site boundary. The active arroyo bottom is classified as Riverine Habitat by USFWS; there are also thin Freshwater Emergent Wetlands identified in the 1-km buffer around the site.

Contamination: No contamination is known to exist within a 5-km buffer of the site.

Geologic information: NMBGMR Open-File Geologic Map 19: Geologic Map of the San Felipe Pueblo 7.5-Minute Quadrangle, Sandoval County, New Mexico (Cather and Connell, 1998).

Stratigraphy: Late Quaternary, sandy fan alluvium (some silt and gravel) lies at the mouth of Borrego Canyon and is interpreted to be 70–100 ft thick. The correlative unit in the Albuquerque managed aquifer recharge study (Koning et al., 2019) is Qaya_cs, with vertical conductivity (K_{vert}) of 11–25 ft/day.

The sandy fan alluvium is underlain by Rio Grande deposits (QTsa) interfingering with piedmont deposits derived from the southern Jemez Mountains. Based on comparison with comparable lithologic units in the Albuquerque area (QTsa and QTst), one can infer hydraulic conductivities (horizontal) ranging from to 20 to 64 ft/day (Koning et al., 2019).

Structure: Subhorizontal strata. No mapped faults.

Groundwater considerations: There were insufficient data to provide a quantitative assessment at this site. In particular, data for groundwater were insufficient to create a localized water-table map.

Quantitative assessment: There were also not enough nearby well logs to assess percent clay and sand for the alluvium or the Santa Fe Group.

Qualitative assessment: Overall, this appears to be a good site with permeable strata. Although the groundwater data are minimal, the mounding risk to businesses or homes is low due to the semiremote nature of the site. The groundwater maps constructed by Plummer et al. (2012) show that groundwater flow should be converging with the trend of the river valley. This is consistent with the poorly constrained groundwater-table contours from sparse well data reviewed for this project. The qualitative rating for this site is 5 out of 5 due to the lack infrastructure around the site and what is believed to be generally permeable strata.

Overall score: This site did not receive an overall score due to the low data coverage (Table 6).

Next steps: This site is the most data-poor of the seven locations evaluated for this project, but it also received the highest qualitative score due to favorable subsurface geology (such as the likely presence of ancestral Rio Grande sands possessing high permeability) and the lack of human structures and infrastructure that could be impacted by potential groundwater mounding. Site-specific depth to water information would be very helpful for better understanding of the water table here. Coring or boreholes (to 100–150 ft depth) can confirm our inference of sandy alluvial fan alluvium underlain by ancestral Rio Grande deposits. These subsurface data can be supplemented with shallow geophysical surveys (like electrical resistivity or electromagnetic surveys) to ascertain the proportion and geometry of low-permeability, clayey strata as well as the water table. Site permitting and access could potentially be difficult in the Pueblo Joint Use area.

Table 6. Module ratings for Borrego Arroyo and overall score (out of 5, with 5 being best).

MRGABI Module (40%)	Clay/Sand Ratio Alluvium (20%)	Clay/Sand Ratio Santa Fe Group (10%)	Qualitative Score (30%)	Overall Score
0	NA	NA	5	NA

NA = not available due to inadequate data availability

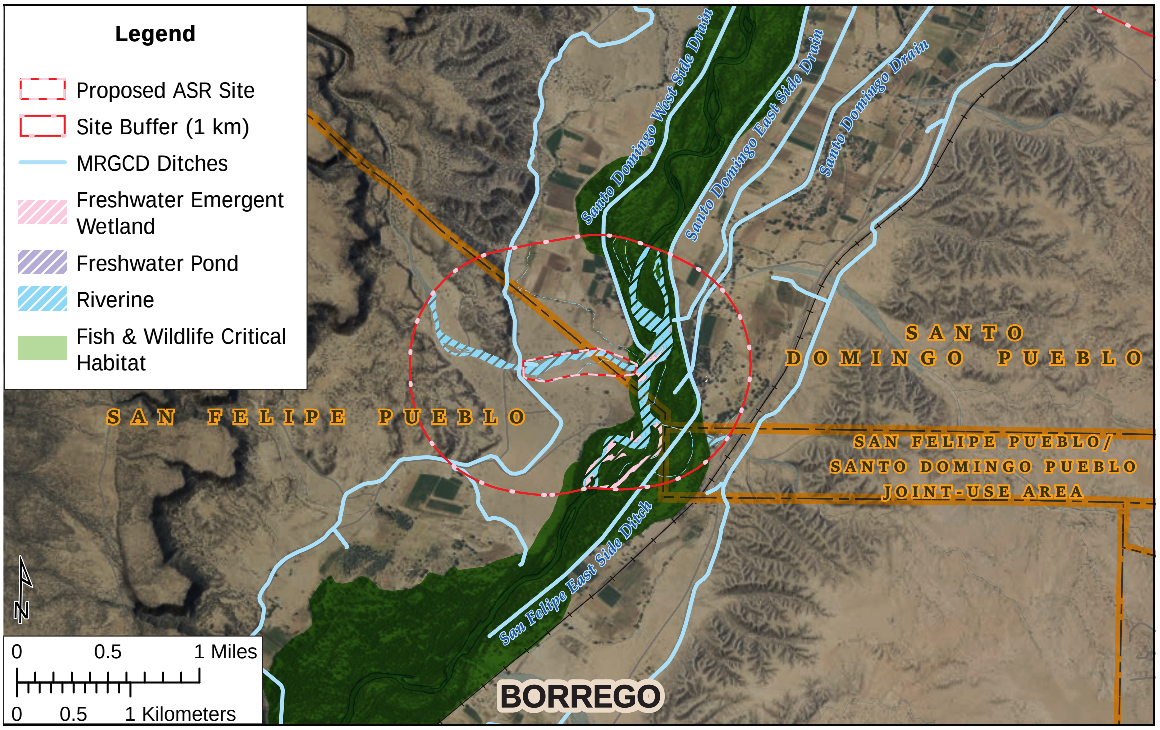

Figure 5a. Borrego Arroyo. Surface land ownership and land uses, including wildlife habitat.

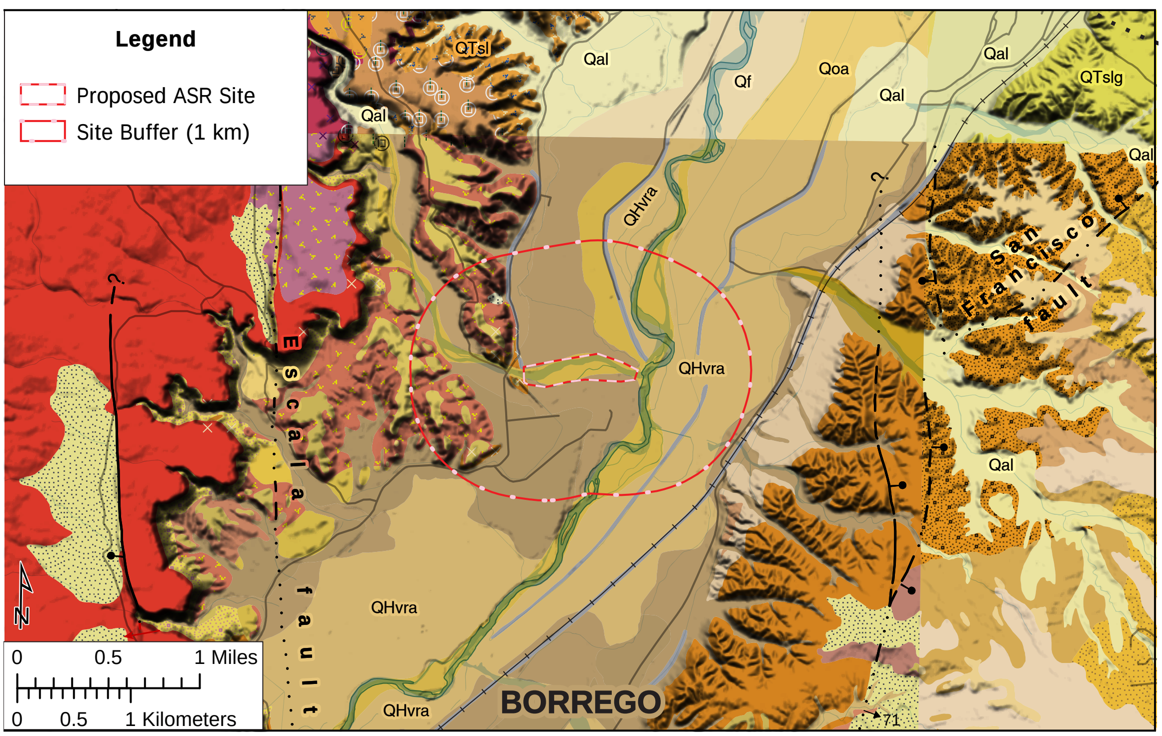

Figure 5b. Borrego Arroyo surface geology. Map includes geologic features from these mosaicked 1:24,000-scale quadrangles: Smith and Kuhle (1998), Cather and Connell (1998), and Black et al. (2000). Note that map units vary per these three maps, and each should be consulted for full legends and geologic unit descriptions. Site-relevant geologic units include QHvrg – modern to historic sand and gravel alluvium; QHvaf2 and QHvaf1 – late Holocene to historic fan alluvium; QTsts(v) – Sierra Ladrones Formation (Santa Fe Group), interfingering piedmont and river sediments, primarily sand; and QTstcs(v) – Sierra Ladrones Formation (Santa Fe Group), interfingering piedmont and river sediments, primarily conglomeratic sand.

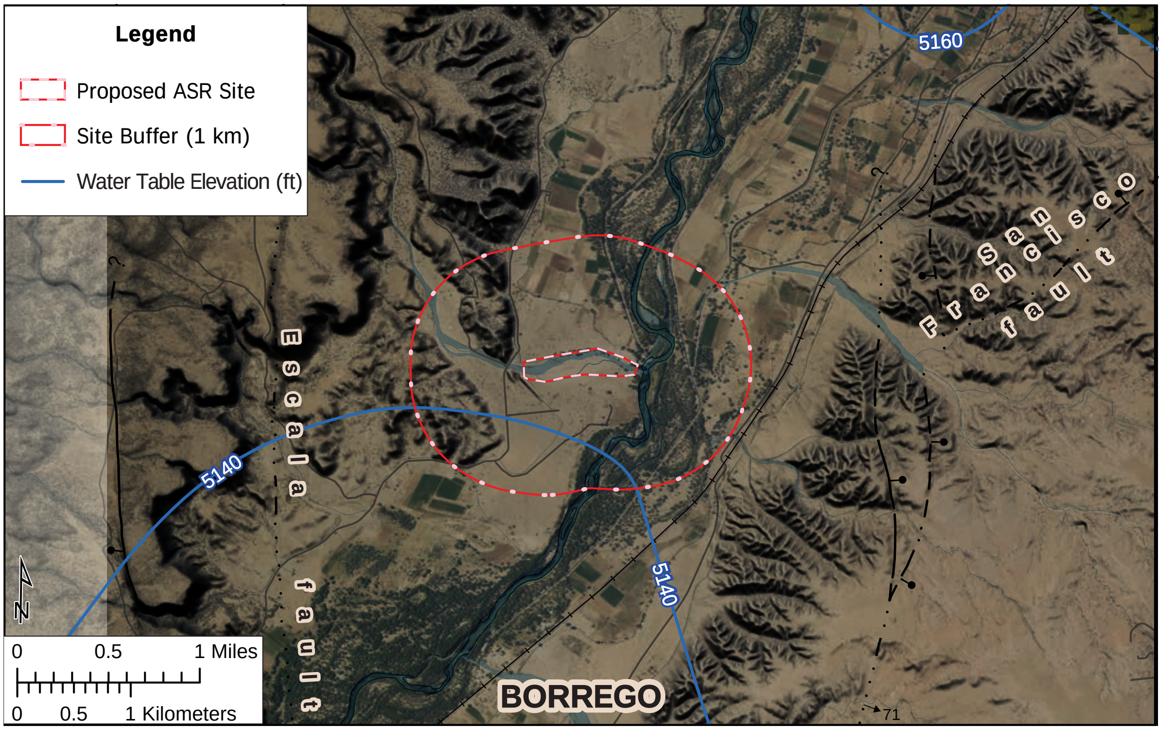

Figure 5c. Borrego Arroyo. MRGABI ranking results, water-table contours, and well locations. Faults are shown here and in Figure 5b following Federal Geographic Data Committee Standards. Solid black lines represent where a fault is mapped with certainty; the ball and bar show the downthrown side of the fault. Dashed lines and question marks indicate where the exact fault location is uncertain. Readers should refer to the location-specific geologic map for more details.

TONQUE ARROYO

Size: 241 acres

Land ownership: San Felipe Pueblo

Land use: This site follows the sandy Tonque Arroyo for approximately 2 mi between Interstate 25 and the Rio Grande. Satellite imagery shows the largest concentration of homes is at the northwestern edge of the site; in addition, several businesses, including the San Felipe Governor's Office and the San Felipe Health Clinic, run along its western length. The majority of the site is considered Riverine Habitat by USFWS. Within the 1-km site buffer, USFWS has also identified Freshwater Emergent Wetlands and Freshwater Forested/Shrub Wetland.

Contamination: The San Felipe gas station is within 5 km of the site, but no known contamination sites are reported by the NMED.

Geologic information: NMBGMR Open-File Geologic Map 19: Geologic Map of the San Felipe Pueblo 7.5-Minute Quadrangle, Sandoval County, New Mexico (Cather and Connell, 1998). This map includes a cross section (A–A´) parallel to the Tonque Arroyo site and located 1.0–1.5 km to the south.

Stratigraphy: Holocene alluvial fan sediment (some silt and gravel) forms a valley fill in lower Tonque Arroyo that is 50–100 ft thick. The correlative unit in the Albuquerque managed aquifer recharge study (Koning et al., 2019) is Qaya_cs (K_{vert} of 11–25 ft/day).

The Holocene sandy valley fill is underlain by Rio Grande deposits (QTsa) directly comparable to QTsa in the Albuquerque managed aquifer recharge study, which was assigned a hydraulic conductivity (horizontal) of 64 ft/day (Koning et al., 2019).

Structure: Subhorizontal strata. The north–south Escala fault passes through the westernmost part of the Tonque study area. It may potentially act as a groundwater barrier for the deeper Santa Fe Group, but the Holocene alluvium is thick enough (and very likely not faulted due to its young age) that the fault is not expected to notably impact ASR.

Groundwater considerations: A total of six water wells were available within the 5-km site buffer, which were supplemented with 13 artificial 0-ft depth to water points along the Rio Grande to interpolate a water-table surface. The results show a region of high hydraulic head in the southeastern part of the model area, where the groundwater contour lines are closely spaced. The wrapping of the contours forms a groundwater "ridge" that splits the groundwater flow into a gradient flowing west–northwest toward the Rio Grande and a gradient flowing north–northeast. Depth to water exceeds 30 ft beneath most of the length of Tonque Arroyo within the proposed site. Only the approximately final downstream 500 m of the arroyo have less than 30 ft depth to water.

Quantitative assessment: The MRGABI score for this site is 62%, primarily due to an adequate water-table depth for the majority of the site. Unfortunately, there are not enough site-specific well log data to evaluate clay and sand percentage for the alluvium or the Santa Fe Group.

Qualitative assessment: Good site and permeable strata. Mounding risk is moderate for the many houses located on the fan at the mouth of Tonque Arroyo. Groundwater flow under the site is likely toward the Rio Grande (San Felipe Pueblo area). Qualitative score is 4 out of 5.

Overall score: This site did not receive an overall score due to insufficient clay and sand percentage data (Table 7).

Next steps: This site shows good potential from the initial MRGABI score and the qualitative assessment; however, site-specific well log data were not available to evaluate the clay and sand percentages. Coring or boreholes (to 100–150 ft depth) can confirm our inference of sandy alluvial fan alluvium underlain by ancestral Rio Grande deposits. These subsurface data can be supplemented with shallow geophysical surveys (like electrical resistivity or electromagnetic surveys) to ascertain the proportion and geometry of low-permeability, clayey strata.

Table 7. Module ratings for Tonque Arroyo and overall score (out of 5, with 5 being best).

MRGABI Module (40%)	Clay/Sand Ratio Alluvium (20%)	Clay/Sand Ratio Santa Fe Group (10%)	Qualitative Score (30%)	Overall Score
4	NA	NA	4	NA

NA = not available due to inadequate data availability

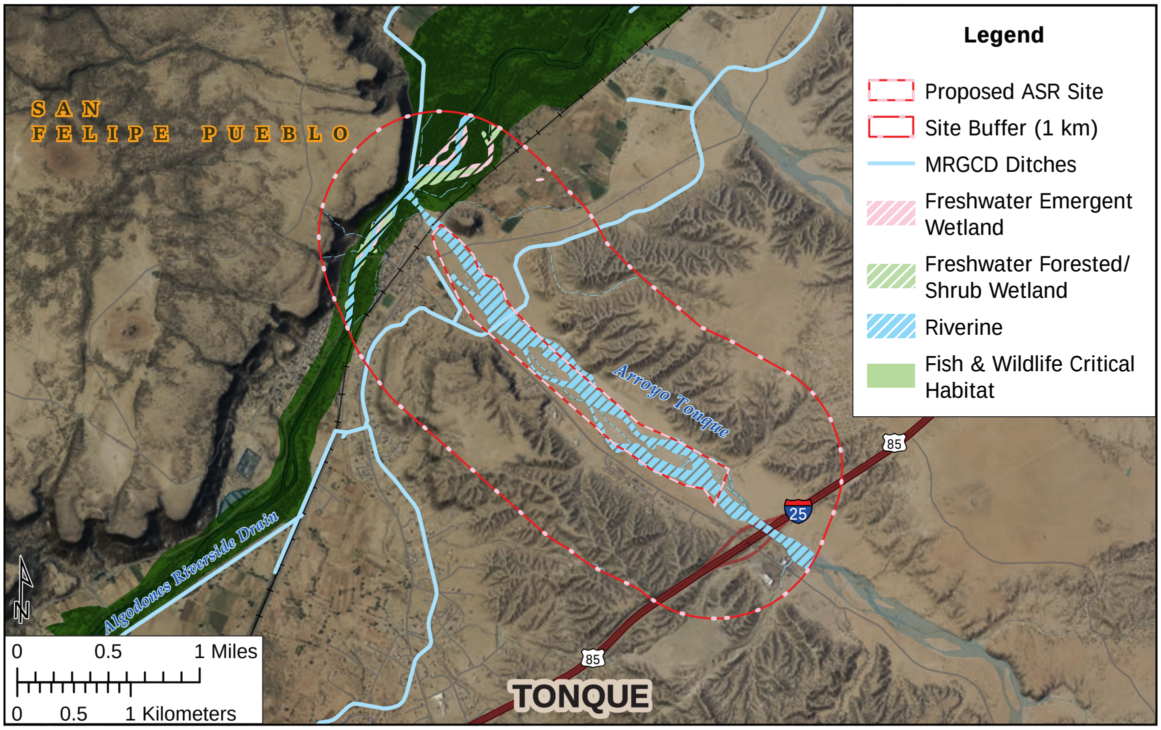

Figure 6a. Tonque Arroyo. Surface land ownership and land uses, including wildlife habitat.

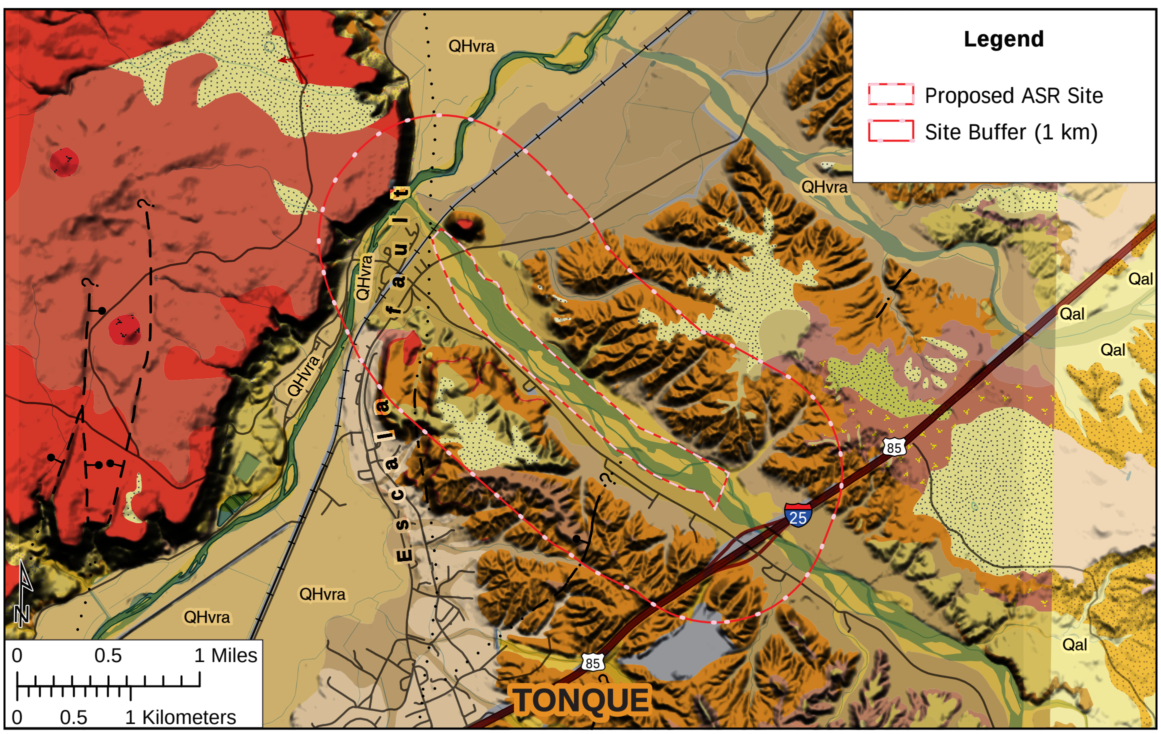

Figure 6b. Tonque Arroyo. Surface geology and faults. Map includes geologic features from these mosaicked 1:24,000-scale quadrangles: Cather and Connell (1998) and Black et al. (2000). Note that map units vary per these two maps. Site-relevant geologic units include QHvrg – modern to historic sand and gravel alluvium; QHvaf – historic to late Holocene fan alluvium; QHvat – historic to late Holocene terrace alluvium; Qvm – middle Pleistocene sand and gravel alluvium; and QTsacs – Sierra Ladrones Formation (Santa Fe Group), older Rio Grande gravel and sand.

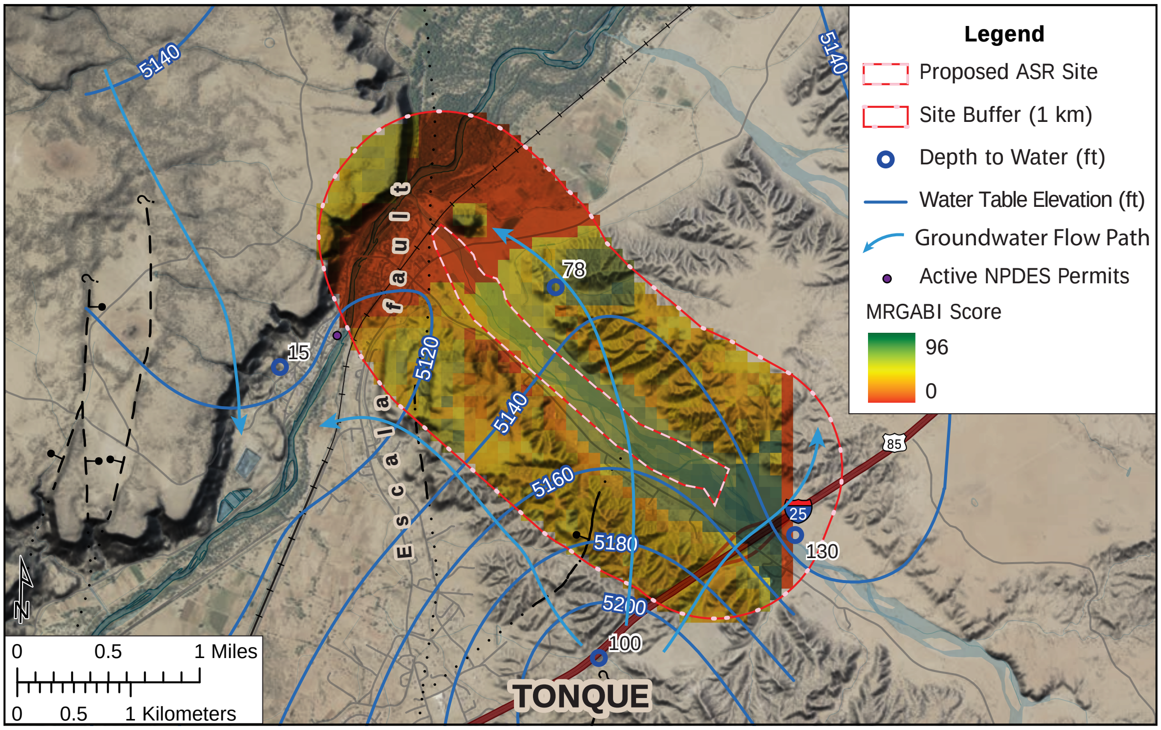

Figure 6c. Tonque Arroyo. MRGABI ranking results, water-table contours, and well locations. The active National Pollutant Discharge Elimination System (NPDES) permit is located just south of the site 5-km buffer. Faults are shown here and in Figure 6b following Federal Geographic Data Committee Standards. Solid black lines represent where a fault is mapped with certainty; the ball and bar show the downthrown side of the fault. Dashed lines and question marks indicate where the exact fault location is uncertain. Readers should refer to the location-specific geologic map for more details.

ANGOSTURA ARROYO (LAS HUERTAS CREEK)

Size: 8.19 acres

Land ownership: San Felipe Pueblo; private inholdings on the northeast side

Land use: Angostura Arroyo is a tributary to the Rio Grande that flows in from the southeast. This site is just south of Algodones and follows approximately 0.5 mi of Las Huertas Creek. The available area is quite narrow, only approximately 100 ft wide, with irrigated agriculture on both sides of the arroyo and site boundary. The tail end of this site is an MRGCD ditch, approximately 1,500 ft from the Rio Grande and flood control structures.

Contamination: Several possible contamination sites were identified in the NMED dataset, including a leaky petroleum tank and a jet fuel spill 6–7 km upstream.

Geologic information: Combined NMBGMR Open-File Geologic Maps 2 and 16: Geology of the Bernalillo and Placitas Quadrangles, Sandoval County, New Mexico (Connell et al., 1995). This map combines two individual 7.5-minute geologic maps: Bernalillo (Connell, 1998) and Placitas (Cather et al., 1995). The northernmost part of the site includes two additional maps: (1) NMBGMR Open-File Geologic Map 19: Geologic Map of the San Felipe Pueblo 7.5-Minute Quadrangle, Sandoval County, New Mexico (Cather and Connell, 1998), and (2) USGS Miscellaneous Field Studies Map MF-2405: Geologic Map of the Santa Ana Pueblo Quadrangle, Sandoval County, New Mexico (Personius, 2002).

A cross section approximately 300–500 m northeast of the Angostura study area runs parallel to the study area trend. This cross section is labeled B–B´ on Connell et al. (1995).

Stratigraphy: Unconsolidated, Holocene fan alluvium (some silt, clay, and gravel) immediately underlies lower Angostura Arroyo and is 60–90 ft thick (Table 2). The correlative unit in the Albuquerque managed aquifer recharge study (Koning et al., 2019) is Qaya_cs, with a K_{hor_vert} of 11–26 ft/day.

The Holocene fan alluvium is underlain by the distal piedmont deposits of the Santa Ana Mesa Member of the Ceja Formation. This consists of reddish, fine-grained, silty sandstone interbedded with mudstone and scattered gravelly sandstone beds. The K_{hor} is probably comparable to unit QTst of the Albuquerque managed aquifer recharge study, which had a median hydraulic conductivity (horizontal) of 18 ft/day (Koning et al., 2019).

Structure: Subhorizontal strata. A northeast-trending fault (Personius, 2002) projects to the southernmost part of the site.

Quantitative assessment: The 8 acres identified at this site received a MRGABI score of 0 due to the shallow groundwater at this location. A total of 13 water wells were available within the 5-km buffer of the proposed site. These were supplemented with nine artificial 0-ft depth to water points along the Rio Grande. Water-table interpolation shows areas of high hydraulic head 2 mi northeast of the study site. Otherwise, the hydraulic gradient is generally toward the south-southwest, approximately in the Rio Grande downstream direction. Water-table contours are irregular due to poor data coverage. Depth to water is less than 30 ft beneath the entirety of Angostura Arroyo within the proposed study site.

The ratio of sand (95%) and clay (5%) in the Holocene alluvium is favorable and was ranked 4 out of 5. Santa Fe Group sediment is less favorable, with lower sand (63%) and higher clay (37%) proportions, leading to a rank of 2 out of 5.

Qualitative assessment: The Santa Ana Mesa Member is less permeable than Rio Grande deposits of the Sierra Ladrones Formation (QTsa), and there may be perching issues for infiltrating water. There are a moderate number of houses on the fan north of the mouth of Angostura Arroyo, but groundwater flow appears to be southeast, parallel to the trend of the Rio Grande.

Table 8. Module ratings for Angostura Arroyo and overall score (out of 5, with 5 being best).

MRGABI Module (40%)	Clay/Sand Ratio Alluvium (20%)	Clay/Sand Ratio Santa Fe Group (10%)	Qualitative Score (30%)	Overall Score
0	5	2	4	2.4

Few houses exist in that direction, and the alluvium is relatively thick and sandy. The fault projecting to the westernmost tip of the site from the northwest very likely does not offset Holocene alluvium, but it may act as a groundwater barrier in the deeper Santa Ana Mesa Member.

Overall score: The overall score for this site was 2.5 out of 5, with the largest impact to this score from the shallow groundwater (Table 8).

Next steps: The estimated shallow groundwater should be confirmed by measuring depth to water within the 5-km site buffer.

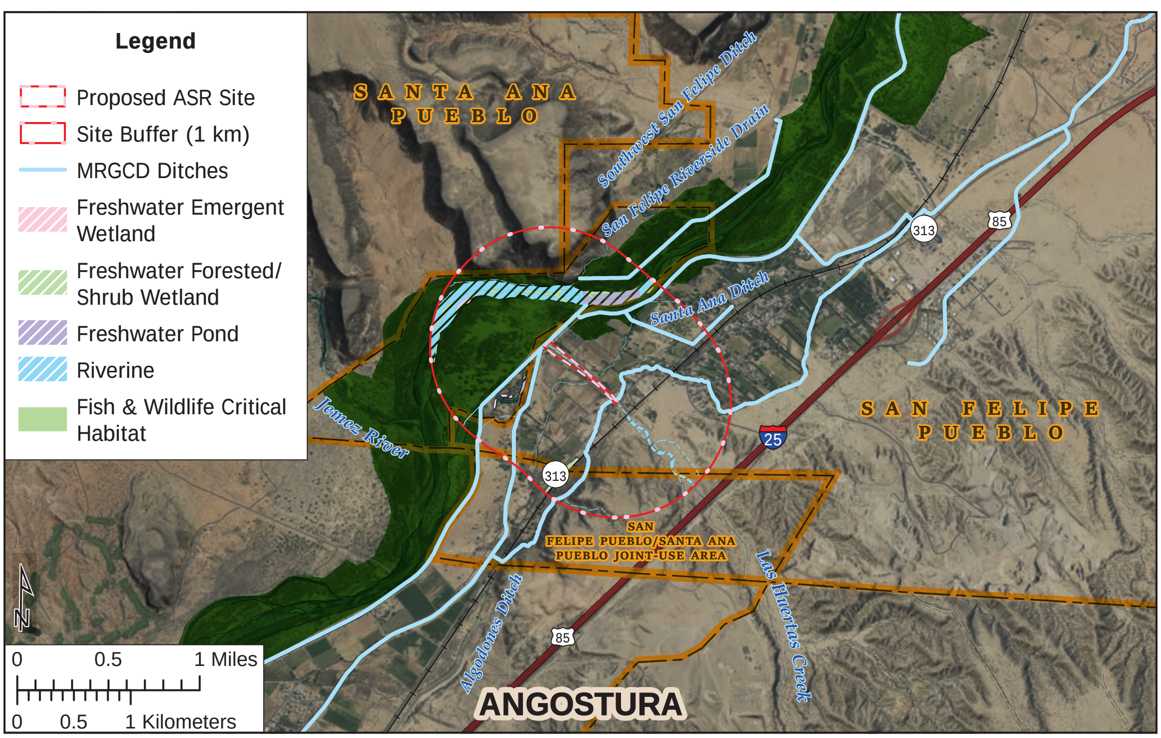

Figure 7a. Angostura Arroyo. Surface land ownership and land uses, including wildlife habitat.

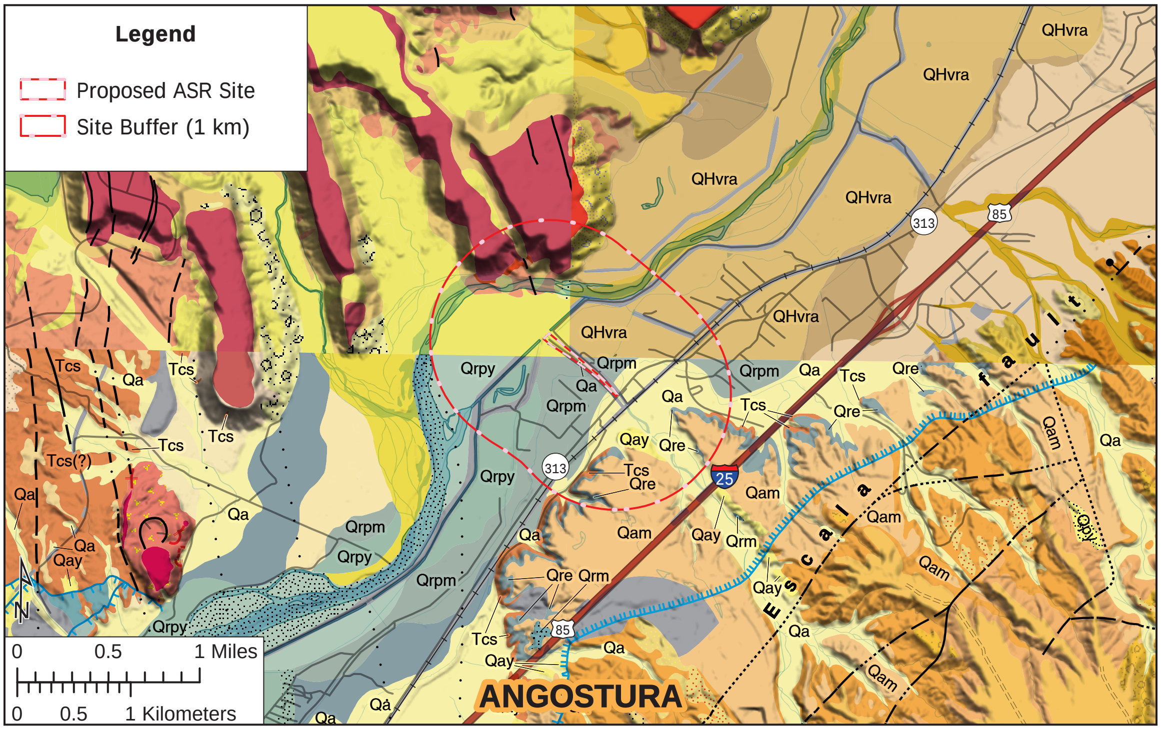

Figure 7b. Angostura Arroyo. Surface geology and faults. Map includes geologic features from these mosaicked 1:24,000-scale quadrangles: Personius (2002), Cather and Connell (1998), and Connell et al. (1995). Note that map units vary per these maps. Site-relevant geologic units include Qrpm, Qrpy, and QHvra – historic, unconsolidated alluvium of Rio Grande; Qa and Qay – Holocene, unconsolidated fan alluvium; Qrm, Qre, and Qam – Pleistocene, weakly consolidated terrace sediment; and Tcs – Santa Ana Mesa Member of Ceja Formation (Santa Fe Group), fine-grained, silty sandstone interbedded with mudstone and scattered gravelly sandstone beds.

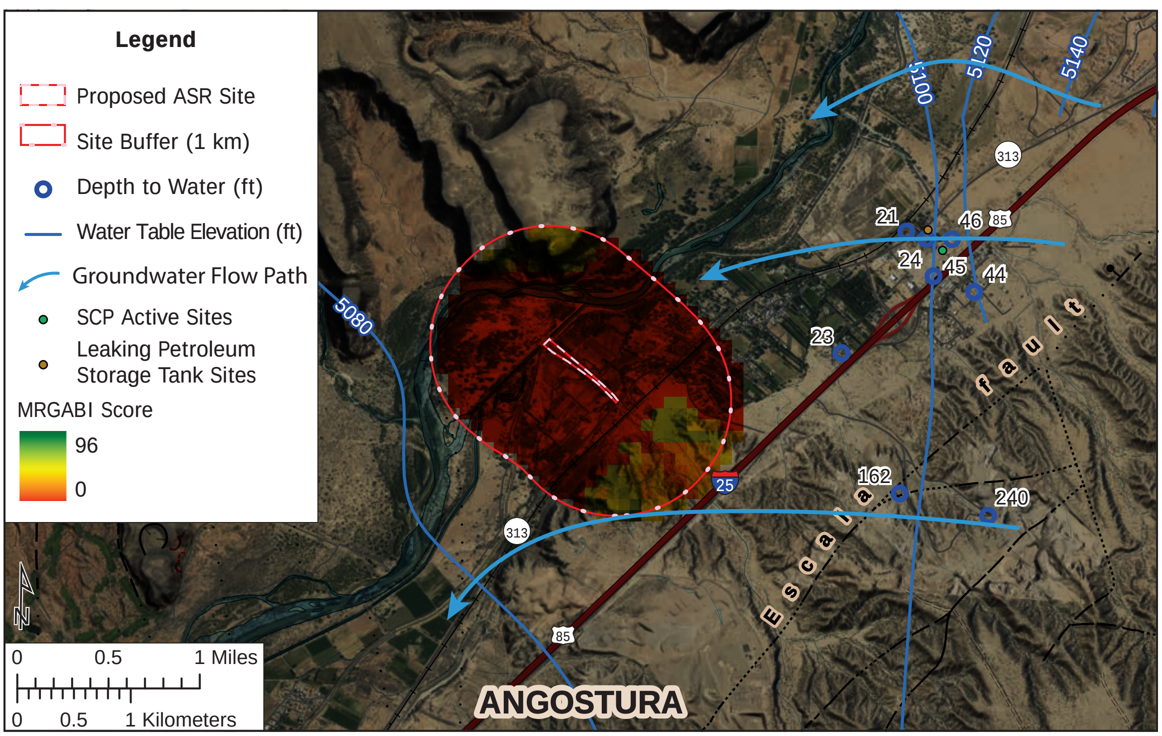

Figure 7c. Angostura Arroyo. MRGABI ranking results, water-table contours, and well locations. A State Cleanup Program (SCP) site and known leaking petroleum storage tank have been identified by the New Mexico Environment Department northeast of the site buffer. Faults are shown here and in Figure 7b following Federal Geographic Data Committee Standards. Solid black lines represent where a fault is mapped with certainty; the ball and bar show the downthrown side of the fault. Dashed lines and question marks indicate where the exact fault location is uncertain. Readers should refer to the location-specific geologic map for more details.

TIJERAS ARROYO

Size: 41.7 acres

Land ownership: Private

Land use: Tijeras Arroyo is a tributary to the Rio Grande that flows in from the east-northeast from the foothills of the Sandia Mountains. This site is located just east of Interstate 25 and south of the Albuquerque Sunport. The site-specific area is unpopulated, but there are abundant businesses within 1 mi to the southwest, and the growing Mesa del Sol business and residential complex is located 1–2 mi to the south-southeast.

Contamination: New Mexico Environment Department data included the following sites: 900 m downstream are two leaking fuel tanks, 2 km downstream is a petroleum contamination site, and 3 km upstream is a soil contamination site.

Geologic information: NMBGMR Open-File Geologic Map 17: Geology of the Albuquerque West 7.5-Minute Quadrangle, Bernalillo County, New Mexico (Connell et al., 1998).

Stratigraphy: Sand and silty sand valley fill (some silt-clay and gravel) form a valley fill in lower Tijeras Canyon that is latest Pleistocene–Holocene in age and 80–120 ft thick. The correlative unit in the Albuquerque managed aquifer recharge study is Qaya_cs, in which K_{vert} ranged from 11 to 23 ft/day.

The latest Pleistocene–Holocene alluvium is underlain by gravelly sands of the Rio Puerco Member of the Ceja Formation, which intertongues eastward with sandy ancestral Rio Grande deposits of the Sierra Ladrones Formation. The Rio Puerco and Rio Grande deposits (QTcr and QTsa, respectively) in the Albuquerque managed aquifer recharge study have mean hydraulic conductivity (horizontal) values of 20 to 64 ft/day (Koning et al., 2019).

Structure: Subhorizontal strata. No mapped faults.

Quantitative assessment: This site has the highest MRGABI module score of the seven sites analyzed for this report: 82%, or 5 out of 5. This is primarily due to good water-table depth, with 145 wells available within a 5-km buffer of the proposed site—the most of any proposed ASR site. Eight supplemental artificial points along the Rio Grande were included in the interpolation. The water-table map shows two apparently isolated areas of high hydraulic head: one west of the river and one north of the site near Interstate 25. Low hydraulic head areas are to the east and south of the site. Depth to water beneath the site falls within the acceptable range of 30–500 ft.

Both the alluvium and the Santa Fe Group are relatively permeable. Exposures of Santa Fe Group strata (ancestral Rio Puerco and Rio Grande gravelly sands of the Ceja and Sierra Ladrones Formations, respectively) indicate very little floodplain sediment. Analyses of well logs indicate 31% clay and 69% sand in the Holocene alluvium—a higher clay percentage than any other Holocene alluvium analyzed using well logs. A similar proportion (36%) of clayey beds was tabulated for the ancestral Rio Puerco and Rio Grande deposits (Santa Fe Group), notably higher than that observed in outcrops. The percent sand and clay for the alluvium and the Santa Fe Group were both ultimately ranked at 2 out of 5.

Qualitative assessment: A major issue with this site is the presence of several contamination sites and groundwater flow that is southeast, away from the river, about 1 mi downgradient of the site. The abundance of wells and studies of these contamination sites make this groundwater flow direction relatively certain. Thus, water infiltrating here is predicted to eventually flow to the southeast and not be readily recovered by the MRGCD. Given these concerns, the qualitative assessment of the site was given a 1, even though the sediment-related permeability features are favorable for infiltration.

Overall score: The overall score for this site is 2.9 out of 5 (Table 9).

Table 9. Module ratings for Tijeras Arroyo and overall score (out of 5, with 5 being best).

MRGABI Module (40%)	Clay/Sand Ratio Alluvium (20%)	Clay/Sand Ratio Santa Fe Group (10%)	Qualitative Score (30%)	Overall Score
5	2	2	1	2.9

Next steps: This site is one of the most data-rich of the seven sites evaluated. Careful consideration of ASR operations would be necessary to alleviate concerns regarding groundwater flow direction and contamination.

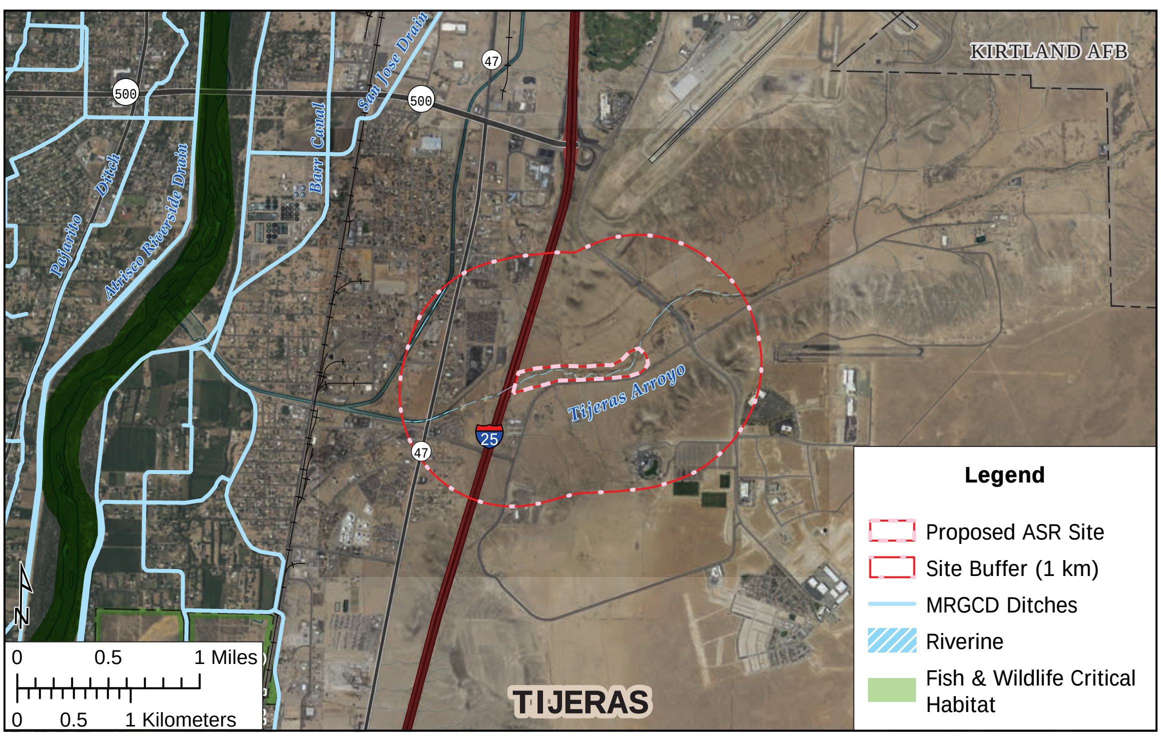

Figure 8a. Tijeras Arroyo. Surface land ownership and land uses, including wildlife habitat.

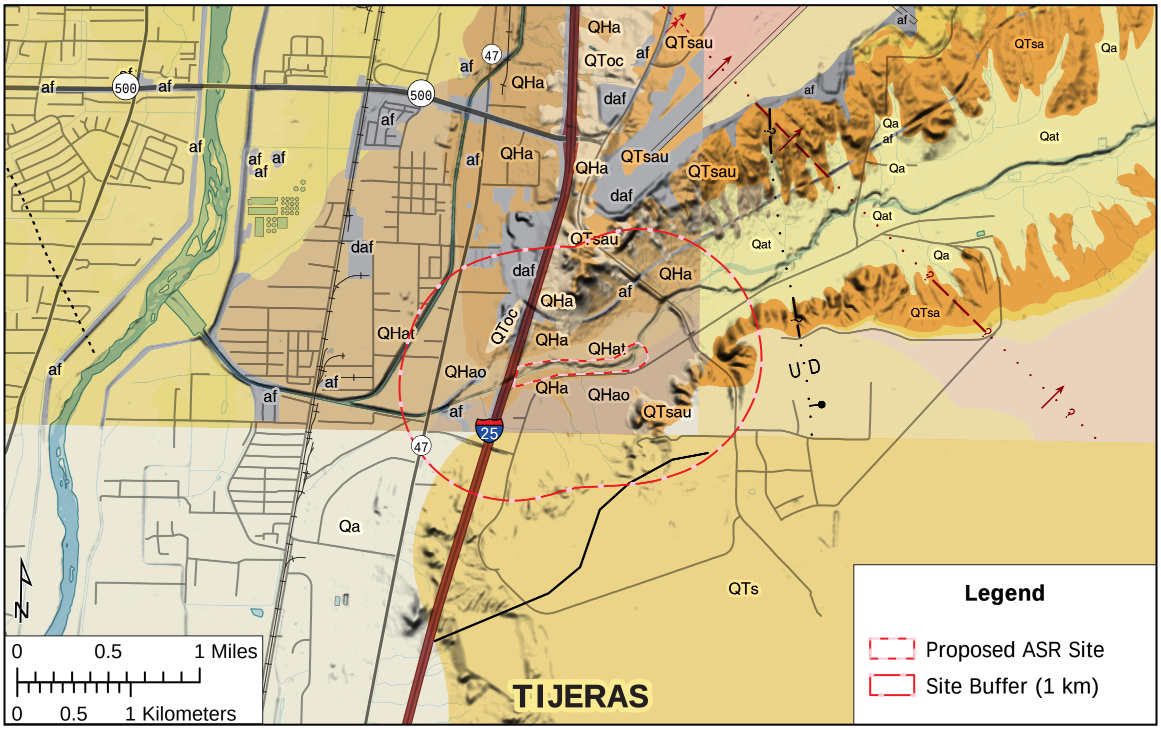

Figure 8b. Tijeras Arroyo. Surface geology and faults. Map includes geologic features from these mosaicked 1:24,000-scale quadrangles: Connell et al. (1998) and Hawley et al. (1996). Southern part of geologic map is from NMBGMR (2003). Note that map units vary per these maps. Site-relevant geologic units include daf – disturbed land; QHat, QHa, QHao, Qat, and Qa – Holocene, valley-floor and fan alluvium (sand and silty-clayey sand); and QToc and QTsau – Sierra Ladrones Formation (Santa Fe Group), sandy deposits of the Rio Grande interfingering westward with Rio Puerco sand and gravel. Faults are shown following Federal Geographic Data Committee Standards. Solid black lines represent where a fault is mapped with certainty; the ball and bar show the downthrown side of the fault. Dashed lines and question marks indicate where the exact fault location is uncertain. Readers should refer to the location-specific geologic map for more details.

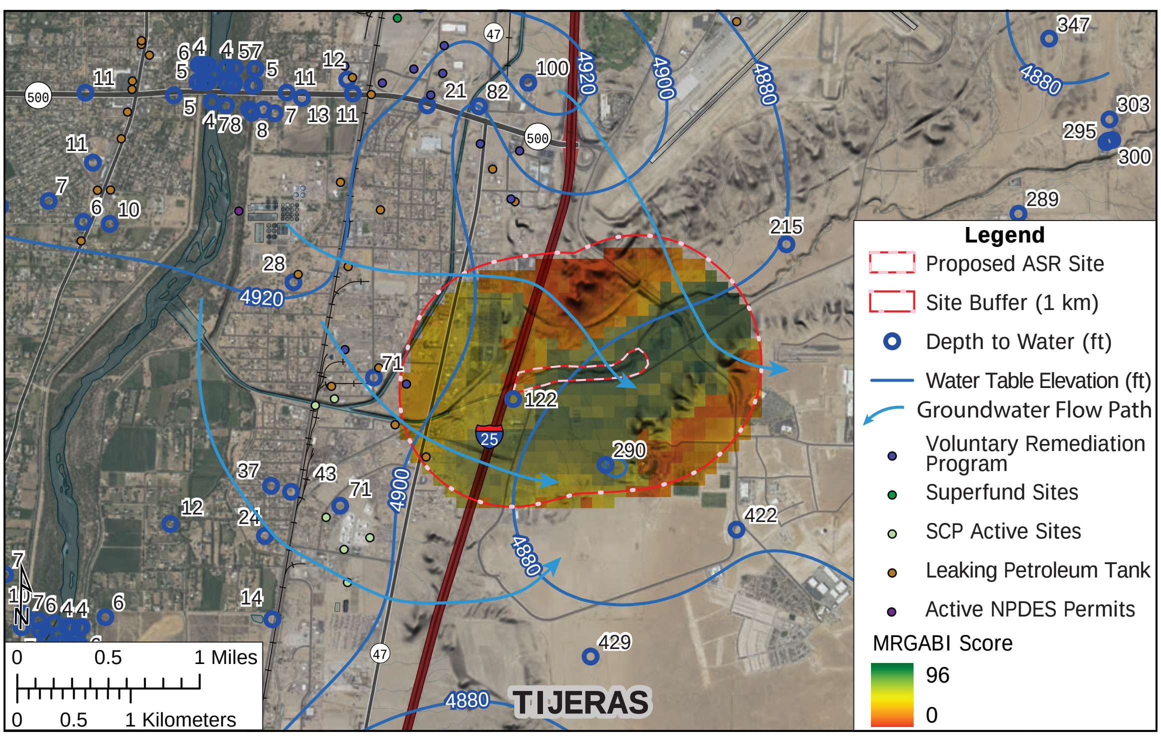

Figure 8c. Tijeras Arroyo. MRGABI ranking results, water-table contours, and well locations. Several contamination sites have been identified by the New Mexico Environment Department upstream of the proposed ASR site, including a State Cleanup Program (SCP) site. Groundwater flow paths indicate water is moving away from the Rio Grande and toward the site at this location.

BELEN HIGHLINE

Size: 1,732 acres

Land ownership: Various private owners

Land use: Belen Highline is a broad area south of Belen that lies between Interstate 25 and the east edge of the broad mesa about 1–1.5 mi west of the interstate. This is the largest site considered in this study and is not developed for agriculture or residential homes. Within a 500- to 1,000-ft buffer along the east side of the site are active pecan orchards and MRGCD ditches.

Contamination: A leaking petroleum tank site is 700 m to the east (downstream) of the site boundary. Additional leaking petroleum tanks are 4 km to the northwest and 1.5 km to the southeast (downstream) of the boundary.

Geologic information: NMBGMR Open-File Geologic Map 28: Geologic Map of the Veguita 7.5-Minute Quadrangle, Valencia and Socorro Counties, New Mexico (Love, 1999).

Stratigraphy: The authors assume the terrain of interest is the sloping Holocene alluvium, rather than the steep slopes underlain by the Ceja Formation. The sandy alluvial fan sediment (Holocene) is probably 20–60 ft thick and unsaturated away from the Rio Grande floodplain. On the floodplain, the depth of alluvium is 40–110 ft and it is composed of sand with minor silt and clay. This Holocene sediment very likely overlies interbedded sandstones (sheet-like forms and channel fills) and mudstones of the Ceja Formation (ancestral Rio Puerco). Tongues of ancestral Rio Grande sand (Sierra Ladrones Formation) within the Ceja Formation can also be expected. This sequence (Ceja and Sierra Ladrones Formations) probably extends to at least 500 ft depth. Well data would be particularly important at this site.

The alluvium is lithologically similar to unit Qaya_cs in the Albuquerque managed aquifer recharge study and may have a comparable K_{vert} of 11–23 ft/day. Conservatively, the intertonguing, underlying Santa Fe Group would probably have K_{hor} similar to QTst in Koning et al. (2019), with a median of 18 ft/day. The Ceja Formation contains about 25% low-permeability sediments, and these extend laterally 100 m to several hundred meters (Davis et al., 1993, 1997). Analyses of well logs suggest roughly subequal clayey versus sandy sediment—the highest clay proportion in the Santa Fe Group of any site. The chance of vadose-zone, infiltration-related perching is relatively high.

Structure: Subhorizontal strata. No mapped faults.

Quantitative assessment: The MRGABI module rating for this site was 67%, or 4 out of 5. The site has a more favorable MRGABI ranking along the eastern flank than the western flank. Eighteen wells were available within a 5-km buffer of the proposed site. Eleven supplemental artificial points along the Rio Grande were included in the interpolation. The highest hydraulic head is northwest and northeast of the proposed site, with water-table contours bending to form a south-trending, trough-like feature near the western study area boundary. In most of the study area, groundwater flow is to the southwest or south-southwest, away from the Rio Grande. Depth to water beneath the proposed site is within the acceptable range of 30–500 ft.

The 81% sand in the alluvium is also favorable, ranking 4 out of 5. The underlying Santa Fe Group is estimated to be 50% sand, leading to a much lower ranking of 1 out of 5 for this unit.

Qualitative assessment: The Holocene alluvium is probably relatively thin at this site. The relative abundance of mudstones in the underlying Santa Fe Group and their lateral continuity (Davis, 1993) increase the chance of water being perched on a laterally extensive mudstone and carried to the Holocene fan toe, causing flooding and mounding issues for farms there. However, groundwater-table contouring, based on limited data, suggests a southwest flow direction in the southern part of the

Table 10. Module ratings for Belen Highline and overall score (out of 5, with 5 being best).

MRGABI Module (40%)	Clay/Sand Ratio Alluvium (20%)	Clay/Sand Ratio Santa Fe Group (10%)	Qualitative Score (30%)	Overall Score
4	4	1	2	3.1

study area. This would ameliorate the mounding risk, but, if the contouring is accurate, the recharged water would then head away from the Rio Grande valley in the subsurface.

Overall score: The overall site score is 3.1 out of 5 (Table 10).

Next steps: Groundwater-level data are limited at this location, particularly west of the site. New groundwater-level data would benefit the hydrologic understanding of this site. Such data could be obtained from direct measurement of water levels in wells near the eastern boundary of the study area; approximation of the water-table elevation could be extended to the west-southwest using geophysical data from electrical resistivity or electromagnetic surveys.

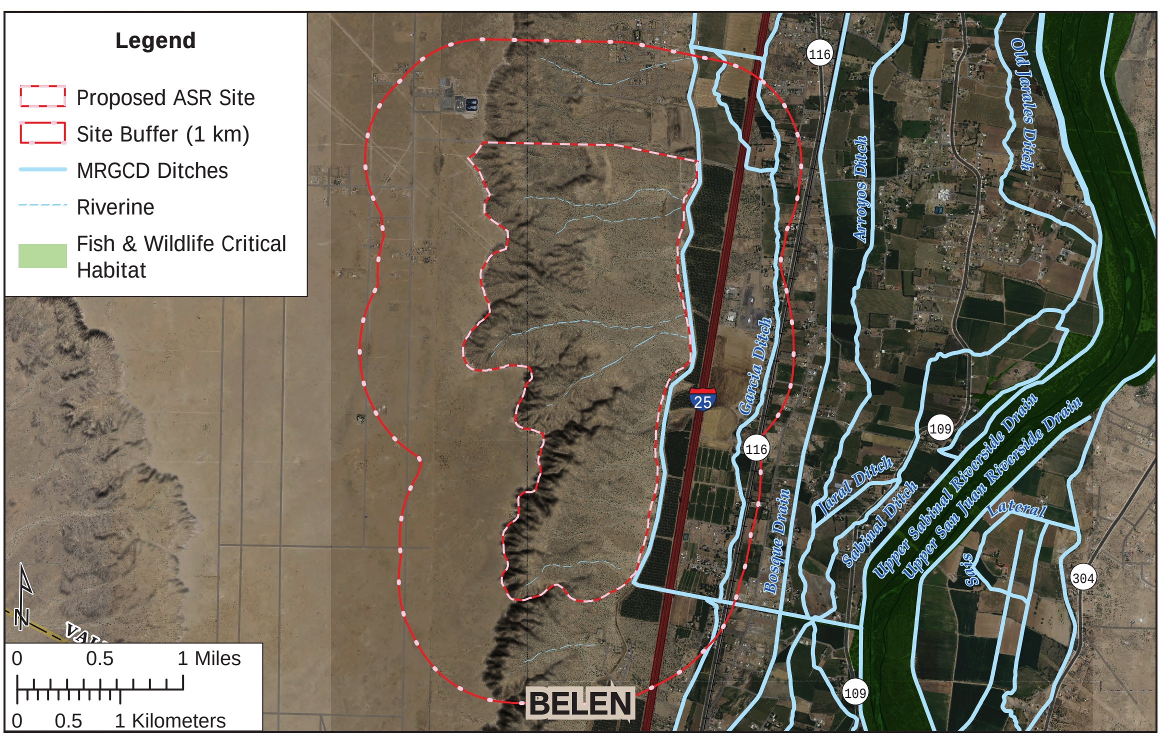

Figure 9a. Belen Highline. Surface land ownership and land uses, including wildlife habitat.

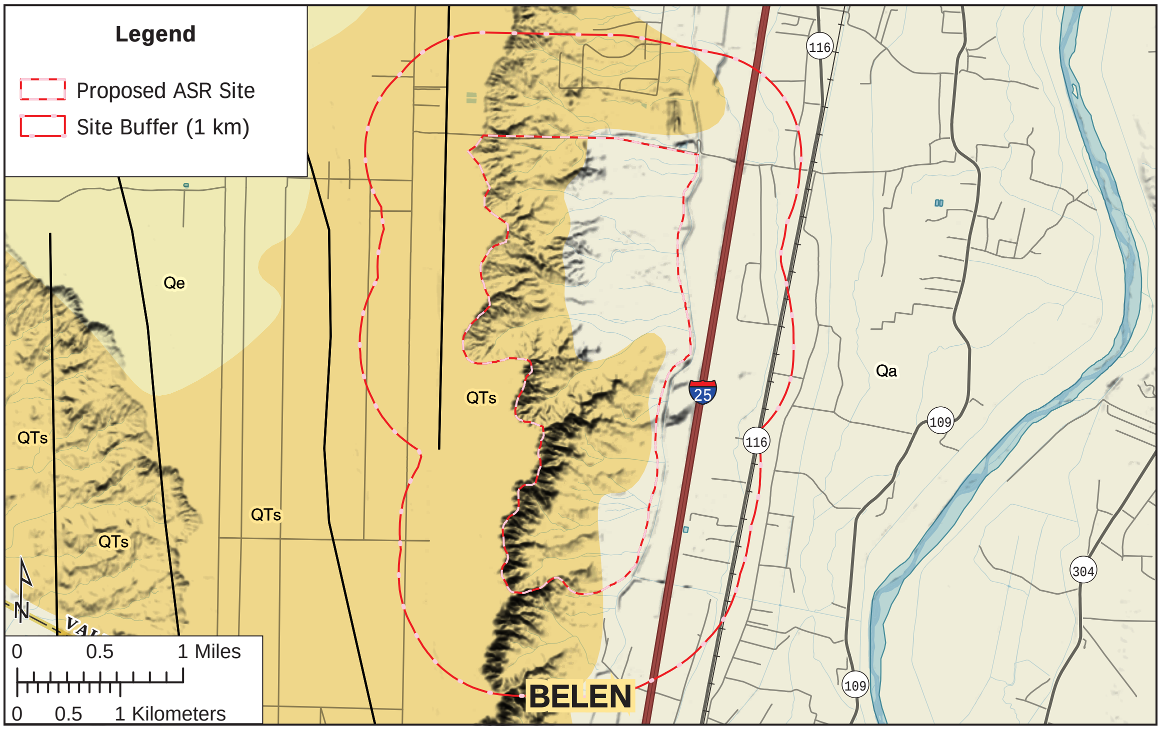

Figure 9b. Belen Highline. Surface geology and faults. Map includes geologic features from NMBGMR (2003). Site-relevant geologic units include Qa – Holocene valley-floor alluvium (sand with minor silt and clay) east of about Highway 116, to west of Highway 116 lies Holocene sandy fan; and QTs – Ceja and Sierra Ladrones Formations (Santa Fe Group), interbedded sandstones and mudstones deposited by the ancestral Rio Puerco and Rio Grande. Faults are shown following Federal Geographic Data Committee Standards. Solid black lines represent where a fault is mapped with certainty. Readers should refer to the location-specific geologic map for more details.

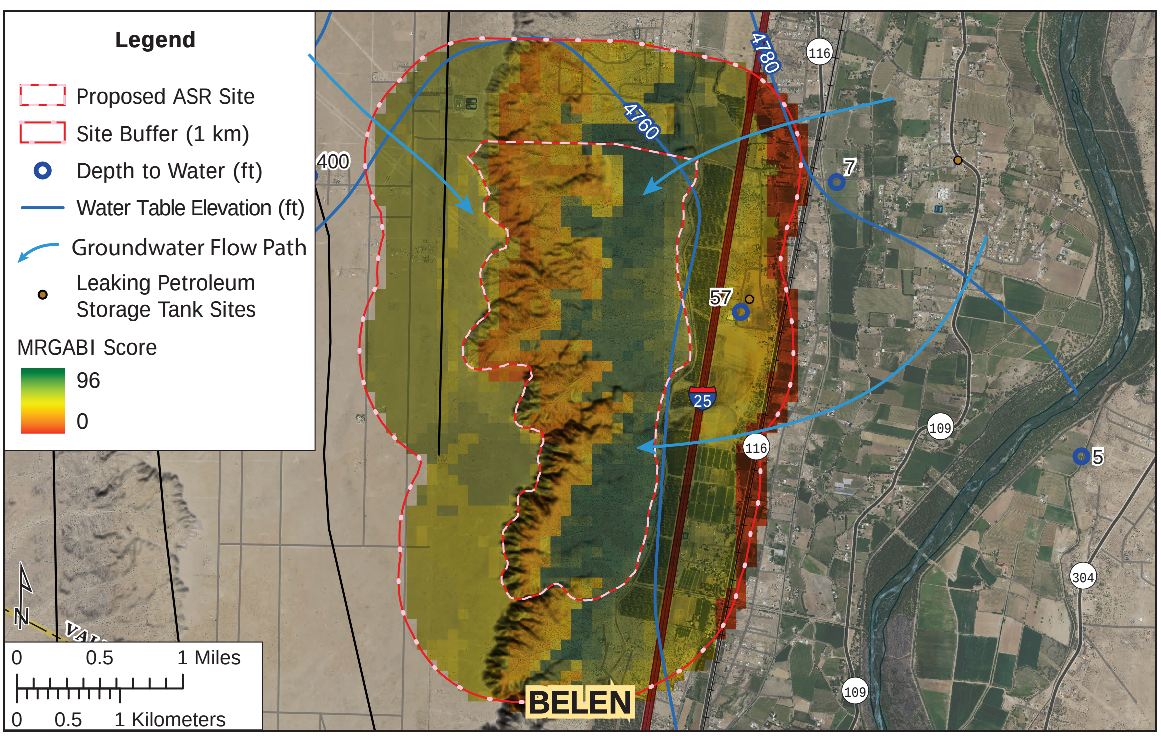

Figure 9c. Belen Highline. MRGABI ranking results, water-table contours, and well locations.

SAN ACACIA

Size: 133 acres

Land ownership: The west half is the Sevilleta National Wildlife Refuge; the east half is private.

Land use: Grazing land and wildlife habitat; farms are present immediately south-southeast of the eastern toe of the site.

Contamination: No known contamination sites exist within a 5-km buffer.

Geologic information: USGS Geologic Quadrangle 1415: Geologic Map of the San Acacia Quadrangle, Socorro County, New Mexico (Machette, 1978); and NMBGMR Open-File Geologic Map 38: Geologic Map of the Lemitar 7.5-Minute Quadrangle, Socorro County, New Mexico (Chamberlin et al., 2001).

Stratigraphy: Sandy (minor mud, gravel) alluvial fan sediment of latest Pleistocene–Holocene age is probably 20–80 ft thick. This sediment interfingers eastward with Rio Grande alluvium (primarily sand with minor clayey-silty beds), which is about 40–80 ft thick. Clay versus sand analyses using well logs indicate 80% sand and 20% clayey sediment in the alluvium. There are two units in the underlying Santa Fe Group sediment: (1) the western 20% of the recharge reach is sandy ancestral Rio Grande sediment of the Sierra Ladrones Formation and probably >300 ft thick and (2) the eastern 80% of the recharge reach is sandstone and subordinate muddy sandstone and conglomerates of the piedmont deposits of the Sierra Ladrones Formation (see Hinojosa, 2021; Love et al., 2022). The piedmont deposits have about 60% sand and 40% clayey sediment.

The alluvium is lithologically similar to unit Qaya_cs in the Albuquerque managed aquifer recharge study and may have a comparable K_{vert} of 11–23 ft/day. The Rio Grande sand would have hydraulic conductivity similar to the QTsa unit in the Koning et al. (2019) Albuquerque managed aquifer recharge study, with a mean of 64 ft/day. The piedmont deposits of the Sierra Ladrones Formation would be of relatively low hydraulic conductivity because of cemented sandstones and muddy layers. The associated K_{hor} would probably be similar to unit QTsp of the Albuquerque managed aquifer recharge study, which had a median value of 13 ft/day (Koning et al., 2019).

Structure: The ancestral Rio Grande sediment of the Sierra Ladrones Formation is dipping west-northwest at 15–20°. The main strand of the Loma Blanca fault crosses somewhere near the head of the recharge area. The Sierra Ladrones piedmont deposits probably dip about 5° to the west.

Quantitative assessment: Twenty-eight water wells were available for water-table interpolation. Eleven supplemental artificial points along the Rio Grande were included in the interpolation. The highest hydraulic head is northwest of the site, and the hydraulic gradient is predominantly to the east or southeast (the latter near the eastern toe of the study area). Depth to water is less than 30 ft beneath the downstream 10% of the site. The site received a score of 31%, rating it 2 out of 5 in the MRGABI module.

Qualitative assessment: The relative abundance of muddy strata in the Santa Fe Group (piedmont deposits of the Sierra Ladrones Formation) increases the chance of infiltrating water being perched below fan alluvium. However, the fan alluvium is probably quite thick on the east side of the recharge zone and would likely have high storativities and permeabilities. Many dwellings at the foot of the alluvial fan could potentially be impacted by mounding (e.g., the town of Alamillo). The southern continuation of the Loma Blanca fault is poorly understood southwest of Alamillo. Even though hydraulic conductivity (K_{sat}) values are better in QTsa on the footwall (west side) of the fault, this aquifer may have poor groundwater-flow connection between QTsa and the Rio Grande valley. The recharge area should be strictly on the hanging wall of the fault. Groundwater flow is toward the Rio Grande floodplain.

Table 11. Module ratings for San Acacia and overall score (out of 5, with 5 being best).

MRGABI Module (40%)	Clay/Sand Ratio Alluvium (20%)	Clay/Sand Ratio Santa Fe Group (10%)	Qualitative Score (30%)	Overall Score
2	4	1	4	2.9

Overall score: The overall score for this site is 2.9 out of 5 (Table 11).

Next steps: Electromagnetic or resistivity surveys extending west-northwest from areas with well control could refine the water-table map and possibly indicate where strands of the Loma Blanca fault are buried beneath alluvium.

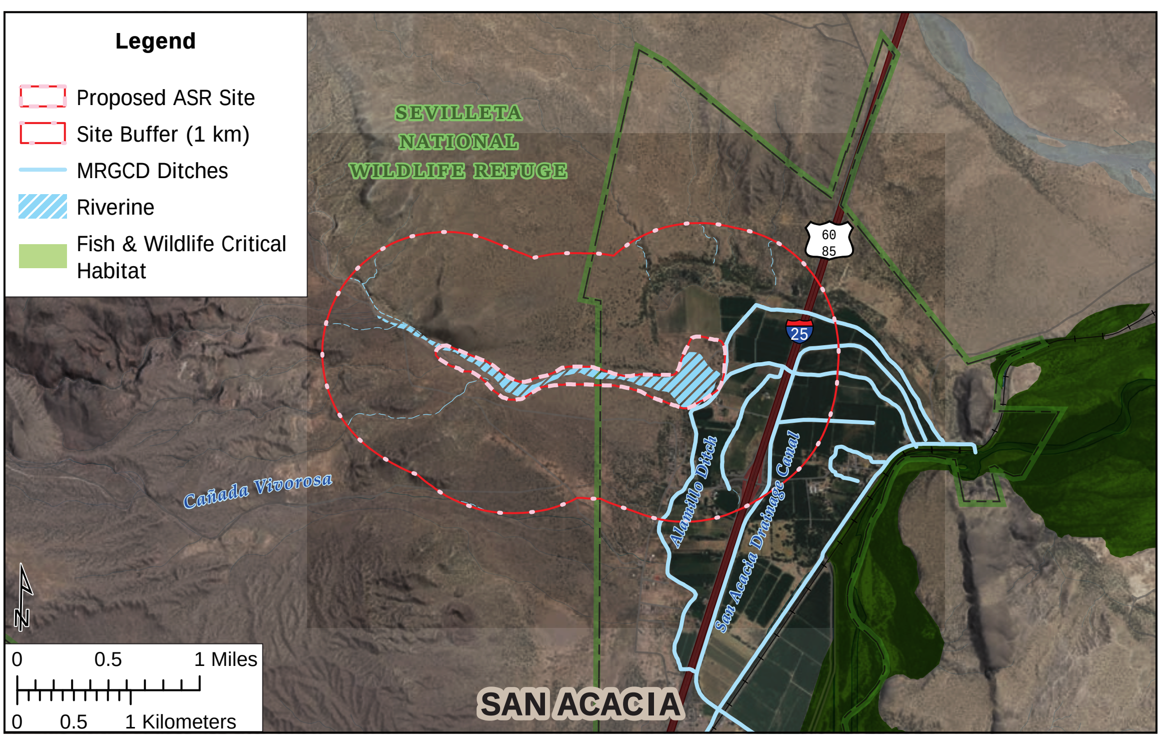

Figure 10a. San Acacia. Surface land ownership and land uses, including wildlife habitat.

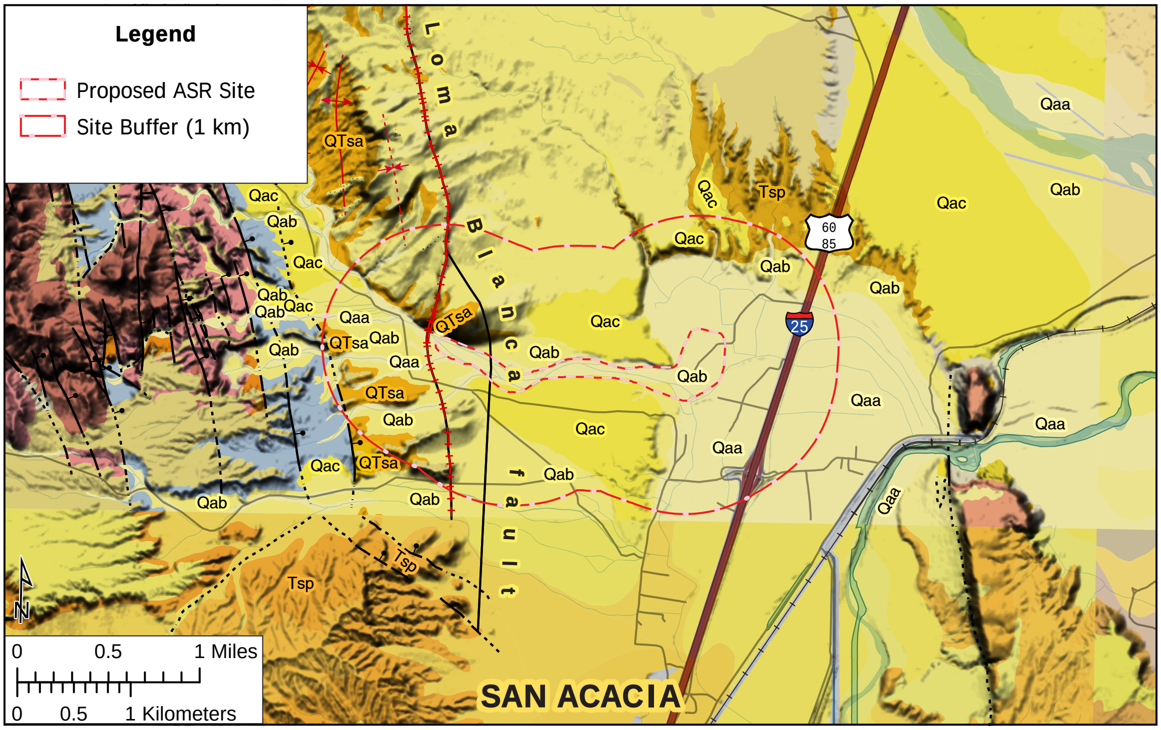

Figure 10b. San Acacia. Surface geology and faults. Map includes geologic features from these mosaicked 1:24,000-scale quadrangles: Chamberlin et al. (2001) and Machette (1978). Site-relevant geologic units include Qaa – recent to historic alluvium in active channels and underlying Rio Grande floodplain (in latter are subordinate clayey-silty layers); Qab and Qac – Holocene alluvium composed of silty sand to gravelly sand; QTsa – Sierra Ladrones Formation (Santa Fe Group), ancestral Rio Grande sand; and Tsp – Sierra Ladrones Formation (Santa Fe Group), piedmont sandstone with subordinate muddy sandstone and conglomerates.

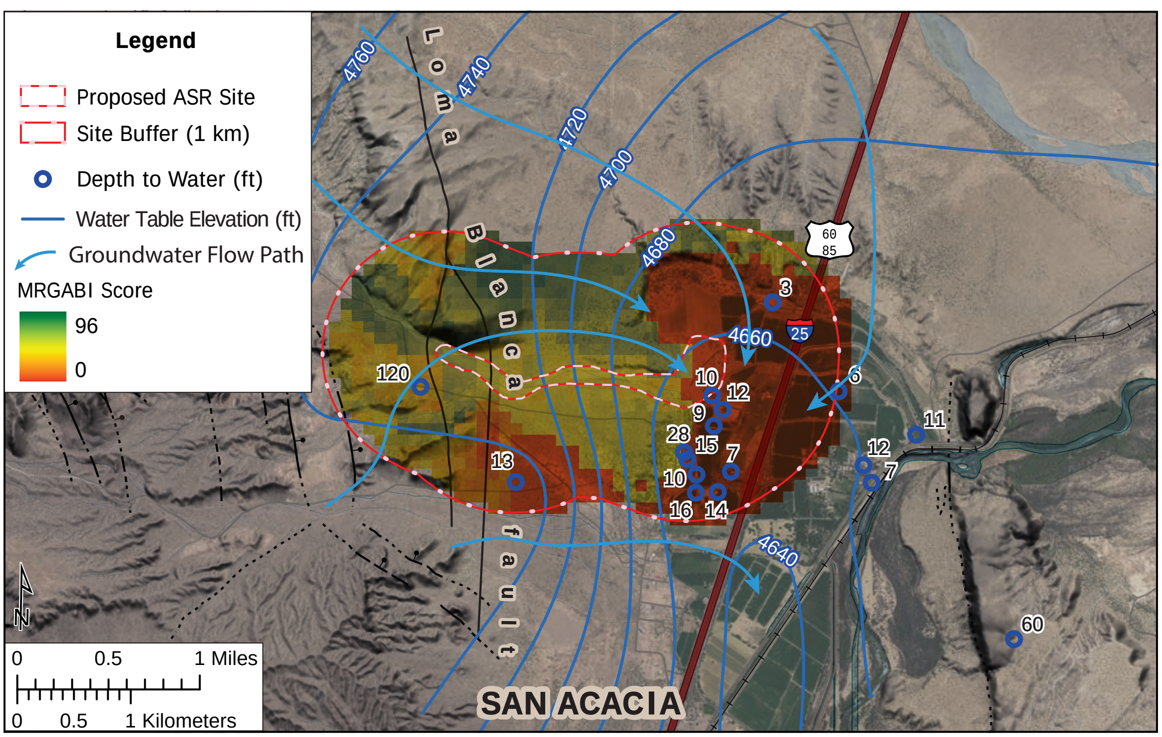

Figure 10c. San Acacia. MRGABI ranking results, water-table contours, and well locations. Faults are shown here and in Figure 10b following Federal Geographic Data Committee Standards. Solid black lines represent where a fault is mapped with certainty; the ball and bar show the downthrown side of the fault. Dashed lines and question marks indicate where the exact fault location is uncertain. Readers should refer to the location-specific geologic map for more details.

DISCUSSION

The seven sites in this study can be divided into two groups: those lacking data for comparative purposes and those with adequate data. The sites with inadequate data coverage are the northern three sites on Pueblo land: Galisteo Arroyo, Borrego Arroyo, and, to a lesser extent, Tonque Arroyo. Based on qualitative assessment of the geologic and hydrologic context, these sites are inferred to be relatively favorable (4 out of 5 and 5 out of 5 rankings). But the three northern sites lack well data, and that makes it difficult to compare them directly to the other four sites. The site with the 5 out of 5 qualitative assessment ranking is Borrego Arroyo. It has relatively permeable sediment in the Holocene alluvium and underlying Santa Fe Group and lacks human habitation at the foot of the alluvial fan. So, if groundwater mounding did occur here, it would likely have minimal societal impacts. According to Plummer et al. (2012), the Rio Grande is a gaining stream in that area, so the recharged area should stay in the MRGCD boundaries. However, a water-table map could not be made there due to lack of well data. Both the Galisteo Arroyo and Tonque Arroyo sites have many houses near the toe of the corresponding alluvial fans, so relatively high degrees of detrimental societal impact would ensue if groundwater mounding occurred. North-south fault lines are found in the Galisteo Arroyo and Tonque Arroyo sites. Within the Santa Fe Group, below the inferred 50- to 100-ft-thick Holocene alluvium, these faults may redirect the flow of groundwater (probably to the south).

Table 4 indicates the remaining four sites have relatively similar overall scores (2.4–3.1), indicating moderate favorability. Of these four, Angostura Arroyo has a 0 rating in the MRGABI module due to relatively high groundwater-table elevations. San Acacia also has a relatively low rating in the MRGABI module (due in large part to relatively high groundwater elevations in the eastern portion of that site) as well as a relatively high clay proportion in the underlying Santa Fe Group. The other two sites—Belen Highline and Tijeras Arroyo—have the lowest qualitative assessment scores. Tijeras Arroyo, which has the best well dataset, has relatively confident groundwater flow to the southeast, away from the MRGCD jurisdiction. Plus, several contamination sites are present within 2.5 km of that study area (Fig. 8c). Belen Highline achieved the highest final score at 3.1, but available data indicate that groundwater flow may be directed to the southwest, away from the MRGCD jurisdiction. Critical habitat or wetlands do not appear to be a detriment to ASR at any of the study sites.

Of the seven sites in consideration, Borrego Arroyo may be the most suitable site for ASR. However, further data acquisition is absolutely critical for the next step in ASR evaluation, and the costs of acquiring these data must be weighed. Additional data could include shallow wells to better constrain subsurface lithology and water-table depths, coupled with shallow electrical resistivity and magnetotelluric or electromagnetic surveys to map the water table beyond these well control points. Since this site has the fewest data, it may require the most effort to secure additional data for an adequate assessment.

The second most favorable sites are Rio Galisteo and Tonque Arroyo, but again further data acquisition is needed. This would involve securing permission from tribal well owners for water-level measurements to build a more robust water-table map. A few shallow well borings spaced evenly along the length of the arroyo could help ascertain whether there are extensive clay layers that could cause perching and whether the overall proportion of clay is relatively low. Electrical resistivity or magnetotelluric surveys could be tied to these borings to achieve more robust interpretations of the stratigraphy and spatial distribution of permeability (clayey versus sandy sediment) in the subsurface.

Tijeras Arroyo is likely the least suitable ASR site. The relatively robust well data there indicate water is flowing away from the Rio Grande valley to the southeast. Abundant contamination sites are also present there. Moreover, the clay percentage in the Holocene alluvium at the Tijeras site is relatively higher than at the other six sites (Table 4). However, the water-table depth is quite favorable, indicating a low potential for mounding.

In the middle tier of suitability for ASR are the Angostura Arroyo, Belen Highline, and San Acacia sites. The shallow groundwater at Angostura Arroyo and San Acacia is problematic, but the groundwater flow paths (toward the Rio Grande) are favorable. The alluvium at Angostura Arroyo is relatively coarse and likely permeable, based on analyses of eight wells, but the underlying Santa Fe Group unit has the highest proportion of clays of any of the sites. Further work to better assess these three sites would include more water-level measurements, especially at the Belen Highline site, to verify that groundwater flow is in a favorable direction. At the San Acacia and Angostura Arroyo sites, detailed calculations of mounding potential (likely involving coring of Holocene alluvium and conducting in-situ permeability tests of the samples) could possibly allow for ASR if recharge/discharge rates occur in a restricted range.

CONCLUSIONS

Presented above are several methods of assessing the potential for ASR activities at seven New Mexico sites; individual ratings for each site are weighted averages, producing an overall score for each site. The Middle Rio Grande Aquifer Banking Index (MRGABI) code was developed to rate these sites based on four soil properties, soil and groundwater contamination, surface slope, and depth to groundwater. The sites were also ranked on the percent clay and sand in the Holocene alluvium and underlying Santa Fe Group layers based on drillers' logs. Finally, the opinion of an expert geologist on the hydrogeologic setting of the site was also considered. A combined quantitative and qualitative score was created for each site. Due to overall data scarcity and the fact that this investigation is in its initial phase, any numerical ranking of these sites is preliminary and should be used to guide further research.

The Belen Highline site had the highest combined score (3.1 out of 5). However, existing well data suggest a flow direction away from MRGCD jurisdiction. Relatively inexpensive groundwater-level measurements can be undertaken to confirm this unfavorable flow direction; if confirmed, then this site can be ruled out (along with Tijeras Arroyo). Although it has the best subsurface dataset, the Tijeras Arroyo site probably is the least suitable for ASR due to the presence of relatively nearby contamination sites and a groundwater flow direction away from MRGCD jurisdiction.

The Borrego Arroyo site ranked highest in our qualitative scoring for potential ASR, but it had the fewest site-specific data. For the remaining four sites plus Borrego Arroyo, more data acquisition is necessary for further suitability analyses. These data could include water-level measurements, borings to collect subsurface samples (of Holocene alluvium and Santa Fe Group), groundwater-level measurements, and electrical and magnetotelluric surveys tied to these borings. Qualitative assessment of geologic data suggests the northern three sites (Galisteo Arroyo, Borrego Arroyo, and Tonque Arroyo) should be prioritized for conducting further data acquisition.

In addition to collecting site-specific data, refining the MRGABI code should be considered. Adding modules that consider groundwater flow direction and soil percentages of sand and clay to the ranking could be helpful. These modules would have to be developed after more site-specific data have been collected.

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APPENDIX 1: MRGABI PYTHON CODE

MRGABI Python Code is available for download at
https://geoinfo.nmt.edu/publications/openfile/details.cfml?Volume=631 and **https://github.com/NMBGMR**

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