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Biogeochemistry Of The Middle Rio Grande Bosque: Links Among Surface Water, Groundwater, And Sediments

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BIOGEOCHEMISTRY OF THE MIDDLE RIO GRANDE BOSQUE--LINKS AMONG SURFACE WATER, GROUNDWATER, AND SEDIMENTS

BY

SUSAN E. BLOCK

B.S. GEOLOGY, THE UNIVERSITY OF ALABAMA, 1998

THESIS

Submitted in Partial Fulfillment of the
Requirements for the Degree of

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Albuquerque, New Mexico

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Biogeochemistry of the Shallow Alluvial Aquifer of the Middle Rio Grande Bosque, NM—Links Among Surface Water, Groundwater, and Sediments

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B.S., Geology, University of Alabama, 1998

M.S., Earth and Planetary Sciences, University of New Mexico, 2002

ABSTRACT

The potential for water contamination is great in areas where land use is both urban and agricultural. Such land uses can load the surface water and groundwater with nutrients and toxic trace metals. Water pollution can be further increased when natural watersheds have been altered by human activities. The surface and groundwaters of the Middle Rio Grande, NM, USA are part of one such ecosystem.

Because redox processes are important controls on nutrient cycling and contaminant transport, it is vital to understand the redox zonation of an aquifer. This research has been conducted to address such biogeochemical zonation in the shallow alluvial aquifer of the Middle Rio Grande bosque—a threatened riparian forest. To characterize the groundwater chemistry of this aquifer, groundwater, Rio Grande water, and aquifer sediment samples were collected at two sites—flood capable Belen and non-flooding Albuquerque South Valley.

Comparisons of groundwater and river water samples show that the groundwater is better connected to its surface water source at 13 m depth. Wells at 3 and 5 m have reduced dissolved oxygen conditions, allowing for denitrification, metal reduction, and sulfate reduction to occur. The use of dialysis multi-level samplers has documented the occurrence of these processes in the upper 2.5 m of the aquifer. Additionally, concentrations of redox sensitive anions (nitrate and sulfate) and the conservative tracer chloride are increased due to hydrochemical processes. Groundwater uptake by bosque vegetation at the zone of greatest root density concentrates these solutes in the groundwater.

Floodwater is depleted in oxygen and nitrogen compounds, but enriched in all other chemical parameters. The mobilities of the redox-sensitive trace metals Mn and Fe are enhanced by the dissolution of solid phase metal-oxides during flooding. This dissolution also releases phosphate.

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Introduction

In the arid and semi-arid U.S. southwest, "water " is a fighting word. Whether the fight is over the use of water for an endangered species, irrigation, or a city, allocation of water resources is contentious.

Albuquerque, NM currently holds the distinction as the only large city in the U.S. solely to use groundwater as its water supply. Figure 1a (Kernoudle, 1995) illustrates the simulated depletion of water resulting from City of Albuquerque withdrawals from 1900 to 1995. According to this analysis, 121,623,100 m^3 per year of aquifer depletion and 97,199,800 m^3 per year of streamflow depletion are expected by the year 2020 (Figure 1b). With slower growth rates and 30% water conservation, this depletion is decreased (Figure 1c). By 2005, the city plans to use both groundwater and surface water of the Rio Grande for its water supply. Although not the source of most city water, the shallow alluvial aquifer of the Rio Grande is influenced by human decisions controlling water. In the Middle Rio Grande (the reach of river between Otowi gage and Elephant Butte Dam), these controls include the restriction of the river by levees and dams, how much water is released from dams, and the quality of water added to the river (through runoff and wastewater input).

The groundwater below the bosque (the riparian forest paralleling the Rio Grande) and the surface waters of the Rio Grande intermingle in the dynamic groundwater interface, termed the hyporheic zone (Figure 2). One of the first to acknowledge the importance of this zone was Hynes (1983). Later, Triska et al.

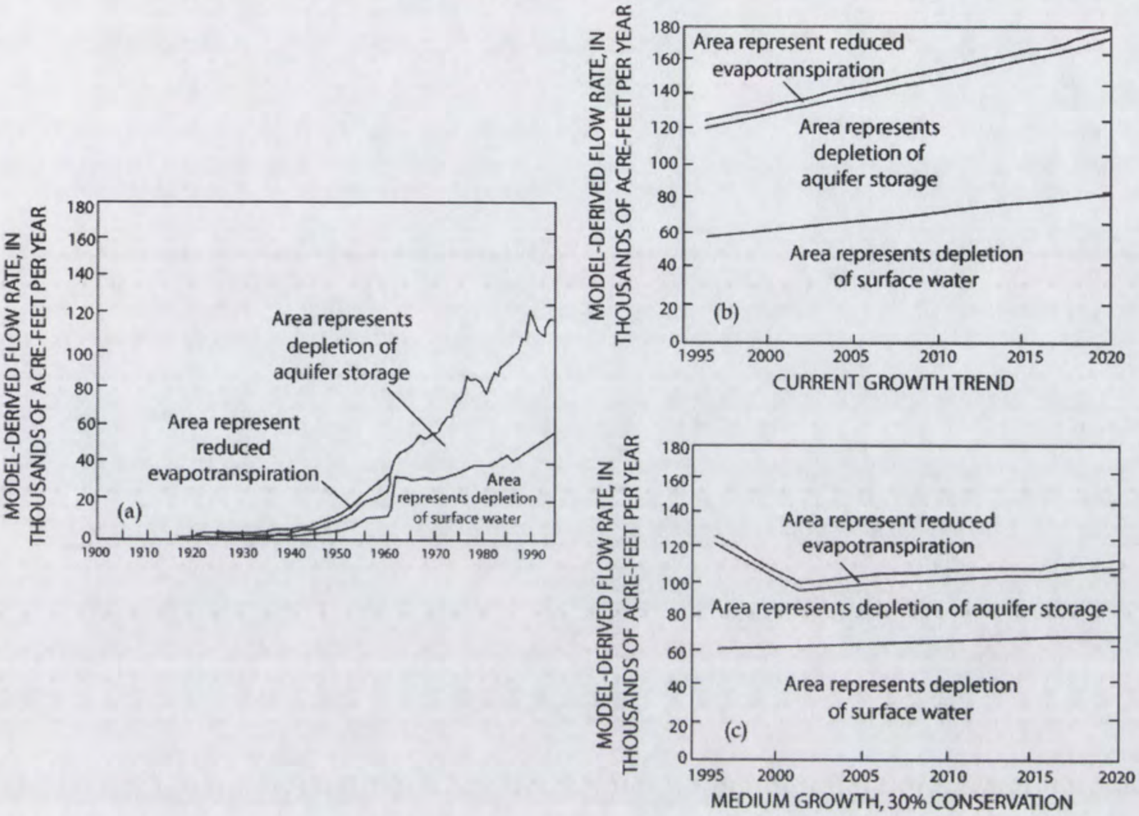


Figure 1: (a) simulated depletion of Albuquerque aquifer and surface water 1900-1995, (b) projected water depletions assuming current growth trend, and (c) projected depletions assuming medium growth and 30% water conservation (after Kernoudle, 1995).

(1989) illustrated the significance of this zone on nutrient mobility. At this interface, water can move laterally and vertically through the floodplain and can chemically vary both temporally and spatially depending on factors such as the porosity of the aquifer and the rate of recharge or discharge to or from the aquifer. Such convergence of waters in these dynamic corridors allows for exchange of materials. This chemical exchange results in an explosion of biological activity and mineralogical reactions. Consequently, hyporheic zones

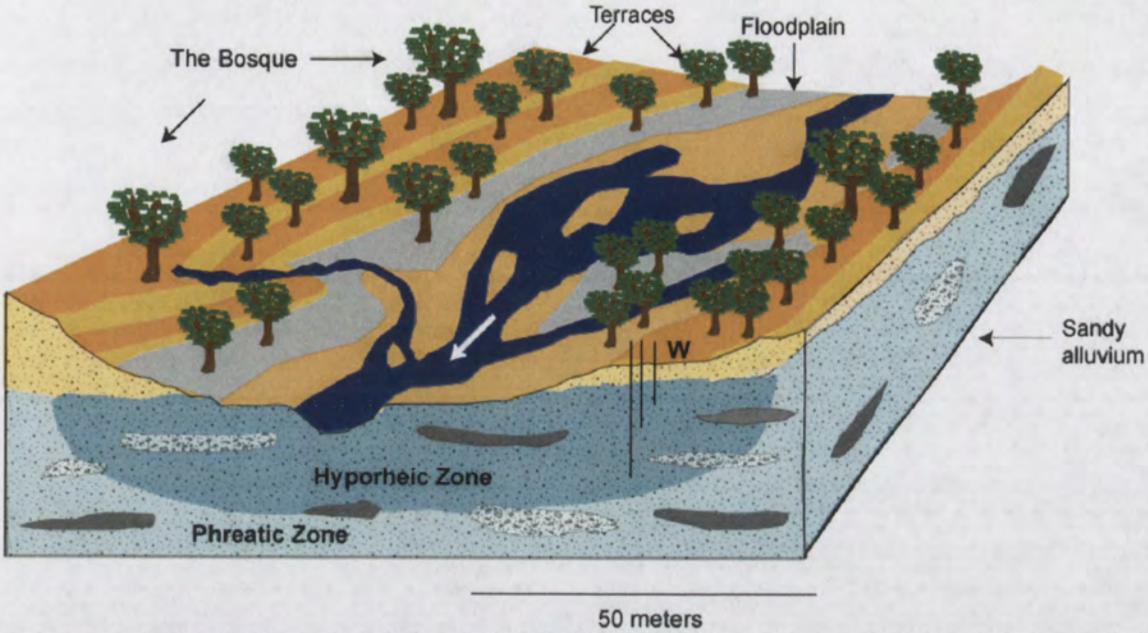


Figure 2: Schematic view of the Middle Rio Grande bosque study area. "W" indicates approximate location of the groundwater well field (modified from Stanford, 1998).

are often rich in both microbial production and biodiversity. Both biologic and geologic processes in the area load the groundwater with solutes that can influence the productivity of riparian ecosystem vegetation. In fact the interaction of waters in this zone may control not only biological production but also the organization and biodiversity in the riparian ecosystem. Concurrently, riparian organisms may influence the movement of materials to groundwater, by processes such as nitrogen fixation, litter production, the release of organic compounds, and decomposition (Stanford and Ward, 1993). La Force et al. (1998) showed that microbes enhance trace metal contaminant release in nutrient enriched waters. Additionally, natural attenuation of contaminants (by dispersion, sorption, dilution, or biodegradation) affects the biogeochemistry of these waters. For example, Barker et al. (1987) showed that benzene, toluene, and xylene concentrations decreased in an unconfined, sandy aquifer due to microbial breakdown and that this biodegradation is greater when dissolved oxygen is higher.

Currently, the Middle Rio Grande bosque is the focus of interdisciplinary research. Both cottonwood dominated and salt cedar dominated flooding and non-flooding sites along the river are being studied by ecologists, hydrologists, geomorphologists, civil engineers, and geochemists. These studies include evapotranspiration studies, biomass, soils and groundwater characterizations. Because groundwater is thought to be the primary water source for the bosque vegetation, chemical characterization of this water is critical for a complete understanding of its effects on the bosque.

This thesis presents a year of data from groundwater monitoring in the bosque and includes water table elevation and characterization of the major element and redox chemistry of the groundwater at two cottonwood bosque sites, Belen and Albuquerque South Valley (ASV). The goals of this work are to understand the redox processes of this shallow alluvial aquifer by:

- evaluating the geochemical effects of evapotranspiration on redox sensitive solutes in the upper water table of this shallow aquifer, and
- evaluating the effects of surface waters (including flooding) on redox-sensitive species and on nutrient availability and cycling.

Background

The bosque of the Middle Rio Grande is a riparian forest consisting historically of cottonwoods (*Populus deltoides*) and willows (*Salix gooddingii*). These forests are established by the flood pulse of the river, a predictable advancement and retraction of stream water onto the floodplain, which occurs from May to June due to snowmelt and in July and August due to monsoonal storms (Molles et al., 1995). This pulse helps establish the riparian ecosystem. Floodwaters mobilize nutrients stored in the floodplain and bring both dissolved and particulate nutrients from the stream to the riparian forest. This increased flux of nutrients in turn increases the productivity of the ecosystem. During drawdown of the floodwaters, stabilization of the ecosystem occurs through drying of stream banks and by the germination of terrestrial plants (Junk et al., 1989; Bayley, 1995).

In the Middle Rio Grande, the flood pulse has largely been eliminated by modern flow regulations controlling the river. Although the peak discharge naturally varies from year to year, there is a decrease in the natural flood pulse. Without this pulse, new stands of bosque have not been created. Cottonwoods, for example, are dependent on floods for reproduction. Floods disperse the cottonwood seeds to disturbed areas and enable these trees to establish themselves throughout the floodplain along scoured sandbars, as floodwaters subside (Mahoney and Rood, 1998; Molles et al., 1998). Records indicate that the last major floods of the Middle Rio Grande that have established cottonwoods throughout the reach occurred in the springs of 1941 and 1942. As a result of this long inter-flood interval, major changes in the bosque have occurred. Cottonwoods are in decline and non-native salt cedar (*Tamarix chinensis*) and Russian olive (*Elaeaguus angustifolia*) are invading. Other ecosystem effects attributed to the absence of the flood pulse include decreases in foliage density, leaf litter fall, and N and P content of leaves. Additionally, the decay rate of organic matter on the forest floor increases with flooding. Without floods, organic matter decays slowly and vital nutrients remain immobilized (Molles et al., 1998).

Another important process in this riparian ecosystem is evapotranspiration. Evapotranspiration (ET) is the term used to account for water lost from a system through both evaporation and transpiration (the process by which water is lost from plant leaves). ET affects the groundwater ecosystem, as transpiring plants draw down the water table while photosynthesizing. During nighttime, respiring plants do not uptake water allowing the water table to rise, as the river recharges the aquifer (described below). ET accounts for approximately 28% (9% evaporation, 19% transpiration) of water lost above San Acacia diversion in the Middle Rio Grande (ACMRGWA, 1999). This daily fluctuation also influences the geochemistry of the aquifer as the oxic-anoxic interface rises and falls. Not only is the distribution of redox-sensitive elements affected, but dissolved salts also are concentrated. McCarthy and Ellery (1994) have shown that evapotranspiration is a control on groundwater chemistry and consequently vegetation zonation in the Okavango Delta of Botswana.

The behavior of redox-sensitive species is particularly crucial to understanding groundwater biogeochemistry, as both the fate of contaminants and the cycling of nutrients are influenced by microbial redox processes. Processes by which microorganisms obtain energy are the transfer of electrons from electron donors to electron acceptors. Reduced inorganic compounds or organic carbon are the donors. Oxidized compounds or elements (such as nitrate, Fe (III), Mn (IV), sulfate, or carbon dioxide) are electron acceptors (Chapelle, 2001). When oxygen is removed from the system, microbes turn to other electron acceptors for oxidants. A gradient is set up typically in order of decreasing redox potential—O_2/H_2O, NO_3^-/N_2, Mn (IV)/Mn (II), Fe (III)/Fe (II), NO_3^-/NH_4^+, NO_2^-/NH_4^+, SO_4^{2-}/H_2S, CO_2/CH_4, H_2O/H_2 (Drever, 1997). Studies have shown that the reduction of Fe (III) and Mn (IV) can release both the nutrient phosphate (Mortimer, 1941) and toxic trace metals (La Force et al., 1998). Additionally, microorganisms may utilize minerals or create them through metabolic processes. However, the role of microorganisms in formation and/or dissolution of minerals is not well understood (Nealson and Stahl, 1997).

Study Areas

The study sites are both cottonwood dominated bosques located within approximately 100 m of the Rio Grande at an elevation of approximately 1463 m (Figures 3, 4). The site termed "Belen" is located in Belen, NM 75 km south

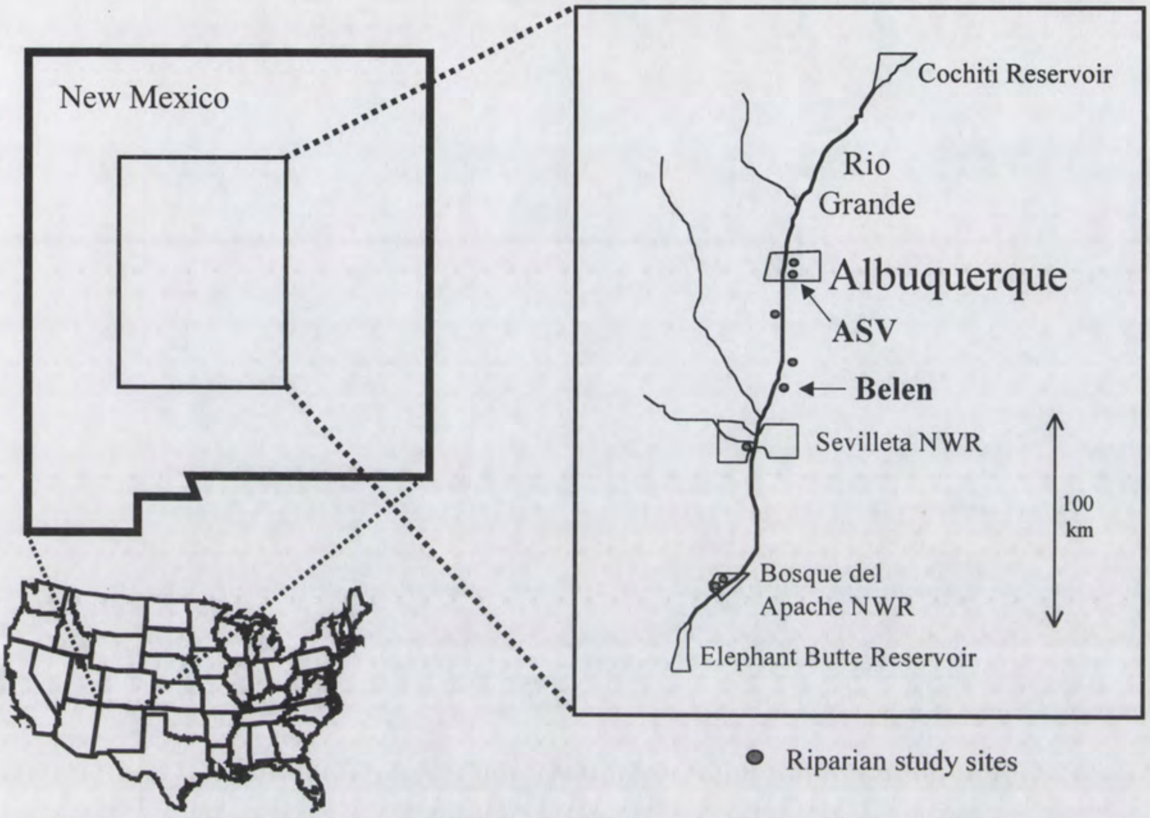


Figure 3: Location map of study sites Belen and ASV (Albuquerque South Valley) in the Middle Rio Grande watershed in New Mexico.

of Albuquerque, and the second site is located in the Albuquerque South Valley (ASV). The Belen site consists of vegetation stands that experience short inter-flood intervals, while ASV has long inter-flood intervals (non-flooding). Land use around Belen is predominately agricultural. ASV is surrounded by small farms, just south of the City of Albuquerque.

In addition to groundwater monitoring instrumentation (described below), these sites are equipped with 25 m towers with 3-D eddy covariance systems and meteorological instruments for evapotranspiration measurements and wells with automatic pressure transducers to measure piezometric data.

(a)

(b)

Figure 4: Aerial photos of (a) Belen and (b) ASV taken by D. Groeneveld.

Geologic Setting

Belen and ASV are located in the Albuquerque Basin, one of a series of basins of the Rio Grande Rift (Figure 5), which extends from central Colorado south through New Mexico (Connell et al., 1998). The basin is approximately 164 km long and 40-64 km wide (Kelley, 1977). River alluvium is a late Pleistocene to Holocene age unit, about 20 meters thick, corresponding to an upper shallow aquifer in the Rio Grande and Rio Puerco valleys (Hawley and Haase, 1992).

Terrace deposits are the result of incision and backfilling of the Rio Grande and Rio Puerco valleys in the mid-to-late Quaternary. The late Quaternary inner-valley fill, in which the study is being conducted, is a slender fluvial deposit about 20 meters thick deposited during the river's latest aggradational period (Hawley and Haase, 1992). Aquifer sediments consist predominately of coarse sand, with scattered pebbles and cobbles throughout, and minor clay lenses.

Hydrologic Setting

This shallow bosque aquifer is highly connected to the surface water of the Rio Grande. Examination of the 1999 river and water table hydrographs illustrates this connectivity (Figure 6). Changes in river discharge are reflected in the groundwater elevations within one to two days at both sites.

Examination of the 2000 and 2001 groundwater hydrographs of the sites (Figure 7) illustrates the hydrologic setting of the bosque. As seen in figure 6, the

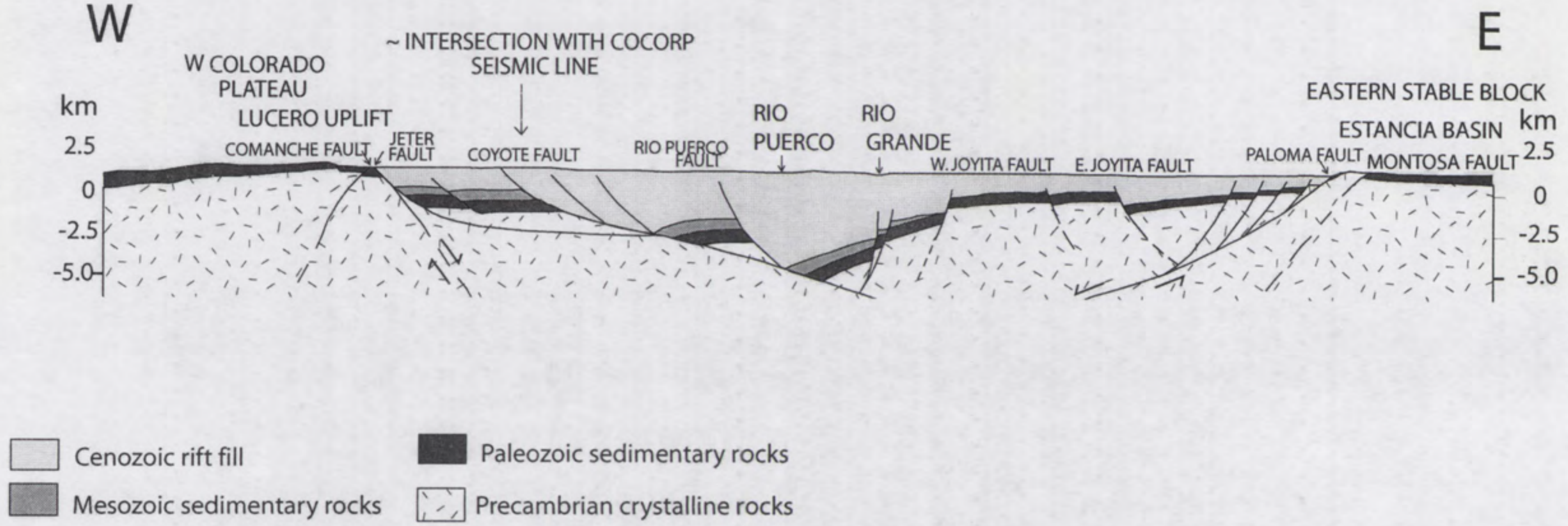


Figure 5: Cross-sectional view of the Albuquerque Basin, 18 km south of Albuquerque. The study areas are located in the upper 20 meters of the Cenozoic rift fill of the Rio Grande (modified from Russell and Snelson, 1991).

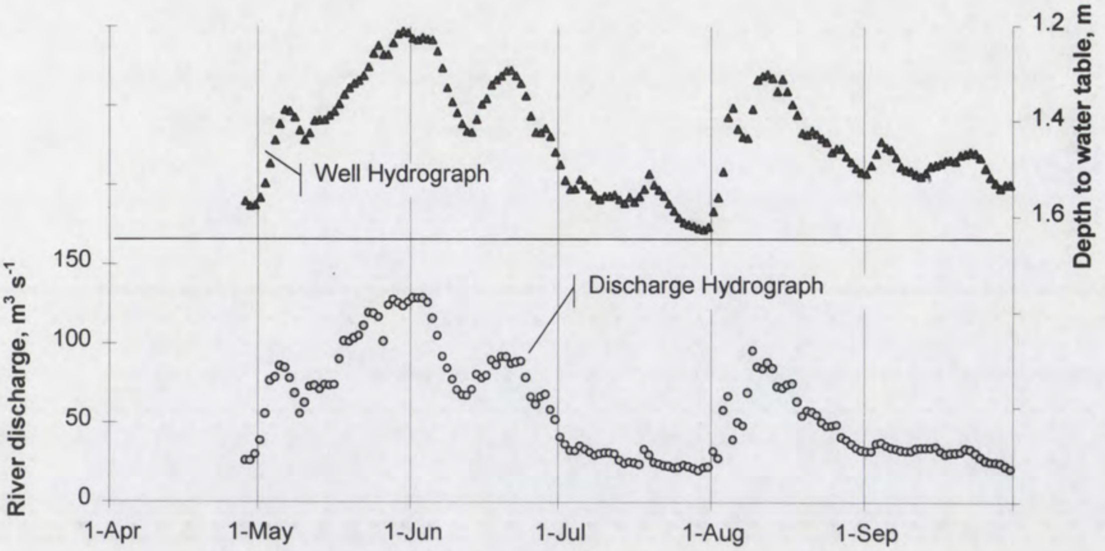


Figure 6: The Rio Grande and its alluvial water table at the Albuquerque South Valley, water year 1999.

bosque aquifer is intimately connected to the river, and consequently, to climatic conditions within the watershed. The year 2000 had little precipitation from winter to summer (reflected in the lack of large fluctuations in the hydrograph), while October was characterized by heavy rainfall (shown in the increase in the water table (Figure 7a). The year 2001 was characterized with higher snow and rainfall, shown in the stronger snowmelt pulse and late summer monsoon spikes on the 2001 groundwater hydrographs (Figure 7b). Baseflow conditions typically prevail from late summer to mid-spring, followed by a rise in the water table due to snowmelt (Figure 7b). In mid to late summer, monsoonal storms also contribute to the water table. Additionally, an experimental flood pulse from a dam release in May 2001 is recorded in the hydrographs (Figure 7b).

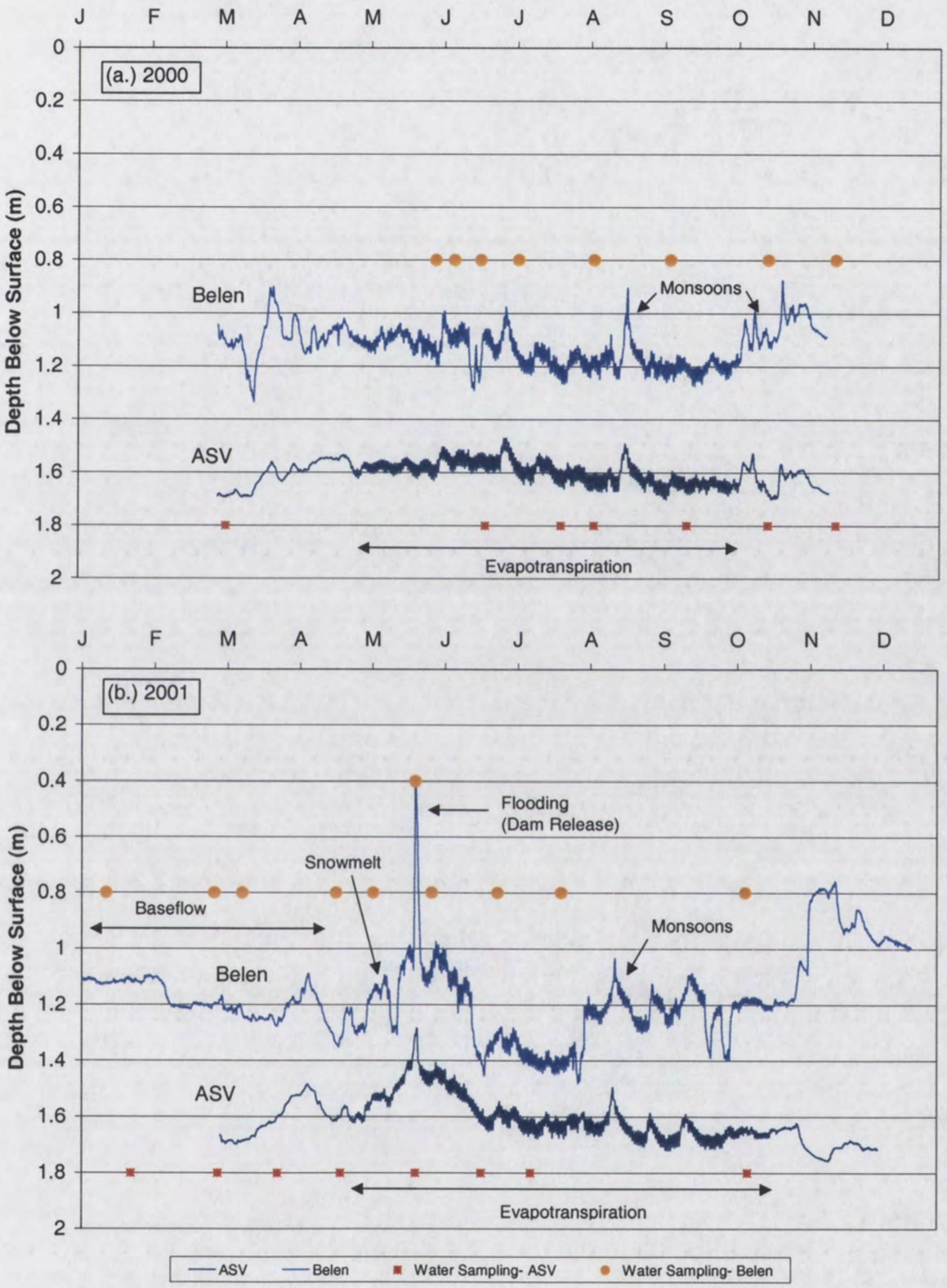


Figure 7: Groundwater hydrographs of the study sites for 2000 (a.) and 2001 (b.), with hydrological influences. Water sampling dates are highlighted by circles (Belen) and squares (ASV). Data courtesy of the Department of Biology, UNM.

Overprinting the well hydrographs from late April to October is the diel signal of evapotranspiration (Figure 7a, b).

Site Instrumentation and Methods

For this groundwater investigation, the study sites were equipped with four wells — one 3 m conventionally screened, two 5 m (one conventional and one fully screened), and one 13 m (conventional) (Figure 8). See Table 1 for well specifications. Groundwater sampling was performed for one year (July 2000 to July 2001) at Belen and ASV. Rio Grande water sampling was performed in conjunction with groundwater sampling from January to July 2001.

All wells deeper than 3 m were drilled by a SIMCO 2800 hydraulic rotary drill rig. Sediment samples were taken from each well core for iron and manganese extraction and textural and mineralogical analyses. For the 5 m fully screened and partially screened wells, sediment samples are taken every 15 cm (~ 40 samples per well). The 13 m wells are sampled every 76 cm (16 samples). Additionally, a core was taken at ASV. Sediment samples taken during well installation underwent particle size analysis using methods modified from Day (1965) and Jackson (1969). Subsets of these sediments were epoxy impregnated and thin-sectioned for mineral identification. Finally, Fe-oxyhydroxides and Mn-oxides were extracted from sediments using the citrate-dithionite-bicarbonate method (Mehra and Jackson, 1960; McKeague and Day, 1966).

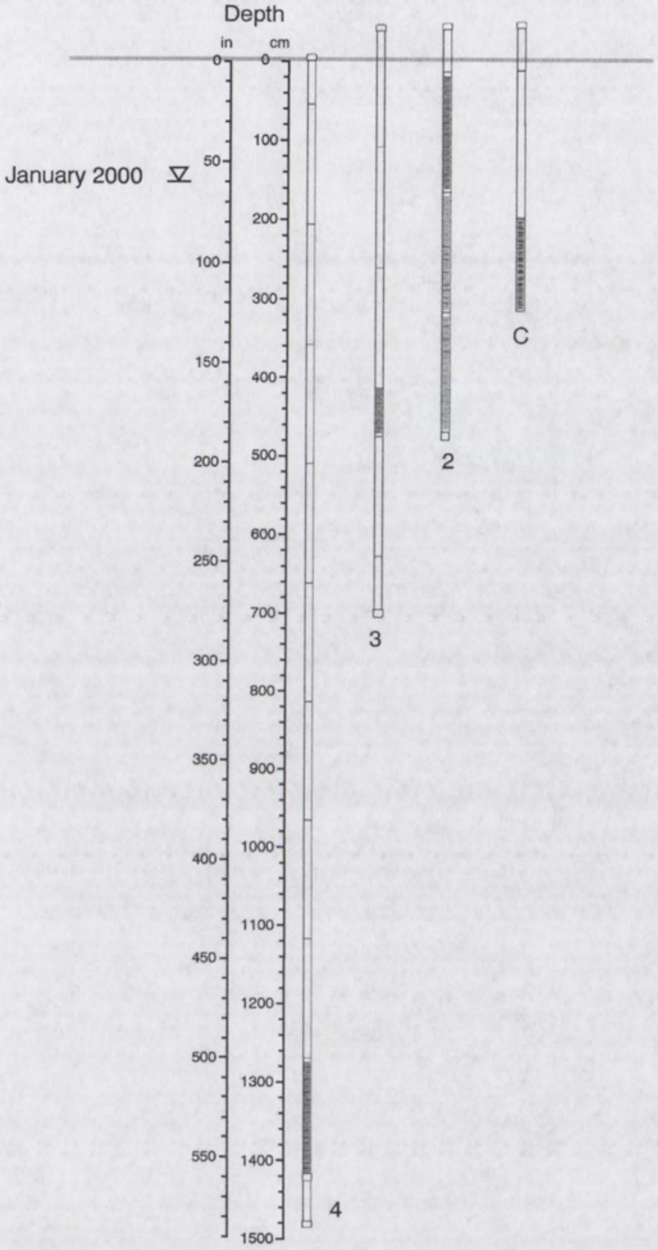


Figure 8: Illustration of groundwater wells at ASV. Wells are termed C (center) and 2-4 at both sites. Belen has comparable wells but no stilling well for wells "3" and "4."

Table 1: Groundwater well specifications. C denotes conventional; FS denotes fully screened.

Well Name	Type	PVC Diameter (cm)	Slot Diameter (cm)	Depth (m)	Screened Interval (cm)	Stilling Well
ASV C	C	5	0.05	3	212-300	No
ASV 2	FS	5	0.05 /0.03	5	12-469	No
ASV 3	C	5	0.05	5	421-482	Yes, 230 cm
ASV 4	C	5	0.05	13	1270-1410	Yes, 69 cm
Belen C	C	5	0.05	3	208-300	No
Belen 2	FS	5	0.05	5	5-462	No
Belen 3	C	5	0.05	5	348-500	No
Belen 4	C	5	0.05	13	1219-1371	No

Sampling Techniques

Two sampling techniques were employed at each site—conventional and dialysis multi-level sampler (DMLS). The conventional method of sampling involves first bailing the well, then pumping water into a sample bottle. In the DMLS method (Ronen et al., 1986; Margaritz et el., 1989), a sampler consists of piping with dialysis cells, spaced every 5 cm along the length of the pipe, filled with distilled water and separated by rubber seals to prevent mixing (Figure 9). Each rubber seal separates intervals of either two or three dialysis cells on the rod. These cells hold approximately 15 ml each. The DMLS is then inserted into the screened interval of a well and allowed to equilibrate with the groundwater. Equilibration times were determined using a LiBr tracer. After equilibration, the DMLS was removed and samples were transferred into bottles for lab analysis. Alkalinity of DMLS samples was determined by modifying the Gran Titration technique (Wetzel and Likens, 1991) using 5 ml of sample. Three milliliters of sample were used for field pH determination. The remaining samples were

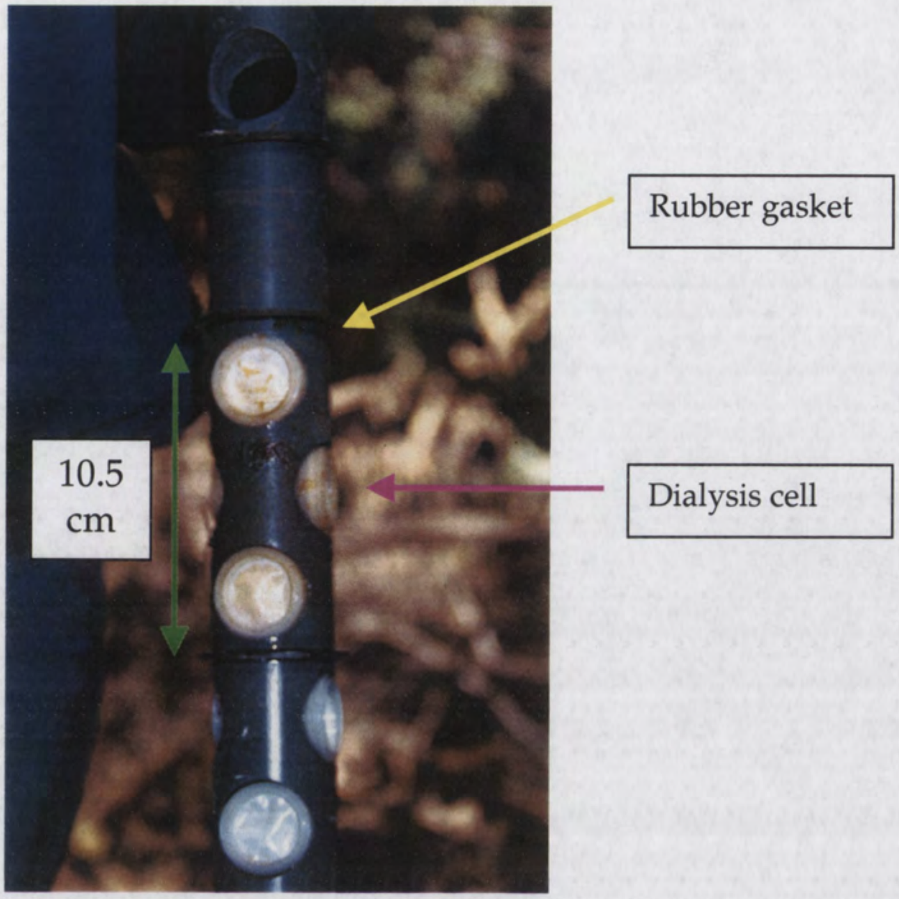


Figure 9: Dialysis Multi-Level Sampler used at ASV.

divided for anion and cation analysis. Cations samples were preserved to 2 % $^{v}/_{v}$ with nitric acid.

Field Methods

In the field, depth to water table was measured, followed by bailing of the wells. Next, dissolved oxygen (DO) was measured with a down-hole probe and the YSI-55 DO meter. Vertical profiles of DO were collected by gradually lowering the probe down-hole. Samples were then collected using a peristaltic pump (Geopump). pH of unfiltered samples was measured using an Orion pH electrode and meter in the field. Unfiltered samples were collected for alkalinity analysis in the lab, and 0.45 μm filtered samples were collected in polyethylene bottles for cation and anion lab analyses. Cation samples were acidified to 2 % $^{v}/_{v}$ with nitric acid and refrigerated until analysis (APHA, 1992).

Analytical Methods

In the lab, alkalinity was quantified by the Gran Titration Method (Wetzel and Likens, 1991) immediately after collection. Bicarbonate was determined using the measured pH and total alkalinity of the waters. Major cations (K^+, Na^+, Ca^{2+}, Mg^{2+}) were diluted 1:10 with CsCl solution and deionized water to prevent interference from the alkali elements. These cations along with undiluted total Fe and total Mn concentrations were measured on a Perkin Elmer 303 Atomic Absorption Spectrophotometer. Dissolved silica was measured by the molybdate blue method (Brown et al., 1970). Anion samples were analyzed on a Dionex- 500 ion chromatograph for F^-, Cl^-, Br^-, NO_3^-, SO_4^{2-}, and PO_4^{3-} concentrations using an AS-14 column and an isocratic method with bicarbonate eluent. Analytical duplicates were within ±5% for cations and anions. Charge balance percent error is included with chemical data in Appendix A.

Stable isotopic measurements of $\delta^{18}O$ and δD values were measured seasonally on Rio Grande and groundwater samples from Belen and ASV. Samples for $\delta^{18}O$ analysis were first equilibrated using the CO_2 equilibration and extraction technique modified from Epstein and Mayeda (1953). Samples for δD

analysis were directly injected into the mass spectrometer using a method described by Sharp et al. (2001). $\delta^{18}O$ and δD values were measured on the Finnigan ThermoQuest Delta plus XL mass spectrometer.

Results

Sediment Characterization and Geochemistry

Particle size analysis (Day, 1965; Jackson 1969) of the bosque aquifer sediment yielded sand dominated particles (~95%) at both sites, although some variability does exist with depth (Figure 10). See Appendix B for supplemental particle size data. Examination of 20 laboratory lithified (epoxy impregnated) sediment samples of the shallow aquifer shows that the sediments are dominated by quartz (approximately 60 to 70 %) with lesser amounts of igneous lithics (~ 20%). Point counting of these thin sections classifies these "rocks" as sublitharenites to litharenites (Figure 11), according to the McBride classification scheme (1963). Also observed under the optical microscope were grains coated in Fe-oxyhydroxides (Figure 12). However, there is no observable trend in the number of Fe-oxide coated grains observed with depth or between sites.

To better document the amount of oxide formation both between the sites and with depth, the extraction of authigenic iron and manganese oxides was performed on sediment samples (collected January 2000) from Belen and the Albuquerque South Valley. This dithionite-citrate extraction method removes all non-silicate bound iron and manganese (Mehra and Jackson, 1960; McKeague and Day, 1966). Dissolution and precipitation of these crystalline and

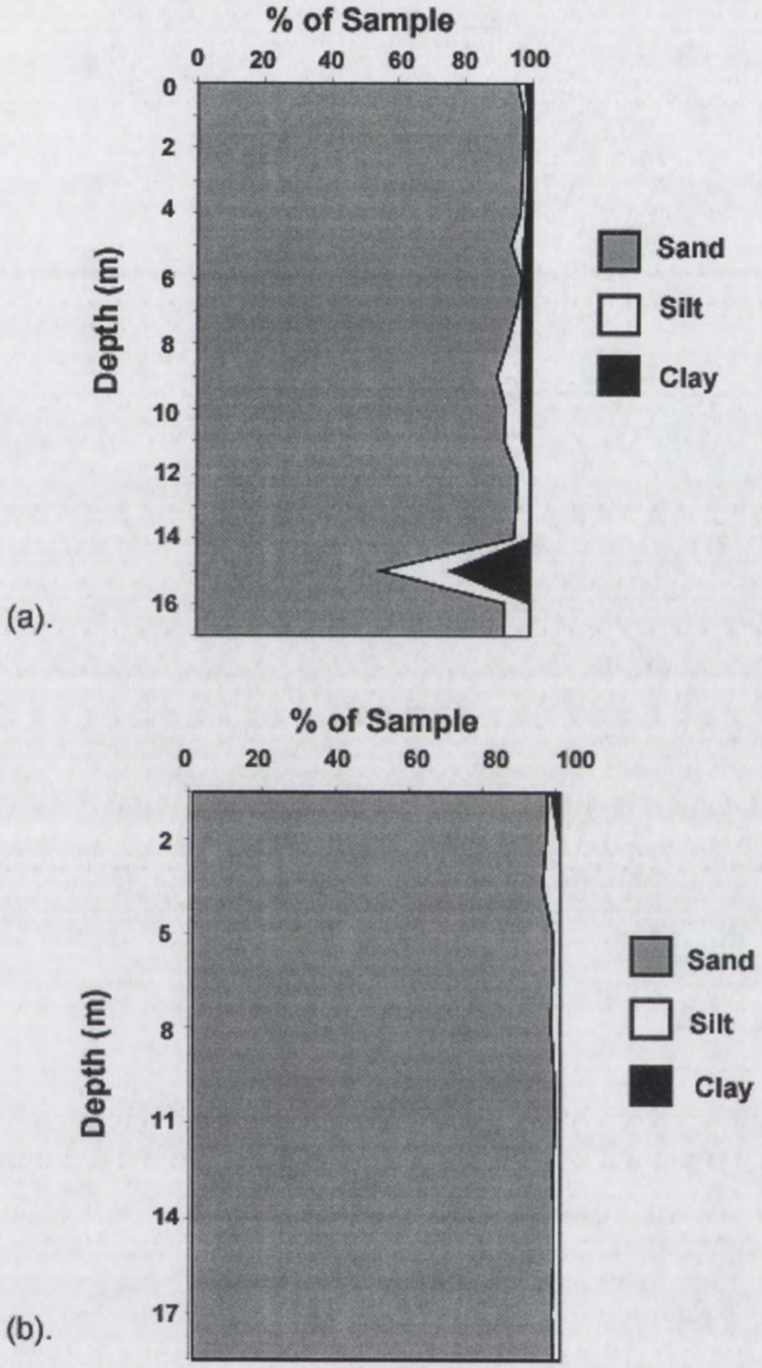


Figure 10: Particle size results (percent sand, silt, and clay) for (a) Belen and (b) the Albuquerque South Valley at 1 m resolution.

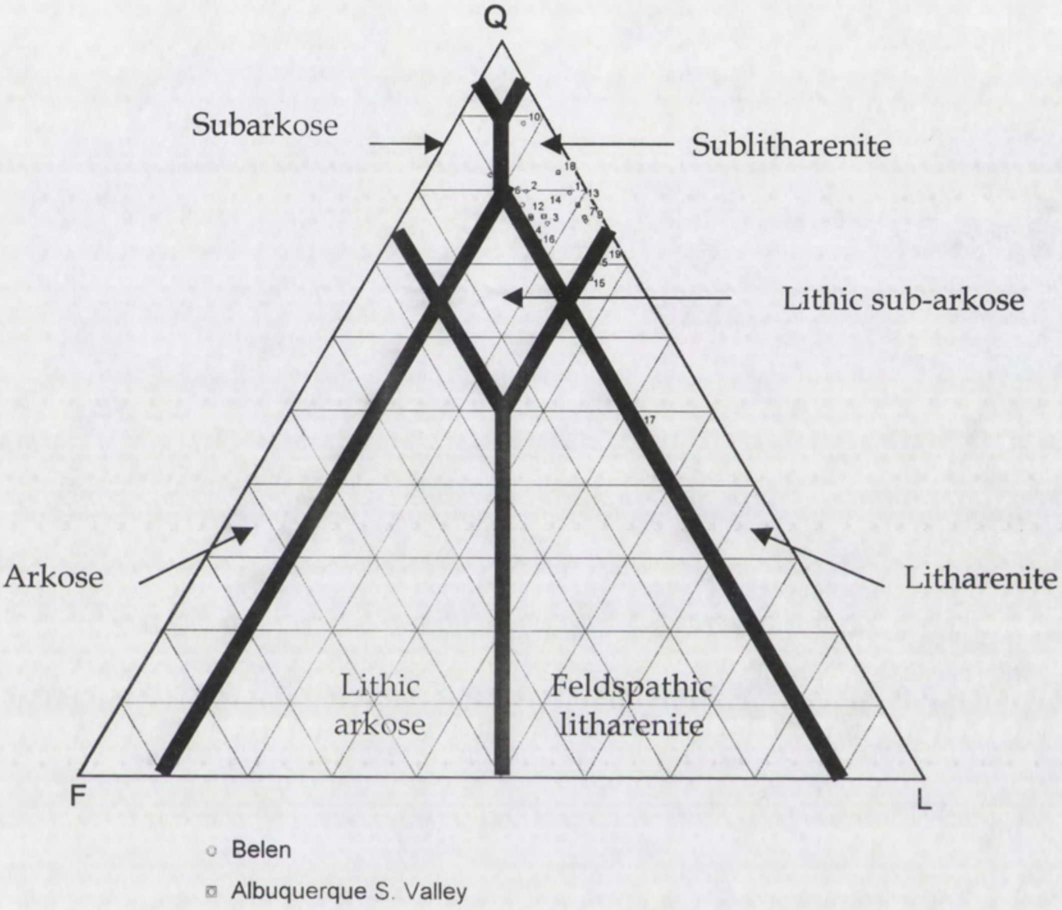


Figure 11: QFL classification of Belen and ASV sediments according to McBride (1963).

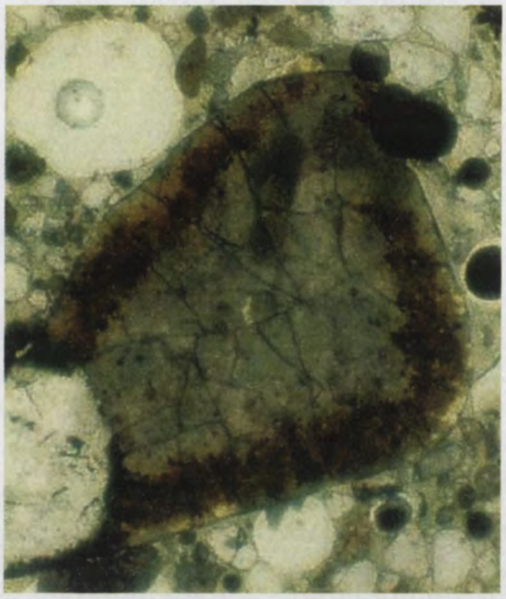


Figure 12: Fe-oxyhydroxide coating on a quartz grain from ASV.

amorphous oxides are biologically mediated, and hence, these extractions illustrate the relationship between iron-oxidizing bacterial processes and the shifting oxic-anoxic interface in the shallow alluvial aquifer.

Table 2 summarizes the iron and manganese extraction data for Belen and ASV sediments. Belen sediments range from 0.11 to 0.26 in weight percent Fe_2O_3, with the most extractable iron concentrated in the upper 130 cm below the ground surface. The weight percent MnO_2 ranges from 0.0048 to 0.0092, with the greatest concentrations occurring between 312 and 500 cm. At ASV, weight percent Fe_2O_3 ranges from 0.11 and 0.28, the most extractable iron available below 200 cm. Weight percent MnO_2 ranges from 0.0038 to 0.0095 in ASV sediments with more MnO_2 extracted below 400 cm.

River and Groundwater Geochemistry

All water chemical results are summarized in Appendix A.

Table 2: Weight percent iron and manganese extracted from Belen (a) and ASV (b) sediments using the dithionite-citrate extraction method (Mehra and Jackson, 1960; McKeague and Day, 1966).

Belen Sediment Trace Metal Extractions			**ASV Sediment Trace Metal Extractions**		
Avg depth (cm)	**Wt % Fe_2O_3**	**Wt % MnO_2**	**Avg depth (cm)**	**Wt % Fe_2O_3**	**Wt % MnO_2**
8	0.23	0.0063	8	0.13	0.0079
38	0.24	0.0048	17	0.14	0.0082
53	0.24	0.0063	33	0.14	0.0076
69	0.22	0.0060	50	0.19	0.0079
84	0.26	0.0062	62	0.16	0.0095
99	0.26	0.0059	74	0.15	0.0079
114	0.22	0.0059	91	0.18	0.0078
130	0.24	0.0082	107	0.16	0.0067
145	0.14	0.0062	124	0.20	0.0079
160	0.13	0.0073	140	0.11	0.0038
175	0.20	0.0063	157	0.23	0.0054
191	0.13	0.0060	173	0.19	0.0057
206	0.12	0.0060	190	0.25	0.0079
221	0.17	0.0048	206	0.28	0.0079
236	0.17	0.0063	225	0.17	0.0048
267	0.11	0.0063	244	0.26	0.0079
312	0.15	0.0085	294	0.25	0.0079
358	0.13	0.0073	344	0.21	0.0067
404	0.14	0.0079	393	0.19	0.0067
450	0.15	0.0079	410	0.15	0.0048
495	0.14	0.0092	443	0.21	0.0079
526	0.18	0.0048	497	0.27	0.0084
541	0.18	0.0082	530	0.21	0.0048
			563	0.26	0.0095
			613	0.25	0.0093
			648	0.20	0.0063
			683	0.22	0.0082
			714	0.20	0.0079
Total Wt % to 541 cm:	4.15	0.1526	**Total Wt % to 541 cm:**	4.43	0.1620

In order to understand the groundwater chemistry, Rio Grande samples were collected because river water recharges the alluvial aquifer at Belen and ASV. Rio Grande water is well-oxygenated, with dissolved oxygen (DO) values ranging from 5 to 9 mg/L at both sites. Total Fe and Mn are typically below detection limits, while nitrate ranges from 1 to 5 mg/L and sulfate ranges from 30 to 70 mg/L.

In the groundwater, DO values range from 0.2 mg/L in 3 and 5 m wells to 1-2 mg/L in 13 m wells. Nitrate concentrations vary from 0-6 mg/L, with the higher nitrate values characteristic of ASV. Total Fe is commonly below detection limits in the 13 m wells and up to 2.5 mg/L in the shallow well. Total Mn ranges from 0.3 to 2 mg/L. Sulfate ranges from 34 to 86 mg/L. Non-redox sensitive parameters are generally found in ranges consistent with river water (see Appendix A for details).

Dialysis Multi-Level Sampling

To more clearly understand the redox zonation in the aquifer, multi-level sampling rods were deployed twice at both sites in the spring of 2001. Belen-A corresponds to rod equilibration from April 19 to May 5. Belen-B equilibrated May 5 to May 30. ASV-A equilibrated May 23 to June 20, and ASV-B equilibrated June 20 to July 11. Flooding occurred May 23 at Belen. Redox chemical profiles of these samplings are presented in figures 13 through 16, along with chloride concentrations. The full suite of chemical analyses for each DMLS sampling is presented in Appendix A.

Dissolved oxygen (DO) concentrations decrease with depth in Belen-A (Figure 13a) from 0.79 to 0.29 mg/L, pushing the detection limits of the DO-probe. Total iron increases at the top of the profile and then begins to decline steadily to 2.1 m, followed by an abrupt decrease at 2.2 m. Total manganese concentrations increase from 0.9 to 1.4 mg/L with depth. Nitrate values were undetermined for these samples. Belen-A shows steady chloride concentrations (Figure 13b) while sulfate decreases slightly from 26.8 mg/L in the upper 20 cm of the profile and increases to 97.4 mg/L from 1.4 to 2.3 m.

After the May 23rd flooding (Belen-B, Figure 14a), Belen again exhibits a decrease in DO and an increase in total manganese with depth. Nitrate shows a decrease with depth, except at 1.4 m (where total Fe is low) where it returns to the initial high value (0.5 mg/L). Total iron decreases from 2.6 mg/L until mid-profile (1.4 m), then begins a steady increase to the previous high value. Sulfate and the conservative ion chloride exhibit a similar trend (Figure 14b), spiking at 1.7 m depth.

ASV-A (Figure 15a) is characterized by decreasing DO and nitrate with depth. Both total iron and manganese increase to concentrations of 0.6 and 0.3 mg/L respectively at 1.9 m depth, being constant for the remainder of the profile. Both sulfate and chloride increase around 1.8 m, then decrease slightly and show approximately constant concentrations for the remaining profile (Figure 15b). Like ASV-A, DO and nitrate decreases with depth in ASV-B (Figure 16a). Total manganese remains steady, while total iron increases to 0.7 mg/L at 2.1 m, then decreases. Both sulfate and chloride show near steady concentrations (Figure 16b).

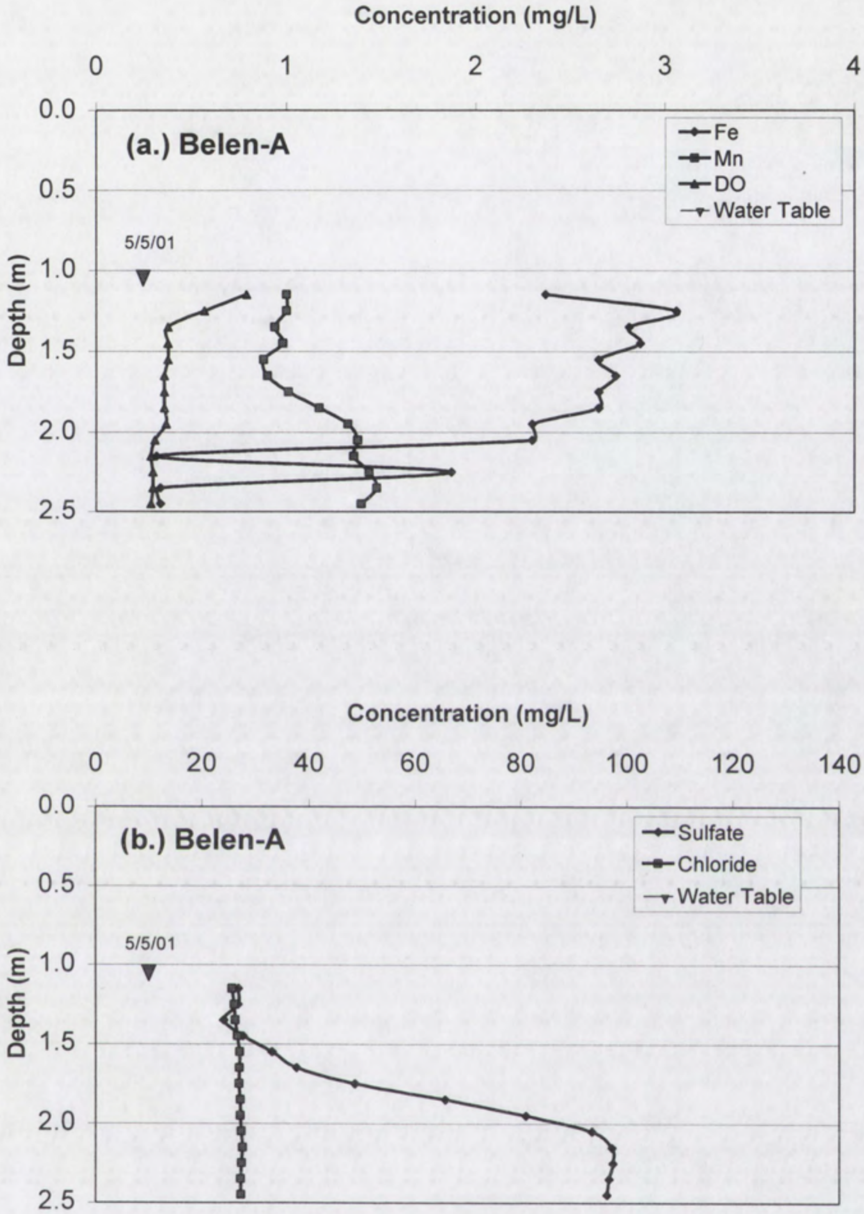
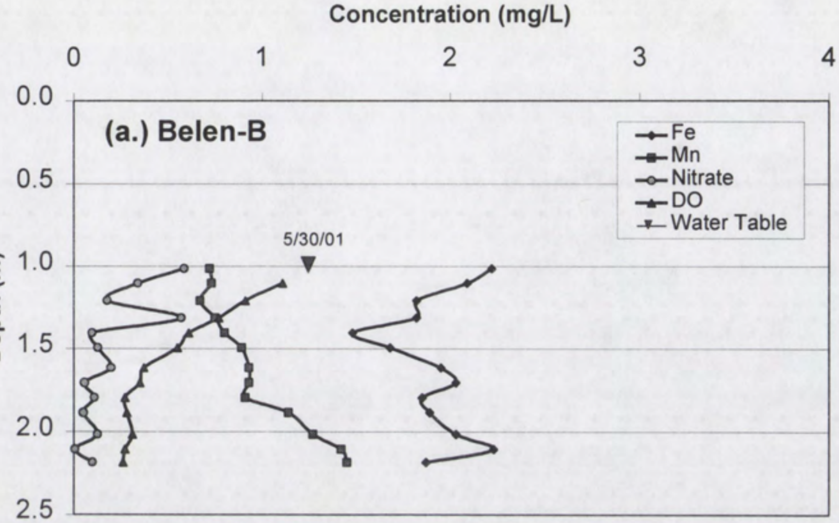


Figure 13 (a-b): DMLS profiles of redox parameters and chloride at Belen on May 5, 2001.



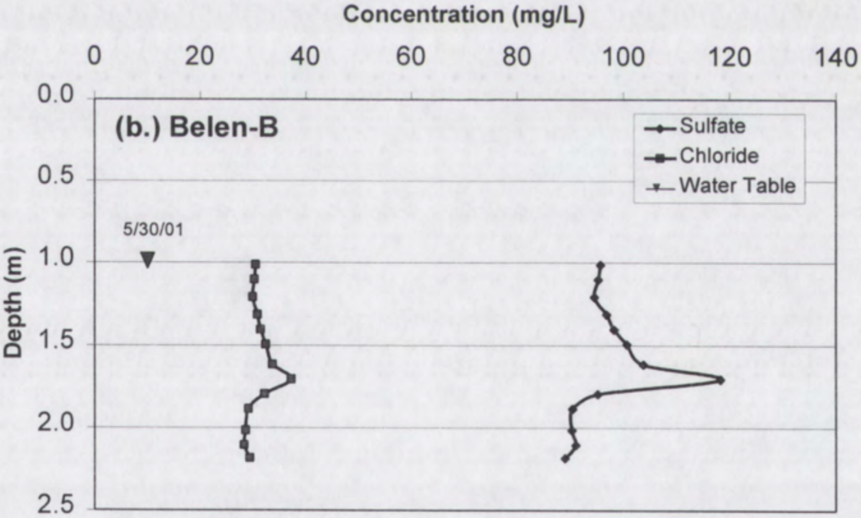


Figure 14 (a-b): DMLS profiles of redox parameters and chloride at Belen on May 30, 2001.

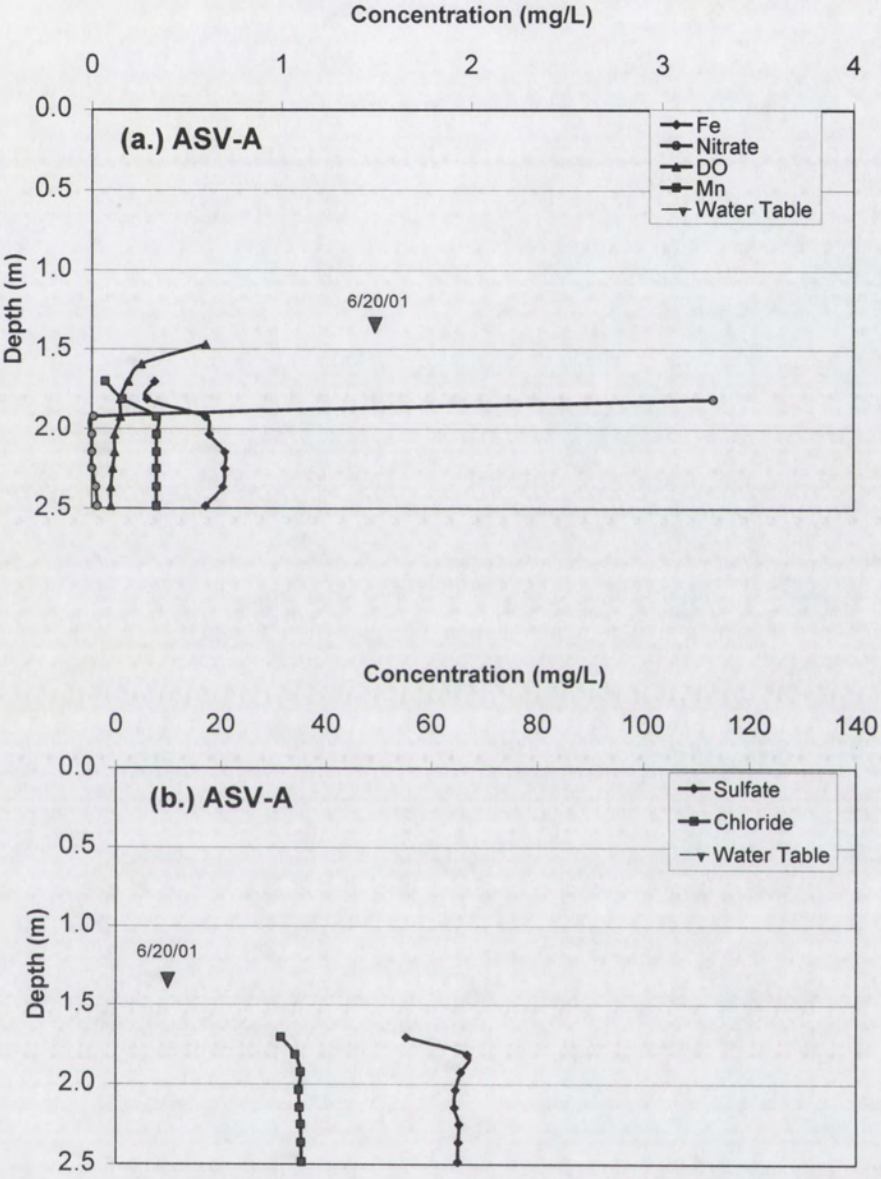


Figure 15 (a-b): DMLS profiles of redox parameters and chloride at Albuquerque South Valley on June 20, 2001.

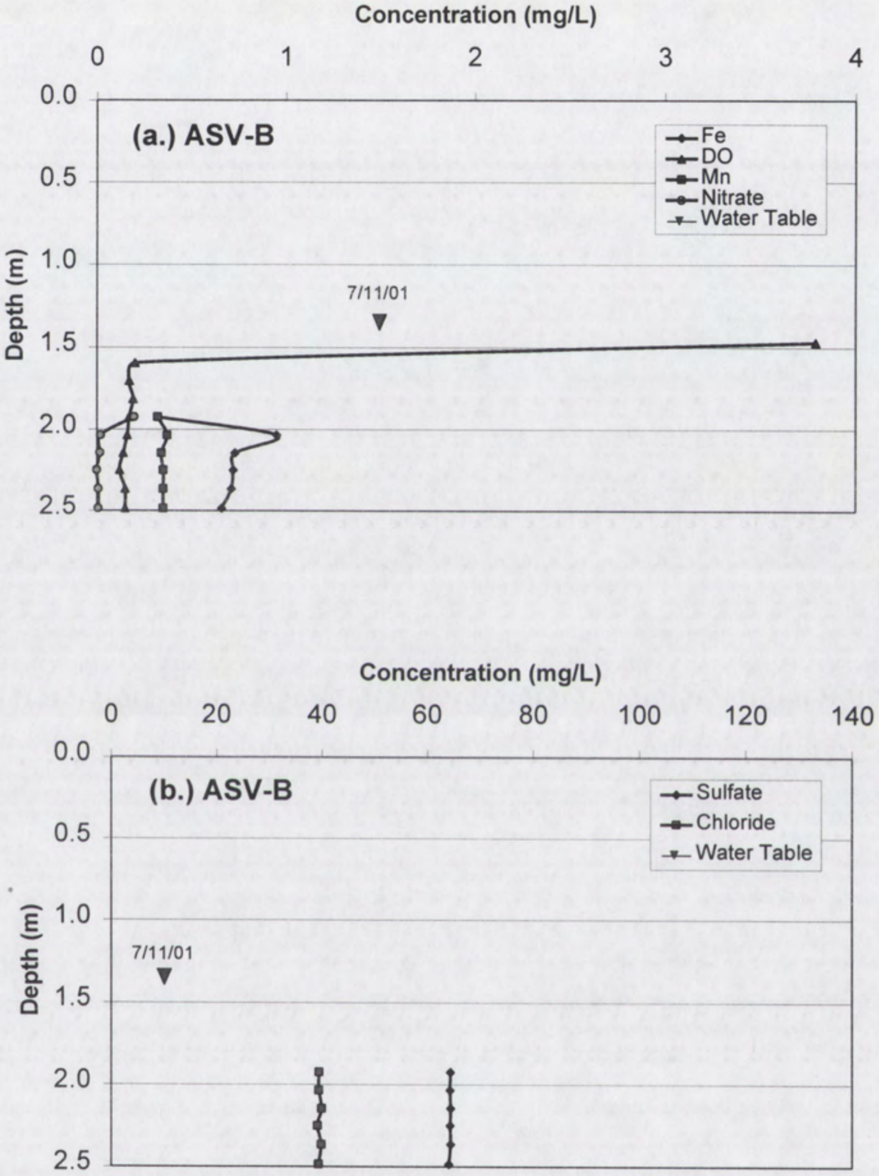


Figure 16 (a-b): DMLS profiles of redox parameters and chloride at Albuquerque South Valley on July 11, 2001.

Flooding

The Belen site was flooded May 23, 2001 by a controlled dam release. There was no flooding at ASV. Water samples were collected from the river and groundwater at both sites and floodwater at Belen. Chemical analyses show the floodwater is slightly enriched in most elements compared to its source water. See Table 3 for an overview of floodwater chemistry compared to the Rio Grande composition.

Table 3: Chemical composition (mg/L) of floodwater and Rio Grande water on May 23, 2001.

	Floodwater	Rio Grande Belen	Rio Grande ASV
Ca^{2+}	56	27	27
Mg^{2+}	9.5	7	5.7
K^+	11	4	4
Na^+	37	33	27
Fe (T)	0.53	0	0
Mn (T)	0.26	0	0
SiO_2	23.83	20.73	21.99
F^-	0.38	0.27	0.36
Cl^-	20.58	14.19	16.75
NO_2^-	0	0.17	0
Br^-	0.06	0.04	0.05
NO_3^-	0.03	1.20	1.03
PO_4^{3-}	2.08	0.53	0.11
SO_4^{2-}	73.20	33.13	29.33
HCO_3^-	164	111.1	103.1
CO_3^{2-}	0.07	0.28	0.08
pH	7.08	7.84	7.35
DO	0.6	5.6	6.15
Charge balance	5.92 %	7.60 %	4.74 %

Stable Isotopes

The results of seasonal δ^{18}O and δD stable isotope analyses of ground and surface waters are listed in Table 4, along with deuterium-excess values.

Table 4: δ^{18}O and δD values (per mil) versus SMOW for Belen and ASV samples.

Sample	d^{18}O	dD	d-excess
BLN C 1/11/01	-11.14	-86.24	2.91
BLN 3 1/11/01	-11.06	-85.79	2.71
BLN 4 1/11/01	-10.21	-82.37	-0.73
BLN Rio 1/11/01	-12.64	-87.70	13.39
ASV C 1/21/01	-10.27	-76.64	5.50
ASV 3 1/21/01	-10.06	-78.56	1.95
ASV 4 1/21/01	-11.80	-87.87	6.54
ASV Rio 1/21/01	-11.81	-88.09	6.41
BLN C 5/23/01	-11.21	-83.23	6.45
BLN 3 5/23/01	-12.08	-86.55	10.09
BLN 4 5/23/01	-11.45	-84.09	7.51
BLN Rio 5/23/01	-12.30	-88.70	9.70
BLN Flood 5/23/01	-12.10	-89.19	7.61
ASV C 5/23/01	-12.07	-85.51	11.05
ASV 3 5/23/01	-12.17	-89.19	8.17
ASV 4 5/23/01	-11.82	-85.56	9.00
ASV Rio 5/23/01	-12.74	-90.64	11.28
BLN C 7/24/01	-11.58	-85.18	7.44
BLN 3 7/24/01	-11.82	-86.53	8.05
BLN 4 7/24/01	-11.86	-85.43	9.48
BLN Rio 7/24/01	-11.65	-85.15	8.03
ASV C 7/11/01	-12.48	-86.58	13.28
ASV 3 7/11/01	-12.30	-87.18	11.18
ASV 4 7/11/01	-11.94	-85.79	9.76
ASV Rio 7/11/01	-12.17	-87.83	9.56
BLN C 10/10/01	-11.51	-87.45	4.66
BLN 3 10/10/01	-11.84	-88.54	6.15
BLN 4 10/10/01	-11.84	-84.87	9.81
BLN Rio 10/10/01	-11.13	-83.50	5.51
ASV C 10/11/01	-11.78	-89.73	4.48
ASV 3 10/11/01	-12.64	-90.95	10.19
ASV 4 10/11/01	-11.91	-87.02	8.24
ASV Rio 10/11/01	-11.96	-81.49	14.15

Discussion

Groundwater chemistry in the bosque aquifer is controlled by 3 processes—(1) dynamic composition of Rio Grande surface water, (2) the concentration of solutes by evapotranspiration or solute rinsing from infiltration, and (3) microbial redox reactions.

The chemical composition of the Rio Grande surface water is dynamic in response to variations in its source waters—seen from both the results of this study (Appendix A) and in historical records (e.g. Healy, 1997; Clark and Mauger, 1932). As shown in figure 6, head changes in bosque groundwater occur in response to Rio Grande stage variation within a 1-2 day time period. Therefore, compositional variations in the river are expected to affect solute concentrations in groundwater.

Evaporation and transpiration concentrate solutes as plant roots uptake water and leave salts behind (Mazor, 1991) (Figure 17). Naff et al. (1975) showed salt concentrations in and above the capillary fringe as phreatophytes transpired. Accumulated salts are then washed into the groundwater as percolating waters redissolve the salts or as the water table rises or through daily fluctuations of the water table during the growing season (Naff et al., 1975; Smith and Drever, 1976; Mazor, 1991).

Microbes affect the redox state of the water through terminal electron accepting processes (TEAPs). Microorganisms obtain energy by the transfer of

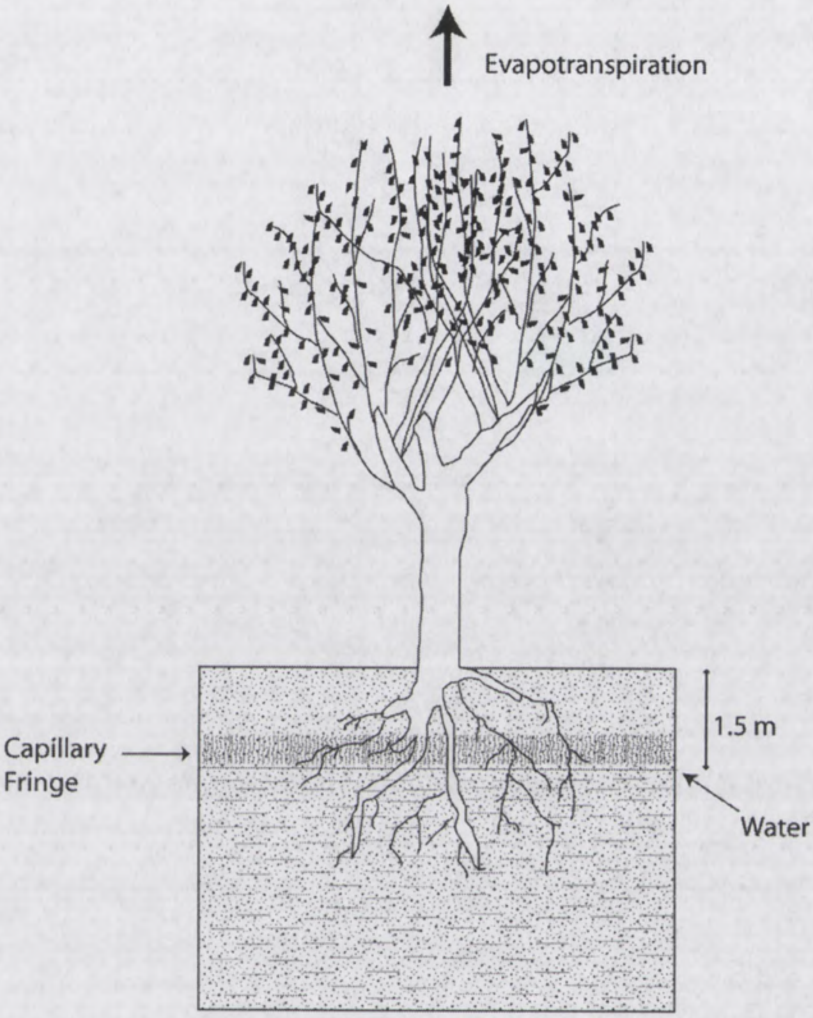


Figure 17: Schematic view of a phreatophyte. Water is drawn up through the tree's roots from the saturated zone and capillary fringe, leaving salts behind as water is transpired (after Robinson, 1958).

electrons from electron donors to electron acceptors. In the decay process, electrons are generated (Equation 1).

Equation 1 $C_{organic} + 2H_2O \rightarrow CO_2 + 4H^+ + 4e^-$

Because free electrons cannot accumulate in the environment, there must be a mechanism to utilize these electrons. Microorganisms will use terminal electron acceptors (TEAPs) to uptake these free electrons and obtain energy

(Drever, 1997). In aerobic metabolism, microorganisms utilize oxygen as a terminal electron acceptor. This process is the most energetically favorable pathway for microbes to oxidize carbon (Chapelle, 2001). As oxygen is removed from a groundwater system through respiration and metabolism, microorganisms must utilize other terminal electron accepting processes for energy. Terminal electron acceptors (TEAs) that yield the greatest Gibbs free energy (Table 5) are preferentially reduced by microbes first according to the following gradient of oxidized/ reduced elements—O_2/H_2O, NO_3^-/N_2, Mn (IV)/Mn (II), Fe (III)/Fe (II), NO_3^-/NH_4^+, NO_2^-/NH_4^+, SO_4^{2-}/H_2S, CO_2/CH_4, H_2O/H_2—commonly resulting in redox zonation in an aquifer (Drever, 1997).

Table 5: Potential standard free energy released for successive redox reactions (Chapelle, 2001).

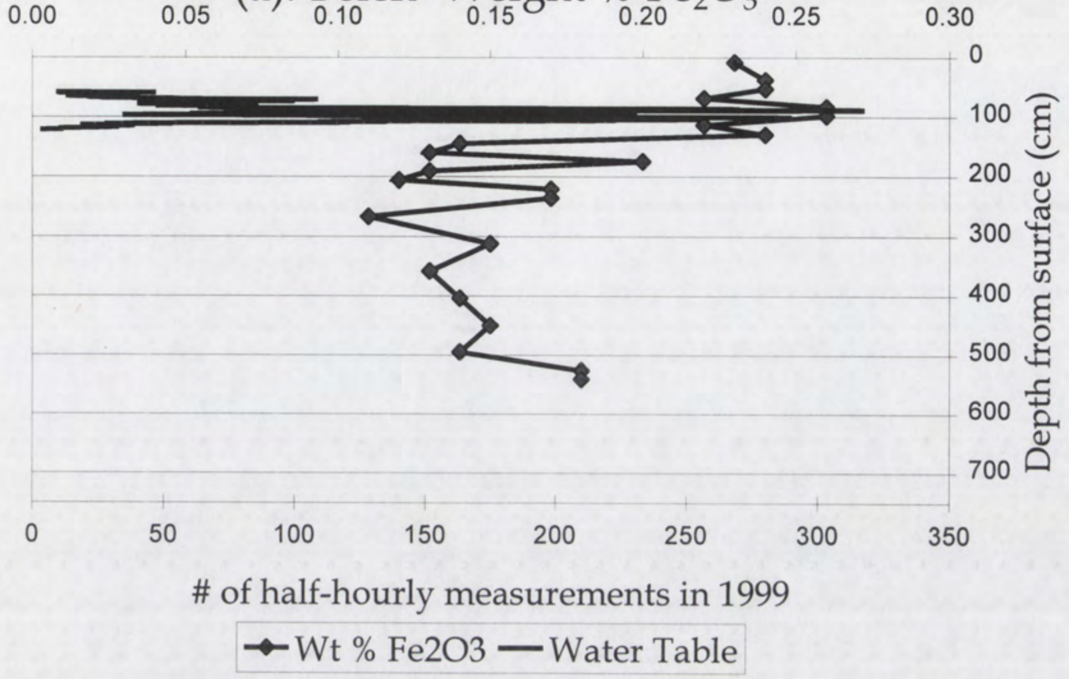
Redox Process	**Potential Standard Free Energy (kJ/H_2)**
Denitrification	224
Mn Reduction	163
Fe Reduction	50
Sulfate Reduction	38
Methanogenesis	34

Sediment Geochemistry

In order to understand groundwater chemistry, one must first understand the chemistry of the aquifer matrix. Figures 18 and 19 show the weight percent iron and manganese oxides extracted from the sediment samples at Belen and ASV versus depth below the ground surface. The frequency that the water table was situated at a particular depth (presented as the number of half-hourly measurements the water table was at this depth in 1999) is overlain on these data. At the flood-capable Belen site, the spike in authigenic Fe-oxides occurs between 69 and 114 cm (Figure 18a), closely following the pattern of the 1999 water table. Although there are variations in the profile, the weight percent Fe_2O_3 generally decreases below this spike. The presence of the Fe-spike near the water table suggests that oxygenated recharge drives the formation of iron-oxide phases via biotic and/or abiotic iron (II) oxidation at the oxic-anoxic interface. The Mn-oxide extractions from Belen exhibit a small spike just below the water table from 130 to 160 cm and a larger Mn-spike from 312 to 495 cm (Figure 18b). The presence of greater extractable iron below the water table illustrates the kinetic sluggishness of the oxidation of manganese (Hem, 1963).

At the Albuquerque South Valley, extractable iron generally increases with depth in the upper 200 cm of the profile, spiking just below the water table and at 400 cm depth (Figure 19a). No clear trend emerges from the ASV manganese extraction data (Figure 19b).

The concentrations (with depth) of extractable iron and manganese in sediments are markedly different between the study sites. It was shown that the sediment of both Belen and ASV is predominately sand sized (Figure 10). Therefore, no correlation exists between grain size and concentration of extractable metals at either site. However, Belen and ASV have different flooding histories. Belen is a flooding site, and ASV is non-flooding. Lab experiments conducted by La Force et al. (1998) on trace metal contaminated (a). Belen -Weight % Fe_2O_3



(b). Belen Weight % MnO_2

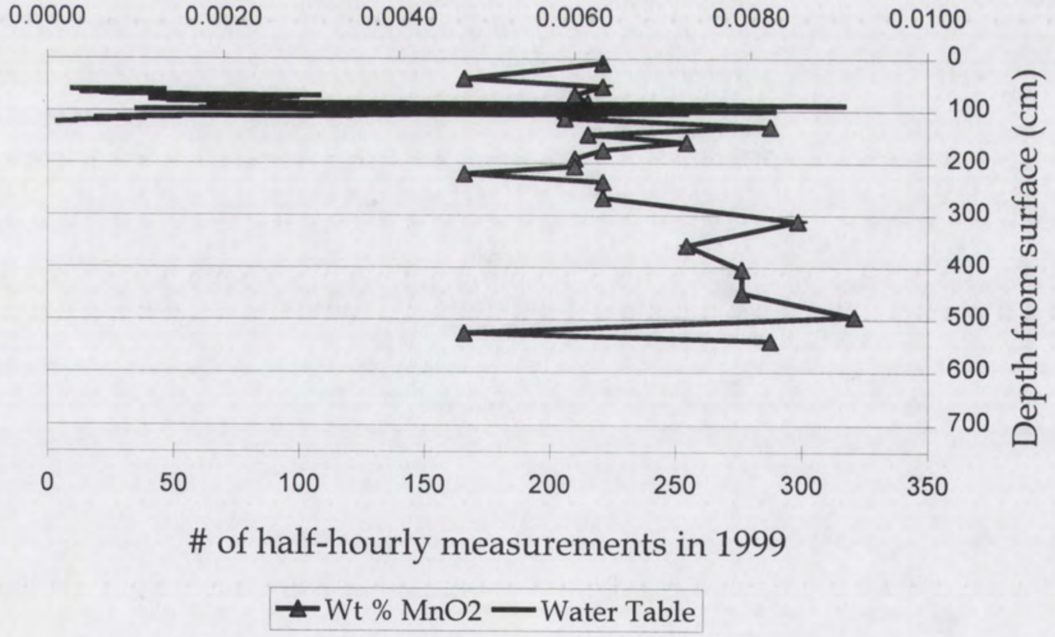
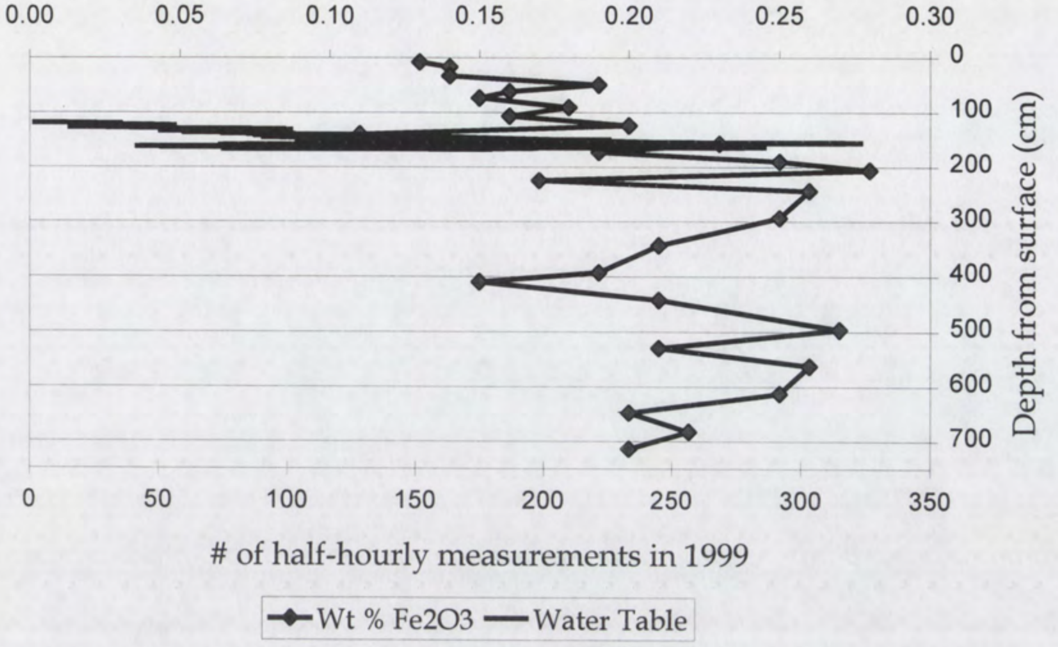
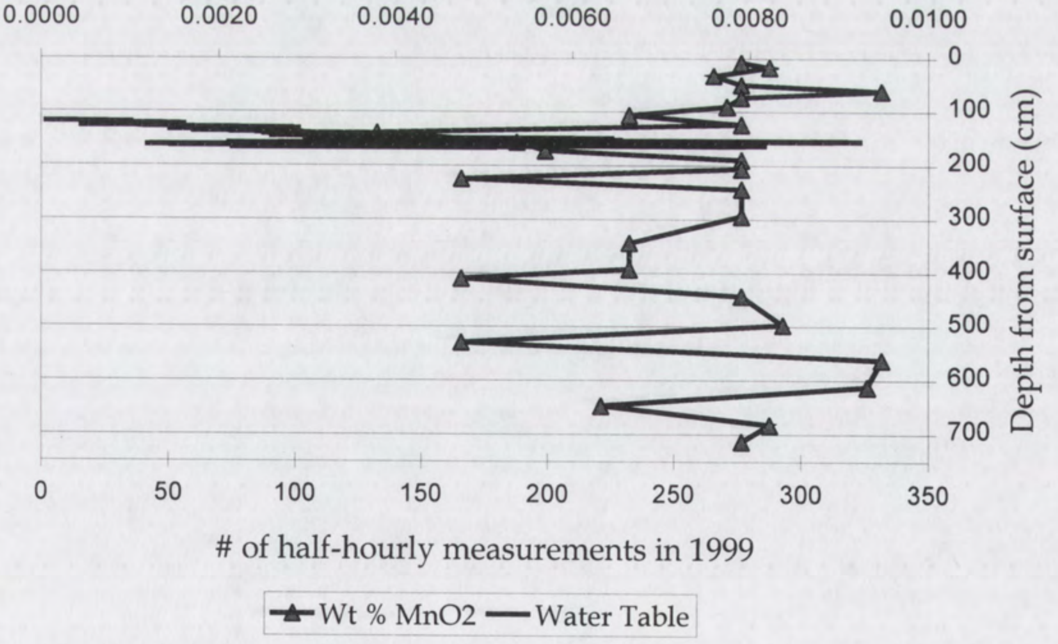


Figure 18: Weight-percent iron oxide (a) and manganese oxide (b) with depth and the frequency the water table is at a given depth at Belen.



(a). ASV- Weight % Fe_2O_3



(b). ASV Weight % MnO_2

Figure 19: Weight percent iron oxide (a) and manganese oxide (b) with depth and the frequency the water table is at a given depth for ASV.

waters and sediments from the Coeur d'Alene River system show that flooding can enhance the mobility of trace metals. Darke and Walbridge (2000) have shown that flooding reduces the amount of crystalline Fe-oxides by converting crystalline forms to non-crystalline oxides and by dissolving Fe-oxides as conditions become anaerobic and Fe (III) is converted to Fe (II). For the upper 540 cm of sediment, the total weight percent Fe_2O_3 extracted at Belen is 4.15 and 4.43 at ASV (Table 2). Therefore, given the flooding regimes of these sites, it is not surprising that more extractable iron is present at ASV.

Examination of total Fe concentrations in water samples shows more total Fe available at Belen than at ASV, further supporting the hypothesis that dry-conditions (non-flooding) limits the mobility of this trace metal by binding Fe up in crystalline and amorphous phases (Figure 20). However, this higher total Fe in the groundwater at Belen may be related to greater Fe (II) reduction.

River and Groundwater Geochemistry

Interactions of surface water and groundwater in the hyporheic zone will affect redox zonation of the shallow aquifer. Where oxygenated surface waters combine with low oxygen/ anaerobic groundwater, reduced compounds will be oxidized. Where water is anoxic, the reverse is true. Microorganisms readily use available oxygen from surface waters to metabolize organic matter and aerobic metabolism occurs. Geochemically, the influx of oxygen into the system also will catalyze reactions with dissolved metals to form metal oxides (such as FeOOH, $Fe(OH)_3$). These chemical reactions have rates controlled by solution

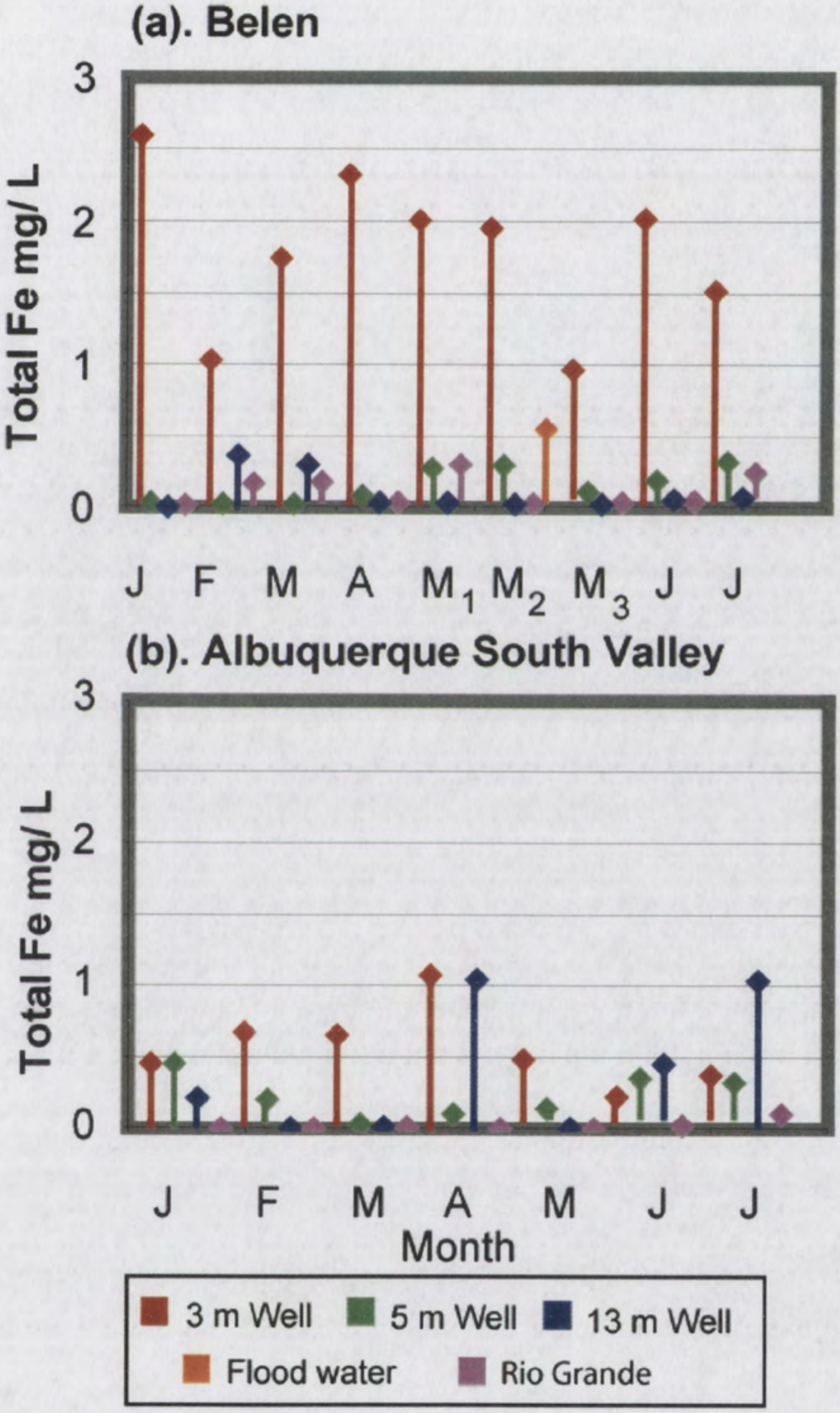


Figure 20: Total iron concentrations in mg/L from ground and surface waters at Belen (a) and ASV (b) in 2001. M_1, M_2, and M_3 denote early May, May flooding, and late May, respectively.

pH. When in anaerobic hyporheic zones, metal oxides will dissolve (Winter et al., 1998). Groffman and Crossey (1999) have shown spatial and temporal shifts in the redox regime in a shallow alluvial aquifer at Rio Calaveras in the Jemez Mountains in New Mexico. O_2/H_2O dominates in the spring, shifting to Fe^{3+}/Fe^{2+}, Mn^{4+}/Mn^{2+}, and SO_4^{2-}/HS^- in the summer. In the fall, iron and sulfate reduction predominate until spring snowmelt, when the upper aquifer becomes moderately oxidizing. Because these redox sensitive elements and compounds can control nutrient and contaminant distributions, concentration ranges both vertically and seasonally are important.

Chloride is included with the presentation of aqueous redox chemistry (oxygen, nitrate, iron, manganese, and sulfate) as a conservative species, because chloride concentration generally is not affected by water-rock interactions, nor will its concentration be affected by redox processes (Mazor, 1991). Chloride does, however, show the dilution or concentration effects of infiltration and evapotranspiration (e.g. Naff et al., 1975; Smith and Drever, 1976; McCarthy and Ellery, 1994). Therefore, changes in concentrations of redox species due to biological processes can be distinguished from hydrochemical processes. To fully understand how the groundwater composition evolved from its surface water source (the Rio Grande), well compositions were normalized relative to river water compositions from each site from January to July 2001. Because the river itself has dynamic concentrations, the well values were normalized to river values taken at the same time the wells were sampled. All three well values at each site are plotted for each sampling date (Figures 20-24). Values closest to zero indicate the element concentration in groundwater is close to the value of the river. Values greater than zero indicate an enrichment of the element, and values less than zero indicate a depletion of the element compared to river values. To account for hydrochemical effects, nitrate to chloride and sulfate to chloride ratios were normalized to these same ratios of Rio Grande water for each sampling period.

Chloride concentrations of the groundwater normalized relative to the Rio Grande concentrations from the same sampling date show that the deep wells (13 m) at both sites are most closely tracking the river chemistry (values closest to zero) (Figure 21). Both Belen and ASV show increases of chloride in the groundwater compared to the river in the late spring and early summer coinciding with leafout and growth of bosque vegetation, indicating ET is concentrating solutes. Several studies (e.g. Naff et al., 1975; Smith and Drever, 1976; Emme and Prudic, 1991; McCarthy and Ellery, 1994) have shown increases in chloride concentrations due to evapotranspiration. The greatest concentration of chloride occurs in late May at Belen, a week after flooding. This further increase in chloride concentration in all wells is attributed to the rinsing of salts from the vadose zone into the saturated zone as floodwaters infiltrate the sediments.

Rio Grande dissolved oxygen (DO) levels are variable and lowest after flooding (Figure 22). Molles et al. (1998) have shown DO concentrations in

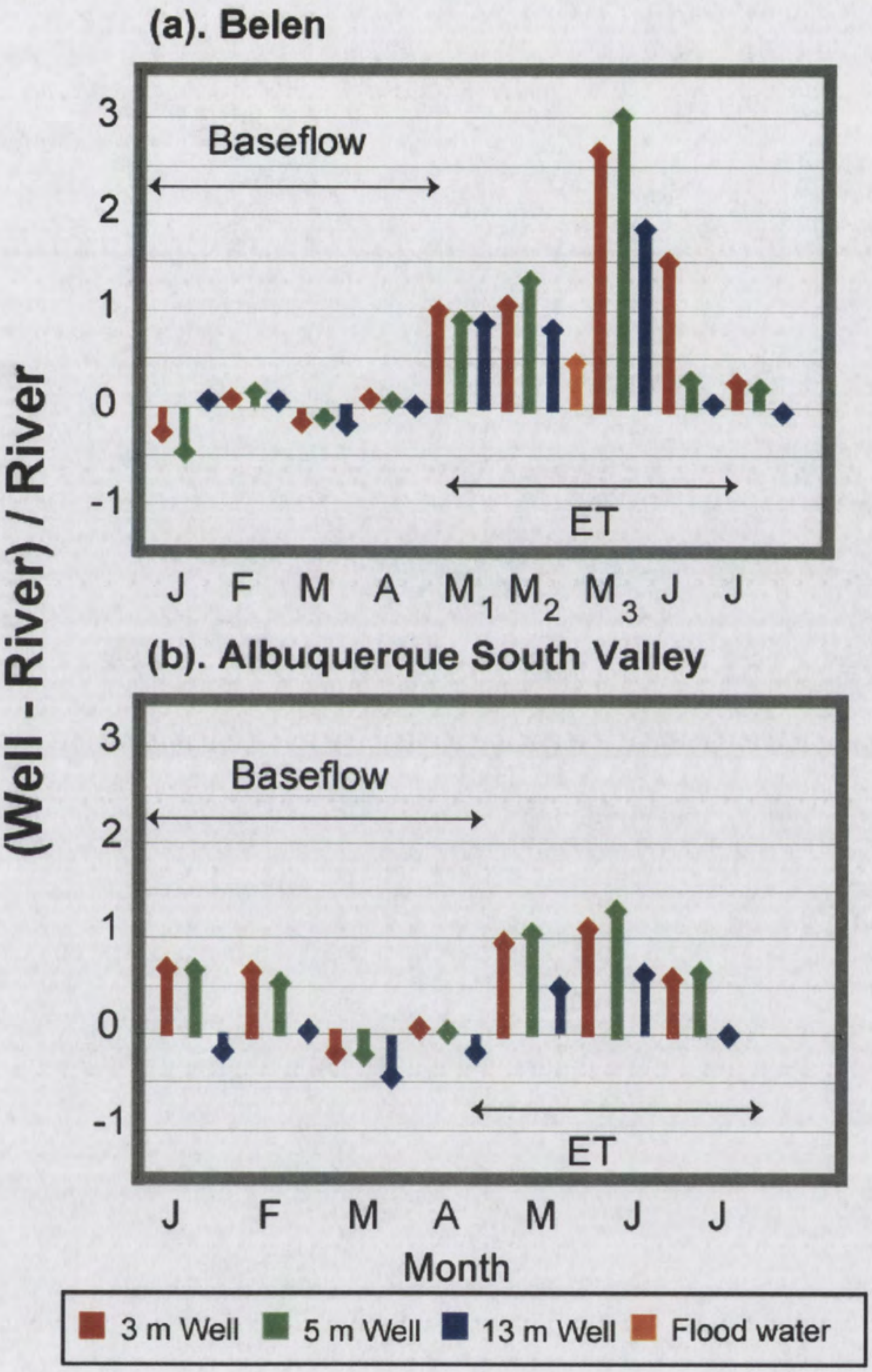


Figure 21: Groundwater chloride concentrations normalized relative to Rio Grande values for Belen (a) and ASV (b). M_1, M_2, and M_3 denote early May, May flooding, and late May, respectively.

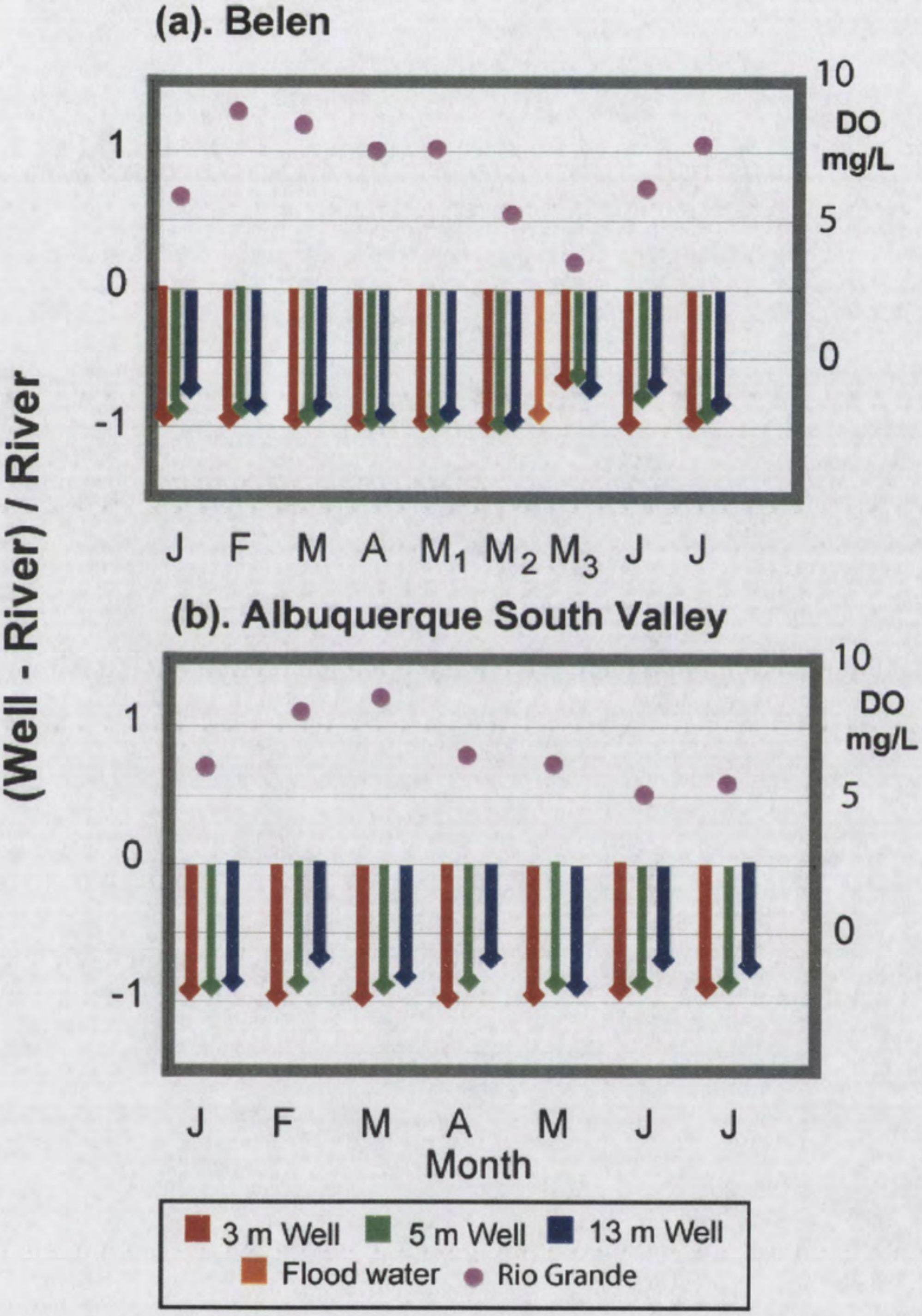


Figure 22: Rio Grande dissolved oxygen (DO) values (circles) and groundwater DO concentrations normalized relative to river values (arrows) for Belen (a) and ASV (b) in 2001. M_1, M_2, and M_3 denote early May, May flooding, and late May, respectively.

floodwater are rapidly depleted due to a high biological oxygen demand. River water was oxygenated (5.6 to 6.15 mg/L) on the flood day, but DO of floodwater was near anoxic (0.6 mg/L). DO measurements of the river a week after flooding indicate decreased oxygen (3.13 mg/L) due to the mixing of this low DO floodwater with river water.

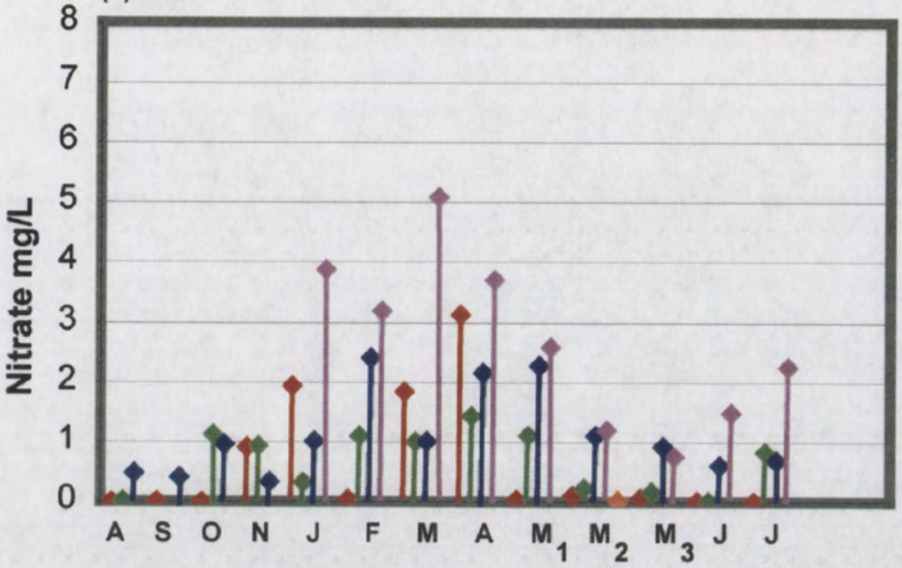
As expected, dissolved oxygen concentrations in all wells were depleted compared to river values throughout the sampling period (Figure 22). Oxygen is the first terminal electron acceptor to be utilized by microorganisms for energy (Chapelle, 2001). Therefore, DO is often lowest deeper in an aquifer. However, Winograd and Robertson (1982) have shown that high DO can be present at depth in an aquifer, so it is not unusual that the deepest wells (13 m) at Belen and ASV have higher DO concentrations. This trend is similar to the trend seen in chloride values. Both these data suggest that the deepest wells show less chemical modification of river water, indicating a less bio-reactive pathway than the shallower wells. Sediment size classification (Figure 10) does not show any significant grain size variation that would result in a more rapid transit time with depth. Therefore, it is hypothesized that there is less organic carbon available at depth to be consumed by microorganisms either because less was deposited with the sediments originally or because it has already been consumed through microbial activity (Drever, 1997).

For either aerobic or anaerobic respiration to occur, there must be an energy supply (carbon) available. Carbon is oxidized as a terminal electron acceptor (such as oxygen, nitrate, Fe (III), sulfate) is reduced. Consequently, if less organic carbon is available, less respiration will occur. Baker et al. (2000) have shown that metabolism in the hyporheic zone at Rio Calveras, NM was supported by dissolved organic carbon derived from snowmelt infiltration of the region of seasonal saturation (RoSS). Baker et al. (1999) have also shown CO2 production increased at this site when acetate was injected. Likewise, respiration rates in the bosque groundwater ecosystem may be controlled by organic carbon availability. The 13 m wells may be carbon limited, resulting in higher DO concentrations than the 3 and 5 m wells.

According to Gibbs free energy calculations, nitrate is predicted to be the first compound to be reduced after DO is consumed (Chapelle, 2001). Therefore, we expect nitrate to be highest where DO is greatest. Where DO is low, nitrate can be converted to N_2 in a three-step denitrification reaction or through nitrate reduction to ammonium (Wetzel, 2001).

Figure 23 presents nitrate concentrations (mg/L) of groundwater at Belen and ASV over time. Commonly nitrate is highest in 13 m (high DO) wells at ASV. Belen nitrate concentrations show more variability but often the deep (more oxygenated) well has the highest values of groundwater samples. The greatest nitrate concentrations in groundwater occur from October to April, and the lowest occur May to September. This trend is likely due to interactions between plants and groundwater. Nitrate and other nutrients are taken up during the growing season (late April to September) by riparian vegetation.

(a) Belen



(b) Albuquerque South Valley

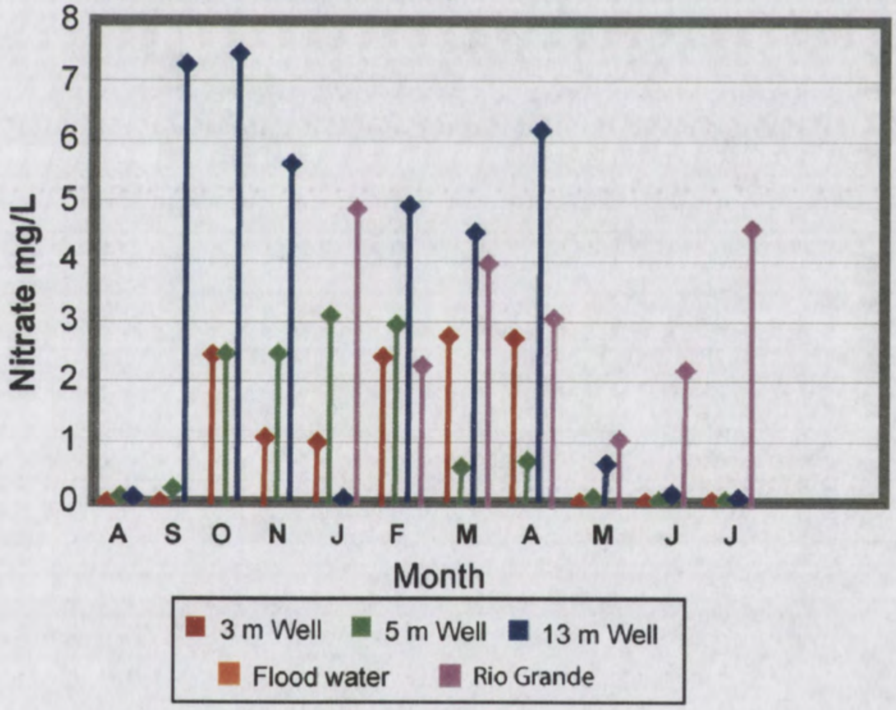


Figure 23: Nitrate concentrations in mg/L at Belen (a) and ASV (b) from August 2000 to July 2001.

Also striking about these data is the comparison of nitrate values between the sites. A quick glance at figure 23 shows higher nitrate concentrations at ASV. Examination of the mean nitrate values for well and river waters shows ASV samples typically have twice the nitrate as Belen samples (Table 6). A Student's T-test was performed on nitrate values for the same depth wells and river water samples to determine if Belen and ASV nitrate values are from the same population. The results of these tests (Table 6) show with 95% certainty that the waters are from different populations. Supplemental statistical data are included in Appendix B. Therefore, I hypothesize that groundwater nitrate at ASV reflects input of the third largest tributary to the Middle Rio Grande, the Albuquerque Waste Water Treatment Plant (AWWTP), located 6.4 km upstream of ASV. Effluent from the AWWTP typically contains 1 to 20 mg/L N (AWWTP, unpub. data 2002). Porter (1980) and Smith and Duff (1988) have shown groundwater contamination from sewaged waters. This wastewater input is therefore believed to load the river water with nitrate, which, in turn, increases groundwater nitrate concentrations. Molles et al. (pers. comm. 2002) have shown that ASV also has higher nitrogen enrichment in both soils and cottonwood leaves than Belen, results that emphasize the importance of riparian vegetation in water quality.

To fully understand biological processes that affect nitrate concentrations at these sites, one must analyze the groundwater values in the context of river values. Examination of groundwater nitrate normalized to Rio Grande nitrate

Table 6: Mean nitrate concentrations (mg/L) and Student's T-test results from Belen and ASV.

	Belen *n = 14*	**ASV** *n = 12*	**T-test results**
3 m	0.58	1.03	0.31
5 m	0.60	1.00	0.30
13 m	1.03	2.88	0.06
Rio Grande	2.77	4.88	0.29

concentrations (Figure 24) suggests that nitrate is generally depleted compared to river values, due to both the uptake of this nutrient by plants and the conversion of nitrate to N_2 by denitrification (DNF) or ammonium through either dissimilatory nitrate reduction to ammonium (DNRA) or assimilatory nitrate reduction by microorganisms (Chapelle, 2001; Tobias et al., 2001). However, this approach does not take into account hydrochemical effects on the concentration of this nutrient.

To account for these processes, nitrate to chloride ratios were determined for all waters. Chloride was chosen as a conservative species because it is not redox sensitive (Drever, 1997). These ratios were then normalized to the ratio of nitrate to chloride in river water for each sampling. Consequently, values greater than zero will indicate an enrichment process in groundwater, while values less than zero indicate a removal of the anion. Nitrate to chloride ratios in the groundwater relative to these ratios in the river generally illustrate depletion of nitrate in the aquifer (Figure 25), indicating plant uptake or the reduction of nitrate by microbes.

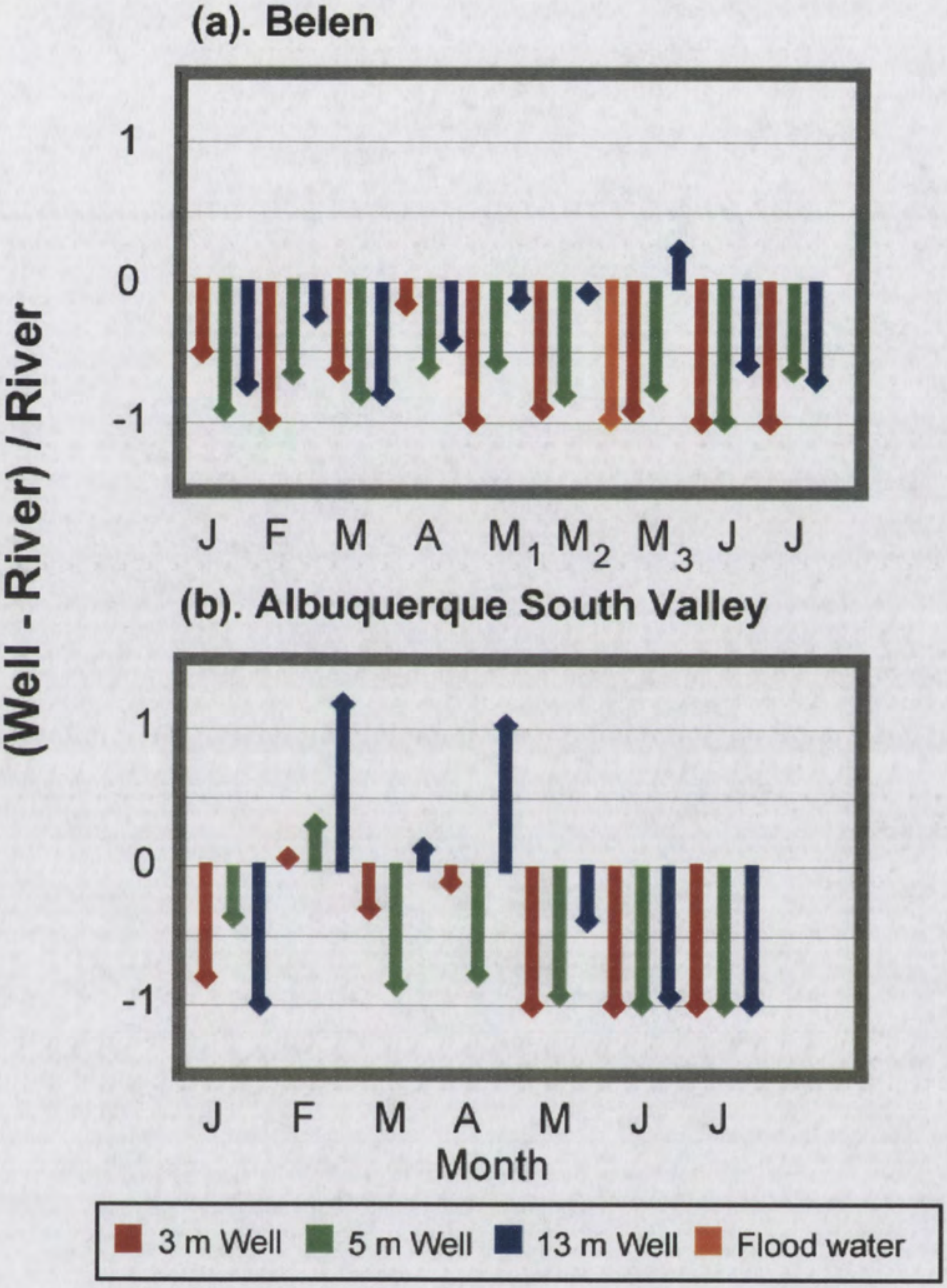


Figure 24: Groundwater nitrate concentrations normalized relative to Rio Grande values for Belen (a) and ASV (b). M_1, M_2, and M_3 denote early May, May flooding, and late May, respectively.

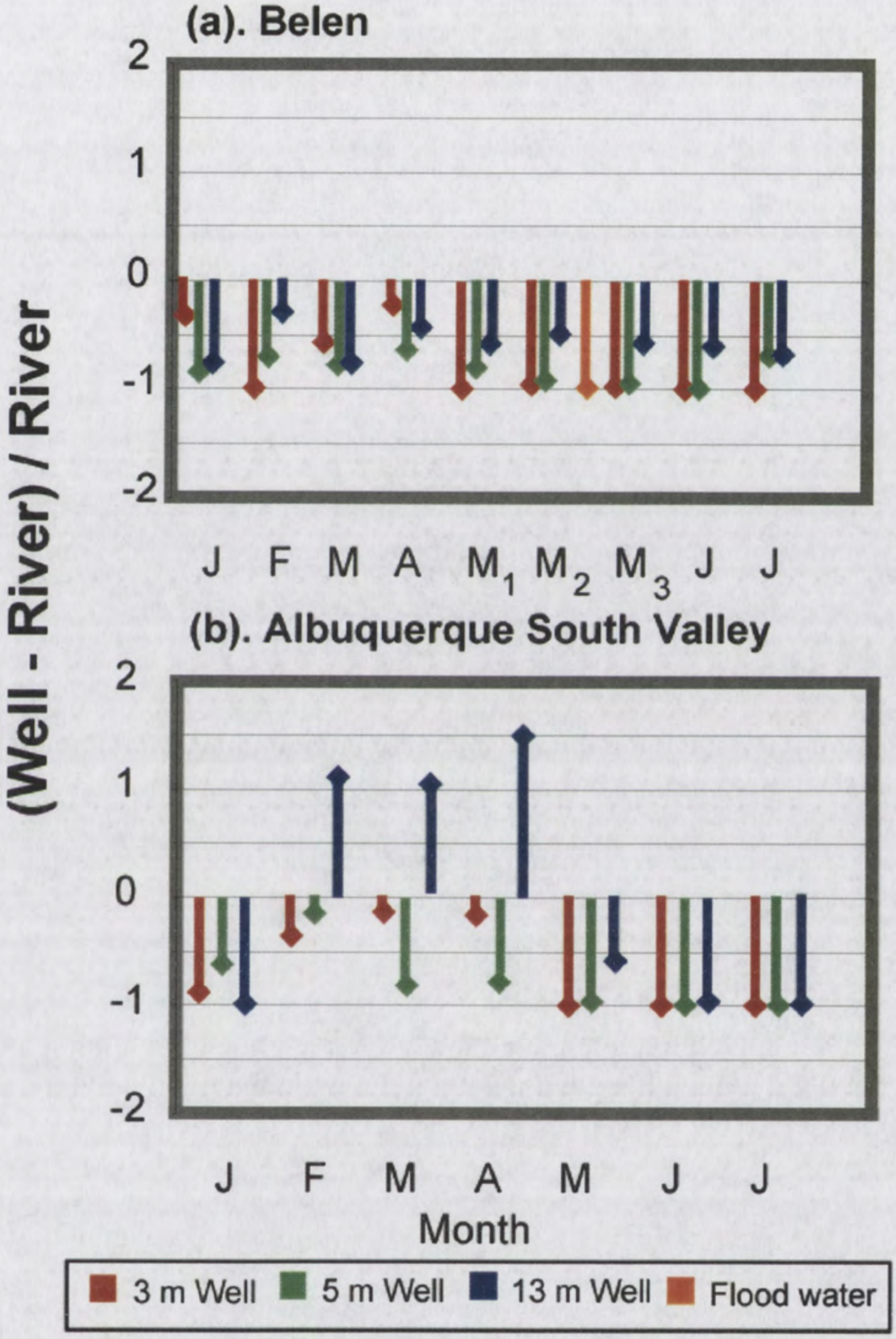


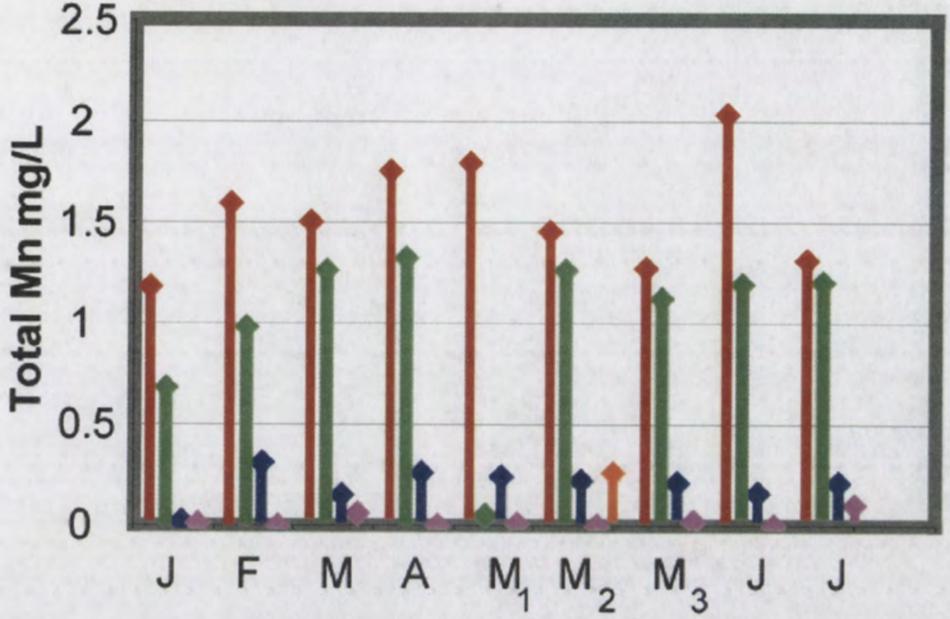
Figure 25: Groundwater nitrate to chloride ratios normalized relative to Rio Grande nitrate to chloride ratios for 2001 at Belen (a) and ASV (b). M_1, M_2, and M_3 denote early May, May flooding, and late May, respectively.

Samples from dialysis multi-level samplers emplaced in the upper 2.5 meters at Belen and ASV support the hypothesis that nitrate reduction is occurring. As shown in figures 14-16, nitrate decreases with depth in the upper aquifer as dissolved oxygen is consumed. Considering this pattern with the nitrate source evaluation discussed earlier, it appears that microbial processes occurring in the "bio-reactive zone" and uptake by riparian vegetation attenuate nitrate additions to the Rio Grande in the shallow groundwater at ASV.

However, ASV exhibited increases in nitrate to chloride ratios relative to the river in the 13 m well in February, March, and April, while Belen showed only depletions (Figure 25). These periods of increased nitrate occur when DO is high in the deep wells (1.6 to 2.6 mg/L), suggesting that nitrification may be occurring.

When nitrate is depleted, the next TEAP is metal reduction. As previously discussed, reduction of Mn (IV) to Mn (II) occurs first followed by reduction of Fe (III) to Fe (II) (Chapelle, 2001). As the oxidized forms of these metals are commonly in solid phases, Mn (II) and Fe (II) will come into solution through these metal-reducing processes (Drever, 1997). Therefore, it is presumed that much of the total Mn and Fe measured are Mn (II) and Fe (II).

Figure 26 shows the total dissolved Mn concentrations at Belen and ASV. Based on increasing Mn concentrations with depth in DMLS profiles, Mn reduction is believed to be occurring in the upper aquifer (Figures 13-16). Examination of well chemistry shows Mn concentrations are consistently higher (a). Belen



(b). Albuquerque South Valley

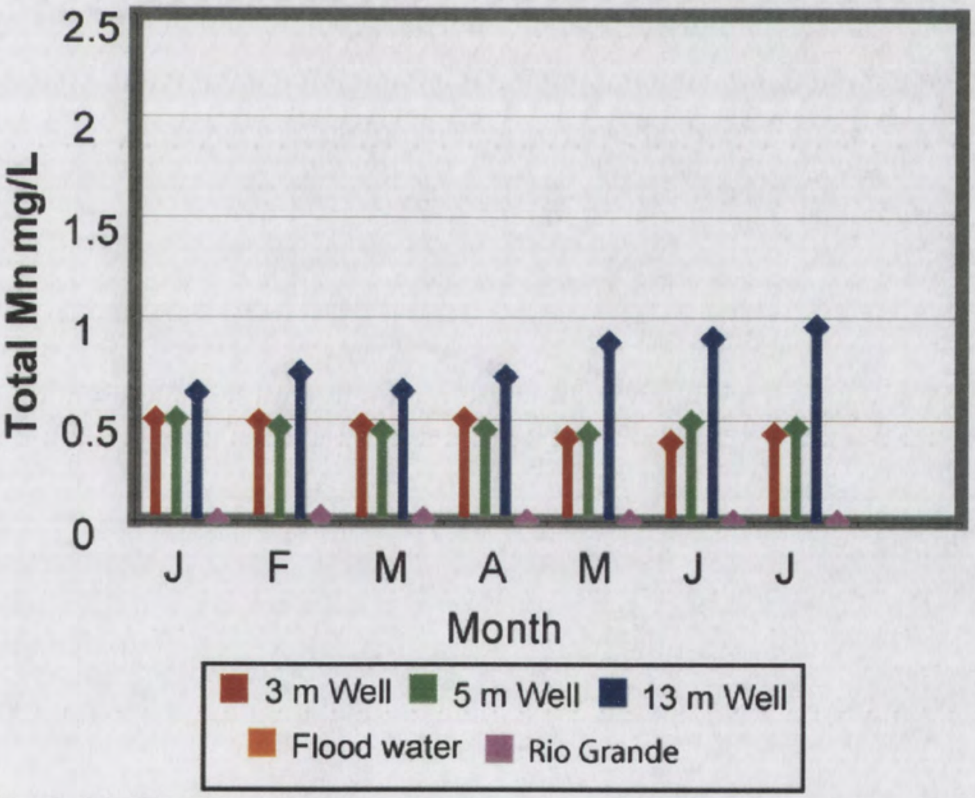


Figure 26: Total manganese concentrations in mg/L from ground and surface waters at Belen (a) and ASV (b) in 2001. M_1, M_2, and M_3 denote early May, May flooding, and late May, respectively.

at Belen than ASV. Within the Belen data set, the 3 and 5 m wells have greater total Mn concentrations than the 13 m well and the Rio Grande (Figure 26). These data suggest that the reduction of Mn (IV) is occurring within the upper 5 meters of the aquifer where anaerobic conditions have been recorded. At ASV, total Mn is always highest in the 13 m well, and the difference in total Mn from shallow to mid-depth to deep wells is less than the difference in concentration between 3 and 5 m and 13 m wells at Belen.

Because Mn can be co-precipitated with Fe at circumneutral pH values (Hem, 1963), the greater weight percent extractable Mn at ASV than at Belen (Table 2) indicates that flooding may control the mobility of Mn in a manner similar to that of Fe as reported by Darke and Walbridge (2000) and supporting the hypothesis of La Force et al. (1998) that flooding enhances trace metal mobility. Lower total dissolved Mn concentrations in 3 and 5 m ASV wells may be attributable to Mn kinetics. The rates of Mn oxidation are slower than those of iron. The rates of Mn oxidation reactions depend on temperature, pH, and concentration of reactants and products. Hem (1963) has shown that the rate at which Mn (II) is oxidized and precipitated in aerated solutions increases with increasing pH, but this rate is decreased when bicarbonate and sulfate are present.

Fe (III) is also an electron acceptor for microbes through metal reduction (Chapelle, 2001). Total dissolved iron concentrations are highest in the shallow well (3 m) at Belen and higher than the concentrations found at ASV (Figure 20).

The ASV shallow well also typically has the highest total dissolved iron of the three wells at ASV; however, more variability is seen between ASV wells (Figure 20). Ferric iron (Fe (III)), therefore, is reduced to Fe (II), the more soluble iron species. The higher total iron values seen in these shallow wells are consequently attributed to Fe (II), and the greater total dissolved Fe at Belen is the result of Fe-oxide dissolution due to flooding (see sediment discussion). During flooding, dissolved oxygen is rapidly consumed by the uptake of microbes and in the breakdown of organic matter, as conditions become anoxic. Fe-oxides can then be reduced, allowing Fe (II) to come into solution (Darke and Walbridge, 2000; Chapelle, 2001).

Total dissolved Fe decreases in the DMLS Belen-A profile and varies in Belen-B, while both ASV profiles show increasing total dissolved Fe with depth. Fe reduction may be occurring in the upper 2 m of both the Belen and ASV aquifers. Variations in total dissolved Fe profiles at Belen further illustrate the enhanced mobility of Fe due to flooding.

Sulfate is the final TEA considered here, because methane concentrations were below detection limits. Sulfur in the sulfate anion is reduced to sulfide by either assimilatory or dissimilatory sulfate reduction. In assimilatory reduction, sulfur is reduced for use in sulfur-containing compounds such as amino acids in proteins. Dissimilatory reduction occurs when sulfate acts as a TEA in the oxidation of organic matter. As sulfide is produced (commonly in the form of H_2S) some may react with metals (Fe) to form sulfide minerals, or sulfide may be converted back to sulfate (in aerobic zones) by microorganisms, such as *Thiobacillus* (Chapelle, 2001). Figure 27 presents groundwater sulfate concentrations relative to river water sulfate in order to determine how sulfate concentrations have been changed from surface water values. This approach was not considered for total Mn and Fe because concentrations of these metals were often below detection in the Rio Grande.

When examining sulfate concentrations of groundwater relative to river water, sulfate is generally shown to increase in the groundwater (Figure 27). Similar to the trend seen in chloride concentrations (Figure 21), shallow and mid-depth wells (3 and 5 m) show the greatest increase in sulfate and overall increases in all wells occur in the late spring/ early summer months, indicating enrichment due to evapotranspiration. Factoring out this concentration-effect using sulfate to chloride ratios, it is shown that sulfate is being consumed and reduced to hydrogen sulfide, predominately in the 3 m wells (Figure 28). Both olfactory observations and colorimetric Hach field tests have verified the presence of sulfide in these waters, although exact concentrations were not determined.

As shown on DMLS profile Belen-A (Figure 13b), sulfate increases with depth while chloride concentrations are constant. These two trends suggest sulfate reduction is occurring in the upper portion of the profile. Belen-B shows a slight increase in both sulfate and chloride at approximately 1.7 m depth (Figure 14b). These parallel trends suggest hydrochemical processes are adding

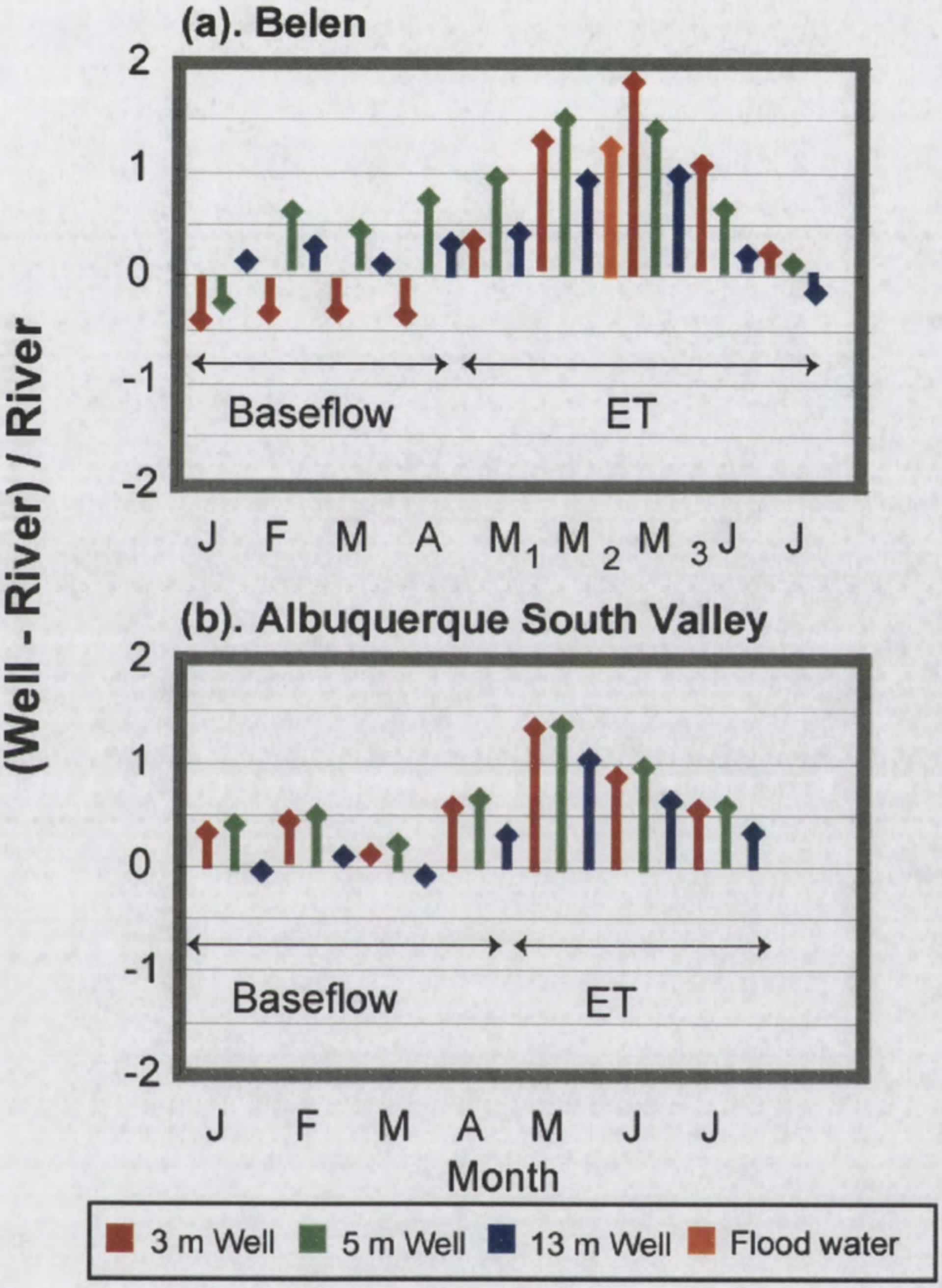


Figure 27: Groundwater sulfate concentrations normalized relative to Rio Grande sulfate values for 2001 at Belen (a) and ASV (b). M_1, M_2, and M_3 denote early May, May flooding, and late May, respectively.

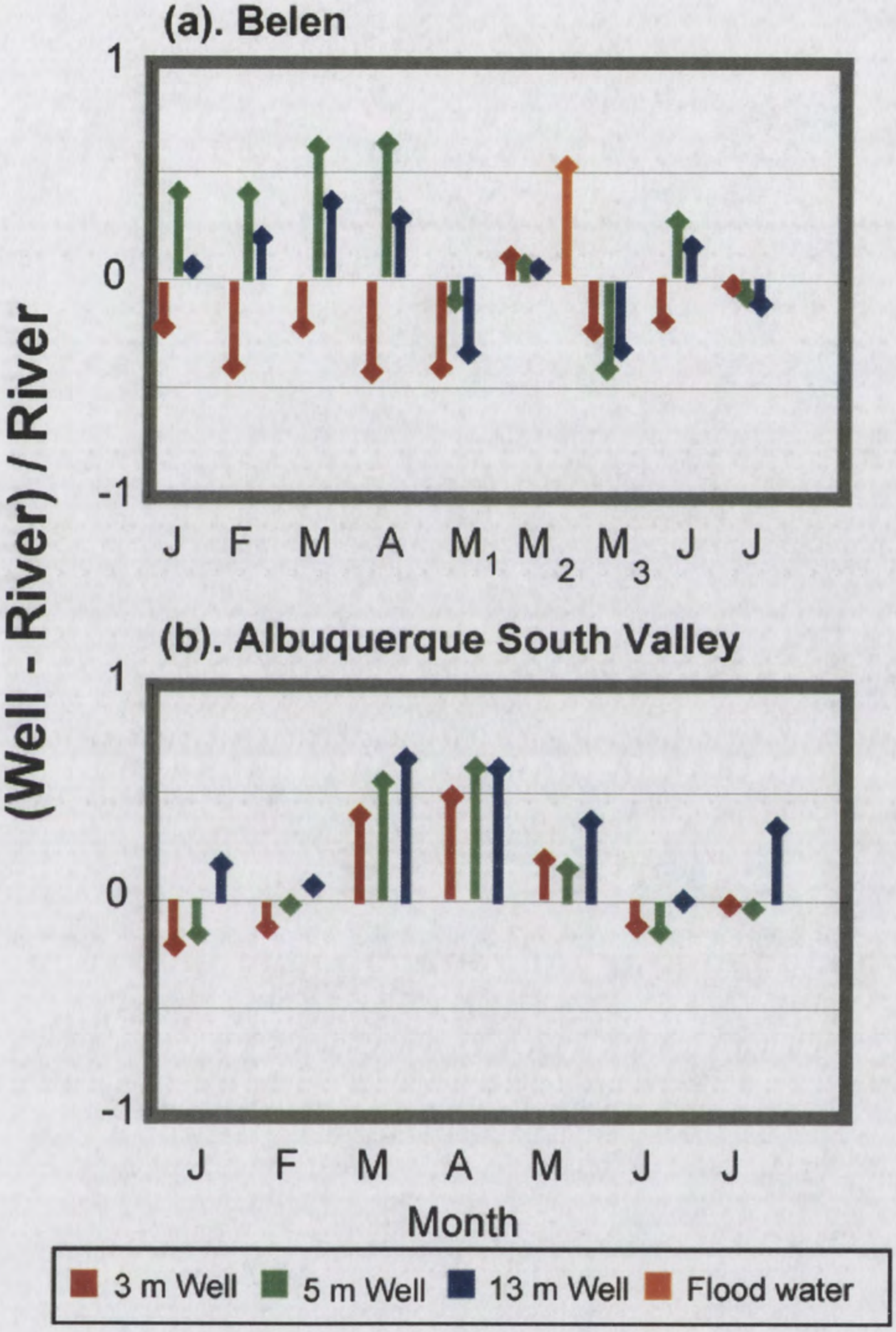


Figure 28: Groundwater sulfate to chloride ratios normalized relative to Rio Grande sulfate to chloride ratios for 2001 at Belen (a) and ASV (b). M_1, M_2, and M_3 denote early May, May flooding, and late May, respectively.

to solute concentrations. I hypothesize that the 1.7 m depth below the surface corresponds to the zone of greatest root density. Consequently, groundwater withdrawal by riparian vegetation concentrates these salts at this zone.

Examination of profile ASV-A (Figure 15b) further supports this idea. Like Belen-B, there is a concentration maximum of sulfate at approximately 1.8 m in ASV-A. Concentrations of these salts are steady on ASV-B. However, it is noted that the upper dialysis cells of the DMLS rod at ASV-B were not equilibrated, so the profile begins at 1.9 m depth—10-20 cm below the hypothesized root zone.

Flooding

Floodwaters are slightly enriched in all elements except dissolved oxygen, nitrate and nitrite when compared to Rio Grande values (Table 3). The DO in this slow moving/ standing water has been consumed in the oxidation of organic matter. Consequently, nitrate might be removed through microbial denitrification. Alternatively, nitrate also may be taken up by decomposers or riparian vegetation.

Increases in total Fe and Mn support previous evidence that trace metal mobility is enhanced by flooding. Additionally, the phosphate concentration of floodwater is higher (2.08 mg/L) than in river water (0.53 mg/L Belen, 0.11 mg/L ASV). Phosphorous is often bound up in metal-oxides. Consequently, it may be released into solution when these metal oxides (Mn or Fe) are reduced

(Darke and Walbridge, 2000). Therefore, this increase in phosphate may be attributable to release from solid trace metal phases during the reduction of Mn and Fe.

Stable Isotopes

Isotopes can be fractionated based on their varying weights. Because lighter isotopes have higher vibrational energy than heavier isotopes, the light isotopes form weaker bonds, which are easier to break. For example, fractionation from evapotranspiration will leave the plant water and groundwater (reservoir water) enriched in D and ^{18}O, while light isotopes (H and ^{16}O) are preferentially incorporated into the vapor phase (Epstein and Mayeda, 1953; Walker and Brunel, 1990).

In the bosque ecosystem, stable isotopes of water were examined to distinguish seasonal variations in isotopic composition and to determine if the hydrochemical processes affecting groundwater (documented by other geochemical methods) could be ascertained by isotopic investigation. Examination of the results (Table 4) shows little variation in $\delta\,^{18}O$ and δ D values. A plot of $\delta\,^{18}O$ versus δ D values of these waters (Figure 29) shows these waters fall between the global meteoric water line ($\delta D = 8 * \delta\,^{18}O + 10$) and the local meteoric water line for New Mexico ($\delta D = 6.7 * \delta\,^{18}O + 5.5$) (Kendall and Coplen, 2001).

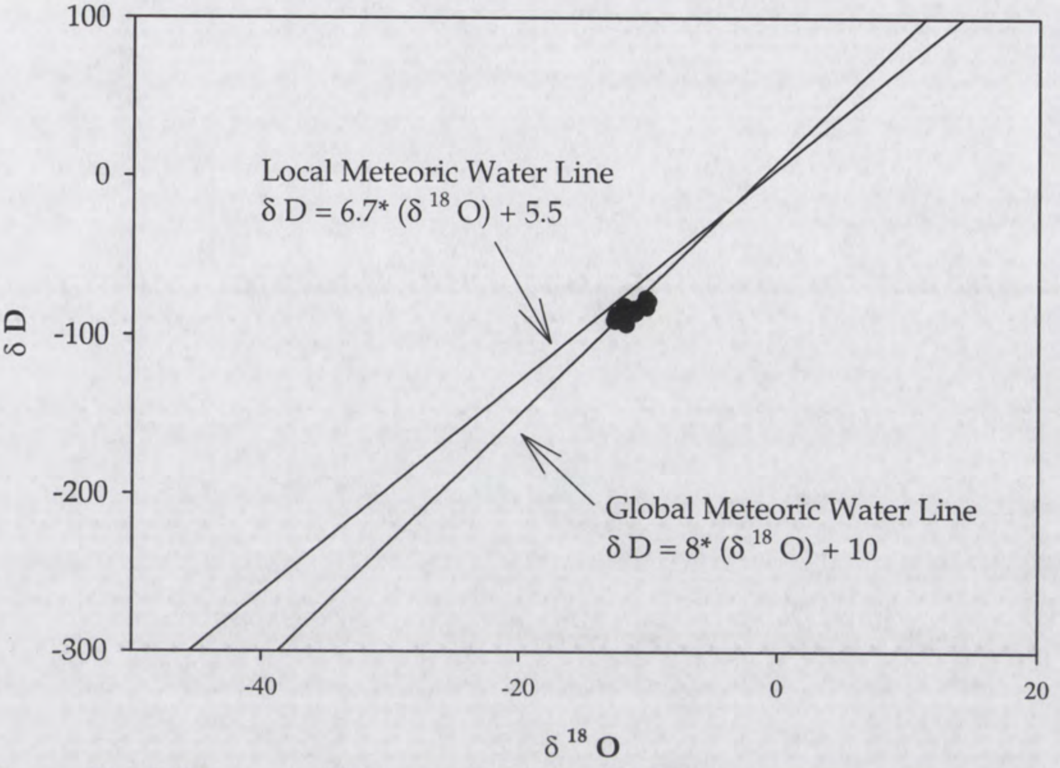


Figure 29: δ ^{18}O versus δ D (per mil versus SMOW) of bosque water samples (black circles) and the local and global meteoric water lines.

Deterium-excess (d-excess) values were calculated to determine the processes affecting the isotopic composition of these bosque waters. High d-excess is indicative of more evaporated moisture added to the atmosphere (wetter climates), while low d-excess values indicate samples fractionated by evaporation (more arid environments). The Colorado Plateau and surrounding region to the southwest towards Mexico is characterized by high d-excess values (Kendall and Coplen, 2001). Kendall and Coplen (2001) suggest that this d-excess zone may be caused by the mingling of storms from the Gulf of Mexico and from the Pacific. In general, the d-excess values of bosque waters fall in the 6 to 10 range characteristic of this region. Low d-excess values (Belen—January 2001; Table 4) are consistent with fractionation due to evaporation. However, these values seem somewhat anomalous, as evaporation should be lower during the winter. More study is warranted before drawing firm conclusions about these waters. Overall, this study has shown no significant variation between the isotopic composition of the groundwater and its surface water source the Rio Grande.

Conclusions

This groundwater investigation has highlighted the importance of considering both source water and sediment geochemistry in understanding groundwater biogeochemistry. As a result, a new view of this ecosystem has emerged (Figure 30). Oxygenated Rio Grande water recharges these shallow alluvial aquifers, with a less reactive pathway occurring at 13 m depth (as illustrated by the overall chemical composition similarity between river water and 13 m groundwater). Less than 5 m depth in the aquifer, chemistry is controlled by both microbial activity and hydrochemical processes in the bio-reactive zone.

Use of the dialysis multi-level sampler has indicated denitrification, metal reduction, and sulfate reduction are occurring in the upper 2.5 m, while evapotranspiration concentrates both chloride and the redox-sensitive sulfate around 1.7-1.8 m depth at both Belen and ASV. This zone is believed to correspond to the zone of greatest root density, where phreatophyte riparian vegetation withdraws water, leaving salts behind.

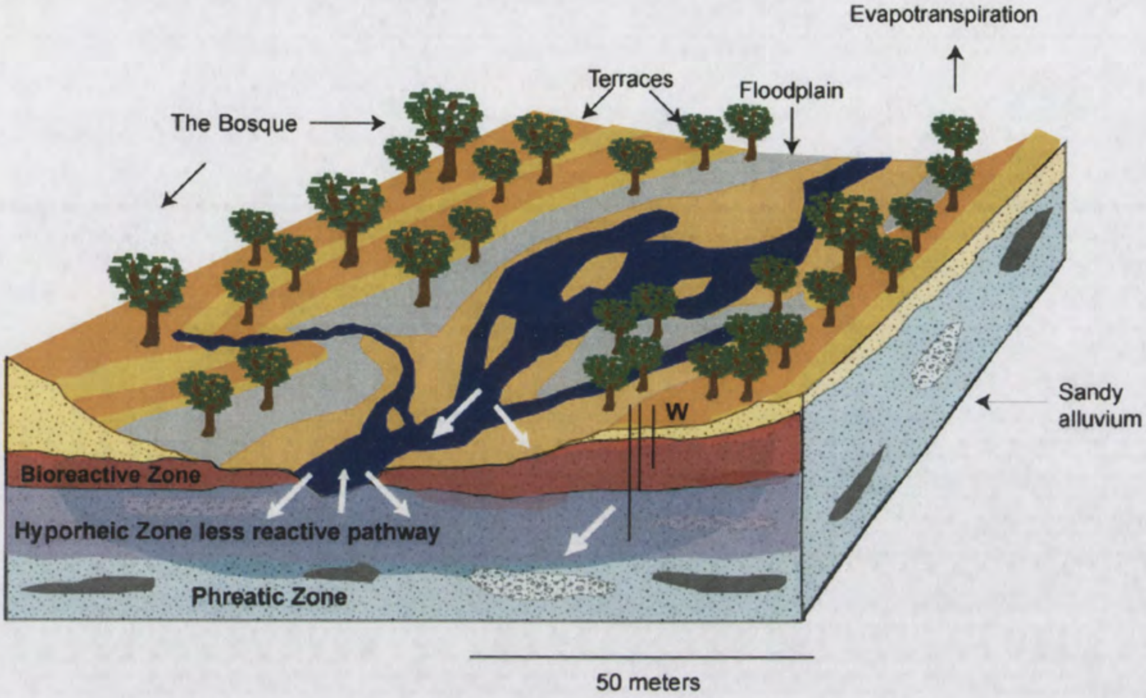


Figure 30: Schematic view of the bosque ecosystem, showing water pathways (arrows) and chemical zones (modified from Stanford, 1998).

Floodwaters are enriched in all parameters measured except for nitrogen compounds and oxygen, indicating uptake by bosque vegetation or decomposers. Because dissolved oxygen is low in this standing water, the reduction of nitrate may be occurring as well. Concentrations of the trace metals Fe and Mn also are increased in the floodwater, suggesting the dissolution of solid phase metal-oxides is occurring. This dissolution releases phosphate and has the potential to release toxic trace metals. Sediment extractions and year long chemical monitoring at both sites also supports enhanced metal mobility at flood-capable Belen.

Additionally, this research has documented that nitrate concentrations are higher at ASV (the site directly downstream of the Albuquerque wastewater treatment plant) than at Belen. Molles et al. (pers. comm. 2002) have shown leaf and soil nitrogen content are higher at ASV than at Belen, illustrating the impact of enhanced nutrients on riparian vegetation.

Finally, stable isotopic analyses of the Rio Grande and the bosque groundwaters has indicated that the $\delta\,^{18}O$ and δD values of these waters due not vary significantly and are consistent with the values obtained for other area waters.

These geochemical data emphasize the need to characterize both major element and redox chemistry in an aquifer in predicting nutrient pathways and contaminant transport. To further understand the redox zonation of this aquifer, future work should include microbial and mineralogical investigations with dialysis multi-level samplers. Additionally, hydrologic characterizations of the sites would provide insight into how the flow paths of source waters vary seasonally, a necessity in predicting pathways of groundwater contamination and rates of solute and solid phase transformations.

Appendix A. Chemical Data

Sample	Well Depth (m)	Depth to water (m)	Ca (mg/L)	Fe (mg/L)	Mg (mg/L)	Mn (mg/L)	K (mg/L)	Na (mg/L)	SiO_2 (mg/L)	F (mg/L)	Cl (mg/L)	NO_2 (mg/L)	Br (mg/L)	NO_3 (mg/L)	PO_4 (mg/L)	SO_4 (mg/L)	HCO_3 (mg/L)	CO_3 (mg/L)	pH	DO (mg/L)	Alk (meq/kg)	T (C)	Charge balance %
BLN 3 7/6/00	5	1.1	46	0.23	7.4	1.09	4	31.5	25.4	0.54	18.63		0.09	0.04	0.76	56.6	164	0	7.07	1.7	2.68	15.3	-0.12
BLN 4 7/6/00	13	1.23	54	0.05	9.2	0.38	5.5	35.5	23.1	0.42	21.85		0.23	0.94	0.58	66.3	160	0.13	7.36	1.8	2.63	14.1	4.74
BLN C 8/7/00	3	1.16	45	1.05	8	0.97	3.6	35.5	33.5	0.53	15.3	2.01	0.13	0	0.6	35.8	183	0.23	7.55	0.32	3	17.6	3.83
BLN 3 8/7/00	5	1.11	48	0.18	7	1.09	3	30	28.2	0.54	19.6	0	0.1	0.02	0.84	59.5	166	0.6	7.81	0.6	2.73	15	-2.07
BLN 4 8/7/00	13	1.24	50	0.07	8.7	0.37	3.8	35.5	24.3	0.5	22.3	0	0.09	0.49	0.81	73.2	169	0.39	7.8	2.16	2.78	15.2	-1.27
BLN C 9/8/00	3	1.19	43	1.3	7	1.13	4.4	38	43.7	0.52	17.7	2.09	0.12	0.01	0.41	34.4	177	0.13	7.3	0.28	2.9	17.5	4.24
BLN 3 9/8/00	5	1.15	48	0.11	7	1.14	5.5	33	34.8	lost	lost	lost	lost	lost	lost	lost	143	0.6	7.81	1.33	2.35	15.3	32.17
BLN 4 9/8/00	13	1.28	51	0	7.5	0.3	5.5	38	34	0.41	18	0	0.07	0.41	0.58	65.3	150	0.28	7.7	1.63	2.47	15.7	6.27
BLN C 10/19/00	3	1.09	50	0.17	7.6	0.94	5	35	33	0.55	18.6	0	0.06	0	0.28	49.9	lost	lost	lost	0.32	lost	15.4	
BLN 3 10/19/00	5	1.06	52	0.06	8	1.01	4.4	34	36.8	0.46	17.7	0	0.1	1.13	0.8	55.9	145	0.6	7.8	1.13	2.37	15.2	8.71
BLN 4 10/19/00	13	1.18	50	0	8	0.3	6	37.5	39.1	0.42	17.2	0	0.09	0.97	0.64	67.7	148	0.3	7.7	1.32	2.43	15.2	6.09
BLN C 11/17/00	3	1.08	48	0.04	8	0.88	4.5	34	32.1		20.3			0.92		55.3	161	0.1	7.22	0.6	2.65	12.3	3.34
BLN 3 11/17/00	5	1.05	55	0.38	8	1.31	6	35	28.4		17.1			0.94	0.69	72.1	145	0.05	6.96	0.66	2.37	13.9	7.88
BLN 4 11/17/00	13	1.17	55	0.4	8.5	0.58	7	38	28.4		20.5			0.34	0.59	72.8	152	0.05	7.01	1.33	2.49	13.8	7.11
BLN C 1/11/01	3	1.13	55	2.53	9	1.18	3.5	35	29.1	0.43	15.1	0	0.08	1.94	0.52	36.9	202	0.29	7.6	0.5	3.32	8.8	6.61
BLN 3 1/11/01	5	1.12	69	0	10.5	0.68	3.7	44	22.4	0.29	10.8	0	0.06	0.33	0.41	47.5	189	0.27	7.59	0.79	3.11	10.8	17.68
BLN 4 1/11/01	13	1.15	55	0	9	0.02	4.9	40	22.3	0.4	22	0	0.1	1.02	0.7	73	170	0.31	7.7	1.71	2.8	11	3.41
Rio BLN 1/11/01	River	N/A	46	0	7.2	0.01	5	43	22.3	0.49	20.6	0	0.12	3.88	0.31	64.5	167	0.77	8.1	6	2.76	N/A	1.16
BLN C 2/26/01	3	1.20	67	1.04	10.5	1.59	3.6	40	22	0.42	23.8	0	0.12	0.04	0	37.2	289	0.17	7.22	0.6	4.75	7.8	-0.60
BLN 3 2/26/01	5	1.13	61	0	9.3	0.98	5	50	17.7	0.39	25.2	0	0.1	1.1	0.79	92.3	131	0.14	7.48	1.3	2.16	9.3	11.80
BLN 4 2/26/01	13	1.47	55	0.31	9	0.31	5.1	41	18.4	0.33	23.3	0	0.1	2.41	0.53	73.1	189	0.19	7.44	1.47	3.1	9.8	0.62
Rio BLN 2/26/01	River	N/A	43	0.18	6.9	0	5.2	44	17.8	0.51	21.9	0.3	0.11	3.19	0.32	57.6	166	0.88	8.16	9.07	2.75	9.3	1.12

Sample	Well Depth (m)	Depth to water (m)	Ca (mg/L)	Fe (mg/L)	Mg (mg/L)	Mn (mg/L)	K (mg/L)	Na (mg/L)	SiO_2 (mg/L)	F (mg/L)	Cl (mg/L)	NO_2 (mg/L)	Br (mg/L)	NO_3 (mg/L)	PO_4 (mg/L)	SO_4 (mg/L)	HCO_3 (mg/L)	CO_3 (mg/L)	pH	DO (mg/L)	Alk (meq/kg)	T (C)	Charge balance %
BLN C 3/10/01	3	1.25	64	1.69	12	1.5	3	40	23.3	0.38	23.8	0	0.16	1.85	0.17	42.1	284	0.14	7.14	0.51	4.66	8.3	-1.22
BLN 3 3/10/01	5	1.15	56	0	10	1.26	3.5	45	18.3	0.35	25	0	0.11	1.01	0.74	90.8	208	0.18	7.38	0.79	3.41	8.9	-3.05
BLN 4 3/10/01	13	1.27	50	0.26	9.5	0.15	4.25	38	19.9	0.37	23.1	0	0.01	1.02	0.51	70.7	181	0.17	7.4	1.35	2.97	9.4	-0.94
Rio BLN 3/10/01	River	N/A	42	0.16	8.5	0.06	4.75	47	20.3	0.46	28.4	0	0.17	5.08	0.45	64	170	0.25	7.6	8.58	2.8	12	-0.83
BLN C 4/19/01	3	1.27	66	2.24	13.5	1.75	3.5	43	28.7	0.42	26.3	0	0.14	3.13	0.15	32.8	273	0.21	7.32	0.34	4.49	10.3	4.18
BLN 3 4/19/01	5	1.25	64	0.11	11	1.32	4	46	20.4	0.42	25.6	0	0.1	1.44	0.66	90	188	0.22	7.5	0.4	3.08	8.7	4.23
BLN 4 4/19/01	13	1.37	53	0	9.3	0.26	4	35.5	21.2	0.35	24.5	0	0.09	2.16	0.55	68	173	0.22	7.54	0.72	2.85	9.5	0.44
Rio BLN 4/19/01	River	N/A	41	0	7.5	0	4.5	46	23.5	0.44	24.2	0.37	0.1	3.71	0.47	52.3	138	1.32	8.42	7.6	2.3	17.2	6.68
BLN C 5/5/01	3	1.09	78	1.92	18	1.79	3.5	42	28.9	0.38	26.8	0	0.11	0.04	0.08	62.4	279	0.06	6.75	0.34	4.58	11.9	5.45
BLN 3 5/5/01	5	1.08	63	0.21	10.9	0.05	3.75	49	20.8	0.45	25.6	0	0.12	1.11	0.7	90	191	0.15	7.33	0.34	3.13	9.1	4.02
BLN 4 5/5/01	13	1.20	55	0	9.4	0.24	4	38	21.1	0.34	25.2	0	0.14	2.28	0.51	65.4	165	0.09	7.17	0.84	2.71	9.8	4.21
Rio BLN 5/5/01	River	N/A	40	0.28	7.5	0.01	4	26	21.1	0.38	12.1	0.02	0.05	2.59	0.15	46.9	129	0.5	8.02	7.54	2.14	14.9	4.58
BLN C 5/23/01	3	0.28	72	1.95	12.3	1.45	4.5	47	30.1	0.51	29.2	0	0.2	0.11	0	75.3	214	0.19	7.38	0.2	3.51	14.6	7.43
BLN 3 5/23/01	5	0.31	59	0.25	10	1.26	3.9	53	22.1	0.52	32.8	0.48	0.11	0.23	0.49	81.9	193	0.06	6.94	0.17	3.17	11.2	3.05
BLN 4 5/23/01	13	0.49	55	0	9.3	0.22	4.9	43.9	24.3	0.44	25.6	0	0.09	1.11	1.79	62.8	170	0.23	7.58	0.3	2.79	11.6	6.12
Rio BLN 5/23/01	River	N/A	27	0	7	0	4	33	20.7	0.27	14.2	0.17	0.04	1.2	0.53	33.1	111	0.28	7.84	5.6	1.83	21	7.60
Flood 5/23/01	Flood	N/A	56	0.53	9.5	0.26	11	37	23.8	0.38	20.6	0	0.06	0.03	2.08	73.2	164	0.07	7.08	0.6	2.69	20.6	5.92

Sample	Well Depth (m)	Depth to water (m)	Ca (mg/L)	Fe (mg/L)	Mg (mg/L)	Mn (mg/L)	K (mg/L)	Na (mg/L)	SiO_2 (mg/L)	F (mg/L)	Cl (mg/L)	NO_2 (mg/L)	Br (mg/L)	NO_3 (mg/L)	PO_4 (mg/L)	SO_4 (mg/L)	HCO_3 (mg/L)	CO_3 (mg/L)	pH	DO (mg/L)	Alk (meq/kg)	T (C)	Charge balance %
BLN 2 5/30/01	3	0.97	60	0.92	10	1.27	5.5	50	25.7	0.42	29.5	0	0.11	0.06	0.24	86.9	203	0.78	8.02	1.11	3.36	14.3	1.52
BLN 3 5/30/01	5	0.94	60	0.13	10	1.12	4	53	22	0.51	32.4	0	0.1	0.18	0.45	73.1	209	0.31	7.61	1.2	3.43	11.6	2.90
BLN 4 5/30/01	13	1.06	47	0	8.1	0.21	3.9	41	25.1	0.39	23	0	0.06	0.93	0.55	59.8	169	0.32	7.72	0.91	2.78	11.1	1.84
Rio BLN 5/30/01	River	N/A	33	0.02	6	0.02	3.1	20	21.3	0.27	8.09	0	0	0.76	0.13	30.8	117	0.74	8.24	3.13	1.93	20.2	4.40
BLN C 6/27/01	3	1.17	72	2	12.5	2.03	4.3	54	29.9	0.47	43.6	0	0.02	0.01	0.06	85.6	263	0.11	7.07	0.22	4.31	14.7	-0.84
BLN 3 6/27/01	5	1.21	49	0.22	8.1	1.19	3.9	45	21.2	0.57	22.3	0	0.08	0.02	0.53	68.3	193	0.1	7.15	1.43	3.16	12.5	-0.35
BLN 4 6/27/01	13	1.32	40	0.05	7.5	0.16	4	38	24.9	0.52	18	0	0.06	0.61	0.41	50	156	0.01	7.09	2	2.56	13	2.59
Rio BLN 6/27/01	River	N/A	36	0	6.1	0	4.7	36.3	22.2	0.45	17.4	0	0.06	1.49	0.14	41.9	139	0.25	7.69	6.33	2.29	24.6	3.83
BLN C 7/24/01	3	1.27	47	1.46	9	1.31	3.9	46	30.7	0.54	21.2	0	0.11	0	0.3	67.2	188	0.2	7.49	0.43	3.08	16.8	1.60
BLN 3 7/24/01	5	1.30	47	0.27	8.4	1.2	5.8	47	21.4	0.49	20.3	0	0.09	0.84	0.66	61	193	0.29	7.63	0.84	3.16	14.2	2.07
BLN 4 7/24/01	13	1.42	39	0.07	6.5	0.21	6	36	24.6	0.5	16.1	0.1	0.63	0.69	0.65	46.3	154	0.46	7.93	1.4	2.52	14.2	2.35
Rio BLN 7/24/01	River	N/A	44	0.2	8	0.1	5	37	23.9	0.44	17	0	0.09	2.25	0.48	55	162	2.3	8.59	7.68	2.66	24.5	1.98

Sample	Well Depth (m)	Depth to water (m)	Ca (mg/L)	Fe (mg/L)	Mg (mg/L)	Mn (mg/L)	K (mg/L)	Na (mg/L)	SiO_2 (mg/L)	F (mg/L)	Cl (mg/L)	NO_2 (mg/L)	Br (mg/L)	NO_3 (mg/L)	PO_4 (mg/L)	SO_4 (mg/L)	HCO_3 (mg/L)	CO_3 (mg/L)	pH	DO (mg/L)	Alk (meq/kg)	T (C)	Charge balance %
ASV 3 7/24//00	5	1.37	54	0.28	9.5	0.41	3.3	32.9	18.95	0.44	28.7		0.11	0.18	0.32	72.2	155	0.13	7.34	1.15	2.54	14.1	1.27
ASV 4 7/24/00	13	1.45	43	0.14	7.5	0.75	5	33.5	26.03	0.58	23.2		0.1	0.18	0.64	55.4	181	0.13	7.32	0.6	2.96	14.5	-4.28
ASV C 8/7/00	3	1.61	52	0.41	9	0.45	3	35.5	22.53	0.46	30		0.12	0	0.57	60.8	173	0.15	7.37	0.52	2.84	20.4	-0.1
ASV 3 8/7/00	5	1.41	56	0.32	9.9	0.48	3.5	33.5	19.47	0.42	35.2		0.14	0.1	0.18	86.2	165	0.37	7.79	2	2.72	14.2	-3.22
ASV 4 8/7/00	13	1.48	45	0.13	8	0.76	5	37	26.48	0.48	25.5		0.12	0.09	0.83	60.4	163	0.21	7.55	1.93	2.68	16.3	-0.34
ASV C 9/15/00	3	1.44	53	0.04	8	0.43	5.5	38	20.45	0.36	23	0	0.12	0	0.3	64.1	160	0.07	7.1	0.23	2.63	23	4.82
ASV 3 9/15/00	5	1.43	53	0.2	7.4	0.42	5.5	38	18.93	0.39	22.1	2.07	0.11	0.23	0.42	77.9	143	0.24	7.66	1.51	2.35	13.3	4.06
ASV 4 9/15/00	13	1.5	46	1.65	7.4	0.81	7	37	25.58	0.46	22.4	0	0.12	7.28	1.19	51.1	143	0.2	7.58	1.14	2.36	13.4	6.11
ASV C 10/19/00	3	1.67	31	0.28	6	0.34	4.4	43	26.96	0.45	19.1	0	0.11	2.45	0.45	63.4	43.3	0.12	7.8	0.24	0.71	14	20.82
ASV 3 10/19/00	5	1.44	43	0.26	6	0.36	4.8	41	23.75	0.49	19.4	0	0.13	2.46	0.52	65.1	140	0.16	7.5	1.1	2.3	13.7	3.17
ASV 4 10/19/00	13	1.51	46	0.24	7.4		6.5	37.5	28.36	0.48	23.3	0	0.11	7.46	1.02	53.9	186	0.36	7.7	1.23	3.05	14	-3.14
ASV C 11/17/00	3	1.67	42	0	6	0.33	4.9	45	22.04		24.1		0.11	1.07	0.39	61.4	143	0.04	6.83	0.51	2.34	13.5	3.94
ASV 3 11/17/00	5	1.44	34	2.09	5.3	0.37	5.5	46	25.79		23.4		0.1	2.46	0.48	65	145	0.2	7.57	0.54	2.38	14.6	-0.92
ASV 4 11/17/00	13	1.52	50	0.74	7.4	0.81	6.8	37.5	25.68		25.4		0	5.62	0.92	60	144	0.05	6.97	1.6	2.36	14.5	5.54
ASV C 1/21/01	3	1.67	61	0.45	10	0.5	4.2	50	29.53	0.49	50.5	1.37	0.18	1	0.37	82	153	0.2	7.56	0.51	2.51	13.5	3.81
ASV 3 1/21/01	5	1.46	61	0.45	10	0.5	5	48	22.15	0.51	50.1	0	0.2	3.1	0.4	86.5	147	0.22	7.6	0.66	2.41	15.5	3.36
ASV 4 1/21/01	13	1.54	32	0.21	5	0.63	3	24	20.87	0.45	24.7	3.52	0.16	0.06	0.83	59	172	0.08	7.1	0.9	2.83	14.5	-20.35
Rio ASV 1/21/01	River	N/A	45	0	6.90	0	6.1	48		0.54	30	0.16	0.15	4.87	0	61.5	156	0.4	7.85	6	2.58	NV	2.51
ASV C 2/27/01	3	1.65	59	0.67	9	0.49	4	46	26.44	0.48	39.1	0	0.15	2.41	0.37	79.6	177	0.07	7.03	0.38	2.91	13.1	0.79
ASV 3 2/27/01	5	1.45	58	0.2	8.00	0.46	4.8	42	21.87	0.48	36.4	0	0.15	2.95	0.43	82.6	171	0.13	7.31	1.14	2.8	15.3	-0.98
ASV 4 2/27/01	13	1.56	50	0	7.50	0.73	5	39	19.69	0.44	24.6	0	0.12	4.93	0.86	61	178	0.14	7.35	2.64	2.91	15.2	-0.42
Rio ASV 2/27/01	River	N/A	40	0	6.9	0.02	4.9	42	19.75	0.49	23.8	0.49	0.09	2.26	0.17	55.1	165	0.29	7.68	8.15	2.72	9.2	-1.09

Sample	Well Depth (m)	Depth to water (m)	Ca (mg/L)	Fe (mg/L)	Mg (mg/L)	Mn (mg/L)	K (mg/L)	Na (mg/L)	SiO_2 (mg/L)	F (mg/L)	Cl (mg/L)	NO_2 (mg/L)	Br (mg/L)	NO_3 (mg/L)	PO_4 (mg/L)	SO_4 (mg/L)	HCO_3 (mg/L)	CO_3 (mg/L)	pH	DO (mg/L)	Alk (meq/kg)	T (C)	Charge balance %
ASV C 3/25/01	3	1.60	51	0.65	10	0.47	4	43	23.7	0.46	34.6	0	0.19	2.75	0.41	73.6	176	0.31	7.68	0.36	2.9	14	-0.99
ASV 3 3/25/01	5	1.38	50.5	0.03	10	0.44	4.5	43	26.48	0.49	34	1.38	0.13	0.58	0.36	80.1	176	0.27	7.62	1.06	2.9	15	-2.33
ASV 4 3/25/01	13	1.44	44	0.01	9.3	0.64	4.75	38	23.77	0.44	23.9	0	0.16	4.48	0.86	60.2	163	0.25	7.63	1.6	2.68	14.9	0.34
Rio ASV 3/25/01	River	N/A	37	0.01	8.3	0.01	6	63	26.62	0.65	43.3	0	0.15	3.96	0.23	65.6	162	0.61	8.01	8.72	2.67	16.7	0.58
ASV C 4/21/01	3	1.60	54	1.07	9.5	0.5	3.5	40	26.48	0.46	30.4	0	0.13	2.72	0.45	71.5	159	0.13	7.33	0.22	2.62	14.9	3.08
ASV 3 4/21/01	5	1.35	56	0.1	9.3	0.45	4.5	42.5	25.8	0.48	29.3	1.83	0.13	0.68	0.44	75.2	164	0.23	7.59	1.03	2.7	15.4	3.39
ASV 4 4/21/01	13	1.43	51	1.04	8.5	0.71	5.5	36.5	25.26	0.49	23.3	0	0.15	6.19	0.88	59.4	161	0.16	7.44	2.19	2.64	15.2	3.54
Rio ASV 4/21/01	River	N/A	37	0	6.2	0	6.25	42	28.58	0.57	28.7	1.51	0.13	3.05	0.16	45.4	142	0.35	7.83	6.79	2.33	15.2	1.66
ASV C 5/23/01	3	1.38	51	0.48	8.2	0.41	4	52	25.09	0.46	32.7	0	0.19	0	0.34	68.5	170	0.04	6.82	0.32	2.79	15.9	4.08
ASV 3 5/23/01	5	1.04	51	0.14	8.9	0.43	4	49	24.57	0.53	34.3	0	0.09	0.08	0.33	69.2	175	0.2	7.49	0.85	2.88	15.6	1.92
ASV 4 5/23/01	13	1.12	49	0	8.6	0.88	6.5	43	27.97	0.47	24.9	0.31	0.08	0.63	0.8	59.8	178	0.14	7.32	0.75	2.92	15.3	2.92
Rio ASV 5/23/01	River	N/A	27	0	5.7	0	4	27	21.99	0.36	16.8	0	0.05	1.03	0.11	29.3	103	0.08	7.35	6.15	1.7	19.3	4.74
ASV C 6/20/01	3	1.67	50	0.22	8	0.39	4	47.8	23.66	0.44	34.7	0	0.11	0	0.25	61.2	202	2.5	8.53	0.47	3.39	16.9	-2.87
ASV 3 6/20/01	5	1.36	52	0.35	8.1	0.49	4.3	46	21.44	0.4	37.8	0	0.12	0.03	0.28	64.3	179	0.24	7.56	0.71	2.94	14.8	0.3
ASV 4 6/20/01	13	2.54	46	0.45	7.9	0.9	8	40	27.57	0.46	26.9	0	0.1	0.14	0.75	53.6	166	0.19	7.48	1.57	2.73	16.4	3.04
Rio ASV 6/20/01	River	N/A	29	0.07	4.9	0	5	29	25.14	0.41	16.5	0	0.09	2.19	0.24	32.8	109	0.16	7.61	5.1	1.8	26.1	3.78
ASV C 7/11/01	3	1.67	49	0.37	8.5	0.43	3.9	48	22.85	0.44	38.2	0	0.13	0.01	0.37	60.7	172	0.05	6.92	0.58	2.82	17	1.58
ASV 3 7/11/01	5	1.37	49	0.32	8.6	0.46	4	44	20.9	0.4	39.8	0	0.1	0.03	0.25	61.9	171	0.08	7.12	0.78	2.81	14.3	-0.53
ASV 4 7/11/01	13	1.46	46	1.03	7.5	0.96	6.5	39	27.03	0.52	24.1	0	0.1	0.07	0.75	52.2	165	0.98	8.21	1.44	2.74	15.1	3.17
Rio ASV 7/11/01	River	N/A	32	0.1	5.6	0	5	36.1	23.19	0.44	24.2	0.12	0.08	4.54	0.32	39.1	104	0.04	7.00	5.4	1.71	26.7	6.26

BLN 2 DMLS 4/19/01-5/5/01

Depth Range (m)	Avg Depth (m)	Ca (mg/L)	Fe (mg/L)	Mg (mg/L)	Mn (mg/L)	K (mg/L)	Na (mg/L)	F (mg/L)	Cl (mg/L)	NO_2 (mg/L)	Br (mg/L)	NO_3 (mg/L)	PO_4 (mg/L)	SO_4 (mg/L)	HCO_3 (mg/L)	CO_3 (mg/L)	pH	DO (mg/L)	Alk (meq/kg)	T (C)	Charge balance %
1-1.1	1.05	54	1.67	8.5	0.73	3	35.5		1.04		382.5			0.00			2.53		5.55	18.2	
1.1-1.2	1.15	73	2.37	11.9	1	3.5	46		25.62			0.98		26.82	361.8	0.27	7.31	5.93	0.79	12.6	-2.80
1.2-1.3	1.25	73	3.06	11.5	1	3.5	45		26.00					26.73					0.57	10.6	
1.3-1.4	1.35	74	2.81	12	0.94	3.5	43		26.23					24.09					0.38	9.7	
1.4-1.5	1.45	73	2.87	11.8	0.98	3.5	48.5		26.62					27.67					0.38	9.4	
1.5-1.6	1.55	74	2.65	11.5	0.88	3.5	45		27.08					33.11	387.5	0.44	7.49	6.35	0.38	9.4	-6.79
1.6-1.7	1.65	75	2.74	11.9	0.9	3.5	45		27.01					37.67					0.36	9.3	
1.7-1.8	1.75	73	2.65	11.8	1.01	3.25	42.5		26.95					48.52	382	0.44	7.5	6.26	0.36	9.3	-9.19
1.8-1.9	1.85	73	2.65	12	1.17	4.5	45		27.16					65.72					0.36	9.2	
1.9-2.0	1.95	69	2.3	11.5	1.32	3.25	39		27.19					80.97					0.37	9.1	
2.0-2.1	2.05	63	2.3	11.5	1.37	3.25	40		27.34					93.46					0.31	9	
2.1-2.2	2.15	63	0.32	11.3	1.35	3	42		27.60					97.20					0.29	9	
2.2-2.3	2.25	57	1.87	11	1.43	3	44		27.39					97.41					0.3	8.9	
2.3-2.4	2.35	56	0.34	11	1.47	3	46.5		27.26					96.66	236.1	0.17	7.3	3.87	0.3	8.9	-6.27
2.4-2.5	2.45	56	0.34	11	1.39	3	46		27.29					96.24					0.29	8.8	

4/19/01 water table (m)	1.27	Values above dashed line indicate cells did not equilibrate.
5/5/01 water table (m)	1.06	

BLN 2 DMLS 5/5/01-5/30/01

Depth Range (m)	Avg Depth (m)	Ca (mg/L)	Fe (mg/L)	Mg (mg/L)	Mn (mg/L)	K (mg/L)	Na (mg/L)	F (mg/L)	Cl (mg/L)	NO_2 (mg/L)	Br (mg/L)	NO_3 (mg/L)	PO_4 (mg/L)	SO_4 (mg/L)	HCO_3 (mg/L)	CO_3 (mg/L)	pH	DO (mg/L)	Alk (meq/kg)	T (C)	Charge balance %
88-97	0.9	74	1.50	12	0.8	12	57	lost	lost	lost	lost	lost	lost	lost	333	0.06	6.78	5.45		23.6	
97-106	1.0	68	2.22	11.5	0.72	10.5	54	0.47	30.51	0.18	0.10	0.59	0.44	95.7	212	0.23	lost	3.49		lost	5.02
106-115	1.1	67	2.09	11.7	0.73	10.5	54	0.40	30.26	0.00	0.09	0.34	0.45	95.3			8.1		1.11	27.0	
115-127	1.2	65	1.82	11.2	0.67	10	55	0.40	29.98	0.00	0.08	0.18	0.33	94.5			7.9		0.91	lost	
127-136	1.3	68	1.82	11.6	0.75	9.5	59	0.47	30.87	0.28	0.07	0.57	0.33	96.8			7.81		0.77	25.4	
136-145	1.4	67	1.48	12.1	0.8	9.3	58	0.44	31.45	0.00	0.07	0.10	0.23	98.3			7.7		0.61	25.7	
145-154	1.5	68	1.68	10.9	0.89	8.9	59	0.44	32.43	0.21	0.09	0.13	0.24	100.7			7.52	lost	0.55	25.6	
157-166	1.6	72	1.95	11.6	0.93	8.9	63	0.44	33.73	0.16	0.07	0.20	0.12	103.8			7.49		0.37	26.4	
166-175	1.7	74	2.03	12.5	0.93	10.4	72	0.41	37.25	0.00	0.08	0.06	0.25	118.3			7.47		0.35	26.5	
175-184	1.8	73	1.85	11.7	0.91	6.5	63	0.44	32.21	0.00	0.08	0.11	0.08	95.2			7.44		0.27	26.5	
184-197	1.9	67	1.89	10.9	1.14	4.6	49	0.50	29.14	0.10	0.07	0.05	0.10	90.4	224	0.09	7.38	3.67	0.28	25.4	1.46
197-206	2.0	63	2.03	11	1.27	4.6	47	0.46	28.57	0.27	0.09	0.13	0.09	90.4			7.34		0.31	26.2	
206-214	2.1	64	2.23	10.8	1.42	4.5	47	0.45	28.30	0.12	0.07	0.01	0.11	91.1			7.36		0.27	24.4	
214-223	2.2	63.5	1.87	10.8	1.45	4.7	46	0.44	29.40	0.00	0.09	0.10	0.19	89.1	196	0.09	7.36	3.21	0.26	26.8	3.02

5/30/01 water table (m) 1.06

5/5/01 water table (m) 1.00

SHK 2 MLS 5/23/01-6/20/01

Depth Range (m)	Avg Depth (m)	Ca (mg/L)	Fe (mg/L)	Mg (mg/L)	Mn (mg/L)	K (mg/L)	Na (mg/L)	F (mg/L)	Cl (mg/L)	NO$_2$ (mg/L)	Br (mg/L)	NO$_3$ (mg/L)	PO$_4$ (mg/L)	SO$_4$ (mg/L)	HCO$_3$ (mg/L)	CO$_3$ (mg/L)	pH	DO (mg/L)	Alk (meq/kg)	T (C)	Charge balance %
1.2-1.3	1.25	2	0.11	BD	0	BD	1	0.01	1.04	0	0.15	113	0.04	0.21			3.04				
1.3-1.4	1.35	2	0.09	BD	0	BD	1	0.01	0.81	0	0.19	89.81	0.00	0.22			3.13				
1.4-1.54	1.47	2	0.1	BD	0	BD	1	0.02	1.36	0	0.21	89.24	0.21	0.27			3.08	0.60		19.4	
1.54-1.65	1.60	4	0.09	BD	0	BD	1	0.01	1.69	0	0.18	88.37	0.00	0.39	55.53	0	5.88	0.26	0.91	16.6	
1.65-1.76	1.71	63	0.33	7.8	0.07	3.8	46.1	0.43	31.42	0.017	0.14	11.21	0.15	55.18	145.2	0.02	6.21	0.19	2.38	15.8	12.14
1.76-1.87	1.82	51	0.29	8.5	0.16	4	47	0.45	34.12	0	0.10	3.27	0.26	66.79	164.1	0.02	6.15	0.15	2.69	15.5	2.66
1.87-1.98	1.93	54	0.6	8.9	0.34	3.9	50	0.46	35.17	0	0.11	0.01	0.22	65.56	163.5	0.02	7.19	0.15	2.68	15.4	6.17
1.98-2.09	2.04	48	0.62	8.1	0.34	3.8	49	0.48	34.81	0	0.12	0.00	0.37	64.55	134.9	0.16	7.29	0.12	2.21	15.3	7.54
2.09-2.2	2.15	51	0.7	8.6	0.34	3.9	49	0.45	34.92	0	0.10	0.00	0.42	64.37	164.8	0.14	7.37	0.12	2.70	15.1	4.30
2.2-2.3	2.25	51	0.7	8.8	0.34	3.9	47	0.41	35.15	0	0.10	0.00	0.43	65.20	153.2	0.11	7.28	0.11	2.51	15	5.34
2.3-2.43	2.37	50	0.69	8.5	0.34	4	49	0.46	35.21	0	0.12	0.02	0.47	65.07	164.8	0.17	7.46	0.10	2.70	14.9	3.54
2.43-2.54	2.49	48	0.6	7.8	0.34	3.7	47	0.50	35.31	0	0.10	0.03	0.30	64.97	lost	lost	7.42	0.10	lost	14.7	

5/23/01 water table (m)	0.32	Values above dashed line indicate cells did not equilibrate.
6/20/01 water table (m)	1.35	

SHK 2 MLS 6/20/01-7/11/01

Depth Range (m)	Avg Depth (m)	Ca (mg/L)	Fe (mg/L)	Mg (mg/L)	Mn (mg/L)	K (mg/L)	Na (mg/L)	F (mg/L)	Cl (mg/L)	NO_2 (mg/L)	Br (mg/L)	NO_3 (mg/L)	PO_4 (mg/L)	SO_4 (mg/L)	HCO_3 (mg/L)	CO_3 (mg/L)	pH	DO (mg/L)	Alk (meq/kg)	T (C)	Charge balance %
1.2-1.3	1.25	3	0.19	BD	BD	BD	BD	0.01	65.57	0	0.03	0.19	0.07	0.64			2.89				
1.3-1.4	1.35	2	0.18	BD	BD	BD	BD	0.01	61.93	0	0.00	0.16	0.04	0.37			2.94				
1.4-1.54	1.47	2	0.27	BD	BD	BD	BD	0.01	65.54	0	0.00	0.21	0.00	0.65			2.92	3.79		19.5	
1.54-1.65	1.60	2	0.16	BD	BD	BD	BD	0.01	60.28	0	0.02	0.28	0.00	0.50			lost	0.2		16	
1.65-1.76	1.71	0	0.11	BD	BD	BD	BD	0.00	18.83	0	0.15	117	0.03	0.27			2.75	0.17		15.6	
1.76-1.87	1.82	0	0.08	BD	BD	BD	1	0.01	19.49	0	0.14	107	0.04	0.18			2.74	0.19		15.2	
1.87-1.98	1.93	42	0.32	8.9	0.32	3.9	49	0.42	39.41	0.33	0.11	0.20	0.30	64.32	162.3	0.11	7.28	0.17	2.66	14.9	-0.71
1.98-2.09	2.04	48	0.95	8.8	0.37	4	50	0.46	39.37	0	0.11	0.02	0.43	64.22	170.9	0.19	7.48	0.16	2.8	14.7	1.43
2.09-2.2	2.15	45	0.73	8.6	0.34	4	47	0.48	39.88	0	0.11	0.02	0.37	64.37	181.8	0.41	7.79	0.14	2.98	14.6	-3.33
2.2-2.3	2.25	44	0.72	8.9	0.35	3.9	47	0.43	39.09	0	0.13	0.00	0.33	64.27	178.8	0.14	7.33	0.12	2.93	14.5	-2.80
2.3-2.43	2.37	42	0.71	8.5	0.35	3.9	46.1	0.43	39.82	0	0.12	0.01	0.36	64.36	164.8	0.12	7.31	0.15	2.7	14.3	-2.57
2.43-2.54	2.49	45	0.66	8.5	0.35	3.7	47	0.46	39.27	0	0.11	0.01	0.40	64.02	155.6	0.12	7.25	0.15	2.55	14.2	0.89

6/20/01 water table (m)	1.35	Values above dashed line indicate cells did not equilibrate.
7/11/01 water table (m)	1.35	

Appendix B. Particle Size Data

Belen 1:

Depth Range (cm)	Average Depth (m)	% Sand	% Silt	% Clay
0-30	0.15	95.71	2.15	2.14
30-182	1.07	97.55	1.22	1.23
182-335	2.59	97.50	1.25	1.25
335-488	4.11	96.65	1.65	1.70
488-563	4.50	93.95	3.65	2.40
563-640	6.02	97.10	0.50	2.40
640-716	6.78	95.55	2.05	2.40
792-869	8.31	92.85	4.75	2.40
869-945	9.07	89.76	7.84	2.40
945-1021	9.83	92.50	5.10	2.40
1021-1097	10.59	92.10	5.50	2.40
1173-1250	12.12	95.80	4.20	0.00
1250-1326	12.88	95.65	4.35	0.00
1326-1402	13.64	95.15	4.85	0.00
1495-1555	15.25	54.87	21.14	23.99
1555-1631	15.93	92.91	7.79	0.00
1631-1717	16.74	92.15	7.85	0.00

Belen 3:

Depth Range (cm)	Average Depth (m)	% Sand	% Silt	% Clay
0-15	0.08	53.92	31.80	14.29
15-30	0.23	58.62	31.78	9.60
30-45	0.38	83.15	12.05	4.80
45-60	0.53	78.06	12.34	9.60
60-76	0.69	65.77	12.64	21.59
76-91	0.84	93.45	1.75	4.80
91-107	0.99	96.45	1.15	2.40
107-122	1.14	97.20	0.40	2.40
122-137	1.30	96.90	0.70	2.40
137-152	1.45	95.25	2.35	2.40

Belen 2:

Depth Range (cm)	Average Depth (m)	% Sand	% Silt	% Clay
0-15	0.08	98.41	1.59	0.00
15-30	0.23	99.30	0.70	0.00
30-45	0.38	99.20	0.80	0.00
45-60	0.53	99.30	0.70	0.00
60-76	0.69	99.20	0.80	0.00
76-91	0.84	99.40	0.60	0.00
91-107	0.99	99.20	0.80	0.00
107-122	1.14	98.95	1.05	0.00
122-137	1.30	98.45	1.55	0.00
137-152	1.45	99.10	0.90	0.00
152-168	1.60	99.05	0.95	0.00
168-183	1.75	99.15	0.85	0.00
183-198	1.91	98.90	1.10	0.00
198-213	2.06	99.05	0.95	0.00
213-229	2.21	99.15	0.85	0.00
229-244	2.36	98.98	1.05	0.00
244-259	2.51	99.10	0.90	0.00
259-274	2.67	99.00	1.00	0.00
274-290	2.82	99.15	0.85	0.00
290-305	2.97	99.15	0.85	0.00
305-320	3.12	99.05	0.95	0.00
320-335	3.28	99.25	0.75	0.00
335-350	3.43	99.05	0.95	0.00
350-366	3.58	99.10	0.90	0.00
366-381	3.73	99.15	0.85	0.00
381-396	3.89	99.20	0.80	0.00
396-411	4.04	99.15	0.85	0.00
411-427	4.19	99.30	0.70	0.00
427-442	4.34	99.25	0.75	0.00
442-457	4.50	98.90	1.10	0.00
457-472	4.65	99.05	0.95	0.00
472-488	4.80	98.45	1.55	0.00
488-503	4.95	99.05	0.95	0.00
503-518	5.11	98.70	1.30	0.00
518-533	5.26	98.75	1.25	0.00
533-549	5.41	98.40	1.60	0.00

ASV 1:

Depth Range (cm)	Average Depth (m)	% Sand	% Silt	% Clay
0-101	0.51	96.60	1.00	2.40
101-254	1.78	96.45	3.55	0.00
254-406	3.30	95.40	4.60	0.00
406-559	4.83	98.20	1.80	0.00
559-711	6.35	98.00	2.00	0.00
711-864	7.87	97.70	2.30	0.00
864-1016	9.40	98.60	1.40	0.00
1016-1168	10.92	98.85	1.15	0.00
1168-1320	12.45	98.20	1.80	0.00
1320-1473	13.97	98.50	1.50	0.00
1473-1626	15.49	98.40	1.60	0.00
1626-1778	17.02	97.95	2.05	0.00
1778-1930	18.54	98.20	1.80	0.00

ASV 3:

Depth Range (cm)	Average Depth (m)	% Sand	% Silt	% Clay
0-17	0.08	97.95	2.05	0.00
8-25	0.17	98.15	1.85	0.00
25-41	0.33	98.05	1.95	0.00
41-58	0.50	98.15	1.85	0.00
58-66	0.59	98.40	1.60	0.00
66-83	0.75	98.25	1.75	0.00
83-99	0.91	98.25	1.75	0.00
99-116	1.08	98.45	1.55	0.00
116-132	1.24	98.30	1.70	0.00
132-149	1.41	86.30	13.70	0.00
149-165	1.57	98.61	1.39	0.00
165-182	1.74	98.57	1.43	0.00
182-198	1.91	98.46	1.54	0.00
198-215	2.07	98.75	1.25	0.00
215-236	2.24	98.05	1.95	0.00
236-253	2.40	98.30	1.70	0.00
253-269	2.57	97.69	2.31	0.00
269-286	2.73	98.24	1.76	0.00
286-302	2.90	98.00	2.00	0.00
302-319	3.06	98.45	1.55	0.00
319-337	3.23	98.80	1.20	0.00
337-352	3.39	98.56	1.44	0.00
352-368	3.56	98.96	1.04	0.00
368-385	3.72	98.30	1.70	0.00
385-401	3.89	98.57	1.43	0.00
401-418	4.05	98.75	1.25	0.00
418-434	4.22	47.80	49.88	2.32
434-451	4.38	98.25	1.75	0.00
451-467	4.55	98.35	1.65	0.00
467-489	4.76	98.30	1.70	0.00
489-505	4.93	97.00	3.00	0.00
505-522	5.09	95.45	4.55	0.00
522-538	5.26	97.70	2.30	0.00
538-555	5.42	98.20	1.80	0.00
555-572	5.59	97.55	2.45	0.00
572-588	5.75	98.91	1.09	0.00
588-604	5.92	98.57	1.43	0.00
604-621	6.08	96.70	3.30	0.00
621-638	6.25	98.05	1.95	0.00
638-658	6.45	98.21	1.79	0.00
658-674	6.62	98.71	1.29	0.00
674-691	6.78	99.25	0.75	0.00
691-707	6.95	98.10	1.90	0.00
707-721	7.11	98.25	1.75	0.00

ASV 4:

Depth Range (cm)	Average Depth (m)	% Sand	% Silt	% Clay
0-76	0.38	98.20	1.80	0.00
76-229'	1.14	97.85	2.15	0.00
229-381	3.05	97.60	2.40	0.00
381-533	4.57	96.71	3.29	0.00
533-610	5.72	97.76	2.24	0.00
610-686	6.48	98.15	1.85	0.00
686-762	7.24	98.05	1.95	0.00
762-838	8.00	96.25	3.75	0.00
838-914	8.76	98.05	1.95	0.00
914-991	9.53	98.70	1.30	0.00
991-1067	10.29	98.10	1.90	0.00
1067-1143	11.05	97.95	2.05	0.00
1143-1219	11.81	96.85	3.15	0.00
1219-1295	12.57	95.10	4.90	0.00
1295-1372	13.34	95.35	4.65	0.00
1372-1448	14.10	96.40	3.60	0.00

Core ASV 4A:

Depth Range (cm)	Average Depth (m)	% Sand	% Silt	% Clay
0-5	0.03	40.25	55.02	4.73
5-10	0.08	33.94	56.55	9.51
10-15	0.13	31.33	63.87	4.80
15-20	0.18	31.02	61.89	7.09
20-25	0.23	22.65	72.62	4.73
25-30	0.28	73.11	19.68	7.21
30-35	0.33	28.91	67.09	4.79
35-40	0.38	22.11	68.44	9.45
40-45	0.43	59.68	30.79	9.53
45-50	0.48	57.92	37.33	4.75
50-55	0.53	52.07	45.50	2.43
55-60	0.58	84.73	12.98	2.29
60-66	0.64	94.26	5.75	0.00
66-71	0.69	93.1	6.90	0.00
71-76	0.74	96.3	3.70	0.00
76-81	0.79	95.2	2.40	2.40
81-86	0.84	96.75	3.25	0.00
86-91	0.89	97.9	2.10	0.00
91-96	0.94	95.6	4.40	0.00
96-101	0.99	97.35	2.65	0.00
106-117	1.12	97.35	2.65	0.00
117-127	1.22	95.15	4.85	0.00
147-152	1.50	96.35	3.65	0.00

Appendix C. Nitrate Statistics

	Belen 3 m	ASV 3 m	Belen 5 m	ASV 5 m
Mean	0.58	1.03	0.60	1.00
Standard Error	0.27	0.35	0.14	0.34
Median	0.04	0.51	0.58	0.23
Mode	0.00	0.00	N/A	N/A
Standard Deviation	1.00	1.21	0.52	1.24
Sample Variance	1.01	1.46	0.27	1.53
Kurtosis	2.06	-1.73	-1.80	-1.12
Skewness	1.72	0.54	0.14	0.92
Range	3.13	2.75	1.43	3.07
Minimum	0.00	0.00	0.02	0.03
Maximum	3.13	2.75	1.44	3.10
Sum	8.11	12.40	8.44	12.97
Count	14	12	14	13

	Belen 13 m	ASV 13 m	Belen RG	ASV RG
Mean	1.03	2.88	2.77	4.88
Standard Error	0.18	0.86	0.43	1.81
Median	0.94	0.63	2.89	3.51
Mode	N/A	N/A	N/A	N/A
Standard Deviation	0.71	3.10	1.36	5.11
Sample Variance	0.50	9.61	1.86	26.07
Kurtosis	0.06	-1.88	-0.76	6.52
Skewness	1.02	0.38	0.05	2.47
Range	2.27	7.40	4.33	16.07
Minimum	0.14	0.06	0.76	1.03
Maximum	2.41	7.46	5.08	17.10
Sum	15.51	37.48	27.70	39.01
Count	15	13	10	8

Statistical data on nitrate concentrations (mg/L). RG indicates Rio Grande samples.

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