Investigation of the Hydrologic Connection between the Moab Mill Tailings and the Matheson Wetland Preserve

by

Philip Gardner and D. Kip Solomon
Department of Geology and Geophysics, University of Utah

December 11, 2003

Table of Contents

List of Tables

Table 1. Well information including; type of installation, survey coordinates, top of casing elevation, depth to center of screen below measuring point, and screen length. All horizontal survey coordinates were converted to UTM relative to NAD 27 datum using Corpscon for Windows 5.11.08 software. This was done for plotting on an orthophotoquad obtained from Utah Division of Water Rights website (http://nrwrt1.nr.state.ut.us/gisinfo/default.htm).

Table 2. Field parameters and water levels measured at the Moab Mill Tailings and Matheson Wetland Preserve between July 4 and August 5, 2003.

Table 3. Ground and surface water chemistry data from the Moab Mill Tailings and Matheson Wetland Preserve between July 4 and August 5, 2003.

Table 4. Equivalent freshwater hydraulic heads and values used in their calculation.

Table 5. Stable isotope ratios of hydrogen versus oxygen in surface and ground water samples collected during April, July, and August, 2003.

Table 6. Tritium and dissolved gas data from surface and ground water samples collected during July and August, 2003.

List of Figures

Figure 14. Stable isotope ratios of hydrogen versus oxygen in surface and ground water samples from the Moab Mill Tailings and Matheson Wetland Preserve compared to the Utah meteoric water line from Kendall and Coplen, 2001.

Figure 15. Cross section A-A' showing $\delta^{18}O$ values displayed at sampling points in the subsurface.

Figure 16. Cross section B-B' showing $\delta^{18}O$ values displayed at sampling points in the subsurface.

Figure 17. Cross section A-A' showing ^{3}H values displayed at sampling points in the subsurface.

Figure 18. Cross section A-A' showing R/Ra values displayed at sampling in the subsurface.

Figure 19. Cross section A-A' showing terrigenic ^{4}He values displayed at sampling points in the subsurface.

Figure 20. Cross section B-B' showing ^{3}H values displayed at sampling points in the subsurface.

Figure 21. Cross section B-B' showing R/Ra values displayed at sampling points in the subsurface.

Figure 22. Cross section B-B' showing terrigenic ^{4}He values displayed at sampling points in the subsurface.

Executive Summary

We have investigated the subsurface hydrologic connection between the Moab Mill Tailings and the Matheson Wetland Preserve. Geochemical, geological, and hydrophysical data were collected from existing wells along with 9 new wells installed specifically for this project. Specific goals of this project included:

Further definition of the extent of channel gravels that underlie the site that might be a conduit allowing ground water to pass beneath the Colorado River from the Moab Mill Tailings toward the Matheson Wetland Preserve.

Investigation of the sources of ground water recharge and the extent of evaporation that waters have undergone in order to further understand the hydrodynamics of the alluvial aquifer near the Colorado River in Moab valley.

Determination of the age of contaminated uranium mill process water in order to define the age of fluids associated with contamination.

Investigation of the brine as a lower boundary to the shallow water flow system.

Assembling a collection of baseline chemistry data from sites on both sides of the river that were collected at the same period in time. The seasonal dynamics of the groundwater system make this important so that chemistry data is directly comparable.

Clearer definition of the extent of channel gravels was accomplished by successfully drilling three new boreholes in these gravels on the Matheson Wetland property and collecting and logging core. Lithologic logs from these boreholes show that the channel gravels exist at a depth of around 5.5 m (18 ft) beneath ground surface across the northwestern portion of the Wetland Preserve and that they extend more than 700 m (2,300 ft) inland from the present river channel.

Tritium, noble gas, and stable isotope analyses were used to understand groundwater ages and sources of recharge. Oxygen and hydrogen isotopes indicate a wide range of recharge elevations and

together with noble gas data, suggest hydrologic connection exists beneath the river between the Moab Mill Site and the Matheson Wetland. Tritium concentrations together with noble gas data delineate very old brine at depth from shallower briny waters that include components of young water. Tritium concentrations in waters of four highly contaminated wells on the Moab Mill Tailings property confirm their age as less than 50 years and imply downward migration of contaminated waters to depths of more than 21 m (70 ft).

Comparison of ammonia, sulfate, and chloride data from both the Mill Tailings and the Wetland Preserve indicate that the reactive nature of ammonia coupled with the natural and artificial sources of highly saline waters make difficult to distinguish naturally occurring ammonia from contamination; reinforcing the need for additional isotopic studies such as nitrogen-15 analyses. Uranium concentrations in ground water from the Mill Site and the Wetland Preserve reveal a pattern that suggests contamination has migrated beneath the river and this pattern is reinforced by southeast trending equivalent freshwater hydraulic head gradients within the brine near the top of the of channel gravels.

1.0 Introduction

The University of Utah (U of U) has been investigating the hydrology of the Matheson Wetland Preserve, located near Moab, Utah since the fall of 2001. As part of this investigation, shallow piezometers have been installed to monitor ground water levels and to evaluate geochemical conditions in the subsurface. In March, 2003, the U. S. Department of Energy (DOE) sampled some of these piezometers for uranium (U) and ammonia (NH_3). Both are known contaminants to ground water beneath the Moab Mill Tailings resulting from uranium milling operations from 1956 to 1984. Uranium concentrations ranged from 0.0159 to 0.007 mg/L while ammonia as nitrogen ranged from 3 to 0.01 mg/L (DOE, 2003). The highest concentrations found by the DOE in the Matheson Wetland occur in piezometers that were driven into the top of channel gravels that underlie the site and that are located near the Colorado River and south of the Moab Mill Tailings. The magnitude of these concentrations and the location of the highest values suggest that ground water from the Mill Tailings is flowing under the Colorado River and impacting ground water beneath the Matheson Wetland Preserve.

This project was undertaken to further investigate the hydrologic connection between the Moab Mill Tailings and the Matheson Wetland Preserve. Three new boreholes (BL1, BL2, and BL3) were drilled on the Wetland Preserve and lithologic logs were constructed to further understand the spatial distribution of high-permeability channel gravel deposits. Samples were collected from 44 sites on both sides of the Colorado River and analyzed for oxygen-18 and deuterium isotopes on water, nitrogen-15 isotopes on total ammonia-nitrogen, tritium, noble gases including helium-3 and helium-4, chloride, sulfate, ammonia-nitrogen, and uranium. In addition, water levels and field parameters (specific conductance, temperature, and total dissolved gas pressure) were measured. Ten of the sites were existing DOE monitoring wells on the Moab Mill Tailings property on the north side of the Colorado River. Twenty five of the sites were existing shallow piezometers and surface water sites on the Matheson Wetland Preserve. The remaining nine sites were triple completion well nests installed in the three new boreholes drilled on the Wetland Preserve (BL1-S, M, and D; BL2-S, M, and D; BL3-S, M, and D).

Oxygen-18 and Deuterium analyses were preformed to provide insight regarding the elevation of recharge, and the degree of evaporation that has occurred in tailings water. Tritium and noble gases were measured in order to understand the age distribution of ground water. In particular, they help define the age of fluids associated with uranium and ammonia concentrations at the Mill Tailings site.

Nitrogen-15 isotopes are currently being measured in hopes of establishing an isotopic "fingerprint" for nitrogen species that originated from the processing of mill tailings. The hypothesis is that the nitrogen-15 signature of ammonium in the mill tailings fluids will be distinct from "natural" sources of nitrogen in groundwater. The high salinity of waters sampled for nitrogen isotopes prohibits extraction of nitrogen species from these waters in the usual manner. A process to perform these extractions that insures 100% recovery of nitrogen species is being developed. As such, the results of these analyses are not available and will be included in a subsequent report to the DEQ.

Prior investigation by the University of Utah of the Matheson Wetland Preserve has shown the hydrodynamics of the alluvial aquifer in this area to be complicated and seasonally variable. Therefore, Cl, SO_4, NH_3 and U analyses were conducted on wells that had been sampled previously along with samples from the newly constructed wells in order to obtain a data set that was temporally consistent.

The conceptual model of the hydrology of the Mill Tailings (presented by the DOE at the Moab Stakeholders meeting held May 31, 2003) implies that the Colorado River is a boundary to fluid flow. The data presented in this report (especially the uranium, hydraulic head, and stable isotope data) indicate that the DOE conceptual model may be incomplete.

2.0 Methods

2.1 Drilling and Well Installation

Three new boreholes were drilled and logged on the Matheson Wetland Preserve. The drilling was performed by Boart Longyear Company using a Gus Pech 300 Rotosonic Rig. Each hole was drilled with 9-inch casing so that three 2-inch monitoring wells could be installed at different depths at each location. Lithologic and well completion logs for the 3 boreholes and 9 monitoring wells are included as appendix A.

2.2 Water Level Measurements and Field Parameters

Water levels were measured in 55 wells using a Slope Indicator Inc. electric water level tape with a sensitivity adjustment that facilitated measuring water levels in wells with highly saline waters. Well survey coordinates and other pertinent information are included in Table 1. Water temperature, specific conductance, dissolved oxygen, and total dissolved gas pressure (TDGP) measurements were made down hole in the field using the Hydrolab Corporation Minisonde 4a Water Quality Multiprobe on all 2 inch monitoring wells. On smaller diameter piezometers (less than 2 inches), specific conductivity was measured using the Hydrolab Minisonde 4a on sample water after the well was purged of a minimum of 3 casing volumes of water. Temperature measurements in these small-diameter piezometers were made in-situ using a thermister with an accuracy of ± 0.2 ^{o}C. Total dissolved gas pressure measurements in small diameter piezometers were made using advanced passive diffusion samplers that are conceptually similar to those described in Sanford et al. (1996). These samplers preserve the TDGP so that it can be determined by a baritron pressure gauge on the vacuum line when the sample is inlet to the mass spectrometer for analysis.

2.3 Water Sample Collection, Preservation and Analyses

All ground water samples were collected after wells had been purged of a minimum of 3 casing volumes of water or, in the case of very large volume wells, until field parameters (temperature, total dissolved gas pressure, and specific conductance) had stabilized to within +/- 5%. No groundwater samples were collected from BL3-S since the filter pack interval of the well was contaminated by bentonite slurry resulting from heaving sands during well construction. However, well BL3-S was used to acquire water level and specific conductivity measurements.

The reader will notice that not all wells or piezometers were sampled for the complete suite of constituents (denoted in data tables). The reason for this is that some of the wells, especially small-diameter piezometers screened in fine-grained material, do not yield ample volumes of water required for some of the analyses.

2.3.1 Sulfate and Chloride

Sulfate and chloride samples were collected and analyzed from 40 monitoring wells and 3 surface water locations (all sites except BL3-S). Samples were collected in clean 250 ml plastic bottles that had been triple rinsed with well water. All samples were immediately stored at a temperature of less than 4 ^{o}C and analyzed within 28 days of collection. Analyses for both constituents on 23 of the samples were conducted in the laboratory by the U of U using the Hach Company DR/890 Colorimeter with the Hach Method 8051 for Sulfate and the Hach Company Digital Titrator model 16900 with Hach Method 8206 for Chloride. These samples were filtered in the field using a 0.45 micron filter in order to avoid turbidity. High concentration samples were analyzed after making appropriate dilutions in the laboratory with de-ionized water. Analyses for both constituents on the remaining 20 samples were performed by Energy Laboratories Inc. in Casper, Wyoming using Standard Method 4500-SO4 E for sulfate and Standard Method 4500-Cl B for chloride.

2.3.2 Ammonia

Ammonia samples were collected and analyzed from 40 monitoring wells and 3 surface water locations (all sites except BL3-S). Samples were collected in clean 250 ml plastic bottles that had been triple rinsed with well water. Analyses for ammonia on 23 of the samples were conducted by the U of U in the field using the Hach Company DR/890 Colorimeter with the Hach Method 10023 after field filtering the water to 0.45 microns in order to avoid turbidity. Ammonia analyses on the remaining 20 samples were performed by Energy Laboratories Inc. using Standard Method 4500-NH3-G after being preserved in the field with sulfuric acid and stored and transported at below 4 ^{o}C.

2.3.3 Uranium

Samples for Uranium were collected and analyzed from 38 monitoring wells and 3 surface water sites. Wells N5-7 and W1-4 were omitted (in addition to BL3-S) because of poor recovery after the wells were purged. Samples were collected in clean 250 ml plastic bottles that had been triple rinsed with well water and then preserved with nitric acid. Analyses were conducted by Energy Laboratories Inc. using Inductively Coupled Plasma – Mass Spectrometry USEPA method E200.8.

2.3.4 Oxygen-18 and Deuterium

Samples for Oxygen-18 and Deuterium isotope analyses were collected from 40 monitoring wells and 3 surface water sites (all sites except BL3-S). Samples were collected in clean 10 ml glass vials that had been triple rinsed with well water. The threaded caps of the vials were wrapped with wax film and the bottles were kept cool to avoid any evaporative fractionation during storage. Samples were then analyzed with an isotope-ratio mass spectrometer at the University of Utah Stable Isotope Ratio Facility for Environmental Research. The $\delta^{18}O$ of water was determined by CF-IRMS (after Fessenden et al., 2002) and the δD of water was also measured via IRMS after 5 μl sub-samples were reduced to H_2 using a zinc catalyst at 500^{o}C (modified after Coleman et al., 1982).

2.3.5 Nitrogen-15

Samples for Nitrogen-15 isotope analyses were collected from 40 monitoring wells and 3 surface water sites. Samples were collected in clean 1 L plastic bottles that had been triple rinsed with well water. The threaded caps of the bottles were wrapped with wax film and the bottles were kept cool to avoid any evaporative fractionation during storage. Samples are currently being analyzed at the University of Utah Stable Isotope Ratio Facility for Environmental Research by a new method being developed specifically for high salinity samples.

2.3.6 Tritium

Water samples for Tritium analyses were collected from 39 monitoring wells and 3 surface water sites. Well N9-4 was omitted (in addition to BL3-S) because of poor recovery after the well was purged. Samples were collected in clean 1 L plastic bottles that had been triple rinsed with well water. Tritium analyses were performed at the U of U Dissolved Gas Service Center by the helium in-growth method (Clark and others, 1976). Samples were transferred to copper flasks, degassed and sealed for a minimum radioactive decay period of 5 weeks after which tritiogenic helium-3 concentrations were determined by mass spectrometry and converted to tritium concentrations.

2.3.7 Dissolved Gasses

Dissolved gas samples were collected from 41 monitoring wells using passive submersible diffusion samplers that are conceptually similar to those shown in Sanford et al. (1996). The analyses were performed at the U of U Dissolved Gas Service Center by mass spectrometry on a vacuum clean-up line used to separate gases during analysis (described by Sheldon, 2002).

3.0 Results and Discussion

3.1 Boring Logs

Lithologic logs of the three new borings are included as Appendix A. These borings helped to expand our knowledge of the aerial extent and thickness of the high permeability deposit of ancestral Colorado River gravels. These new borings (now well nests) are shown on the location map of Figure 1 as BL1, BL2, and BL3. Large continuous sequences of these gravels were found in borings BL1 and BL2. Well rounded cobbles of pink granites, diorite porphyry, and mafic schists are evidence that the deposits were laid down by the Colorado River. The top of the river gravels at BL1 is approximately 1202.5 m elevation (3945.2 ft) and the sequence continues as one hydrogeologic unit for a total thickness of more than 40.0 m (131.2 ft). Findings were similar in BL2 with the top of the gravels at 1202.8 m elevation (3946.3 ft) and extending for more than 43.3 m (142.0 ft) beyond the total depth of drilling. Approximately 5.5 m (18 ft) of fine grained sand and silty overbank deposits covered the gravels at both of these sites. The fine grained sand and silt overbank deposits appear to be slightly thicker at BL3, about 8.5 m (28 ft). Although core from BL3 lacked the distinct large sequence of river gravels found at depth in the other two holes, a few high permeability units in the form of small channel deposits with sub-angular to well rounded gravels were found. These small channel deposits are interbedded within finer grained material indicating that the location of BL3 was on the edge of the main Colorado River channel. River gravels found in BL1 and BL2 correlate well with the findings in the DOE logs from their drilling in the summer of 2002 showing the gravel deposit to be more than 1.5 km (4,920 ft) wide in the center of the valley with a maximum thickness of more than 53 m (174 ft) and with the top of the deposit at between 1200 and 1204 m (3937 and 3950 ft) elevation across the site. These logs in conjunction with the lithologic logs from the DOE 2002 summer drilling were used to create cross sections for the purpose of displaying data in the vertical dimension. Figure 2 shows the site map with the minimum extent of the river gravel deposit shaded as well as the two cross section lines, A-A' toward the southwest and B-B' toward the northeast. The lithology shown on all cross sections in figures presented in this report was constructed from the boring logs of sites located near the A-A' and B-B' lines. It is intended to giver the reader a general indication of the distribution of hydrogeologic units. However, with limited information and at the scale of these figures, the lithologic contacts are uncertain and these figures should not be considered as strict geologic cross sections.

3.2 Water Level Measurements and Field Parameters

All water level measurements and parameters directly measured in the field are listed in Table 2. Distinctly different hydraulic heads were encountered in each of the three wells at each of the new boreholes (BL1, BL2, and BL3) on the wetlands indicating that the bentonite seal between well screens in these boreholes is functioning properly. Note that there are no dissolved oxygen measurements from small diameter sampling wells and piezometers (< 2 inch diameter) because the probe is too large to be inserted in them. Total dissolved gas pressure measurements were only made in wells where dissolved gas concentrations were also being measured.

Expected anoxic conditions exist at depth in the alluvial aquifer. Dissolved oxygen (DO) concentrations in the brine layer were all below 0.2 mg/L with the exception of the SMI-PZ1S well where DO was 0.43 mg/L. Wells 432 and 433 had DO concentrations of 4.38 and 1.75 mg/L respectively. These high DO concentrations are consistent with ground water from the Glen Canyon Group Aquifer (Solomon, 2001 – included as Appendix B). These two wells are screened on the outer fringes of the alluvial aquifer in fractured sandstone and ground water from them appears distinctly different throughout the range of analyses performed.

Total dissolved gas pressures vary dramatically across the site with values ranging from 0.805 to > 2.40 atm. The highest pressures were always found in the deepest wells and in brines. In the simplest sense, TDGP values are in equilibrium with the atmospheric pressure at the time of recharge and will be preserved. Dissolved gasses are considerably less soluble in highly saline solutions (Smith and Kennedy, 1983) and would not remain dissolved without sufficient hydrostatic pressure keeping them in solution. Since the expected atmospheric pressure at the elevation of Moab is close to 0.860 atm and waters recharged at higher elevations would have dissolved gas pressures in equilibrium with lower atmospheric pressures, one would expect to find TDGP values close to or less than 0.860 atm in fresh groundwater here. This uniquely wide range of reported values is most likely the result of salinity forced increases in TDGP. In other words, the ground water in many of the samples was considerably less saline (had lower TDS) at the time of its recharge into the aquifer and became substantially saltier after traveling through the subsurface.

Specific conductivity (SpC) measurements yield values ranging from 871 μS/cm in shallow relatively fresh ground and surface water to 150,000 μS/cm in the deeper brine. Ten water samples (including one surface water sample, CR2-river) that spanned the range of SpC values were submitted to Energy Labs Inc. for laboratory total dissolved solids (TDS) analysis. Specific conductivities were then correlated with TDS in order to develop the relationship used to estimate TDS values for the remaining waters sampled across the site. The plot of TDS vs. SpC shown in Figure 3 yields the relationship:

$$TDS(mg/L) = SpC(mS/cm) \times 0.7308\,.$$

Although 0.7308 is a higher than usual slope for the TDS vs. SpC correlation, the same standard solutions were used to calibrate the SpC probe throughout the sampling period; therefore the relationship gives adequate estimates of TDS that are listed in Table 3. Cross sections showing TDS distribution for lines A-A’ and B-B’ are included as Figures 4 and 5.

Water level measurements alone cannot be used to examine directions of ground water flow when the water salinities (thus water densities) vary as they do across this site. Rather, one must compare Equivalent Freshwater Hydraulic Head (EFH) values. The EFH is computed simply by scaling the pressure head (the height of water in a well above the well screen) to what that height would be if the water were fresh. Water level measurements in conjunction with TDS data were used to calculate equivalent freshwater head values as follows:

$$h_f = Z + y \frac{r}{r_f},$$

where

h_f = equivalent freshwater hydraulic head,

Z = elevation head (taken to be the midpoint of the well screen),

Y = pressure head,

r = density of water in the well, and

r_f = density of fresh water.

Water density (r) was estimated for this purpose by adding the TDS value to the density of freshwater (assumed to be 1,000 g/L). For example, water with a TDS value of 100,000 mg/L (100 g/L) in Table 3 has an estimated density of 1,100 g/L. Thus, in the equivalent freshwater head calculation shown above, the pressure head (y) is scaled up by the specific gravity (r/r_f) of 1,100/1000 or 1.1. These EFH values along with the data used to calculate them are included as Table 4. Figures 6 and 7 are constructed from this EFH data. Figure 6 shows water table surface contours compiled from equivalent fresh water hydraulic head values for shallow piezometers and wells where the water had TDS values of less than 20,000 mg/L. At the shallow water table, the highest hydraulic heads are located behind the camp park on the eastern edge of the Wetland Preserve where springs from the Glen Canyon Group Aquifer (GCG) discharge and enter the preserve in surface water ponds. The general horizontal direction of ground water flow is to the west and south across the preserve and toward the Colorado River. Shallow fresh water appears to move southward across the Mill Tailings site, also toward the river.

Figure 7 shows potentiometric surface contours of brine at a common elevation (1190 m or 3904 ft) below the top of the ancestral Colorado River gravels. This figure was compiled from equivalent fresh water hydraulic head values for deep wells with TDS values greater than 40,000 mg/L. In order to create a potentiometric surface for the brine, it was necessary to use measurements from well nests with multiple wells screened in the brine so that the EFH values could be extrapolated back to the common elevation. The elevation of 1190 m (3904 ft) was chosen since boring logs from both the DOE and the U of U confirm this to be below the top of the river gravels and since ground water at this elevation is unvaryingly saline. These restrictions leave only 7 points of EFH available to contour and although it is difficult to present detailed lines of EFH, a clear pattern emerges; EFHs are higher toward the northwest and lower toward the southeast and appear to drop uniformly across the river. This pattern shows that deep ground water in these river gravels has the potential to move beneath the river.

3.3 Water Chemistry

3.3.1 Sulfate and Chloride

Results of 43 sulfate and chloride samples as well as SO_4/Cl ratios are included in Table 3. Sulfate concentrations range from 53 mg/L in the shallow fresh water on the eastern most portion of the preserve (N4-6) to 15,000 mg/L in the most contaminated of the wells sampled on the DOE property. It has been suggested that elevated SO_4/Cl ratios are a useful indicator of contaminated source water since sulfuric acid was used in the uranium extraction process (DOE, 2003). However, the data presented in Table 3 do not show SO_4/Cl to be useful in this respect across these two sites. Groundwater concentrations of SO_4 are greatly elevated in the most contaminated wells at the Mill Tailing site (SMI-PZ1S, SMI-PZ1M, SMI-PZ1-D, and SMI-PZ3-D2) and are well correlated with the highest Uranium concentrations in the same wells. Yet, while three of the most contaminated wells sampled at the Mill Tailings (SMI-PZ1S, SMI-PZ1M, and SMI-PZ3-D2) have slightly elevated molar SO_4/Cl ratios ranging from 0.44 to 1.8, waters that are less likely to be contaminated by the Mill Tailings and may represent background brine and fresh water have an overlapping range of molar SO_4/Cl ratios ranging from 0.02 to 3.1. It appears that natural variability effectively masks SO_4/Cl ratios that could be used to trace contaminated source waters.

3.3.2 Ammonia

Results of the 43 ammonia samples are reported in Table 3 as mg/L of NH_3-N. Ammonia as nitrogen concentrations were found to be below the detection limit of 0.1 mg/L in the shallow fresh water on the northern most portion of the Mill Tailings site (wells 432 and 433) as well as in one shallow well on the northern most portion of the Wetland Preserve (N6-6). Both of these locations are likely fed by a considerable component of GCG aquifer water. The highest concentrations of NH_3-N were found in the same group of highly contaminated wells mentioned above (SMI-PZ1S, SMI-PZ1M, SMI-PZ1D, and SMI-PZ3-D2) with values ranging from 418 to 2100 mg/L (see Figure 9). Fresh water (< 20,000 mg/L TDS) NH_3-N concentrations are all less than 1 mg/L (see Figure 8). Excluding the 4 highly contaminated DOE wells previously mentioned, the remaining brine (> 40,000 mg/L TDS) NH_3-N concentrations span a range from 0.11 to 5.06 mg/L with many samples in the 2 to 5 mg/L range.

Ammonia is a known contaminant from the Moab Mill Tailings. Although the concentrations of NH_3-N initially detected in ground water near the river at the Matheson Wetland are not high enough to be considered hazardous, they did suggest that more comprehensive sampling might reveal a spatial distribution useful in tracing NH_3 to its source. However, examination of these results led to the conclusion that NH_3 is controlled by geochemical (and possibly biological) processes to the extent that this solute does not map out ground water flowpaths. Figure 10 is a map showing maximum NH_3-N concentrations at each well nest across the site.

Ion exchange competition may be responsible for the trend of increasing NH_3 with salinity across the site (Figures 8 and 9). For example, as ground water salinity increases, there are more ions competing for a limited number of sorption sites on charged mineral surfaces likely resulting in less sorbed NH_3 (thus more in solution). Despite the correlation between NH_3 and salinity, there are low concentrations in some brines with TDS values more than 100,000 mg/L. Consequently, the underlying Paradox Formation does not appear to be a significant source of naturally occurring NH_3.

3.3.3 Uranium

Results of 41 samples submitted for uranium (U) analysis are reported in Table 3 in units of µg/L. Concentrations of uranium in all samples range from below detection (< 0.3 µg/L) to 3,940 µg/L. The four highly contaminated wells previously mentioned (SMI-PZ1S, SMI-PZ1M, SMI-PZ1D, and

SMI-PZ3-D2) contained the highest concentrations of U with values 1,430, 3,940, 1,280, and 3,170 µg/L respectively. Uranium concentrations were found to be below the detection limit (0.3 µg/L) in two distinctly different locations: in the brine of the two deepest wells at the ATP-1 nest on the DOE property (see Figure 12, wells ATP-1-D and ATP-1-1D) and in the shallow fresh water of the N9 nest just down gradient of the surface ponds on the Matheson Wetland (see Figure 11). Wells 432 and 433 are upgradient of any source from the Mill Tailings and have low U concentrations of 1 to 2 µg/L (Figures 11, 12, & 13). Other samples collected during this study that may represent background of both deep brine and shallow fresh water have U concentrations of between 0.4 and 3.1 µg/L.

In an effort to better understand what background concentrations of uranium might be, previous analyses of groundwater from other nearby wells in the valley that are not on the DOE property have been examined. Oak Ridge National Laboratory sampled a well (designated RW-01) located approximately 1,200 feet northwest of the northwest corner of the DOE property along highway 191 on December 1, 1997 and found U concentration of 12.8 µg/L (Oak Ridge National Laboratory, 1998). Well RW-01 was screened at a depth of 69 to 79 feet and, although it is located upgradient of the Mill Tailings with regard to groundwater flow, it is in an area where surface soils are known to have been contaminated by the Mill Tailings and is therefore not a reliable indicator of background uranium in groundwater. Blanchard (1990) reports uranium concentrations of around 1 µg/L (0.7 and 0.6 pCi/L) in waters of two wells screened in bedrock of the Glen Canyon Group on the east side of the river in Moab. Although these wells can confidently be considered unaffected by the Mill Tailings, the total number is not great enough for a strict statistical analysis of background concentrations. Nevertheless, it seems likely that local background U is on the order of a couple of µg/L at most.

The spatial distribution of U is shown in Figure 11 and reveals a pattern of elevated U values in ground water beneath the Matheson Wetland that are highest close to the river and decrease toward the southeast with the N3 local as the one exception. There are anomalously high U concentrations (between 23 and 60 µg/L) in both shallow ground water and the surface water pond located next to N3. These high levels of U in the water are well above background and might be explained by contaminated material being transported to the N3 area in a flood, or by a spill of contaminated material at some time in the past. This explanation is further supported by tritium concentrations found near site N3 discussed in section 3.4.2. Whatever the case may be, the cause of these high values is not known at this point in time.

The elevated U concentrations (between 5.5 and 111 µg/L) in wells near the Colorado River on the Matheson Preserve are all found in close proximity to the top of the river gravel contact and are in waters with TDS > 40,000 mg/L. When this pattern is examined together with the brine potentiometric surface in Figure 7, it appears likely that uranium from the Mill Tailings has been transported below the river through the gravel deposit.

Cross sections are presented as Figures 12 and 13 with uranium data displayed at sampling points (well screens) in the subsurface. Both cross sections are oriented roughly perpendicular to the horizontal gradient of the brine shown in Figure 7 and also show a distribution suggestive of U transport from the Mill site beneath the river.

3.4 Isotopes and Dissolved Gasses

3.4.1 Oxygen-18 and Deuterium

Stable isotopes analyses of oxygen (^{18}O and ^{16}O) and hydrogen (^{2}H or deuterium and ^{1}H) in water provide a useful geochemical tool for determining sources of aquifer recharge and identifying waters that have undergone evaporation. The ratios of these isotopes vary in precipitation primarily from changes in elevation, temperature, and relative humidity (Drever, 1997). Because these isotopic ratios are generally conservative in ground water systems, they are indicative of the relative elevation of recharge. Oxygen isotope ratios ($^{18}O/^{16}O$) and hydrogen isotope ratios (D/H) are reported in delta (δ) units permil (parts per thousand) deviation from a reference standard of Standard Mean Ocean Water (SMOW) (Craig, 1961). Once the isotope ratio of sample has been measured via mass spectrometry, the delta value is determined from the following equation:

$$dR = \left[\frac{(R_{sample} - R_{std})}{R_{std}} \right] \times 1000$$

where

$\delta R = \delta^{2}H$ or $\delta^{18}O$ in the water sample,

$R_{sample} = {}^{18}O/{}^{16}O$ or D/H ratio in the water sample, and

$R_{std} = {}^{18}O/{}^{16}O$ or D/H ratio in the reference standard (SMOW).

Waters that have not undergone evaporation plot on a meteoric water line. Precipitation that falls at higher altitudes is more depleted in the heavy isotope (more negative δ-value) since heavier isotopes condense first and fall out in lower latitude precipitation. Stable isotope ratios of hydrogen versus oxygen are compared to the Utah meteoric water line (MWL) described by Kendall and Coplen (2001) in Figure 14. The isotope values from the Moab Mill Tailings and the Matheson Wetland wells range from -15.4 to -7.7 permil for oxygen-18 and from -118.8 to -73.5 permil for deuterium (Table 5). All of the waters sampled plot near the MWL indicating that they are of meteoric origin. The large spread of values across the MWL indicates that ground water recharges from a wide variety of elevations. Waters that plot near the negative end of the MWL ($\delta^{18}O$ = -15 to -14) in Figure 14 probably entered the ground water system as recharge in the La Sal Mountains to the east. Waters that plot near the MWL in the middle of the figure ($\delta^{18}O$ = -13 to -12) may have recharge elevations not far above river.

Waters that have undergone evaporation tend to diverge from the MWL along a line with a shallower slope. The lighter isotope of both oxygen and hydrogen is more readily evaporated leading to fractionation. More fractionation is seen in the oxygen than in the hydrogen isotopes for a given amount of evaporation primarily because the masses of hydrogen isotopes are much more similar. The four highly contaminated SMI wells on the Mill Tailings property all appear to have undergone some degree of evaporation. This is likely the result of recycling of process water at the mill when it was in operation exposing the waters to evaporation. Waters from M11-7 and all wells at the N8 nest on the Wetland stand out as having undergone evaporative fractionation of these isotopes as well. Ground water at N8 is likely local recharge that seeps into the ground from the nearby surface water ponds, where it has ample time and exposure to undergo evaporative enrichment in the heavy isotopes (see Figures 1 and 14). The M11-7 samples may well be enriched by the same process and then diluted slightly by a component of deeper water.

Shallow fresh waters and shallow brine on the Matheson Wetland side of the river tend to have $\delta^{18}O$ values around -15 to -14 permil indicting high elevation source waters as one would expect at the tail end of a ground water flow system where deep ground water flowpaths rise toward the surface to discharge. Fresh waters and brines from the Mill Tailings side of the river tend to have $\delta^{18}O$ values around -13 to -12 permil indicating source waters from a lower recharge elevation which is also expected based on local topography. If the river were truly a ground water divide, it should be seen when examining these isotope ratios in cross section. In a model where the river were a ground water divide, the waters that recharged at the highest elevations would be the deepest in the aquifer and would be forced upward at the river. Therefore, the $\delta^{18}O$ values should become more negative with depth, especially in wells near the river. Figures 15 and 16 display $\delta^{18}O$ values in the cross sections A-A' and B-B' respectively. These figures, along with the map in Figure 2, show that water with oxygen isotope signatures of sources on the northwest side of the river ($\delta^{18}O$ = -13 to -12) appear to have traveled beneath the river and beneath water with oxygen isotope signatures of sources from the east side of the river ($\delta^{18}O$ = -15 to -14).

3.4.2 Tritium and Noble Gasses

Tritium (^3H) is a radioactive isotope of hydrogen that decays with a half life of 12.3 years. Although tritium does occur naturally in the atmospheric precipitation at concentrations of around 2 to 8 TU [one TU (tritium unit) = one ^3H atom per 10^{18} H atoms], the most important source has come from above ground nuclear weapons testing that occurred between 1952 and 1969 (Drever, 1997). During that time period, tritium levels in rainwater increased by more than three orders of magnitude. By 1998, atmospheric levels of tritium had decreased to between 10 and 30 TU as result of radioactive decay and widespread reduction of above ground weapons testing. Because groundwater tritium exists as part of the water molecule, it is not significantly affected by chemical processes in the subsurface. Therefore, the presence of ^3H concentrations greater than about 5 TU are strong evidence for a component of water that entered an aquifer post-1952 (Solomon and Cook, 2000).

Samples for tritium were collected from 39 wells and 3 surface water sites in order to perform ^3H-^3He dating on the waters. More specifically, this was done to determine the age of waters with known contamination. However, the ^3H - ^3He dating technique is complicated by excess dissolved N_2 and He in the water sample (Solomon and Cook, 2000). As a result, dates have not been calculated at the present time. Despite this limitation, tritium analyses still allowed the determination of where in the aquifer there exist components of relatively young (post-bomb peak) water. Figures 17 – 22 display ^3H and related helium isotope data in the cross sections of A-A' and B-B'. The R/Ra ratios and ^4He concentrations displayed in Figures 18, 19, 21, and 22 are explained below.

Six of the 42 samples collected for tritium had to be resealed for reanalysis at a later date because of complications caused by excess gas in the holding flask. Tritium concentrations ranged from < 0.1 to 17.6 TU with highest values found in the SMI wells from the Mill Tailings site (Table 6). The high tritium values in waters of the SMI-PZ1 well nest decrease with depth. These highly contaminated waters are relatively modern (< 50 years) and their ^3H distribution implies downward migration of ground water at this location (Figure 17). This also illustrates that ^{3}H has penetrated to significant depth in close proximity to the river. Whether or not it is physically possible for tritiated water to reach these depths and rise again in a short distance to discharge into the river has not been evaluated. However, these data provide a calibration target for numerical modeling that is required to answer this question.

The lowest ^{3}H values are generally in the deepest wells with a few exceptions. The 432 and 433 wells north of the Mill site have concentrations of <0.1 and 0.6 TU dating these as pre-bomb waters. Significant levels of tritium were found in the two wells of intermediate depth at the ATP-1 well nest below waters that were tritium free (Figure 17). This is most likely the result of younger water traveling down through preferential flow paths. Surface water from the Colorado River had 12 TU while pond water from next to the N3 well nest at the Wetland Preserve had only 1 TU. The tritium concentration in the river is expected for modern waters. The low tritium found in N3-surface water, together with the water table map of Figure 6, suggest that the greatest source of water to ponds on the north end of Wetland Preserve is spring discharge from the Glen Canyon Group aquifer.

Dissolved gasses were collected from 41 wells in order to further evaluate the relative ages of ground water. The diffusion samplers used for the collection of dissolved gases in this study have been tested in moderately saline waters. However, they have not been lab tested in waters of comparable salinity to the deep brines encountered at this site. These tests are to be conducted soon and although errors arising from equilibration complications in waters with TDS values ranging from 30,000 to 100,000 mg/L are not expected, the dissolved gas data presented here should be considered provisional at this time. Values for R/Ra and terrigenic helium-4 are included in Table 6.

Terrigenic ^{4}He is the component of ^{4}He derived from subsurface production, the largest source in most aquifers coming from the radioactive decay of ^{238}U, ^{235}U, and ^{232}Th. Atmospheric concentrations of ^{4}He are extremely stable to an altitude of 100km (Solomon, 2000) making it possible to subtract the atmospheric component from the bulk concentration measured. Recharging water in equilibrium with the atmosphere at 10 ^{o}C will contain 4.8 $X10^{-}$ 8 cm^{3} of ^{4}He per gram of water at standard temperature and pressure of 0 ^{o}C and 1atm (ccSTP/g) and the concentration will increase with age as the water acquires terrigenic ^{4}He from the in-situ decay of these natural radioactive elements bound to the aquifer matrix.

The helium isotope ratio of water samples is reported as R/Ra which is the $^{3}He/^{4}He$ ratio of the sample (R) compared to the $^{3}He/^{4}He$ ratio of air (Ra). Relatively young waters that have recently been in equilibrium with the atmosphere will have R/Ra values close to 1. Waters that are much older will have lower R/Ra values resulting from excess terrigenic ^{4}He. Based on values of ^{4}He production rates reported in the literature (Solomon, 2000), significant concentrations of ^{4}He will not accumulate until ground water has spent around 1,000 years in the aquifer. Therefore, ^{4}He (and thus, R/Ra) gives an indication of the relative age of ground water on the scale of thousands of years whereas ^{3}H is an indicator of ground water that is younger or older than about 50 years.

R/Ra values in ground water at this site vary between 0.04 and 1.78 and generally decrease with depth (Figures 18 and 21). Many of the shallowest wells have R/Ra values close to 1 indicating water in equilibrium with the atmosphere. Low R/Ra in the deep wells is indicative of water that is quite old and has picked up excess ^{4}He from a terrigenic source. R/Ra values greater than 1 occur in waters with the highest tritium concentrations and are the result of excess radiogenic ^{3}He derived from tritium decay.

Concentrations of terrigenic ^{4}He from samples collected at the site range from 0 in modern water to 4.5 X10^{-} 6 ccSTP/g in brine that is presumably quite old. The spatial distribution of ^{4}He, shown in cross sections on Figures 19 and 22, compare well with the R/Ra values. There exists a clear boundary below which brine has a relatively constant ^{4}He concentration of around 2 X10^{-} 6 to 3 X10^{-} 6. This boundary is shown in both figures at an approximate concentration of 1.0 X10^{-} 6. This line appears to mark a significant boundary in the aquifer below which waters are relatively stagnant and above which waters are accumulating ^{4}He by upward diffusive transport. It can be seen in Figure 19 that this boundary has been depressed beneath the Mill Tailings extending underneath the river. This could be the result of high hydraulic heads forcing a downward advective flow that suppressed the upward diffusion of ^{4}He.

Ground water dating using accumulation of ^{4}He requires knowledge of the ^{4}He production rate and that is site specific depending on local geology and hydrodynamics. However, the constant concentration in deep brines implies that the bulk volume of these waters is of similar age and that significant amounts of ^{4}He are not diffusing through it, but that it is the source of ^{4}He diffusing upward through shallower waters. Assuming this is true of the deep brine, and assuming average ^{4}He release rates from aquifer sediments to be between 0.28 and 2.4 μcc STP m^{-3} yr^{-1} (Solomon, 2000), ages of these deep brines are on the order of 10^{5} to 10^{6} years old with emphasis on the younger age since sedimentary units of the southeastern portion of the Colorado Plateau contain above average uranium.

4.0 Conclusions

The University of Utah has investigated the hydrologic connection between the Moab Mill Tailings and the Scott M. Matheson Wetland Preserve located along the Colorado River near Moab, Utah. The study was conducted by collecting water samples from 44 sites on both sides of the Colorado River and analyzing them for oxygen-18 and deuterium isotopes, tritium, noble gases including helium-3 and helium-4, chloride, sulfate, ammonia-nitrogen, and uranium. In addition, water levels and field parameters (specific conductance, temperature, and total dissolved gas pressure) were measured. Ten of the sites sampled were existing monitoring wells on the Moab Mill Tailings property on the north side of the Colorado River. Twenty five of the sites were existing shallow piezometers and surface water sites on the Matheson Wetland Preserve. The remaining nine monitoring wells were newly constructed in three new boreholes that were drilled on the Wetland Preserve. The lithology of these boreholes revealed large, continuous sequences of gravels and cobbles that contain cobbles of pink granites, diorite porphyry, and mafic schists laid down by the ancestral Colorado River. Borehole logs were used in conjunction with logs by the DOE to determine that the gravel deposit is more than 1.5 km (4,920 ft) wide in the center of the valley and reaches a maximum thickness of more than 53 m (174 ft). These gravels lie beneath an average of 5.5 m (18 ft) of silty overbank river deposits with the top at between 1200 and 1204 m (3937 and 3950 ft) elevation across the site.

While shallow groundwater at the site is relatively fresh with TDS values around 1,000 to 3,000 mg/L, the deeper part of the system is dense brine with TDS values as high as 110,000 mg/L. Ground water salinities were used along with water level measurements to calculate equivalent freshwater hydraulic heads across the site. These EFH values show that the horizontal direction of ground water movement in the shallow fresh water system is generally toward the river and that movement of the brines within the channel gravels is more southeasterly, with a component likely continuing beneath the river.

Uranium concentrations in four highly contaminated wells near the Mill Tailings ranged from 1,280 to 3,940 µg/L. Elsewhere, levels spanned a range from > 0.3 to 111 µg/L. The spatial distribution of elevated Uranium concentrations coupled with the EFH data suggests that high levels of U in wells near the river on the Wetland Preserve (between 5.5 and 111 µg/L) are derived from the Moab Mill Tailings site.

Oxygen and deuterium isotopes of the waters are indicative of a variety of sources of ground water recharge. Shallow fresh ground water and shallow brine on the Matheson side of the river tend to have $\delta^{18}O$ values around -15 to -14 permil indicating high elevation source waters. The same is true of Colorado River water sampled at CR1. Fresh waters and brines from the Mill Tailings side of the river tend to have $\delta^{18}O$ values around -13 to -12 permil signifying source waters from a lower elevation. Isotopic signatures of deep ground water flowing toward the river do not indicate that the river is a distinct hydrologic divide. Rather, waters with heavier $\delta^{18}O$ ratios are seen beneath waters with lighter $\delta^{18}O$ ratios signifying that waters recharging on the north side of the river are, at least in some locations, underflowing waters that recharge on the south side of the river

Tritium concentrations from waters across the site range between <0.1 to 17.6 TU with the lowest values generally in the deep brines and the highest values found in the SMI-PZ1 well nest on the Mill Tailings site. High tritium concentrations in waters of the SMI-PZ1 well nest decrease with depth, implying that these highly contaminated waters are relatively modern (< 50 years) and moving downward. Downward movement of ground water on the DOE property in such close proximity to the river may be another indication that the river is not a hydrologic boundary and instead that ground water has the potential to flow underneath the river and beneath the Matheson Wetland.

Dissolved gasses were measured to further evaluate relative ground water ages. R/Ra ratios vary between 0.04 and 1.78 and generally decrease with depth. Many of the shallowest wells have R/Ra values close to 1 indicating water in equilibrium with the atmosphere and low R/Ra in the deep wells indicates that the deep brine is quite old and has picked up excess ^4He from a terrigenic source. Concentrations of terrigenic ^4He in ground water range from 0 in modern water to 4.5×10^{-6} ccSTP/g in brine that is presumably quite old and the spatial distributions of ^4He compare well with reported R/Ra values.

There exists a clear boundary below which brine has a relatively constant ^4He concentration of around 2×10^{-6} to 3×10^{-6}. This line appears to mark a significant lower limit in the active portion of the aquifer below which waters are relatively stagnant and above which waters are accumulating ^4He by upward diffusive transport. Beneath the Mill Tailings and extending beneath portions of the river, this boundary appears to have been depressed. A plausible hypothesis is that this was the result of high hydraulic heads on the Mill Tailings forcing a downward advective flow that suppressed the upward diffusion of ^4He. It remains unknown whether the passage of fluids beneath the river through highly conductive channel deposits is ongoing or a response to discontinuous driving forces (seasonal or otherwise). Regardless, the distribution of contaminants and geochemical tracers measured during this study indicate that fluids have, at some point migrated, from north to south beneath the Colorado River.

The data presented in this report lead to a conceptual model of subsurface hydrologic connection between the Moab Mill Tailings and the Matheson Wetland Preserve. In other words, the Colorado River is not an absolute hydrologic divide. Although it does appear that ground water passes beneath the Colorado River in the channel gravel deposits, there is no doubt that a substantial fraction of the ground water does discharge directly into the river. In all probability, areas where the silt layer is thick enough to isolate the river from the underlying channel gravels are the areas where ground water has the potential to pass beneath the river. One can envision that this dividing layer is continuously replenished as the Colorado River is depositing fine silt when baseflow (low water velocity) conditions persist. However, during annual spring runoff and other flood events, the silt in the main channel could be scoured down to the top of the channel gravels creating a highly conductive pathway for ground water to discharge directly into the river. The river bed is apt to be scoured down to the gravels (permitting ground water discharge to the river) at times and, at other times, covered with enough silt to cause ground water to move through the gravels and beneath the river. This dynamic scenario, if correct, could cause considerable shifting of contaminant plumes and would certainly have bearing on any groundwater remediation design.

5.0 Recommendations

While the data presented in this report along with the results of previous studies allow for the development of a conceptual model of groundwater flow and solute transport, there remain many uncertainties. In particular, the dynamic nature of this system could lead to large changes in flow paths through time. Furthermore, we have focused on the connection between the Moab Mill Tailings and the Matheson Wetland Preserve while the connection between the wetlands and the alluvial aquifer in Spanish Valley (to the south where municipal and public withdrawals occur) remains poorly defined. The following recommendations are offered to help understand the response of this system to seasonal hydrologic changes and to future pumping stresses:

1) More comprehensive vertical profiling of the aquifer with piezometers near the river on both the Mill Tailings and the Matheson Wetland sides of the river will help to fill in the most important data gaps that presently exist.

2) Determination of the silt thickness on the bottom of the river will help to answer the question of whether or not scour has exposed the highly conductive river gravels.

3) A time series of hydraulic head and solute concentration measurements will reveal the response of the groundwater system to seasonal dynamics.

4) Numerical modeling of ground water flow and solute transport should be performed and constrained to the data presented in this report (tritium, dissolved gas concentrations, etc.).

5) Background levels of contaminants should be defined using more wells outside of the immediate sampling area. There are a very limited number of wells that were sampled in this study which can, with assurance, be considered unaffected by the tailings pile.

Finally, it should be mentioned that the connection between the portion of the alluvial aquifer examined in this study and the alluvial aquifer utilized by the city of Moab is poorly understood. Without knowledge of this connection, it is impossible to know what effects (if any) future pumping of ground water in Moab will have on contaminant plumes sourced at the Mill Tailings. The understanding of this connection would be greatly improved by defining the southern extent of the channel gravel deposit and determining where Glen Canyon Group groundwater transitions into paradox brine.

6.0 References

Blanchard, P.J. 1990. Groundwater Conditions in the Grand County Area, Utah, With Emphasis on the Mill Creek-Spanish Valley Area. State of Utah Dept. of Nat. Res. Tech. Pub. No. 100.

Clark, W.B., W.J. Jenkins, and Z. Top. 1976. Determination of tritium by mass spectrometric measurements of 3He. Int. J. Appl. Radiat. Isot. 27: 515-522.

Coleman, M. L., T. J. Shepard, J. J. Durham, J. E. Rouse, and G. R. Moore. 1982. Reduction of water with zinc for hydrogen isotope analysis. Ann. Chem. 54: 993-995.

Craig, H. 1961. Isotopic variation in meteoric waters. Science 133: 1702-1703.

Drever, James I. 1997. *The Geochemistry of Natural Waters: Surface and Groundwater Environments*. Prentice Hall, Inc. Upper Saddle River, New Jersey. 314-323.

Fessenden, J. E., C. S. Cook, M. J. Lott, and J. R. Ehleringer. 2002. Rapid ^{18}O analysis of small water and CO_2 samples using a continuous-flow isotope ratio mass spectrometer. Rapid Commun. Mass Spectrom. 16: 1257-1260.

U.S. Department of Energy. prepared by Environmental Sciences Laboratory. 2003. Expedited Site Characterization Ground Water and Surface Water Monitoring Scott Matheson Wetland Preserve. ESL-DP-2003-05. MOA 19.1.2.

Kendall, C. and T.B. Coplen. 2001. Distribution of oxygen-18 and deuterium in river waters across the United States. Hydrological Processes 15: 1363-1393.

Oak Ridge National Laboratory. 1998. Limited Groundwater Investigation of the Atlas Corporation Moab Mill, Moab, Utah. Prepared by Oak Ridge National Laboratory in Grand Junction Colorado for U.S. Fish and Wildlife Service in Salt Lake City, Utah.

Sanford, W.E., R.G. Shropshire, and D.K. Solomon. 1996. Dissolved gas tracers in groundwater: Simplified injection, sampling, and analysis. Water Resour. Res. 32: 1635-1642.

Sheldon, A. L. 2002. Diffusion of Radiogenic Helium in Shallow Groundwater: Implications for Crustal Degassing. Ph.D.Dissertation, University of Utah, Salt Lake City.

Smith, S.P. and B.M. Kennedy. 1983. The solubility of noble gases in water and in NaCl brine. Geochimica at Cosmochimica Acta 47: 503-515.

Solomon, D.K. 2001. Reconnaissance Study of Age and Recharge Temperature of Groundwater Near Moab, Utah. Prepared for Moab Mesa Land Company, *Included as Appendix B*.

Solomon, D.K. 2000. ^{3}H and ^{3}He. In *Environmental Tracers in Subsurface Hydrology*. Kluwer Academic Publishers, Boston. 397-424.

Solomon, D.K., and P.G. Cook. 2000. ^{4}He in Groundwater. In *Environmental Tracers in Subsurface Hydrology*. Kluwer Academic Publishers, Boston. 425-440.

U.S. Department of Energy. October 2002. Lithologic, Well Construction, and Field Sampling Results from the 2002 Field Investigation. GJO-MOA 19.2.3.

Tables

Well / PZ ID	Type of Installation	ID (cm)	ID (in)	Easting (UTM)	Northing (UTM)	TOC Elevation (m)	Depth to Center of Screen Below MP (m)	Screen Length (m)	Screen Length (ft)
CR1-3	Drive pt. PZ	1.27	0.50	623247.68	4273179.69	1206.50	3.37	0.15	0.5
CR1-5	Drive pt. PZ	1.27	0.50	623247.68	4273179.69	1206.45	4.93	0.15	0.5
CR2-3	Drive pt. PZ	1.27	0.50	624030.74	4270345.90	~1203	3.00	0.15	0.5
M11-4	Drive pt. PZ	1.27	0.50	623219.45	4271625.04	1208.35	4.01	0.15	0.5
M11-7	Drive pt. PZ	1.27	0.50	623219.45	4271625.04	1208.34	6.30	0.15	0.5
M11-12	Drive pt. PZ	1.27	0.50	623219.45	4271625.04	1208.22	12.14	0.15	0.5
M11-14	Drive pt. PZ	1.27	0.50	623219.45	4271625.04	1208.34	13.15	0.15	0.5
N2-1.5	Drive pt. PZ	1.27	0.50	623848.09	4272145.76	1207.72	1.56	0.15	0.5
N2-4	Drive pt. PZ	1.27	0.50	623848.09	4272145.76	1207.82	4.34	0.15	0.5
N2-6	Drive pt. PZ	1.27	0.50	623848.09	4272145.76	1207.87	6.45	0.15	0.5
N2-12	Drive pt. PZ	1.27	0.50	623848.09	4272145.76	1207.90	10.78	0.15	0.5
N3-4	Drive pt. PZ	1.27	0.50	624344.54	4272616.79	1208.38	4.36	0.15	0.5
N3-8	Drive pt. PZ	1.27	0.50	624344.54	4272616.79	1208.48	8.65	0.15	0.5
N4-3	Drive pt. PZ	1.27	0.50	624246.04	4271055.98	1207.67	3.21	0.15	0.5
N4-6	Drive pt. PZ	1.27	0.50	624246.04	4271055.98	1207.76	6.52	0.15	0.5
N4-12	Drive pt. PZ	1.27	0.50	624246.04	4271055.98	1207.95	11.97	0.15	0.5
N5-4	Drive pt. PZ	1.27	0.50	624559.89	4271661.70	1208.60	4.37	0.15	0.5
N5-7	Drive pt. PZ	1.27	0.50	624559.89	4271661.70	1208.72	7.80	0.15	0.5
N5-10	Drive pt. PZ	1.27	0.50	624559.89	4271661.70	1208.63	10.84	0.15	0.5
N5-14	Drive pt. PZ	1.27	0.50	624559.89	4271661.70	1208.65	14.80	0.15	0.5
N6-6	Drive pt. PZ	1.27	0.50	623887.32	4273414.68	1207.77	6.15	0.15	0.5
N6A-4	Hand augured	2.54	1.00	623887.32	4273414.68	1208.05	4.00	open pipe	open pipe
N6-9	Drive pt. PZ	1.27	0.50	623887.32	4273414.68	1210.93	8.50	0.15	0.5
N7-4	Drive pt. PZ	1.27	0.50	624031.26	4270346.59	1208.27	4.56	0.15	0.5
N7-7	Drive pt. PZ	1.27	0.50	624031.26	4270346.59	1208.28	6.55	0.15	0.5
N7-10	Drive pt. PZ	1.27	0.50	624031.26	4270346.59	1208.29	10.12	0.15	0.5
N7-11	Drive pt. PZ	1.27	0.50	624031.26	4270346.59	1208.12	10.85	0.15	0.5

Table 1. Well information including; type of installation, survey coordinates, top of casing elevation, depth to center point of screen below measuring point, and screen length. All horizontal survey coordinates were converted to UTM relative to NAD 27 datum using Corpscon for Windows 5.11.08 software. This was done for plotting on an orthophotoquad obtained from Utah Division of Water Rights website (http://nrwrt1.nr.state.ut.us/gisinfo/default.htm).

Well / PZ ID	Type of Installation	ID (cm)	ID (in)	Easting (UTM)	Northing (UTM)	TOC Elevation (m)	Depth to Center of Screen Below MP (m)	Screen Length (m)	Screen Length (ft)
N8-3	Drive pt. PZ	1.27	0.50	623525.90	4271614.88	1208.48	2.95	0.15	0.5
N8-6	Drive pt. PZ	1.27	0.50	623525.90	4271614.88	1208.41	6.57	0.15	0.5
N8-10	Drive pt. PZ	1.27	0.50	623525.90	4271614.88	1208.45	10.80	0.15	0.5
N8-14	Drive pt. PZ	1.27	0.50	623525.90	4271614.88	1208.45	13.90	0.15	0.5
W1-4	Machine augured	5.08	2.00	623206.25	4272714.14	1208.59	4.00	1.50	5.0
W1-7	Drive pt. PZ	1.27	0.50	623206.25	4272714.14	1208.60	7.00	0.15	0.5
N9-2	Drive pt. PZ	1.27	0.50	623860.24	4272127.88	1208.06	4.25	0.15	0.5
N9-4	Drive pt. PZ	1.27	0.50	623860.24	4272127.88	1208.15	8.53	0.15	0.5
N9-6	Drive pt. PZ	1.27	0.50	623860.24	4272127.88	1208.26	10.69	0.15	0.5
N11-6	Drive pt. PZ	1.27	0.50	623112.80	4272097.67	1209.44	6.38	0.15	0.5
N11-10	Drive pt. PZ	1.27	0.50	623112.80	4272097.67	1209.51	8.54	0.15	0.5
SMI-PZ1S	Drilled Sampling Well	5.08	2.00	622805.66	4273086.46	1209.73	4.22	1.52	5.0
SMI-PZ1M	Drilled Sampling Well	5.08	2.00	622805.66	4273086.46	1209.48	16.92	1.52	5.0
SMI-PZ1D	Drilled Sampling Well	5.08	2.00	622805.66	4273086.46	1209.47	21.26	1.52	5.0
ATP-1-S	Drilled Sampling Well	5.08	2.00	622738.91	4273091.67	1210.34	44.19	3.05	10.0
ATP-1-1S	Drilled Sampling Well	5.08	2.00	622738.91	4273091.67	1210.30	65.53	1.52	5.0
ATP-1-1D	Drilled Sampling Well	5.08	2.00	622738.91	4273091.67	1210.26	89.91	1.52	5.0
ATP-1-D	Drilled Sampling Well	5.08	2.00	622738.91	4273091.67	1210.22	120.39	1.52	5.0
SMI-PZ3-D2	Drilled Sampling Well	5.08	2.00	622822.37	4273587.05	1211.56	22.94	1.52	5.0
433	Drilled Sampling Well	5.08	2.00	622402.29	4273783.53	1216.09	30.11	3.05	10.0
432	Drilled Sampling Well	5.08	2.00	622386.26	4273865.06	1219.59	16.69	3.05	10.0
BL1-S	Drilled Sampling Well	5.08	2.00	623679.59	4272622.35	1209.03	16.64	0.61	2.0
BL1-M	Drilled Sampling Well	5.08	2.00	623679.59	4272622.35	1209.12	30.36	0.61	2.0
BL1-D	Drilled Sampling Well	5.08	2.00	623679.59	4272622.35	1209.16	42.89	0.61	2.0
BL2-S	Drilled Sampling Well	5.08	2.00	623148.95	4272089.96	1209.25	17.43	0.61	2.0
BL2-M	Drilled Sampling Well	5.08	2.00	623148.95	4272089.96	1209.29	31.46	0.61	2.0
BL2-D	Drilled Sampling Well	5.08	2.00	623148.95	4272089.96	1209.34	43.90	0.61	2.0
BL3-S	Drilled Sampling Well	5.08	2.00	623533.69	4271026.80	1208.41	10.22	0.61	2.0
BL3-M	Drilled Sampling Well	5.08	2.00	623533.69	4271026.80	1208.46	15.14	0.61	2.0
BL3-D	Drilled Sampling Well	5.08	2.00	623533.69	4271026.80	1208.49	31.15	0.61	2.0

Table 1 (cont.) Well information including; type of installation, survey coordinates, top of casing elevation, depth to center point of screen below measuring point, and screen length. All horizontal survey coordinates were converted to UTM relative to NAD 27 datum using Corpscon for Windows 5.11.08 software. This was done for plotting on an orthophotoquad obtained from Utah Division of Water Rights website (http://nrwrt1.nr.state.ut.us/gis info/default.htm).

Well / Site ID	Depth to water below TOC (m)	SpC (mS/cm)	Temp. (°C)	DO (mg/L)	TDGP (atm)
CR1-river	--	--	27.3	--	--
CR1-3	1.38	78,000	16.1	--	0.839
CR1-5	1.32	78,000	15.7	--	--
M11-4	3.24	8,180	14.1	--	--
M11-7	3.18	5,420	13.8	--	0.843
M11-12	3.01	14,400	13.9	--	0.836
M11-14	3.19	60,700	14.1	--	0.869
N2-1.5	1.41	--	--	--	--
N2-4	2.54	--	--	--	--
N2-6	1.60	--	--	--	--
N2-12	1.61	--	--	--	--
N3-4	1.39	5,300	14.2	--	0.853
N3-8	1.48	3,130	14.9	--	0.862
N4-3	1.53	1,000	--	--	--
N4-6	0.95	984	11.7	--	0.840
N4-12	1.04	871	13.6	--	0.855
N5-4	2.15	1,400	--	--	--
N5-7	0.87	1,490	13.2	--	0.881
N5-10	0.76	1,560	14.1	--	0.812
N5-14	0.84	1,410	14.3	--	0.842
N6-6	1.98	4,340	14.1	--	0.824
N6A-4	2.19	4,400	--	--	--
N6-9	5.15	4,550	14.3	--	0.845
N7-7	4.18	3,090	11.8	--	0.820
N7-10	4.22	148,000	12.0	--	0.858
N7-11	4.21	150,000	12.1	--	0.926
N8-3	--	--	11.2	--	--
N8-6	2.27	3,630	10.7	--	--
N8-10	2.24	2,180	11.0	--	0.829
N8-14	2.27	2,260	11.0	--	0.832
W1-4(OW)	3.37	84,600	14.9	--	0.843
W1-7	3.39	81,400	14.9	--	0.849
N9-2	3.81	2,000	--	--	--
N9-4	1.44	2,780	11.4	--	0.805
N9-6	1.57	2,860	11.6	--	--
N11-6	4.41	63,400	14.7	--	0.819
N11-10	4.51	67,900	14.7	--	0.845
SMI-PZ1S	4.60	16,700	17.0	0.43	0.997
SMI-PZ1M	4.32	53,400	16.4	0.12	1.67
SMI-PZ1D	4.31	138,000*	16.5	0.18	1.70
ATP-1-S	5.90	146,000*	16.9	0.18	0.846
ATP-1-1S	6.13	162,000*	17.2	0.01	1.65
ATP-1-1D	6.25	164,000*	17.3	0.07	1.54
ATP-1-D	6.43	165,000*	16.8	0.11	1.50
SMI-PZ3-D2	5.99	27,600	17.7	0.15	>2.40
432	12.78	2,900	19.2	4.38	0.882
433	9.58	4,390	18.9	1.75	0.853
BL1-S	3.97	49,200	13.5	0.10	1.10
BL1-M	4.45	96,200	13.8	0.12	1.31
BL1-D	4.95	143,000*	14.0	0.18	1.67
BL2-S	4.86	113,000*	14.9	0.13	1.38
BL2-M	5.13	144,000*	14.9	0.14	1.59
BL2-D	5.24	149,000*	15.2	0.14	1.53
BL3-S	4.18	39,700	--	--	--
BL3-M	4.36	90,400	11.5	0.00	1.27
BL3-D	4.80	169,000*	12.7	0.00	1.75

Table 2. Field parameters and water levels measured at the Moab Mill Tailings and Matheson Wetland Preserve between July 4 and August 5, 2003. All measurements made downhole except * based on a 1:1 field dilution of sample water and deionized water, TDGP = total dissolved gas pressure, -- means not measured (e.g DO only measured in 2” diameter wells where probe fits downhole and TDGP not measured if dissolve gas concentrations not measured).

Well / Site ID	SO_4 (mg/L)	SO_4 (mol/L)	Cl (mg/L)	Cl (mol/L)	NH_3 as N (mg/L)	U (μg/L)	TDS (mg/L)	molar SO_4/Cl ratio
N3-pond water	145*	1.51E-03	1,290*	3.64E-02	0.19*	25.1*	3,810	0.041
CR2-river water	297*	3.09E-03	93.8*	2.65E-03	0.62*	5.9*	816*	1.169
CR1-river water	319	3.32E-03	222	6.26E-03	< 0.1	3.9*	2,340	0.530
CR1-3	2,600	2.71E-02	39,900	1.13E+00	0.69	111*	56,900	0.024
M11-7	612	6.37E-03	1,170	3.30E-02	0.28	5.5*	3,960	0.193
M11-12	766	7.97E-03	9,500	2.68E-01	0.35	1.8*	10,500	0.030
M11-14	2,570	2.68E-02	39,300	1.11E+00	1.13	2.3*	44,300	0.024
N3-4	328	3.41E-03	1,190	3.36E-02	< 0.1	23*	3,870	0.102
N3-8	450	4.68E-03	591	1.67E-02	0.3	59.2*	2,290	0.281
N4-6	25	2.60E-04	53.0	1.49E-03	< 0.1	2.4*	718	0.174
N4-12	147	1.53E-03	97.5	2.75E-03	< 0.1	2.0*	636	0.556
N5-7	582	6.06E-03	690	1.95E-02	0.27	--	1,090	0.311
N5-10	669	6.96E-03	99.0	2.79E-03	< 0.1	1.8*	1,140	2.494
N5-14	730	7.60E-03	54.0	1.52E-03	< 0.1	3.1*	1,030	4.989
N6-6	340	3.54E-03	1,220	3.44E-02	< 0.1	6.9*	3,170	0.103
N6-9	242	2.52E-03	1,200	3.38E-02	< 0.1	4.5*	3,320	0.074
N7-7	695	7.24E-03	907	2.56E-02	0.87	0.4*	2,250	0.283
N7-10	4,640	4.83E-02	56,800	1.60E+00	1.44	7.9*	108,000	0.030
N8-10	393	4.09E-03	188	5.30E-03	0.1	2.3*	1,590	0.772
N8-14	386	4.02E-03	229	6.46E-03	< 0.1	0.8*	1,650	0.622
W1-4	1,610	1.68E-02	34,800	9.82E-01	0.11	--	61,700	0.017
W1-7	1,570	1.63E-02	44,800	1.26E+00	0.25	35.3*	59,400	0.013
N9-4	1,380	1.44E-02	167	4.71E-03	< 0.1	< 0.3*	2,030	3.050
N9-6	1,580	1.64E-02	190	5.36E-03	< 0.1	< 0.3*	2,090	3.069
N11-6	4,050	4.22E-02	34,000	9.59E-01	0.56	19.1*	46,300	0.044
SMI-PZ1S	6,950*	7.24E-02	1,400*	3.95E-02	418*	1430*	12,800*	1.832
SMI-PZ1M	15,000*	1.56E-01	12,500*	3.53E-01	1240*	3940*	41,600*	0.443
SMI-PZ1D	8,000*	8.33E-02	43,300*	1.22E+00	2100*	1280*	78,700*	0.068
ATP-1-S	4,770*	4.97E-02	59,100*	1.67E+00	4.53*	1.9*	109,000*	0.030
ATP-1-1S	4,570*	4.76E-02	55,600*	1.57E+00	5.06*	0.8*	118,000	0.030
ATP-1-1D	4,680*	4.87E-02	59,800*	1.69E+00	4.76*	< 0.3*	119,000	0.029
ATP-1-D	4,770*	4.97E-02	60,500*	1.71E+00	4.71*	< 0.3*	121,000	0.029
SMI-PZ3-D2	10,200*	1.06E-01	3,940*	1.11E-01	564*	3170*	20,200	0.955
432	334*	3.48E-03	643*	1.81E-02	< 0.1*	2.0*	1,740*	0.192
433	346*	3.60E-03	1,060*	2.99E-02	< 0.1*	1.3*	2,530*	0.120
BL1-S	1,420*	1.48E-02	17,700*	4.99E-01	1.53*	11.6*	40,500*	0.030
BL1-M	2,490*	2.59E-02	37,500*	1.06E+00	1.71*	3.8*	80,300*	0.025
BL1-D	4,650*	4.84E-02	51,400*	1.45E+00	3.72*	1.8*	95,100*	0.033
BL2-S	3,710*	3.86E-02	40,300*	1.14E+00	4.3*	2.4*	78,800	0.034
BL2-M	4,360*	4.54E-02	52,400*	1.48E+00	4.4*	2.7*	105,000	0.031
BL2-D	4,430*	4.61E-02	54,200*	1.53E+00	4.3*	2.4*	109,000	0.030
BL3-S	--	--	--	--	--	--	--	--
BL3-M	4,180*	4.35E-02	34,700*	9.79E-01	2.55*	0.5*	66,000	0.044
BL3-D	5,340*	5.56E-02	62,400*	1.76E+00	4.6*	< 0.3*	124,000	0.032

Table 3. Ground and surface water chemistry data from the Moab Mill Tailings and Matheson Wetland Preserve between July 4 and August 5, 2003. Analyses performed by the U of U unless otherwise noted, *measured by Energy Laboratories, TDS estimate using SpC unless otherwise noted, -- means not measured (e.g. because of poor well yield or, in the case of BL3-S, well development failed and well was never sampled).

Well/PZ ID	TOC elevation (m)	TDS (g/L)	Specific Gravity (r/r_f)	Total elevation head / screen elevation (m)	Depth to water (m)	Total hydraulic head (m)	Total pressure head (m)	Adjusted pressure head (m)	Equivalent Freshwater Hydraulic Head (m)
CR1-3	1206.50	56.9	1.057	1203.127	1.375	1205.122	1.995	2.108	1205.24
CR1-5*	1206.45	56.9	1.057	1201.519	1.320	1205.129	3.610	3.815	1205.33
M11-4	1208.35	5.97	1.006	1204.344	3.244	1205.111	0.766	0.771	1205.12
M11-7	1208.34	3.96	1.004	1202.039	3.180	1205.159	3.120	3.133	1205.17
M11-12	1208.22	10.5	1.010	1196.077	3.009	1205.208	9.131	9.227	1205.30
M11-14	1208.34	44.3	1.044	1195.192	3.186	1205.156	9.964	10.405	1205.60
N2-1.5*	1207.72	1.50	1.002	1206.163	1.408	1206.315	0.152	0.152	1206.32
N2-6*	1207.87	2.00	1.002	1201.417	1.601	1206.266	4.849	4.859	1206.28
N2-12*	1207.90	2.00	1.002	1197.117	1.613	1206.284	9.167	9.185	1206.30
N3-4	1208.38	3.87	1.004	1204.025	1.394	1206.991	2.966	2.978	1207.00
N3-8	1208.48	2.29	1.002	1199.832	1.479	1207.003	7.171	7.188	1207.02
N4-3*	1207.67	0.730	1.001	1204.455	1.534	1206.132	1.676	1.677	1206.13
N4-6	1207.76	0.718	1.001	1201.240	0.952	1206.808	5.568	5.572	1206.81
N4-12	1207.95	0.636	1.001	1195.976	1.043	1206.903	10.927	10.934	1206.91
N5-4*	1208.60	1.02	1.001	1204.234	2.146	1206.458	2.224	2.226	1206.46
N5-7	1208.72	1.09	1.001	1200.923	0.866	1207.857	6.934	6.941	1207.86
N5-10	1208.63	1.14	1.001	1197.788	0.760	1207.869	10.080	10.092	1207.88
N5-14	1208.65	1.03	1.001	1193.853	0.836	1207.817	13.964	13.979	1207.83
N6-6	1207.77	3.17	1.003	1201.619	1.976	1205.793	4.174	4.188	1205.81
N6A-4*	1208.05	3.21	1.003	1204.050	2.192	1205.858	1.808	1.814	1205.86
N6-9	1210.93	3.32	1.003	1202.427	5.155	1205.772	3.345	3.356	1205.78
N7-7	1208.28	2.25	1.002	1201.731	4.179	1204.102	2.371	2.376	1204.11
N7-10*	1208.29	108	1.108	1198.173	4.219	1204.074	5.901	6.536	1204.71
N7-11*	1208.12	110	1.110	1197.269	4.210	1203.910	6.640	7.367	1204.64
N8-6	1208.41	2.65	1.003	1201.839	2.268	1206.141	4.302	4.313	1206.15
N8-10	1208.45	1.59	1.002	1197.655	2.241	1206.214	8.559	8.573	1206.23
N8-14	1208.45	1.65	1.002	1194.546	2.265	1206.180	11.635	11.654	1206.20
W1-4(OW)	1208.59	61.7	1.062	1204.592	3.368	1205.224	0.632	0.671	1205.26
W1-7	1208.60	59.4	1.059	1201.604	3.387	1205.217	3.613	3.828	1205.43

Table 4. Groundwater equivalent freshwater hydraulic heads and values used in their calculation as explained in section 3.2 of the text. Wells with * next to their ID in the first column had very poor yield after initial purging therefore, their TDS values used in these calculations are based on SpC values estimated using adjacent wells.

Well/PZ ID	TOC elevation (m)	TDS (g/L)	Specific Gravity (ρ/ρ_f)	Total elevation head / screen elevation (m)	Depth to water (m)	Total hydraulic head (m)	Total pressure head (m)	Adjusted pressure head (m)	Equivalent Freshwater Hydraulic Head (m)
N9-4	1208.15	2.03	1.002	1199.623	1.442	1206.711	7.088	7.102	1206.73
N9-6	1208.26	2.09	1.002	1197.567	1.567	1206.690	9.123	9.142	1206.71
N11-6	1209.44	46.3	1.046	1203.064	4.411	1205.033	1.969	2.060	1205.12
N11-10	1209.51	49.6	1.050	1200.975	4.509	1204.996	4.021	4.221	1205.20
SMI-PZ1S	1209.73	12.8	1.013	1205.507	4.602	1205.129	0	0	1205.13
SMI-PZ1M	1209.48	41.6	1.042	1192.551	4.322	1205.154	12.603	13.127	1205.68
SMI-PZ1D	1209.47	78.7	1.079	1188.208	4.313	1205.154	16.946	18.279	1206.49
ATP-1-S	1210.34	109	1.109	1166.151	5.901	1204.443	38.293	42.467	1208.62
ATP-1-1S	1210.30	118	1.118	1144.773	6.130	1204.172	59.399	66.438	1211.21
ATP-1-1D	1210.26	119	1.119	1120.351	6.245	1204.017	83.666	93.656	1214.01
ATP-1-D	1210.22	121	1.121	1089.829	6.428	1203.791	113.962	127.722	1217.55
SMI-PZ3-D2	1211.56	20.2	1.020	1188.616	5.989	1205.571	16.955	17.297	1205.91
433	1216.09	2.53	1.003	1185.980	9.583	1206.507	20.527	20.579	1206.56
432	1219.59	1.74	1.002	1202.895	12.783	1206.805	3.910	3.917	1206.81
BL1-S	1209.03	40.5	1.041	1192.385	3.975	1205.051	12.666	13.179	1205.56
BL1-M	1209.12	80.3	1.080	1178.768	4.447	1204.676	25.908	27.989	1206.76
BL1-D	1209.16	95.1	1.095	1166.267	4.950	1204.210	37.943	41.552	1207.82
BL2-S	1209.25	78.8	1.079	1191.816	4.859	1204.388	12.571	13.562	1205.38
BL2-M	1209.29	105	1.105	1177.824	5.130	1204.156	26.332	29.097	1206.92
BL2-D	1209.34	109	1.109	1165.441	5.243	1204.096	38.656	42.859	1208.30
BL3-S	1208.41	29.0	1.029	1198.190	4.185	1204.225	6.035	6.210	1204.40
BL3-M	1208.46	66.0	1.066	1193.318	4.356	1204.105	10.787	11.499	1204.82
BL3-D	1208.49	124	1.124	1177.335	4.798	1203.688	26.354	29.612	1206.95

Table 4 (cont.) Groundwater equivalent freshwater hydraulic heads and values used in their calculation as explained in section 3.2 of the text. Note that the zero pressure head listed for SMI-PZ1-S is a result of the water level occurring below the top of the 5 ft well screen.

Sampled in April, 2003			Sampled in July, 2003			Sampled in August, 2003		
Well / PZ ID	**dD (permil)**	**d^{18}O (permil)**	**Well / PZ ID**	**dD (permil)**	**d^{18}O (permil)**	**Well / PZ ID**	**dD (permil)**	**d^{18}O (permil)**
central pond	-110.7	-14.9	CR-1river	-118.3	-15.8	N3-surface water	-78.8	-7.7
CR-1river	-113.4	-15.4	CR1-3	-111.4	-14.4	CR2-river	-111.6	-14.6
CR2-river	-94.5	-12.0	M11-7	-82.0	-9.3	SMI-PZ1S	-103.3	-12.5
CR1-3	-107.9	-13.8	M11-12	-93.4	-11.5	SMI-PZ1M	-108.9	-12.0
CR2-3	-110.6	-14.8	M11-14	-103.3	-13.7	SMI-PZ1D	-109.7	-12.9
M11-12	-91.4	-11.1	N3-4	-109.2	-14.7	ATP-1-D	-103.0	-13.2
M11-14	-99.7	-13.0	N3-8	-109.6	-15.2	ATP-1-S	-104.0	-13.1
M11-4	-91.0	-11.7	N4-6	-104.1	-14.7	ATP-1-1D	-103.2	-13.2
M11-7	-84.5	-10.0	N4-12	-118.8	-14.5	ATP-1-1S	-103.0	-13.0
N2-12	-109.0	-14.9	N5-7	-108.4	-14.6	SMI-PZ3-D2	-101.0	-12.1
N2-6	-108.5	-14.5	N5-10	-106.2	-14.5	433	-98.0	-12.6
N4-12	-106.3	-14.0	N5-14	-106.2	-14.7	432	-97.5	-13.1
N4-6	-104.3	-14.2	N6-6	-108.0	-14.9	BL1-S	-108.3	-14.4
N4-3	-105.8	-14.1	N6-9	-108.9	-15.2	BL1-M	-109.3	-14.2
N7-10	-107.8	-14.4	N7-7	-108.4	-14.9	BL1-D	-105.9	-13.5
N7-11	-106.4	-13.2	N7-10	-108.3	-14.0	BL2-S	-106.8	-13.7
N7-7	-107.3	-14.3	N8-10	-79.2	-8.8	BL2-M	-105.4	-13.5
N8-10	-73.5	-8.2	N8-14	-77.8	-8.7	BL2-D	-103.5	-13.2
N8-14	-76.3	-8.6	N9-4	-109.4	-15.0	BL3-M	-101.5	-12.9
N8-6	-77.2	-8.7	N9-6	-107.5	-15.0	BL3-D	107.9	-13.1
W1-4	-105.8	-14.3	W1-4	-108.5	-14.2			
W1-7	-97.1	-14.2	W1-7	-108.9	-14.2			
			N11-6	-105.4	-13.8			

Table 5. Stable isotope ratios of hydrogen versus oxygen in surface and ground water samples collected during April, July, and August, 2003. Samples were analyzed by CF-IRMS at the University of Utah Stable Isotope Ratio Facility for Environmental Research during September , 2003.

Sample ID	R/Ra	Tritium (TU)	^{3}H plus/minus	Terr ^{4}He (ccSTP/g)
CR1-river	NS	12.02	0.60	NS
CR2-river	NS	resealed	resealed	NS
N3-surface	NS	1.07	0.05	NS
CR1-3	0.105	1.21	0.24	4.5E-06
M11-7	0.969	4.73	0.24	0.0E+00
M11-12	0.221	3.51	0.18	1.9E-07
M11-14	0.127	0.96	0.05	1.0E-06
N3-4	0.486	1.53	0.08	5.2E-08
N3-8	0.926	resealed	resealed	4.1E-09
N4-6	0.932	8.95	0.45	3.0E-08
N4-12	1.785	10.46	0.52	0.0E+00
N5-7	1.146	12.13	0.61	0.0E+00
N5-10	1.071	9.16	0.46	0.0E+00
N5-14	1.102	9.45	0.45	0.0E+00
N6-6	0.397	1.38	0.07	8.0E-08
N6-9	0.385	resealed	resealed	9.4E-08
N7-7	0.803	1.29	0.06	8.6E-09
N7-10	0.141	< 0.1	0.06	1.3E-07
N7-11	0.071	NS	NS	1.2E-06
N8-10	0.981	6.09	0.30	5.6E-10
N8-14	0.965	5.02	0.25	5.2E-10
W1-4	0.398	resealed	resealed	3.8E-08
W1-7	0.038	4.26	0.21	6.0E-08
N9-4	1.180	NS	NS	5.8E-09
N9-6	NS	8.79	0.44	NS
N11-6	0.490	4.30	0.21	2.6E-08
N11-10	0.103	NS	NS	9.0E-07
SMI-PZ1S	0.418	17.57	0.88	4.1E-08
SMI-PZ1M	0.190	14.54	0.73	1.8E-07
SMI-PZ1D	0.169	5.60	0.28	1.6E-07
ATP-1-S	0.071	< 0.1	0.04	6.8E-07
ATP-1-1S	0.065	0.22	0.01	2.3E-06
ATP-1-1D	0.062	0.52	0.03	2.3E-06
ATP-1-D	0.062	0.15	0.02	2.4E-06
SMI-PZ3-D2	0.114	8.69	0.43	7.8E-07
Atlas 432	1.088	< 0.1	0.00	0.0E+00
Atlas 433	0.142	0.60	0.03	6.2E-07
BL1-S	0.127	0.91	0.05	6.6E-07
BL1-M	0.091	< 0.1	0.04	2.4E-06
BL1-D	0.079	< 0.1	0.23	2.9E-06
BL2-S	0.079	< 0.1	0.02	2.4E-06
BL2-M	0.074	< 0.1	0.15	2.6E-06
BL2-D	0.069	resealed	resealed	2.3E-06
BL3-S	NS	NS	NS	NS
BL3-M	0.085	2.89	0.14	1.2E-06
BL3-D	0.065	resealed	resealed	3.0E-06

Table 6. Tritium and dissolved gas data from surface and ground water samples collected during July and August, 2003. Samples were analyzed by University of Utah Dissolved Gas Service Center during September and October, 2003.

Figures

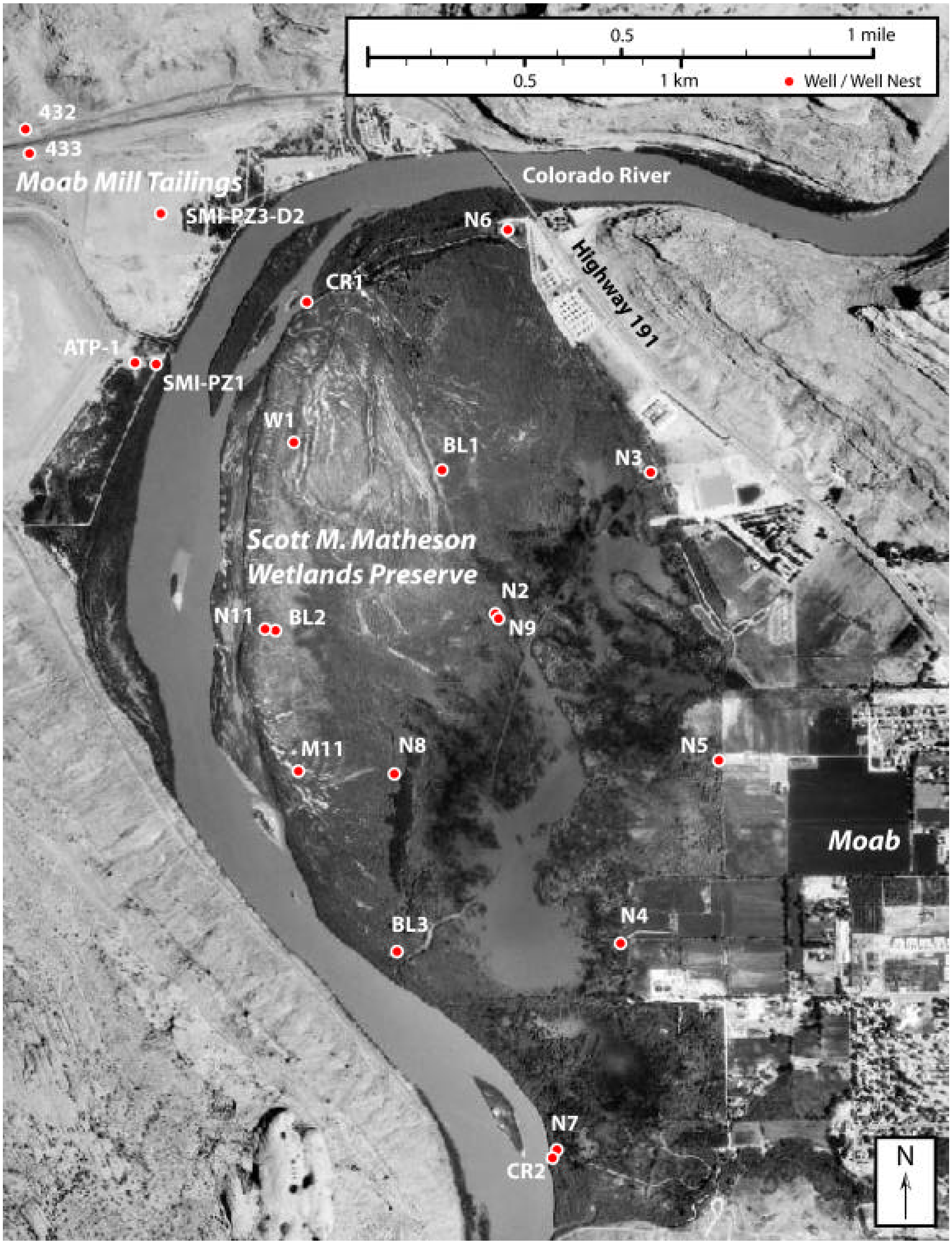


Figure 1. Location map showing all well nest and single well locations at the Moab Mill Tailings and the Scott M. Matheson Wetland Preserve.

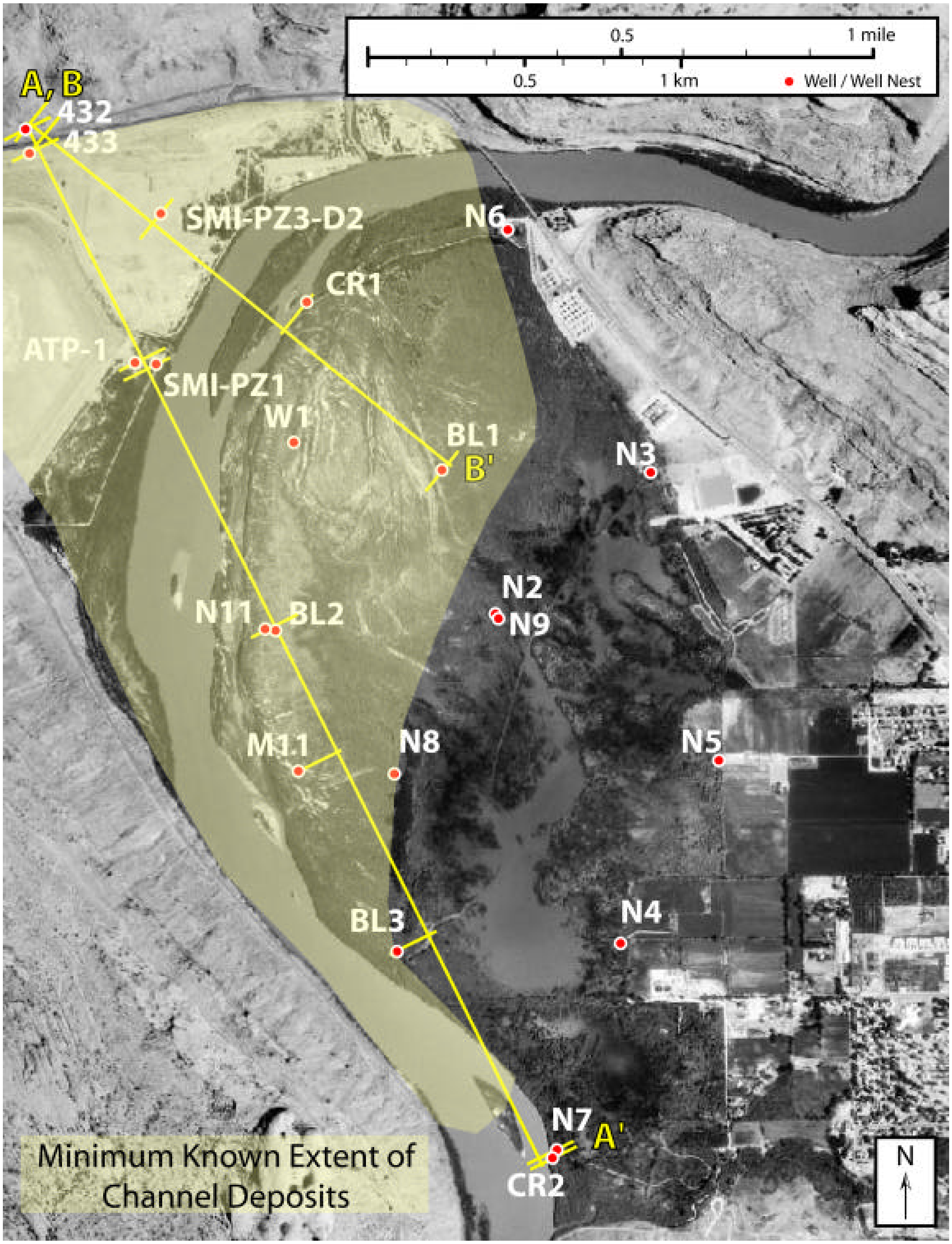


Figure 2. Map view of the Moab Mill Tailings and Matheson Wetland Preserve showing the minimum extent of the river gravel deposit shaded as well as the two cross section lines A-A' and B-B'. These cross sections are used throughout the report to display spatial distribution of data in the subsurface.

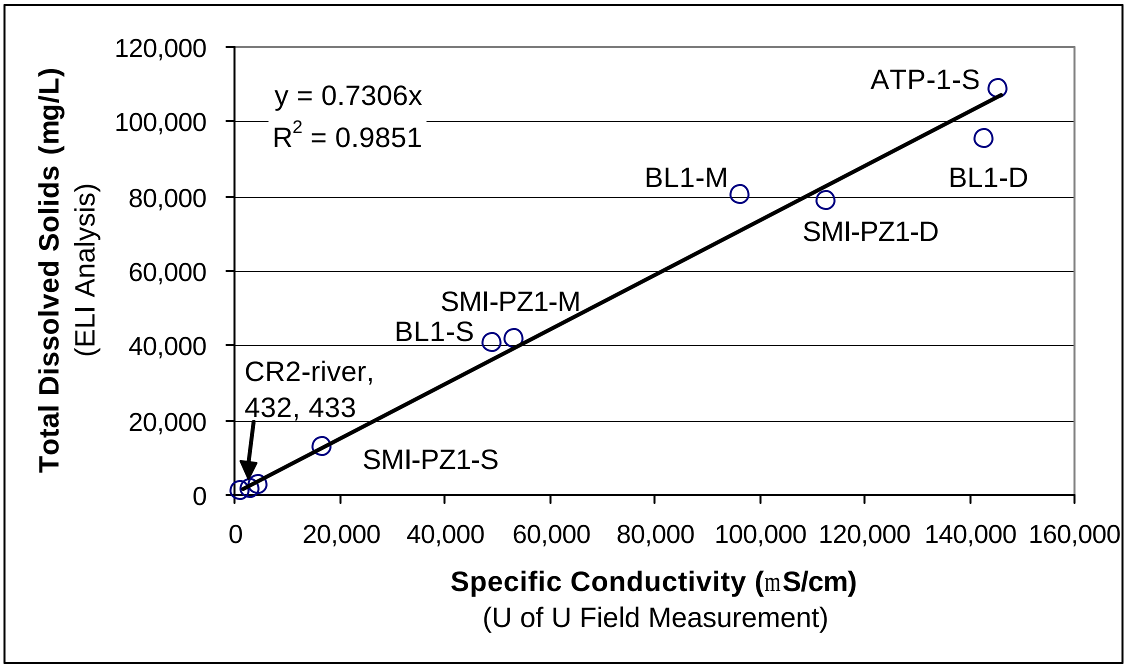


Figure 3. Plot of Total Dissolved Solids (mg/L) versus Specific Conductivity (µS/cm) for nine ground water and one surface water sample showing correlation used to deduce TDS values for the remaining waters sampled across the site.

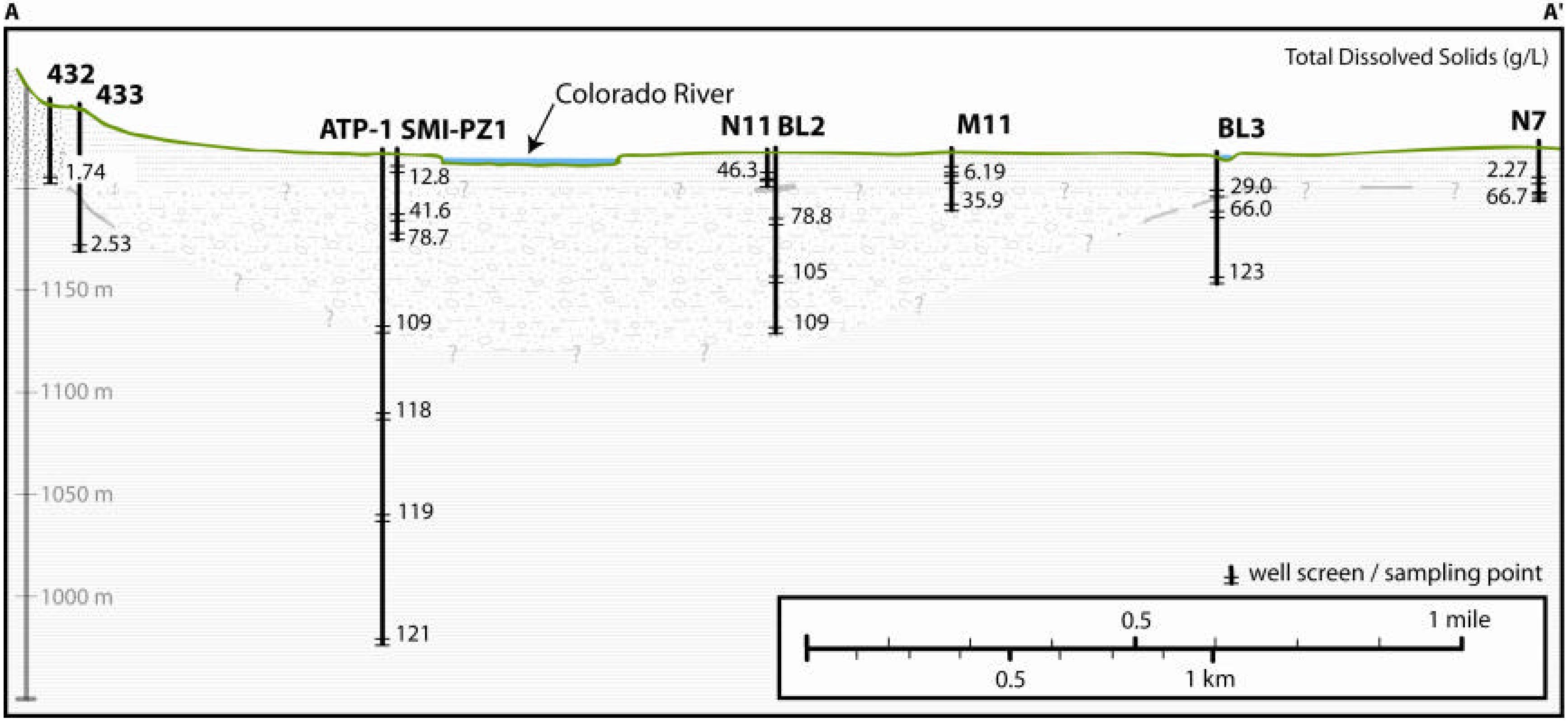


Figure 4. Cross section A-A' showing TDS (g/L) values displayed at sampling points (well screens) in the subsurface. To convert to units of mg/L, multiply g/L by 1,000. Vertical eaggeration 10:1.

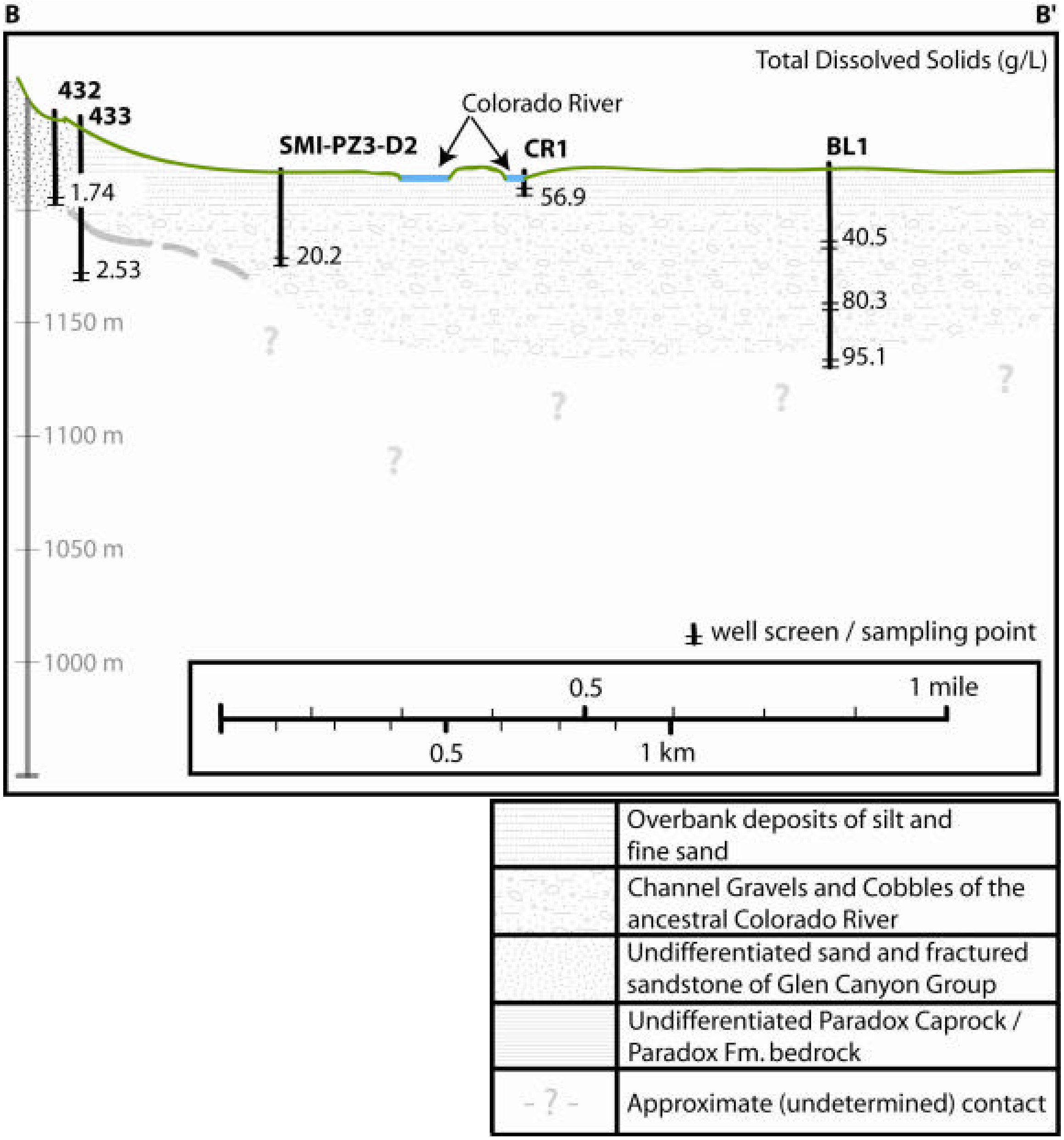


Figure 5. Cross section B-B' showing TDS (mg/L) values displayed at sampling points (well screens) in the subsurface. To convert to units of mg/L, multiply g/L by 1,000. Vertical eaggeration 10:1.

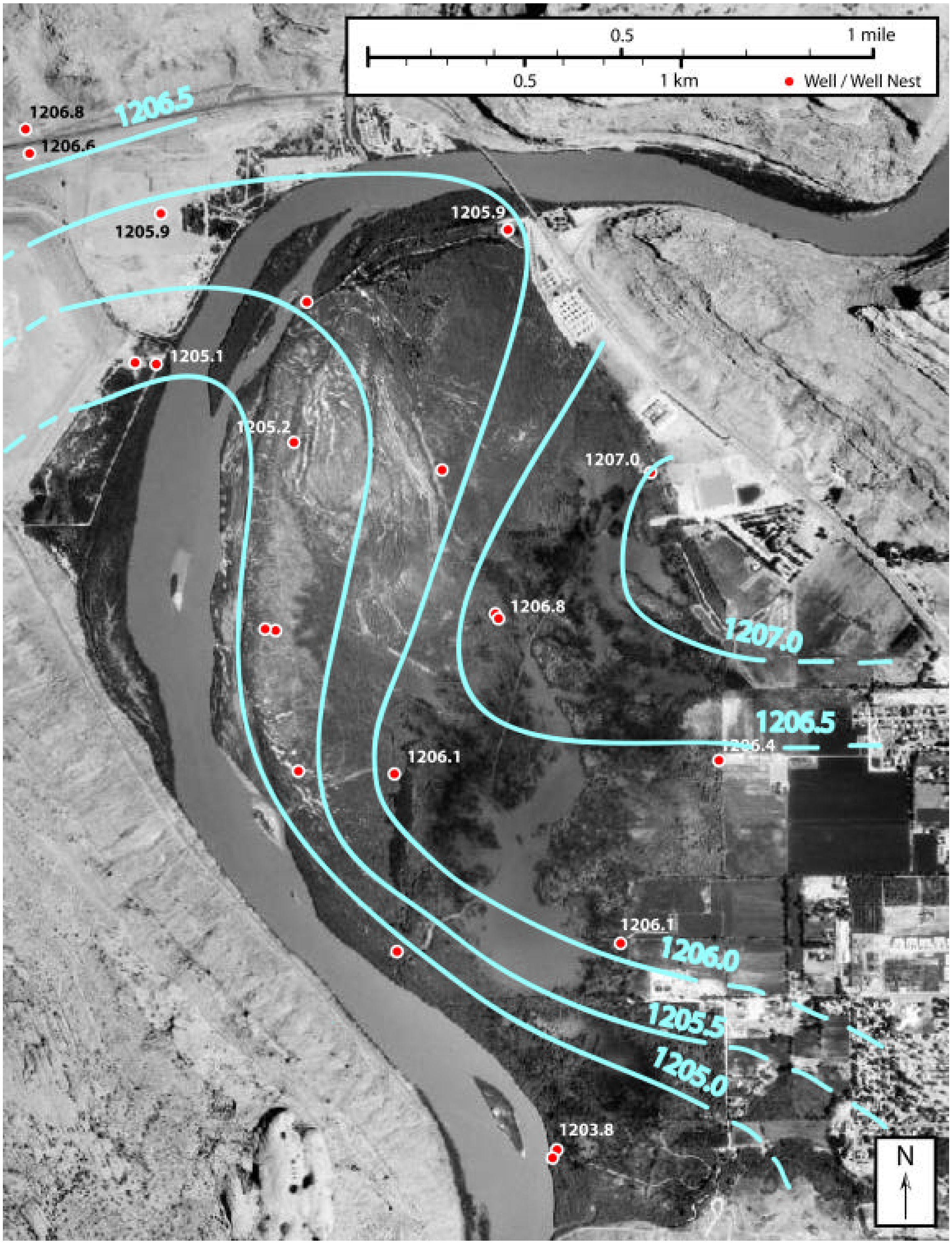


Figure 6. Interpolated water table surface contours compiled from equivalent fresh water hydraulic head values for shallow piezometers and wells with TDS values less than 20,000 mg/L. The contours represent a hypothetical water table for a shallow system composed of all fresh water.

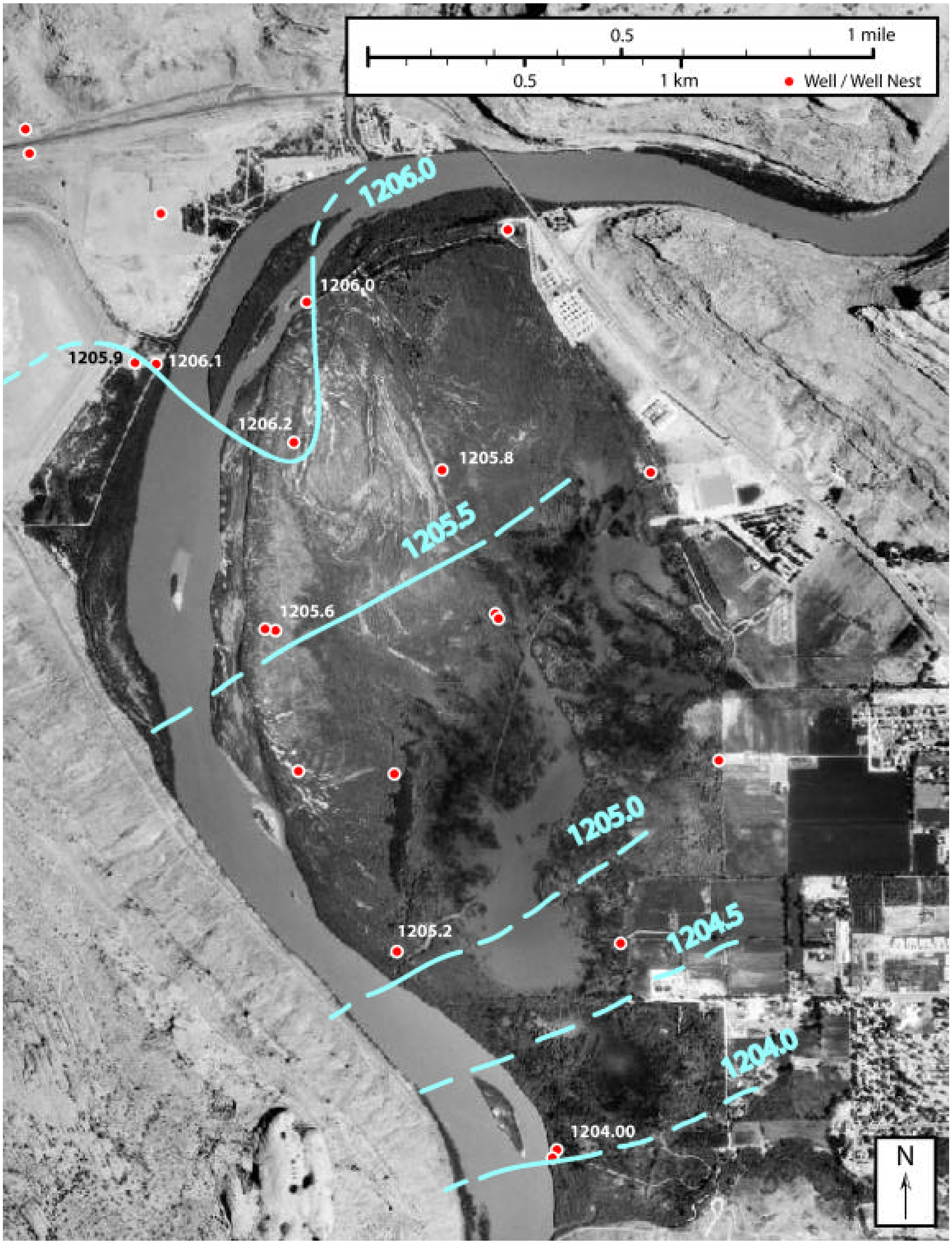


Figure 7. Potentiometric surface contours of brine at a common elevation (1190 m) below the top of the ancestral Colorado River gravels compiled from equivalent fresh water hydraulic head values for deep wells with TDS values greater than 40,000 mg/L.

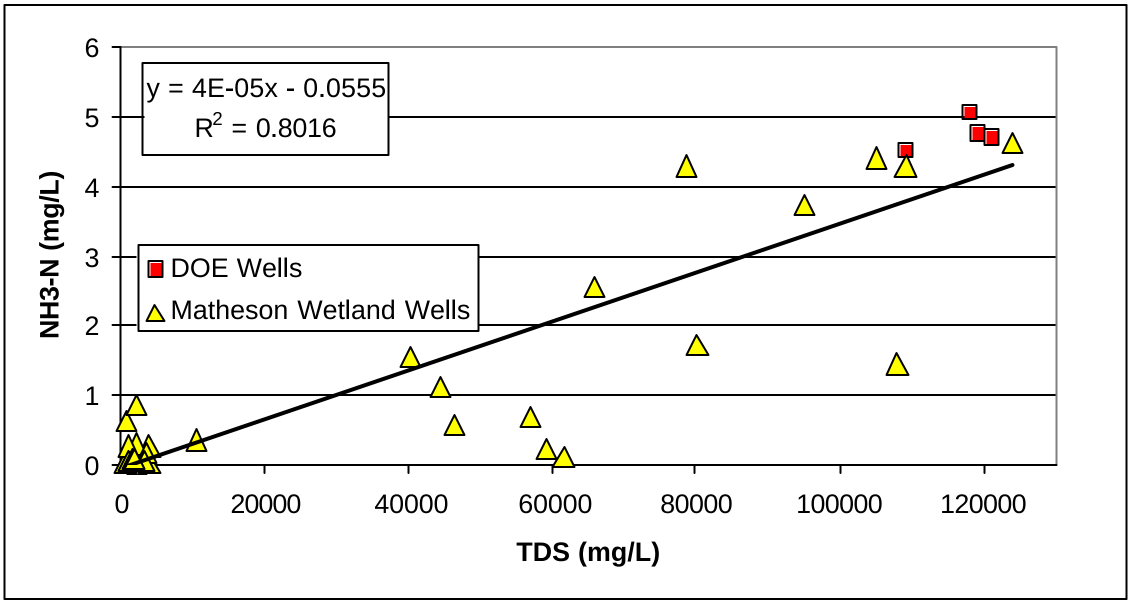


Figure 8. Plot showing correlation between NH_3-N and TDS for all of waters sampled except for the four high ammonia SMI wells on the Mill Tailings property

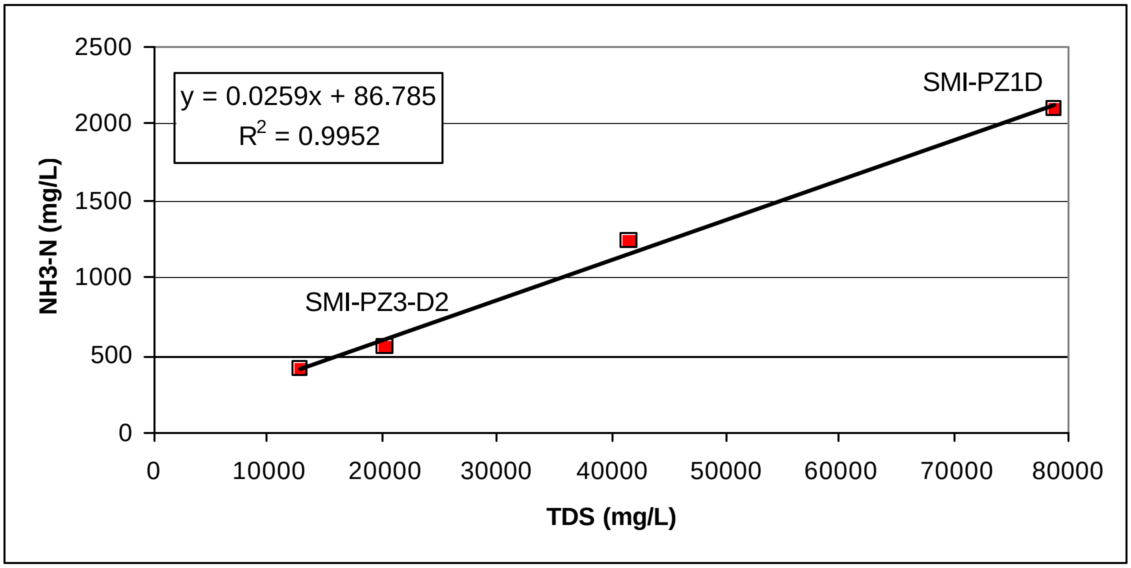


Figure 9. Plot showing correlation between NH_3-N and TDS for the four high ammonia SMI wells on the Mill Tailings property.

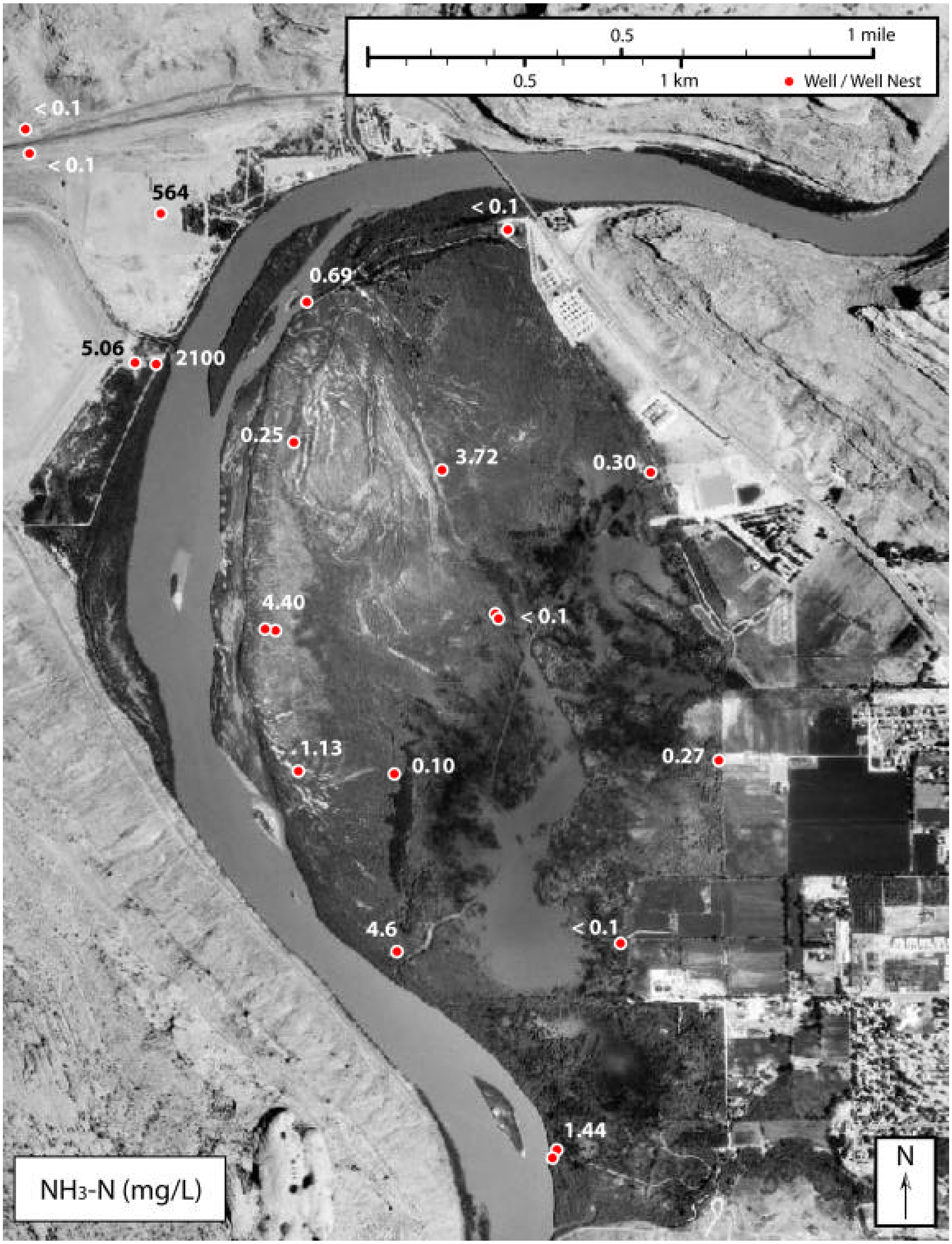


Figure 10. Map view of the Moab Mill Tailings and Matheson Wetland Preserve showing concentrations of ammonia as nitrogen (mg/L) measured in ground water. Values plotted are the maximum concentration at each well nest.

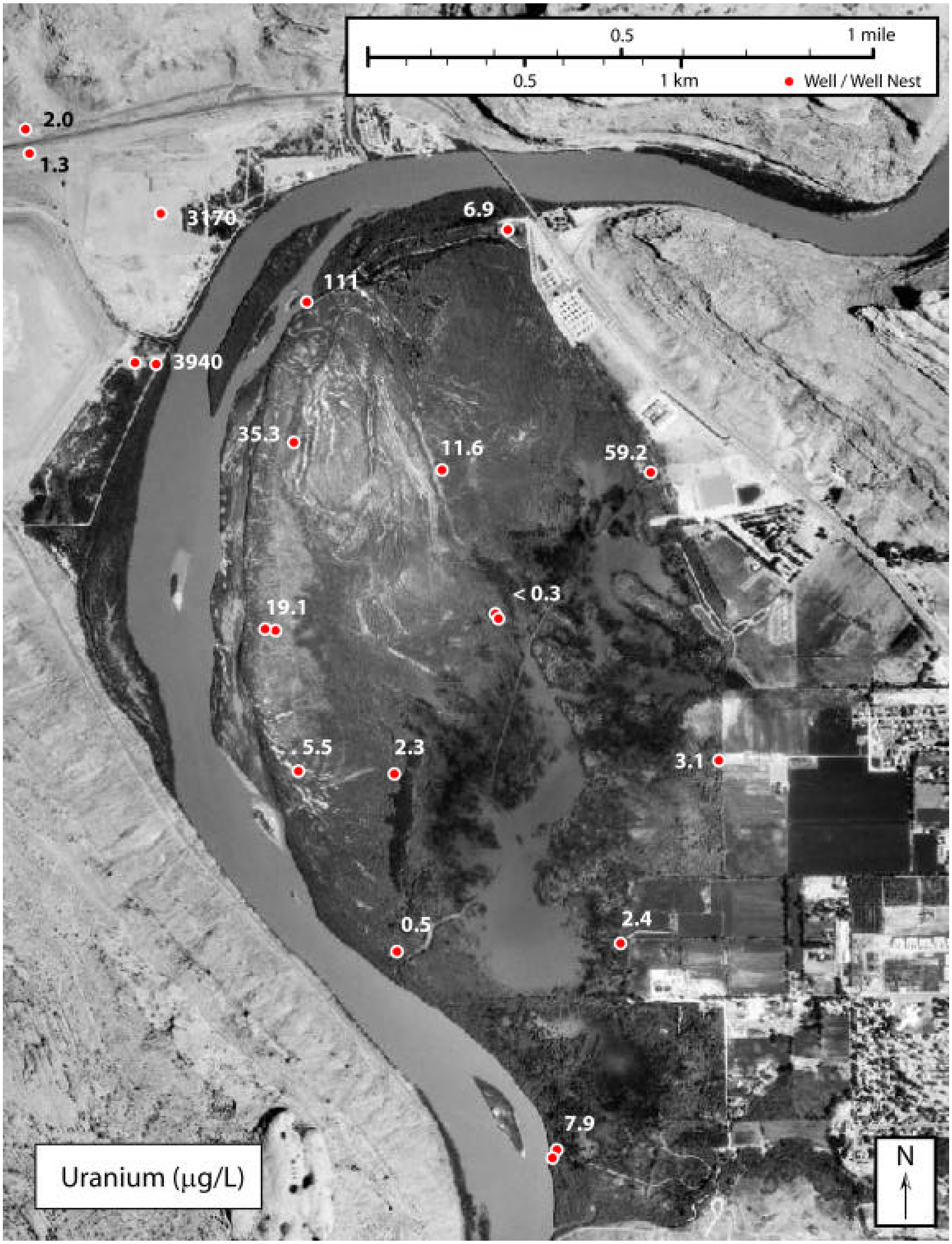


Figure 11. Map view of the Moab Mill Tailings and Matheson Wetland Preserve showing concentrations of uranium (µg/L) measured in ground water. Values plotted are the maximum concentration at each well nest.

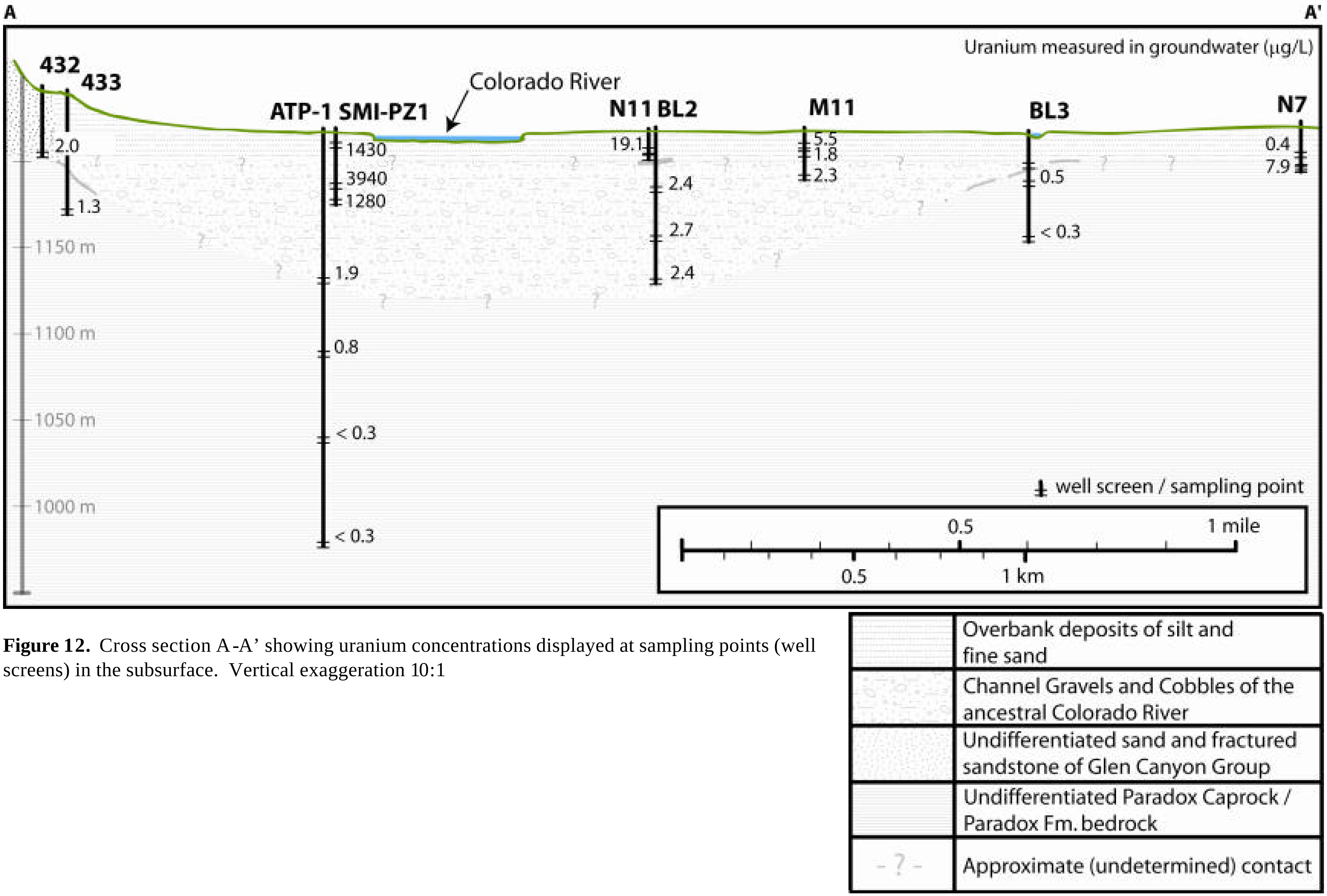


Figure 12. Cross section A-A' showing uranium concentrations displayed at sampling points (well screens) in the subsurface. Vertical exaggeration 10:1

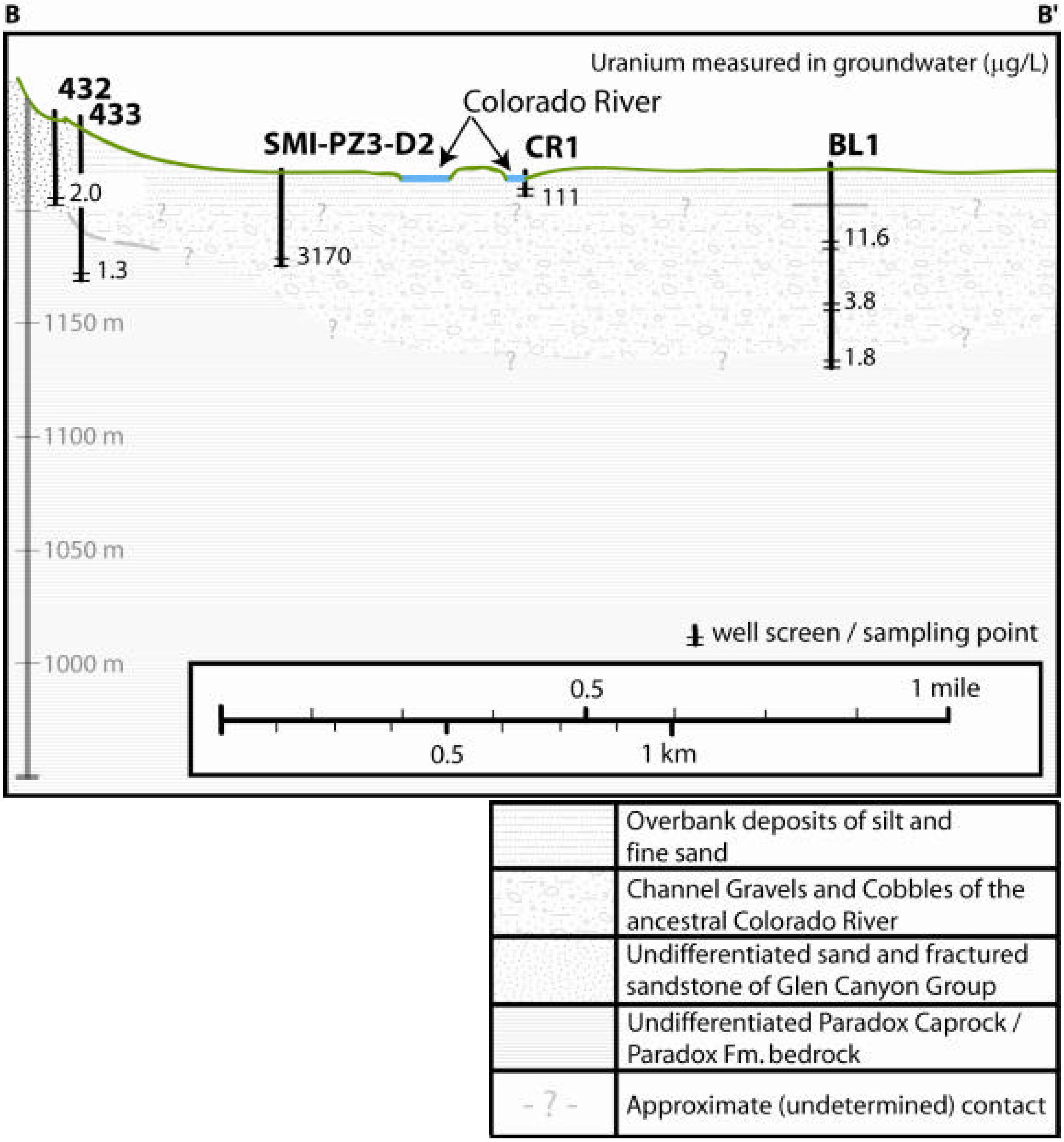


Figure 13. Cross section B-B' showing uranium concentrations displayed at sampling points (well screens) in the subsurface. Vertical exaggeration 10:1

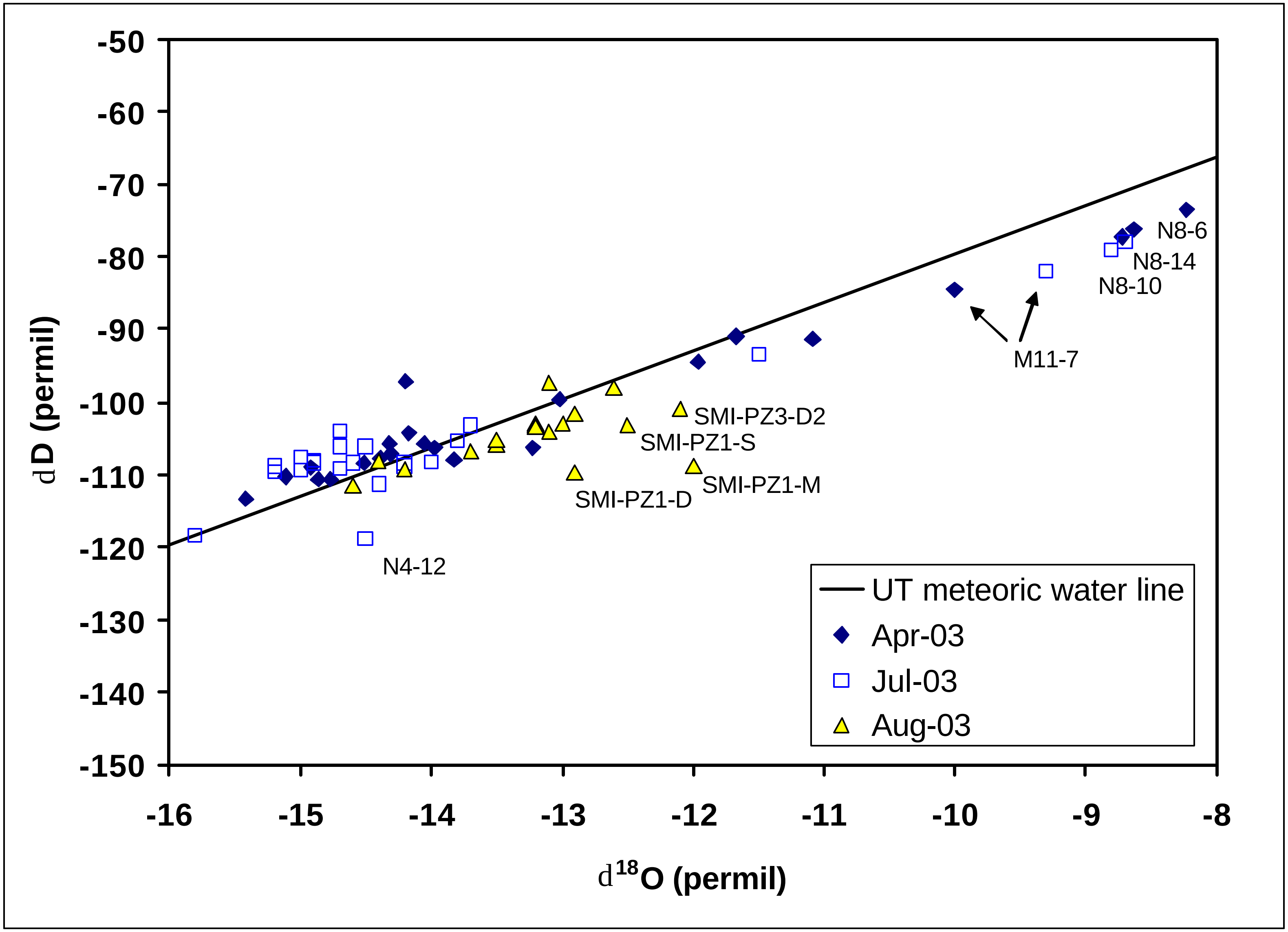


Figure 14. Stable isotope ratios of hydrogen versus oxygen in surface and ground water samples from the Moab Mill Tailings and Matheson Wetland Preserve compared to the Utah meteoric water line from Kendall and Coplen, 2001.

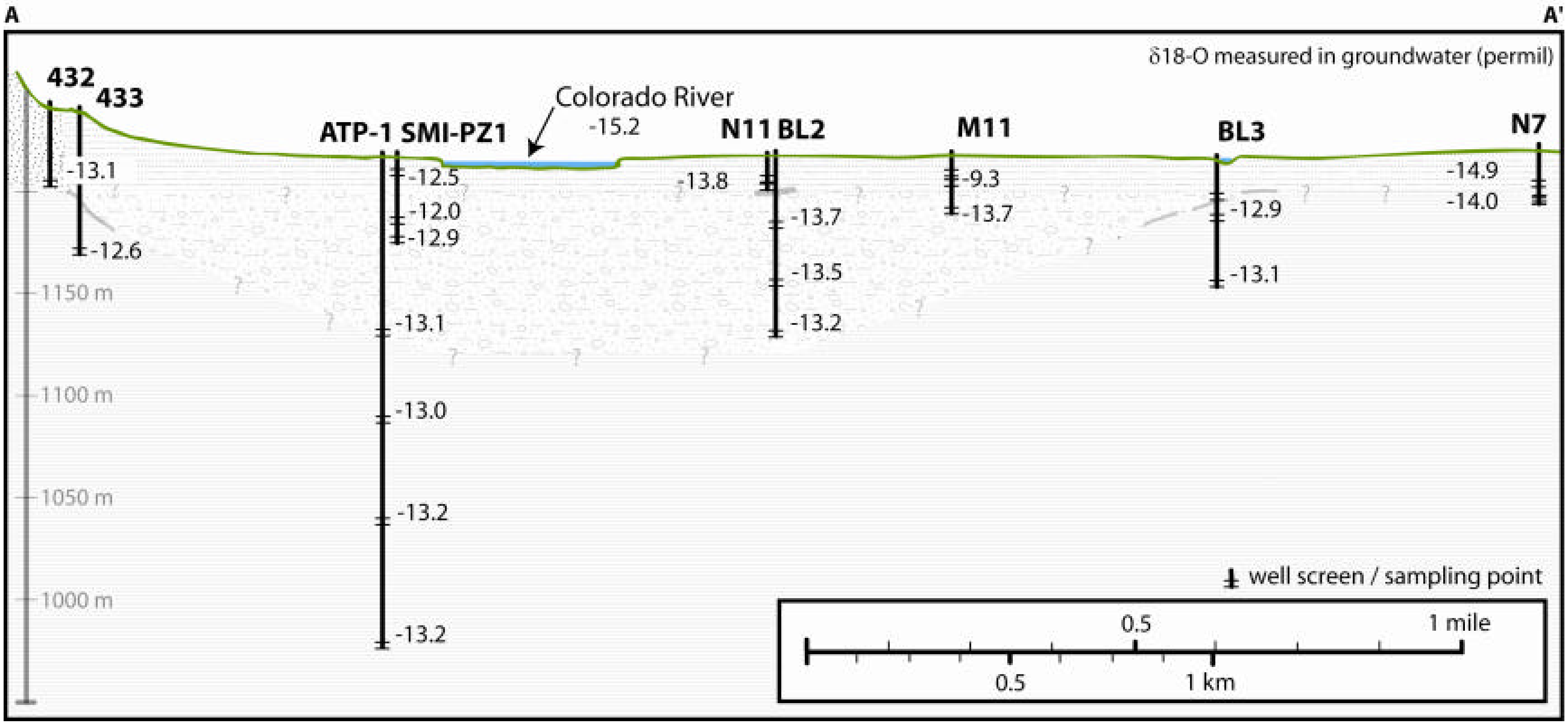


Figure 15. Cross section A-A' showing δ18O values displayed at sampling points (well screens) in the subsurface. Vertical exaggeration 10:1

▤	Overbank deposits of silt and fine sand
░	Channel Gravels and Cobbles of the ancestral Colorado River
░	Undifferentiated sand and fractured sandstone of Glen Canyon Group
▤	Undifferentiated Paradox Caprock / Paradox Fm. bedrock
- ? -	Approximate (undetermined) contact

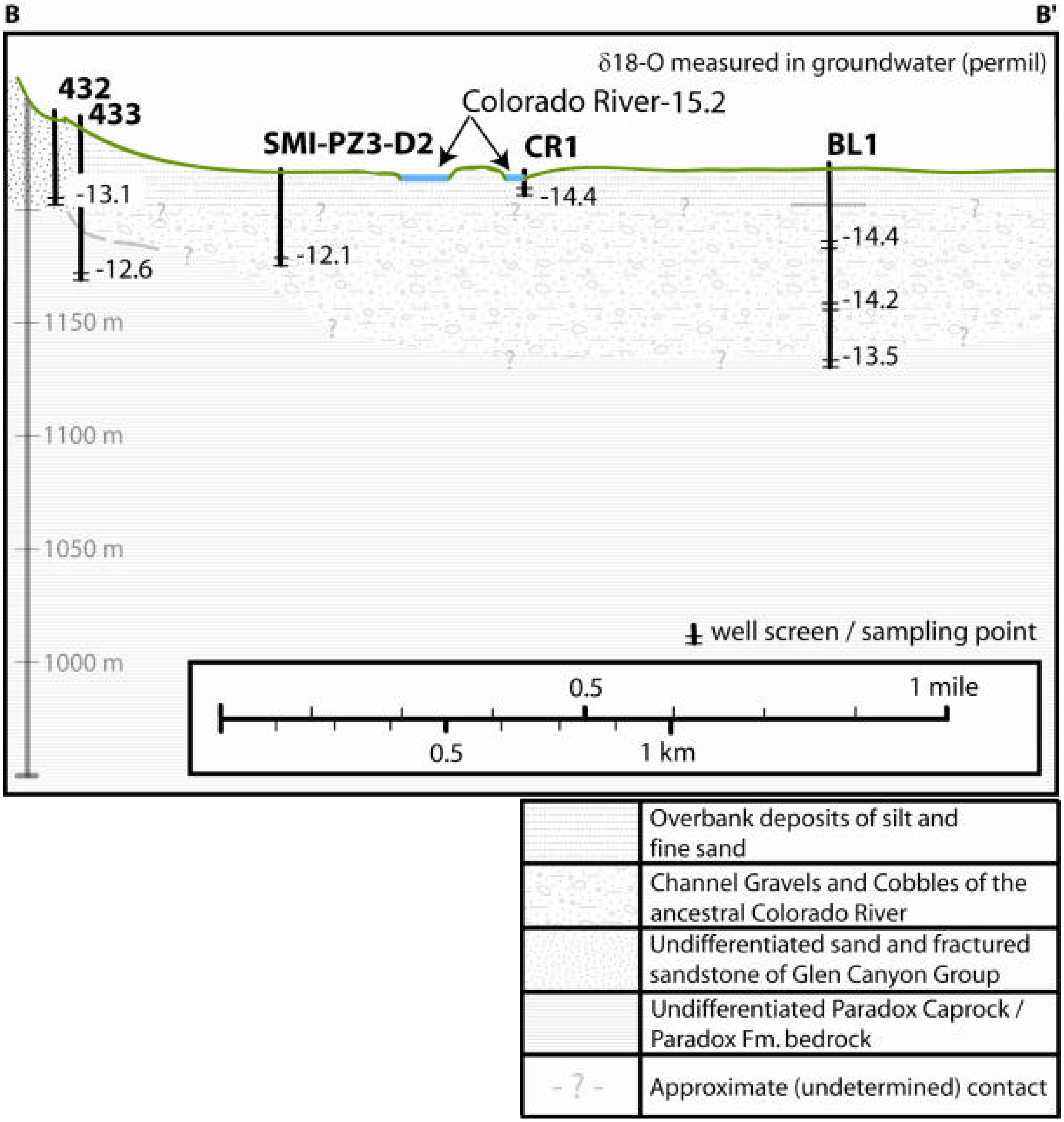


Figure 16. Cross section B-B' showing δ^{18}O values displayed at sampling points (well screens) in the subsurface. Vertical exaggeration 10:1

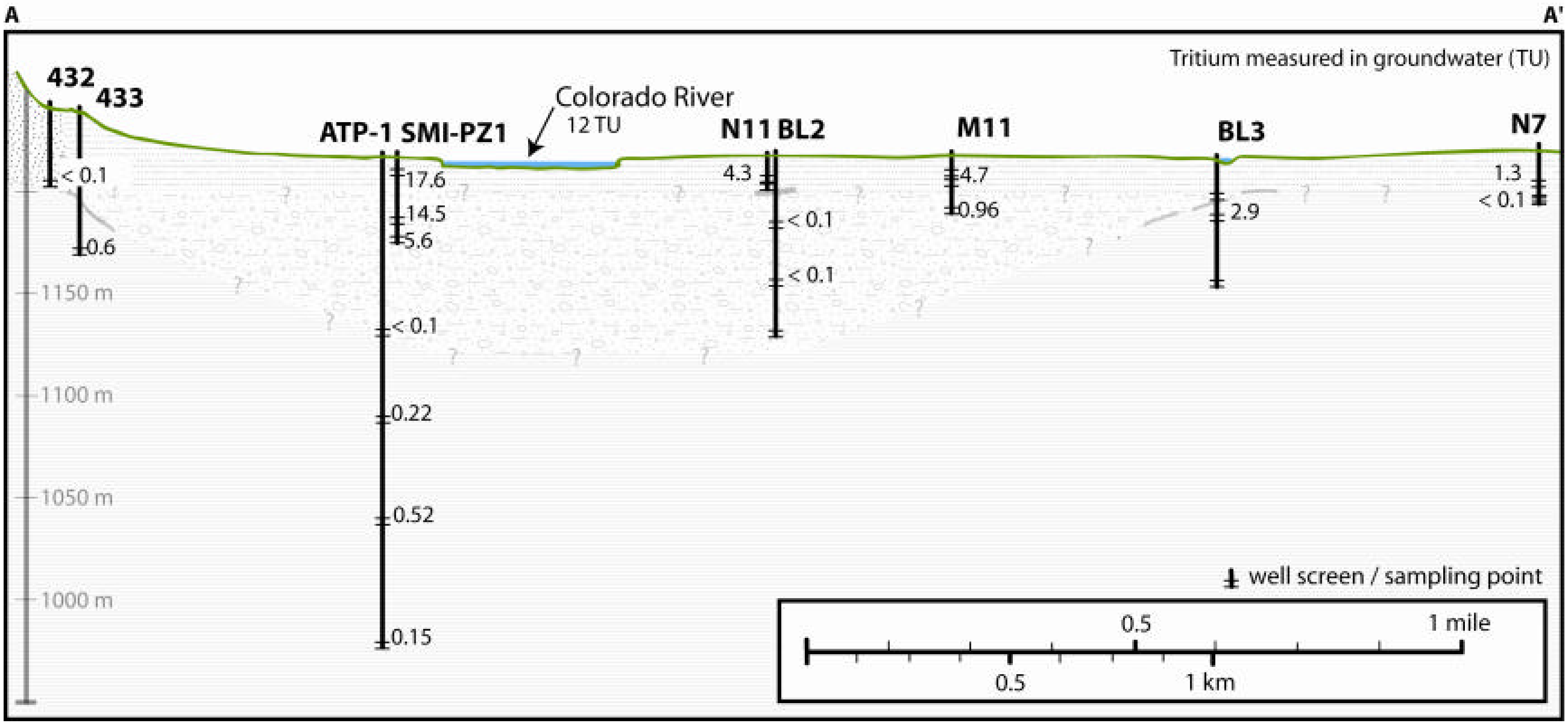


Figure 17. Cross section A-A' showing ^{3}H values displayed at sampling points (well screens) in the subsurface. Vertical exaggeration 10:1

▤	Overbank deposits of silt and fine sand
░	Channel Gravels and Cobbles of the ancestral Colorado River
░	Undifferentiated sand and fractured sandstone of Glen Canyon Group
▤	Undifferentiated Paradox Caprock / Paradox Fm. bedrock
- ? -	Approximate (undetermined) contact

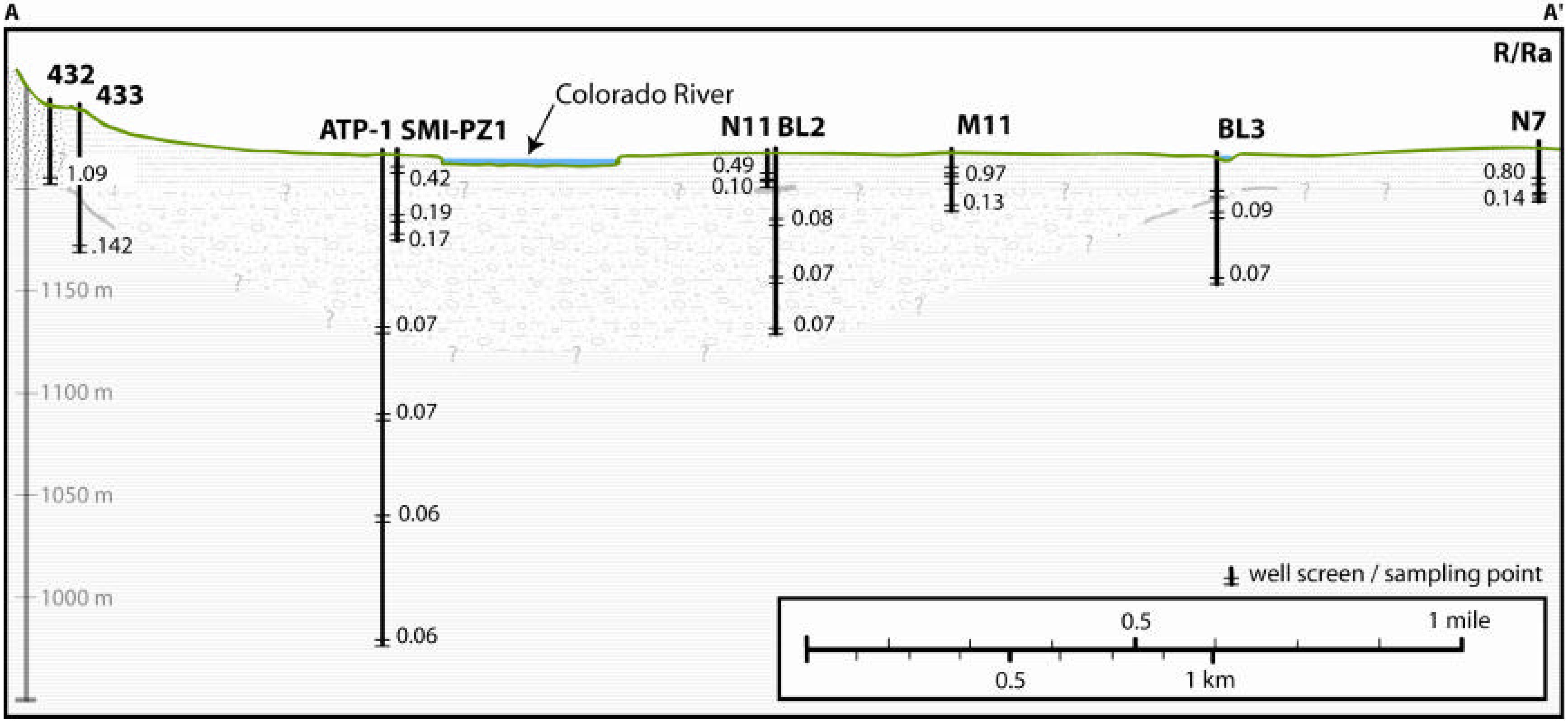


Figure 18. Cross section A-A' showing R/Ra values displayed at sampling points (well screens) in the subsurface. Vertical exaggeration 10:1

▤	Overbank deposits of silt and fine sand
▨	Channel Gravels and Cobbles of the ancestral Colorado River
▨	Undifferentiated sand and fractured sandstone of Glen Canyon Group
▨	Undifferentiated Paradox Caprock / Paradox Fm. bedrock
- ? -	Approximate (undetermined) contact

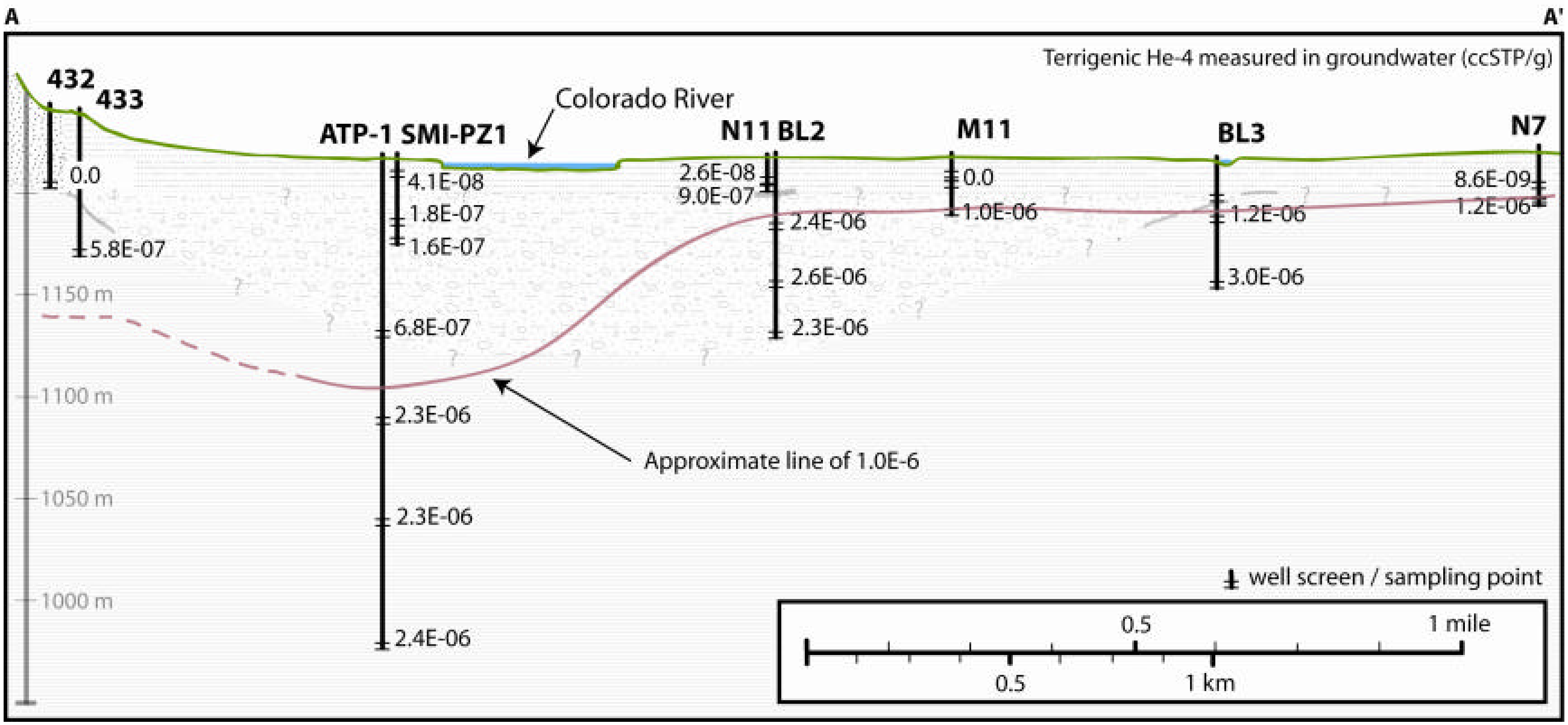


Figure 19. Cross section A-A' showing terrigenic ^{4}He values displayed at sampling points (well screens) in the subsurface. Vertical exaggeration 10:1

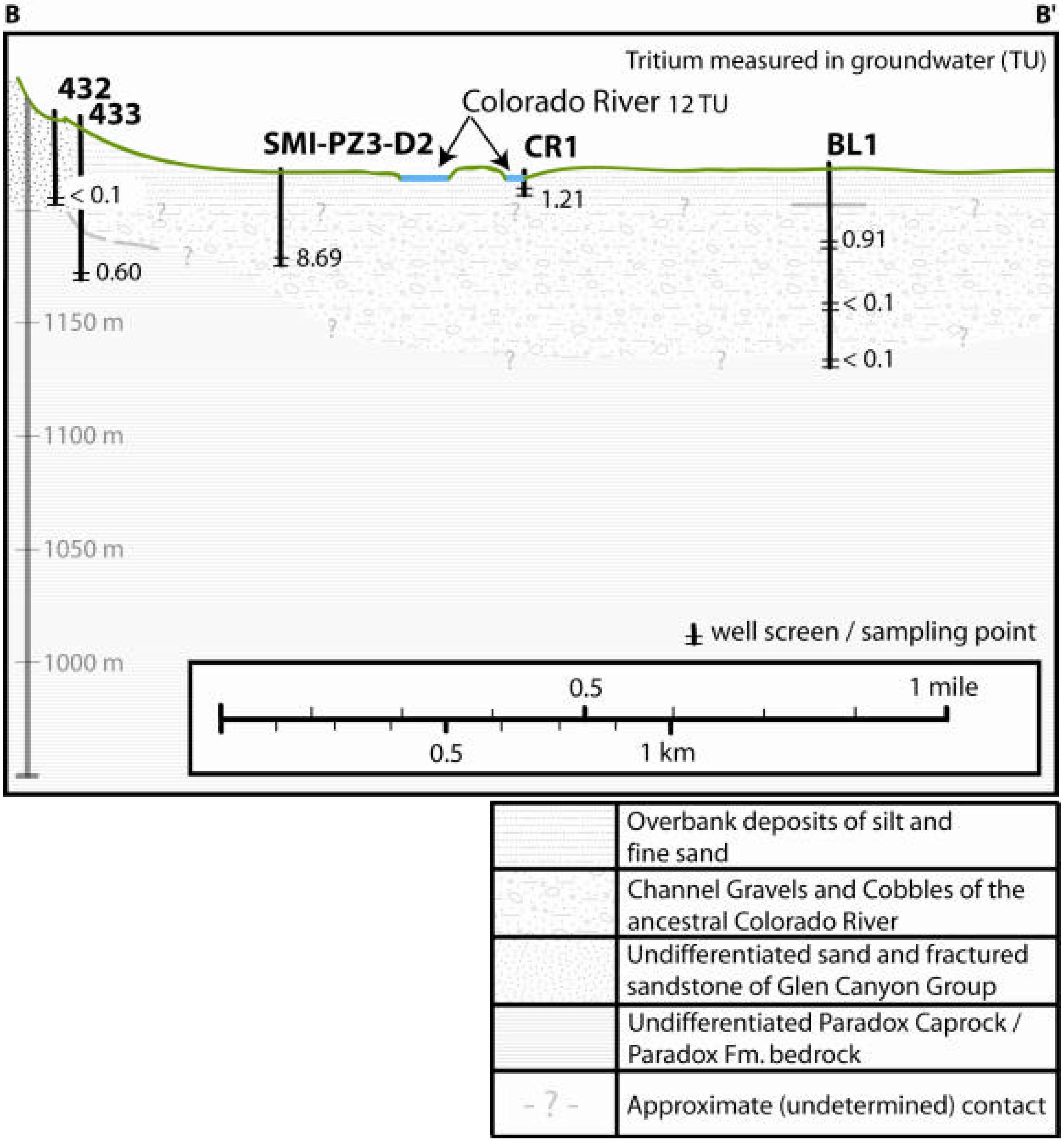


Figure 20. Cross section B-B' showing ^{3}H values displayed at sampling points (well screens) in the subsurface. Vertical exaggeration 10:1

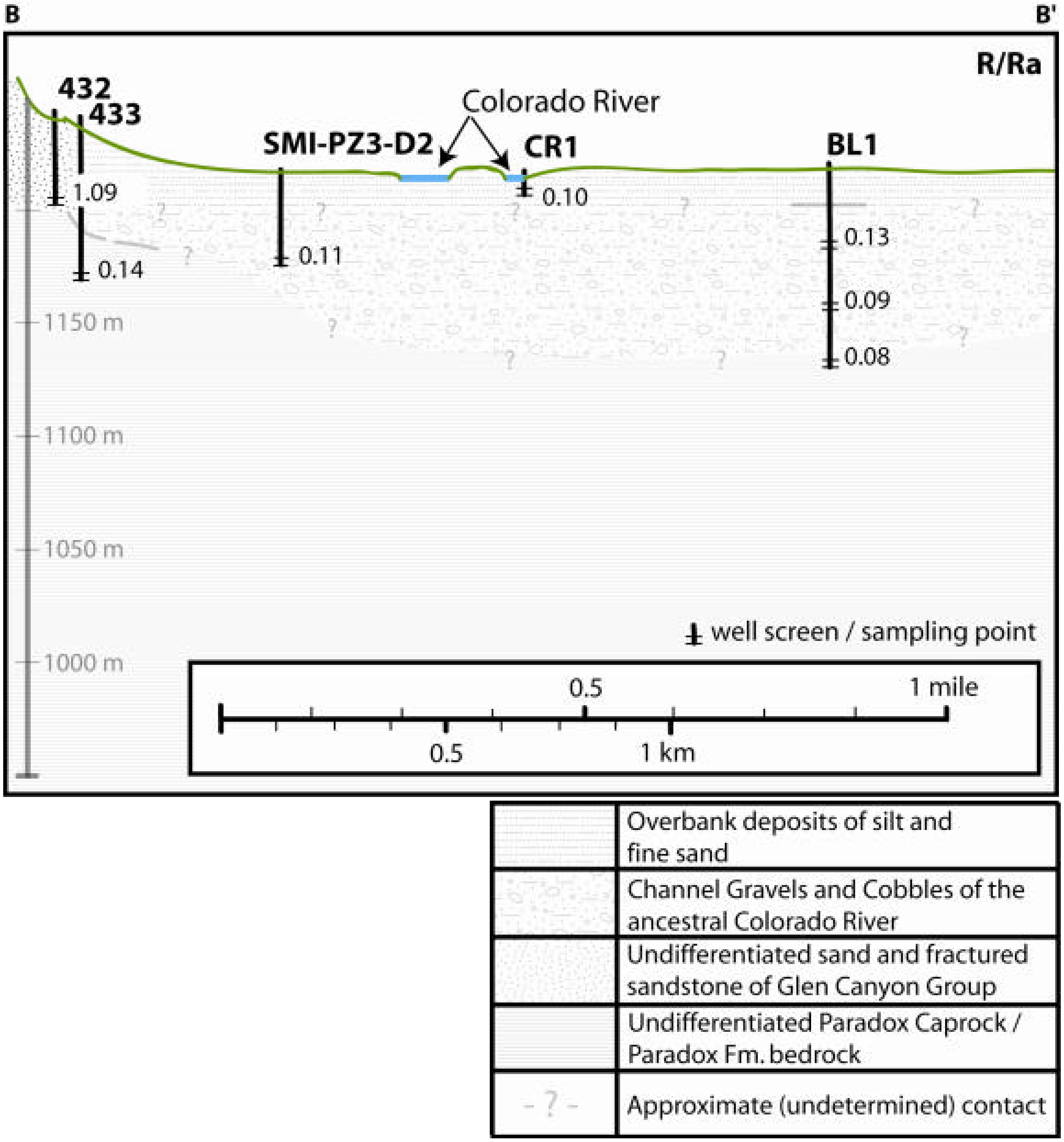


Figure 21. Cross section B-B’ showing R/Ra values displayed at sampling points (well screens) in the subsurface. Vertical exaggeration 10:1

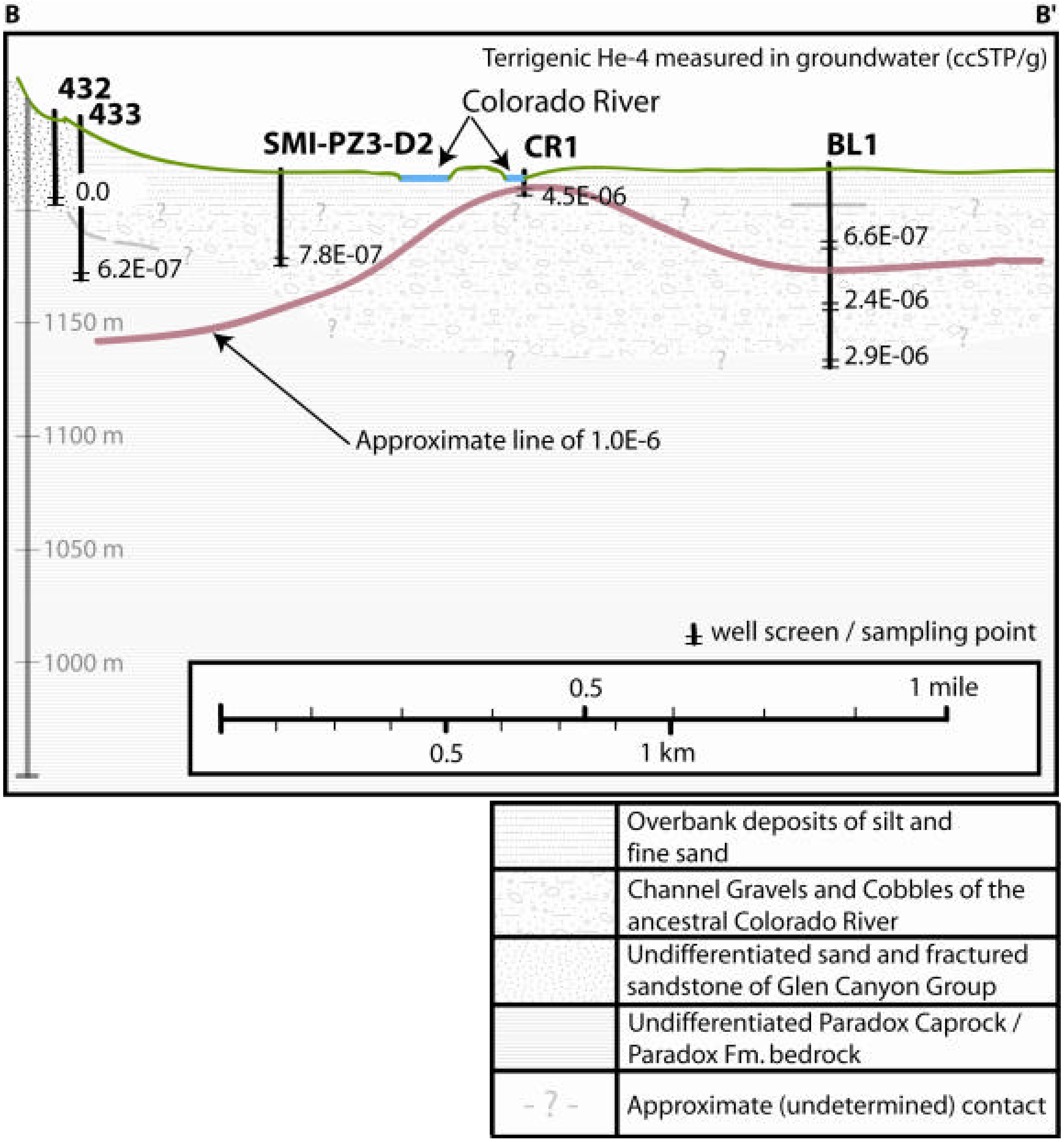


Figure 22. Cross section B-B' showing terrigenic ^{4}He values displayed at sampling points (well screens) in the subsurface. Vertical exaggeration 10:1

Appendix A: Boring Logs

Three new boreholes were drilled and logged on the Matheson Wetland Preserve between July 28 and August 4, 2003. The drilling was performed by Boart Longyear Company using a Gus Pech 300 Rotosonic Rig. Three wells of schedule 40 PVC casing were installed in each borehole. Each well consists of 2" solid PVC casing with a 2' long 0.020" slotted PVC screen at the end. Drilling of each borehole began with 9" diameter drill casing to allow room for three PCV pipes. Below the depth of the first well screen, drilling continued with 8" drill pipe. The holes are designated as BL1, BL2, and BL3 with the individual wells designated as S, M, and D (e.g. the three wells completed in the first borehole are referred to as BL1-S, BL1-M, and BL1-D). Well installation and development information for the 9 monitoring wells in 3 boreholes is included below.

BL1

Well BL1-S was screened from 51.6' to 53.6' with a silica sand pack surrounding the screen from 49.9' to 56.5' and a thin layer of bentonite chips emplaced below 56.5'. Well BL1-M was screened from 96.5' to 98.5' with a silica sand pack surrounding the screen from 94.3' to 100.7' and bentonite chips used from 100.7' to 110'. Well BL1-D was screened from 137.6' to 139.6' with a silica sand pack surrounding the screen from 136.2' to 140.1'. Bentonite slurry (with the small intervals of bentonite chips) was used to completely seal the area between well screens. Well development of the new wells began by using a waterra hand-pump to remove the first 25 gallons (at least) of very silty water. After the water began to clear, well development was continued using a Whale® submersible pump in each well until field parameters (temperature, total dissolved gas pressure, and specific conductance) had stabilized to within +/- 5%. The total volume of ground water purged from BL1-S, BL1-M , and BL1-D was 105, 150, 190 gallons respectively.

BL2

Well BL2-S was screened from 54' to 56' with a silica sand pack surrounding the screen from 49.5' to 58' and a 0.4' layer of bentonite chips was emplaced beneath 58'. Well BL2-M was screened from 100' to 102' with a silica sand pack surrounding the screen from 97.7' to 104.2' and a 0.4' layer of bentonite chips used below 104.2'. Well BL2-D was screened from 140.8' to 142.8' with silica sand pack surrounding the screen from 138.5' to 147.3'. Bentonite slurry (with the small intervals of bentonite chips) was used to completely seal the area between well screens. Well development of the new wells began by using a waterra hand-pump to remove the first 25 gallons (at least) of very silty water. After the water began to clear, well development was continued using a Whale® submersible pump in each well until field parameters (temperature, total dissolved gas pressure, and specific conductance) had stabilized to within +/- 5%. The total volume of ground water purged from BL2-S, BL2-M, and BL2-D was 120, 135, 195 gallons respectively.

BL3

Well BL3-S was screened from 30' to 32' with a silica sand pack surrounding the screen from 27.9' to 32.5'. Well BL3-M was screened from 46.1' to 48.1' with a silica sand pack surrounding the screen from 44' to 50' and a layer of bentonite chips was emplaced down to 63.2'. Well BL3-D was screened from 98.6' to 100.6' with a silica sand pack surrounding the screen from 96.3' to 101.1'. Bentonite slurry (with the small intervals of bentonite chips) was used to completely seal the area between well screens. Well development of these new wells began by using a waterra hand-pump to remove the first 25 gallons (at least) of very silty water. After the water began to clear, well development was continued using a Whale® submersible pump in each well until field parameters (temperature, total dissolved gas pressure, and specific conductance) had stabilized to within +/- 5%. The total volume of ground water purged from BL3-S, BL3-M, and BL3-D was >200, 135, >110 gallons respectively.

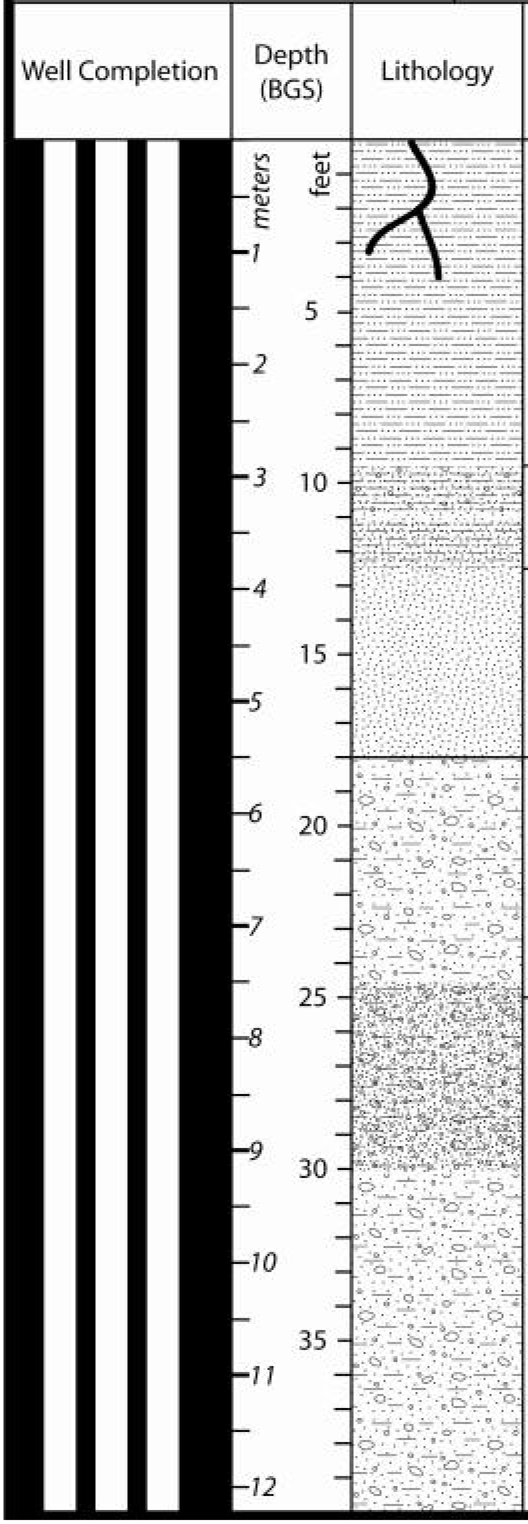
Heaving sands are believed to be the cause of the borehole collapse that forced the silica pack and bentonite slurry up into to the screen of BL3-S. As a result, BL3-S yielded nothing but bentonite slurry upon development (after purging >200 gallons over two days). Water level measurements were made from BL3-S but ground water pumped from this well never cleared enough to collect samples for the constituents included in this report.

The BL3 borehole was stopped approximately 50’ shallower that the BL1 and BL2 boreholes. The reason for this is that the drill met refusal at ~100’ below ground surface when the caprock of the Paradox Formation was encountered. Drilling was continued for one hour during which time only one additional foot of progress was made.

Matheson Wetlands Summer Drilling Boring Log

Scott M. Matheson Wetlands, Moab, Utah

Drill Rig: Boart Longyear Rotosonic	Dates Drilled: 07-28-03 to 07-30-03	Logged By: J. Weigel
Boring Diameter: 9 inches	Boring Number: **BL1**	



Description

0 - 9.5' Silty SAND, light to dark brown, tamarisk roots found to 4'.

9.5' - 12.5' Silty SAND, brown, with <3% angular gravel.

11.5' Sand content increases.

12.5' - 17.8' Fine SAND, brown.
Initial water level at 14.2' as evidenced by saturation of core.

GRAVEL and COBBLE encountered at 17.8', 0.4- 4.3 inch diameter, well rounded, well graded, cobbles mostly quartzite and fine-grained metemorphics with occasional granite in a fine to medium sand matrix.
River gravels of ancestral Colorado River.
(Appx. 55% gravel, 28% silty sand, 17% cobble)

25' - 30' SAND and GRAVEL, fining upward sequence with 7 inch diameter cobbles at 30' and 10% fine to coarse gravel at 25'.

30' - 50' Sandy GRAVEL with COBBLES up to 5inch dia. Well graded.
Some cobbles of granite with substantial muscovite indicate gravels are ancestral Colorado River deposits.

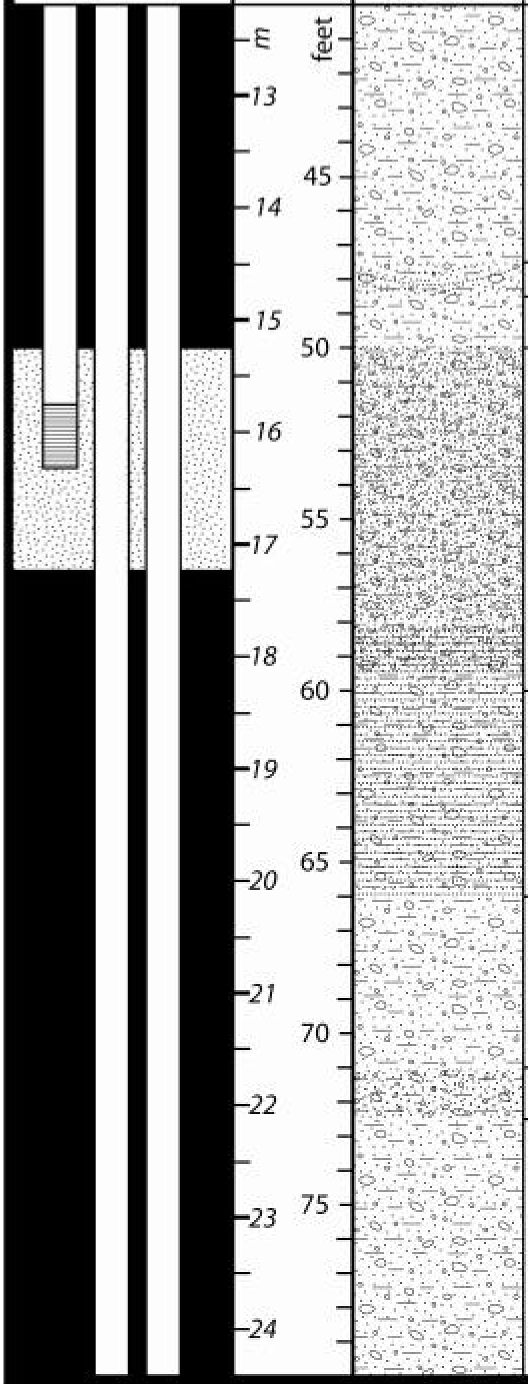
Page 1

Matheson Wetlands Summer Drilling Boring Log

Scott M. Matheson Wetlands, Moab, Utah

Drill Rig: Boart Longyear Rotosonic	Dates Drilled: 07-28-03 to 07-30-03	Logged By: J. Weigel
Boring Diameter: 9 inches	Boring Number: **BL1**	

Well Completion	Depth (BGS)	Lithology	Description



60% GRAVEL, 35% med.to coarse SAND, 5% COBBLE up to 7 inches.

55% GRAVEL, 40% fine to med. SAND, 5% COBBLE, max cobble size 5 inches.

47.5' - 48.5' cross bedded sands, possiblechannel deposit

Cobbles of red SS, mudstone, shale, granite, and meta seds.

Fining upward sequence from ~50' to 59'. No Cobbles at 50' - 51'. Max cobble size at 55' is 4 inches. 50' to 55' interval composed of 65% fine to med. GRAVEL, 5% COBBLES, and 30% fine to med. sand.

Notable increase in silt content at 58' to 59' interval.

60' - 66 '50% GRAVEL, 45% SAND with intermitent silt, 5% COBBLES, max size 5.5 inches.

66' - 71' 65% GRAVEL, 32% SAND, 3% COBBLES, max cobble size 5.5 inches, average size 2 inches. Little or no silt.

71' - 72.5' Gravelly med. SAND. 90% Sand, 10% Gravel

72.5' - 89' GRAVEL content increases to 70%, gravel subangular to well rounded. 30% SAND, fine to coarse.

Matheson Wetlands Summer Drilling Boring Log

Scott M. Matheson Wetlands, Moab, Utah

Drill Rig: Boart Longyear Rotosonic

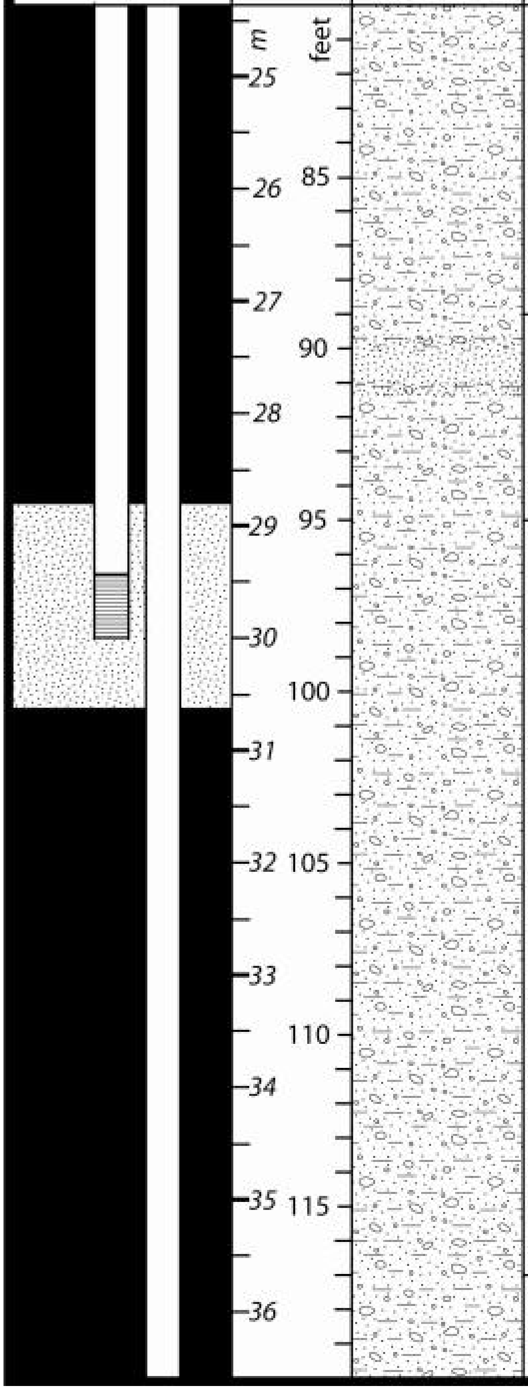
Dates Drilled: 07-28-03 to 07-30-03

Logged By: J. Weigel

Boring Diameter: 9 inches

Boring Number: **BL1**

Well Completion	Depth (BGS)	Lithology	Description



70% GRAVEL, 25% fine to coarse SAND, 5% COBBLES, cobbles up to 6 inches. Gravels are angular to sub-rounded. Cobbles are sub to well rounded and mainly composed of granites and metasediments. Some cobble sized redSS present at ~ 86'.

2' thick fining upward sequence. 90' to 91' is coarse sand without gravel. 91' to 92' is 85% fine gravel, angular to sub rounded with 15% sand
Cobble size increases to 6.75 inches.

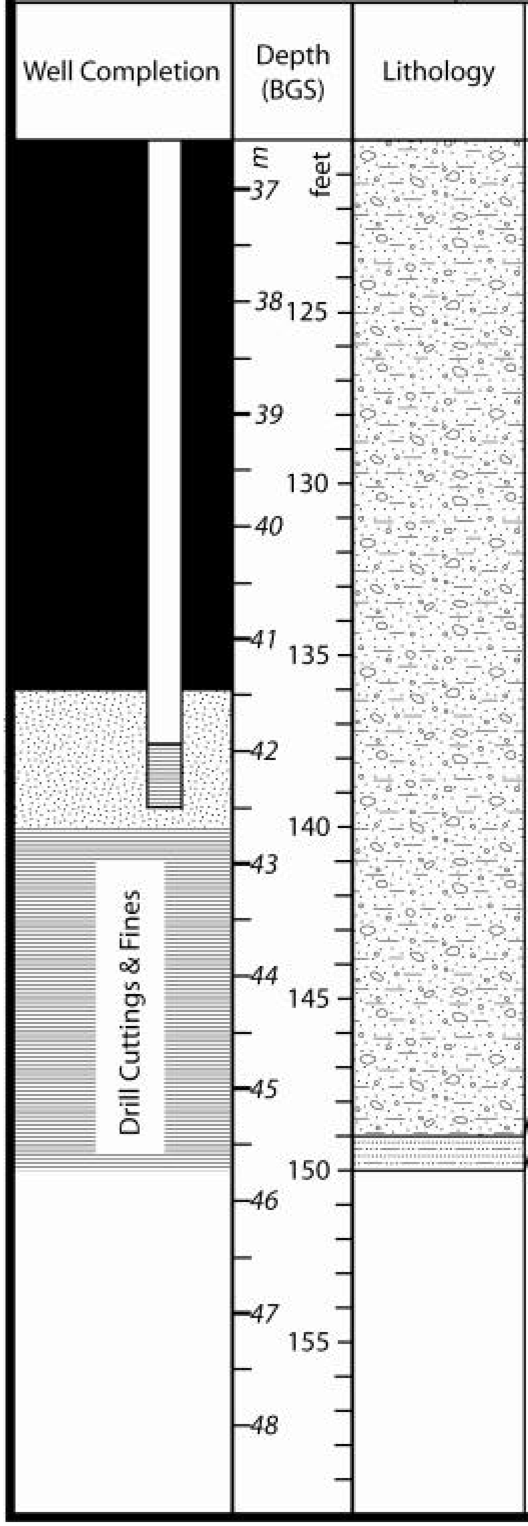
95' - 117' 65% GRAVELS, 30% silty SAND, 5% COBBLES. Silty sand matrix grades downward into med. sand. Sand changes from brown to reddish.

117' - 149' 50% GRAVEL, 45% SAND, 5% COBBLES up to 5 inch dia.

Matheson Wetlands Summer Drilling Boring Log

Scott M. Matheson Wetlands, Moab, Utah

Drill Rig: Boart Longyear Rotosonic	Dates Drilled: 07-28-03 to 07-30-03	Logged By: J. Weigel
Boring Diameter: 9 inches	Boring Number: **BL1**	



Description

From 120' to 149', cobbles and gravels of the ancestral Colorado River persist at approximately the same proportions. 65%-80% GRAVEL, 20%-30% SAND, 1%-5% COBBLES.

Cobbles composed of Diorite Prophyry, Granite, Gneiss, Shale, Mudstone, with some red Sandstone (Navajo or Wingate?).

100% med. stiff SILT encountered at 149'.
Total Depth = 150'.

Completion Notes: Three wells of schedule 40 PVC casing installed in 9 inch diameter borehole. Each well consists of 2" solid PVC casing with 2' long 0.020" slotted PVC screen at end. Bentonite slurry used to completely seal the area between well screens with some small intervals of bentonite chips used. Well BL1-S screened from 51.6' to 53.6' with silica sand pack surrounding screen from 49.9' to 56.5' and a thin layer of bentonite chips used beneath 56.5'. Well BL1-M screened from 96.5' to 98.5' with silica sand pack surrounding screen from 94.3' to 100.7' and bentonite chips used from 100.7' to 110'. Well BL1-D screened from 137.6' to 139.6' with silica sand pack surrounding screen from 136.2' to 140.1'.

Matheson Wetlands Summer Drilling Boring Log

Scott M. Matheson Wetlands, Moab, Utah

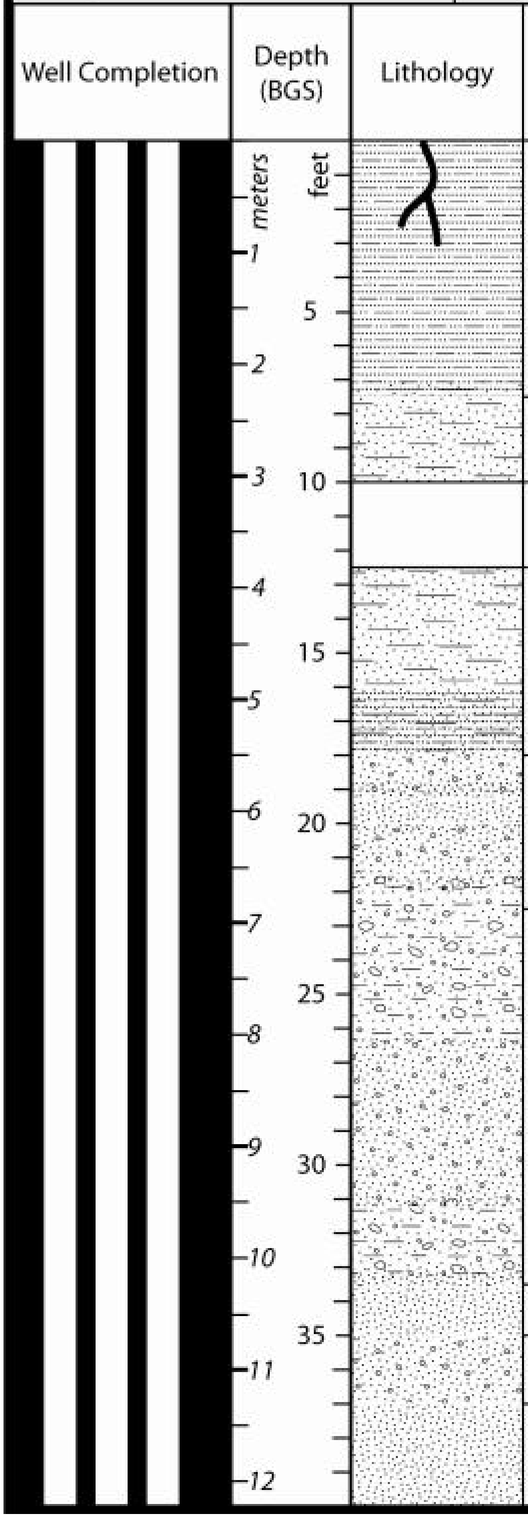
Drill Rig: Boart Longyear Rotosonic

Dates Drilled: 07-31-03 to 08-01-03

Logged By: J. Weigel

Boring Diameter: 9 inches

Boring Number: **BL2**



Description

0' - 7.3' Fine, tan sandy SILT, very dry. Tamarisk roots present.

Moist fine sandy SILT. Dark brown caliche. Small roots.

7.3' - 10' 50% Fine SAND, 50% SILT. Tan to reddish in color.

Lost core from 10' to 12.5'.

10' - 18' Brown silty SAND grading downward into orange-brown sandy SILT that appears saturated.

Increasing moisture content.

18' - 22.5' First river gravels encountered at 18' w/ pink granites. 19' to 20' is 100% coarse SAND. GRAVEL content increases to >10%, approx. 90% SAND with a few percent cobbles up to 3.5 inches.

22.5' - 33.3' 50% med. to coarse SAND, 45% GRAVEL, 5%COBBLES. Gravels are rounded to well rounded. Maximum cobble size is 9 inches.

GRAVEL content increases to 80%. Avg. size ~2 inces. 20% Sand.

100% fine to med. tan colored SAND from 33.5' to 35'.

33.5' - 37' 80% SAND and 20% GRAVEL with minor COBBLES to 4 in. dia.

~100% fine to med. SAND from 37' to 40'.

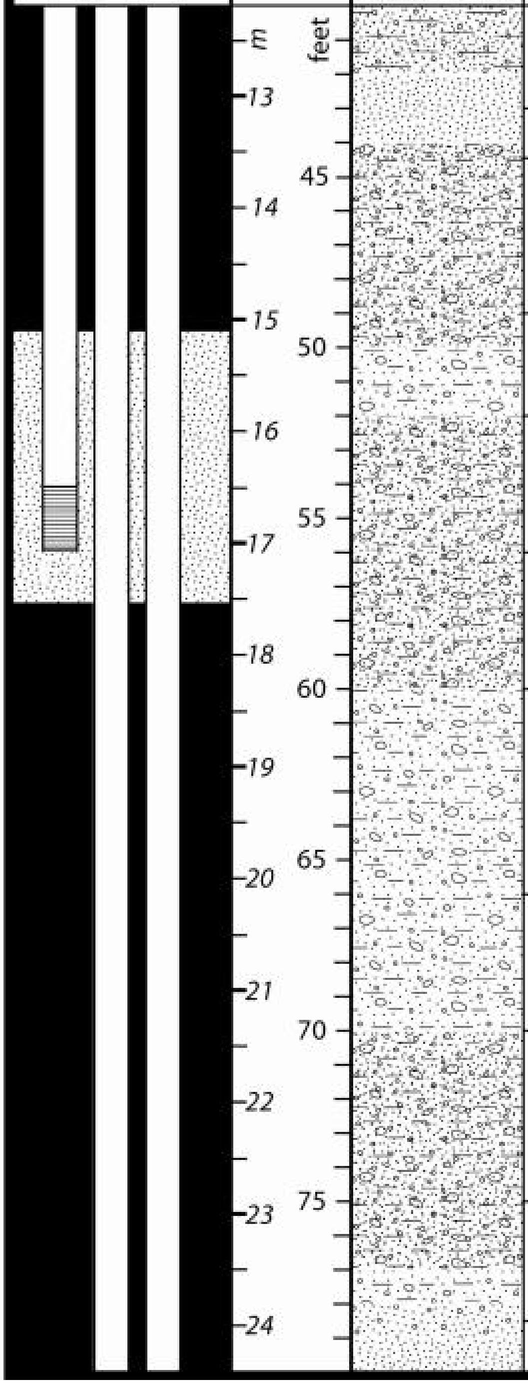
Page 1

Matheson Wetlands Summer Drilling Boring Log

Scott M. Matheson Wetlands, Moab, Utah

Drill Rig: Boart Longyear Rotosonic	Dates Drilled: 07-31-03 to 08-01-03	Logged By: J. Weigel
Boring Diameter: 9 inches	Boring Number: **BL2**	

Well Completion | Depth (BGS) | Lithology | Description



Description
40' - 43' Olive green to dark gray silty fine SAND with occasional GRAVEL up to 3.75 inches. Organic smell (H2S). Some wood fragments found at 41'.
Fine grained red SAND
43' - 49' 60% well graded GRAVEL, 40% fine to med.SAND, sand is an olive gray color. Gray colored sediments persist throughout remainder of core.
49' - 52' 95% fine to med. gray SAND with well rounded COBBLES and GRAVEL up to 6 inches.
52' - 56' Sand above grades into 80% poorly graded GRAVEL with 20% gray colored med. sand. Gravels range from angular to well rounded.
56' - 60' 70% angular to well rounded GRAVEL with 30% fine to med. sand
60' - 66' Gravel content decreases and COBBLE content increases to around 5% down to 66'. Max. cobble size ~ 5 inches.
66' - 70' 55% GRAVEL, 45% SAND, occasional cobble up to 4 inches.
70' - 75' 65% GRAVEL, 35% silty SAND.
75' - 78.5' 80% med. to coarse, olive brown GRAVEL, 15% med. to coarse SAND, 5% COBBLES up to 5 inch dia.
78.5' - 80' Fine to med. grayish SAND.

Page 2

Matheson Wetlands Summer Drilling Boring Log

Scott M. Matheson Wetlands, Moab, Utah

Drill Rig: Boart Longyear Rotosonic

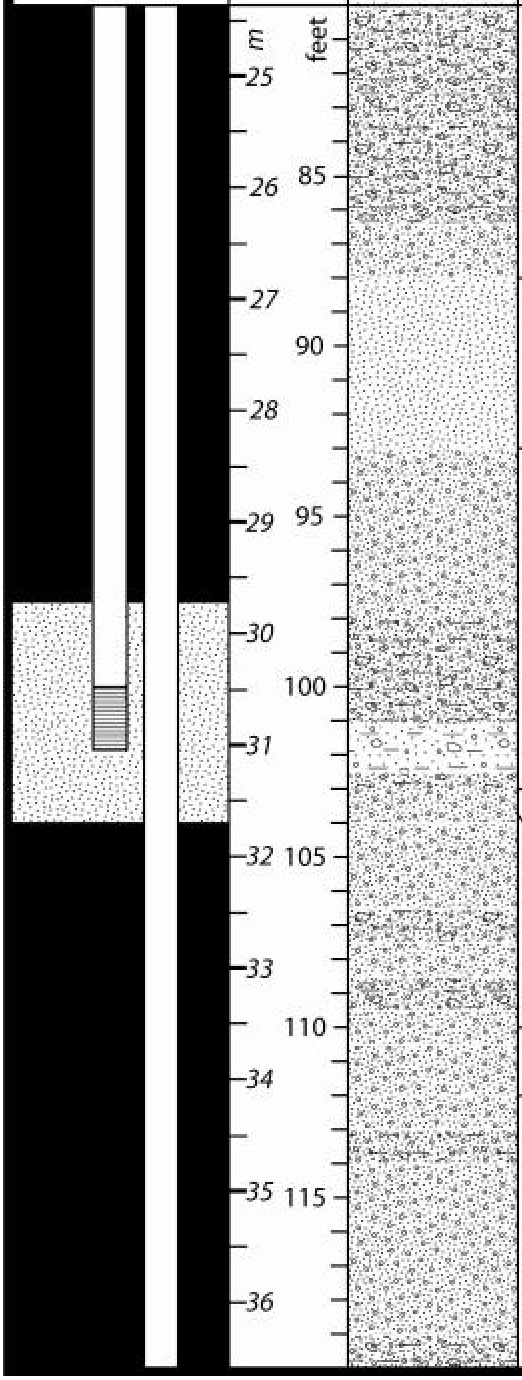
Dates Drilled: 07-31-03 to 08-01-03

Logged By: J. Weigel

Boring Diameter: 9 inches

Boring Number: **BL2**

Well Completion	Depth (BGS)	Lithology	Description



80' - 88' 60% GRAVEL, 35% med. to coarse SAND, 5% COBBLE up to 7 inches. Gravel sub angular to well rounded.

88' - 93' Fine to med. gray SAND

93' - 103' 85% GRAVEL, 10% fine to med. SAND with some silt. Reddish silt in matrix grades into Brownish gray silt.

Minor 5 inch COBBLES reappear by 98' and persist to 103'.

103' - 104' 95% - 100% clean river GRAVEL with minor silt & sand.

104' - 110' Approximately 60 % med. to coarse SAND and 40% GRAVEL with minor ammounts of COBBLE sized material up to 5 inches.

110' - 112' 95% - 100% clean river GRAVEL with minor silt & sand.

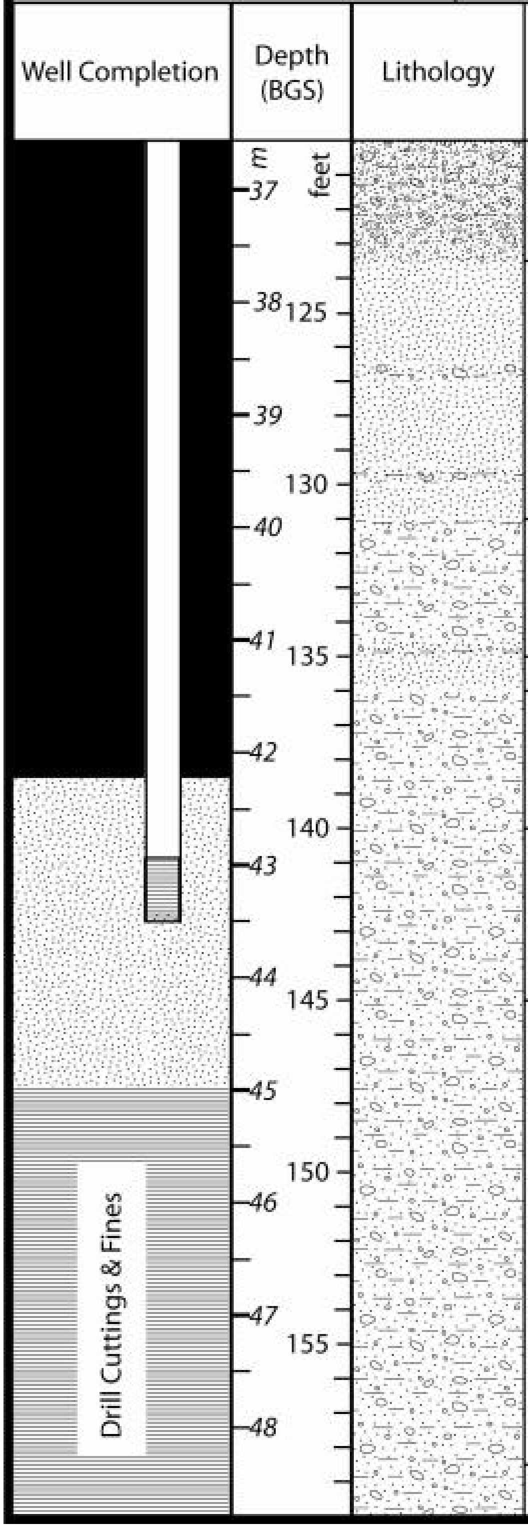
112' - 120' Approximately 60 % med. to coarse SAND and 40% GRAVEL with minor amounts of COBBLE sized material up to 5 inches.

Cobbles composed of Diorite Prophyry, Granite, Gneiss, Shale, Mudstone, with some red Sandstone (Navajo or Wingate).

Matheson Wetlands Summer Drilling Boring Log

Scott M. Matheson Wetlands, Moab, Utah

Drill Rig: Boart Longyear Rotosonic	Date Drilled: 07-31-03	Logged By: J. Weigel
Boring Diameter: 9 inches	Boring Number: **BL2**	



Description

120' - 123.5' 60% GRAVEL, 35% med.to coarse SAND, 5% COBBLE, up to 7 inches. Gravel sub angular to well rounded.

123.5' - 131' 95% fine to med. gray Sand

Occasional COBBLE and GRAVEL.

131' - 135' 70% GRAVEL , 25% med.to coarse SAND, 5% well rounded COBBLES, cobbles up to 4.5 inches.

135' - 136' 100% fine to med. SAND

136' - 140' 70% sub to well rounded GRAVEL , 22% fine to med.SAND, 5% SILT, and 5% COBBLES up to 4 inches.

140' - 160' The remainder of the boring was approximately 40% rounded to well rounded GRAVEL, 50% fine to med. SAND, and 5%-10% rounded to well rounded COBBLES averaging 4 to 6 inches in long diameter.

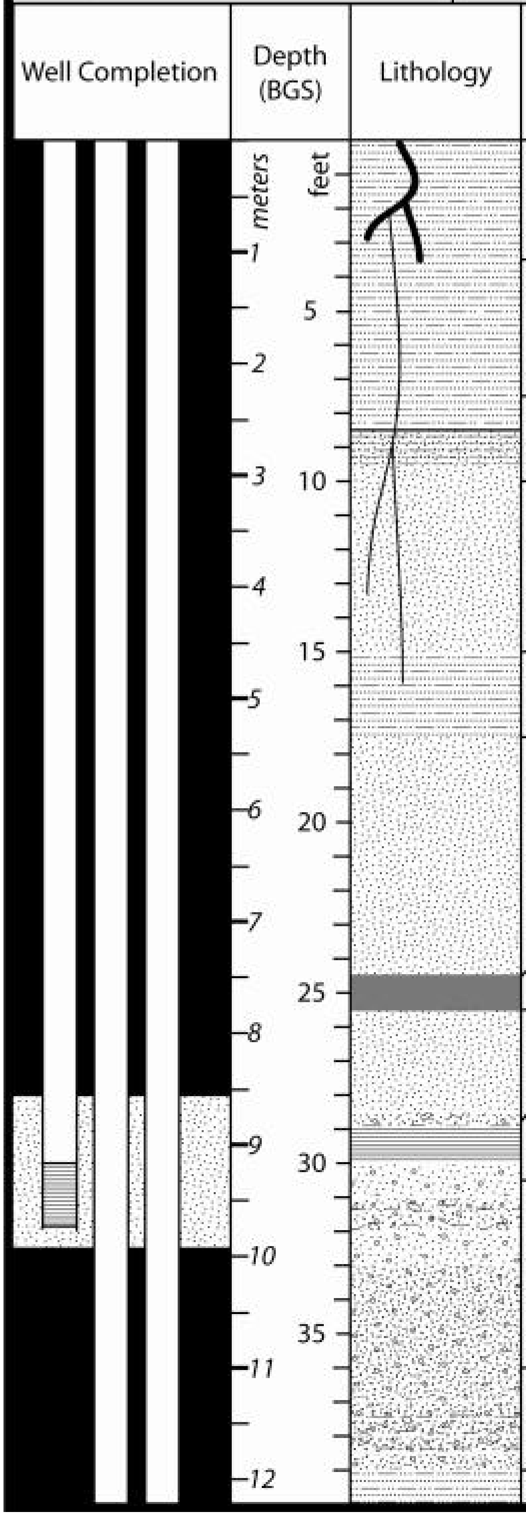
Completion Notes: Three wells of schedule 40 PVC casing installed in 9 inch diameter borehole. Each well consists of 2" solid PVC casing with 2' long 0.020" slotted PVC screen at end. Bentonite slurry used to completely seal the area between well screens with some small intervals of bentonite chips used. Well BL2-S screened from 54' to 56' with silica sand pack surrounding screen from 49.5' to 58' and a 0.4' layer of bentonite chips used beneath 58'. Well BL2-M screened from 100' to 102' with silica sand pack surrounding screen from 97.7' to 104.2' and a 0.4' layer of bentonite chips used from below 104.2'. Well BL2-D screened from 140.8' to 142.8' with silica sand pack surrounding screen from 138.5' to 147.3'.

Total Depth = 160' Page 4

Matheson Wetlands Summer Drilling Boring Log

Scott M. Matheson Wetlands, Moab, Utah

Drill Rig: Boart Longyear Rotosonic	Dates Drilled: 08-02-03 to 08-04-03	Logged By: J. Weigel
Boring Diameter: 9 inches	Boring Number: **BL3**	



Description

0' - 3.5' Tan SILT. Dry to slightly damp. Tamarisk roots to ~3'. Caliche from 2.5' - 3.5'.

3.5' - 7.5' Fine sandy SILT. Brown to lt. tan. Sand fraction increases with depth.
70% SILT, 30% SAND by 7.5'.

7.5' - 10' 75% SILT. 25% fine SAND. Caliche at 9', thin (0.1 inch) horizon of black organics.

10' - 15' 60% fine, brown, moist SAND, 40% SILT. Thin (0.1 inch) horizon of black organics at 11' Spoty caliche, reacts with HCL. Saturated core indicating round water level encountered at 11' bgs.

15' - 17.5' 80% SILT, 20% fine SAND Small roots persist to 16'. Soil is 100% saturated.

17.5' - 24.3' Nearly 100% SAND. Fine near 18' to coarse around 23'. Minor silt. Small bit of wood at 24'.

Gray clay seam, 1' thick, at 24.3'. Wood sample collected at 24.5' for poss. future C-14 age dating.

25.5' - 29' 90% SAND, 10% SILT with minor sub angular to rounded, small GRAVEL.

29' - 30' Fine organics present (Peat). 60% organics and 40% fine sands and silts. Core smells of H2S. Peat sample collected at 29' for poss. future C-14 age dating.

30' - 36 ' 50% med. to coarse reddish brown SAND, 40% sub angular to well rounded GRAVEL, minor silt with some COBBLES of igneous lithologies indicating deposition by Colorado River.

36' - 39' 90% med. to coarse SAND with some GRAVEL and COBBLES up to 4 inches.

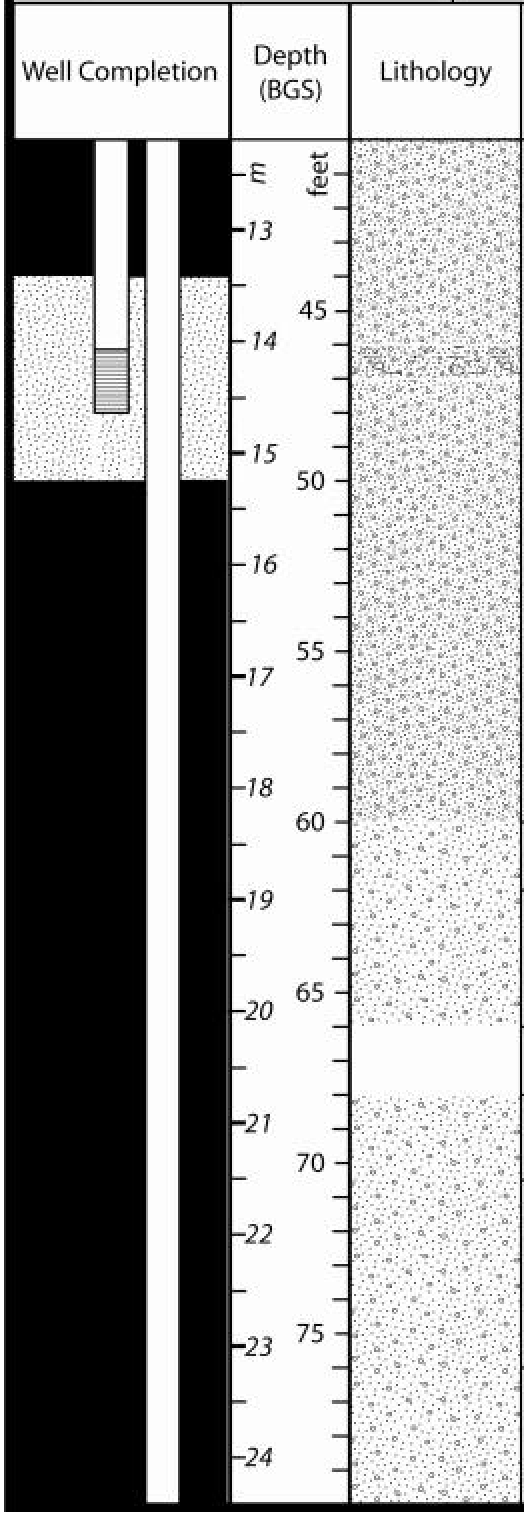
Page 1

39' - 40' 0% gray SILT, 50% gravel sized rock fragments.

Matheson Wetlands Summer Drilling Boring Log

Scott M. Matheson Wetlands, Moab, Utah

Drill Rig: Boart Longyear Rotosonic	Dates Drilled: 08-02-03 to 08-04-03	Logged By: J. Weigel
Boring Diameter: 9 inches	Boring Number: **BL3**	



Description

40' - 46' 40% gray SILT, 60% angular gravel size rock fragments. H2S smell present. Med. to dark gray color persists throught remainder of core.

46' - 48' well rounded pink granitic and black mafic gravels of the ancestral Colorado River.

47' - 58' continues to have the proportions of silt and angular broken rock fragments. Much of the core continues to smell like H2S.

58' appears to be a weathered, fracture zone.

60'- 62' 70% SAND and small GRAVEL, 30% SILT. Strong H2S smell.

62' - 66' 50% broken rock fragments 50% SILT. Strong H2S smell.

66' - 68' No core recovery.

68' - 70.5' 60% broken rock fragments, 40% very fine SILT.

70.5' - 76' 20%-30% rock fragments in fine silty matrix. H2S smell strong throughout.

Rock fragment > 7 inches in dia. at 76'

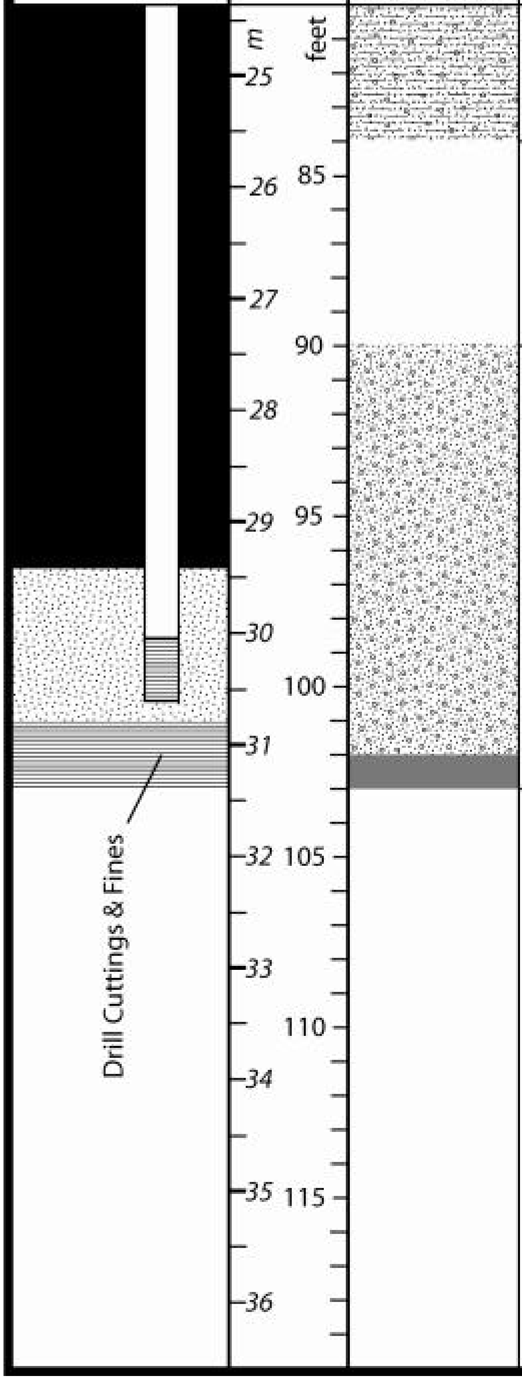
76' - 82 ' 60% broken rock fragments, 40% fine SILT. Section disturbed since core fell in hole and was later recovered.

Matheson Wetlands Summer Drilling Boring Log

Scott M. Matheson Wetlands, Moab, Utah

Drill Rig: Boart Longyear Rotosonic	Dates Drilled: 08-02-03 to 08-04-03	Logged By: J. Weigel
Boring Diameter: 9 inches	Boring Number: **BL3**	

Well Completion	Depth (BGS)	Lithology	Description



60% broken rock fragments 40% fine SILT. Section from 76' to 82' disturbed since core fell in hole and was later recovered.

No core recovery from 84' to 90'.

90' - 103' Average 80% broken rock fragments and 20% fine SILT for the remainder of the borehole. These rock fragments are thought to be fractured and broken portions of the caprock of the upper Paradox Formation.

Around 102' the drill rig met refusal. This is attributed to encountering intact Paradox caprock.

Note: Only trace amounts of Gravels and Cobbles of the ancestral Colorado River were found at BL3.
Total Depth = 103'.

Completion Notes: Three wells of schedule 40 PVC casing installed in 9 inch diameter borehole. Each well consists of 2" solid PVC casing with 2' long 0.020" slotted PVC screen at end. Bentonite slurry used to completely seal the area between well screens with some small intervals of bentonite chips used. Well BL3-S screened from 30' to 32' with silica sand pack surrounding screen from 27.9'to 32.5'. Heaving sands are believed to be the cause of the borehole collapse that forced the silica pack and bentonite slurry up close to the screen. As a result, BL3-S yielded nothing but bentonite slurry upon development and may have to be abandoned. Well BL3-M screened from 46.1' to 48.1' with silica sand pack surrounding screen from 44' to 50' and a layer of bentonite chips used down to 63.2' Well BL3-D screened from 98.6' to 100.6' with silica sand pack surrounding screen from 96.3' to 101.1'.

Appendix B:

Reconnaissance Study of Age and Recharge Temperature Of Groundwater Near Moab Utah

D. Kip Solomon, Ph.D.

March 5, 2001

Introduction

At the request of the Moab Mesa Land Company LLC I performed a reconnaissance study of groundwater in the vicinity of Moab Utah. The objective of the study was to evaluate the age, recharge temperature and recharge elevation of groundwater discharging from springs and wells. Samples were collected from the following sites:

1. Moab City Spring #3 (Somerville Spring #3);
2. Lloyd Somerville Spring;
3. Pioneer Spring;
4. George White Well 4;
5. George White Well 5.

The samples were analyzed for tritium, dissolved noble gases, and the stable isotopes of hydrogen and oxygen. Collectively the results of these analyses can be interpreted in terms of the age of the water, and the approximate elevation at which the water was recharged. This report describes the collection and analysis of these samples and presents the results. It also provides background information regarding the use of these analyses as hydrologic tracers.

Samples from the Moab City Spring #3 (Somerville Spring #3), Lloyd Somerville Spring, and George White Wells 4 and 5 were collected because these represent significant discharge points for the Glen Canyon Group Aquifer that is assumed to be recharge in or on the flanks of the La Sal Mountains. The sample from Pioneer spring was collected as a control as it is assumed to be recharge to the west of Spanish Valley where groundwater flows northeastward toward the Valley.

Background

Tritium

Tritium (^3H) is a radioactive isotope of hydrogen with a half-life of 12.4 years. Tritium is produced naturally in the atmosphere and prior to 1950 the concentration in continental precipitation was about 2 to 5 TU (1 TU is equal to 1 ^3H atom per 10^{18} atoms of ^1H). Beginning in the early 1950s, ^3H concentration in precipitation in the northern hemisphere rose dramatically due to aboveground testing of thermo-nuclear weapons. Because ^3H is incorporated into the water molecule, it is geochemically conservative (apart from its well-known radioactive decay).

The ^3H concentration of precipitation in Salt Lake City from 1963 to 1984 is shown in Figure 1. Some of the same data are shown in Figure 2 for the period 1971 to 1988 with an expanded scale on the vertical axis. Although direct measurements of ^3H in precipitation in Utah were not made prior to 1963, the concentration prior to 1950 was less than about 5 TU as determined by comparison of modern precipitation in Utah with stations having longer records.

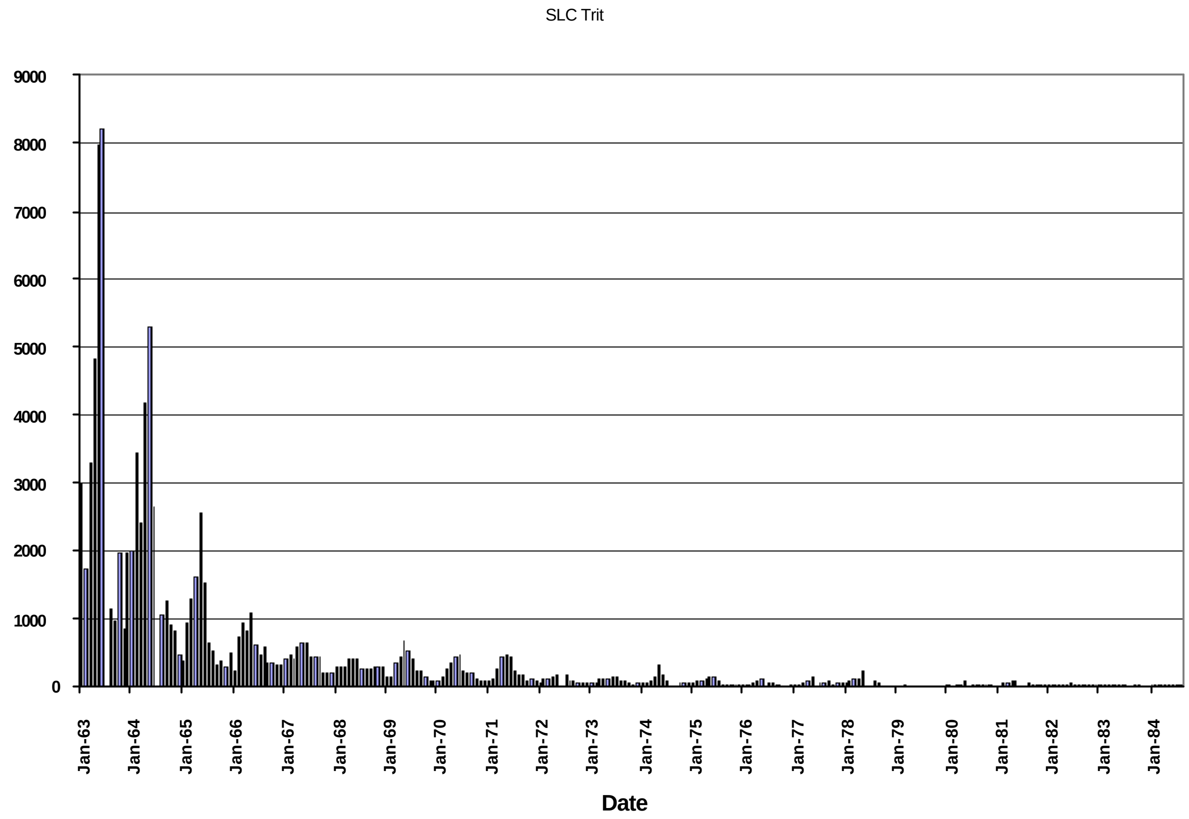


Figure 1. Tritium concentration in precipitation at Salt Lake City for 1963 to 1984.

As seen in Figure 1, peak concentrations in Salt Lake City were approximately 9000 TU. Precipitation that fell after 1950 that then recharge groundwater will have a tritium concentration that is greater than about 3 TU at the present point in time. Thus, the concentration of ^{3}H in groundwater is a guide to whether or not the water was recharged before or after 1950.

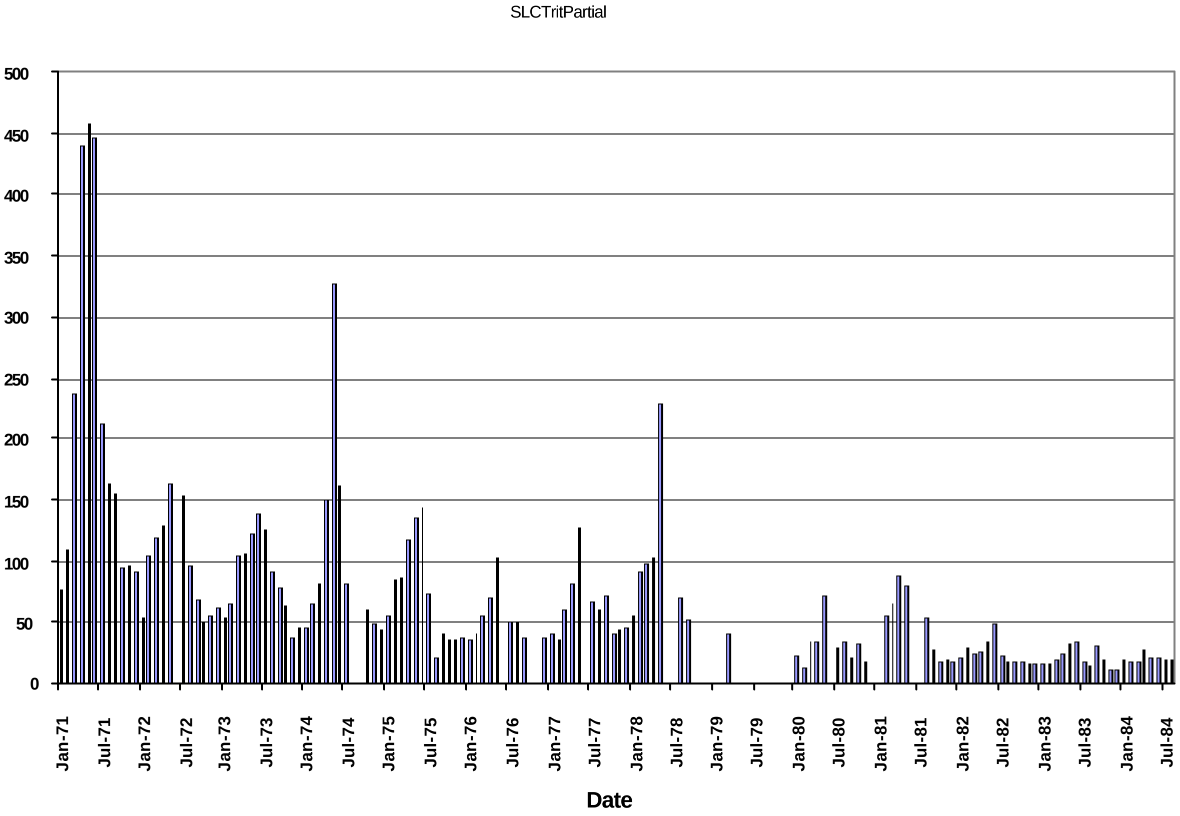


Figure 2. Tritium concentration in precipitation at Salt Lake City for 1971 to 1984.

Noble Gases

The atmosphere contains well-known concentrations of noble and other gases such as neon (Ne), argon (Ar), and krypton (Kr), and nitrogen (N_2). The solubility of these gases in recharging water is a function of the temperature and pressure (elevation) when the water was in final contact with the atmosphere (i.e. just above the water table.) Studies of noble gas concentrations in groundwater indicate the presence of an additional amount of dissolved gas, termed excess air that probably results from trapping air bubbles when the water table rises. Because the production of these gases within aquifers is insignificant, the dissolved concentrations in groundwater are indicators of the temperature and pressure that existed at the water table when the water was recharged. Because the temperature-pressure relationship of the solubility is unique for each gas, it is theoretically possible to determine the recharge temperature and pressure and the amount of excess air (three unknowns) by measuring the concentration of at least three different gases in groundwater. However, this is only possible if "perfect" measurements of dissolved gas concentrations can be made. Since there is uncertainty associated with all analytical results, it is not generally possible using only dissolved gas concentrations to determine all three unknowns. In most dissolved gas studies, the recharge elevation is relatively well known. Solving for only two unknowns generally leads to a recharge temperature that has an uncertainty of ± 1 °C. In order to solve for all three unknowns using real data (i.e. data that contain uncertainty) it is necessary to include additional information. Manning and Solomon (2001) have shown that in the Wasatch Mountains the relationship between recharge temperature and elevation is similar to the atmospheric lapse rate for adiabatic cooling. Air temperature data from 4 stations were obtained in order to determine the atmospheric lapse rate in the Moab area. The mean annual temperature at Moab is 13.2 °C and decreases by just over 6 °C per 1000 m into the La Sal mountains. By assuming that the recharge temperature also decreases by about 6 °C per 1000 m, it is possible to obtain recharge temperature, elevation, and excess air values for samples in which a suite of noble gas analysis is obtained.

Stable Isotopes

The stable isotopic composition of water depends on numerous processes, but mostly the temperature of condensation and the history (origin and trajectory) of an atmospheric water mass. Because temperature decreases with increasing elevation (atmospheric lapse rate), the stable isotopic composition of water is indirectly a function of elevation. However, because of variability in storm histories and temperature, along with other fractionation processes (e.g. sublimation of snow or evaporation of rain) the isotopic composition of individual precipitation events can be variable. Generally a time-series of precipitation values along with a statistically significant number of groundwater samples is needed to interpret stable isotope data in terms of recharge elevations. Samples for stable isotopes in this study were collected as a general check on noble gas thermometry.

Sample Collection and Analysis

Samples were collected during a two-day period from December 21 to 22, 2000. Field measurements included water temperature, dissolved oxygen, barometric pressure, and the total dissolved gas pressure. These measurements were made using probes calibrated at the University of Utah.

Samples for ^{3}H were collected in 1L glass bottles with polyseal caps. Samples for stable isotopes were collected in 500 ml glass bottles and were also sealed using polyseal caps. In both cases care was taken to minimize the amount of headspace present in the bottles. Samples for dissolved gases were collected using two different methods. The most reliable method for collecting dissolved gas samples makes use of diffusion samplers that were custom fabricated at the University of Utah. These devices consist of silicon rubber tubing attached to a short length of 3/16" OD soft copper tubing. The samplers were submerged in discharging spring waters for approximately 24 hours. Dissolved gases in the groundwater permeate the silicone rubber tubing causing the gas inside the samplers to equilibrate with dissolved gases in water. After equilibration, the samplers were removed and the copper tube was sealed using a cold-welding crimping device. While this method is considered the most reliable, it could not be used on George White Well #4 and #5 because the wells could not be operated continuously for a 24-hour period. Samples for dissolved gases from these wells were collected by directing well discharge through 3/8" OD copper tubing, and then sealing these tubes with high-pressure refrigeration clamps.

Tritium analyses were performed at the University of Utah Noble Gas Laboratory using the ^{3}He in-growth method. This technique has the lowest detection limit (<0.1 TU) of all possible methods. The uncertainty in ^{3}H values varies according to the concentration and is approximately ±5% for values greater than 1 TU. Noble gases were also analyzed at the University of Utah Noble Gas Laboratory using a custom-built cleanup system connected to an MAP 215 sector-field mass spectrometer. An air standard was used for calibration that was performed after approximately every 3rd sample. The analytical precision for noble gases is approximately ±0.5 % for ^{3}He and ^{4}He, 1% for N_2, and ^{40}Ar, and less than 3% for ^{20}Ne and ^{84}Kr. Stable isotope analyses were performed at the Stable Isotope Ratio For Ecological Research (SIRFER) laboratory at the University of Utah. The uncertainty in the stable isotope values is approximately ± 1 per mil for deuterium and 0.1 per mil for oxygen.

Results

The results of ^{3}H, noble gases, and stable isotope values are shown in Table 1. Also shown are values measured during sampling such as dissolved O_2, and the temperature of the water.

Table 1. Results of noble gas, ^{3}H, stable isotopes, and field values of groundwater.

	Pioneer Spring	Moab City Spring 3 (Somerville Spring #3)	Lloyd Somerville Spring	George White Well 4	George White Well 5
N_2 (ccSTP/g)	1.14E-02	1.16E-02	1.23E-02	1.42E-02	1.33E-02
^{40}Ar (ccSTP/g)	2.93E-04	3.00E-04	3.11E-04	3.64E-04	3.43E-04
^{84}Kr (ccSTP/g)	3.91E-08	4.00E-08	4.24E-08	NA	NA
^{20}Ne (ccSTP/g)	1.51E-07	1.50E-07	1.58E-07	1.86E-07	1.76E-07
^{4}He (ccSTP/g)	4.00E-08	5.11E-08	6.27E-08	9.24E-08	7.68E-08
R/Ra *	0.985	0.811	0.680	0.571	0.656
^{3}H (TU)	0.3	0.72	0.4	1.2	1.7
±	0.1	0.05	0.1	0.1	0.3
δ^{18}O (‰)	-14.3	-14.6	-14.3	-14.6	-14.5
δD (‰)	-110	-112	-112	-112	-112
Collection Date	12/22/00	12/22/00	12/21/00	12/21/00	12/21/00
Water Temp. when Collected (ÞC)	16.4	16.5	16.5	17.0	16.8
Field measured O_2 (ppm)	7.6	8.7	7.0	7.6	8.2

* R is the ^{3}He/^{4}He ratio of the sample; Ra is the ^{3}He/^{4}He ratio of air (1.384 X 10^{-6})

NA = Not Availabe

The results shown in Table 1 have been interpreted in terms of the age and approximate recharge elevation as discussed in the following sections.

Age

The data shown in Table 1 provide several measures of the age of the samples. By age I refer to the elapsed time between recharge and sample collection. As discussed in the background section, ^{3}H values below about 3 TU in Utah indicate water that was recharged prior to the peak of thermo-nuclear weapons testing in the early 1960s. The highest ^{3}H observed was 1.7 TU and thus in a general sense all of the waters are thought to be older than about 40 years.

The ^{3}H values are consistent with the helium isotope ratios that are all less than 1 indicating the presence of little (if any) tritiogenic ^{3}He (which is the daughter product of ^{3}H decay).

Another measure of age is provided by the concentration of ^{4}He in the samples. Helium-4 is one of the final stable products of the radioactive decay of naturally occurring uranium and thorium. A base amount of ^{4}He is present in groundwater as a result of atmospheric ^{4}He being dissolved in precipitation. If the production of ^{4}He is assumed to be uniform in the subsurface, then the ^{4}He concentration in groundwater (above the base amount from the atmosphere) will reflect the amount of time the water has been in contact with the aquifer. In this study I have not determined the ^{4}He production rate (this is a significant amount of work far beyond the scope of this reconnaissance study) and thus the ^{4}He data cannot be used to precisely estimate ages. However, based on values reported in the literature (Solomon, 2000) the ^{4}He production rate is likely to be such that a significant concentration in groundwater will not occur until the contact time has been about 1000 years. The base amount of ^{4}He in groundwater (that is recharged at an elevation of 1600 m) is about 4.0 X 10^{-8} ccSTP/g which is precisely the amount measured in Pioneer Spring. However, elevated values exist in all other samples with the maximum being 9.2 X 10^{-8} ccSTP/g in George White Well 4. I interpret this to mean that Pioneer Spring water is between about 40 and 1000 years old, whereas the other waters could be older than 1000 years. It is interesting to note that ^{4}He concentrations (and the related helium isotope ratio) vary systematically with space. The highest ^{4}He values occur to the south in George White Well 4 and George White Well 5, and then decline to the lowest value in Pioneer Spring to the northwest.

Figure 3 shows the measured ^{3}H values plotted as a function of the ^{4}He concentration. While some scatter exists, there is a positive correlation between ^{3}H and ^{4}He. At first glance this appears to contradict the interpretation that the higher the ^{4}He concentration the older the water. However, the highest ^{3}H values occur in the wells and represent an integration of water collected over the length of the well screen. It seems likely that majority of water collected by the well is old but that this is being mixed within the well bore with a small amount of younger water. Mixing of waters of different ages in well bores has been observed in many studies. To confirm this interpretation (i.e. mixing a small amount of young water with a large amount of old water) I calculated the $^{3}H/^{3}He$ age of the samples collected from George White Wells 4 and 5. A detailed discussion of the $^{3}H/^{3}He$ dating procedure is beyond the scope of this report, but suffice it to say that when tritium free water is mixed with tritiated water, the apparent $^{3}H/^{3}He$ age of the mixture will be the age of the young fraction (even if only a small amount of young water is added to a large amount of old water.) The $^{3}H/^{3}He$ age of these samples is about 18 to 20 years. Assuming that precipitation near Moab had a similar ^{3}H value as Salt Lake City, the average concentration in 1980 (i.e. 20 years ago) was 31 TU. Radioactive decay during 20 years would reduce this concentration to about 10 TU, but dilution with older water is required to lower this to the observed values of 1.4 TU (average of wells 4 and 5.) The approximate amount of dilution required is 14 parts young water to 86 parts old water.

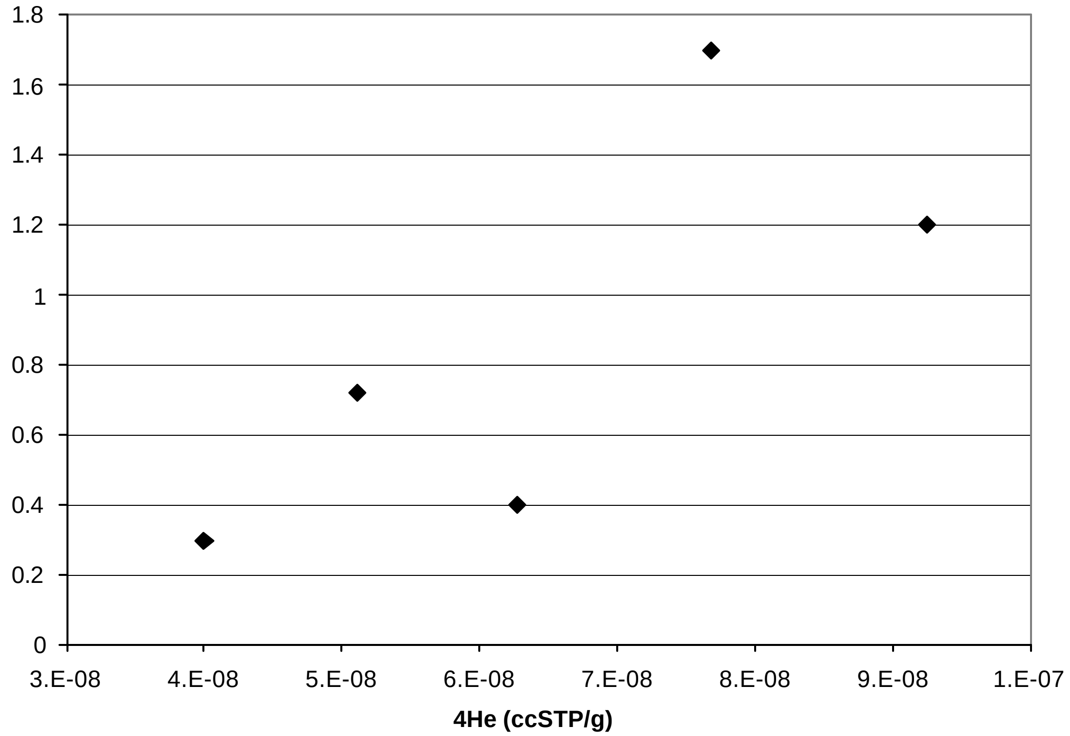


Figure 3 Relationship between ^{3}H and ^{4}He in groundwater.

Recharge Temperature and Elevation

The concentration of dissolved gases is shown in Table 1. I have evaluated the recharge temperature by first assuming a recharge elevation, and then solving an over-determined set of solubility equations representing each of the gases listed in Table 1 (except ^{4}He because it is generated in the subsurface). This procedure results in a value the recharge temperature and excess air that best fits the observed data. A new recharge elevation was then assumed and the set of solubility equations was resolved to provide another estimate of the recharge temperature. This produces a family of solutions for each sample that represent the recharge temperature versus the recharge elevation. These curves are shown in Figure 4.

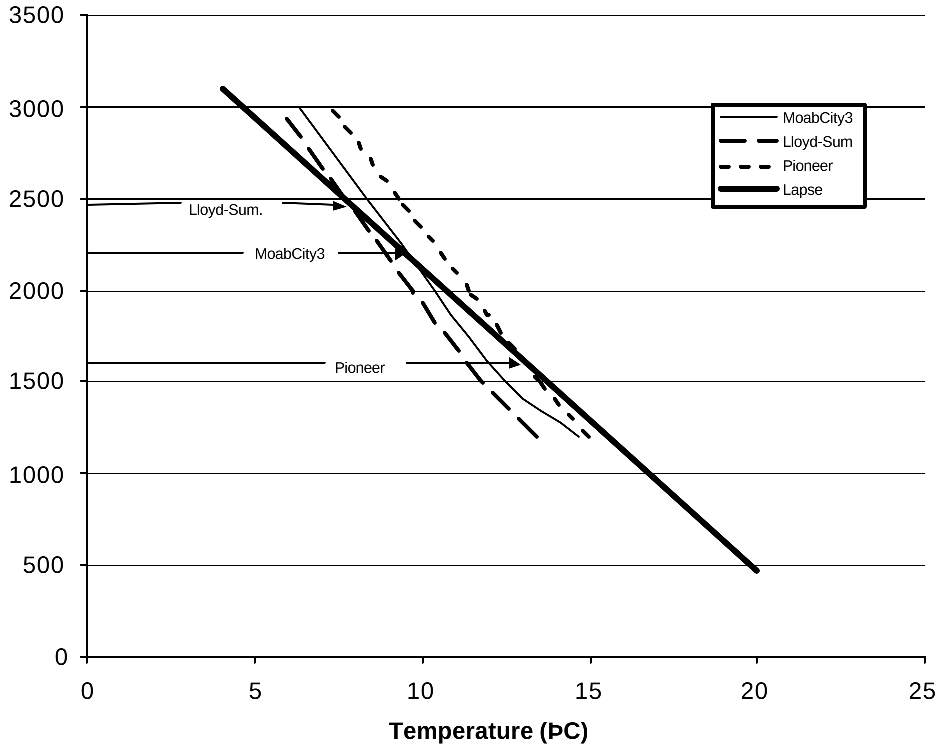


Figure 4 Recharge temperature as a function of recharge elevation. Also shown is the atmospheric lapse rate. The slope of the lapse rate curve is consistent with air temperature values in the Moab area. The intercept was adjusted such that the Pioneer Spring sample has a recharge elevation (assumed) of about 1600 m.

The curves shown in Figure 4 are truncated at an elevation of about 1250 m since this is the approximate elevation of the sample collection points and it is highly unlikely that the recharge elevation is lower than the discharge elevation. Thus, the temperature that corresponds to the lowest elevation on these curves represents the maximum possible recharge temperature.

Also shown in Figure 4 is a curve that represents the lapse rate for recharging water. The slope of this curve is consistent with the atmospheric lapse rate, but the intercept has been adjusted such that the lapse rate curve and the temperature-elevation curve for Pioneer Spring intersect at an elevation of about 1600 m. In other words, I have assumed that the recharge elevation for Pioneer Spring is 1600 m. Pioneer Spring is located on the western slope of Spanish Valley and recharge to this spring is not likely to be derived from the La Sal Mountains, but rather from the western flank of the valley. In a more complete study an empirical lapse curve could be developed by sampling springs that discharge at various elevations. The uncertainty in the lapse rate curve represents the primary uncertainty associated with assigning precise recharge elevations based on dissolved gases. Although this uncertainty is difficult to estimate, it is probably such that the uncertainty in recharge elevations that are derived from this curve are about ± 300 m.

Using the lapse rate curve described above, estimates of the recharge elevation for Moab City Spring 3 and Lloyd Somerville Spring are 2200 m and 2450 m respectively. Similar estimates for George White Wells 4 and 5 were not made because it was not possible to obtain dissolved Kr values from these wells. (The analytical method used at the University of Utah does not provide Kr values for water samples collected in copper tubes. It was not possible to use diffusion samplers on these wells because they could not be operated for a continuous 24 hour period that is required to equilibrate the samplers.)

The consistency between the age and recharge temperature-elevation results was evaluated by plotting the He isotope ratios versus the dissolved N_2 concentration. The He isotope ratio should be completely independent of recharge temperature or elevation, but is proportional to groundwater age. Dissolved N_2 concentrations are a function of recharge temperature and elevation, but should not depend on age (or contact time) because only insignificant amounts of N_2 are likely to be derived from the aquifer. The relationship between the He isotope ratio and dissolved N_2 is shown in Figure 5. In all cases as the dissolved N_2 concentration increases the He isotope ratio decreases. Lower He isotope ratios correspond to older groundwater ages. Higher dissolved N_2 concentrations could result from either lower recharge temperatures, or lower recharge elevations. The relationship shown in Figure 5 makes sense if the higher N_2 values result from colder recharge temperatures because water that was recharged at higher elevations (at colder temperatures) would be older at the discharge point. In contrast the relationship shown in Figure 5 makes little sense if the higher N_2 values result from recharge occurring at a lower elevation that would be closer to the discharge points. In other words, I interpret the relationship shown in Figure 5 to be strong evidence in support of the interpretation of recharge elevation derived using an assumed (and therefore uncertain) lapse rate. The older the water at the discharge point, the higher the recharge elevation.

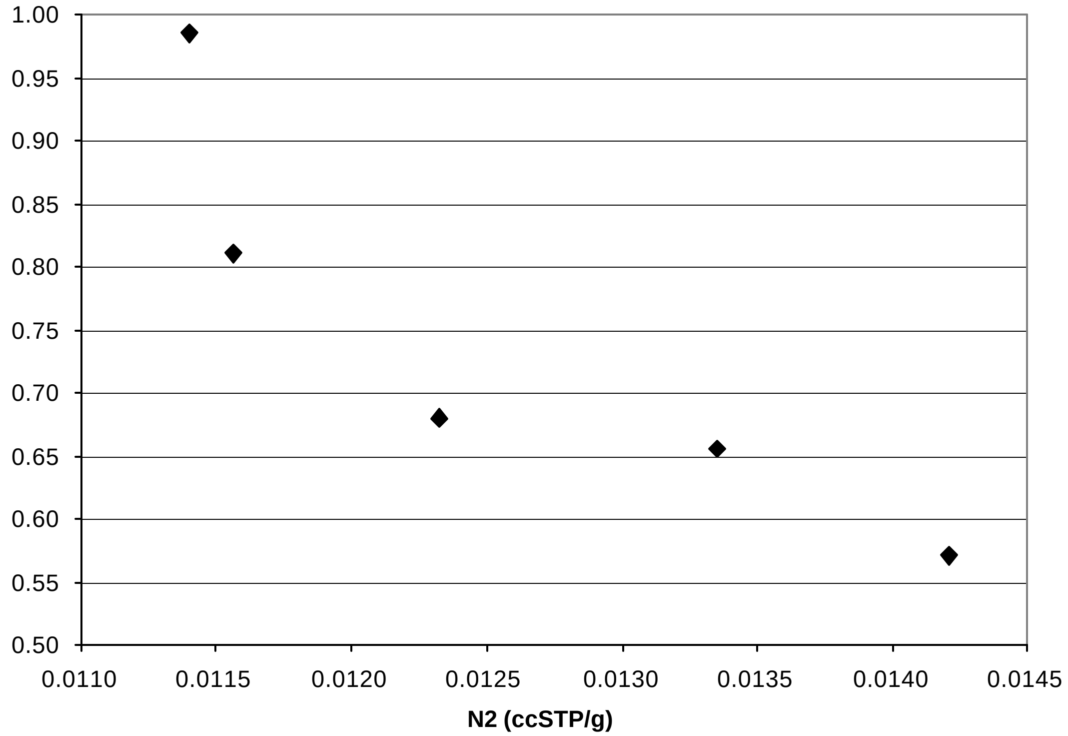


Figure 5. Relationship between the He isotope ratio (R/Ra) and dissolved N_2. Higher values of R/Ra correspond to younger ages. Higher values of N_2 represent colder recharge temperatures that occur at higher elevations. These data support the concept that the older the water at the discharge point, the higher the recharge elevation.

A final check on the recharge temperature and elevation can be made using the stable isotope data shown in Table 1. A precise use of stable isotope data to determine recharge elevation requires extensive sampling of precipitation at various elevations at various points in time to establish an empirical elevation curve. Although this curve has not been generated, the general relationship should be for higher elevation recharge to have lower (more negative) stable isotope values. An examination of Table 1 shows that this is generally the case. However, there is less variability in the stable isotope values than I expected. Until more precipitation values are available, I can only conclude that the stable isotope ratios are consistent with the dissolved gas data, but do not at this time provide an independent check on the elevation of recharge.

Conclusions

Summary

Five samples were collected from springs and wells in the Moab area for the analysis of dissolved gases, tritium, and stable isotopes. These measurements were used to interpret the age and the temperature/elevation of recharge.

Tritium values range from 0.3 to 1.7 TU. These values suggest water that is generally older than 40 years. Dissolved ^{4}He values indicate that some waters may be older than about 1000 years, but a precise date using ^{4}He would require a more extensive analysis of the ^{4}He production rate within the aquifer. The data provide little doubt that the majority of water sampled is older than 40 years, but an upper limit on the age cannot be determined precisely.

There is a general trend of decreasing ^{4}He (and hence decreasing age) moving northwestward from George White Wells 4 and 5 to Pioneer Spring. Also, small amounts of ^{3}H exist in discharge from George White Wells 4 and 5. These values are interpreted to result from the mixing of around 10 % young water (that is about 20 years old) with 90 % older water (that is older than 40 years and may be older than 1000 years) within the well bore.

The concentration of dissolved gases indicates that the maximum possible recharge temperature is around 13 to 15 °C. By combining the dissolved gas data with an assumed curve for the recharge lapse rate, the recharge elevation of water discharging from Moab City Spring 3 and Lloyd Somerville Spring are estimated to be 2200 and 2450 m respectively. The uncertainty in recharge elevation is estimated to be about ± 300 m. The recharge lapse rate curve was developed by assuming that the recharge elevation of Pioneer Spring was 1600 m, and that the slope of this curve is equal to that of the atmospheric lapse rate. The dissolved gas temperature-elevation results are consistent with trends in the age of water. The older the water at the discharge point, the higher the recharge elevation. Stable isotope ratios are generally consistent with the dissolved gas data, but show less of a relationship with other parameters (age and dissolved gas temperatures) than expected. Nevertheless, the stable isotope data do not contradict the dissolved gas results, but do not at this time provide an independent estimate of the recharge elevation.

Implications

The general conclusion that water discharging from springs and wells is old and derived from recharge that occurs at high elevations (ca. 2000 to 2500 m) has implications regarding the location of the recharge area. For the area southeast of Moab, Blanchard (1990) indicates that the direction of groundwater flow in the upper groundwater system of the Glen Canyon Group Aquifer is to the west-northwest. Figure 6 shows areas (shaded in blue) that are up gradient from the sampling locations (Moab City Spring 3, Lloyd Somerville Spring, and George White Wells 4 and 5) and where land surface is at an elevation between 2000 and 2500 m. This area represents the most probable recharge area for waters discharging at the collection sites considered in this study. This conclusion assumes that the water table in the shaded area of Figure 6 is moderately close to land surface. The depth to water in this area has not been considered in this study. If the depth to water were substantially greater than a few hundred meters, then the most probable recharge area (i.e. the shaded area in Figure 6) would be moved eastward. The probable location of recharge shown in Figure 6 is consistent with the conclusions of Steiger and Susong who state that “these areas, called upper mesas in this study, are recharge areas for the Glen Canyon aquifer because water that infiltrates the top of the mesas could eventually reach the underlying Glen Canyon aquifer and because the mesas receive the largest amount of precipitation in the study area.”

Important Note

It is important to emphasize that this was a reconnaissance study that consisted of a very small number of samples that were analyzed for only a selected number of parameters. Although the analyses presented appear to be internally consistent, it is not possible to evaluate how representative these results are of the entire system. The results of this study should be used mostly as a guide to the general nature of the groundwater flow system.

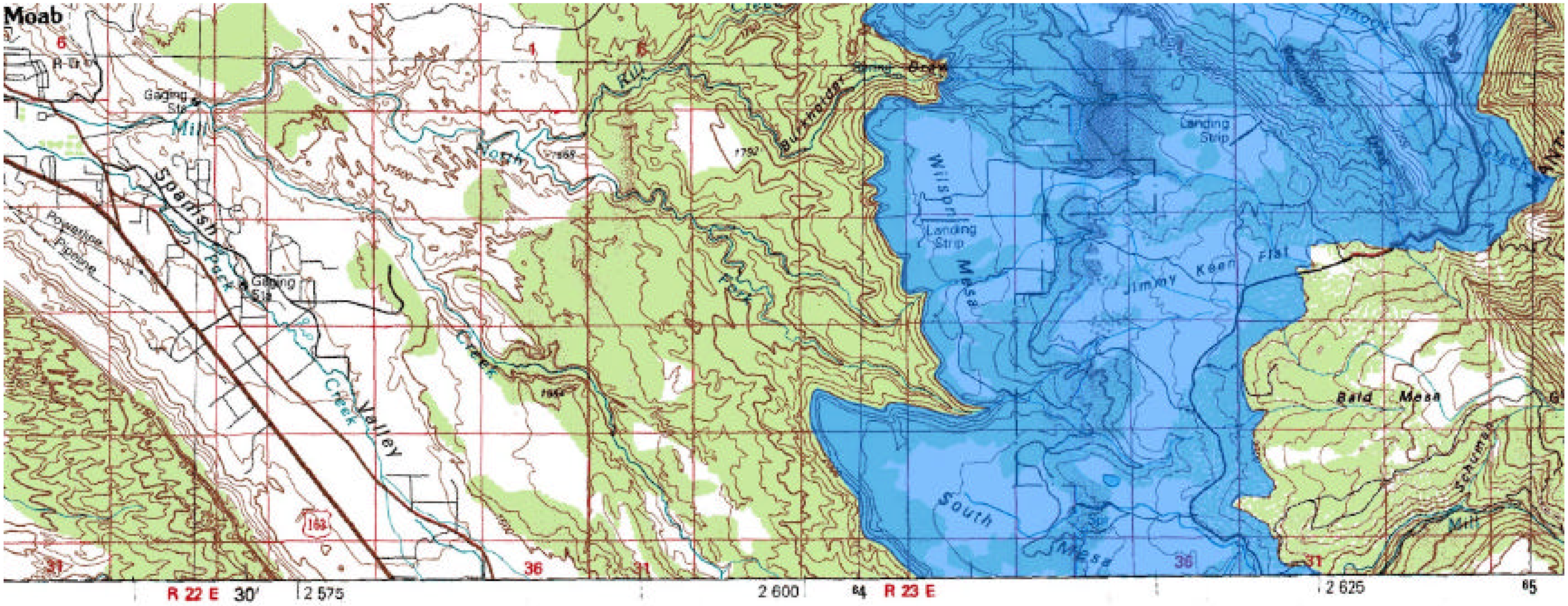


Figure 6 Probable recharge area (blue shading) for samples collected in this study.

References

Blanchard, P. J., Ground-Water Conditions in the Grand County Area, Utah, With Emphasis on the Mill Creek-Spanish Valley Area, State of Utah Dept. of Nat. Res. Tech. Pub. No. 100, 1990.

Manning, A. H., and Solomon D. K., Using Noble Gases to Investigate Mountain-Front Recharge, Journal of Hydrology, in review, 2001.

Solomon, D. K., ^{4}He in Groundwater, Chapter 14 in Environmental Tracers in Subsurface Hydrology, eds. P. Cook and A. Herczeg, Kluwer Academic Publishers, Boston, 2000.

Steiger, J. I., and Susong, D. D., Recharge Areas and Quality of Ground Water for the Glen Canyon and Valley-Fill Aquifers, Spanish Valley Area, Grand and San Juan Counties, Utah, U. S. Geological Survey, WRIR 97-4206, 1997.

Appendix C:

March 22, 2004

Addendum to original report

This addendum to the original document includes the following four items:

1) Results of seven tritium samples previously unreported due to analysis complications,
2) Results of radiocarbon dating of two organic samples from borehole BL3,
3) Well installation information for a drive point piezometer that is intended to replace BL3-S, and
4) Explanation for not completing nitrogen isotope analyses.

Tritium

Seven of the original 42 samples collected for tritium had to be resealed for reanalysis because of complications caused by excess gas in the holding flask. Included below is Table C1 (an updated version of Table 6) showing the results of these seven samples (CR2-river, N3-8, N6-9, W1-4, N9-4, BL2-D, and BL3-D) in bold type. Sample N9-4 was erroneously reported as not NS (not sampled) in the original table (it should have been reported as resealed.) The measurement errors associated with three of the reported concentrations in Table C1 are large due to the same problems encountered during the initial analyses and some explanation is due. The laboratory preparation of these water samples includes removing all excess dissolved gas on a vacuum line aided by heating and sonic vibration prior to sealing the sample and allowing for ^{3}He ingrowth from the decay of tritium. Then the concentration of tritium in a sample is calculated based on measuring the concentration of its daughter product, ^{3}He after a known period of decay. In a perfect measurement, all ^{3}He measured would have come from tritium decay. However, incomplete degassing of the sample or a leaking sample flask could result in measuring ^{3}He that did not come from tritium decay during the holding time. In the calculation of tritium units (TU), the excess ^{3}He is estimated and subtracted from the total based on measuring ^{4}He and using the known atmospheric ratio of ^{3}He/^{4}He. The fact that much of the groundwater at the site has very high dissolved gas pressures (and up to 1000 times as much dissolved helium as is common in groundwater samples) has likely complicated the degassing of some of these samples and it is impossible to precisely know what fraction of measured ^{3}He is from tritium decay and what fraction is from atmospheric leaking. As a result of these complications, analysis of the sample from W1-4 failed and the precision of three samples is high.

In examining these results combined with the reported errors we find no reason to amend the original interpretation of tritium concentrations in waters across the site. This is because the re-run data that have small margins of error are consistent with the original conclusions. Three of the re-run samples have margins of error that are as large as the reported value and therefore these data are not reliable and were not used to reach any conclusions. The river water sample from CR2 is in good agreement with the river water sample from CR1, after consideration of the respective concentrations and error terms reported. Groundwater at N3-8, BL2-D, and BL3-D are expected to be pre-bomb water that is essentially tritium-free. While water from N3-8 has very little tritium, samples from BL2-D and BL3-D were among the most contaminated samples and likely contain very little, if any tritium, but these results are not reliable due to the large margin of error. Finally, waters from N6-9 and N9-4 are relatively shallow with low TDS and contain modest components of young (tritiated) water.

Sample ID	R/Ra	Tritium (TU)	^{3}H plus/minus	Terr ^{4}He (ccSTP/g)
CR1-river	NS	12.02	0.60	NS
CR2-river	NS	**9.99**	**2.49**	NS
N3-surface	NS	1.07	0.05	NS
CR1-3	0.105	1.21	0.24	4.5E-06
M11-7	0.969	4.73	0.24	0.0E+00
M11-12	0.221	3.51	0.18	1.9E-07
M11-14	0.127	0.96	0.05	1.0E-06
N3-4	0.486	1.53	0.08	5.2E-08
N3-8	0.926	**0.06**	**0.02**	4.1E-09
N4-6	0.932	8.95	0.45	3.0E-08
N4-12	1.785	10.46	0.52	0.0E+00
N5-7	1.146	12.13	0.61	0.0E+00
N5-10	1.071	9.16	0.46	0.0E+00
N5-14	1.102	9.45	0.45	0.0E+00
N6-6	0.397	1.38	0.07	8.0E-08
N6-9	0.385	***5.21**	**4.12**	9.4E-08
N7-7	0.803	1.29	0.06	8.6E-09
N7-10	0.141	< 0.1	0.06	1.3E-07
N7-11	0.071	NS	NS	1.2E-06
N8-10	0.981	6.09	0.30	5.6E-10
N8-14	0.965	5.02	0.25	5.2E-10
W1-4	0.398	**NR**	**NR**	3.8E-08
W1-7	0.038	4.26	0.21	6.0E-08
N9-4	1.180	4.65	1.22	5.8E-09
N9-6	NS	8.79	0.44	NS
N11-6	0.490	4.30	0.21	2.6E-08
N11-10	0.103	NS	NS	9.0E-07
SMI-PZ1S	0.418	17.57	0.88	4.1E-08
SMI-PZ1M	0.190	14.54	0.73	1.8E-07
SMI-PZ1D	0.169	5.60	0.28	1.6E-07
ATP-1-S	0.071	< 0.1	0.04	6.8E-07
ATP-1-1S	0.065	0.22	0.01	2.3E-06
ATP-1-1D	0.062	0.52	0.03	2.3E-06
ATP-1-D	0.062	0.15	0.02	2.4E-06
SMI-PZ3-D2	0.114	8.69	0.43	7.8E-07
Atlas 432	1.088	< 0.1	0.00	0.0E+00
Atlas 433	0.142	0.60	0.03	6.2E-07
BL1-S	0.127	0.91	0.05	6.6E-07
BL1-M	0.091	< 0.1	0.04	2.4E-06
BL1-D	0.079	< 0.1	0.23	2.9E-06
BL2-S	0.079	< 0.1	0.02	2.4E-06
BL2-M	0.074	< 0.1	0.15	2.6E-06
BL2-D	0.069	***5.75**	**5.69**	2.3E-06
BL3-S	NS	NS	NS	NS
BL3-M	0.085	2.89	0.14	1.2E-06
BL3-D	0.065	***7.89**	**8.63**	3.0E-06

Table C1 (amended from Table 6). Tritium and dissolved gas data from surface and ground water samples collected during July and August, 2003. Samples were analyzed by University of Utah Dissolved Gas Service Center during September and October, 2003. NS indicates "not sampled" and NR indicates "not reported" due to failed analysis.

*Value has a large margin of error and is not reliable.

Radiocarbon Dates

Two samples of organic material were submitted to Beta Analytic Inc. (BAI) in Miami, Florida for radiocarbon dating. These samples were collected from 24 and 30 feet below ground surface and are labeled accordingly in Table C2. A copy of the original BAI laboratory results is attached below.

Sample	Material	Measured Radiocarbon Age (years BP)	$^{13}C/^{12}C$ (permil)	Conventional Radiocarbon Age (years BP)
BL3-24	wood	20 +/-60	-24.8	30 +/-60
BL3-30	peat	910 +/-50	-25.0	910 +/-50

Table C2. Results of radiocarbon dating of two samples of organic material collected from core of the BL3 borehole drilled in August, 2003. Samples were analyzed by Beta Analytic Inc., Miami, FL.

The "Conventional Radiocarbon Age" listed in Table C2 is the result after applying $^{13}C/^{12}C$ corrections to the measured age and is the most appropriate radiocarbon age. Sample BL3-24 was a piece of wood found in fine-grained sand below the tamarisk root zone (see BL3 boring log in Appendix A) and has a conventional radiocarbon age of 30 +/- 60 years before present (by convention, present = 1950 A.D.). Sample BL3-30 was from a layer of peat found stratigraphically beneath a layer of sand and rounded gravel (~8 cm) as shown in Figure C1 below. Sample BL3-30 has a conventional radiocarbon age of 910 +/- 50 years before present.

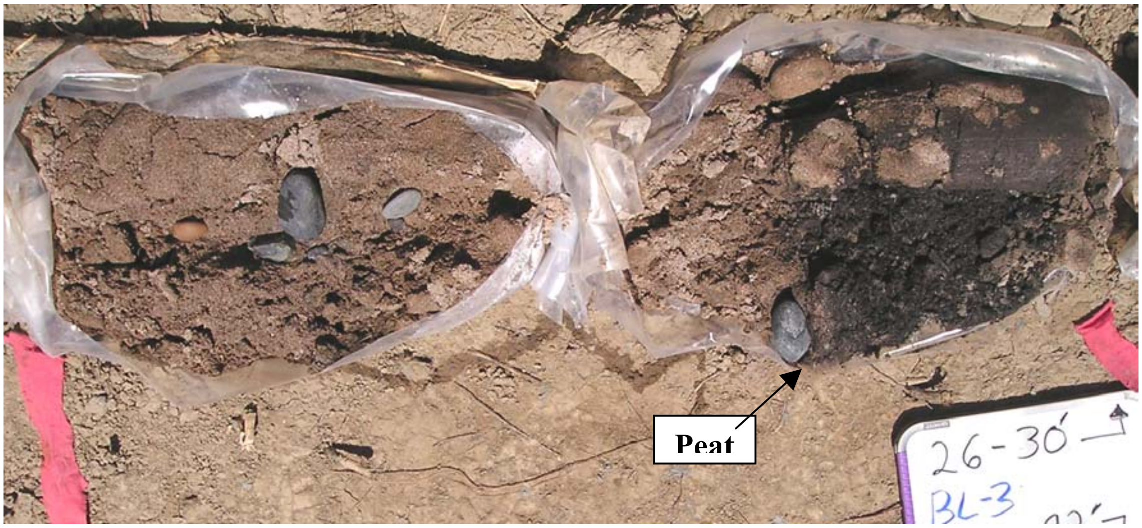


Figure C1. Photograph of borings from 26 to 30 feet below land surface from borehole BL3 showing peat layer and overlying sand and gravel.

The radiocarbon ages of these two samples indicate that there have been two flood events in the last 1000 years that have scoured down to 24 and 30 feet below present land surface, respectively, at a distance of more than 260 feet from the present river channel. At a minimum, it is important to emphasize that channel scour of this magnitude has occurred and needs to be incorporated into any model attempting to accurately predict river migration.

BL3-S2 Piezometer

No groundwater samples were collected from the original BL3-S since the filter pack interval of that well was contaminated by bentonite slurry resulting from heaving sands during well construction. Piezometer BL3-S2 has been installed to replace this well for future sampling. The piezometer was installed directly next to the original BL3 nest by University of Utah staff. Well installation information is included in Table C3 below. Immediately after installation the piezometer was fully developed, and now yields clear groundwater for future sampling.

Well / PZ ID	Type of Installation	ID (cm)	ID (in)	Easting (UTM)	Northing (UTM)	TOC Elevation (m)	Depth to Center of Screen Below MP (m)	Screen Length (m)	Screen Length (ft)
BL3-S2	Drive pt. PZ	1.27	0.50	623533.69	4271026.80	1208.54	9.25	0.31	1.0

Table C3. Well installation information for piezometers BL3-S2 including; type of installation, survey coordinates, top of casing elevation, depth to center point of screen below measuring point, and screen length. Horizontal survey coordinates are UTM relative to NAD 27 datum.

Nitrogen Isotope Analyses

As part of our field program samples were collected for the analysis of nitrogen isotopes on dissolved nitrogen species. Because of the extreme range in salinity and dissolved nitrogen concentrations, we were not able to find a suitable technique for analyzing all samples. Samples with low salinity could have been measured using an ion exchange technique, but high concentrations of salt (greater than about 5000 mg/L) interfere with this method. A distillation technique for high salinity, high nitrogen samples was successfully developed, but this method proved to be imprecise for samples containing less than 10 mg/L NH_3 as N. Because our objective was to compare nitrogen isotope values across the entire site, employing two separate methods was not deemed to be suitable. An agreement with the State of Utah was reached whereby we would not provide (or charge for) any nitrogen isotope analyses.

Analytical Results from Beta Analytic

Dr. Phil Gardner — Report Date: 2/17/2004

University of Utah — Material Received: 1/20/2004

Sample Data	Measured Radiocarbon Age	13C/12C Ratio	Conventional Radiocarbon Age(*)
Beta - 188270 SAMPLE : BL3-24 ANALYSIS : Radiometric-Standard delivery MATERIAL/PRETREATMENT : (wood): acid/alkali/acid 2 SIGMA CALIBRATION : (result is outside of the calibration range)	20 +/- 60 BP = 99.7 ± 0.7 pMC	-24.8 o/oo	30 +/- 60 BP
Beta - 188271 SAMPLE : BL3-30 ANALYSIS : Radiometric-Standard delivery MATERIAL/PRETREATMENT : (peat): acid/alkali/acid 2 SIGMA CALIBRATION : Cal AD 1015 to 1235 (Cal BP 935 to 715)	910 +/- 50 BP	-25.0 o/oo	910 +/- 50 BP

over

CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12=-25:lab. mult=1)

Laboratory number: **Beta-188271**

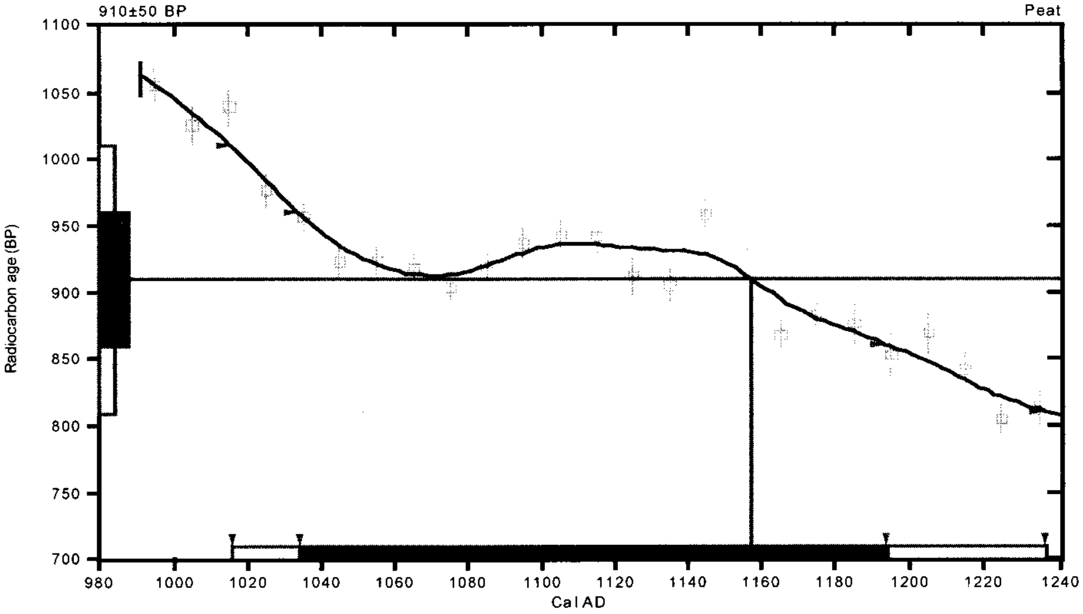
Conventional radiocarbon age: **910±50 BP**

2 Sigma calibrated result: **Cal AD 1015 to 1235 (Cal BP 935 to 715)**
(95% probability)

Intercept data

Intercept of radiocarbon age
with calibration curve: Cal AD 1155 (Cal BP 795)

1 Sigma calibrated results: Cal AD 1035 to 1195 (Cal BP 915 to 755)
(68% probability)



References:

Database used
Intcal98
Calibration Database
Editorial Comment
Stuiver, M., van der Plicht, H., 1998, Radiocarbon 40(3), pxii-xiii
INTCAL98 Radiocarbon Age Calibration
Stuiver, M., et. al., 1998, Radiocarbon 40(3), p1041-1083
Mathematics
A Simplified Approach to Calibrating C14 Dates
Talma, A. S., Vogel, J. C., 1993, Radiocarbon 35(2), p317-322

Beta Analytic Radiocarbon Dating Laboratory

4985 S.W. 74th Court, Miami, Florida 33155 • Tel: (305)667-5167 • Fax: (305)663-0964 • E-Mail: beta@radiocarbon.com