TECHNICAL PROGRESS REPORT

Remediation and Treatment Technology Development and Support for DOE Oak Ridge Office: Moab Model Preliminary Results Summary

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NOTE: The work is based on numerical simulations conducted for the task “Modeling of Groundwater Flow and Transport at the Uranium Mill Tailings Site in Moab, Utah”, which may change as additional data are incorporated or improvements are made to model parameters.

EXECUTIVE SUMMARY

An estimated 16 million tons of uranium mill tailings remained from processing operations at the Moab Uranium Mill Tailings Remedial Action (UMTRA) Project site in 1984. These tailings were accumulated in an unlined impoundment, a portion of which is in the 100-year floodplain of the Colorado River. In 2001, ownership of the Moab site was transferred to DOE along with the responsibility for its remediation in accordance with Title I of the Uranium Mill Tailings Radiation Control Act (UMTRCA). Results of investigations indicated that site-related contaminants have leached from the tailings pile into the shallow groundwater and some of the more mobile constituents have migrated downgradient and are discharging to the Colorado River adjacent to the site. The most pervasive and highest concentration constituents are ammonia and uranium. In order to address concerns regarding elevated ammonia levels in groundwater discharging to the Colorado River from the Moab site, DOE implemented an interim action system consisting of a series of extraction wells which have removed more than 168 million gallons of groundwater and prevented more than 687,000 lbs of ammonia and about 3,150 lbs of uranium from reaching the river. In support of this effort and to better understand the subsurface hydrology, a finite difference transient groundwater flow and transport model was developed by DOE's contractors. FIU is applying this groundwater numerical model to evaluate the tailings pore-water seepage in order to assist in effective dewatering of the tailings pile, and to optimize the groundwater extraction well field as part of the DOE UMTRA for the Moab site. In order to reduce contaminant mass in the groundwater system and to be protective of potential endangered fish habitat in backwater areas of the river, the model was used to simulate remedial actions proposed by DOE including pumping contaminated groundwater from the shallow plume to an evaporation pond on top of the tailings pile, and injecting the diverted Colorado River water into the alluvial aquifer. Numerical simulation of the proposed remedial actions provide information for the time to reach cleanup levels and assist DOE in optimization of the operation of groundwater extraction well fields, infiltration of treated water, and injection of clean fresh water for the DOE UMTRA site in Moab, Utah.

The work was carried out with support from student interns who assisted in the collection of groundwater samples and site data and applied the existing groundwater and transport model (SEAWAT with Groundwater Vistas, MODFLOW and FEFLOW) to analyze the groundwater flow and transport data of the Moab site. The model predicts the capture zones for different operating scenarios, mass removal; and time to complete remediation. Information is provided about the effect of discharge of a legacy ammonia plume from the brine zone after the extraction wells and injection system have been shut off. The tailings pore-water seepage is analyzed to determine the effective dewatering of the tailings pile and to optimize the groundwater extraction well field as part of the DOE Uranium Mill Tailings Remedial Action (UMTRA) for the Moab site.

A series of simulations using the SEAWAT model were completed to analyze the nitrogen and uranium cycle in the environment and provide forecasting capabilities for the fate and transport of contamination within the Moab site. The model provides information which can be used to determine the efficiency of remedial actions in reducing the concentration and load of contaminants and to assist DOE in deciding the effectiveness of remedial actions. The simulations were used to determine the efficiency of remedial actions in reducing the concentration and load of contaminants. The following work is summarized in the report:

1. **Revision and update of the existing model:** The existing model was revised and updated with additional information related to the current remedial actions which include injection and withdrawal well. Additional simulations were conducted to determine parameters of flow and transport of contaminants according to the current remedial actions.
    1.1. Development of U and Nitrogen (Ammonia and Nitrate) plumes (Simulation A01)**:** The existing Moab model was updated by implementing geostatistically interpolated ammonia and uranium plumes and current well operation data into the model to evaluate the effects of pumping on contaminant concentrations and determining potential surface water concentrations in riparian habitat areas for a range of operating conditions. The plumes of aqueous species of concern (nitrate, uranium) were developed with the width of the tailings that would be conservative.

   1.2. Simulate movement of U and Nitrogen (Ammonia and Nitrate) plumes (Simulation BP01): The ammonia transport was simulated by applying as initial condition the ammonia plume (for couple of cycles) and determining the yearly rise and fall in the river to determine if the ammonia concentrations moving up into the saline zone into the brine zone due to the fluctuations of concentrations in the river. The spatial extent of the discharge zone for the ammonia legacy plume in the brine zone and its effect on natural flushing were determined.
   1.3. Simulate effect of brine zone (Simulation BP02): The effects of the brine zone beneath the site on an overlying saline zone were determined.
   1.4. Simulate mobility of ammonia plume (Simulation BP03): The effect of discharge of a legacy ammonia plume from the brine zone after the extraction wells and injection system have been shut off was determined.
2. **Modification of the well injection and withdrawal systems and implementation of diversion ditch:** The model was reconfigured by adding injection and withdrawal wells and modifying the configuration of the wells. A diversion ditch was added to intercept and extract water from the tailings.
   2.1. Implementation of new well configuration (Simulation CC01): A new configuration was implemented that includes infiltration and provide information about the reoccurrence of the concentrations within the recharge assuming the existence of a freshwater lens.
   2.2. Implementation of diversion ditch (Simulation CC02): A diversion ditch was implemented into the flow model (as drain cells) and by setting the head levels will be set in each drain cell at the elevations of the drains. The effect of mixing water from the river and the diversion ditch was determined.
   2.3. Effectiveness of both systems (Simulation CC03): The benefits of running diversion ditch and well extraction at the same time were determined.
3. **Alternative remediation scenarios:** A set of proposed remedial actions simulated including pumping of contaminated groundwater from the shallow plume to an evaporation pond on top of the tailings pile, and injecting the diverted Colorado River water into the alluvial aquifer in order to predict the outcome of each remedial action and to investigate the

effectiveness of each scenario.

- 3.1. Optimization of mass removal with existing system (Simulation DM01): After implementing plumes into the model as initial conditions, additional simulations were conducted to optimize mass removal and capture from the existing system.
- 3.2. Optimization of mass removal including injection (Simulation DM02): The mass removal was optimized without additional bleeding of ammonia from the deep zone into the shallow zone and assuming that injection systems operate at the same time.

4. **Long-Term Performance of Uranium Tailings Disposal Cells:** The recharge of the saturated zone resulting from the mine tailing is an important parameter for water and contaminant mass balance at the site. A model of the tailings was developed to analyze the unsaturated flow as function of daily stochastic hydrologic events (rainfall and precipitation). The Appendix contains an article which provides analysis of the vadose zone of a typical UMTRA site.

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ASCEM	Advanced Simulation Capability for Environmental Management
CFR	Code of Federal Regulations
DNAPL	Dense Non-aqueous Phase Liquid
DOE	Department of Energy
DOM	Dissolved Organic Matter
EPA	Environmental Protection Agency
FIU	Florida International University
NLCD	National Land Cover Data
NPDES	National Pollutant Discharge Elimination System
NRC	Nuclear Regulatory Commission
QA	Quality Assurance
QAPP	Quality Assurance Project Plan
QC	Quality Control
RCRA	Resource Conservation and Recovery Act
ROD	Record of Decision
SOW	Statement of Work
SSURGO	Soil Survey Geographic Database
TDS	Total Dissolved Solids
TMDL	Total Maximum Daily Load
UMTRCA	Uranium Mill Tailings Radiation Control Act
USGS	United States Geological Survey

1 INTRODUCTION

Uranium ore was mined in significant quantities in the United States for more than 40 years. Initially, the ore was mined and milled by private companies for federal government use in national defense programs. After the 1950s, uranium was also needed as fuel for nuclear power plants to produce electricity. These milling operations created process-related wastes and tailings, a radioactive sand-like material. The tailings were transported as a slurry to unlined impoundments that accumulated over time, forming piles. Excess water in the piles drained into underlying soils, contaminating the groundwater. Scientists, community leaders, and public officials became more aware of the potential health risks associated with long-term exposure to uranium mill tailings during the 1970s. Public concern about potential human health and environmental effects of uranium mill tailings led the U.S. Congress to pass the Uranium Mill Tailings Radiation Control Act (UMTRCA) in 1978 (Public Law 95–604), which required the cleanup of inactive uranium-ore processing sites. In 1983, the U.S. Environmental Protection Agency (EPA) developed regulations (more specifically, Title 40 Code of Federal Regulations Part 192) to protect the public and the environment from potential radiological and non-radiological hazards at inactive uranium-ore processing sites. The U.S. Department of Energy (DOE) is responsible for cleaning up the mill sites and for bringing groundwater contamination at the former processing sites into compliance with EPA standards (Subpart B of 40 CFR 192). The radioactive materials are encapsulated in U.S. Nuclear Regulatory Commission (NRC)-accepted disposal cells. The NRC general license for post-closure requirements of UMTRCA sites is established in 10 CFR 40.27.

The DOE Moab Uranium Mill Tailings Remedial Action (UMTRA) Project site (Figure 1 and Figure 2) is located approximately 3 miles northwest of the city of Moab in Grand County, Utah, and includes the former Atlas Minerals Corporation (Atlas) uranium-ore processing facility. The site is situated on the west bank of the Colorado River at the confluence with Moab Wash and the northern portion of Moab Valley. The valley is within the Salt Anticline Section of the Colorado Plateau province, which includes the plateaus, mesas, and canyons of western Colorado, eastern Utah, northern Arizona, and northwestern New Mexico. The floor of Moab Valley lies at an elevation of about 4,000 feet (ft) above mean sea level. Sandstone cliffs that form the valley walls near the former mill site rise about 1,000 ft above the valley floor. The Moab site is irregularly shaped and encompasses approximately 400 acres; a 130-acre uranium mill tailings pile occupies much of the western portion of the site. The Moab site is bordered on the north and southwest by steep sandstone cliffs. The Colorado River forms the southeastern boundary of the site.

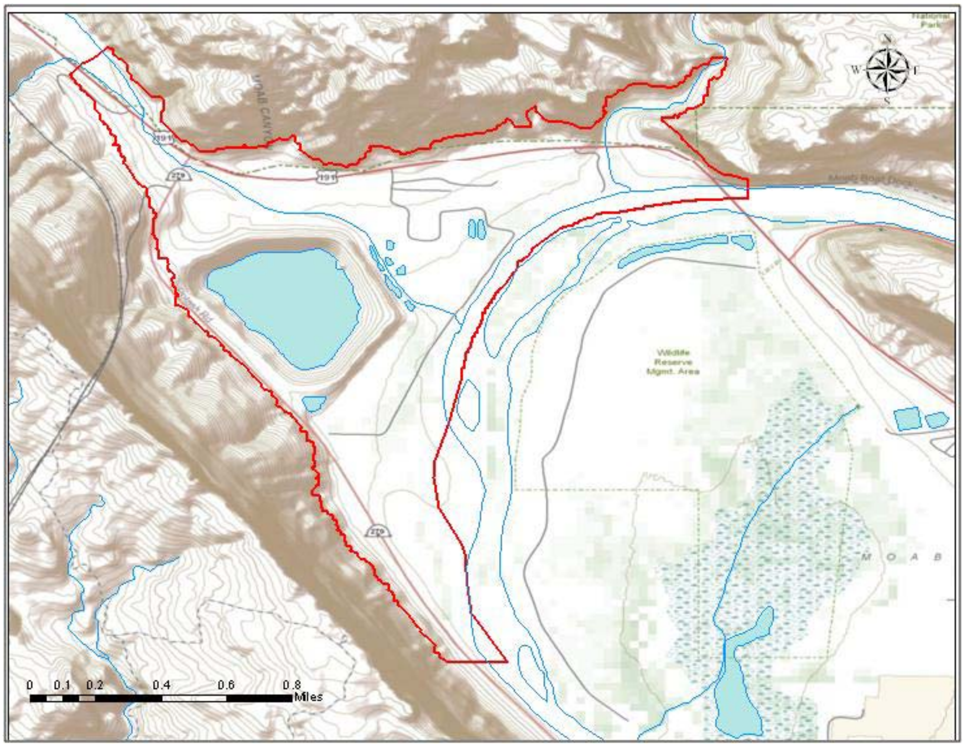

Figure 1 Location of Moab site and boundary of the model domain (red line)

The entrance to Arches National Park is located less than 1 mile northwest of the site across US-191; Canyonlands National Park is about 12 miles to the southwest. The Union Pacific Railroad traverses a small section of the site just west of SR-279, then enters a tunnel and emerges several miles to the southwest. Moab Wash runs northwest to southeast through the center of the site and joins with the Colorado River. The wash is an ephemeral stream that flows only after precipitation or during snowmelt. Courthouse Wash, another ephemeral stream, but with a larger drainage than Moab Wash, discharges to the Colorado River about 300 ft east of the easternmost boundary of the site [**9**].

Figure 2 Moab site [nap.edu].

The Moab mill was constructed in 1956. The mill was originally owned by the Uranium Reduction Company, but was acquired by Atlas Corporation in 1962. The original uranium milling process used an acid leach circuit, which was converted to an alkaline process due to changes in ore composition. In 1967, an acid leaching and solvent extraction process was added to recover copper and vanadium as by-products. The acid-leach processing circuit was subsequently destroyed by fire in December 1968. All ore was brought to the site by truck and stored in 50- to 800-ton lots in the ore receiving area. Processing operations ceased in 1984, leaving behind an estimated 16 million tons of uranium mill tailings, material that ranges from dry sand to wet “slime” clay that remains after the ore is processed. These tailings were accumulated in an unlined impoundment, a portion of which is in the 100-year floodplain of the Colorado River. In 2001, ownership of the Moab site was transferred to DOE along with the responsibility for its remediation in accordance with Title I of UMTRCA.

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Figure 3 Atlas Mill site Photo (1959)

According to GCAP [8] the process descriptions and flow sheets for the Atlas Mill indicate that all processing was carried out using closed circuits that allowed a significant portion of the liquids to be recycled. Tailings from all process circuits were combined into a common sump (presumably located in the processing area) and pumped to the tailings disposal ponds via distribution pipes located on three sides of the tailings pond (Figure 4). In early operations, the slurry had a neutral pH as a result of mixing materials from the alkaline and acid circuits. Decanted water from the tailings pond was removed through piping under the main pond to two small settling ponds (Drain Sumps on Figure 4 and barium chloride ponds ($BaCl_2$ Ponds on Figure 4 on the northeast and southeast sides of the tailings pond outside the tailings dike. Part of this water was recycled to the water treatment plant for eventual reuse in the mill circuit; the remainder flowed through the ponds in series. A small amount of $BaCl_2$ was added to the second pond to coprecipitate radium from solution along with barium sulfate ($BaSO_4$). Clarified water from the second pond was discharged to the Colorado River (probable location shown on aerial photo Figure 4 muddy “delta” area). During the early processing period, water withdrawal from the Colorado River for use in processing was estimated at 1,300 gallons per minute (gpm) (DOE 2003).

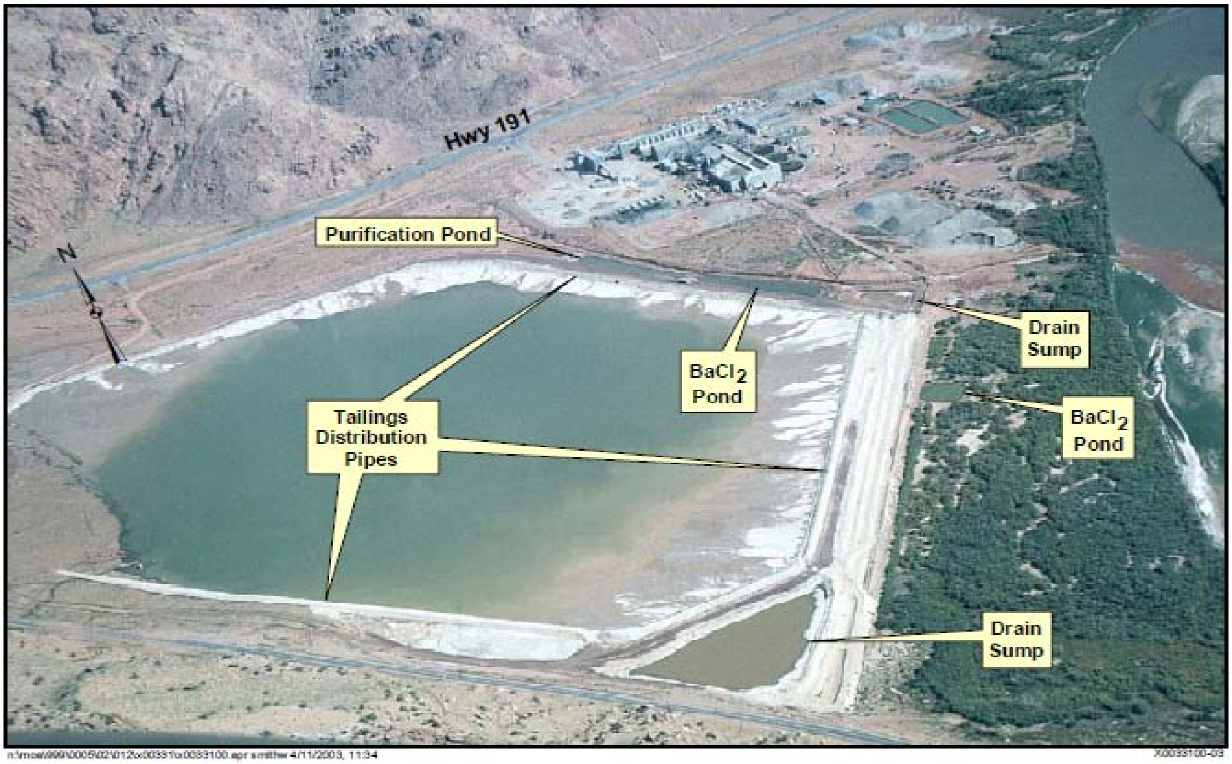

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Figure 4 Atlas Tailings Pile Photo (1966)

Several modifications to the ore processing operations were made in 1974:

- Construction of an acid-leach processing circuit to replace the one destroyed in a 1968 fire.
- Modification of the alkaline-leach circuit to reduce the volume of liquid effluents disposed of in the tailings pond.
- Elimination of direct discharge of effluent (liquids and solids) to the Colorado River.
- Implementation of process modifications aimed to decrease water usage an order of magnitude to 130 gpm

Furthermore, with less effluent for disposal, evaporation of liquids from the tailings pond was adequate to keep pace with processing, and discharge to the Colorado River was no longer required. Presumably, use of the settling ponds adjacent to the southeast side of the pile was discontinued. Also, sludge from the initial treatment of water withdrawn from the Colorado River were disposed of in the tailings impoundment rather than discharged to the river. From 1982 to 1984, only an acid leach process was used, and no process water was neutralized. The 1989 ground water corrective action plan suggests that this resulted in disposal of low pH process water and increased metals mobilization. Atlas submitted a license renewal application in 1984; however, at that time the site went on standby, and processing operations did not resume (DOE 2003).

Interim cover placement on the pile began in 1989 and was completed in phases as the center of the pile dried up. Placement of the cover was finished in November 1995. Many of the on-site buildings and equipment were dismantled and deposited in the southern portion of the tailings pile. From 1990 to 1996, Atlas pumped tailings pore water from wells in the pile to the top of the pile for evaporation to accelerate dewatering and consolidation of the pile.

The United States Fish and Wildlife Service (USF&WS) submitted a final biological opinion to NRC in July 1998 saying that a ground water corrective action plan had to be developed that was related to the Reclamation Plan. The final biological opinion stated that, as proposed, the reclamation project would jeopardize the razorback sucker and Colorado pikeminnow; concerns were over water depletion as well as destruction or adverse modification (chemical and physical) of critical habitat. It also indicated that the effects on endangered fish from ground water discharging to the river could be significant. The USF&WS developed alternatives to avoid the likelihood of jeopardy and habitat destruction or modification to:

- Perform ground water corrective action that includes dewatering the tailings pile, cleanup of ground water to meet surface water standards in 7 years, removal of exposure/risk to listed fish in 10 years, and monitoring of surface water quality.
- Incorporate ammonia standards in Atlas' license.

- Conduct bioassay studies to evaluate toxicity of ammonia plume on endangered fish and develop a site-specific ammonia standard.
- Establish an ACL for protection of human health and aquatic life that would be met at a point of compliance.
- Provide a water depletion payment for the endangered fish recovery program.

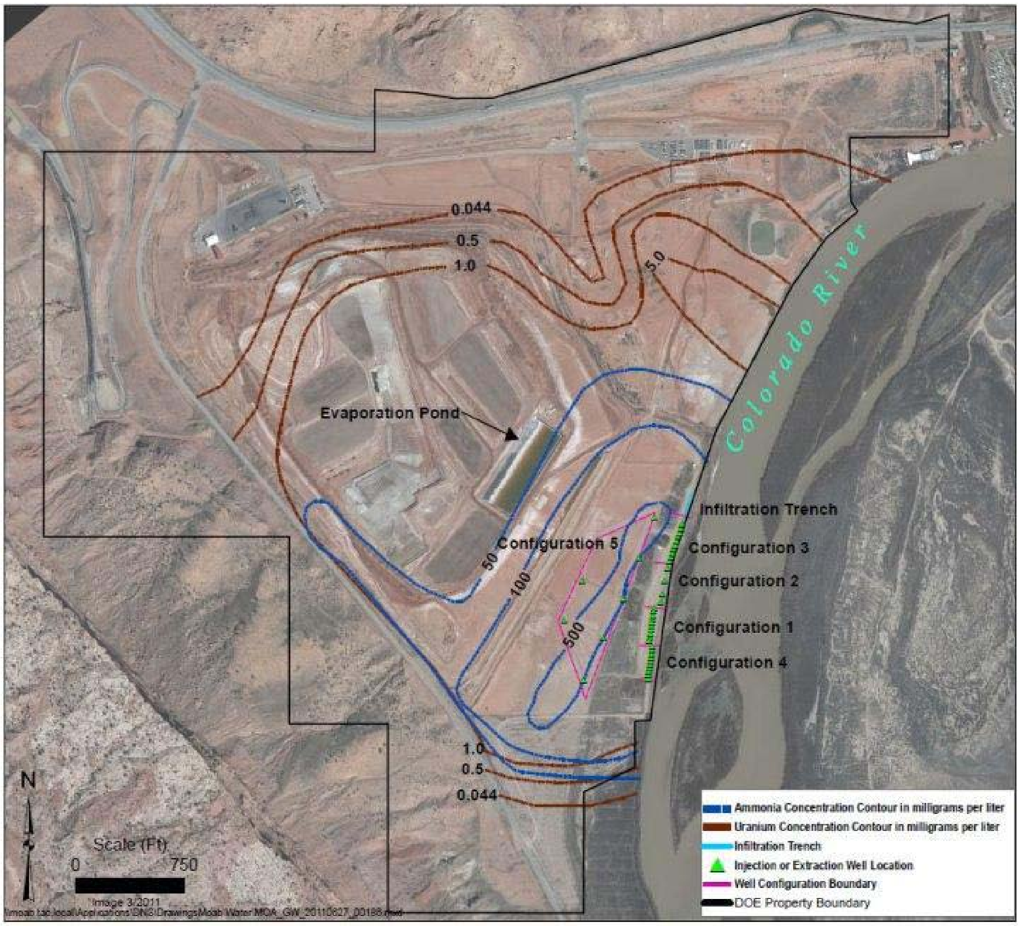

Figure 5 Interim action well field [**13**]

Remediation of surface contamination at the Moab UMTRA processing site began in 2009 and it is expected to be completed within the next 15 years. A Ground Water Interim Action has been performed since 2003 to mitigate the ecological risk to fish from ammonia in ground water that discharges to the habitat areas adjacent to the Colorado River. Detailed information about the site, nature and extent of contamination, and ecological risks are provided in the Site Observational Work Plan (SOWP) (DOE 2003). Relocation of the tailings, by rail, began in April

2009 to a disposal cell constructed 30 miles north near Crescent Junction, also in Utah. Results of investigations indicate that site-related contaminants have leached from the tailings pile into the shallow groundwater and some of the more mobile constituents have migrated downgradient and are discharging to the Colorado River adjacent to the site. The most pervasive and highest concentration constituents are ammonia and uranium.

In 2003, DOE implemented the first phase of an interim action system (Figure 5) at the Moab site to address concerns regarding elevated ammonia levels in groundwater discharging to the Colorado River. This first phase consisted of 10 extraction wells (called Configuration 1). Four additional configurations of wells have been added since then, for a current total of 42 wells that are designed to prevent ammonia from discharging to the river. The well configurations are shown in Figure 5.

To date, a total of more than 168 million gallons of groundwater have been extracted through the interim action system, preventing more than 687,000 pounds of ammonia and about 3,150 pounds of uranium from reaching the river. DOE continues to evaluate the effectiveness of the interim action system, which will likely become part of the final groundwater remedy.

2 MODEL UPDATE

The groundwater system is represented by a relatively shallow groundwater in alluvium that mostly contains slightly saline to very saline water and flows southeastward toward the Colorado River over an extensive deeper zone containing brine. The TDS concentrations are larger than the TDS levels commonly reported for river water (100 to 1,000 mg/L). Salinity data collected from groundwater in alluvium on both sides of the river show that TDS concentrations in both areas span a large range, typically from as low as 700 mg/L to as high as 110,00 mg/L or more. Thus much of the groundwater in these areas consists of very saline and brine. In accordance with the DOE site conceptual model, the TDS concentrations generally increased with increasing depth.

The data collected at the Matheson Wetlands indicate a mirror image of brine distribution below the Moab site, as depth to brine is greatest in wells located some distance southeast of the river and much smaller near the river’s east bank. Such observation when combined with previous studies showing the river acting as a site of regional groundwater discharge, suggest that the larger TDS concentrations in shallow groundwater at the river are due to saltwater upcoming, with the river acting much like a well that induces the upward migration of underlying brine when shallow groundwater is pumped.

Also for data collected at wells located both on and downgradient of the tailings pile, the brine source appears to be dissolution of the Paradox Formation sediments located part of the way down a steep bedrock face situated just to the northwest of the pile. Extrapolation of TDS concentration data close to the river indicates that the brine surface intersects the river near its west bank. With such a large range of TDS concentrations on either side of the river, groundwater flow toward the river from both the project site and the wetlands preserve is a density-dependent process, since water density increases with increasing salinity.

As a consequence, the vertical interval containing most groundwater flow between the brine surface and the top of the saturated zone decreases with proximity to the river, causing progressively larger groundwater velocities as the river approaches.

2.1 Objectives

In accordance with Title I of UMTRCA, DOE has implemented an interim action system at the Moab site to address concerns regarding elevated ammonia levels in groundwater discharging to the Colorado River. In support of this effort and to better understand the subsurface hydrology, a finite difference transient groundwater flow and transport model was developed by one of DOE's contractors. FIU, in collaboration with DOE's Moab site scientists, applied this model to evaluate the tailings pore-water seepage in order to assist in effective dewatering of the tailings pile and to optimize the groundwater extraction well field as part of the DOE Uranium Mill Tailings Remedial Action (UMTRA) for the Moab site.

The main objectives of this work are to:

1. Use an existing groundwater numerical model to simulate the fate and transport of contaminants, including uranium and ammonia, in the subsurface domain at the Moab site in Utah. The model simulates nitrogen and uranium transformations along the flow path and density dependent flow related to brines in the groundwater system beneath the site.
2. Perform numerical simulations of current remedial scenarios including pumping of contaminated groundwater from the shallow plume to an evaporation pond on top of the tailings pile, and injecting the diverted Colorado River water into the alluvial aquifer. The model provides information for each remedial action and investigates the effectiveness of each scenario in reducing contaminant mass in the groundwater system and protecting potentially endangered fish habitat in the backwater areas of the river. Numerical simulations of the proposed remedial actions aid in prediction of the time to reach cleanup levels and assist DOE in optimization of the operation of groundwater extraction well fields, infiltration of treated water, and injection of clean fresh water for the DOE UMTRA site in Moab, Utah.

2.2 Methodology

The numerical model used in this study is SEAWAT 2000. SEAWAT 2000 (Langevin et al. 2003) is a widely used program that was developed to simulate three-dimensional, variable density, transient groundwater flow in porous media. SEAWAT is formulated using finite-difference principles and combines the code MODFLOW (Harbaugh and McDonald 1996) for porous media flow with advective-dispersive transport algorithms found in MT3DMS (Zheng and Wang 1999) [Figure 6]. The MT3DMS code allows model users to simulate the transport of multiple dissolved constituents. When applying it with SEAWAT, TDS is treated as the primary constituent, and a formula built into the code facilitates the conversion of TDS into values of water density. Individual chemical components are treated as secondary constituents.

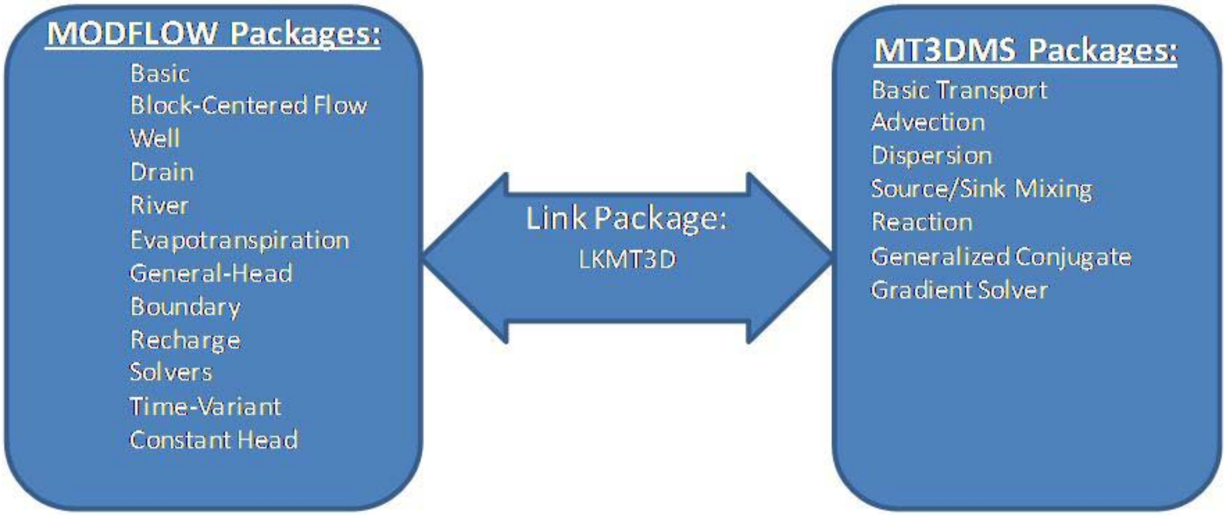

Figure 6 MODFLOW and MT3DMS packages.

The numerical model uses Groundwater Vistas for modeling platform because of its superior modeling capabilities, such as advanced solvers and the ability to change model parameters easily and quickly. Modeling of the groundwater flow and transport at Moab site is composed of the following sequence of modeling tasks:

The following outlines the series of subtasks.

- Subtask 1: Model Update and Improvement

    1. Hydrologic budget calculations were evaluated using historical meteorological data, surface water flow rate data, seep flow rate data and human induced stresses. The locations where these inputs and outputs manifest were detailed, along with known or expected changes with time due to climatic variations, pumping, seepage and surface-groundwater interaction. Results of the water budget analysis was used for developing constraints for the surface water model and the groundwater model.
    2. New geostatistically interpolated plumes were created for model input and the model was used to predict concentration in habitat areas for various river stages. The lateral extent of groundwater contamination emanating from the tailings pile was delineated.
    3. Analysis of groundwater quality data adjacent to the Colorado River for calculating the flux of contamination into the river was conducted. Water quality contour maps were generated by using the results from all of the monitoring wells and the pattern of contaminant transport were developed
    4. Flow boundary conditions to represent the inflow from the Glen Canyon Group and Entrada Sandstone aquifers were implemented along with inflow from bedrock along the Moab Fault zone, evapotranspiration, inflow due to seepage from the tailings pile, and with hydraulic heads for simulating the inflow from the Moab Wash.

- Subtask 2: Model Calibration and Validation

    1. The model was calibrated with water level measurements collected from 44 different wells. In addition to water level elevations, the model was calibrated to estimated fluxes

for Moab Wash, the surrounding bedrock, the Colorado River during the base flow conditions and evapotranspiration. In the existing model, rather than using zones corresponding to like hydraulic conductivity values, hydraulic conductivity distribution was determined using pilot points. Variable hydraulic conductivity values were used for the top 3 layers and uniform conductivity values for the rest.

2. Pumping test data and several years of regular monitoring data which shows the natural seasonal variations and responses to other stresses were used for transient calibration of the model.
3. Calibration effort involved systematically adjusting the values of effective porosity (ne), dispersivities (αL, αT), and distribution coefficients (K_d) in successive simulations, and comparing the results against the observed concentration at the monitoring wells.

- Subtask 3: Prediction and Sensitivity Analysis

1. Predictive simulations were carried out with maximum and minimum values of flow parameters such as the hydraulic conductivity fluxes from Glen Canyon and Moab Fault, evapotranspiration and recharge. Simulations were carried out with maximum and minimum values of transport parameters such as dispersivities, ammonia distribution coefficients, effective porosities and ammonia tailings seepage.
2. Simulations to analyze the effects of pumping at well field Configuration 5 on ammonia and uranium concentrations in the upper saline zone and infiltration of freshwater in Configuration 1 to 4 were conducted. Upgradient infiltration locations were optimized relative to the tailings and extraction wells to maximize the number of pore volumes for flushing and reduce remediation time. The rate at which ammonia in the brine zone migrates into the overlying brackish and freshwater were calculated. The model was used for well field optimization to predict capture zones and mass removal.
3. Simulations to identify the discharge zone for the legacy plume in the brine zone and to identify areas of uncertainty were conducted. The effect of discharge of a legacy plume in the brine zone after the extraction wells have been shut off were modeled.

The subsurface model of Moab site consists of 15 layers. The top of model layer 1 corresponds to ground surface and the bottom of the layer has a uniform elevation of 3,945 feet mean sea level (msl). The remaining model layers (2-15) have uniform thicknesses of 10 feet. Horizontally, the SEAWAT model has uniform 25 foot by 25 foot grid cells and consists of 671,055 active cells.

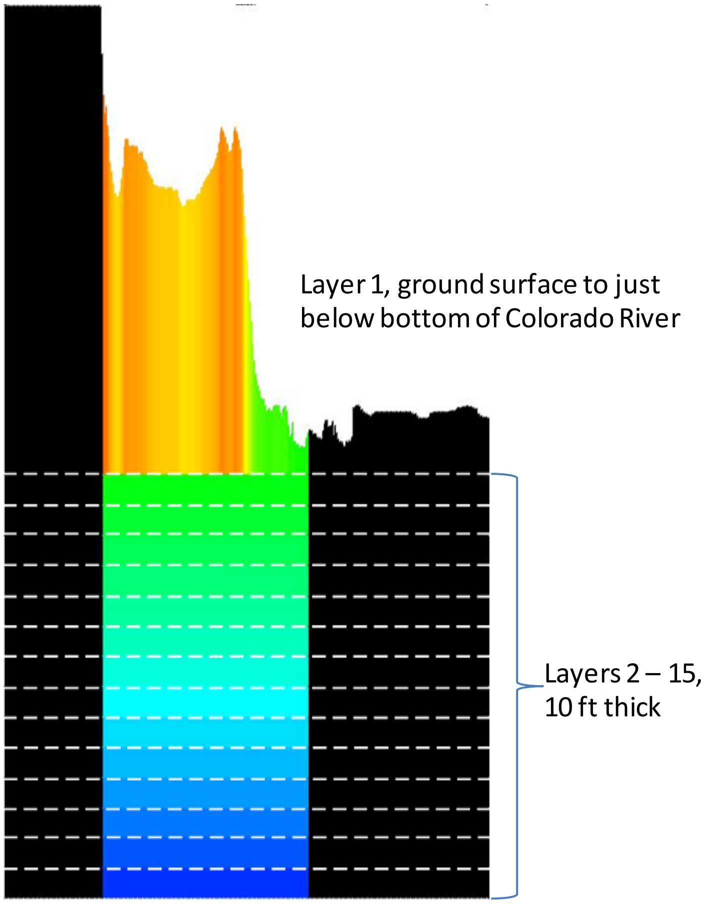

Figure 7 Model layers.

Temporally, the model was divided into 13 stress periods, an initial steady-state period followed by 12 transient stress periods corresponding to the months of January through December. The SEAWAT model used a fixed total dissolved solids (TDS) concentration.

2.3 Domain

The model domain (Figure 8) was selected on the basis of local hydrogeological features which control flow and transport at the site and the site conceptual model. Table 1 provides information about the numerical discretization:

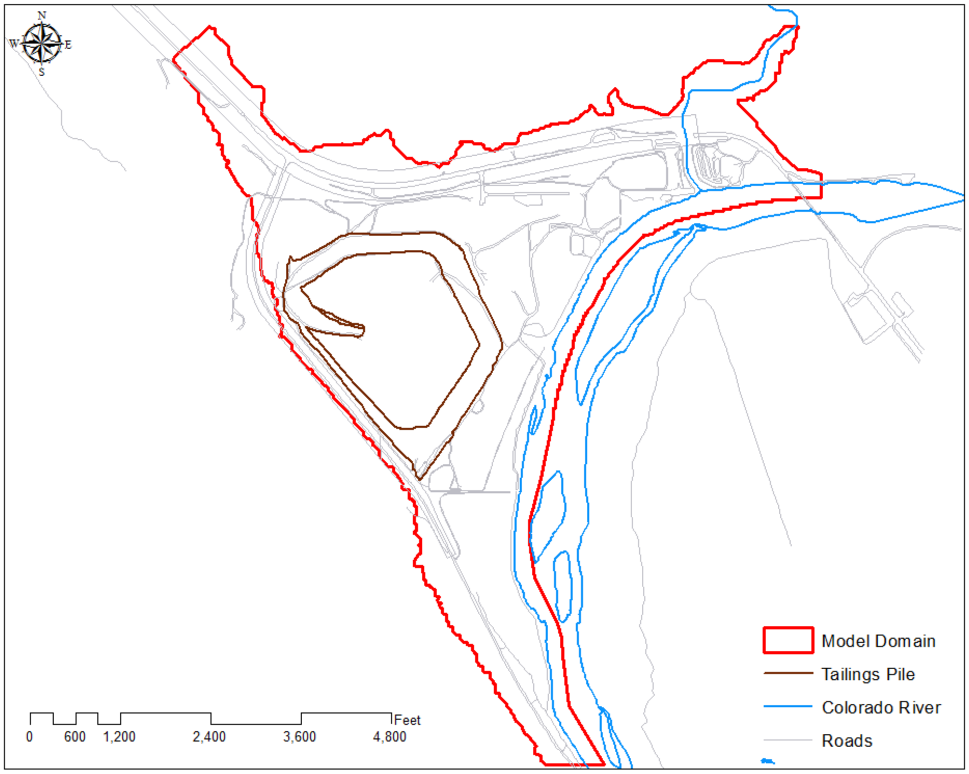

Figure 8 Model domain

The top of model layer 1 corresponds to ground surface and the bottom of the layer has a uniform elevation of 3,945 feet mean sea level (msl). The remaining model layers (2-15) have uniform thicknesses of 10 feet. Horizontally the SEAWAT model has uniform 25 foot by 25 foot grid cells, in all the model consists of 671,055 active cells.

Table 2 Model discretization

Parameter	Value
Number of Layers	15
Number of Rows (y-direction)	393
Number of Columns (x-direction)	354
Total Number of Cells (Active and Inactive)	2086830
Total Number of Active Cells	671055

2.4 Hydrogeology

The Moab site is located at the northwest end of Moab Valley, which formed during late Tertiary and Quaternary time by salt-dissolution-induced subsidence along the axis of the Moab-Spanish Valley salt-cored anticline [14]. The site is in the fold and fault belt in the northern part of the ancestral Paradox Basin. The fold and fault belt is characterized by northwest-striking salt-cored anticlines and synclines that are cut in places by normal faults and joints that also mainly strike northwest. At the northeast and southwest edges of Moab Valley, the Colorado River flows in deeply incised bedrock canyons cut by the superimposed river during the past several million years. The Colorado River flows southward out of Moab Valley through the Portal, the 1,000-ft sandstone cliffs flanking the river canyon mouth. The steep slope southwest of the site flanking Moab Valley rises 1,200 to 1,400 ft to the top of Poison Spider Mesa, capped by sandstones of the Wingate and Kayenta Formations. Just north of the site, north of US-191 and at the north end of Moab Valley, is a steep slope that rises approximately 600 ft and consists of highly fractured and faulted sandstones of the Wingate, Kayenta, and Navajo Formations (composing the Glen Canyon Group of Jurassic age). Dips of bedrock on this slope express the form of the Moab anticline, which is the northwest extension of the Moab Valley salt-cored anticline. The Moab Wash is an ephemeral drainage passing through the site, follows Moab Canyon northwestward and also is approximately along the trace of the Moab fault.

Groundwater at the site occurs mostly in alluvial sediments that may be as deep as 120 m or more. Total dissolved solids (TDS) concentrations in the alluvial groundwater vary naturally from those for slightly saline water (TDS = 1 to 3 kg/m^3 [1000 to 3000 mg/l]), to those categorized as moderately saline (TDS = 3 to 10 kg/m^3), very saline (TDS = 10 to 35 kg/m^3), and briny (TDS > 35 kg/m^3) (McCutcheon et al. 1993).

The primary source of the slightly saline water, which is found only in the shallowest parts of the saturated zone is groundwater discharge from bedrock aquifers that subcrop both near the site's northwest border and north of the tailings pile.

Brine waters dominate the deepest parts of the alluvium and are attributed to chemical dissolution of the underlying Paradox Formation, a large and relatively deep evaporite unit that has been deformed to create a salt-cored anticline aligned with and underlying the Moab Valley (Doelling et al. 2002).

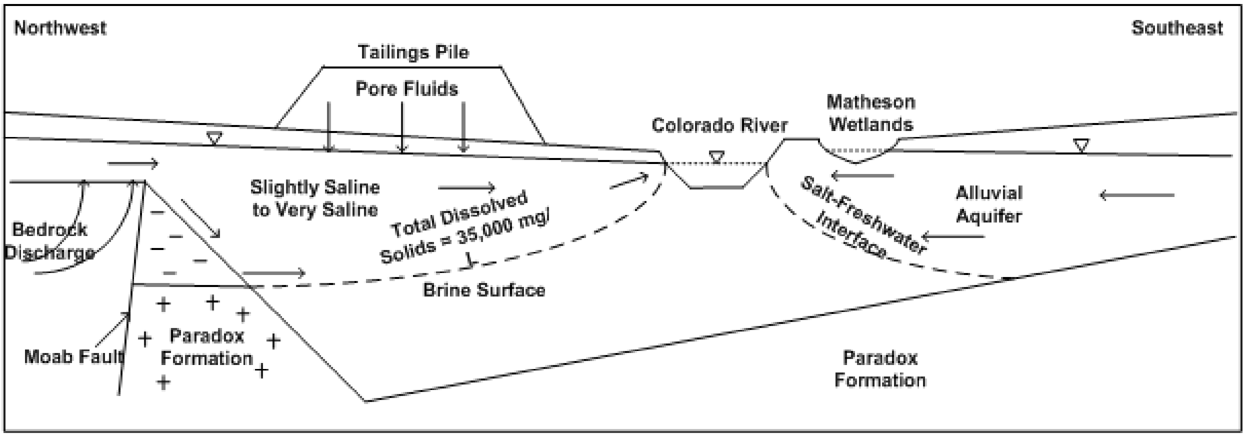

Figure 9 Conceptual model, Saltwater/Freshwater Interface [9].

Over the geologic history of the alluvial basin, mixing of the brine with overlying slightly saline water created an interlying and relatively diffuse high salinity zone. However, some of the highly saline groundwater was attributed to downward seepage of high- TDS fluids (TDS > 35 kg/m^3) from the base of the tailings pile, a process that occurred during and immediately after the years of facility operation. Depth to the top of the brine (brine surface) is greatest in the western portion of the site (approximately 45 m) and shallowest at the Colorado River, where TDS concentrations directly below the riverbed exceeds 35 g/m^3.

Hydrologic data indicate that the river and much of the alluvium immediately adjacent to it collectively act as a site of groundwater discharge, both on a regional scale (Blanchard 1990) and locally (Sumsion 1971). These observations suggest that brine is discharging to the Colorado River naturally. However, because some of the saline groundwater west of the Colorado River was probably derived from tailings seepage, a portion of the saline discharge to the river is likely anthropogenic (DOE 2003b).

Flow directions and the observed distribution of TDS in the local alluvial aquifer are analogous to those in a groundwater system overlying a salt dome (e.g. Oldenburg and Preuss 1995, Konikow et al. 1997). Such a system maintains distinct zones of recharge and discharge, and groundwater dissolves formation salts as it moves slowly between the two zones and across the dome. Depth to brine is greatest under the zone of recharge and gradually decreases with distance toward the discharge zone. At the Moab site, the Paradox Formation is analogous to a salt dome; the greatest depth to the brine surface is observed a short distance downgradient from bedrock units that contribute system recharge; and the brine surface approaches ground level in the vicinity of the Colorado River, where regional discharge of groundwater appears to concentrate.

The top aquifer in Moab Valley at the mouth of Moab Canyon is the Colorado River alluvium. Near the Moab site, the alluvium is comprised of two distinct depositional facies: the Moab Wash alluvium and the basin-fill alluvium.

- Moab Wash alluvium is composed of fine-grained sand, gravelly sand, and detrital material that has traveled down Moab Wash and grades and interfingers near the northwest boundary of the site into the basin-fill alluvium deposited by the ancestral Colorado River.
- The basin-fill alluvium has two distinct layers. The upper type consists mostly of a fine-grained alluvium (fine sand, silt, and clay), which ranges in thickness from 15-ft near the river to 40-ft in the northern and northwestern portions of the site and extends into the saturated zone in some areas. This shallow unit, referred to as the silty-sand unit, probably represents fine-grained overbank deposits from the Colorado River. The lower part of the basin-fill alluvium consists of a gravelly sand and sandy gravel, with minor amounts of silt and clay. The gravel clasts consist of subrounded pebbles and cobbles of resistant crystalline rocks that have been eroded and transported from metamorphic and igneous terranes present in the upper Colorado River Drainage Basin. This coarser alluvium, referred to as the gravelly unit, thins and pinches out to the northwest along the subsurface bedrock contact and thickens to the southeast toward the river to over

450 ft near the deepest part of the basin. Most of the borings drilled within the site boundary penetrate both the upper silty-sand unit and the lower basin-fill gravelly unit (DOE 2003).

The transmissivity of the upper basin alluvium ranges from 400 to 1200 ft^2/day. Assuming layer thickness of 15 ft the hydraulic conductivities range from 27 to 81 ft/day. Drawdown data indicates that the specific storage ranges from 0.006 to 0.031 (DOE 2003).

The spatial variations in groundwater salinity at the Moab site reflect both historical density-dependent flow processes (during mill operations), and relatively steady density-affected processes in recent years. The collected data by DOE indicate that high TDS concentrations observed in groundwater southeast of the river and the Matheson Wetlands were a result of natural phenomenon and possibly some anthropogenic influences between the City of Moab and the wetlands preserve.

The density-dependent flow modeling was performed to help quantify the processes shown in Figure 9. The model concept was to simulate two-dimensional groundwater flow and transport in a vertical cross-section, the trace for which followed a streamline that originated in the northwest corner of the site on the northeast side of Moab Fault, then trended southeastward across the tailings pile, and terminated in the center line of the Colorado River. A no-flow condition was applied at the vertical model boundary aligned with the river centerline to represent a line of convergence for surmised flow coming from both the southeast and northwest.

2.4.1 Porosity

Porosity is a required parameter in modeling simulations because it enters into transport calculations not only in the seepage velocity term, but also in expressions for the solute mass in a given volume of aquifer and the rate at which that mass changes with time (Zheng and Bennet 1995). Literature values compiled by Morris and Johnson (1967) were used because their values are regarded as reputable averages that span a wide variety of lithologic materials and are widely used in the field of hydrology. On the basis of these published values, bedrock materials were assigned a porosity of 20 percent, and alluvial materials were assigned a porosity of 30 percent.

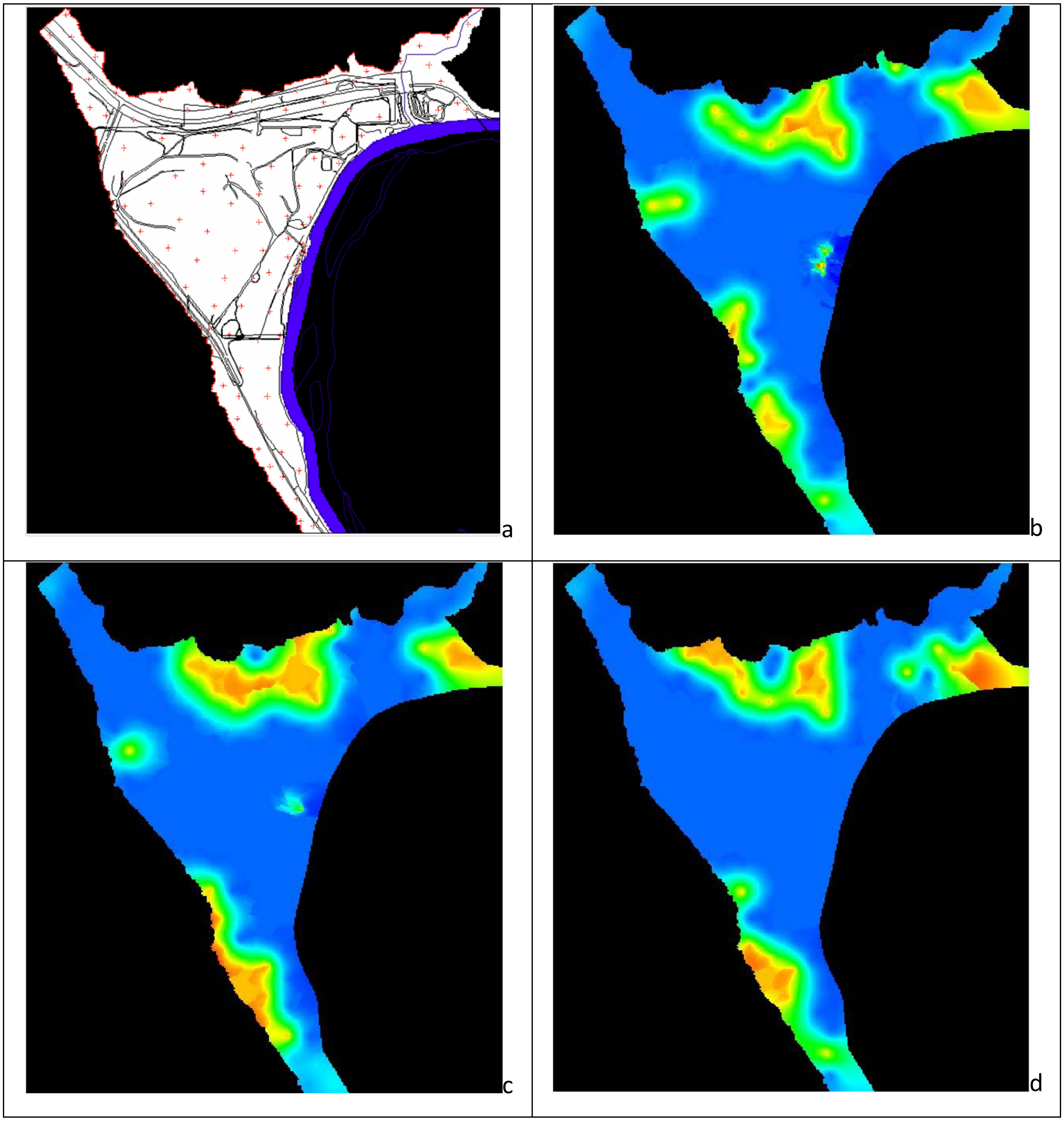

Figure 10 a) Pilot points used to determine hydraulic conductivity distribution, b) Hydraulic conductivity for Layer 1, c) Hydraulic conductivity for Layer 2 and d) Hydraulic conductivity for Layer 3

2.4.2 Hydraulic Conductivity

The hydraulic conductivity distribution in the model was determined using pilot points (Figure 10). The pilot points are located within the model domain and assigned initial, minimum, and maximum hydraulic conductivity values. Automated model calibration adjusts the hydraulic conductivity value at the pilot points between the minimum and maximum allowable values using nonlinear regression techniques. Kriging was used to interpolate hydraulic conductivities in areas between the pilot points. The "calibrated" hydraulic conductivity configuration is the continuous hydraulic conductivity field that produces the best match with the calibration targets.

Variable hydraulic conductivity fields were determined for model layers 1 through 3 using pilot points. Due to a lack of targets in model layers 4 through 15, these layers were assigned uniform hydraulic conductivity zones for calibration. Hydraulic conductivity for Layers 4 to 10 – 20 ft/d & Layers 11 to 15 – 30 ft/d.

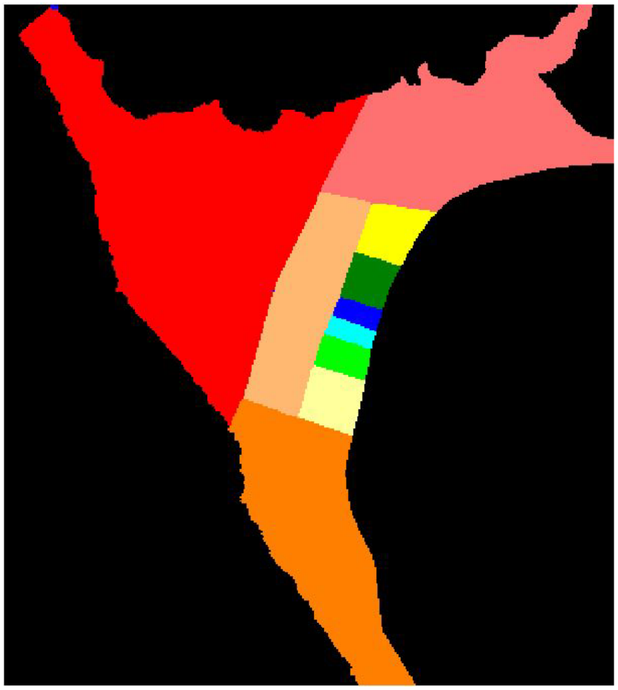

Figure 11 Storativity

2.4.3 Storativity

The storativity was defined by creating 10 different zones of the model domain [Figure 11]. Estimates of aquifer storativity were derived from aquifer tests performed at groundwater wells.

2.5 Surface Water

The Colorado River which is located along the eastern boundary of the site is bounded by the coalesced alluvial fans of Moab and Courthouse Washes in the north and by a large topographic depression known as the Matheson Wetlands Preserve to the south. The USGS Cisco, Utah, gaging station (Station No. 09180500) located approximately 31 river miles upstream of Moab is the closest gaging station to the Moab site along the Colorado River. Post 1950 flow data show an average peak flow of approximately 28,000 cfs. Daily mean discharges measured at the Cisco gaging station from 1950 through 2010 are shown in Figure 12.

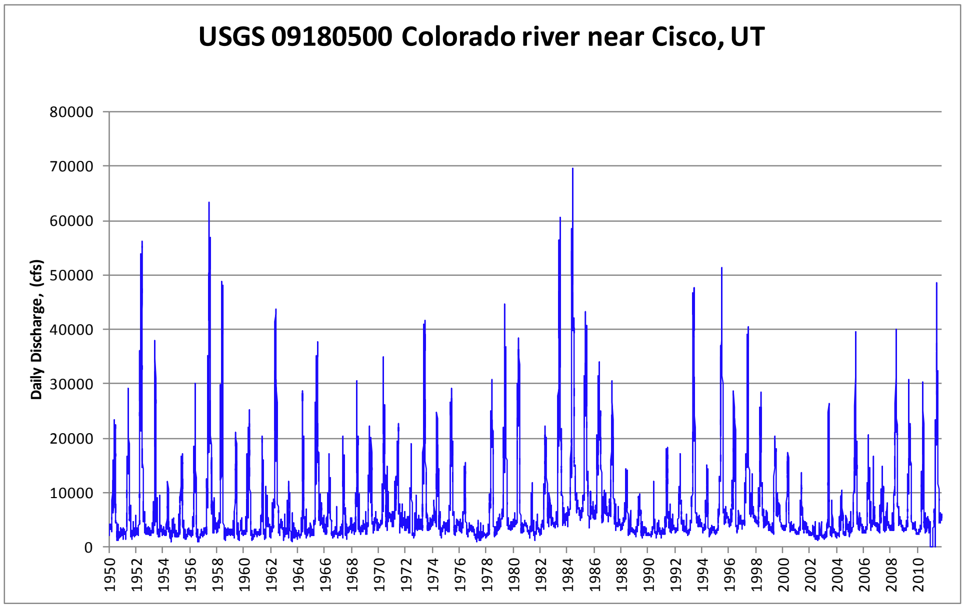

Figure 12 Average peak flows for the Colorado River measured at the Cisco gaging station, through 1950 to 2010.

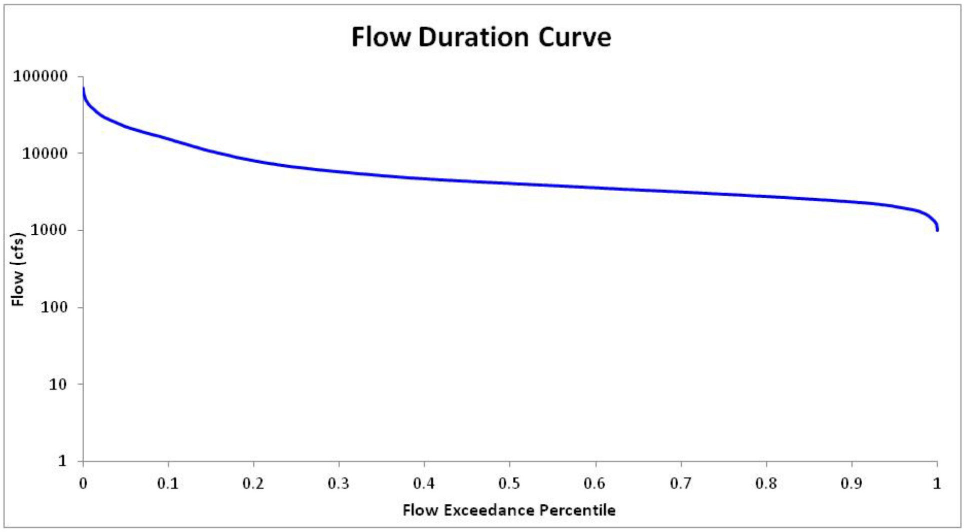

Figure 13 Flow duration curve for Cisco Station No. 09180500.

As the Colorado River crosses the valley it generally curves to the south-southeast toward the downstream portal where it is once again confined and flows toward the southwest. Because of the snowmelt runoff, annual peakflow events in the Colorado River are of long duration and occur during late spring. The base flow is about 3,000-4,000 cfs and the maximum recorded discharge at the Cisco, Utah, gage of 76,800 ft^3/s occurred on June 19, 1917 [**9**].

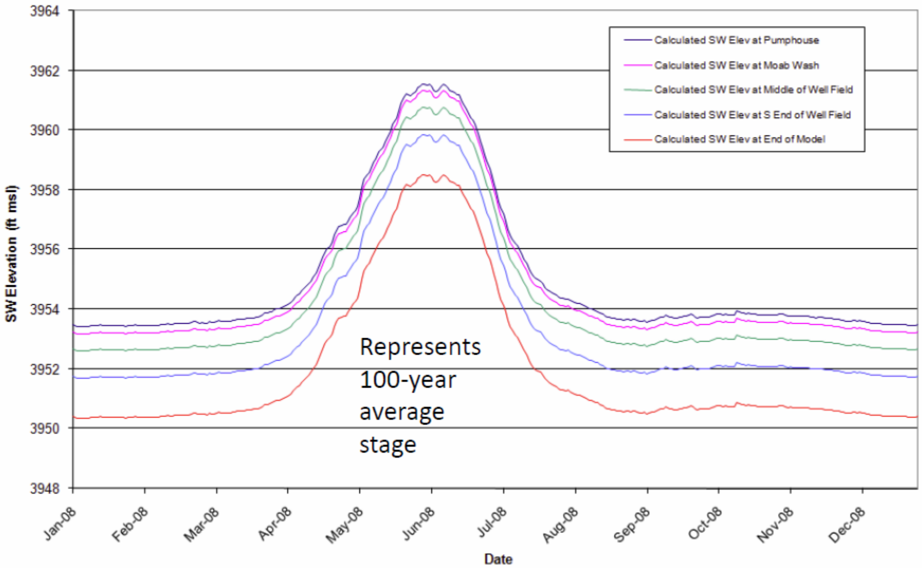

Figure 14 Colorado River stage.

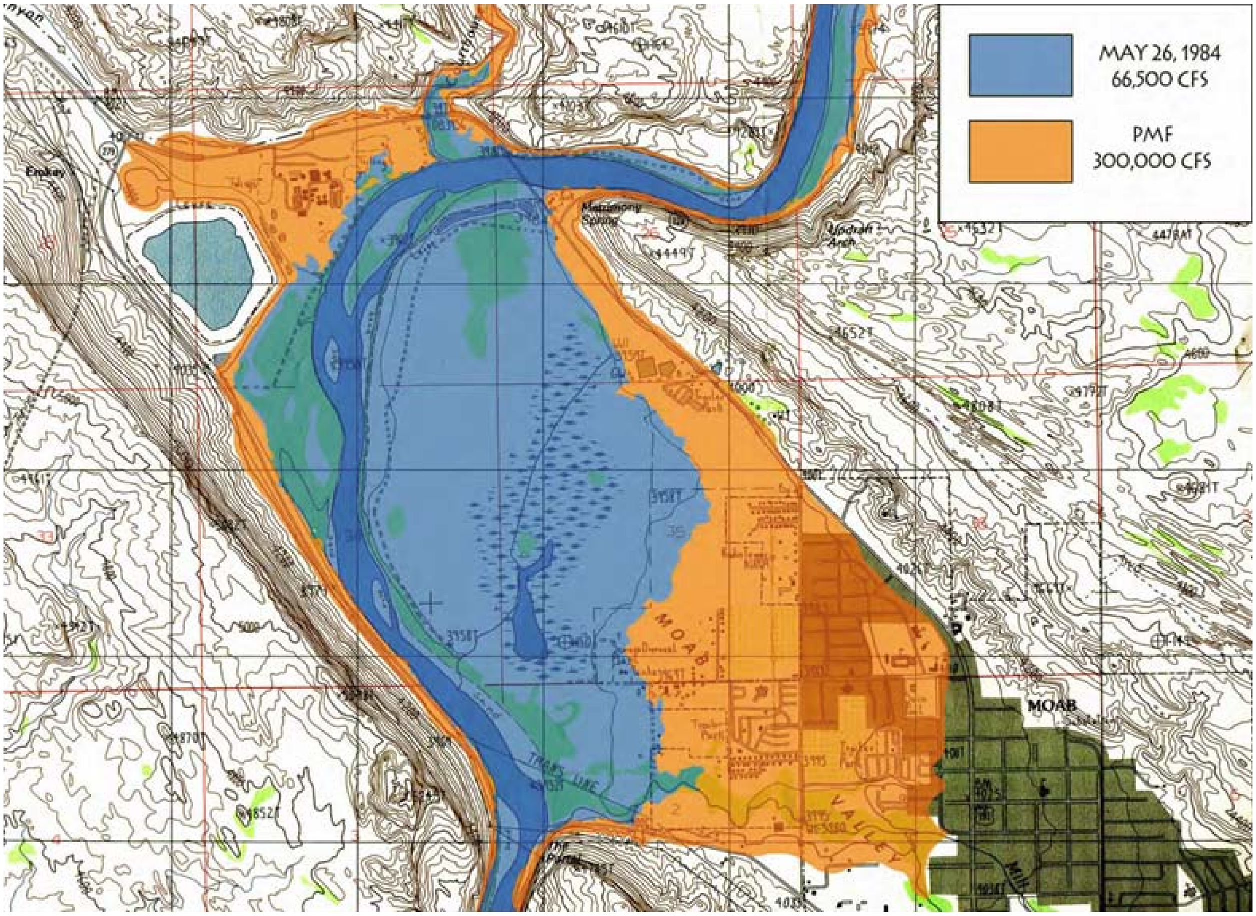

Figure 15 Extent of a 66,500 and 300,000 cfs flood in the Moab Valley [**15**].

During high river stages, surface water inflow may penetrate as much as 200 ft inland from the river bank. The probable maximum flood (PMF) value of the USGS for the Moab Valley is 300,000 cfs [**9**], and the 500-year flood for the Cisco gauging station is 120,000 cfs whereas the 100-year flood is 97,600 cfs. During the highest recorded flood (1984) of 66,500 cfs, the water level was 4 feet above the toe of the tailings pile, and for the PMF, the water level would be 29 feet above the toe of the tailings pile.

2.6 Boundary Conditions

The boundary conditions were the stages of Colorado River (blue color) and flux (red color) at the north and the west boundaries.

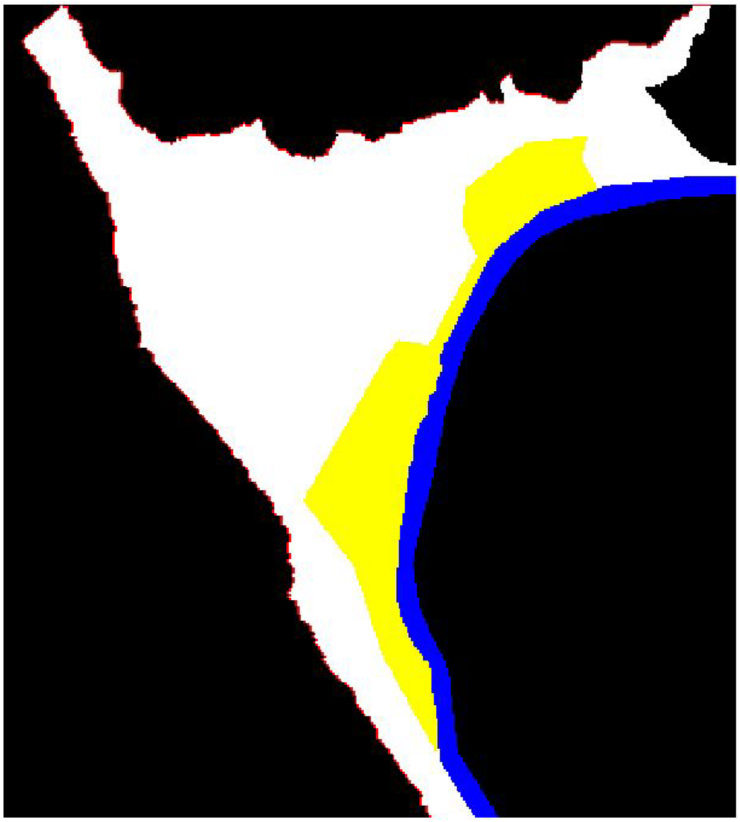

Figure 16 Prescribed head boundary conditions along the Colorado River.

2.6.1 Well Operations

DOE has been operating an interim action to evaluate two scenarios for treating contaminated groundwater and protecting the endangered fish habitat in backwater areas of the river adjacent to the site.

1. The contaminated groundwater was extracted from a series of wells installed in the shallow plume and pumped to an evaporation pond on top of the tailings pile.
2. Water from Colorado River was diverted into a storage pond, where time was allowed settlement of fines, and sediment filtration, the diverted water was injected into a series of wells installed into the alluvial aquifer and/or an infiltration trench.

The well field was installed at the Moab UMTRA site in 2003 with the purpose to reduce the potential environmental impacts from contaminated groundwater in the alluvium discharging to the nearby Colorado River. This system currently consists of CF1 (Configuration 1), CF2, CF3, CF4, CF5, the Baseline Area, and the Infiltration Trench. CF1 consists of 10 groundwater extraction wells installed in 2003, and CF2, CF3, and CF4 were installed in 2004, 2005, and 2006, respectively. Each of these CFs, or groups of wells, consists of 10 remediation wells that are capable of both groundwater extraction and freshwater injection. The Infiltration Trench was installed in 2006 and injects freshwater from the Colorado River.

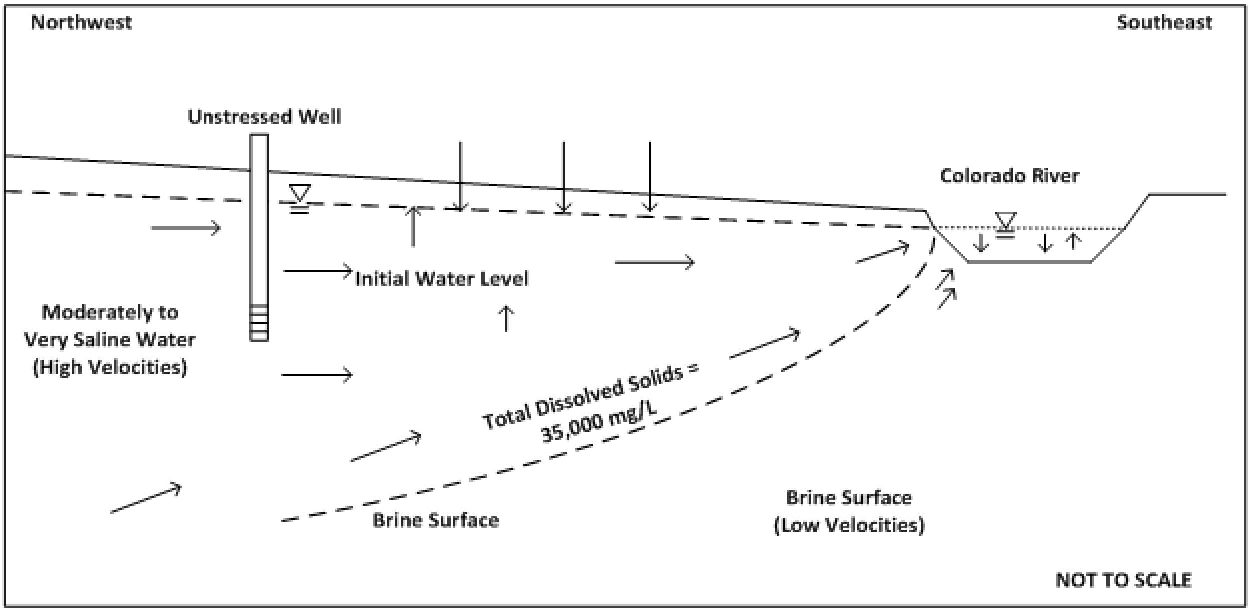

Figure 17 Observed subsurface flow patterns.

Extraction was restarted for 2011 on March 31. Extracted ground water is pumped via pipeline to a lined evaporation pond or to forced air evaporators. The evaporation pond covers approximately 4 acres and is located on top of the tailings pile. Two forced air evaporators operate when weather conditions are conducive to help evaporate the extracted ground water. Wells in Configurations 1 through 4 along the river are used for injection of freshwater (diverted river water) as an additional way of minimizing the discharge of ammonia to the Colorado River. Freshwater injection through wells in Configuration 4 was restarted for 2011 in early March. As the river level rises associated with spring snowmelt, the benefit of injecting additional water is reduced. Therefore, injection was suspended on May 9 due to the level of the river and remains shut down. About 4,420,000 million gallons of freshwater has been injected during 2011.

All extracted groundwater is pumped to the evaporation pond located on the top of the tailings pile. The water is then distributed by a sprinkler system that covers 38 acres of the pile and is equipped with spray heads that enhance evaporation of the water. The distribution of the water provides dust suppression on the top of the pile.

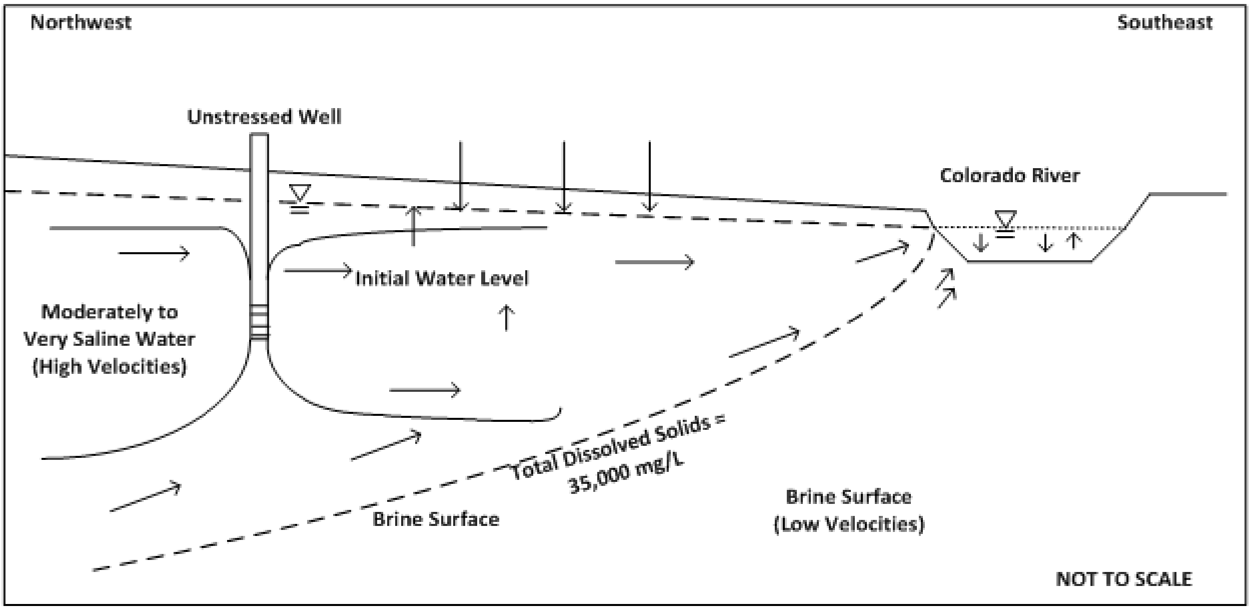

Figure 18 General effects of operating remediation wells for the purpose of contaminant mass removal.

Water quality and well pumping data were collected from 2003 through January 2009 and were analyzed to determine which wells have been efficient at groundwater extraction and under what river stage they remove the most contaminant mass.

The primary purpose of operating any of the well-field configurations in extraction mode is to intercept ammonia in high-concentration areas, thereby reducing mass loading to the river. Results of system operation and monitoring indicate that extraction can pull river water into the aquifer and reverse the groundwater flow gradient, at least locally. Figure 18 shows this reversal conceptually. This reversal should result in reduced discharge of ammonia to near-shore areas. However, it is not clear how groundwater extraction affects the brine surface below the river and locations of ammonia discharge to the river.

The purpose of operating Configurations 2, 3, or 4 in injection mode is to determine the feasibility of and capacity for diluting ammonia concentrations in the backwater habitat via injection of fresh water into the aquifer close to the Colorado River. A conceptual depiction of the effects of operating remediation wells for fresh-water injection is shown in Figure 19. Mounding of fresh water at the injection well(s) helps provide a hydraulic barrier between the ammonia plume and the river near its western shore. At this time, the purpose of the infiltration trench is to obtain operational performance data regarding flow rates and associated groundwater mounding.

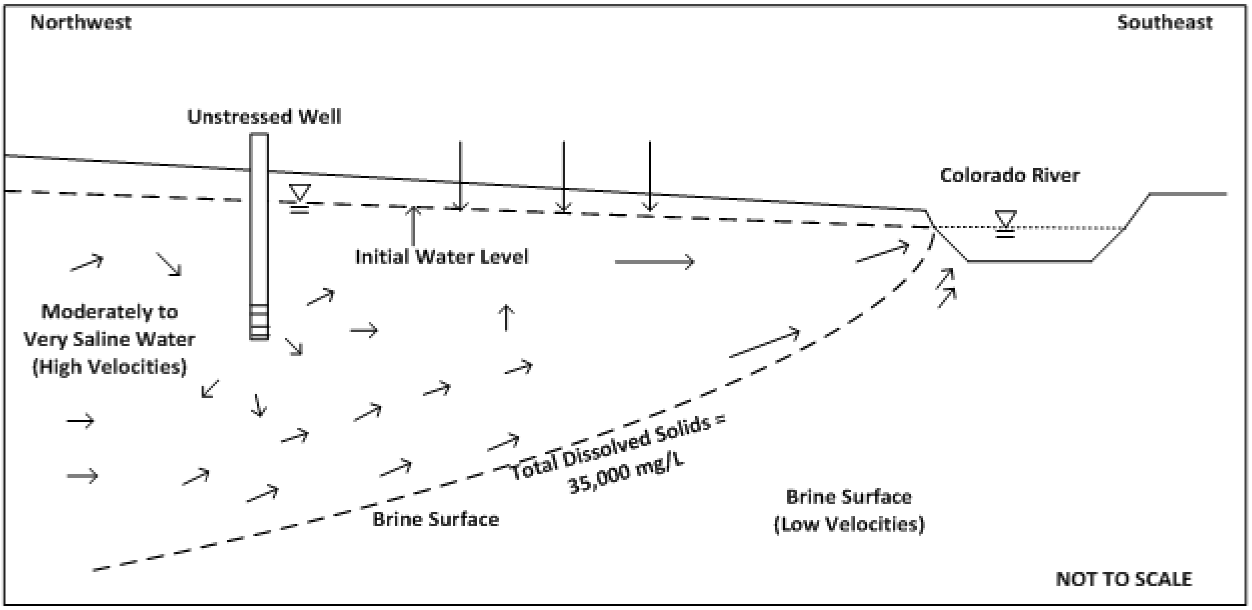

Figure 19 General effects of fresh water injection via remediation wells.

Freshwater injection through wells in Configuration 4 was restarted for 2011 in early March. As the river level rises associated with spring snowmelt, the benefit of injecting additional water is reduced. Therefore, injection was suspended on May 9 due to the level of the river and remains shut down. About 4,420,000 million gallons of freshwater was injected during 2011.

2.6.2 Prescribed Heads

A water table map of the region indicates that groundwater underlying both the site and the Matheson Wetlands flows towards and discharges into the Colorado River (Figure 20). Groundwater under the site flows southeast and discharges along the river's western bank.

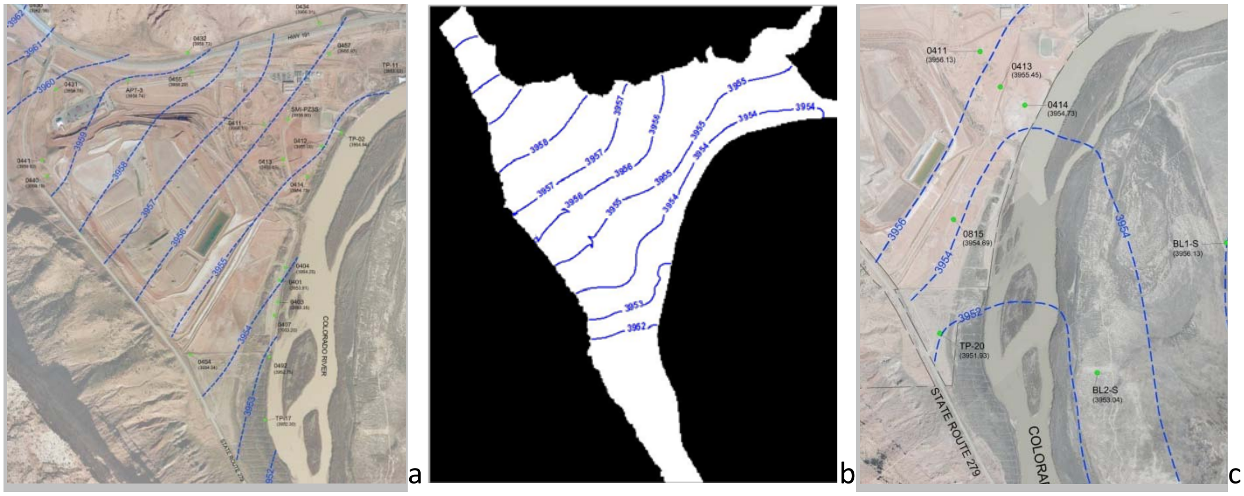

Figure 20 a) observed groundwater levels in October 2010 [GCAP] b) Initial water table used for model runs, c) groundwater levels in Matheson Wetlands in April 2010 [GCAP]

2.6.3 Recharge

The model was configured with two different recharge zones, ambient precipitation (Table 3) and the tailings pile (Table 4). While it is assumed recharge from the tailings pile was constant throughout the year, recharge from precipitation was assumed to vary monthly. Evapotranspiration was assigned to areas of the site having significant plant density and was assumed to vary monthly. The Colorado River was simulated using river cells which can contribute or receive water from the aquifer depending on the river stage and the adjacent groundwater relationship. For the simulation, the Colorado River was assigned monthly stage values corresponding to the average monthly river stage.

According to GCAP, geotechnical and geochemical studies of the tailings pile suggest that dewatering of the pile would decrease seepage rates to ground water and would be required before final cap placement. A vacuum-assisted wick drainage system was recommended for the dewatering option and approximately 17,000 wick drains were installed. The vacuum manifold was never implemented and the wick pond and wick drains were removed in 2010 with the tailings.

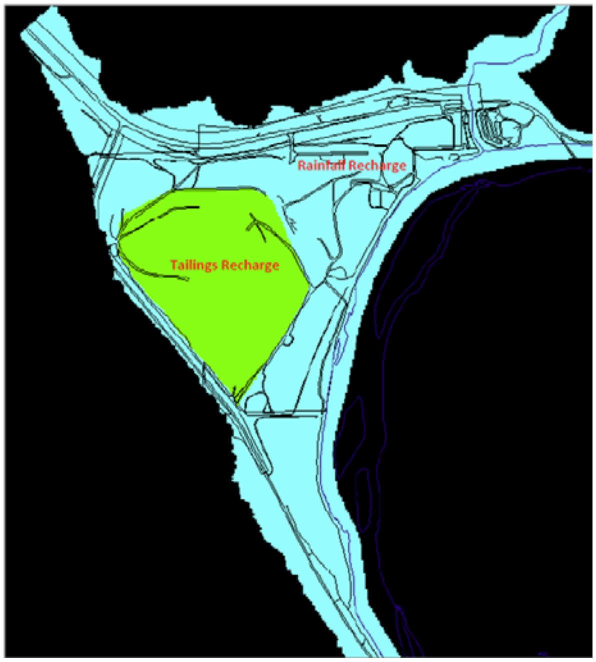

Figure 21 Recharge distribution in the model

Table 3 Rainfall Recharge

Parameter	Value
Area of model domain available for rainfall recharge	451 acres
Mass balance volumetric estimate: 16 gpm to 65 gpm	3,080 ft^3 to 12,513 ft^3
Mass balance estimate rainfall recharge rate	1.55×10^{-4} ft/d to 6.37×10^{-4} ft/d; 0.69 in/yr to 2.79 in/yr
Thornthwaite method recharge rate estimate	1.87 in/yr to 1.97 in/yr

Table 4 Tailings Pile Recharge

Parameter	Value
Area of model domain available for tailings pile recharge	5,831,250 ft^2
Mass balance volumetric estimate	20 gpm; 3,850 ft^3
Mass balance estimate tailings pile recharge rate	6.60×10^{-4} ft/d; 2.89 in/yr

2.7 Groundwater flow and water budget

Groundwater aquifers in the Moab region occur in the unconsolidated Quaternary material deposited on the floor of Moab and Spanish Valleys and in consolidated bedrock formations. The upper groundwater system consists of the unconsolidated and bedrock formations above the very low permeability salt beds of the Paradox Formation. The lower groundwater system includes all stratigraphic units below the Paradox Formation. The salt beds of the Paradox Formation confine units in the regional lower system and occur over most of Moab and Spanish valleys. The Paradox Formation also underlies the Moab site.

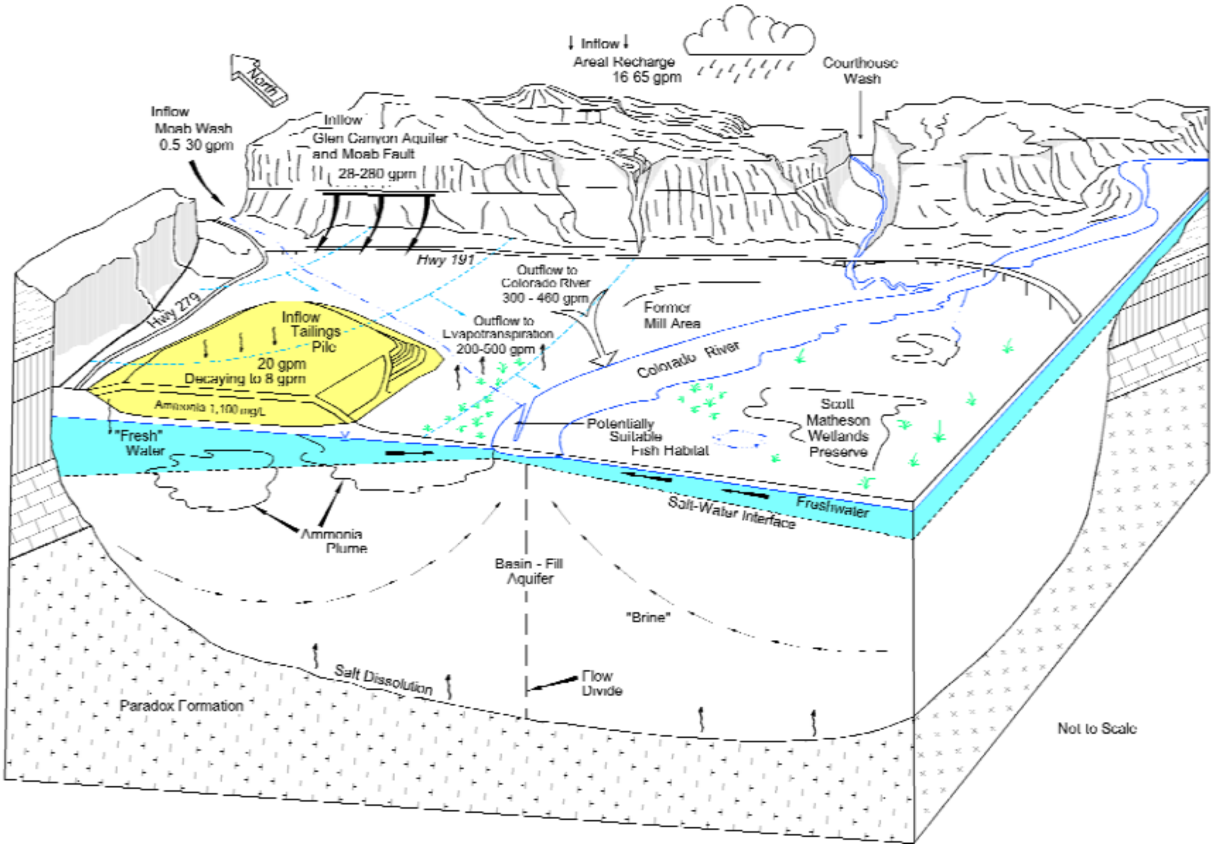

Figure 22 Site conceptual plan [28]

Groundwater flows from the entrance of Moab Canyon towards the Colorado River; however during high river stages, surface water inflow may penetrate as much as 200 ft inland from the river bank. Inflows and outflows for an estimated water budget for the Moab Site are presented in Table 5, Table 6 and Table 7.

The analysis of the model results was based on the conceptual model developed in [28]. All simulations were analyzed using a common set of data related to the site conceptual model and listed Table 5, Table 6 and Table 7.

Table 5 Minimum Water Inflows and Outflows for Moab Site

COMPONENT	In [gpm]	Out [gpm]
Areal Recharge	16	
Moab Wash	0.5	
Bedrock Aquifers	28	
Tailings Pile	20	
Evapotranspiration		208
Colorado River		300
TOTAL	64.5	508

These tables indicate that most of the fresh water in the alluvial aquifer enters the site upgradient along geologic contacts between the alluvium and the Glen Canyon Group and Entrada Sandstone bedrock aquifers, which are present beneath the northwestern and northern portions of the site. None of the bedrock aquifer inflow is attributed to flows through the Paradox Formation, since this formation is of very low permeability. Short-term transient effects such as the small contribution to bank storage via losses from the Colorado River during periods of high flow are not reflected in . Not accounting for this in the water balance partially explains why estimated minimum and maximum total inflows to the site are less than comparable estimated total outflows.

Table 6 Maximum Water Inflows and Outflows for Moab Site

COMPONENT	In [gpm]	Out [gpm]
Areal Recharge	65	
Moab Wash	33	
Bedrock Aquifers	280	
Tailings Pile	20	
Evapotranspiration		504
Colorado River		460
TOTAL	398	964

Though this disparity tends to reflect the considerable uncertainty in estimated water budget components, total flows listed in Table 7 suggest that the rate of water moving through the ground water system during an average year could lie somewhere between the maximum total inflow of 400 gpm and the minimum estimated total outflow of 500 gpm. Previous studies assumed that an average of 450 gpm passes through the Moab site groundwater system.

Table 7 Average Water Inflows and Outflows for the Moab Site

COMPONENT	In [gpm]	Out [gpm]
Areal Recharge	40.5	
Moab Wash	16.75	
Bedrock Aquifers	154	
Tailings Pile	20	
Evapotranspiration		356
Colorado River		380
TOTAL	231.25	736

A 1998 surface water study sampled the Colorado River along transects at distances of 10 ft, 25 ft, and 50 ft from shore.

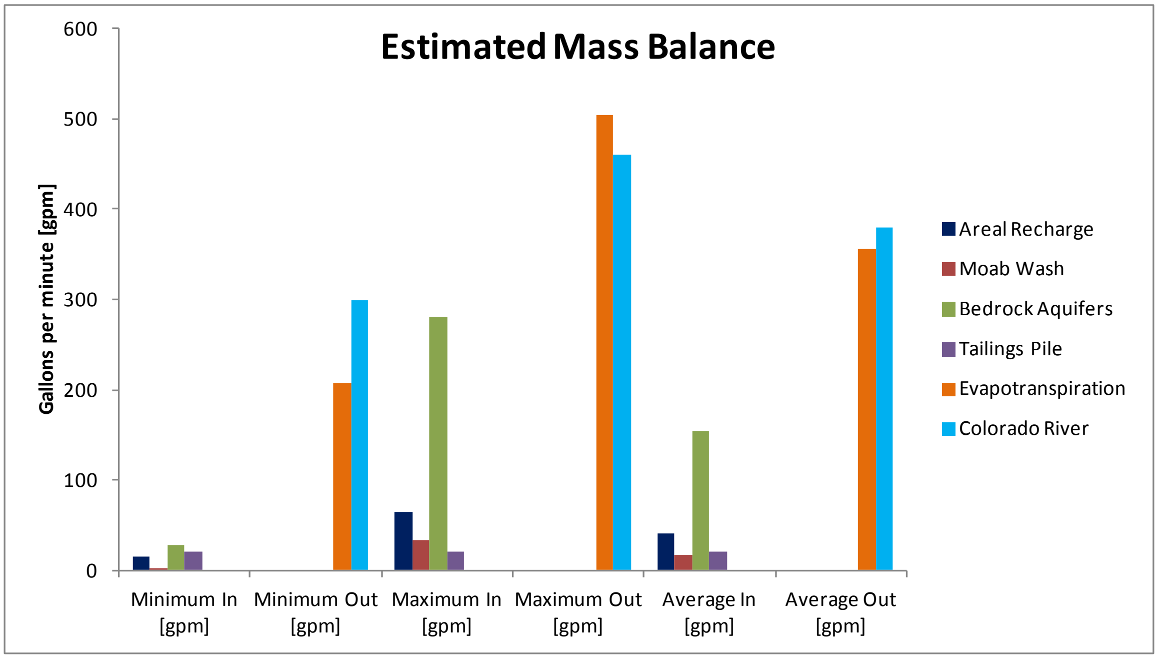

Figure 23 Estimated water balance

Samples were collected from three depths at each location. Ground water samples were also collected from three wells immediately adjacent to the river. The samples were analyzed for ammonia, molybdenum, and uranium and it was determined that water discharging to the river appeared to be diluted by factors ranging from 300 to almost 800.

Ground water at the Moab site discharges to the river during most of the year. Under baseflow conditions (river flows ranging from 3,000 to 4,000 cfs) the alluvial aquifer discharges to the Colorado River. Flow reversal, with the river recharging water to the alluvium and adding to bank storage, typically occurs between the beginning of April and until June. The flow reversal begins once river discharge reaches 10,000 cfs. Following the high runoff season, flow from the aquifer to the river resumes and persists during the rest of the calendar year.

The surface water flow in the Colorado River strongly affects ground water elevations and contaminant concentrations in the well field. During peak spring runoff flows of Colorado River with flows above 10,000 cfs, a lens of freshwater migrates into the well field ground water system. The freshwater lens is more prominent on the southern end of the well field, because of the channel adjacent to the river bank. Well data during five stages of the river (for discharges ranging from baseflow to 29,500 cfs) showed that the freshwater lens migrated into the well field when the water flow was above 12,000 cfs and increased vertically and horizontally during peak flow of 29,500 cfs and receded back once the flow decreased to 4,710 cfs.

2.8 Groundwater contaminants

Ground water at the Moab site was contaminated by the former Atlas Uranium Mill uranium ore-processing operations from 1956 through 1984. Site-specific field investigations reveal the alluvial ground water is affected by the former milling operations. No VOCs, Semi VOCs and pesticides in groundwater were detected, however, the maximum concentrations for arsenic, cadmium, uranium, radium, gross alpha, nitrate, selenium, and molybdenum exceed their respective EPA ground water standards in 40 CFR 192.

Ammonia is the most prevalent contaminant in site ground water, and is a constituent of ecological concern in ground water discharging to the Colorado River in backwater areas adjacent to the site. Sampling of surface water at the site indicates that of the hazardous constituents in limited use groundwater that discharges to surface water, ammonia is the only constituent with the potential to adversely affect endangered species in riparian habitat areas along the Colorado River.

The SOWP has determined that ammonia concentrations of 3 to 6 mg/L in groundwater are protective of fish in the adjacent habitat areas considering a dilution factor of approximately 1000 in surface water (DOE 2003).

An additional study at the Moab site by SMI (2001) examined the potential for relatively low-TDS river water to recharge the alluvium and subsequently return water containing high ammonia levels to the river. Extensive monitoring during this investigation found no evidence of increased ammonia concentrations in either ground water or elevated concentrations in the Colorado River.

The groundwater plumes have migrated considerably within the site domain, and previous studies of ground water/surface water interaction concluded that removal of tailings would have no discernible impact on the loading of constituents to the river through groundwater discharge, and that active ground water remediation would be required for 35 to 50 years to decrease ground water contaminant concentrations to levels that are protective of aquatic life in the river.

It was estimated that ammonia loading to the river in backwater areas at a rate of about 10 pounds per day or less would be protective of aquatic species. Different ground water cleanup methods were evaluated, including typical “pump-and-treat” systems and more passive barrier systems. It was concluded that the fastest restoration could be achieved by installing extraction wells to pump ground water from the aquifer (treatment of extracted groundwater would follow); this alternative was also the most expensive of those considered.

3 SIMULATIONS

The model was calibrated to 2006 water level measurements collected from 44 different wells. Typically multiple water-level measurements were available for the wells. In addition to water-level elevations, the model was calibrated to estimated fluxes for Moab Wash and the surrounding bedrock, the Colorado River during base flow conditions, and evapotranspiration.

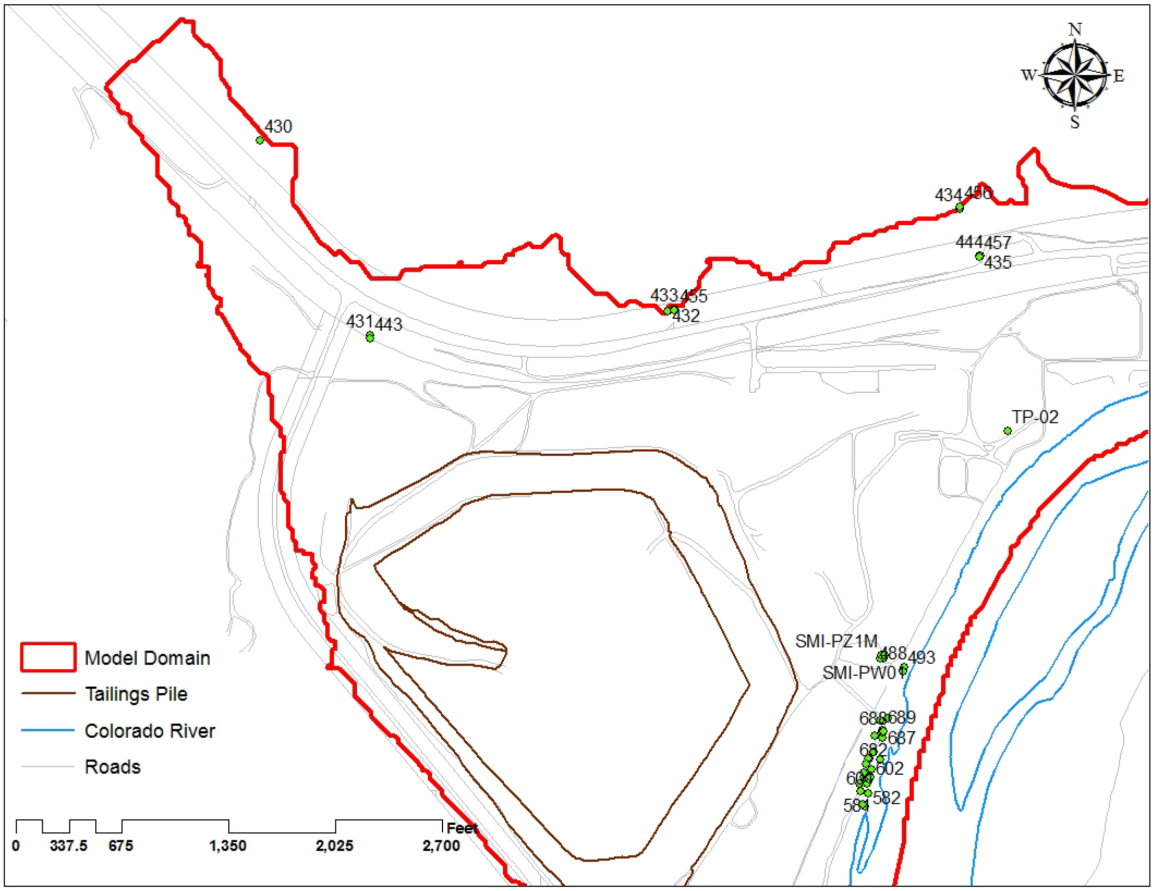

Figure 24 Target points used for model calibration.

A calibration target is a point in space and time where one of the model dependent variables has been measured. Calibration targets (Figure 24) provide a means of assessing calibration quality because an error term, called a residual, is computed for each target location. A residual is computed as the field measurement minus the model-computed value. The range of errors provides information about the quality of the calibration.

The model was configured with two different recharge zones, ambient precipitation and the tailings pile. While it is assumed recharge from the tailings pile was constant throughout the year, recharge from precipitation was assumed to vary monthly. Evapotranspiration was assigned to areas of the site having significant plant density and was assumed to vary monthly. The Colorado River was simulated using river cells which can contribute or receive water from the aquifer depending on the river stage and the adjacent groundwater relationship. For the simulation the Colorado River was assigned monthly stage values corresponding to the average monthly river stage.

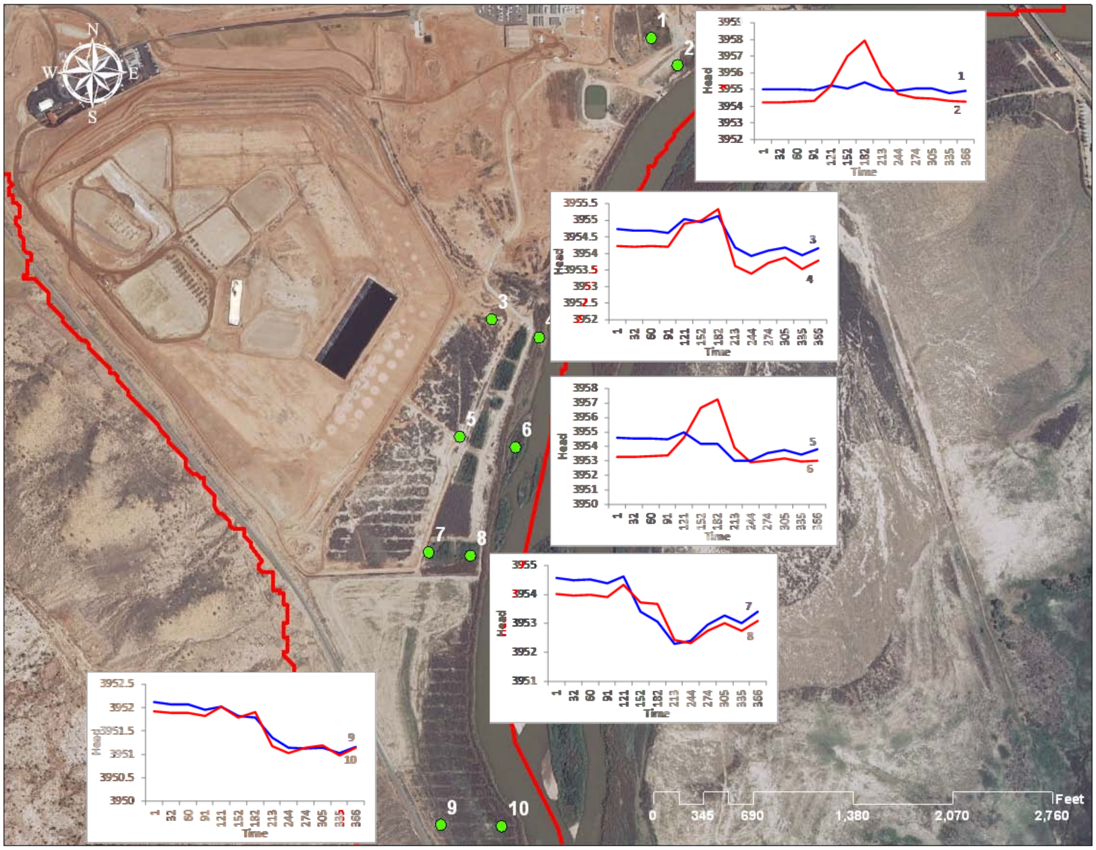

Figure 25 Points selected for showing relationship of stage data.

The following graphs show the relationship of stage data obtained from the simulation results for ten points close to the Colorado River [Figure 25]. For all simulations the data was extracted to determine the effect of remediation scenarios on stages along the river.

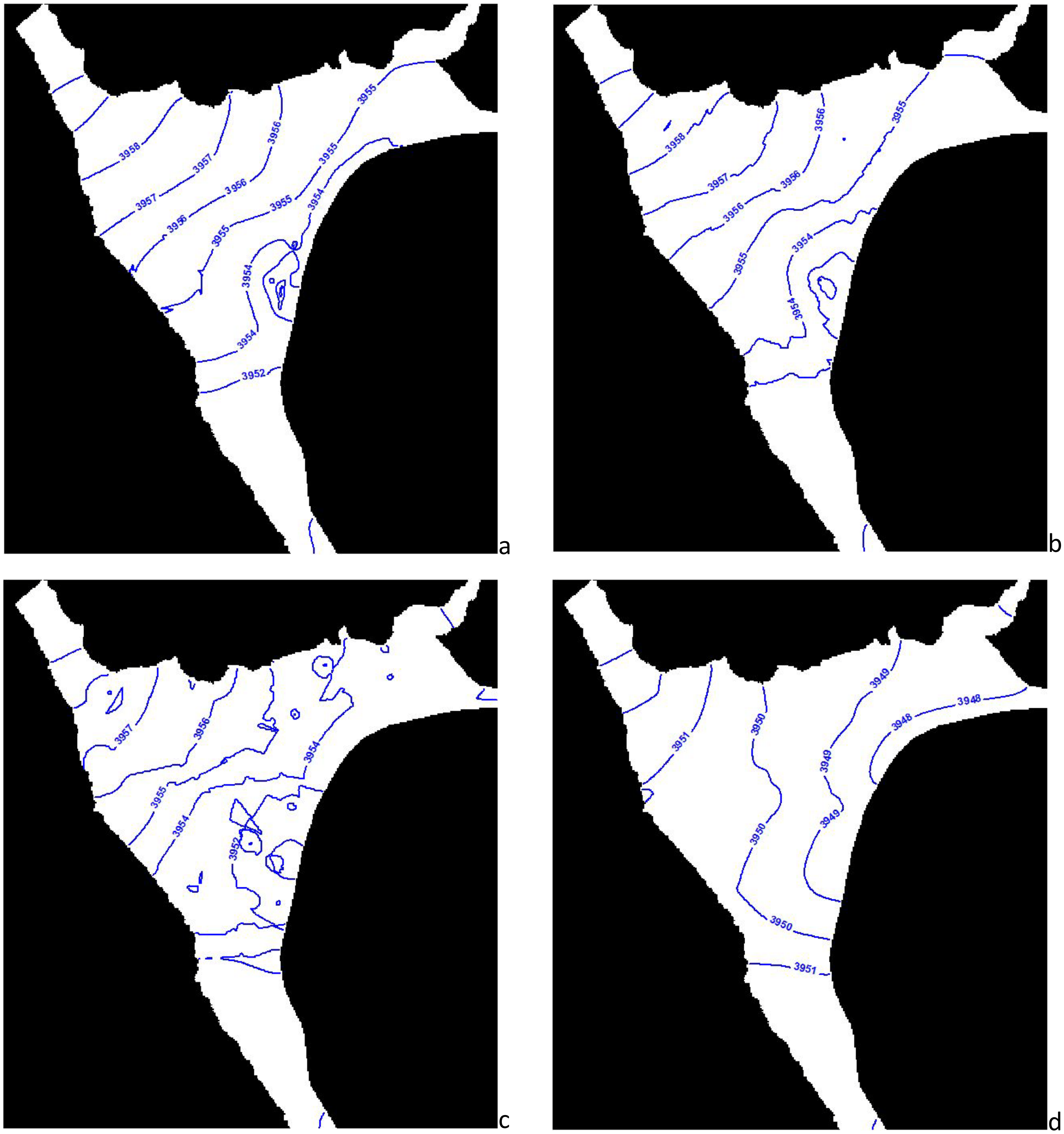

Figure 26 Groundwater contours a) Layer 1, b) Layer 5, c) Layer 10 and d) Layer 15

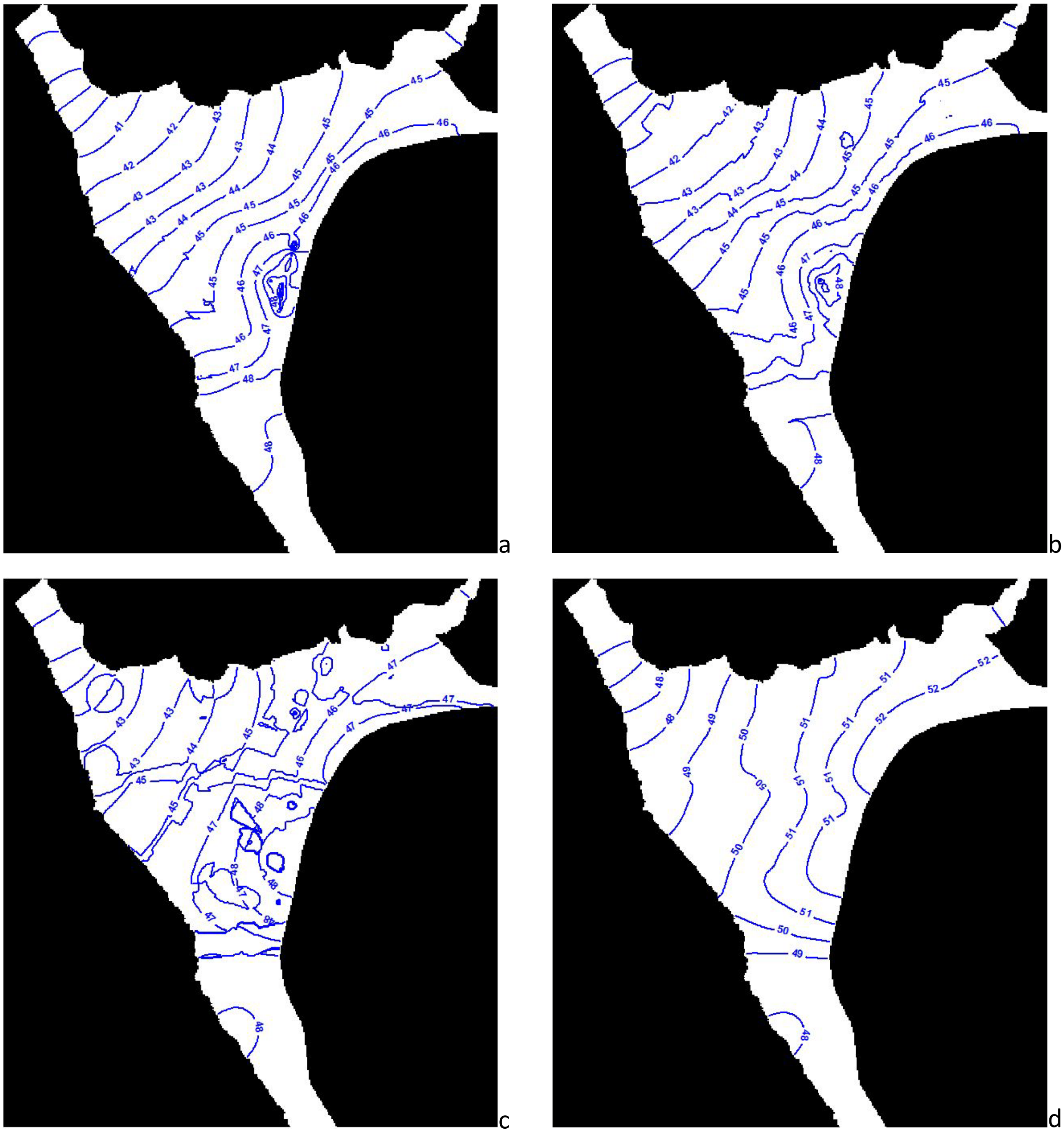

Figure 27 TDS a) Layer 1, b) Layer 5, c) Layer 10 and d) Layer 15

The model was reconfigured by adding injection and withdrawal wells and modifying the configuration of the wells. A diversion ditch was added to intercept and extract water from the tailings.

Additional simulations were developed to determine parameters of flow and transport of contaminants according to the current remedial actions. The following simulations were developed and preliminary data from these simulations is provided in this section.

Table 8 List of simulations developed for the model

Identifier	Objective of simulation	Total Simulations
A01	Updated Model	1
BP01	Simulate movement of U and Nitrogen (Ammonia and Nitrate) and TDS	1
BP02	Simulate effect of brine zone	1
BP03	Simulate mobility of ammonia plume	1
CC01	Implementation of new well configuration	1
CC02	Implementation of diversion ditch	1
CC03	Effectiveness of both systems	1
DM01	Optimization of mass removal with existing system	1
DM02	Optimization of mass removal with injection	1

The existing model was revised and updated with additional information related to the current remedial actions which include injection and withdrawal well.

3.1 Development of Uranium, Nitrogen (Ammonia and Nitrate) and Total Dissolved Solid concentrations

The concentrations of Uranium, Nitrogen (as Ammonia and Nitrate) and Total Dissolved Solids (TDS) were developed and added to the model in order to provide the initial conditions of the model. Figure 28 shows the wells that were included for interpolation of the plumes.

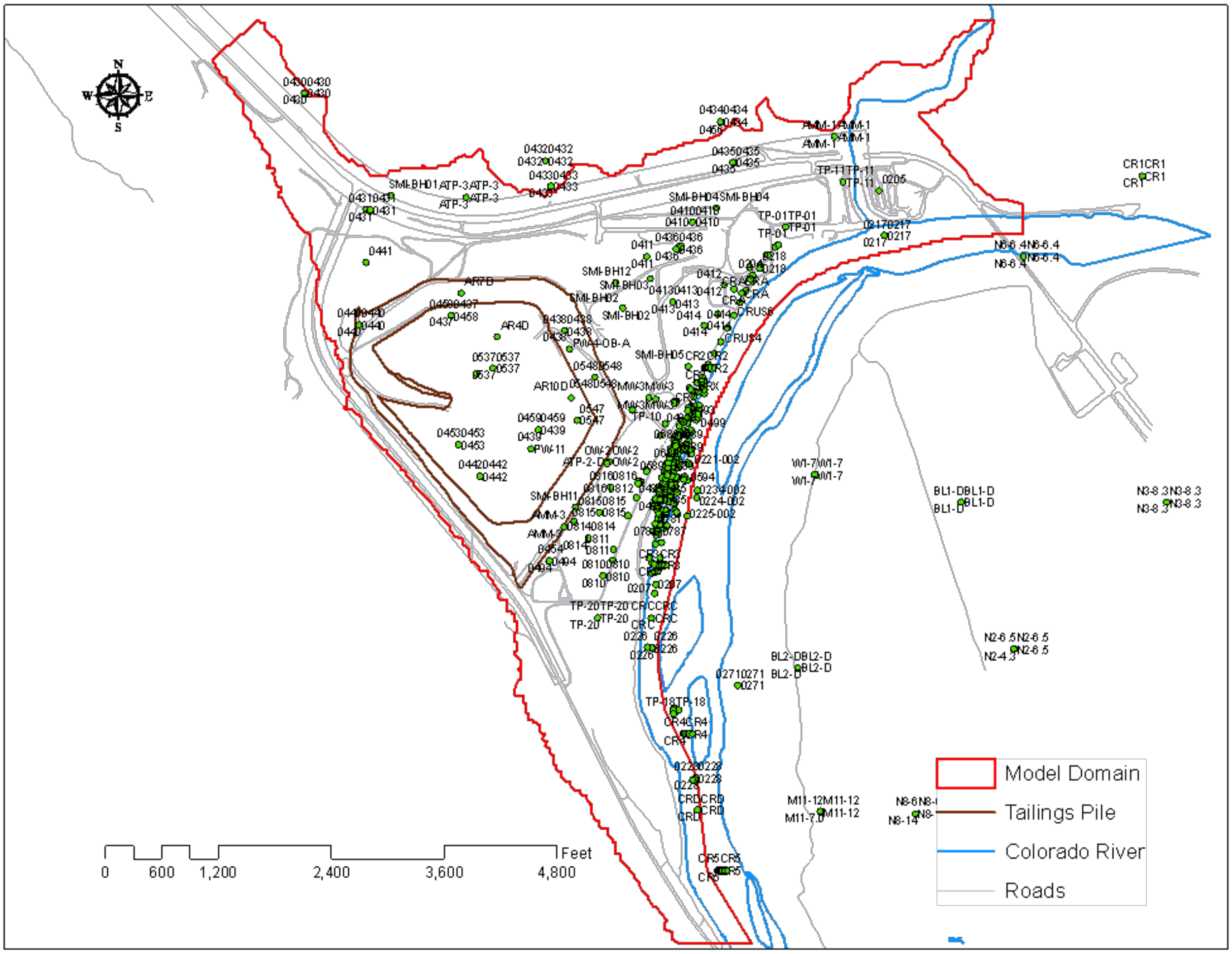

Figure 28 Water quality monitoring wells.

3.1.1 Nitrogen groundwater concentrations

Sampling results showed that a mixing zone for ammonia (exceeding Utah state standards) extended approximately 4,000 ft downstream of the site and 25 ft transversely into the channel; the uranium mixing zone extended 12,000 ft downstream and 50 ft into the river.

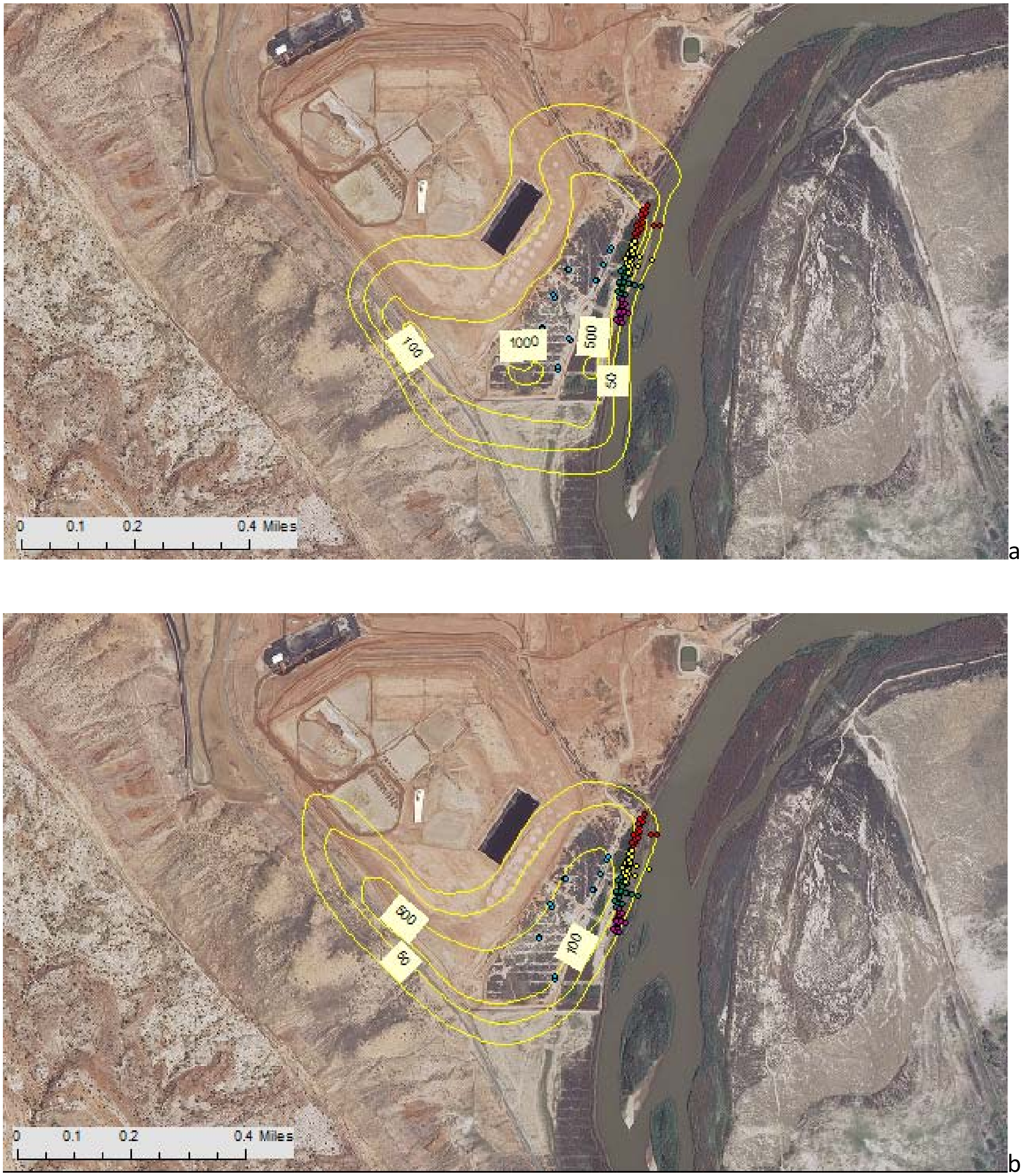

Figure 29 Ammonia (total as N) Concentrations Interpolated on the Upper Surface of the Ground Water a) June 2003 and b) October 2010

Results indicated that uranium and molybdenum concentrations in the river were elevated above ambient levels, but that maximum concentrations were below lowest chronic exposure benchmarks for aquatic life.

The existing Moab model was updated by implementing geostatistically interpolated ammonia and uranium plumes and current well operation data into the model to evaluate the effects of pumping on contaminant concentrations and determining potential surface water concentrations in riparian habitat areas for a range of operating conditions. Figure 28 shows the ammonia monitoring wells that were used for analysis of the ammonia plume.

The GCAP document addressed ammonia due to its potential risk to fish in aquatic habitats. Ammonia concentrations in groundwater were interpolated at the water table and at 50 and 150 ft below the water table. The 50 and 150 ft depths are below the brine interface. Ammonia concentrations at the water table concentrations are also mapped for from 2010 sampling results in future 2010 and are similar to those form 2003. The deeper concentration maps are from historical data from sampling points that have been recently been abandoned due to tailings removal. .

Ammonia concentrations greater than 50 mg/L, were interpolated and contoured on the upper surface of the ground water in Figure 29. The highest concentrations in the shallow ground water, greater than 500 mg/L, were observed near the downgradient edge of the toe of the tailings pile and extend to the Colorado River. The ammonia concentrations in the shallow ground water in this area of the site was attributed to seepage from the former toe drains which were also referred to as the north sump and the south sump as shown on Figure 4.

The spatial extend of ammonia at 50 ft below the surface of the ground water was generated and shown on Figure 30. The maximum ammonia concentration of 4,600 mg/L was detected in a grab sample at monitor well SMI-PZ2M2 (February 2002) at approximately 45 ft below the surface of the ground water. Monitor well SMI-PZ2M2 is located between the toe of the tailings pile and the Colorado River. At the 50-ft depth, an ammonia plume having concentrations greater than 50 mg/L is also present in the former mill site area.

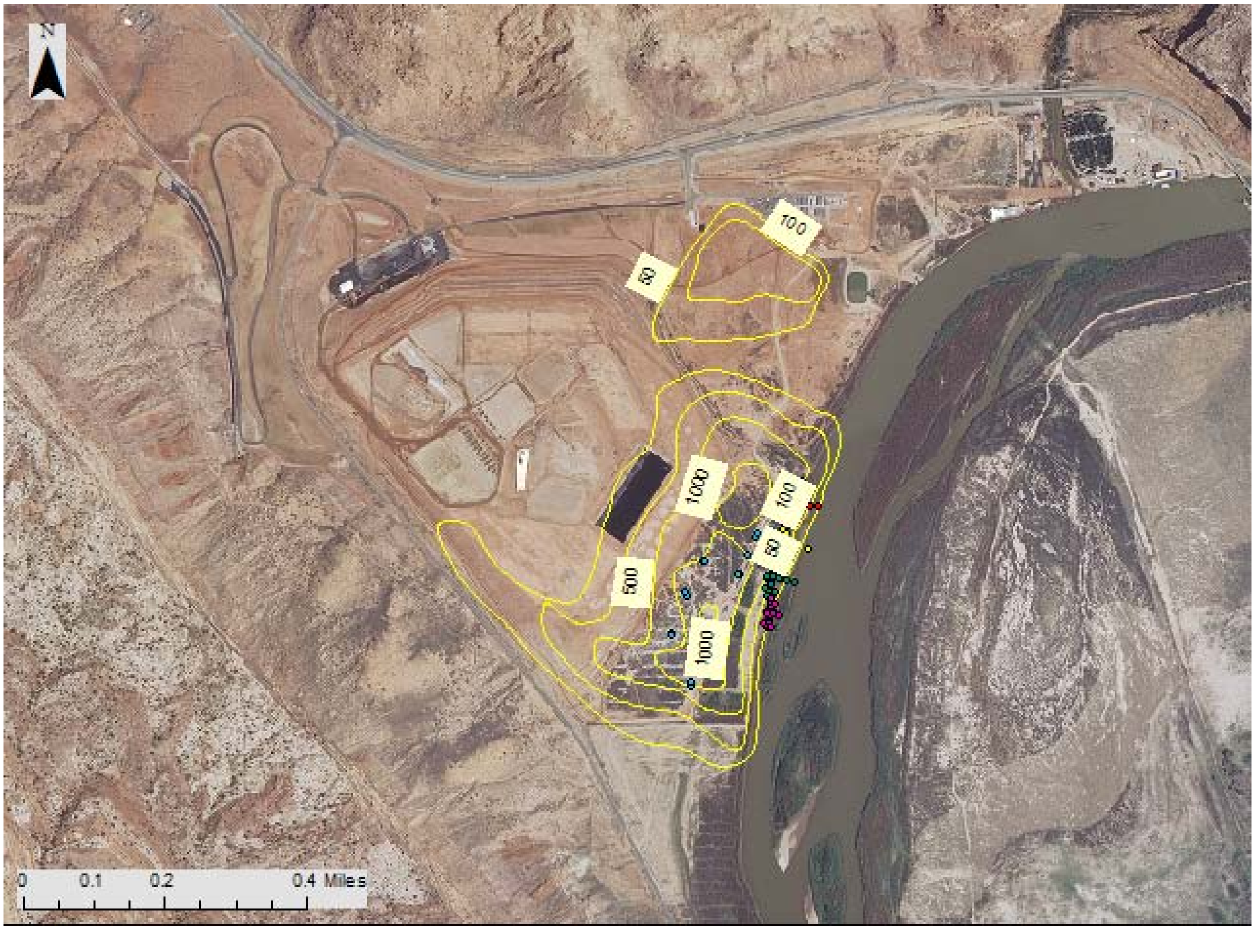

Figure 30 Ammonia (total as N) Concentrations Interpolated at 50 ft Below the Surface of the Ground Water

At 150 ft below the surface of the ground water the ammonia concentrations greater than 50 mg/l were not present in the former mill site area (Figure 31). Ammonia concentrations in general decrease at the toe of the pile, however, increase beneath the center of the tailings pile, indicating the presence of a deeper ammonia plume.

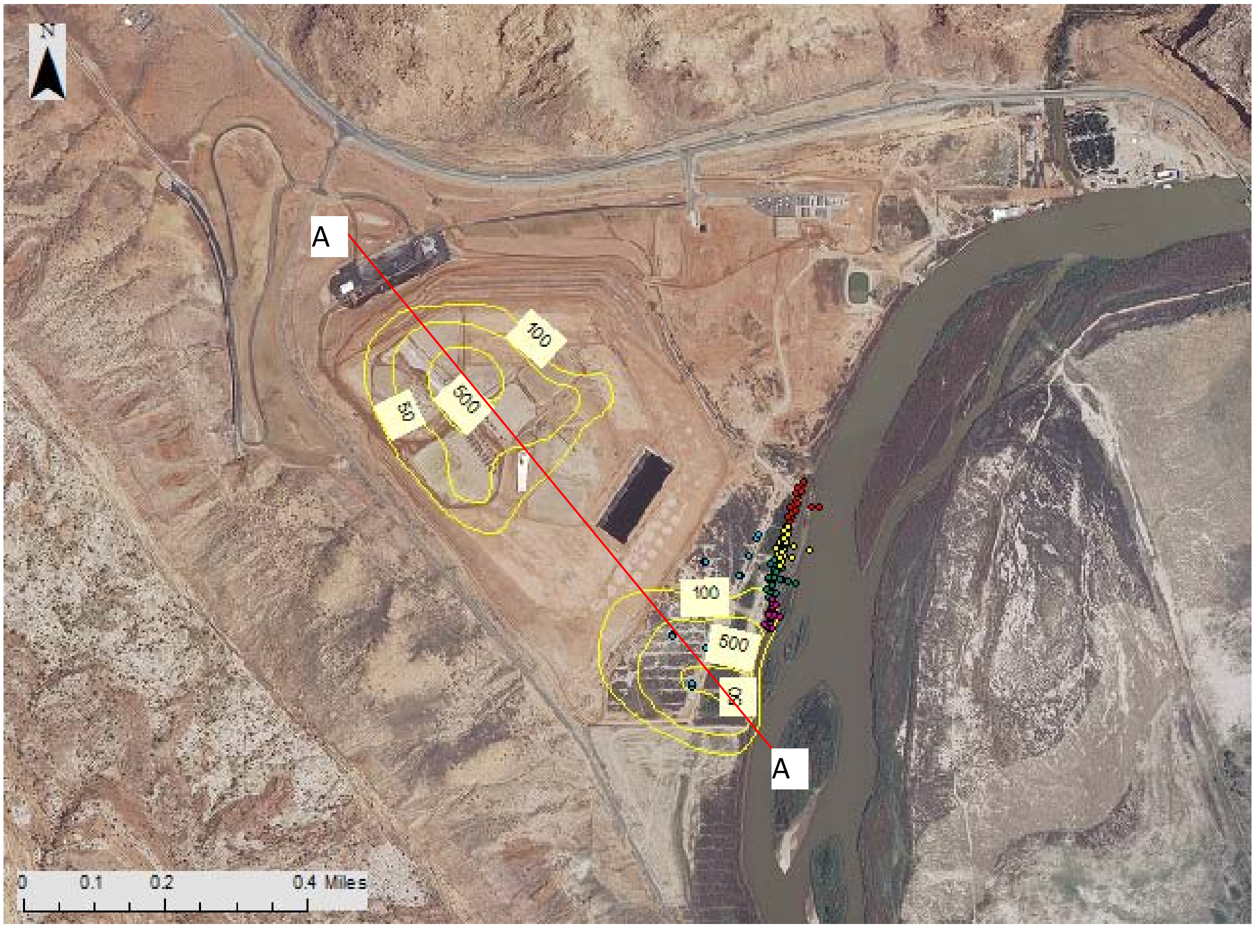

Figure 31 Ammonia (total as N) Concentrations Interpolated at 150 ft Below the Surface of the Ground Water (Section A-A is on the next figure)

This deeper plume extends approximately 200 ft below the surface of the ground water

3.1.2 Uranium plume

Observed concentrations of uranium in shallow water were interpolated and shown on Figure 32. The elevated concentrations of uranium in groundwater adjacent to the mill site is related to milling activities. All of the off pile soil sources have been remediated to the UMTRA Standards.

Figure 32 October 2010 Location of Uranium Plume in Shallow Ground Water

Table 9 Uranium Concentrations for Years 2010 and 2011 (GCAP)

Location	Depth	Apr-10	Oct-10	May-11	November 2011
410	25	0.3	1.1	0.9	1
411	9	5.6	3.9	6.1	8.1
412	11	4.1	4.1	3.2	1.7
413	11	1.4	1.1	1.3	NA
414	7	5.7	4.9	4.9	NA
SMI-MW01	16	5.9	5.6	NA	5.1
SMI-PZ3S	25	1.2	1.8	1.1	1.4

Recent investigation of the uranium plume at the northwestern section of the site showed more detailed information about the concentrations in that area [27], Figure 33. Additional soil samples were collected and the data from soil and dissolved uranium is currently being analyzed to estimate the Kd values of uranium.

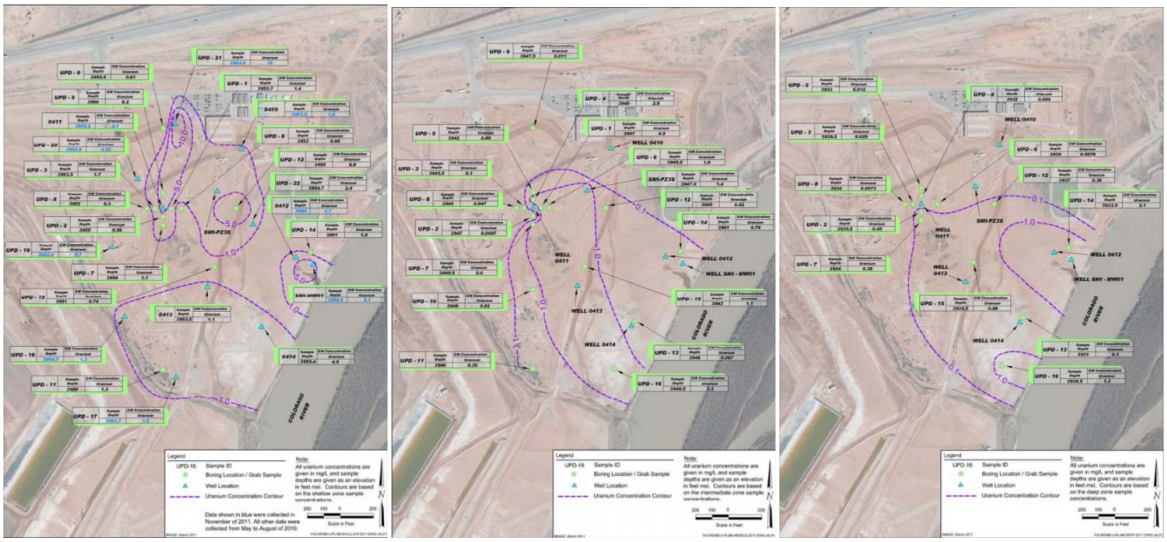

Figure 33 Location of Uranium Plume in shallow, intermediate and deep groundwater zones [27]

3.1.3 Total Dissolved Solids

Data was collected from 27 different locations at depths ranging from 9 ft to 212 ft below ground surface. In general, TDS increases with depth and TDS increases north to south across the site. Total dissolved solids (TDS) concentrations in the alluvial groundwater vary naturally from those for slightly saline water (TDS = 1 to 3kg/m^3 [1000 to 3000mg/l]), to those categorized as moderately saline (TDS = 3 to 10 kg/m^3), very saline (TDS = 10 to 35 kg/m^3), and briny (TDS > 35kg/m^3) (McCutcheon et al. 1993).

Fresh water enters the site from Moab Wash and along geologic contacts between the alluvium and the Glen Canyon Group at the northern boundary of the site where the Moab Fault has highly fractured these bedrock units. The ground water flows from the northern boundary flows toward the river in a southerly direction over the top of a deeper, natural brine zone. The deeper brine water results mostly from dissolution of the underlying salt beds of the Paradox Formation present beneath most of the site. The Chinle and Moenkopi Formations near the northern boundary of the site additionally contribute saline water to the basin-fill alluvium. Background water quality that is highly stratified both vertically and horizontally across the site. Vertical and horizontal variability in the water quality is reflected by the distribution of TDS concentrations. The groundwater beneath and downgradient of the tailings is limited use groundwater based on its high TDS value greater than 10,000 mg/L.

Table 10 Parameters of simulation A01

Simulation Parameter	Value
Identifier	A01.gwv
Objective	Provide an updated model that includes additional wells, diversion ditch, uranium plume, ammonia plume, verify that the model provides results similar to the original model developed by the DOE contractor
Time period	13 months (13 stress periods)
Well Operation CFG 1	Off
Well Operation CFG 2	Off
Well Operation CFG 3	Off
Well Operation CFG 4	Off
Well Operation CFG 5	Off
Diversion ditch	Off
Initial concentrations	From initial plumes
Boundary conditions	From original model
Run time	4 hours

The results from simulation A01.gwv were identical to the results from the original model provided by the contractor. A01 provided additional capabilities to evaluate the flow and transport of the uranium and ammonia.

3.2 Simulation BP01: Transport of U and Nitrogen (Ammonia and Nitrate) and TDS

The ammonia transport was simulated by applying as initial condition the ammonia plume and determining the yearly rise and fall in the river to determine if the ammonia concentrations moving up into the saline zone into the brine zone due to the fluctuations of concentrations in the river. The spatial extent of the discharge zone for the ammonia legacy plume in the brine zone and its effect on natural flushing were determined.

Ammonium readily adsorbs to the soil, and it is present in areas where tailings fluids were stored in unlined ponds outside the tailings. Observed data shows that fluctuations cause alternate adsorption of ammonium and desorption of ammonia into the saline zone. This creates another source of ammonia in water that can potentially discharge to riparian habitats.

Table 11 Parameters of simulation BP01

Simulation Parameter	Value
Identifier	BP01.gwv
Objective	Use the model to provide simulations for the flow and transport of ammonia and uranium. Provide data analysis of the fluxes. The simulation was applied to determine the performance of configurations 1 to 4 with respect to total mass of contaminants removed for 13 months of operation.
Time period	13 months (13 stress periods)
Well Operation CFG 1	ON: Withdrawal of 150 gpm
Well Operation CFG 2	ON: Withdrawal of 150 gpm
Well Operation CFG 3	ON: Withdrawal of 150 gpm
Well Operation CFG 4	ON: Withdrawal of 150 gpm
Well Operation CFG 5	Off
Diversion ditch	Off
Initial concentrations	From initial plumes
Boundary conditions	From original model
Run Time	4:30 hours

3.3 Simulation BP02: Effect of brine zone

The effects of the brine zone beneath the site on an overlying saline zone were determined. During milling, the tailings pile may have contained fluids with TDS ranging from 50,000 to 150,000 mg/L. Because these salinities exceed the 35,000 mg/L concentrations at the saltwater interface, they are believed to have had sufficient density to migrate vertically downward into the brine. This vertical migration of the tailings pore fluids into the saltwater system is believed to have created a reservoir of ammonia that now resides below the saltwater interface. This ammonia plume below the interface probably came to rest at an elevation where it was buoyed by brine having a similar density. Under present conditions, the ammonia plume beneath the saltwater interface represents a long-term source of ammonia to the upper alluvial groundwater system. The ammonia source at the saltwater interface (basal or ammonia flux), the legacy plume, and seepage of ammonia concentrations from the tailings pore fluids are illustrated in the conceptual model presented in Figure 9.

Since the release of tailings pond fluids containing high TDS concentrations infiltrated the groundwater during milling operations, the volume of relatively fresh water entering the site upgradient of the tailings pile may have diluted the ammonia levels in the shallow groundwater. Advective flow of fresh water through the higher-density fluids is insignificant, and thus the ammonia concentrations persist at depth. Oxidation of ammonia to nitrate or nitrogen may also contribute to lower ammonia concentrations observed in the upgradient shallow groundwater beneath the tailings pile where aerobic conditions are more likely.

Table 12 Parameters of simulation BP01

Simulation Parameter	Value
Identifier	BP02.gwv
Objective	The simulation was used to model the flux exchange between the groundwatre flow and the brine zone. The mass of contaminants was determined assuming only diffusion flux without operation of any of the well fields.
Time period	13 months (13 stress periods)
Well Operation CFG 1	OFF
Well Operation CFG 2	OFF
Well Operation CFG 3	OFF
Well Operation CFG 4	OFF
Well Operation CFG 5	OFF
Diversion ditch	OFF
Initial concentrations	From initial plumes
Boundary conditions	From original model
Run Time	4 hours

3.4 Simulation BP03: Transport of ammonia after shutting off wells and injection

The simulation used as initial conditions the results from simulation BP01. The following boundary conditions were applied:

Table 13 Parameters of simulation BP03

Simulation Parameter	Value
Identifier	BP03.gwv

Objective	The simulation was used to model the flux exchange between the groundwatre flow and the brine zone. The mass of contaminants was determined assuming only diffusion flux without operation of any of the well fields.
Time period	13 months (13 stress periods)
Well Operation CFG 1	OFF
Well Operation CFG 2	OFF
Well Operation CFG 3	OFF
Well Operation CFG 4	OFF
Well Operation CFG 5	OFF
Diversion ditch	OFF
Initial concentrations	From simulations using BP01.gwv, after running the simulation the BP01 simulation for a period of 5 years or 60 stress periods
Boundary conditions	From original model
Run Time	4 hours
NOTE	The simulation accumulated more than 6 GB of data, which shows that it is not practical to have a model with the large number of flow cells and more than 15 layers

3.5 Simulation CC01: Implementation of new well configuration:

A set of proposed remedial actions simulated including pumping of contaminated groundwater from the shallow plume to an evaporation pond on top of the tailings pile. A new configuration was implemented that includes information about the reoccurrence of the concentrations within the recharge assuming the existence of a freshwater lens.

Table 14 Parameters of simulation CC01

Simulation Parameter	Value
Identifier	CC01.gwv
Objective	The simulation used a combination of well configurations to determine the performance of the system to extract contaminants and to reduce contaminant fluxes to the river.
Time period	13 months (13 stress periods)
Well Operation CFG 1	ON, EXTRACTION, 50 gpm
Well Operation CFG 2	ON, EXTRACTION, 50 gpm
Well Operation CFG 3	ON, EXTRACTION, 50 gpm
Well Operation CFG 4	ON, INJECTION, 50 gpm
Well Operation CFG 5	ON, EXTRACTION, 50 gpm
Diversion ditch	OFF

Initial concentrations	Initial concentrations from current plume
Boundary conditions	From original model
Run Time	4 hours

3.6 Simulation CC02: Implementation of diversion ditch:

The injection of fresh water along the river into configurations 1 through 4. would create a freshwater lens inland from the Colorado River and prevent ammonia in the saline and brine zone from discharging to riparian habitat areas that could be affected by ground water discharge A diversion ditch was implemented into the flow model (as drain cells) and by setting the head levels will be set in each drain cell at the elevations of the drains. The effect of mixing water from the river and the diversion ditch was determined.. The concept is to create an analog to high river stage where river water flows inland to create a freshwater lens above the brine zone. In this case no high concentrations of ammonia would discharge into critical habitat areas along the Colorado River. In addition, injecting the diverted Colorado River water into the alluvial aquifer in order to predict the outcome of each remedial action and to investigate the effectiveness of each scenario.

Table 15 Parameters of simulation CC02

Simulation Parameter	Value
Identifier	CC02.gwv
Objective	The simulation implemented a diversiond ditch which was continuosly maintained at depth of 5 feet, the purpose was to create a freshwater lence which would serve as a hydraulic barrier for contaminants
Time period	13 months (13 stress periods)
Well Operation CFG 1	OFF
Well Operation CFG 2	OFF
Well Operation CFG 3	OFF
Well Operation CFG 4	OFF
Well Operation CFG 5	OFF
Diversion ditch	OFF
Initial concentrations	Initial concentrations from current plume
Boundary conditions	From original model
Run Time	4 hours

3.7 Simulation CC03: Effectiveness of using both systems

The benefits of running diversion ditch and well extraction at the same time were determined. A Ground Water Interim Action has been implemented to remove ammonia mass from groundwater and prevent ammonia contaminated groundwater from impacting surface water. The Ground Water Interim Action involves pumping 7 extraction wells in Configuration 5 Well field, four fresh water injection well fields (configurations 1,2,3, and 4), and an injection trench on the south side of the tailings to capture of the ammonia plume and injection of fresh water along the Colorado River. In 2011, the extracted water was evaporated on the tailings and the salt residue captured in an evaporation pond. Salt residue for evaporation on the tailings was removed and disposed at the Crescent Junction disposal site with the associated tailings.

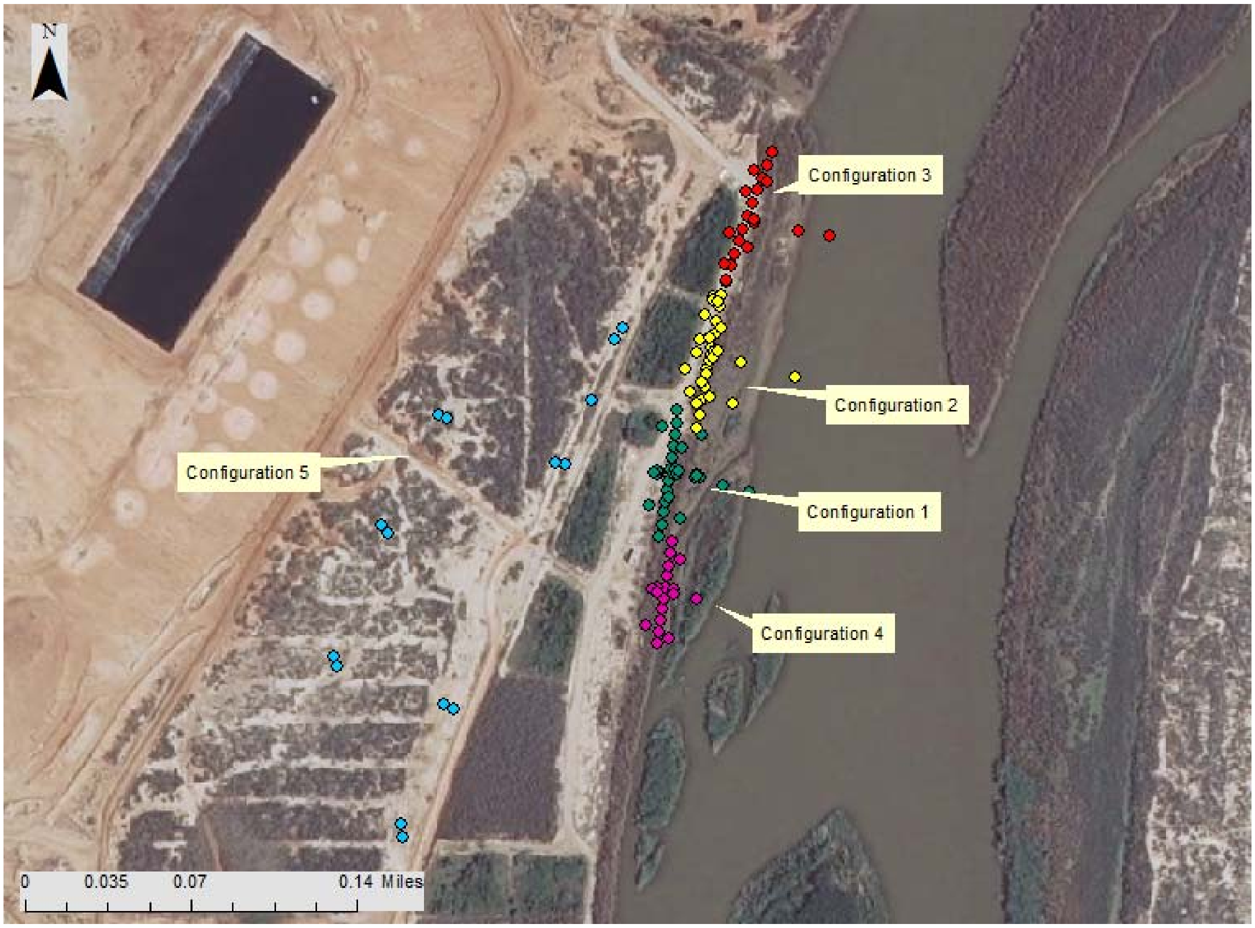

Figure 34 Well Configuration

Locations of the ground water extraction wells (Configuration 5) are shown on Figure 34. The wells are completed above the brine interface where TDS exceeds 35,000 mg/L. Configuration 5 extraction wells produce contaminant capture at flow rates for 200 to 500 gpm for the entire system that will operate from March through November. In 2010, pumping rates were limited to around 100 gpm by the capacity of the evaporation pond and the operation of two Landshark enhanced spray evaporators. Extracted groundwater is evaporated in the evaporation pond. Salt residue from spray evaporators is removed and transported to Crescent Junction with the tailings. Eventually the evaporation pond will be removed and its contents disposed at Crescent Junction.

A fresh makeup pond and filter system provides treats freshwater from the Colorado River for injection along the river in an injection trench and well field configurations 1 through 4. Fresh water is injected prior to the ascending and descending spring runoff stage levels when riparian channels become critical habitat for young of the year fish. Table 16 indicates time frames and river stages with presumed critical habitat conditions. In 2010, the only critical habitat was adjacent to Configuration 4. The purpose of the injection system is to develop a fresh water lens which prevents discharge of high ammonia groundwater during critical habit conditions.

Table 16 Critical Habitat Flow Ranges from 2006 to 2010 []

Well Field Configuration near the River Critical Habitat	2006 Critical Habitat Flow Range (cfs)	2007 Critical Habitat Flow Range (cfs)	2008 Critical Habitat Flow Range (cfs)	2009 Critical Habitat Flow Range (cfs)	2010 Critical Habitat Flow Range (cfs)
1	4,500	5,000-4,000	N/A	4,300-3,700	4,800
2	5,400-4,500	6,790-5,500	7,400-6,000	7,800-6,500	8,890-7,000
3	7,500-4,570	6,790-5,700	7,790-7,400	N/A	N/A
4	N/A	<3,400	N/A	<3,500	<3,000

During periods of high river stage, the infiltration system is turned off as it is redundant to inflow into the groundwater system. The model does not implement this feature, however, in the next update, the ability to turn off the infiltration system as function of peak flows. As the river stage declines, the infiltration system is restarted to maintain the freshwater lens as habitats become critical.

During the late summer months, one main backwater channel flows parallel to the IA well field. As the river flow decreased, the channel gradually dried up from the north to the south. The southern area (adjacent to IA CFs 1 and 4) is typically considered a critical habitat for during the time when the northern portion of the channel quickly becomes stagnant and shut off from the river. Critical habitat flows vary from year to year based on erosion and deposition in the backwater channels (Table 4-1).

The overall trend of ammonia concentrations in groundwater shows a slow decline in the maximum concentrations with time. The slow level of decline is indicative of residual sources of adsorbed ammonium in the soil and alluvial ground water zone. The remediation goal is to reach the projected groundwater cleanup standard of 3 mg/kg before the tailings are completely disposed in Crescent Junction. Modeling described in Section 5.0 addresses the effectiveness of soil source removal/treatment on the time frame to reach the remediation goal and its effect on natural flushing.

During freshwater injection in CF 4, ammonia concentration decreased in the observation wells upgradient of the injection system. Prior to injection (August), the ammonia varied from 190 to 1,100 mg/L, with the highest concentration measured at 33 ft.

GCAP reported that after the injection system had been running for over a month, the ammonia concentrations began to decrease, and by mid-November, the concentrations had decreased to a range of 3.96 to 670 mg/L. The highest ammonia concentration that was measured in November was from well 0781 at 46 ft. Freshwater injection had a more significant impact on the ammonia concentration in the downgradient wells. Prior to injection, the ammonia concentration varied from 190 to 470 mg/L, with the highest concentration measured at location 0782 at 33 ft. After the injection system had been running for over a month, the ammonia concentrations began to decrease, and by mid-November and the concentrations had decreased to a range of 1.89 to 45 mg/L. This indicates that the freshwater injection impacted the ground water ammonia concentration to a depth of 36 ft. The ammonia concentration also rapidly declined during injection operations in the up-gradient wells, at depths to 33 ft.

Table 17 Parameters of simulation CC03

Simulation Parameter	Value
Identifier	CC03.gwv
Objective	The simulation implemented a diversiond ditch which was continuosly maintained at depth of 5 feet, the purpose was to create a freshwater lence which would serve as a hydraulic barrier for contaminants
Time period	13 months (13 stress periods)
Well Operation CFG 1	ON, EXTRACTION, 50 gpm
Well Operation CFG 2	ON, EXTRACTION, 50 gpm
Well Operation CFG 3	ON, EXTRACTION, 50 gpm
Well Operation CFG 4	ON, INJECTION, 50 gpm
Well Operation CFG 5	ON, EXTRACTION, 50 gpm
Diversion ditch	Water depth maintained at 5 feet
Initial concentrations	Initial concentrations from current plume
Boundary conditions	From original model
Run Time	4 hours

3.8 Simulation DM01: Optimization of mass removal with existing system

After implementing plumes into the model as initial conditions, additional simulations were conducted to optimize mass removal and capture from the existing system. Additional simulations [for year 2006] were carried out for understanding the effects of pumping and injection systems on groundwater fluxes. For comparison, simulation results were extracted for a small area close to the Colorado River, tailing and the well fields. Following simulation were carried out:

- No Pumping and Injection
- 0.25 x pumping and injection
- 0.5 x pumping and injection
- 2 x pumping and injection
- 3 x pumping and injection

Figure 35 shows the polygon which was used for extracting results for carrying out the mass balances.

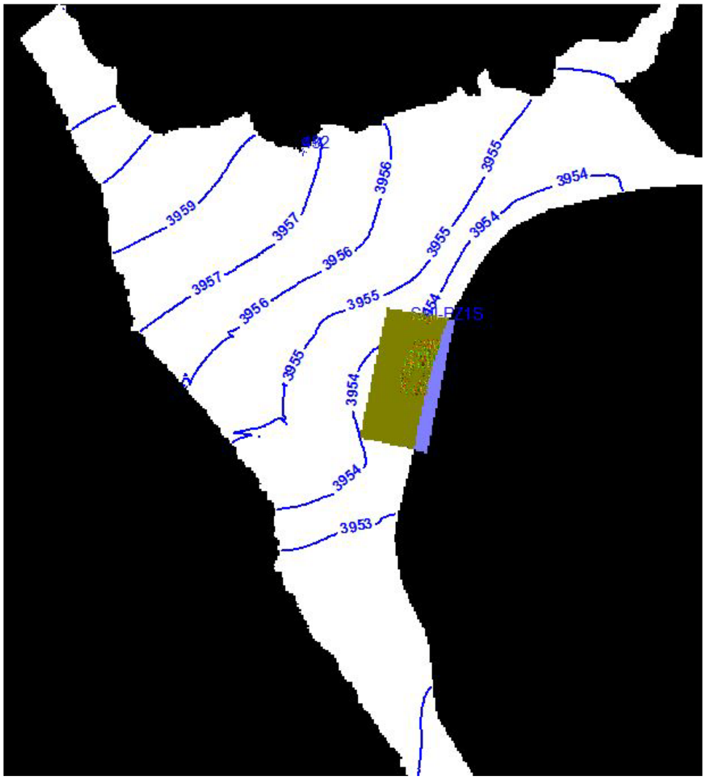

Figure 35 Polygon which was used for extracting results for mass balances.

Table 18 Inflows and outflows from wells

Scenario	Inflows (gpm)	Outflows(gpm)
No Pumping	0	0
Actual scenario	21	118
0.25 X actual	27	148
0.5 X actual	32	177
2 X actual	43	224
3 X actual	64.2	270.70

Table 19 Inflows and outflows from river

Scenario	Inflows (gpm)	Outflows(gpm)
No Pumping	0	50
Actual scenario	15	5
0.25 X actual	28	4
0.5 X actual	41	3
2 X actual	60	1
3 X actual	71	0.7

Table 20 Parameters of simulation DM01

Simulation Parameter	Value
Identifier	DM01.gwv
Objective	A combination of well extraction rate was used to determine the effect of flow rates on contmainant fluxes to the river and the total contaminants withdrawn from the aquifer
Time period	13 months (13 stress periods)
Well Operation CFG 1	ON, EXTRACTION, 20-60 gpm
Well Operation CFG 2	ON, EXTRACTION, 20-60 gpm
Well Operation CFG 3	ON, EXTRACTION, 20-60 gpm
Well Operation CFG 4	ON, INJECTION, 20-60 gpm
Well Operation CFG 5	ON, EXTRACTION, 50 gpm
Diversion ditch	OFF
Initial concentrations	Initial concentrations from current plume
Boundary conditions	From original model
Run Time	5 simulations 4 hours each

3.9 Simulation DM02: Optimization of mass removal including injection

The mass removal was optimized without additional bleeding of ammonia from the deep zone into the shallow zone and assuming that injection systems operate at the same time.

Table 21 Parameters of simulation DM02

Simulation Parameter	Value
Identifier	DM02.gwv
Objective	A combination of well extraction rates were used to determine the effect of flow rates on contmainant fluxes to the river and the total contaminants withdrawn from the aquifer
Time period	13 months (13 stress periods)
Well Operation CFG 1	ON, EXTRACTION, 50 gpm
Well Operation CFG 2	ON, EXTRACTION, 50 gpm
Well Operation CFG 3	ON, EXTRACTION, 50 gpm
Well Operation CFG 4	ON, INJECTION, 20-80 gpm
Well Operation CFG 5	ON, EXTRACTION, 50 gpm
Diversion ditch	OFF
Initial concentrations	Initial concentrations from current plume
Boundary conditions	From original model
Run Time	5 simulations 4 hours each

3.10 Summary of simulated data

A series of simulations using the SEAWAT model were completed to analyze the nitrogen and uranium cycle in the environment and provide forecasting capabilities for the fate and transport of contamination within the Moab site. The model provides information which can be used to determine the efficiency of remedial actions in reducing the concentration and load of contaminants and to assist DOE in deciding the effectiveness of remedial actions. The simulations were used to determine the efficiency of remedial actions in reducing the concentration and load of contaminants. The following work is summarized in the report:

The existing model was revised and updated with additional information related to the current remedial actions which include injection and withdrawal well. Additional simulations were conducted to determine parameters of flow and transport of contaminants according to the current remedial actions.

The existing Moab model was updated by implementing geostatistically interpolated ammonia and uranium plumes and current well operation data into the model to evaluate the effects of pumping on contaminant concentrations and determining potential surface water concentrations in riparian habitat areas for a range of operating conditions. The plumes of aqueous species of concern (nitrate, uranium) were developed with the width of the tailings that would be conservative.

The ammonia transport was simulated by applying as initial condition the ammonia plume (for couple of cycles) and determining the yearly rise and fall in the river to determine if the ammonia concentrations moving up into the saline zone into the brine zone due to the fluctuations of concentrations in the river. The spatial extent of the discharge zone for the ammonia legacy plume in the brine zone and its effect on natural flushing were determined. The effects of the brine zone beneath the site on an overlying saline zone and the effect of discharge of a legacy ammonia plume from the brine zone after the extraction wells and injection system have been shut off were determined. The simulation times were one year which did not provide sufficient information about determining the long term effects of flow and transport.

The model was reconfigured by adding injection and withdrawal wells and modifying the configuration of the wells. A diversion ditch was added to intercept and extract water from the tailings. A new configuration was implemented that includes infiltration and provide information about the reoccurrence of the concentrations within the recharge assuming the existence of a freshwater lens. A diversion ditch was implemented into the flow model (as drain cells) and by setting the head levels will be set in each drain cell at the elevations of the drains. The effect of mixing water from the river and the diversion ditch was determined. The benefits of running diversion ditch and well extraction at the same time were determined.

A set of proposed remedial actions simulated including pumping of contaminated groundwater from the shallow plume to an evaporation pond on top of the tailings pile, and injecting the diverted Colorado River water into the alluvial aquifer in order to predict the outcome of each remedial action and to investigate the effectiveness of each scenario. After implementing plumes into the model as initial conditions, additional simulations were conducted to optimize mass removal and capture from the existing system. The mass removal was optimized without additional bleeding of ammonia from the deep zone into the shallow zone and assuming that injection systems operate at the same time.

The recharge of the saturated zone resulting from the mine tailing is an important parameter for water and contaminant mass balance at the site. A model of the tailings was developed to analyze the unsaturated flow as function of daily stochastic hydrologic events (rainfall and precipitation). The Appendix contains an article which provides analysis of the vadose zone of a typical UMTRA site.

Ammonia levels in Colorado River water in some locations adjacent to and downstream of the Moab site exceed the chronic and acute criteria National Ambient Water Quality Criteria (referred in this document as the NAWQC or “federal criteria”) and State of Utah surface water standards (which are identical to the federal criteria) for protection of aquatic life.

Data for ammonia in surface water associated with the Moab site were analyzed to determine the scope of the contamination problem and help define ground water remediation goals, given the variability of observed ammonia concentrations and the variability of the applicable aquatic criteria (DOE 2003). Ammonia surface water data collected between 2000 and 2002 were used in the analysis.. All ammonia analyses for which pH was also available were converted to total ammonia reported as N for ease in comparison to the federal criteria. GCAP suggested that if the concentrations of ground water discharging to surface water can be reduced to the 3 to 6 mg/L range of total ammonia-N, surface water compliance with both acute and chronic aquatic criteria can be achieved, considering effects of mixing with river water and the allowed chronic mixing zone.

4 FUTURE WORK

During FY12-13, the work for simulating flow and transport under variable conditions will be completed and a repot will be issued which provides detailed analysis of the simulations. A set of additional simulations are proposed including:

1. Additional scenarios as suggested by DOE program manager will be developed and analyzed.
2. Simulations assuming a cutoff wall along critical habitats. The geometry of the cutoff wall will be varied (depth of the wall, location and total length) to provide the most efficient implementation
3. Simulations assuming chemical grouting injected through a set of wells. The location, the number and the injection depth will be varied to provide most efficient approach.
4. During FY12, students will be involved in the DOE-FIU Science and Technology Workforce Development Program, and will work with the transport model to perform numerical simulations of remedial scenarios
5. Modeling is to be performed with MODFLOW, SEAWAT and FEFLOW as a benchmark. The following is a list of the proposed tasks to support this initiative:
6. Simulations will be provided for long term periods in order to provide insight of the temporal trends of flow and contaminant transport during and after ceasing operations.

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6 APPENDIX A: ARTICLE SUBMITTED FOR THE WASTE MANAGEMENT CONFERENCE WM 2013

LONG-TERM PERFORMANCE OF URANIUM TAILINGS DISPOSAL CELLS

ARTICLE 13340 OF WASTE MANAGEMENT CONFERENCE 2013

December 2012

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ABSTRACT

Recently, there has been interest in the performance and evolution of Uranium Mill Tailings Remedial Action (UMTRA) Project disposal cell covers because some sites are not compliant with groundwater standards. Field observations of UMTRA disposal cells indicate that rock covers tend to become vegetated and that saturated conductivities in the upper portion of radon barriers may increase due to freeze/thaw cycles and biointrusion. This paper describes the results of modeling that addresses whether these potential changes and transient drainage of moisture in the tailings affect overall performance of the disposal cells. A numerical unsaturated/saturated 3-dimensional flow model was used to simulate whether increases in saturated conductivities in radon barriers with rock covers affect the overall performance of the disposal cells using field data from the Shiprock, NM, UMTRA site. A unique modeling approach allowed simulation with daily climatic conditions to determine changes in moisture and moisture flux from the disposal cell. Modeling results indicated that increases in the saturated

conductivity at the top of radon barrier do not influence flux from the tailings with time because the tailings behave similar hydraulically to the radon barrier. The presence of a thin layer of low conductivity material anywhere in the cover or tailings restricts flux in the worst case to the saturated conductivity of that material. Where materials are unsaturated at depth within the radon barrier of tailings slimes, conductivities are typically less than 10^{-8} centimeters per second. If the low conductivity layer is deep within the disposal cell, its saturated properties are less likely to change with time. The significance of this modeling is that operation and maintenance of the disposal cells can be minimized if they are allowed to progress to a natural condition with some vegetation and soil genesis. Because the covers and underlying tailings have a very low saturated hydraulic conductivity after transient drainage, eventually the amount of moisture leaving the tailings has a negligible effect on groundwater quality. Although some of the UMTRA sites are not in compliance with the groundwater standards, the explanation may be legacy contamination from mining, or earlier higher fluxes from the tailings or unlined processing ponds. Investigation of other legacy sources at the UMTRA sites may help explain persistent groundwater contamination.

7 INTRODUCTION

Recently, there has been interest in the performance and evolution of Uranium Mill Tailings Remedial Action (UMTRA) Project disposal cell covers because some sites are not compliant with groundwater standards. Field observations of UMTRA disposal cells indicate that rock covers tend to become vegetated and that saturated conductivities in the upper portion of radon barriers may increase due to freeze/thaw cycles and biointrusion. This paper describes the results of modeling that addresses whether these potential changes and transient drainage of moisture in the tailings affect overall performance of the disposal cells. A numerical unsaturated/saturated 3-D flow model was used to simulate whether increases in saturated conductivities in radon barriers with rock covers affect the overall performance of the disposal cells using field data from the Shiprock, NM, UMTRA site. A unique modeling approach allowed simulation with daily climatic conditions to determine changes in moisture and moisture flux from the disposal cell. Modeling results indicated that increases in the saturated conductivity at the top of radon barrier do not influence flux from the tailings with time because the tailings behave similar hydraulically to the radon barrier. The presence of a thin layer of low conductivity material anywhere in the cover or tailings or tailings restricts flux in the worst case to the saturated conductivity of that material. Where materials are unsaturated at depth within the radon barrier of tailings slimes, conductivities are typically less than 10^{-8} centimeters per second. If the low conductivity layer is deep within the disposal cell, its saturated properties are less likely to change with time.

Recent field observations of Uranium Mill Tailings Remedial Action UMTRA (Project) disposal cells indicate that rock covers tend to become vegetated and that saturated conductivities in the radon barriers increase with time. Possible reasons that standard construction and quality assurance practices used for construction of compacted clay soil barriers were not achieving or maintaining design permeabilities include (1,2):

- Clay soils were compacted dry of optimum water content.
- Clay clod formation.

- Insufficient bonding between lifts.
- Desiccation cracking.
- Shrink-swell cracking.
- Freeze-thaw cracking.
- Biointrusion.

This paper describes field testing and the results of modeling at the Shiprock UMTRA site near Shiprock NM, that address whether increases in saturated conductivities in the cover and transient drainage of moisture in the tailings affect overall performance of the disposal cells. The modeling approach is unique in that it evaluates a 3-dimensional flow system with daily climatic conditions and is not subject to the limitations of static upper or lower boundary conditions used in previous one- or two-dimensional models. The results of this modeling can be used to evaluate whether UMTRA rock covers can evolve naturally towards vegetated evapotranspirational covers and still maintain performance. This would eliminate costs of retrofitting covers and reduce maintenance costs for removal of vegetation on disposal cells

8 BACKGROUND

The UMTRA Project involved remediation of 24 uranium tailings sites between the 1980s and 1990s, most of which are in the western United States. The first covers on uranium tailings and other contaminated materials generally consisted of a one- to two-meter thick clay radon barrier overlain by 15 centimeters (cm) of filter sand and 30 cm of erosion protection riprap (Figure 1). The radon barrier in the cover generally has a saturated hydraulic conductivity on the order of 10^{-7} centimeter per second (cm/s). The filter layer consists of sand with a hydraulic conductivity of 0.001 to 1.0 cm/s that protects the radon barrier from erosion, facilitates drainage off the radon barrier, and allows for evaporation of residual moisture. Tailings that were remediated in place at this time may have had perched phreatic surfaces in low permeability tailings slimes. Tailings that were relocated from flood plains were compacted wet of optimum and heavily watered for dust control. These practices may have contributed to high percentages of saturation in the relocated tailings. Figure 36 shows a typical rock cover radon barrier at the UMTRA tailings disposal cell in Shiprock, New Mexico.

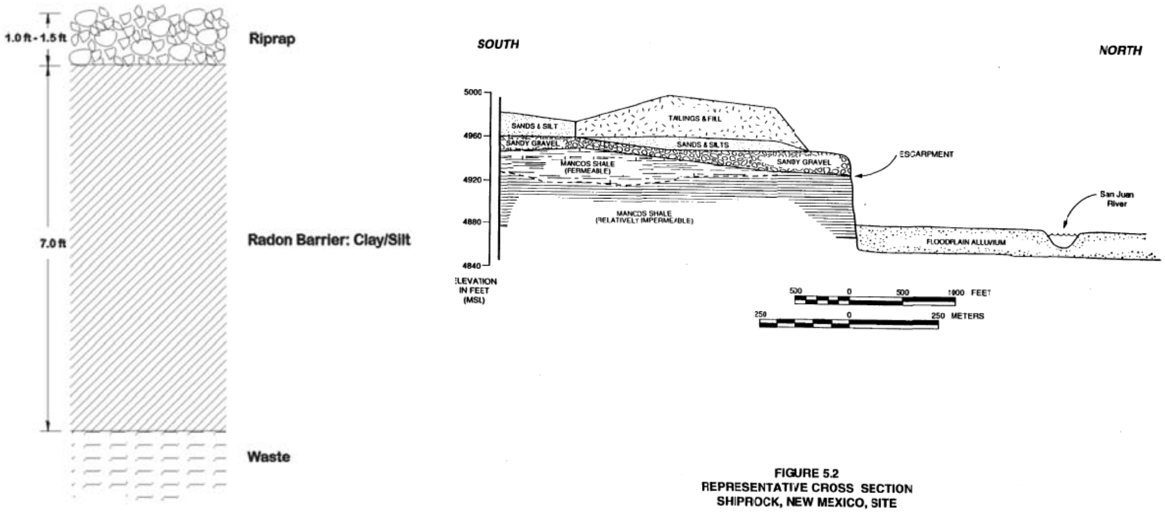

Figure 36 Generalized Early UMTRA Rock Cover over a Radon Barrier Used and representative cross section at the Shiprock Site

Mid-way through the project in1988, the DOE began to comply with U.S. Environmental Protection Agency (EPA) groundwater standards applicable to the UMTRA Project (40 CFR 192).

They established concentration limits for hazardous constituents that cannot be exceeded at the downward gradient limit of the disposal facility (the point of compliance, or POC). Cover designs changed to eliminate freeze thaw cycles and potential biointrusion by plants or vegetation in the radon barrier that might change the hydraulic properties. At this point, relocated tailings and cell covers were compacted dry of optimum and watering for dust control was minimized to eliminate water entrained in the tailings.

Seepage rates through the radon barrier at a rock-covered disposal cell are equal to the product of the hydraulic conductivity (a function of the moisture content) and the hydraulic gradient. For moisture contents that are vertically uniform, the hydraulic gradient is unity. However, using the saturated hydraulic conductivity of 10^{-7} cm/s in the radon barrier for the purpose of calculating seepage rates is highly conservative and in some cases precludes demonstrating compliance with the groundwater standards. If the radon barrier is unsaturated, operational hydraulic conductivities of the radon barrier and long-term seepage rates from the facility may be several orders of magnitude lower.

While the more recent UMTRA disposal cell designs and construction practices recognized the need to prevent infiltration and accumulation of water in the disposal cell, there have been concerns about whether earlier rock covered disposal cells function in regards to the groundwater standards. Presently, the earlier covers are maintained to prevent vegetation. However, as a vegetated cover is a probable plant succession end state, questions have arisen whether the covers will perform as vegetation encroaches and whether pedogenesis in cover layers occurs and affects disposal cell performance. Generally, anywhere there is an annual moisture deficit and the disposal cell cover is shaped to shed surface water runoff, covers will be unsaturated. However, there is concern whether rock rip-rap is increasing percent saturations and downward moisture flux.

The hydrologic conditions at the site, and more specifically the moisture deficit within the soil column may reduce orders of magnitudes the saturated hydraulic conductivity of the cover and the tailings. Three major transient processes affect the moisture distribution within the column:

infiltration from surface water (rainfall and snow melting), evapotranspiration, and depth to groundwater levels. Therefore the distribution of moisture has transient character, in addition of being spatially distributed along the height of the soil column. The temporal and spatial character of the moisture distribution in vertical direction, (i.e. hydraulic conductivity of the tailings and the cover, and corresponding infiltration from the surface to the saturated zone) require analysis of the entire spectrum of hydrologic events with respect to time and better understanding of the behavior of the system with respect to hydrological events. Furthermore, vegetation must be taken into account considering that vegetation roots act as conveyors for extracting water from the subsurface to air when the thermodynamic potential forces water conveyance through vegetation stems. In order to accurately determine flow and transport of chemical constituents through radon cover, the protective rip rap, tailings and saturated zone, an integrated numerical model is required to provide coupling between all of the above processes.

9 EARLY UMTRA INFILTRATION COVER STUDIES

In 1985, Colorado State University performed geotechnical testing on the tailings at the Shiprock, NM, UMTRA site (3) that included in situ and remolded index properties, strength properties, and consolidation characteristics From fifteen borings made in 1981, four interpretive cross-sections were developed that identified areas of sands and slimes. The cross sections provide the basis for the modeling described in this paper. An aerial view of the Shiprock UMTRA site in 1965 and after completions of disposal cell in 1986 is presented in Figure 37.

Figure 37 Aerial View of the Shiprock UMTRA Site in 1965 and after Completions of Disposal Cell in 1986 Disposal Cell

After remediation of the cell in 1986, a field study was undertaken in 1988 to evaluate moisture conditions in the disposal cell cover at the Shiprock, New Mexico site (Figure 37) (4). Limited field data also were obtained for the disposal cell covers at the Clive, Utah, and Burrell, Pennsylvania, sites for comparison. The field study by the U.S. Department of Energy (DOE) to determine whether the rock-covered tailings disposal cells could continue to be used as a design that would allow compliance with the proposed EPA groundwater protection standards. Percent saturation profiles were developed for the clay radon barriers at all three disposal cells, and capillary moisture curves and unsaturated hydraulic conductivity curves were developed for the Shiprock radon barrier. The radon barriers of all three disposal cells were found to be unsaturated within three years of placement and average percent saturation ranged was less than 84 percent. As part of the field study, the Shiprock disposal cell was instrumented to monitor meteorological stresses, relative soil tension, and moisture content profiles in the filter layer and radon barrier.

Geotechnical testing conducted during the 1988 study indicated that the average percent saturation of the radon barrier is 83.6 percent (12.6 percent by weight), with moisture contents relatively uniform with depth. The construction moisture content of the radon barrier was 14.9 percent by weight, indicating some drying of the radon barrier may have occurred. Evidence from neutron logging of the radon barrier in the 1988 study supported this conclusion (Figure 38).

During the 1988 field study, seasonal field evaporation experiments demonstrated that the potential evaporation from the filter layer exceeds the annual precipitation at the Shiprock site, and evaporation may be the primary mechanism for removing excess water from the filter layer. Monitoring of relative soil tensions with time indicated that relative soil tensions in the filter layer and upper portion of the radon barrier are controlled by meteorological stresses. Relative soil tensions in the filter layer decreased during winter, but were generally high the remainder of the year, except after precipitation events. Relative soil tensions were highly variable in the upper portion of the radon barrier, but remained relatively constant below a depth of 100 cm. long-term moisture contents in the Shiprock radon barrier were simulated using the finite element unsaturated flow model UNSAT2. The modeling demonstrated that soil tensions propagate relatively rapidly through the radon barrier, equilibrating to steady state conditions within a few years. By applying a cyclical upper boundary condition based on measured monthly average tensions in the upper portion of the radon barrier and using a seepage face as a lower boundary, soil tensions in the radon barrier were simulated for 100 years (Figure 3). The modeling indicated that soil tensions in the radon barrier were currently at or near equilibrium, and that the radon barrier will remain unsaturated with time. The long-term percent saturation of the Shiprock radon barrier was predicted to be slightly less than the average 83.6 percent saturation measured in analyses of core samples in 1988. The modeling also showed that if the filter layer were to remain saturated year-round, then the saturated moisture front would propagate downward through the entire radon barrier within a year. However, it was surmised that saturation of the radon barrier in the future is unlikely, as its low hydraulic conductivity limits downward migration of water, and evaporation removes excess water from the filter layer. The modeling was limited in that didn't account for flow properties of the tailings or evolution of cover properties with time.

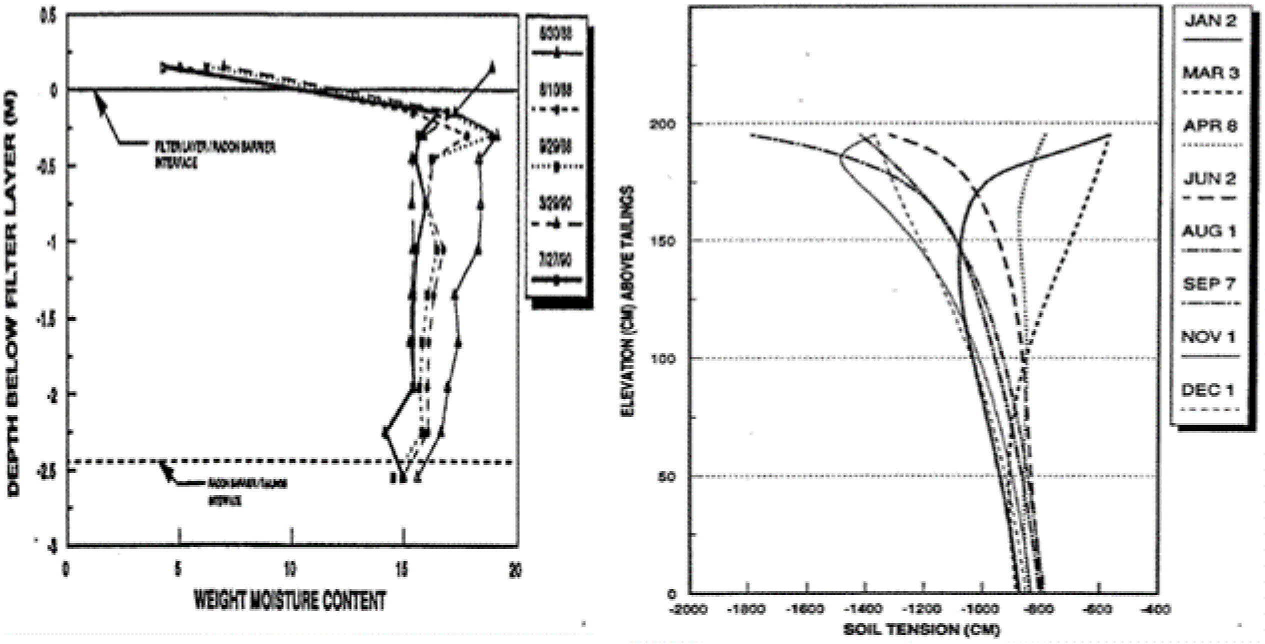

Figure 38 Relative moisture content measured with a neutron moisture meter and simulated soil tension in the Radon Barrier for 1988 Study Using UNSAT2

Based on data from the field study at Shiprock and the unsaturated flow modeling, it was concluded that the operating unsaturated hydraulic conductivity of the Shiprock radon barrier is approximately 10^{-8} cm/second, and moisture conditions within the radon barrier are approaching a state of dynamic equilibrium. Radon barriers of similar UMTRA Project disposal cells in similar climates are also likely to remain unsaturated if potential evaporation from the filter layer exceeds precipitation for most of the year (4).

10 RECENT UMTRA COVER STUDIES

In 1995, the results of a lysimeter study by Sackshewsky et al. showed that significant percolation occurs in landfill covers consisting of nonvegetated soils covered with clean gravel and rock even under very low annual precipitation (160 millimeters per year (mm/yr)) (5). By comparison, no percolation occurred through a vegetated soil-rock cover even under high annual precipitation (450 mm/yr per year). This study generated concern about whether infiltration rates were increasing through early rock cover radon barriers.

In 2001, the DOE reported on the results of six saturated hydraulic conductivity (Ksat) measurements taken in the radon barrier with an air-entry permeameter in the upper portion of the cover on the north side slope in areas where vegetation had encroached on the rock cover (6). The Ksat ranged from 1.19×10^{-4} cm/s to 4.76×10^{-8} cm/s, revealing a high degree of uncertainty. Moisture contents were measured in the same neutron probe tubes that DOE installed through the radon barrier into the tailings in 1988. The paper reported that neutron moisture readings and soil samples from borrow pits indicate saturation throughout the radon barrier and that the neutron probe was dripping wet when extracted from the tubes. The report described that approximately half of the depth of the rock layers was filled with windblown silt. Review of the paper indicates saturation in the cover may be local to areas over slime tailings that limit the downward migration of infiltration. Moisture data from samples collected in vegetated areas suggests there are areas in the cover where moisture contents range from 46 to 90 percent saturation. In addition there was no mention of borrow pits in the cover filling with water that would indicate saturation in the cover. Water in and around the neutron logging tubes may be related to an incomplete seal in the annulus with the cover that allows water in the rock layer from a storm event to penetrate vertically along the annulus of the tube. If this is the case, the neutron data are invalid. Furthermore, neutron moisture data are relative calibrated data and should only be used to determine change in moisture content. Inspection of the 2001 data in Figure 39 indicates the same uniform profile as the 1988 data shown on Figure 3, The conclusion that the cover is saturated in the 2001 study is invalid because two of only three soil samples from test pits with 90 percent saturation were averaged with a 107 percent saturation sample that should have been discarded.

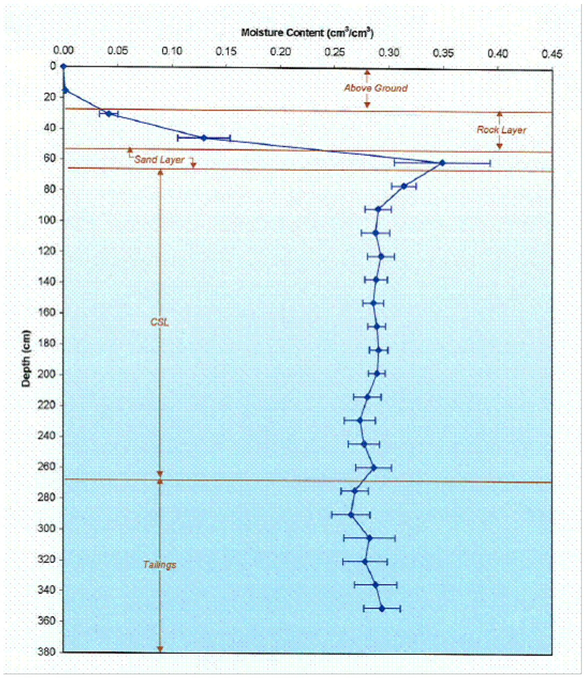

Figure 39 Neutron Moisture Meter Logging Measurements in the Radon Barrier from the 2001 Shiprock Study

A piezocone investigation was conducted on the Shiprock disposal cell in 2001 to determine if free water was present in the cell (7). Twenty-nine soundings were attempted in a more-or-less equally spaced grid over the cover. Eight soundings were able to penetrate the cover below a meter. Refusal in the 18 other soundings was attributed to a former highly compacted interim cover (three soundings were made in off-pile locations in ditches surrounding the disposal cell). Saturated slimes (indicated by a positive pore pressure during the sounding that did not fully dissipate) were observed in six of the soundings; thicknesses varied from 76 cm to 305 cm, median of 152 cm.

Knight Piésold Consulting in a 2002 report .analyzed infiltration through the Shiprock radon barrier using the EPA’s HELP computer code (8). Model results indicate that approximately 20 percent of precipitation falling at the site infiltrates the existing cover, resulting in a flux from the base of the disposal of 22 liters/minute. This flux from the cell occurs over the entire 28.3 hectare base of the modeled cell. According to the model, modifying the existing riprap cover to a vegetation cover will essentially eliminate recharge to the tailings. However, some assumptions made to use this model are questionable; for example, the model does not incorporate drainage of tailings materials. Unsaturated conditions or temporal (transient) conditions are also ignored. The report provides a good discussion of expected moisture contents within the disposal cell.

In 2012 DOE (9) reported on HYDRUS-1D modeling of the Shiprock Disposal Cell for conditions in the northeast portion of the pile that may contain saturated slimes. Results of the modeling indicated that when the influx is greater than the saturated hydraulic conductivity of the slimes, moisture mounds above the slimes. When the influx was less than the saturated hydraulic conductivity of the slimes, steady-state drainage from the slimes was equal to the influx occurs within 5 years for the modeled conditions. When near-zero influx was specified, the tailings drain to residual moisture contents in approximately 20–30 years, dependent on the saturated hydraulic conductivity of the slimes. Drainage rate from the slimes after 20–30 years is around 10^{-9} cm/s under near-zero influx conditions. Drainage from the non-slime material is expected to be nearly constant at the value determined by the Knight Piésold study of 10^{-7} cm/s.

11 RECENT MODELING OF EVOLUTION OF DISPOSAL CELL COVERS AND TRANSIENT DRAINAGE

Potential effects on evolved disposal cell covers on disposal cell performance resulting from an increase in saturated conductivity in the radon barrier with time were recently simulated with the MIKESHE model. In these simulations, material properties for tailings measured at the Shiprock site were placed below the cover at the average percent saturation measured in the field.

The numerical model is based on the MIKE SHE/MIKE 11 modeling system from DHI Water & Environment [6]. It consists of a coupled surface/subsurface flow model using MIKE SHE (a 3-dimensional saturated and unsaturated groundwater flow, 2-dimensional overland/sheet flow model) and MIKE 11 (1-dimensional river flow model which includes structure operation and schedules). MIKE SHE is a distributed hydrological modeling system [7], which solves the subsurface flow and transport using the law of conservation of mass and the laws of momentum and energy (3-D Boussinesq and transport equations). The model requires data in standard GIS format. Spatial data for Shiprock was obtained from USGS[1] National Map Viewer.

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[1] http://nationalmap.gov/viewer.html

12 MODEL DOMAIN

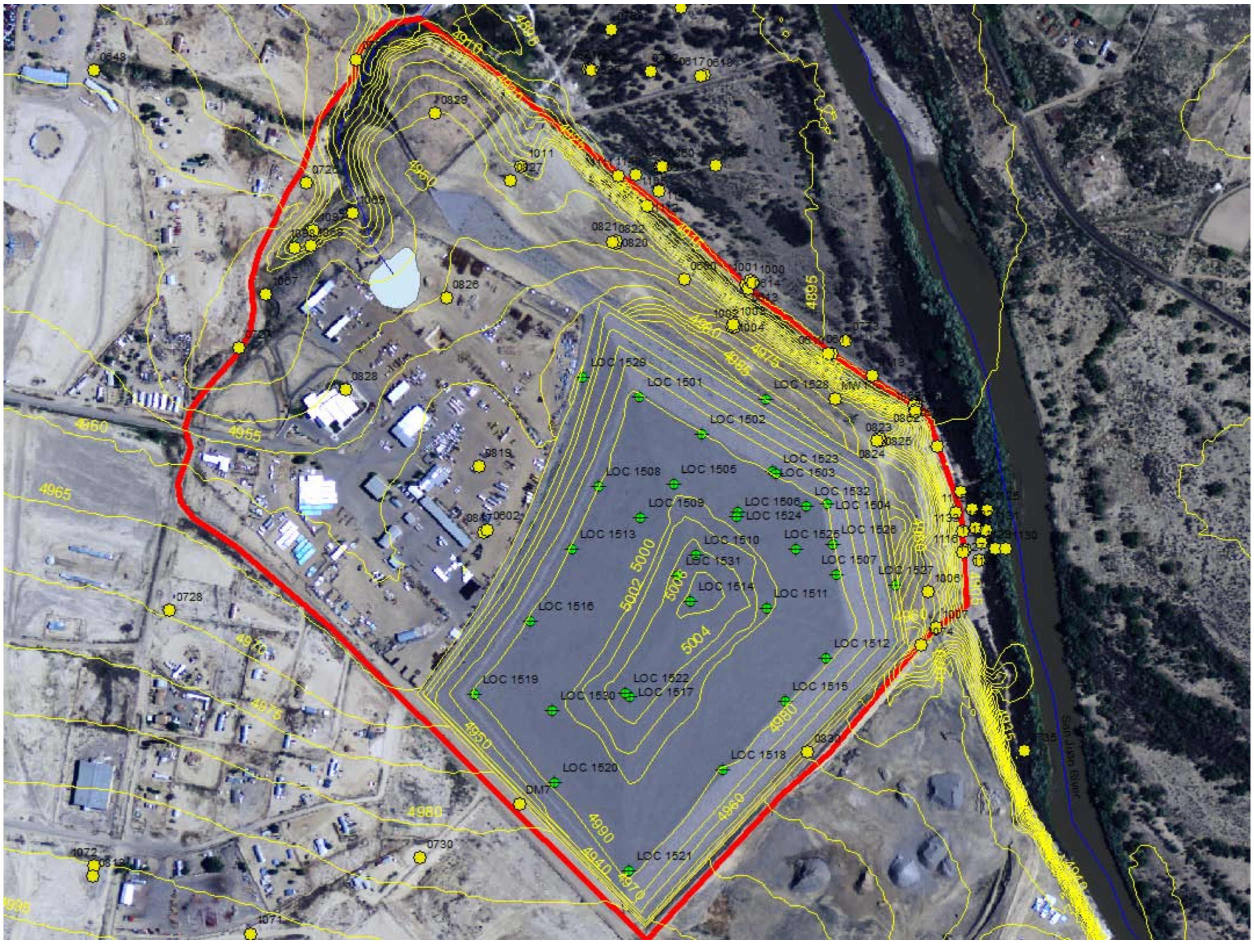

Figure 40 Model domain

Some of the more extreme rainfall events were 1.5 inches on Oct. 22, 1969; 1.9 inches on Sept. 5-6, 1970; 2.7 inches on July 20-23, 1986; 1.9 inches on April 4-5, 1997; and 3.0 inches on Sept. 2-4, 2002. The annual precipitation extremes ranged from a low of 3.57 inches in 1976 to a high of 14.65 inches in 1986 (10). Reference ET (ETo) refers to the ET of a reference crop such as grass or alfalfa that is of a certain height and is growing under optimum conditions for maximum production. ETo is correlated with weather parameters, and it is calculated when these parameters are available. From 1996 to 2003, average daily ETo (using WS-2 data and a modified, grassreferenced Penman formula from the New Mexico Climate Center: http://weather.nmsu.edu/pmcomp.htm) ranged from 0.08 inch/day in January and December to 0.38 inch/day in June, while the total annual ETo averaged 80.5 inches. From May through August, the active growing season for many crops, ETo averaged 10.4 inches/month or 0.34 inch/day. The model domain is shown on Figure 40

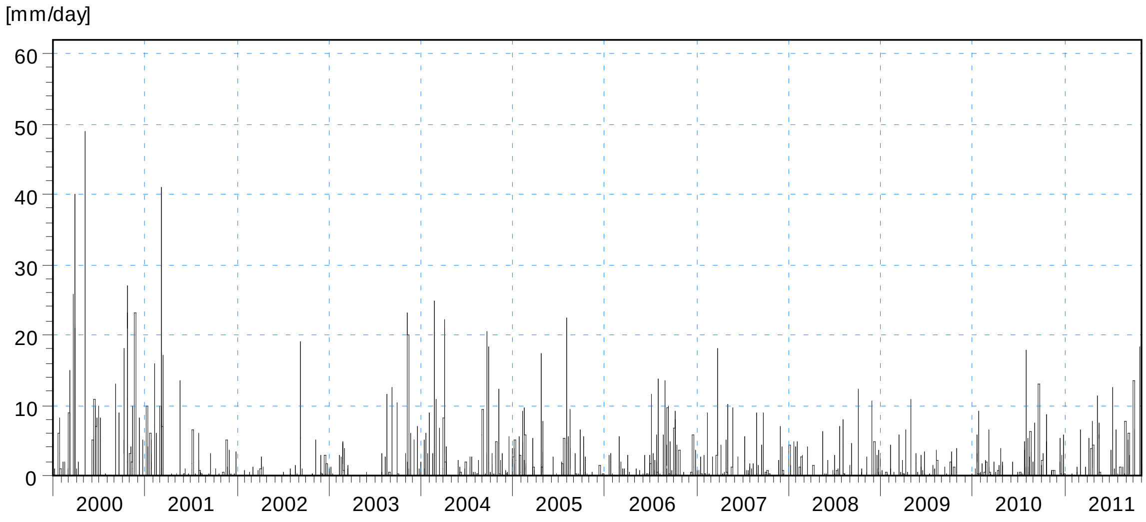

Figure 41 Precipitation events recorded in the period 1981-2008 (Western Regional Climate Center[2])

The model used prescribed head boundary conditions for all boundaries. The top of the model used prescribed rainfall (Figure 41) and prescribed evapotranspiration (Figure 42).

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[2] http://www.wrcc.dri.edu/

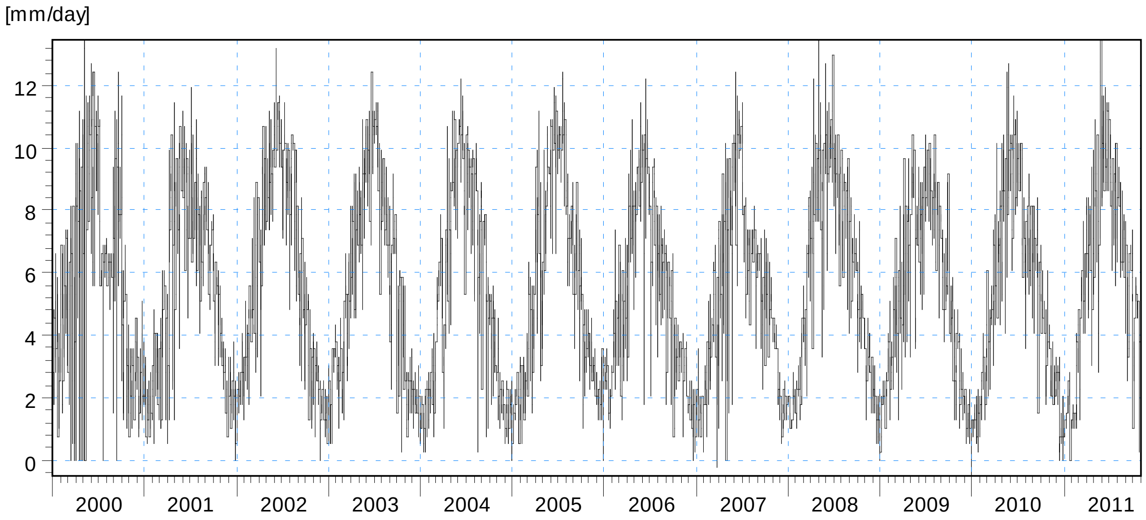

Figure 42 Evapotranspiration daily timeseries for 1981-2008 (Western Regional Climate Center[3])

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[3] http://www.wrcc.dri.edu/

13 UNSATURATED PROPERTIES OF SOIL

The unsaturated hydraulic properties are often described using the pore size distribution model of Mualem (1976) for the hydraulic conductivity in combination with a water retention function introduced by Van Genuchten (1980). The soil water retention equation, θ (Ψ), and the hydraulic conductivity are given by equations (a) and (b) respectively.

$$\theta(\psi)=\theta_r+\frac{(\theta_s-\theta_r)}{\left[1+(\alpha\psi)^n\right]^m} \quad \text{(Eq. a)}$$

$$K(\psi)=K_s\frac{\left(\left(1+|\alpha\psi|^n\right)^m-|\alpha\psi|^{n-1}\right)^2}{\left(1+|\alpha\psi|^n\right)^{m(l+2)}} \quad \text{(Eq. b)}$$

where θ is the volumetric water content ($ft^3\ ft^{-3}$) at pressure head *Ψ* (ft); θ_r and θ_s are the residual and saturated water contents, respectively ($ft^3\ ft^{-3}$); α (in ft^{-1}) is related to the inverse of the air-entry pressure; *n* is a measure of the pore-size distribution (Van Genuchten, 1980); *m* = 1-1/*n*; and K(*Ψ*) is hydraulic conductivity ($ft\ s^{-1}$). Both equations show strong dependence and a variation of the hydraulic conductivity with several orders of magnitude.

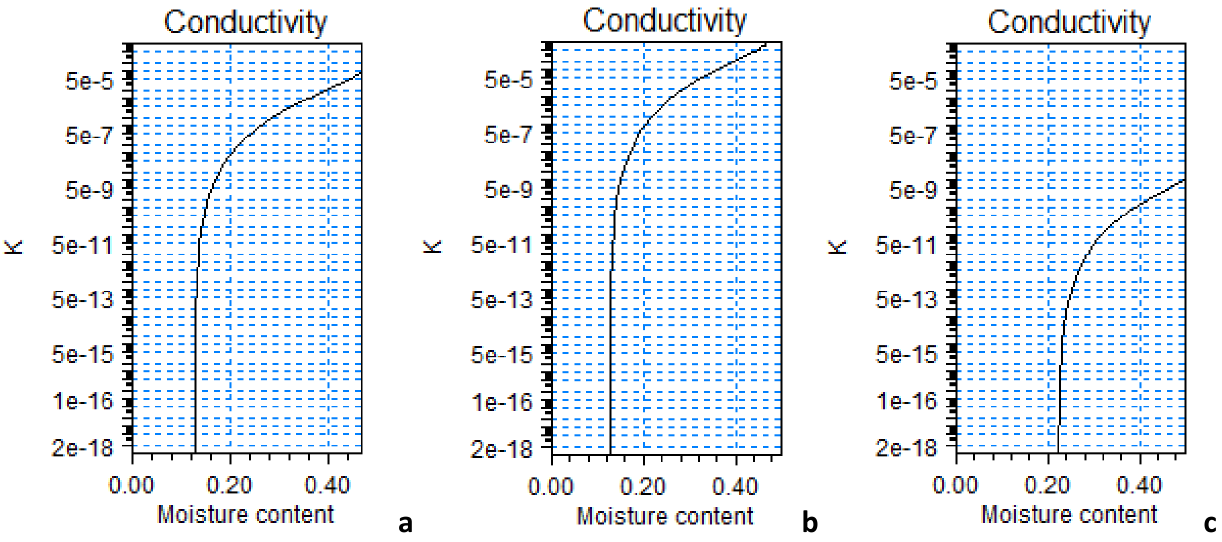


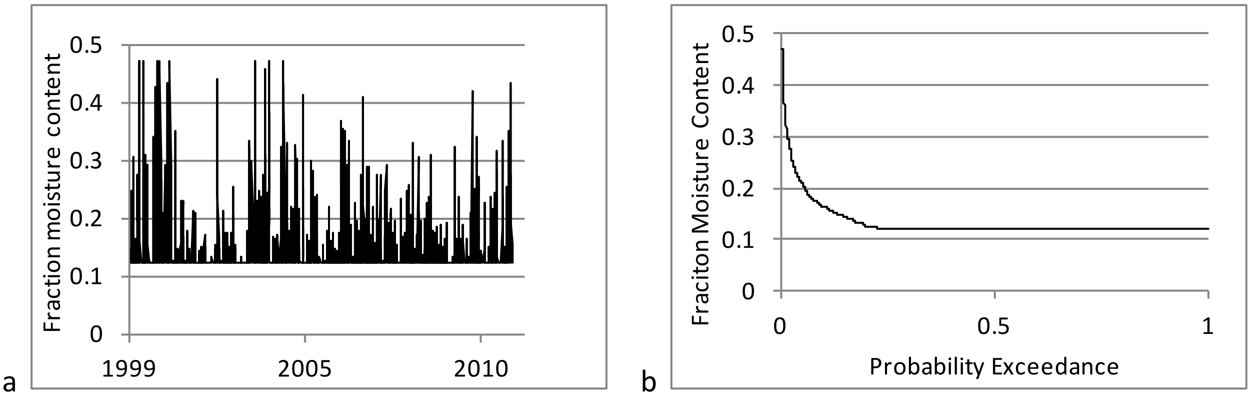
Figure 43 Hydraulic conductivity as function of moisture content: a) upper rip-rap layer, b) sand layer c) radon barrier layer

Table 1 shows the relation between the moisture content of the soil and the hydraulic conductivity at each layer. In the upper rip-rap layer the hydraulic conductivity value ranges from 10^{-6} to 10^{-4}, the sand layer hydraulic conductivity ranges from 10^{-5} to 10^{-3}, and the radon barrier layer hydraulic conductivity ranges from 10^{-11} to 10^{-8}.

Table 22 Hydraulic conductivity in m/s as function of moisture content: a) upper rip-rap layer, b) sand layer c) radon barrier

ϴ	Upper rip-rap layer	Sand layer	Radon barrier layer
0.20	1×10^{-6}	4×10^{-5}	6×10^{-11}
0.30	8×10^{-5}	2×10^{-4}	4×10^{-9}
0.40	1×10^{-4}	6×10^{-3}	1×10^{-8}

A series of simulations were conducted using a ten year period using daily timeseries for precipitation and evapotranspiration. The objective of the simulations were to determine the range of variability of infiltration fluxes, and moisture content within the height of the soil column. Figure 9 shows analysis of moisture content for three selected sol column depths for a ten year period (using 0.1, 0.2 and 0.7 ft). At depth 0.1 ft the highest moisture content reached is 0.5, at depth 0.2 ft the highest moisture content reached is 0.35, and at depth 0.7 ft the moisture content is very low, the value obtained from the model is 0.2.



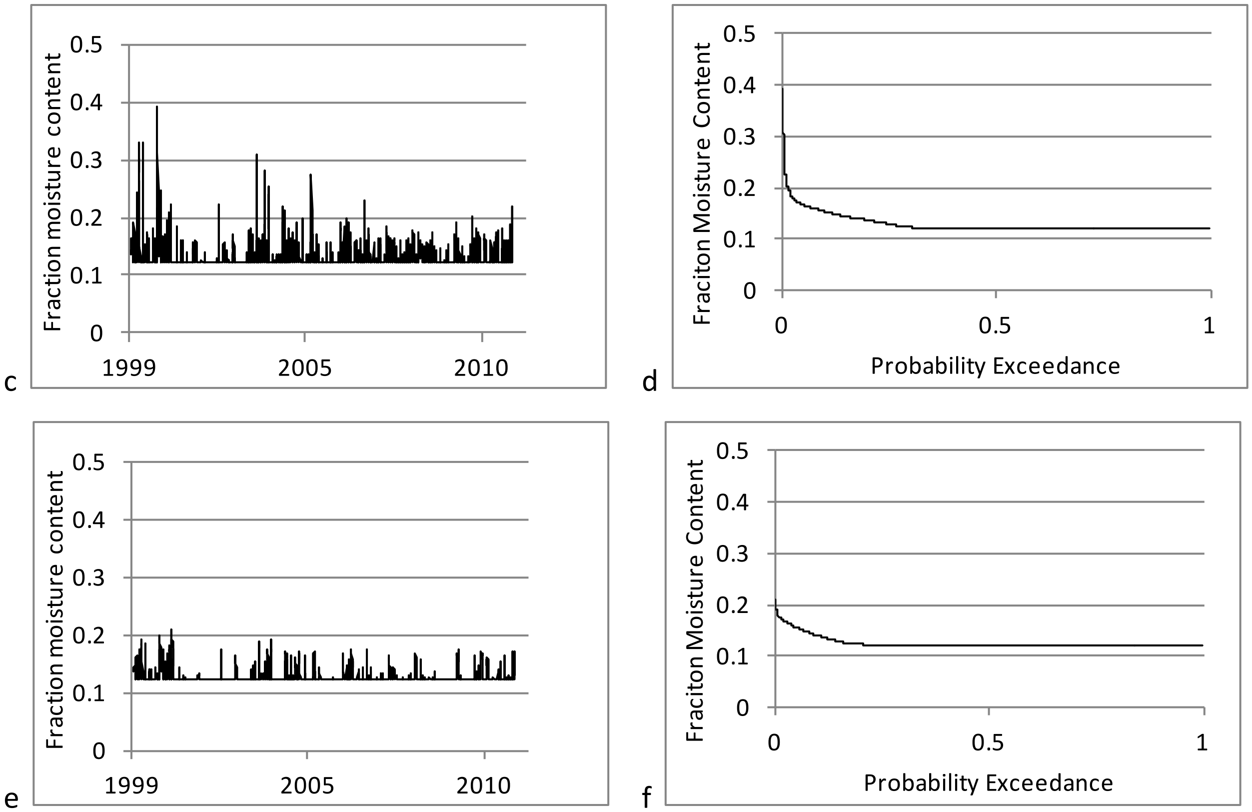


Figure 44 Timeseries of moisture content at depth a) 0.1 ft, c) 0.2 ft, e) 0.7 ft and Probability exceedance of moisture content at depth b) 0.1 ft, d) 0.2 ft, f) 0.7 ft

Similarly, Figure 10 shows the timeseries of infiltration rate from the surface to unsaturated zone over a period of 10 years. The water balance between rainfall, infiltration and evaporation over a period of 10 years is shown in Figure 11. There is a direct correlation between rainfall events and infiltration rates.

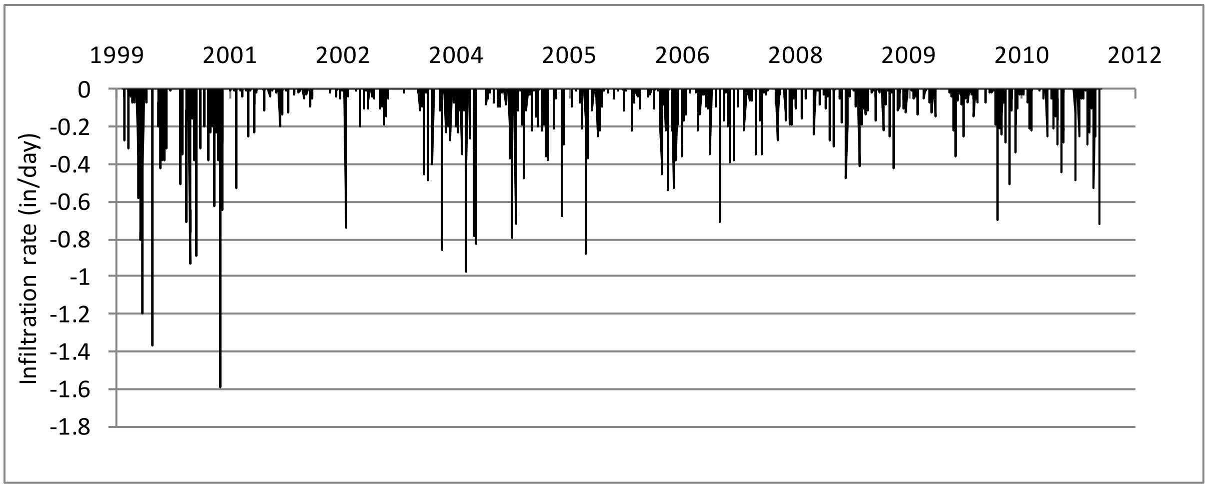


Figure 45 Infiltration to unsaturated zone

In Figure 11 the water balance demonstrate that the accumulated infiltration downwards through the surface of the tailings is equivalent to the accumulated evapotranspiration from the soil, which implies that there is no water reaching the water table in the tailings, since there is no further downward moisture flux.

Figure 12 shows the depth of the unsaturated zone from the surface. At the location of the disposal cell the depth of unsaturated zone (saturation less than is extended to more than 20 ft from the top of the soil.

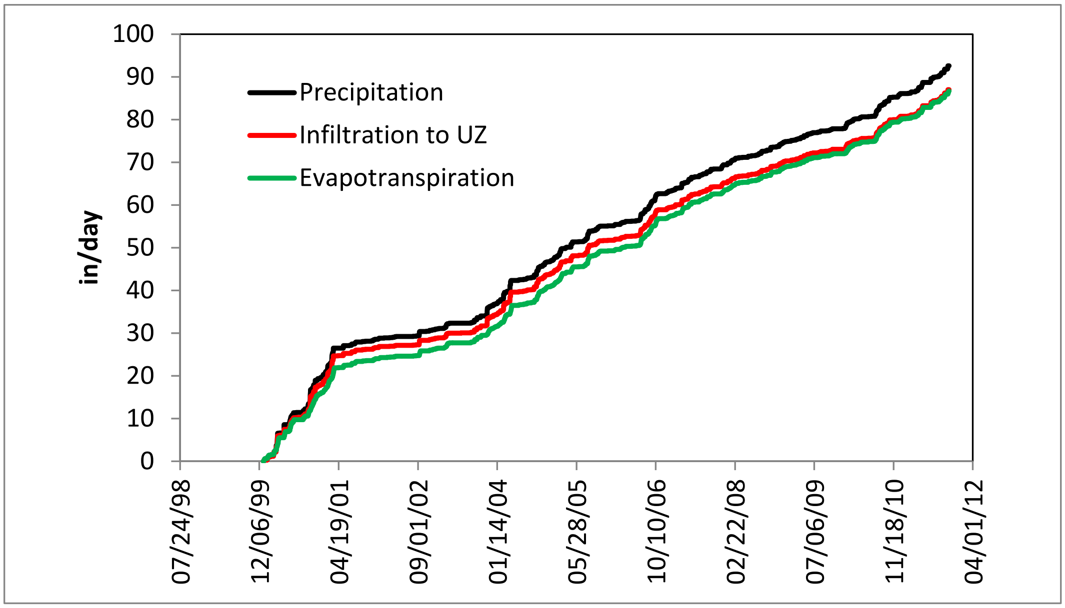


Figure 46 Accumulative water balance at the top of the soil

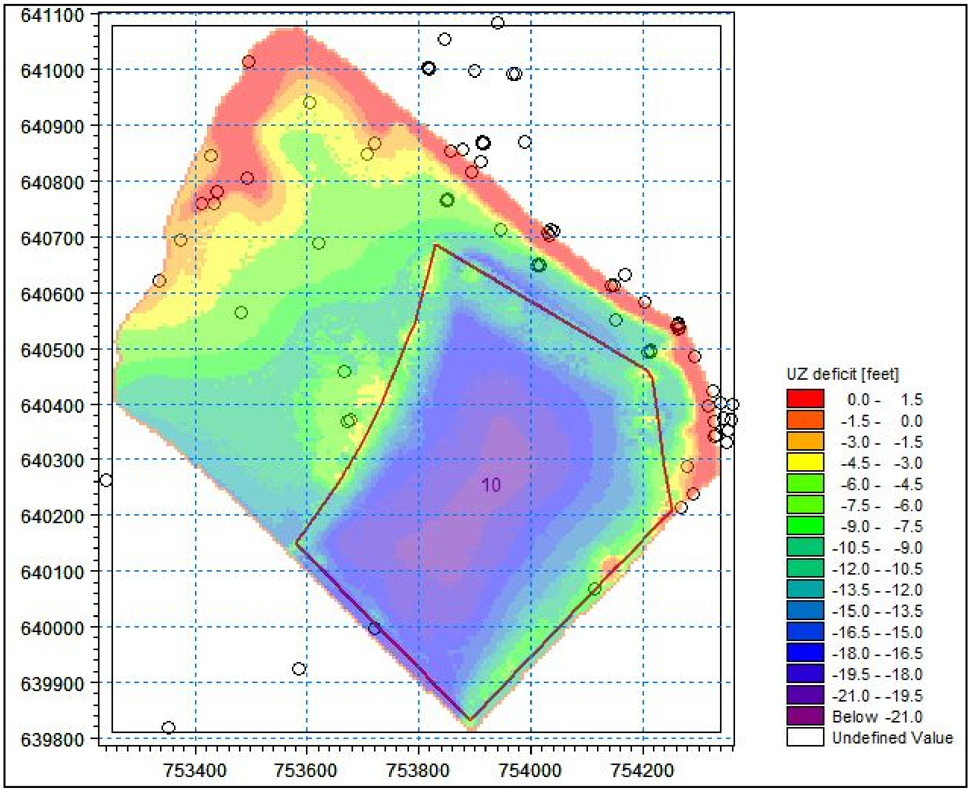


Figure 47 Distance of depth of unsaturated zone (ft)

14 CONCLUSION

To understand the dynamics of the system and changes in moisture and moisture flux it is important to consider the stochastic variation of all hydrological events that control flow and transport at the site. A unique modeling approach simulated the daily climatic conditions and determined the changes in moisture and moisture flux from the disposal cell for a period of ten years. Modeling results indicated that increases in the saturated conductivity at the top of radon barrier do not influence flux from the tailings with time because the tailings behave similar hydraulically to the radon barrier. The presence of a thin layer of low conductivity material anywhere in the cover or tailings restricts flux in the worst case to the saturated conductivity of that material. Furthermore, the precipitation is equivalent to the evapotranspiration losses from the surface layer. Where materials are unsaturated at depth within the radon barrier of tailings slimes, conductivities are typically less than 10^{-8} centimeters per second. If the low conductivity layer is deep within the disposal cell, its saturated properties are less likely to change with time. The model confirmed the following trends:

a) **Infiltration and evapotranspiration**: The accumulated infiltration is equivalent to the accumulated evapotranspiration, resulting in no water reaching the groundwater tailings under the conditions simulated (daily precipitation and evapotranspiration). In general, for the hydrologic conditions at the site, the water from precipitation infiltrates in the shallow surface zone, where it is lost from evapotranspiration.

b) **Extent of Infiltration:** At depth of 0.7 ft in the rip-rap layer (1st layer) the moisture content is very low implying that there is a low possibility of water reaching past that layer (hydraulic conductivity is in the order of 10^{-10} m/s.

c) **Vegetation:** the vegetation affects the rate of evapotranspiration increasing the amount of evaporation thus reducing the amount of water that infiltrates through the layer.

d) **Land cover:** the rip-rap rock cover variations in hydraulic conductivity ranges from 10^{-6} to 10^{-4}. There is no concern that rock rip-rap is increasing percent saturations and downward moisture flux.

The significance of this modeling approach is that the stochastic variations of a variety of hydrologic events are taken under consideration and provide a better understanding of the flow and transport within the site. Therefore, both the operation and the maintenance of the disposal cells can be minimized if they are allowed to progress to a natural condition with some vegetation and soil genesis. Because the covers and underlying tailings have a very low saturated hydraulic conductivity after transient drainage, eventually the amount of moisture leaving the tailings has a negligible effect on groundwater quality. Although some of the UMTRA sites are not in compliance with the groundwater standards, the explanation may be legacy contamination from mining, or earlier higher fluxes from the tailings or unlined processing ponds. Investigation of other legacy sources at the UMTRA sites may help explain persistent groundwater contamination.

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16 APPENDIX B: MODEL CALIBRATION

The model was calibrated by comparing observed with computed data. Preliminary simulation results show a good match of observed and computed monthly data [Figure 48].

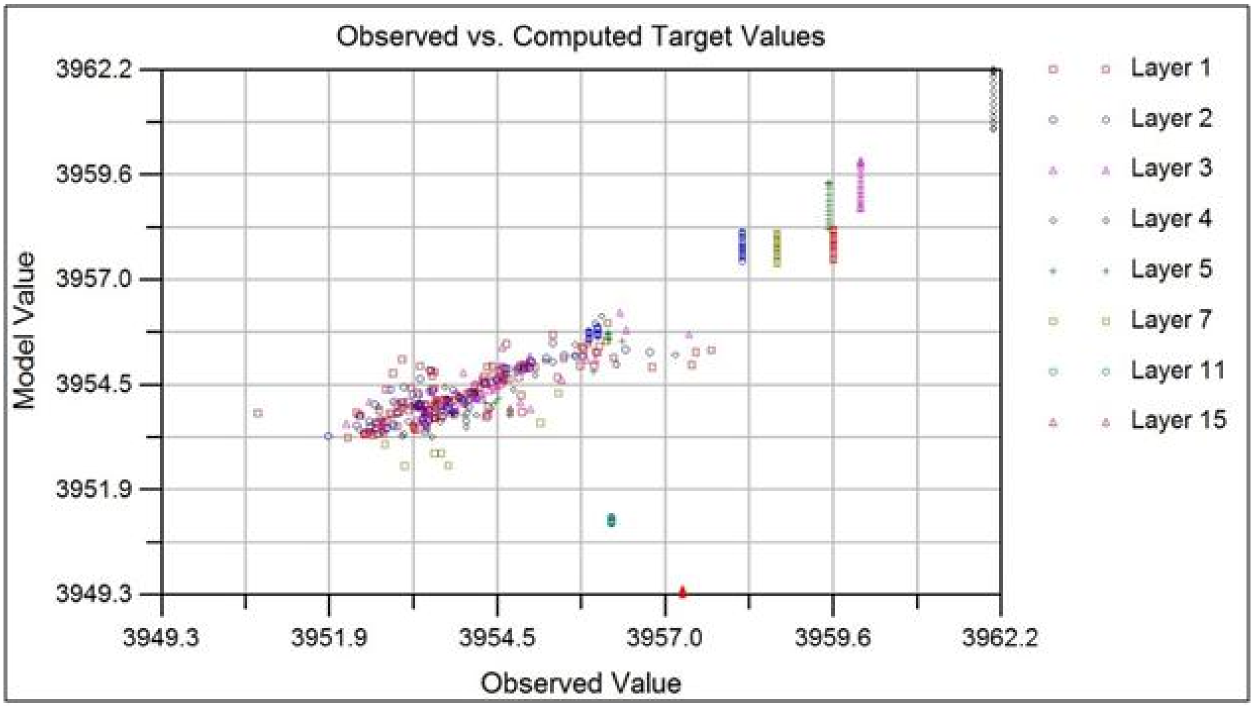


Figure 48 Calibration plot of observed vs. computed heads.

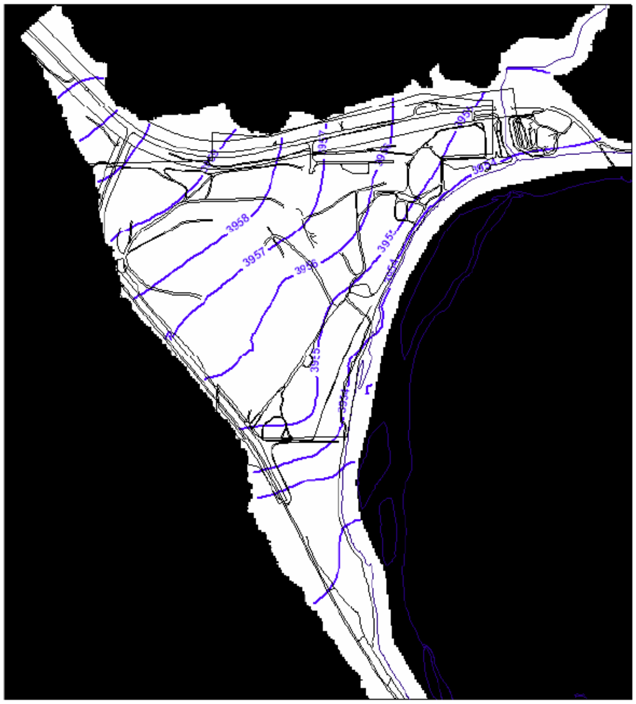
The calibrated model predicts a median monthly groundwater mass balance of 275 gallons per minute. With the exception of April through June, groundwater discharges to the Colorado River from the Moab Site. For April through June, the river recharges the aquifer at between 340 to 1,449 gallons per minute. Simulations results show that ambient recharge (precipitation) occurs in January, February, November and December at rates ranging from 46 to 195 gallons per minute. Tailings pile recharge is constant monthly at 9 gallons per minute. Recharge associated with Moab Wash and the surrounding bedrock is also constant monthly at 39 gallons per minute.

Discharge to the Colorado River is predicted to range between 159 to 495 gallons per minute. Evapotranspiration (ET), which is active May through September and again in November ranges from 22 to 840 gallons per minute.

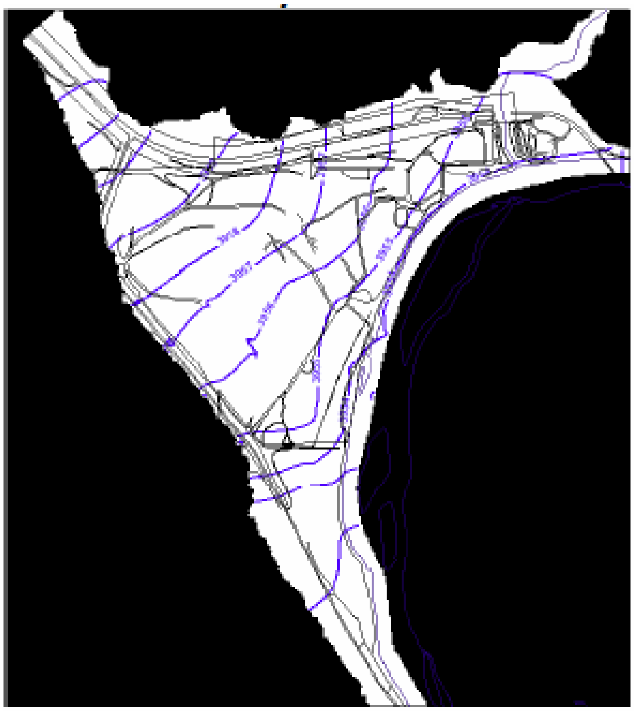
The model predicts that approximately 60% of the water entering the groundwater flow system from Moab Wash and bedrock occurs in the upper three model layers. This result is in agreement with the conceptual model that hypothesizes that recharge and salinity are correlated, the fresher the groundwater the higher the recharge rate.

Examination of the simulated water table shows that January through March groundwater discharges to the Colorado River. The model-predicted April through June water tables shows Colorado River water recharging the aquifer. In July and August simulation results show the effects of ET. September through December the simulated water table once again shows groundwater discharge to the Colorado River.

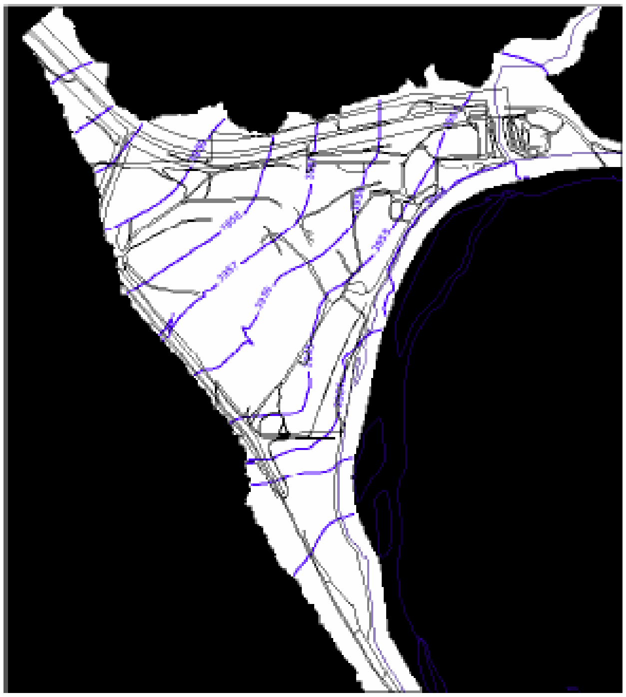
The model reasonably reproduces the general trends present in site well hydrographs [Figure 50, Figure 51 and Figure 52]. Differences in measured and modeled hydrographs are likely a function of assigned Colorado River stage. In summary, the model reasonably matches conceptual mass balance information and replicates expected temporal groundwater flow patterns.



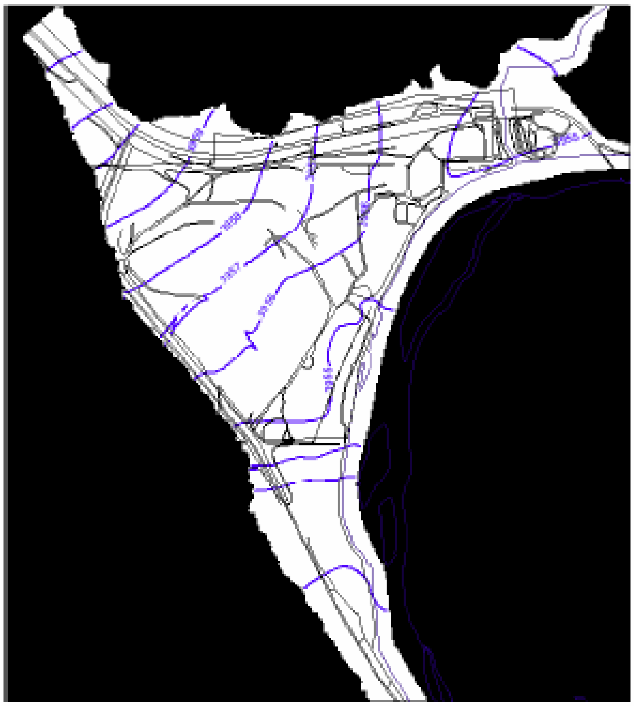
January Water table



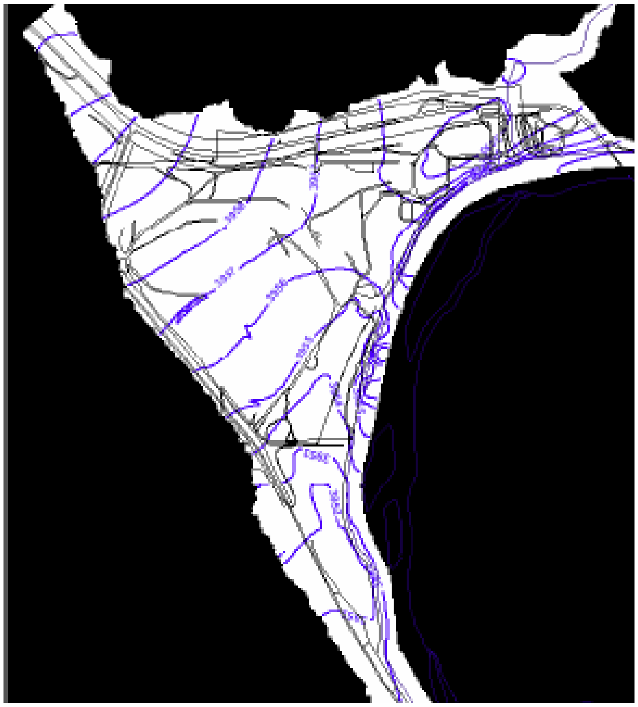
February Water table



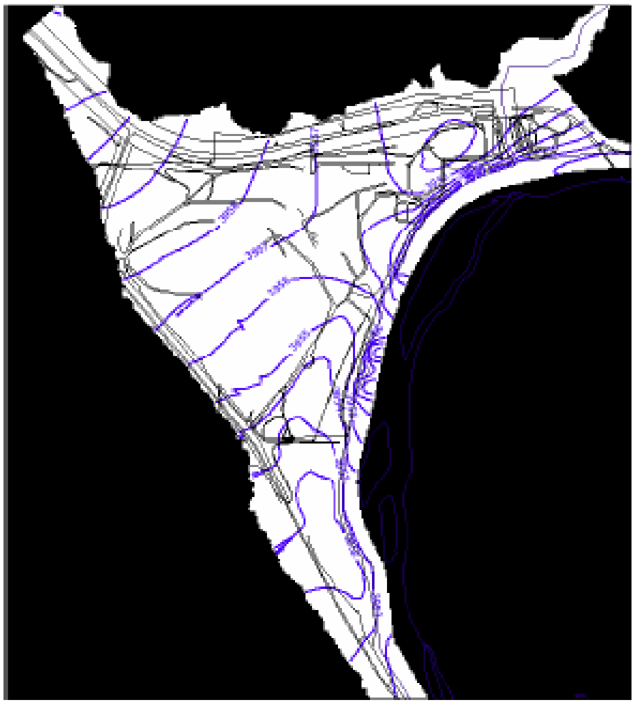
March Water table



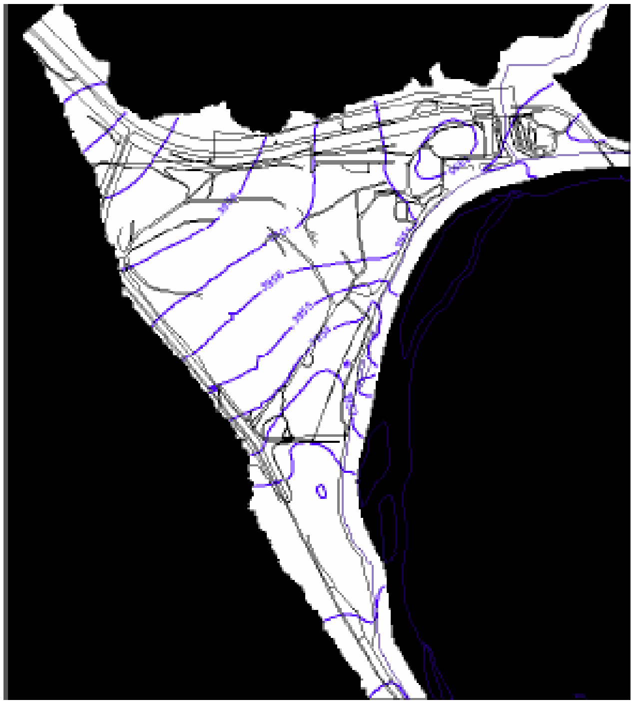
April Water table



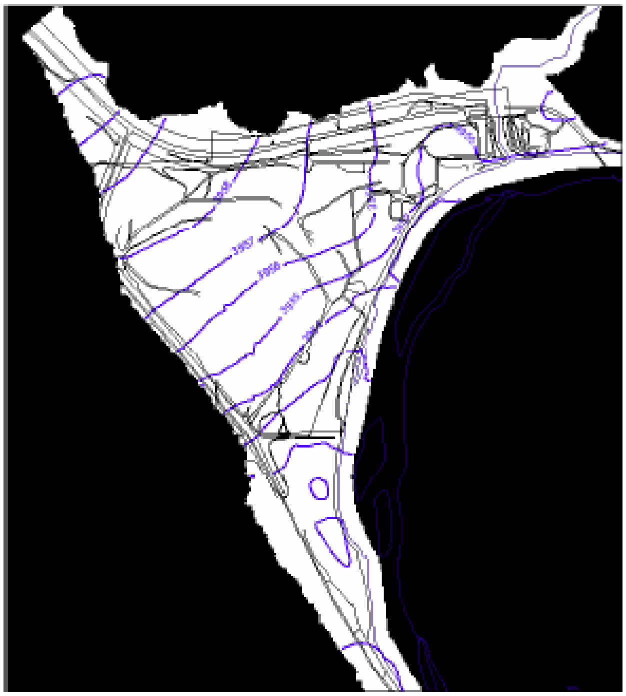
May Water table



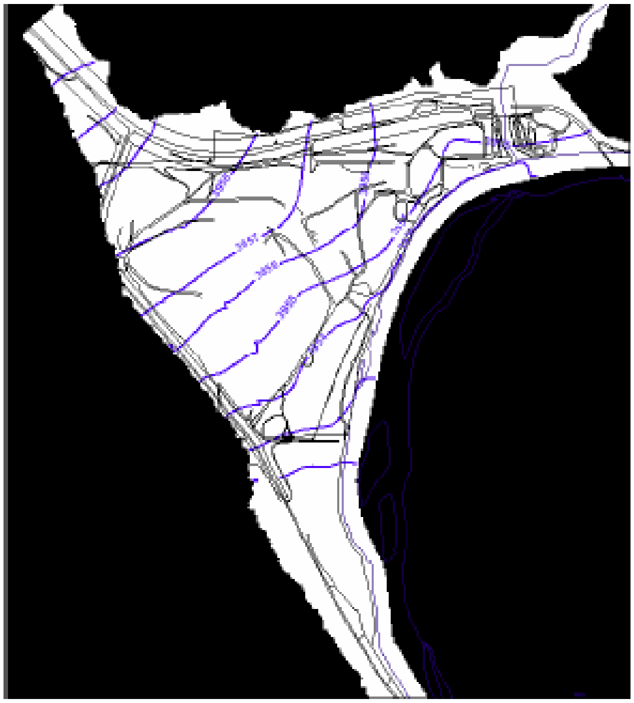
June Water table



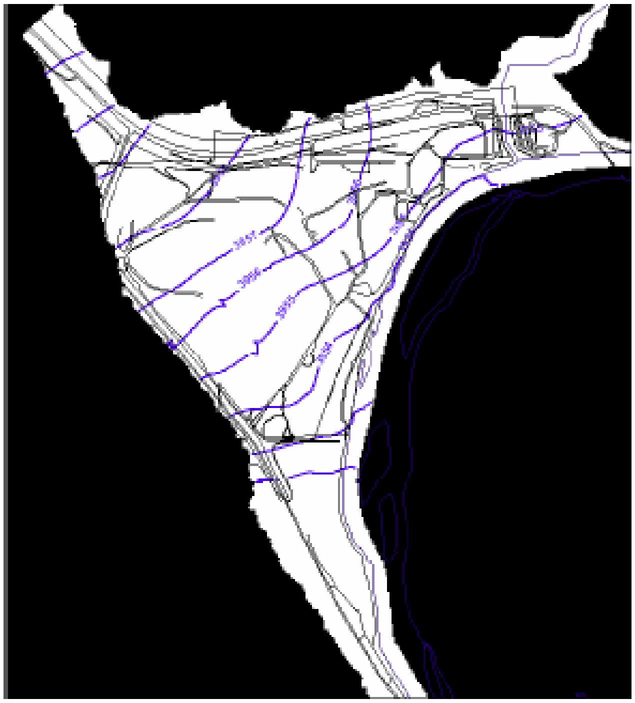
July Water table



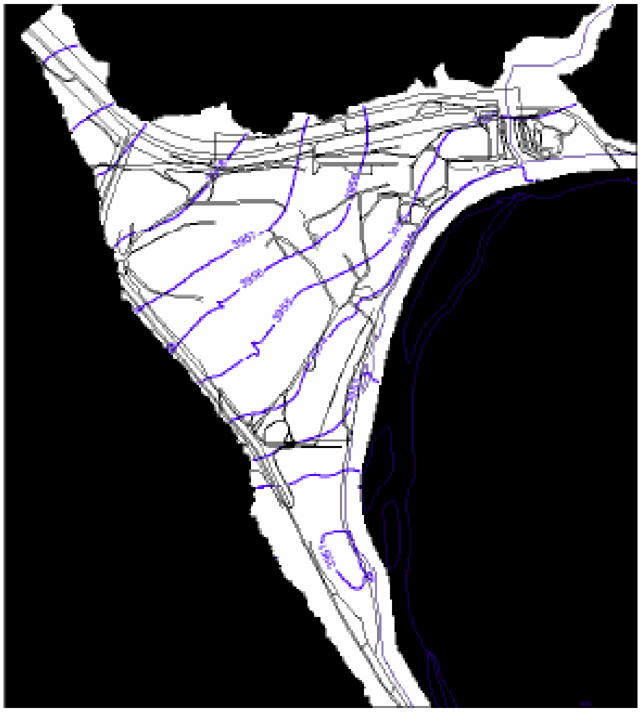
August Water table

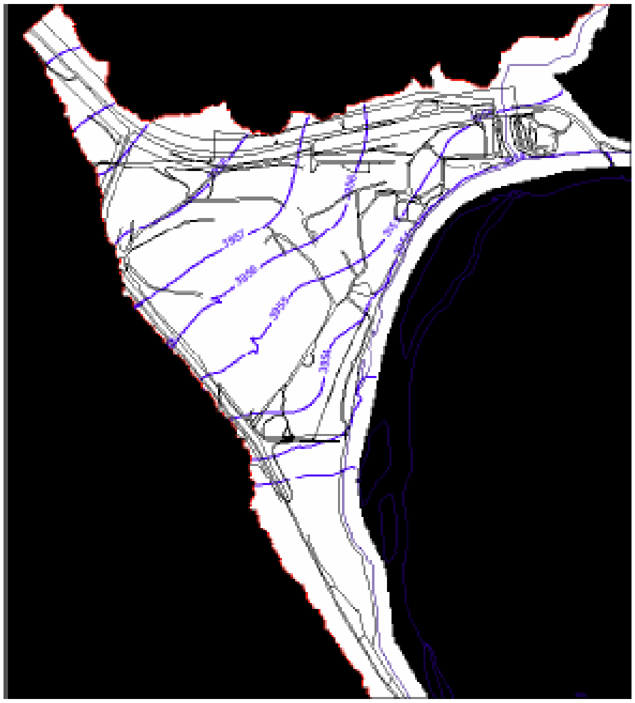


September Water table



October Water table





December Water table

November Water table

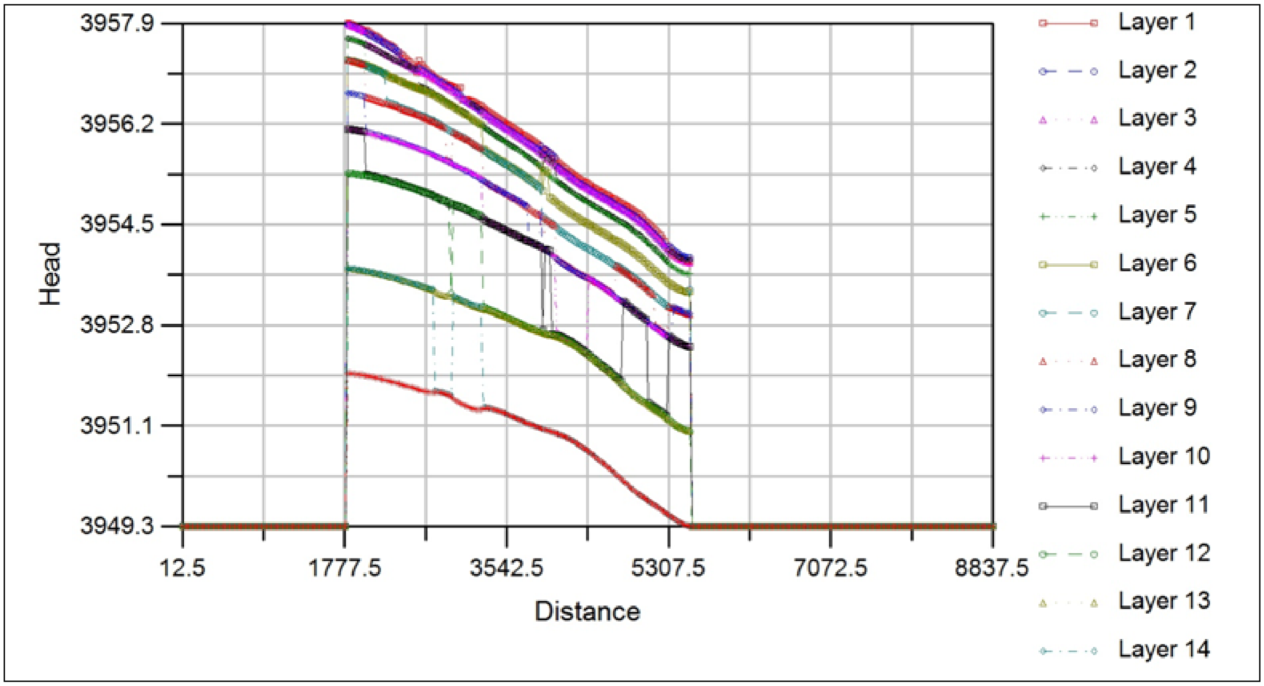


Figure 49 Sectional profile of heads for all layers

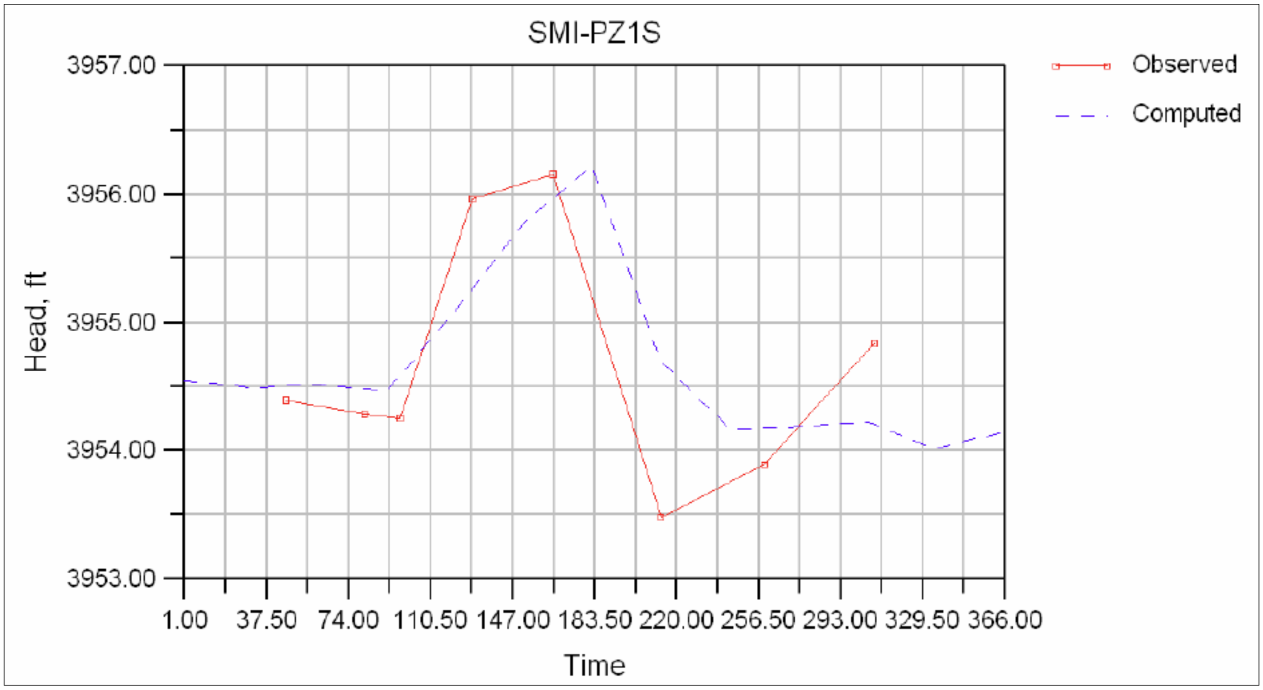


Figure 50 Layer 1 hydrograph at SMI-PZ1S.

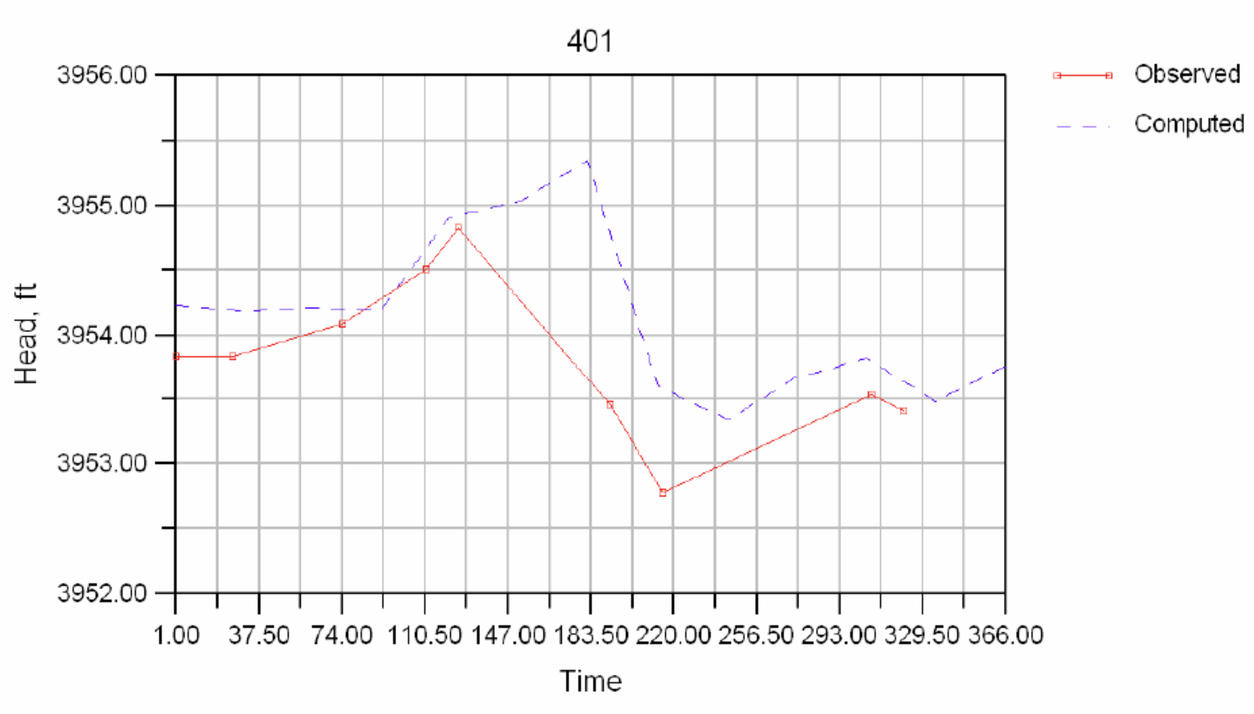


Figure 51 Layer 1 hydrograph at well no. 401.

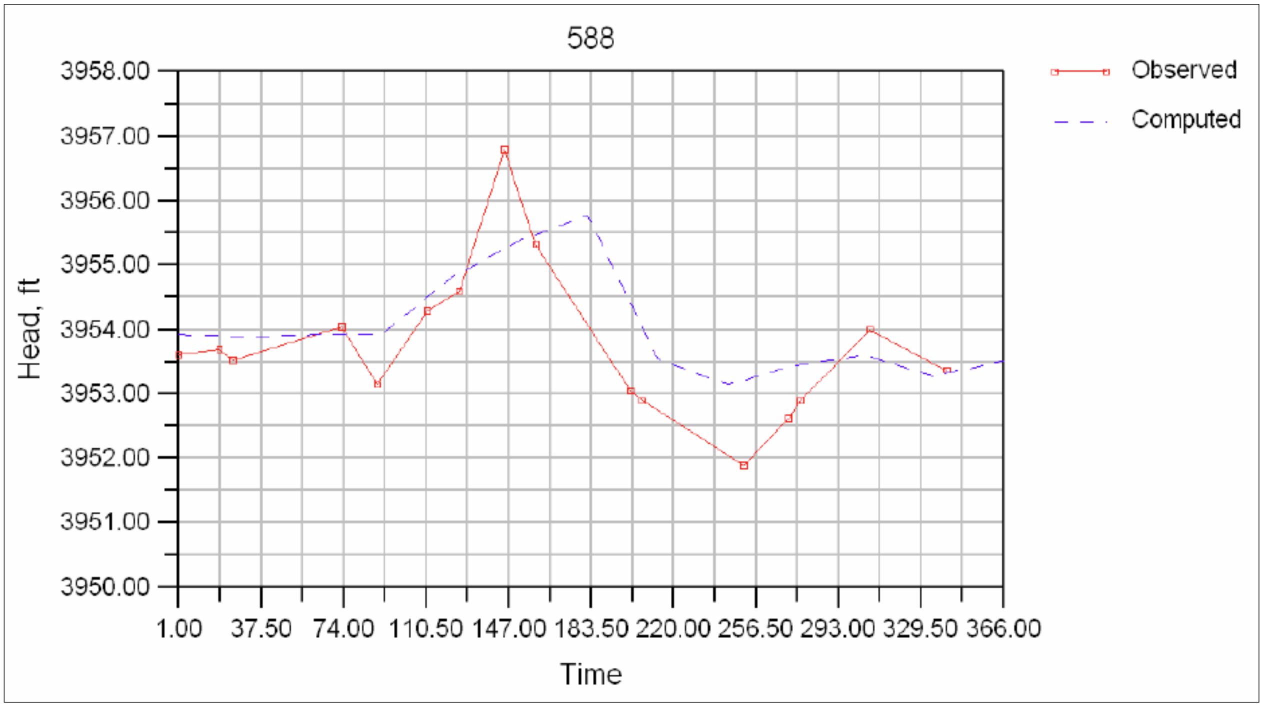


Figure 52 Layer 2 hydrograph at well no. 588.