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UNCC's "Conceptual Groundwater Modeling for Ash Basin Closure – H.B. Robinson Steam Station" Report

Conceptual Groundwater Modeling for Ash Basin Closure
H. B. Robinson Steam Station

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EXECUTIVE SUMMARY

This document reports the results of conceptual groundwater flow and fate and transport modeling of dissolved constituents of concern (COCs) that support development of the conceptual ash basin closure plan at the H. B. Robinson Steam Station. The model is conceptual because a simplified flow system in a vertical 2-D cross section was considered and the three closure options were modeled in limited detail. The conceptual modeling results suggest that limiting infiltration through the ash, either with or without moving ash over about two-thirds of the downgradient ash basin footprint to the remaining upgradient footprint, may have limited benefit in reducing downgradient constituent concentrations. We note that these conceptual modeling results are based on assumed parameters and limited data sets. Calibration for the conceptual model was based on 2014/2015 sampling results for MW-108S, MW-109S, and MW-7. Time dependent source terms for chemical constituents in the fate and transport model were simplified representations of the true constituent loading history of the ash pond. Additional data on COCs in the dissolved and solid phases in the ash would allow the source model to be refined, if needed.

SPLP results from borings and groundwater constituent results from monitoring wells beyond the original thalweg in the ash basin suggest that constituent concentrations in soils and groundwater may be below maximum contaminant levels beyond the ash overlying the thalweg. Thus the two-dimensional model described herein likely represents a conservative assessment of the critical volume of the ash basin that must be considered for closure. The exact lateral and vertical extent of that critical volume is not possible to determine with the data currently available. As noted in the “Robinson Ash Basin Groundwater Assessment for the MW-7 Area, H.B. Robinson Steam Electric Plant, Darlington County, South Carolina” (HDR, February 26, 2015), arsenic was not detected in MW-7D, indicating the vertical extent of contamination in the vicinity of MW-7 is delineated and, laterally, arsenic was not detected above the laboratory reporting limit in MW-120S and MW-120D nor the surface water in the discharge canal or Lake Robinson. Further, it is noted that none of the deep wells (including those installed within the boundary of the basin itself) detected arsenic. Based on these data, further refinement of the fate and transport modeling would be prudent following collection of additional sampling data within the basin that could better define the extent of arsenic within the thalweg.

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1.0 Introduction

Duke Energy Progress (Duke Energy) owns and operates the H.B. Robinson Steam Electric Plant (Robinson Plant) located near Hartsville in Darlington County, South Carolina (Figure 1). The Robinson Plant coal ash management facilities include a former 177-megawatt coal-fired unit (Unit 1), one ash basin located north of the Robinson Plant and west of Lake Robinson, and an older ash storage area (1960 Fill Area) located west of Unit 1 (Figure 2). Coal ash residue generated during the coal combustion process at Unit 1 was stored in the 1960 Fill Area from 1960 until the mid-1970s when the approximate 72-acre ash basin was constructed. The ash basin continued to receive coal ash residue until October 2012 when Unit 1 was retired.

Duke Energy retained HDR to develop a Conceptual Closure Plan (Plan) for the Robinson Plant ash basin. To do so, HDR implemented a geotechnical and environmental exploration program between July and November 2014 that consisted of soil boring completion; monitoring well installation; index property testing of soil and ash; constituent testing of soil, ash, groundwater, and free water; and in-situ hydraulic conductivity testing. The data derived from the field program is being evaluated to achieve the following project objectives:

- Determine the amount of coal ash residue in the ash basin and 1960 Fill Area
- Characterize subsurface materials within the ash management areas, down-gradient of the ash basin, and in background areas of the site
- Develop a Site Conceptual Model (SCM) to serve as the basis for understanding the hydrogeologic characteristics of the site and ash basin (both existing and under the preliminary closure options).
- Use the SCM to develop a conceptual plan for closure of the ash basin that is protective of human health and the environment and acceptable to SCDHEC Bureau of Water per their guidance *Proper Closeout of Wastewater Treatment Facilities*, *Regulation 61-82*, dated April 11, 1980

The subsurface investigation included completion of 22 environmental soil borings; 11 geotechnical soil borings; installation of 30 groundwater monitoring wells; and subsequent soil, ash, groundwater, and free water sample collection and testing. Soil boring and monitoring well locations are shown on Figure 3.

Closure of the 1960 Fill Area will be regulated under a Consent Agreement between Duke Energy and the SCDHEC Bureau of Solid Waste. However, the final disposition of ash within the 1960 Fill Area will be incorporated into the closure plan for the ash basin.

A Conceptual Closure Planning document was submitted to SCDHEC as an update of Duke Energy's progress to date on the Robinson Ash Basin Closure Investigation and describe future work activities that will support development of a preferred ash basin closure plan (HDR 2014 a). A summary of data and information collected as part of the Robinson Ash Basin Closure Investigation, along with a summary of results, was provided in this updated report. A more

detailed description of data collected, methodologies used, and testing results was provided in the companion Robinson Ash Basin Closure Investigation Data Report (HDR 2014b).

2.0 Purpose

The purpose of this document is to report the results of conceptual groundwater flow and fate and transport modeling of dissolved constituents of concern (COCs) that support development of the conceptual ash basin closure plan. The model is conceptual because a simplified flow system in two dimensions was considered and the three closure options were modeled in limited detail.

Data required for the modeling effort were obtained from Robinson Ash Basin Closure Investigation and Data Report (HDR 2014), the Sorption Evaluation for Ash Basin Closure — H. B. Robinson Steam Station (UNC-Charlotte 2015), and the Winter 2014/2015 groundwater sample data set.

Three conceptual closure options were simulated in the conceptual model: cover in place, hybrid cover in place, and no cover. Complete excavation was not modeled, however, the hybrid cover in place is essentially equivalent to complete excavation as material from the eastern two-thirds of the footprint will be removed which represents the vast majority of ash below the groundwater table within the basin boundary.

3.0 Site Background (HDR, 2014)

3.1 Plant Description

The Robinson Plant is a former coal-fired electricity generating facility located approximately 4.5 miles north of Hartsville, Darlington County, South Carolina. The site is bounded by Icy Street to the north, West Old Camden Road to the south, Lake Robinson to the east, and South Carolina Highway 151/West Bobo Newsome Highway to the west.

Development of the Robinson Plant facility began in the late 1950s when Black Creek was impounded to create Lake Robinson. Shortly thereafter, the coal-fired unit (Unit 1) began commercial operation in 1960 until it was retired in October 2012. The 724-megawatt nuclear unit (Unit 2) was brought online in 1971. Duke Energy also owns and operates the H.B. Robinson/Darlington Electric Power Plant (Darlington County Plant) which is located just north of the Robinson Plant and along the western shore of Lake Robinson. The 790-megawatt Darlington County Plant consists of 13 combustion-turbine units fueled by natural gas and oil.

3.2 Ash Management Facilities

The Robinson Plant coal ash management facilities include the coal-fired unit (Unit 1), one ash basin located north of the fossil and nuclear units, and the 1960 Fill Area located west of Units 1 and 2 (Figure 2).

The 1960 Fill Area was created in 1960 and received ash from Unit 1 until the ash basin was constructed in the mid-1970s. Between May 2013 and August 2014, Duke Energy contracted

AMEC Environment & Infrastructure, Inc. (AMEC) to evaluate the extent and volume of ash stored in this area. Based on data obtained during this assessment, ash was found to cover a surficial area of approximately 25.0 acres with a maximum ash thickness of 16.3 feet. The calculated volume of ash within the 1960 Fill Area is 275,800 cubic yards (cy) (AMEC 2014).

The 72-acre ash basin is comprised of a 49-acre basin and a 23-acre dry ash storage area near the upstream (e.g., western) end of the ash basin. The basin was formed via construction of a dam across an unnamed tributary to Black Creek. The basin began receiving sluiced ash from Unit 1 in the mid-1970s, and continued to receive sluiced ash until Unit 1 was retired in October 2012. Based on data obtained during the current exploration program, ash thickness within the basin ranges from 11 feet along the northern flank of the basin to 53 feet in the middle of the basin. Ash thickness is expected to be greatest within the thalweg (i.e., deepest portion of the channel) of the former tributary to Black Creek.

There are no permitted National Pollutant Discharge Elimination System (NPDES) outfalls from the basin to Lake Robinson. However, the ash basin does have a permitted NPDES outfall to the discharge canal located northeast of the basin. In 2014, Duke Energy submitted an NPDES permit application update to re-route stormwater to the discharge canal. The basin also receives discharge from the Darlington County Plant oil/water separator. There is currently no standing water in the 1960 Fill Area or the ash basin, except for the northeastern most corner of the basin where the basin receives discharge from the Darlington County Plant.

3.3 Regional Geology/Hydrogeology

South Carolina is divided into distinct regions by portions of three physiographic provinces: the Atlantic Coastal Plain, Piedmont, and Blue Ridge (Fenneman 1938). The Coastal Plain is a region of broad, relatively flat terraces of primarily unconsolidated sediments and carbonate rocks. These materials, ranging in age from Cretaceous to Quaternary, were deposited in shallow seas by rivers draining the Blue Ridge and Piedmont provinces.

Within the upper Coastal Plain and extending across the middle of South Carolina is a narrow, irregular band of rolling hills known as the Carolina Sandhills. These rounded, gently sloping hills range in elevation from 250 to 450 feet above sea level and are generally higher than either the adjacent Piedmont or Coastal Plain regions. The Sandhills region varies in width from 5 to 30 miles, although it is absent along some large river systems such as the Congaree River near Columbia, South Carolina, where it has cut completely through the Sandhills deposits to expose the underlying Piedmont rocks.

The Robinson Plant is located within the Pee Dee area of South Carolina. According to the “Preliminary Assessment of the Groundwater in Part of the Pee Dee Region, South Carolina” (SCDHEC 2003), aquifer systems beneath the Pee Dee Region are primarily Late Cretaceous in age and include the Black Creek, Middendorf, and Cape Fear systems. Groundwater is the principal source of potable water in the Pee Dee region and the Middendorf and Middendorf/Cape Fear systems together are the primary source of groundwater for Darlington County, South Carolina. Groundwater is also obtainable from the unconfined surficial aquifer that typically extends from land surface to a depth of approximately 30 to 50 feet below land

surface. Groundwater in the surficial aquifer is generally unconfined and recharged primarily from precipitation, losing streams and rivers, and up-flow from underlying aquifers. The surficial aquifer is underlain in the region by fine- to coarse-grained sands with discontinuous layers of sandy clays, kaolins, and gravel. The base of the surficial aquifer typically displays an increase in clay and kaolin and is considered to be the upper confining unit of the Middendorf aquifer. The weathered nature of the sediments in addition to similar parent material makes the exact transition between the surficial aquifer and underlying aquifers very difficult to identify.

The Middendorf aquifer overlies crystalline bedrock and extends from the Fall Line in the upper coastal plain to the Atlantic coast. Sediment within the aquifer is described as sand to gravelly sand with varying degrees of induration. Transmissivity values in the Middendorf aquifer are relatively high with individual supply wells obtaining groundwater from the aquifer producing yields of up to 2,000 gallons per minute. Groundwater in the Middendorf aquifer is under artesian conditions with primary recharge along the outcrop of the aquifer along the Fall Line and minor recharge controlled by differences in hydraulic head with neighboring aquifers. The Middendorf aquifer has reportedly experienced a potentiometric head loss of greater than 195 feet since "predevelopment" in 1927 to current levels. The primary reason for this substantial head loss has been attributed to an increase in groundwater demand in the region (Catlin 2008).

3.4 Site Geology/Hydrogeology

3.4.1 Site Geology

Based on HDR's review of soil boring and monitoring well installation logs provided by Duke Energy for previous work completed on site as well as HDR's observations made during the recent subsurface investigation, stratigraphy in the vicinity of the ash basin consists of the following material types: fill, ash, alluvium, Coastal Plain sediments, and bedrock. In general, fill was restricted to borings advanced through the ash basin dam while ash is restricted to the confines of the basin. Alluvium was present beneath ash in several borings advanced into the historic drainage feature that was dammed to create the ash basin. Coastal Plain sediments consisting predominantly of sand with some silt and clay were encountered across the site. Bedrock was reportedly encountered at 398 feet below ground surface during installation of supply Well D in December 2004. Well D is located adjacent to the Unit 2 facility, approximately 4,900 feet south of the ash basin. The general stratigraphic units, in sequence from the ground surface down to boring termination, are defined as follows:

Fill – Fill material generally consisted of re-worked sand and silt that were borrowed from one area of the site and re-distributed to other areas. Based on a 1956 Earth Dam and Spillway drawing provided by Duke Energy, fill was placed around a 12-foot-wide compacted impervious core during construction of the ash basin embankment.

Ash – Ash is present within the ash basin and 1960 Fill Area. Ash has been characterized in the field as gray to dark gray fine- to coarse-grained material.

Alluvium – Alluvium is unconsolidated soil and sediment that has been eroded and re-deposited by streams and rivers. Alluvium may consist of a variety of materials ranging from silts and clays

to sands and gravels. Alluvium was present beneath ash in several borings advanced into the historic drainage feature that was dammed to create the ash basin.

Coastal Plain Sediments – Coastal Plain sediments representing fluvial or upper delta-plain depositional environments are found across the site. Based on boring logs reviewed, sediments were characterized as yellow, reddish yellow, pink, pale brown, or brown coarse- to fine-grained sand with gray to white to pink clay lenses and extend to an average depth of greater than 300 feet below ground surface (bgs).

Bedrock – Bedrock was encountered in several historic well borings in the vicinity of the Unit 2 facility. Bedrock was described as “greenish rock” and presumed to represent glauconitic basement rock of the Piedmont. Bedrock was not encountered during the current conceptual closure assessment activities.

Based on the presence of alluvium and unconsolidated sediments beneath the ash basin embankment, Duke Energy will conduct liquefaction analyses during the next phase of work to determine susceptibility to differential settlement resulting from seismic events and determine engineering remedies to mitigate for potential differential settlement.

Boring logs and laboratory reports providing detailed geologic information are provided in the Data Report (HDR 2014). Based on the results of exploration activities as well as review of historical borings, well data, and drawings provided by Duke Energy, HDR developed four cross-sections (A-A’ through D-D’) to illustrate their interpretation of the hydrostratigraphy of the site. General section descriptions are:

Section A-A’ extends approximately west to east (i.e., longitudinally) through the ash basin.

Section B-B’ extends north to south across the ash basin and dry stack area in the western extent of the basin.

Section C-C’ extends north to south across the central part of the ash basin.

Section D-D’ extends north to south across the eastern extent of the ash basin.

The locations of cross-section lines are shown on Figure 3. Cross-section A-A’ is shown on Figure 5. Cross-sections B-B’, C-C’ and D-D’ are shown on Figure 6. Note that cross-sections are interpretations and that conditions between borings are estimated and/or inferred and were developed in part from historic drawings.

3.4.2 Site Hydrogeology

Groundwater occurrence within and around the ash basin was relatively uniform and generally follows topography across the site. Hydrogeologically, groundwater was encountered under unconfined conditions in the surficial aquifer at depths ranging from 28.44 to 44.69 feet below the top of well casings in shallow wells in the vicinity of the ash basin (excluding well MW-108S as it is located on top of the dry ash stack). The exploration program was developed to include installation of paired monitoring wells in many locations to evaluate groundwater characteristics in the upper and lower portions of the unconfined aquifer. Note that groundwater elevations

between paired wells seldom varied by more than 1 foot confirming that the portion of the unconfined aquifer that was the subject of this investigation (shallower than 100 feet) is composed of relatively homogenous material with little or no significant confining layers present.

Subsequent to completion of the well installation program, groundwater elevations in the monitoring wells were measured during a comprehensive gauging event on November 17, 2014. A second gauging and sampling event was conducted in late February to early March 2015 for evaluation of groundwater position relative to seasonal variations.

Groundwater elevations measured in shallow monitoring wells installed within the ash basin footprint ranged from 227.82 feet in well MW-110S to 235.53 feet in well MW-108S. Corresponding ground surface elevations at wells MW-110S and MW-108S are 270.17 and 283.97 feet, respectively. Groundwater elevations measured in wells located beyond the ash basin waste boundary ranged from 222.67 in well MW-112S to 236.44 in well MW-107S. Groundwater elevations measured in shallow wells installed within the 1960 Fill Area ranged from 226.30 feet in well MW-118S to 229.25 feet in well MW-117S.

Based on groundwater elevation data collected on November 17, 2014, approximately 18 feet of ash was located below the groundwater table in the vicinity of well pair MW-109S/D. Groundwater elevations for monitoring wells considered in the modeling are presented in Table 1. Potentiometric surface maps for shallow and deeper wells, based on groundwater elevations obtained on November 17, 2014, are shown on Figures 7 and 8. Groundwater table position is shown in each of the four previously referenced cross-sections.

3.4.3 Surface Water

The Robinson Plant site is located along the western edge of Lake Robinson. The ash basin was formed via construction of a dam across an unnamed tributary to Black Creek in the mid-1970s. Modifications to the ash basin and ash basin riser barrel were summarized in HDR (2014). The inlet elevation for the upstream riser barrel (Skimmer-005) is 263.87 feet. The 36-inch reinforced concrete pipe (RCP) exiting the riser barrel and embedded in the ash basin embankment enters Catch Basin No. 2, having an inlet elevation of 256.04 feet. The outlet from Catch Basin No. 2 enters new Catch Basin A with an inlet elevation of 243.5 feet. The outlet pipe (36-inch HDPE) from Catch Basin A exits into the discharge canal with an invert elevation of 234.12 feet.

4.0 Ash Basin Conceptual Groundwater Flow Model

Figures 5 through 8 were used to develop the conceptual groundwater flow model. Figure 9 depicts a conceptual two-dimensional, steady-state groundwater flow model for Cross-section A-A' through ash basin was modified to include MW-7S, MW-7D, and MW-119S. The horizontal extent is from the exposed ground just beyond the western limit of exposed ash to the eastern limit at the discharge canal. The vertical extent is from the exposed ground, ash surface, or dam surface to the lower limit of shallow groundwater flow. The western boundary is considered to be a constant head type where groundwater enters the flow model volume, or domain, and

flows to the east, consistent with the observed site hydrogeology. The eastern boundary is also constant head where groundwater exits the model domain, ultimately discharging to the canal and Lake Robinson. The lower boundary is considered no flow, also consistent with the observed site hydrogeology. Lake Robinson is considered to be the ultimate discharge location for groundwater from the site. The infiltration rate at the water table across the horizontal extent of the domain is that due to precipitation minus evapotranspiration except where the ash basin received additional infiltration from the station's wastewater system. The domain is subdivided to represent zones of similar hydraulic conductivity including ash, fill at the dam, and unconsolidated sediments. Groundwater recharge from infiltration at the water table and inflow from the western constant head boundary ultimately moves horizontally to the east through the dam and unconsolidated sediments as depth, exiting at the downgradient, constant head boundary near the discharge canal.

Two-dimensional models are useful and efficient when they adequately represent general groundwater flow patterns at critical areas of site, making best use of available data and avoiding the effort and expense required to develop more general three-dimensional models. Two-dimensional models have limited applications such as comparing site remediation and closure options in the initial, project planning stage. In plan view, the two-dimensional model of the modified cross section A-A' follows the original thalweg of the tributary to Black Creek from which the ash basin was formed. SPLP results from the AP-series of borings and groundwater constituent results from monitoring wells beyond the thalweg (such as MW-110S) (HDR 2014) suggest that constituent concentrations in soils and groundwater may be below maximum contaminant levels beyond the ash immediately overlying the thalweg. Thus the two-dimensional model described herein likely represents the critical (conservative) volume of the ash basin that must be considered for closure.

5.0 Ash Basin Conceptual Fate and Transport Model

The chemical constituents of interest enter the ash basin system in the dissolved phase and solid phase of the station's sluiced wastewater discharge. Some constituents are also present in native soils and groundwater beneath the basin. In the basin, constituents may incur phase changes through a number of processes that likely include dissolution, precipitation, adsorption, and desorption. Dissolved phase constituents may incur these phase changes as they are transported in groundwater flowing downgradient from the basin. In the conceptual fate and transport model, chemical constituents entered the basin in the dissolved phase by specifying their concentration in recharge applied at the basin's water table. Phase changes (dissolution, precipitation, adsorption, and desorption) were collectively taken into account by specifying a linear sorption coefficient K_d that quantifies the equilibrium relationship between chemical constituents in the dissolved and adsorbed phases. Sorption was modeled as an instantaneous, reversible reaction.

The accumulation and subsequent release of chemical constituents in the ash basin over time is a complex process that cannot be readily quantified. Thus, a simple source zone model that is consistent with measured constituents in groundwater at locations within Cross-section A-A' was applied. The modeled entry of chemical constituents into the ash basin, as represented by

the recharge concentration, decreased with time as described in the section on fate and transport model calibration. We note that the assumed initial source area concentration used in the model (1,900 µg/L arsenic) is 70% higher than the maximum observed concentration (1,100 µg/L in MW-109S).

6.0 Computer Model

Groundwater flow and chemical constituent fate and transport were modeled in two dimensions using Visual MODFLOW version 2011.1, with the MODFOW-2005 groundwater flow engine and the MT3DMS version 5.2 transport engine with linear isotherm sorption (Schlumberger Water Services 2011), to predict pre- and post-closure chemical constituent concentrations over time across the model domain and at or near the compliance boundary. The upstream finite difference solution method with the implicit GCG solver was applied for advection in the transport model.

Slug test results from Table 2 (HDR 2015b) and sorption coefficients (K_d) for native soils beneath and adjacent to the ash basin system (UNC-Charlotte 2015) were applied to calibrate the groundwater flow and fate and transport models to measured water levels and chemical constituent concentrations at locations within Cross-section A-A' as described in Section 6.2.

6.1 MODFLOW Domain and Boundary Conditions

The exposed surfaces (natural soil, ash, and dam material), water table profile for the Fall 2014 gauging event, and lithologic/stratigraphic contacts were provided in digital format as a function of horizontal distance from the upstream limit of Cross-section A-A'. In MODFLOW, the constant column width and constant layer thickness of the finite difference grid were both ten feet. The model domain extended vertically from elevation 100 ft. upward, beyond the upper limit of the exposed surfaces across the domain width. The water table profile for Fall 2014 was assumed to represent steady-state groundwater flow conditions. It was imported into MODFLOW for calibration and comparison with the modeled water table. Constant head boundaries at the horizontal limits of the domain were taken as the water table elevation at the opposite ends of Cross-section A-A' in Figure 5. Unconfined, or water table, conditions were applied throughout the domain. Cross-sections in Figures 6 and 7 provide further definition of the ash basin perpendicular to Section A-A'.

It was anticipated that at least three zones of similar hydraulic conductivity would be assigned to domain: one each for the natural soils, the fill within the dam, and the coal ash. Further discussion on this topic is provided in the next section on flow model calibration.

6.2 MODFLOW Flow Model Calibration

Calibration parameters for the groundwater flow model were the hydraulic conductivity of each zone, the net infiltration rate (groundwater recharge) due to precipitation, and depth of the model domain. These parameters determined the steady-state flow conditions through the cross section and the resulting, model-generated water table that mimics the measured water table, or calibration target, throughout the cross section.

Slug test data (Table 2) which included results for wells located on Cross-Section A-A', were used to initiate the flow model calibration.

Simulated recharge rates for the period from 1999 to 2012 for the wetlands and uplands areas of Chesterfield County, SC, averaged about 6 to 8 inches per year (Campbell and Landmeyer, 2014). Initial flow model calibration runs used 6" per year as the recharge rate from precipitation.

The modeled water table profile was sensitive to the depth of the model domain. As the depth was made shallower, the modeled profile exhibited mounding, which was not consistent with the relatively low gradient, observed water table. With the vertical extent of the model domain set at elevation 100 ft., a realistic flow regime was generated and using hydraulic parameters that were consistent with the site characterization.

For the recharge rates, hydraulic conductivity, boundary conditions, and model domain depth shown on Figure 10, an acceptable flow model calibration was achieved as indicated by the comparison of measured and modeled water table elevations in Figure 11. A single value of horizontal hydraulic conductivity was applied to the ash and dam fill in order to achieve calibration, especially beneath the dam where water table gradient was not significantly greater than other locations in the cross section. These hydraulic conductivities are considered to be consistent with sediments of the type found at the site, and ash reported on for other sites (HDR 2015).

This model represents steady-state flow conditions for Cross-Section A-A' under the pre-closure, condition with no discharge of wastewater to the ash basin. The normalized root mean squared error (NRMSE) of the measured versus modeled water levels for wells gauged in Fall 2014 and Winter 2015 was calculated as 5.05%, which is below the normally accepted standard of 10%.

6.2.1 Groundwater Flow Time

The flow pathlines on Figure 12, indicate that the approximate groundwater travel times from the western and eastern limits of the basin ash to the discharge canal at Station 4450' are 120 years and 20 years, respectively, for steady-state flow conditions in Cross-Section A-A' under the pre-closure, condition with no discharge of wastewater to the ash basin.

6.2.2 Flow Model Sensitivity Analysis

The sensitivity of the calibrated flow model to changes in hydraulic conductivity and recharge are shown in Figure 13 for the pre-closure, steady-state flow condition. The model responded as expected: the predicted water table elevation rose when hydraulic conductivity decreased and infiltration increased, and vice versa. The sensitivity analysis demonstrates the critical nature of flow model parameter selection which has a direct impact on groundwater flow and chemical constituent transport.

6.3 MODFLOW Fate and Transport Model Calibration and Sensitivity Analysis

The chemical constituents of interest for the fate and transport model were arsenic, barium boron, molybdenum, iron, and manganese. These constituents either exceeded SCDHEC regulatory standards or occurred at elevated levels in groundwater within Cross-section A-A', based on the Fall 2014 and Winter 2015 sampling events.

The calibration parameters for the fate and transport model were: the initial recharge concentrations, their first-order recession rate constants, and their horizontal distribution across the exposed ash surface. The calibration targets were the measured concentrations for each chemical constituent of interest, specifically those for monitoring wells MW-108S, MW-109S, MW-7S, and MW-119S from the Fall 2014 and Winter 2015 sampling events. The calibration target list also included locations where constituents were non-detect. The fate and transport model calibration proceeded in general as follows:

(1) A recession rate constant, with units of time, was selected to calculate the initial recharge concentration using a first-order rate equation with the measured constituent concentration in groundwater directly the ash basin at its corresponding time since the basin was first placed in service. The initial recharge concentration calculated in this way reflected both the measured constituent concentration nearest the ash basin and realistic maximum limits of constituent concentrations in the ash basin.

(2) The calibration parameters were varied to match the time-specific, measured concentrations (or detection limits) in shallow groundwater between the ash basin the downgradient extent of Cross-section A-A'.

Recharge rates to groundwater applied at the ash surface were varied to reflect the operational status of the ash basin over time. Assuming the ash basin was placed in service in 1975, recharged rates were applied as follows for the fate and transport model calibration. For the period from 1975 to 2012, the net infiltration rate attributed to wastewater discharged from the steam station was assumed at 6" per year.

1975 to 2012	10" per year on ash basin, and 4" per year elsewhere
2012 forward	4" per year throughout

For the fate and transport models, effective and total porosities and bulk density were taken from the Appendix 7 of Robinson Ash Basin Closure Investigation (HDR 2014). Dispersivity was estimated to be one-tenth of an estimated average plume length of 2,000 feet (Zheng and Bennett 2002). Site specific sorption coefficients for each chemical constituent, taken from the Sorption Evaluation for Ash Basin Closure — H. B. Robinson Steam Station (UNC-Charlotte 2015), were specified as follows:

constituent	soil type	K_d	R
arsenic	sediment	20 ml/gr	124
arsenic	fill	70 ml/gr	434

barium	sediment	18 ml/gr	112
barium	fill	17 ml/gr	106
molybdenum	sediment	4 ml/gr	26
molybdenum	fill	2 ml/gr	13
boron	sediment	1.5 ml/gr	10
boron	fill	1.5 ml/gr	10

The retardation coefficient R is the ratio of groundwater velocity to chemical constituent velocity which is retarded due to sorption. It was calculated as follows:

$$R = 1 + \frac{\rho_b K_d}{n}$$

where ρ_b is the dry bulk density of the soil (M/L^3) and n is the porosity. The referenced sorption evaluation revealed that iron and manganese leached from each of the soil types under the conditions of the batch and column soil tests. Thus, no valid sorption coefficient was derived for these constituents. In the conceptual fate and transport model, a K_d value of 1 ml/gr was applied in the conceptual model under the assumption that the high concentrations of these constituents associated with the ash basin will experience some degree of sorption in the native soils. The source zone model for arsenic is shown in Figure 14. The source zone models for the remaining parameters, which were defined in the same way, are summarized in Table 3.

The primary objective of the fate and transport model calibration was matching the measured constituent concentration in groundwater downgradient of the ash basin at MW-7S at the time corresponding to the Fall 2014 and Winter 2015 sampling events. The fate and transport model calibration for arsenic also included the measured concentration in MW-119S as a target. The calibration result for arsenic is shown in Figure 15. It suggests that an effective arsenic sorption coefficient must be applied to the area downgradient of the dam which is represented by MW-7S and MW-119S. This effective K_d is less than the value cited previously in this section. The increased arsenic mobility at this location may be due to a higher permeability zone associated with the former thalweg. The fate and transport calibration results for all constituents are summarized in Table 4.

Parameters considered in the fate and transport model sensitivity analysis included the sorption coefficient K_d and effective porosity. Figure 16 illustrates the sensitivity of the concentration boron at a specific location in Cross Section A-A' near MW-7S (Station 4005', elevation 215') over time to the sorption coefficient and effective porosity individually and in combination. Lower concentrations arriving later at the specified location were a consequence of higher K_d. A similar result was noted for higher effective porosity although it is significantly less than that for sorption. Modeled concentrations were also sensitive to dispersivity with higher concentrations observed earlier for higher dispersivity (data not shown).

7.0 Conceptual Modeling and Results for Closure Options

Three closure options were considered using the calibrated, conceptual groundwater flow and fate and transport model. Descriptions of each option and their model-specific characteristics and requirements are provided as follows.

7.1 Model-specific Characteristics and Requirements for Closure Options

The Cover Option consists of placing an impermeable cover over the exposed ash surface. Recharge is applied to the model surface according to the following schedule.

1975 to 2012	10” per year on ash basin, and 4” per year elsewhere
2012 to 2015	4” per year throughout
2015 forward	0” per year on ash basin, and 4” per year elsewhere

The Hybrid Cover Option consists of moving landfilled ash currently located east of station 1400’ to the west, followed by placing an impermeable cover over the newly exposed sediments east of station 1400’ and the remaining exposed ash surface to west. Practically speaking, excavating then moving ash from east of station 1400’ will require temporary dewatering of that portion of the ash basin. Thus, recharge to the surface and a permeable drain beneath the newly exposed sediments were applied to the model according to the following schedule.

1975 to 2012	10” per year on ash basin, and 4” per year elsewhere
2012 to 2015	4” per year throughout
2015 to 2017	permeable drain applied at elevation 210’, station interval 1880’ to 3660’
2017 forward	0” per year on ash basin, and 4” per year elsewhere

The No Cover Option consists of allowing the ash basin to remain in its current state over time. This option represents the base case for comparison to active closure options. Recharge is applied to the model surface according to the following schedule.

1975 to 2012	10” per year on ash basin, and 4” per year elsewhere
2012 forward	4” per year throughout

7.2 Flow Model Results for Closure Options

For the No Cover Option, the ash basin receives recharge continuously over time on the ash surface while the Cover and Hybrid Cover Options do not. This difference is reflected in the long

term, steady-state water table elevations shown in Figure 17. As expected the water table is higher for the No Cover Option. The short-term, transient effect of the permeable drain applied for the Hybrid Cover Option is shown in Figure 18. The permeable drain represents the ash basin having been excavated to elevation 210' from station 1880' feet to station 3660' at the toe of the dam. The drain maintains the groundwater elevation at 210' by removing groundwater that has discharged from the model into the excavated basin over the time period from 2015 to 2017. This groundwater originated from the surrounding saturated zone where the water table is higher than 201'. Figure 17 indicates that the long-term, steady-state groundwater flow conditions for the Cover and Hybrid Cover Options are identical.

7.3 Fate and Transport Model Results for Closure Options

The effect of sorption on chemical constituent fate and transport can be seen in Figure 19 where arsenic and boron concentrations are compared over time (100, 200, and 300 years after ash basin start-up) for the No Cover Option. Arsenic, with higher K_d values, is significantly retarded with respect to the pore velocity of flowing groundwater. Boron, with lower K_d values, is much less retarded. Peak concentrations are relatively higher, and they arrive sooner at downgradient locations for non-sorbing constituents such as boron.

A direct comparison of the three closure options is shown in Figures 20 through 25 for each constituent over time at MW-7S downgradient of the dam. The modeled response for each constituent depends its sorption characteristics, its source zone concentration and distribution, and the closure option flow model including recharge distribution and dewatering.

In Figure 20 for the no cover option, recharge to the ash basin mobilizes residual arsenic from the ash basin resulting in higher concentrations downgradient over time relative to the other closure options at MW-7S. The effect of the hybrid cover and cover options are essentially the same – both reduce mobilization of residual arsenic. Each option will eventually reach a peak concentration followed by a decline that approaches zero if the simulation is carried out further in time.

In Figure 21 for the no cover option, recharge from the ash basin mobilizes residual barium from the ash basin resulting in higher concentrations over time relative to the other options at MW-7S. The cover option has a lower peak concentration than the hybrid cover. This effect may be attributed to the two year period of the ash basin excavation and dewatering (2015-2017) when mobilization of barium was intensified as groundwater was drawn to the excavation. At the 1,000 year mark of the simulation period, the three options are converging. Beyond 1,000 years, the cover option may exceed the other options as the release of residual barium lags that of the other options.

In Figure 22 for the no cover option, recharge from the ash basin continues to mobilize molybdenum from the ash basin resulting in a higher concentrations over time relative to the other options at MW-7S. In contrast to barium, the cover option for molybdenum has a higher peak concentration than the hybrid cover. The K_d for molybdenum is one order of magnitude less than that of barium. During the two year period of ash basin excavation and dewatering (2015-2017), molybdenum desorption apparently was less intense and the mobilized

molybdenum was more diluted as groundwater was drawn to the excavation. During the 300 to 350 year interval of the simulation period, the three options converged. Beyond this time period, the no cover option was at the lowest concentration with the other options at essentially the same, higher concentration.

The simulation result for boron in Figure 23 is similar to that for molybdenum. Both have similar K_d values. The difference in peak concentrations between the cover and hybrid cover options is more well-defined because boron concentrations are higher and its K_d is slightly less. During the 250 to 400 year interval of the simulation period, the no cover option crossed below the other two options. All three options approached zero concentration at 1,000 years.

In Figure 24, the order of peak iron concentrations, for each closure option, from greatest to least are: cover option, hybrid cover option, and no cover. This response is most likely a dilution effect given the high concentration and relatively low estimated K_d for iron. The no cover option provided the greatest dilution due to recharge across the surface of the ash basin. Dilution for the hybrid cover is greater than that for the cover option due to dewatering during the period of excavation (2015-2017). The three options converge at about the 550 year mark of the simulation. In Figure 25, the response for manganese is essentially the same as that for iron except peak concentrations are lower.

These results suggest that limiting infiltration through the ash or moving the ash upgradient has limited effects in reducing downgradient constituent concentrations. Residual constituents that can be mobilized will migrate downgradient until they are depleted.

8.0 Summary and Limitations

Results from the conceptual groundwater flow model calibration are summarized as follows:

- The effective hydraulic conductivity of each soil type in Cross Section A-A' is of similar magnitude.
- Recharge to groundwater due to precipitation across the surface of Cross Section A-A' is approximately 4" per year.
- The approximate lower limit of the shallow groundwater flow zone is at elevation 100'.

Results from the fate and transport model are summarized as follows:

- The relative rates at which chemical constituents move through Cross Section A-A' are dependent on their respective sorption coefficients.
- Residual dissolved and adsorbed chemical constituents in native soils beneath the ash basin may be mobilized over time until they are depleted.
- An effective sorption coefficient for arsenic which is less than the measured values is appropriate for the zone downgradient of the dam and overlying the former thalweg.

Limitations of the conceptual model approach and results include the following:

- Three dimensional groundwater flow in the ash basin was simplified by considering 2D flow only in Cross Section A-A'.

- The net infiltration rate attributed to wastewater from the steam station was assumed at 6” per year, actual infiltration rates were likely larger, perhaps on the order of 18 to 36 inches per year.
- Time dependent source terms for chemical constituents in the fate and transport model were simplified representations of the true constituent loading history of the ash pond. Additional data on COCs in the dissolved and solid phases in the ash will allow the source model to be refined, resulting in a more cost-effective and efficient closure plan.
- The processes determining the fate of some of the chemical constituents in native soils of Cross Section A-A’ are numerous and are likely to include dissolution, precipitation, adsorption, and desorption.
- In the model, sorption only was considered using a single-valued sorption coefficient.
- The facts that arsenic is not detected in the deeper wells beneath the basin (even though there appears to be a significant downward component to groundwater flow); arsenic is not detected in groundwater or surface water to the east of MW-119S (even though estimated horizontal groundwater flow velocities indicate impacted groundwater from the basin would have passed that area by now); and that SPLP samples from the ash within the basin are more than 10 times less than the assumed source concentrations, combined possibly indicate that source conditions are less concentrated and/or the source has a smaller mass than has been assumed in the conceptual model. Verification sampling in the source area would be necessary to better quantify the source zone concentrations and reduce the degree of uncertainty in the model’s ability to project future arsenic levels in groundwater and is therefore recommended prior to proceeding with finalizing the closure plan.

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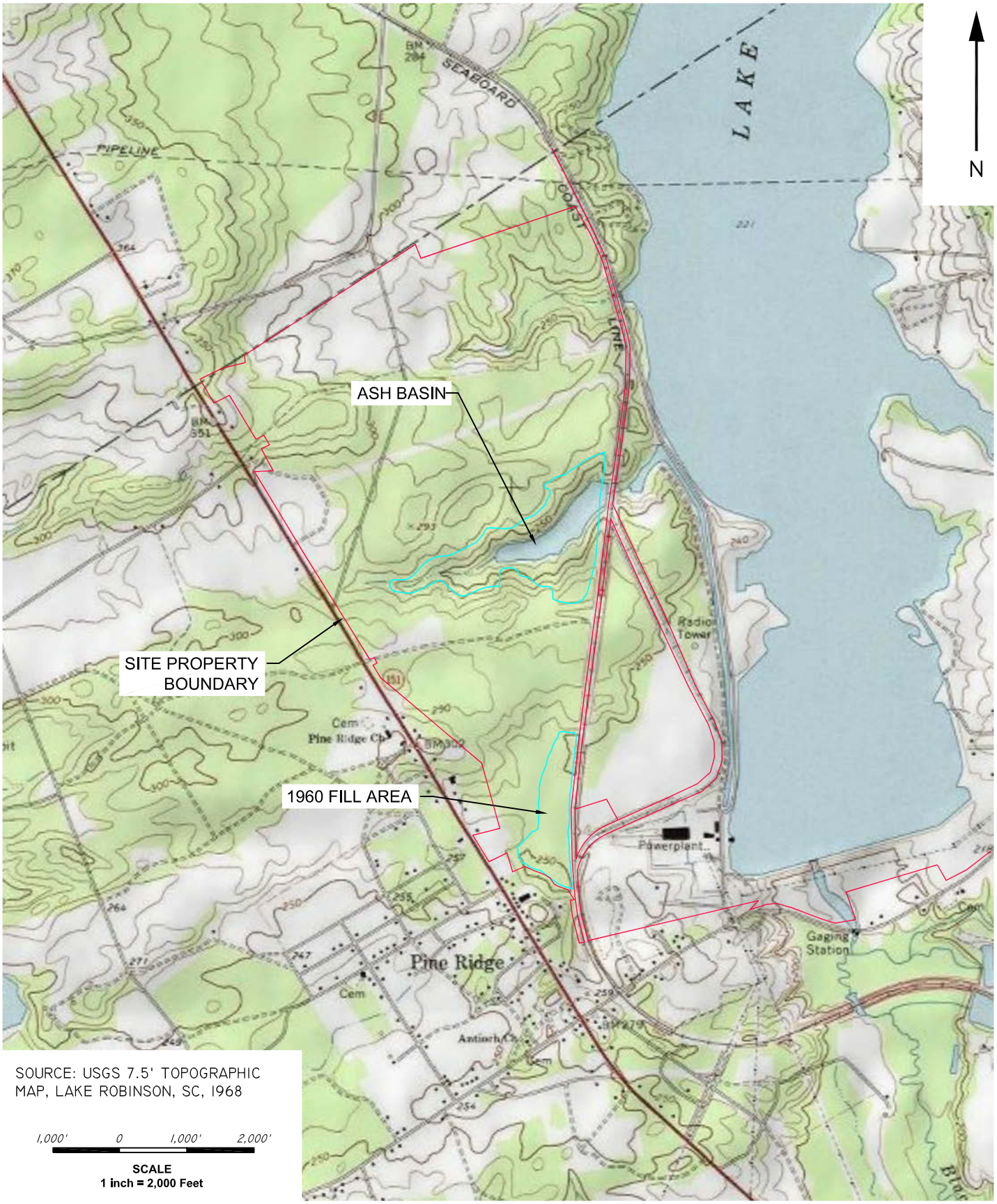
Zheng, C. and Bennett, G., Applied Contaminant Transport Modeling Second Edition, Wiley Interscience, 2002.



SITE LOCATION MAP
H.B. ROBINSON STEAM ELECTRIC PLANT
DUKE ENERGY PROGRESS
DARLINGTON COUNTY, SOUTH CAROLINA

DATE
DECEMBER 17, 2014

FIGURE
1

SCALE (FEET)
300' 0 300' 600'
1" = 600'

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SITE LAYOUT MAP
ASH BASIN CLOSURE
DUKE ENERGY PROGRESS
ROBINSON PLANT - ASH BASIN CLOSURE PROJECT
DARLINGTON COUNTY, SOUTH CAROLINA

DATE
12/10/2014

FIGURE
2

SCALE (FEET)

200' 0 200' 400'

1" = 400'

HDR

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MONITORING WELL AND BORING LOCATION MAP
ASH BASIN CLOSURE (ASH BASIN)
DUKE ENERGY PROGRESS
ROBINSON PLANT - ASH BASIN CLOSURE PROJECT
DARLINGTON COUNTY, SOUTH CAROLINA

DATE
12/17/2014

FIGURE
3

SCALE (FEET)

200' 0 200' 400'

1" = 400'

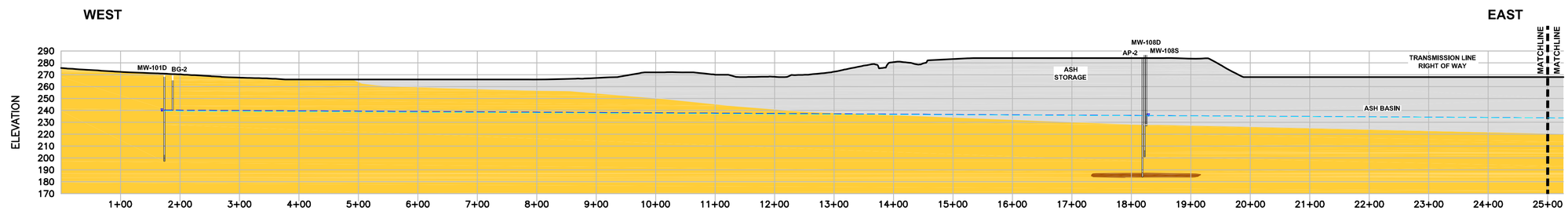
HDR

North Carolina Engineering Firm Number: F-0116
440 South Church Street Charlotte, NC 28202

WELL AND BORING LOCATION MAP
ASH BASIN CLOSURE (1960 FILL AREA)
DUKE ENERGY PROGRESS
ROBINSON PLANT - ASH BASIN CLOSURE PROJECT
DARLINGTON COUNTY, SOUTH CAROLINA

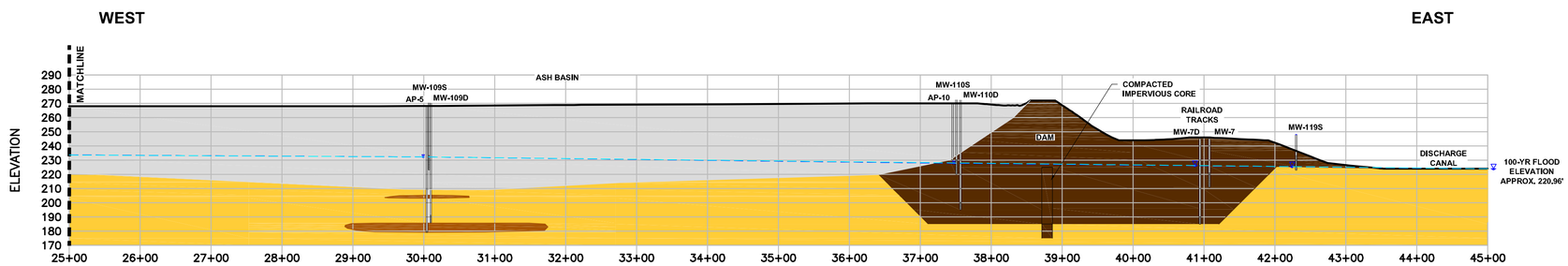
DATE
12/17/2014

FIGURE
4



SECTION A–A' (1 of 2)

HORIZONTAL: 1"=100'; VERTICAL: 1"=50'



SECTION A–A' (2 of 2)

HORIZONTAL: 1"=100'; VERTICAL: 1"=50'

LEGEND:

- EXISTING LAND SURFACE
- WATER TABLE SURFACE (ESTIMATED)
- ASH
- FILL
- UNCONSOLIDATED SEDIMENTS
- DISCONTINUOUS CLAY LENS

NOTES:

1. SEE FIGURE 3 FOR CROSS SECTION LOCATIONS.
2. EXISTING LAND SURFACE BASED ON TOPOGRAPHIC SURVEY PERFORMED BY WSP IN JULY 2014.
3. LITHOLOGY SHOWN IS ESTIMATED BASED ON BORING DATA OBTAINED DURING THE JULY AND AUGUST 2014 CLOSURE INVESTIGATION ACTIVITIES.
4. WATER TABLE SURFACE SHOWN IS APPROXIMATE AND BASED ON MONITORING WELL WATER ELEVATIONS MEASURED ON NOVEMBER 17, 2014.

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PLUMBING	
ELECTRICAL	
DRAWN BY	C. HEARN, P.E.
PROJECT NUMBER	011237-243758-.012

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CROSS SECTION A-A'

0 1" 2"

FILENAME 01C-04.DWG
SCALE AS SHOWN

SHEET
FIGURE 5

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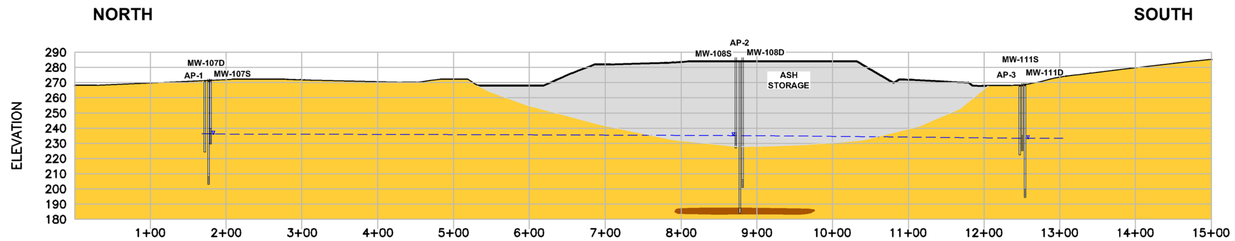
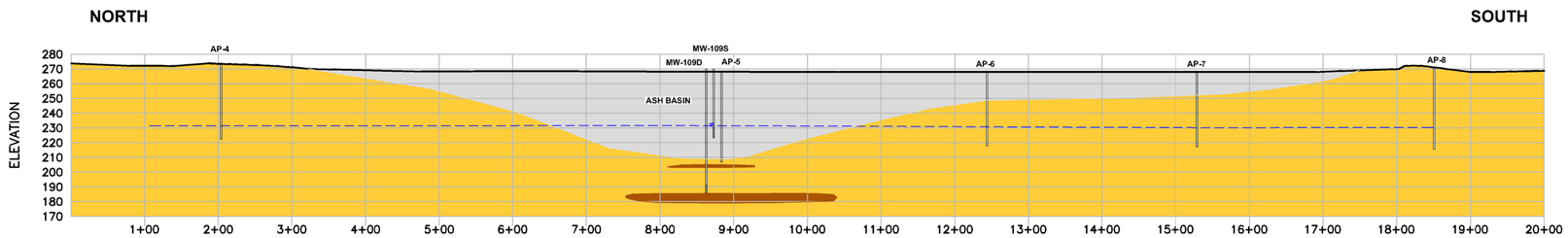


SECTION B–B'

HORIZONTAL: 1"=100'; VERTICAL: 1"=50'



SECTION C–C'

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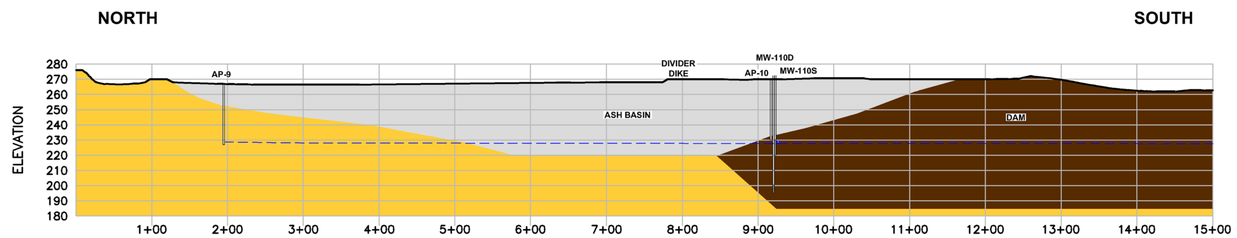

SECTION D–D'

HORIZONTAL: 1"=100'; VERTICAL: 1"=50'

LEGEND:

- EXISTING LAND SURFACE
- WATER TABLE SURFACE (ESTIMATED)
- ASH
- FILL
- UNCONSOLIDATED SEDIMENTS
- DISCONTINUOUS CLAY LENS

NOTES:

1. SEE FIGURE 3 FOR CROSS SECTION LOCATIONS.
2. EXISTING LAND SURFACE BASED ON TOPOGRAPHIC SURVEY PERFORMED BY WSP IN JULY 20 14.
3. LITHOLOGY SHOWN IS ESTIMATED BASED ON BORING DATA OBTAINED DURING THE JULY AND AUGUST 2014 CLOSURE INVESTIGATIO N ACTIVITIES.
4. WATER TABLE SURFACE SHOWN IS APPROXIMATE AND BASED ON MONITORING WELL WATER ELEVATIONS MEASURED ON NOVEMBER 17, 2014.

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PROJECT NUMBER	011237-243758-.012

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CROSS SECTIONS B-B', C-C' AND D-D'

0 1" 2"

FILENAME 01C-04.DWG
SCALE AS SHOWN

SHEET
FIGURE 6

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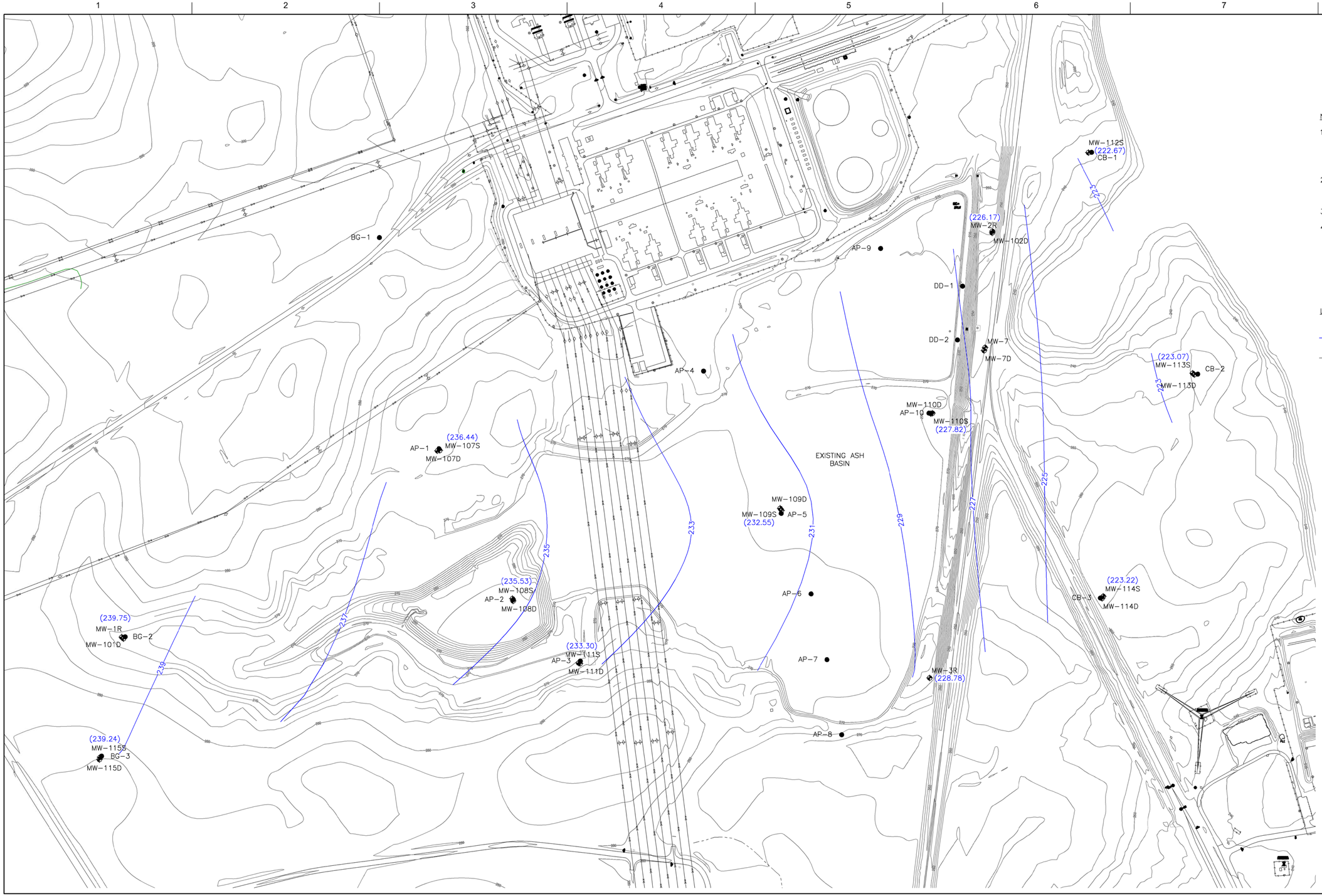

NOTES:

1. BASE MAP PROVIDED BY WSP TRANSPORTATION AND INFRASTRUCTURE DATED NOVEMBER 13, 2014 BASED ON PHOTOGRAMMETRIC MAPPING COLLECTED ON JULY 27, 2014.
2. ALL DISTANCES ARE HORIZONTAL GROUND DISTANCE IN U.S. SURVEY FEET UNLESS OTHERWISE NOTED.
3. BASIS OF BEARINGS: NAD83.
4. VERTICAL DATUM: NAVD88.

LEGEND

229 — GROUNDWATER CONTOUR (APPROXIMATE)

OVERHEAD UTILITY LINES

UTILITY POLE

MW-115S — MONITORING WELL

(232.55) — GROUNDWATER ELEVATION

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POTENTIOMETRIC SURFACE MAP
ASH BASIN
NOVEMBER 17, 2014

0 1" 2"

FILENAME 01C-03.dwg

SCALE 1" = 200'

SHEET

FIGURE 7

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N

NOTES:

1. BASE MAP PROVIDED BY WSP TRANSPORTATION AND INFRASTRUCTURE DATED NOVEMBER 13, 2014 BASED ON PHOTOGRAMMETRIC MAPPING COLLECTED ON JULY 27, 2014.
2. ALL DISTANCES ARE HORIZONTAL GROUND DISTANCE IN U.S. SURVEY FEET UNLESS OTHERWISE NOTED.
3. BASIS OF BEARINGS: NAD83.
4. VERTICAL DATUM: NAVD88.
5. LIMITS OF 1960 FILL AREA OBTAINED FROM DRAWING ENTITLED 'ROBINSON STEAM PLANT LAY OF LAND AREA ASH THICKNESS ISOPACH' DATED AUGUST 20, 2014 BY AMEC ENVIRONMENT AND INFRASTRUCTURE.

LEGEND

229	GROUNDWATER CONTOUR (APPROXIMATE)
	OVERHEAD UTILITY LINES
	UTILITY POLE
MW-105S	MONITORING WELL
(226.30)	GROUNDWATER ELEVATION
	APPROXIMATE LIMITS OF ASH (SEE NOTE 5)

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POTENTIOMETRIC SURFACE MAP
1960 FILL AREA
NOVEMBER 17, 2014

0 1" 2"

FILENAME 01C-03.dwg
SCALE 1" = 200'

SHEET
FIGURE 8

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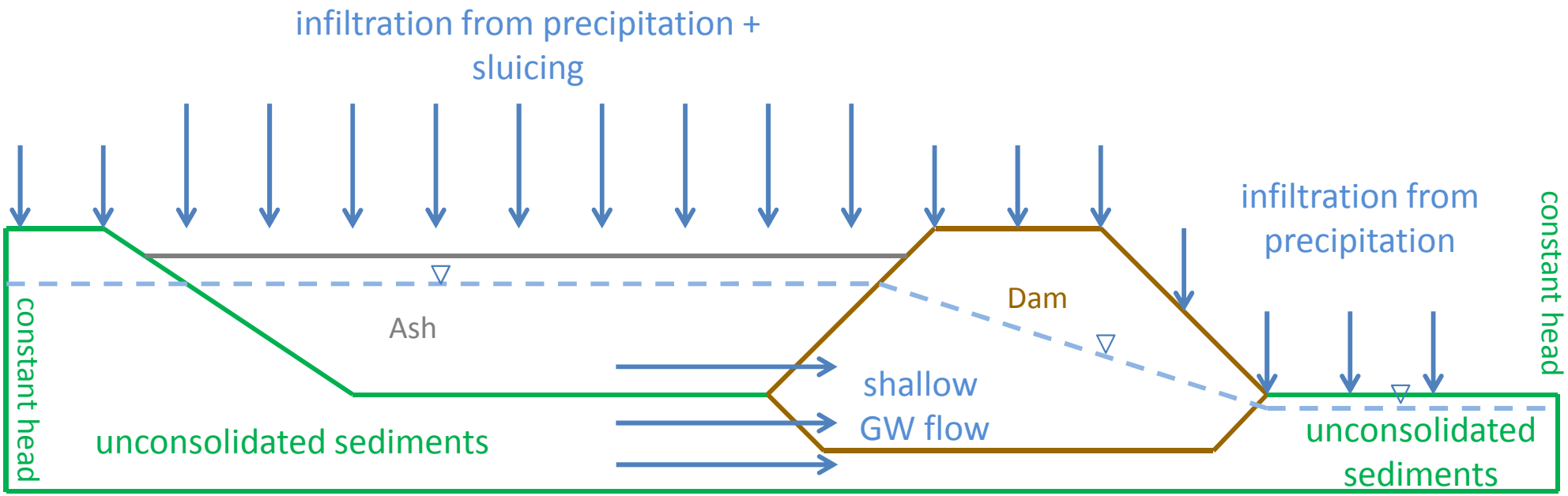
Figure 9. Ash Basin Conceptual Groundwater Flow Model



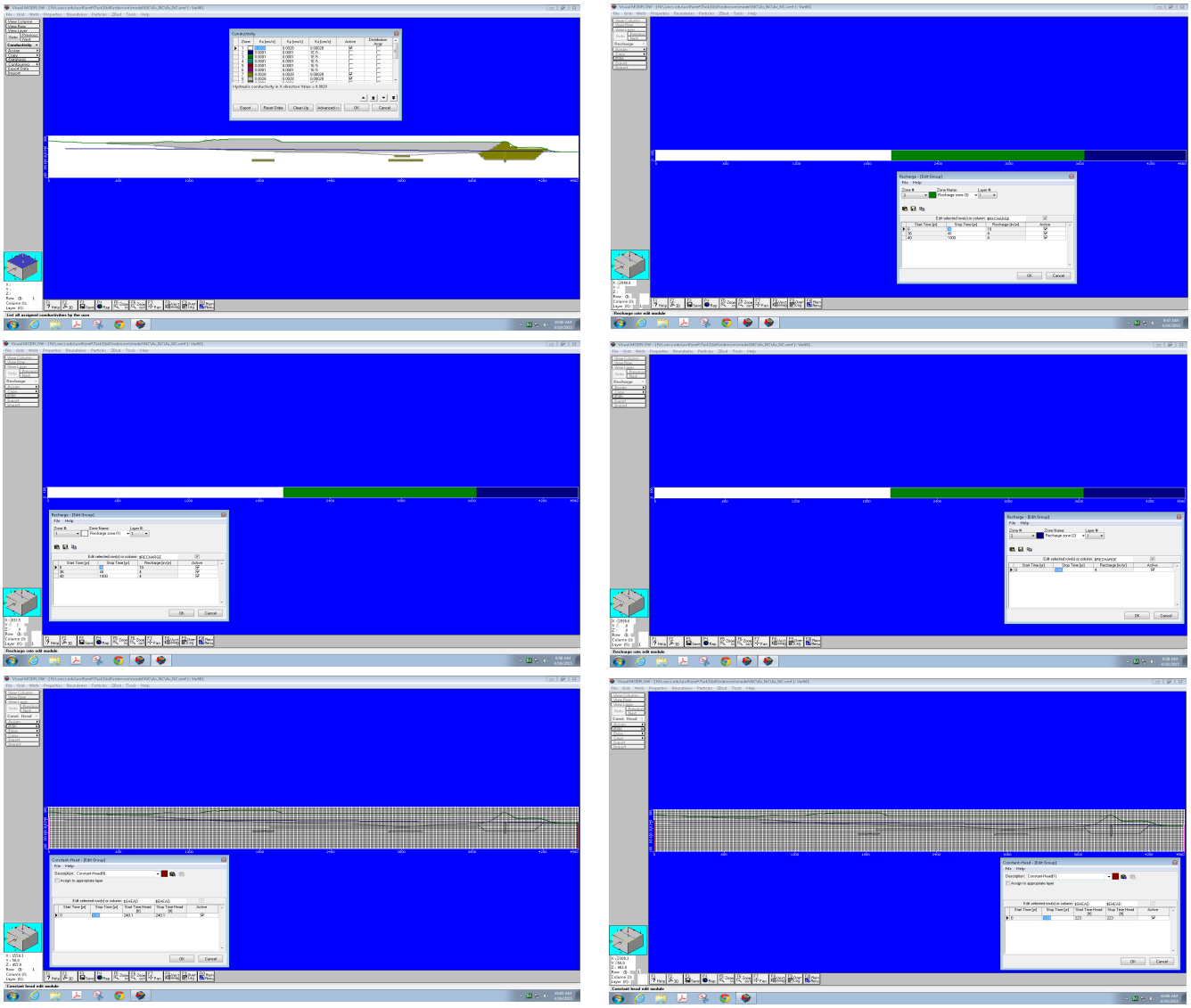


Figure 10. Calibrated Flow Model Parameters:
Recharge, Hydraulic Conductivity, Constant Head Boundaries, and Domain Depth

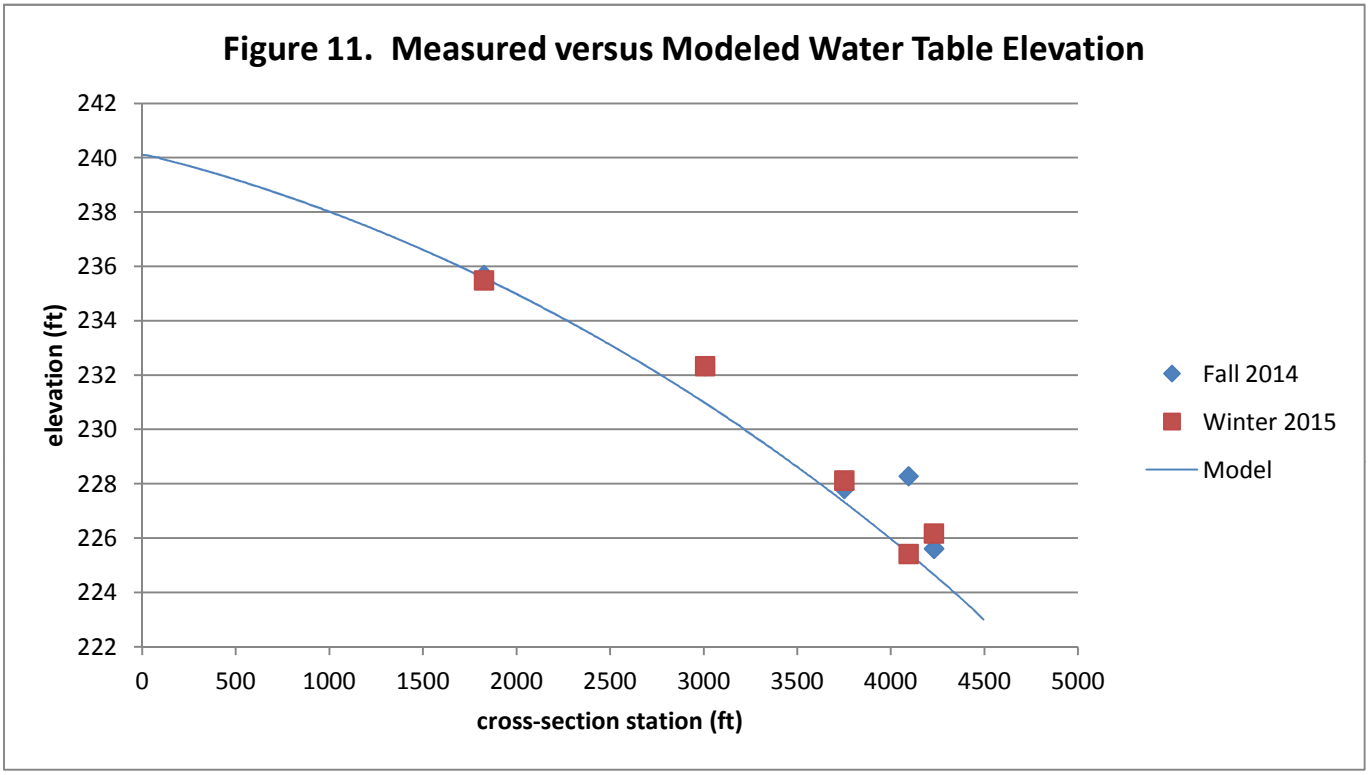


Figure 11. Measured versus Modeled Water Table Elevation
242
240
238
236
234
232
230
228
226
224
222
elevation (ft)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
cross-section station (ft)
Fall 2014
Winter 2015
Model

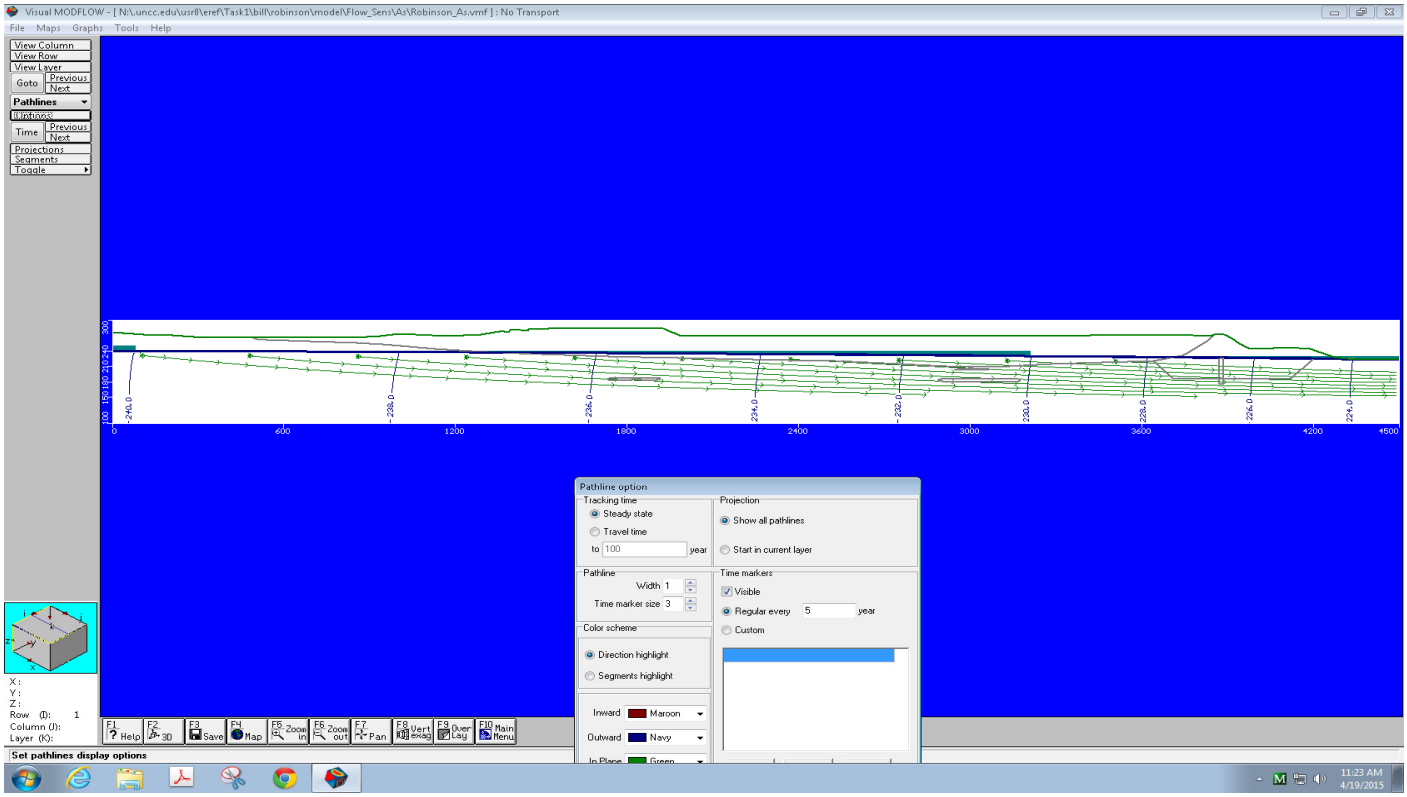
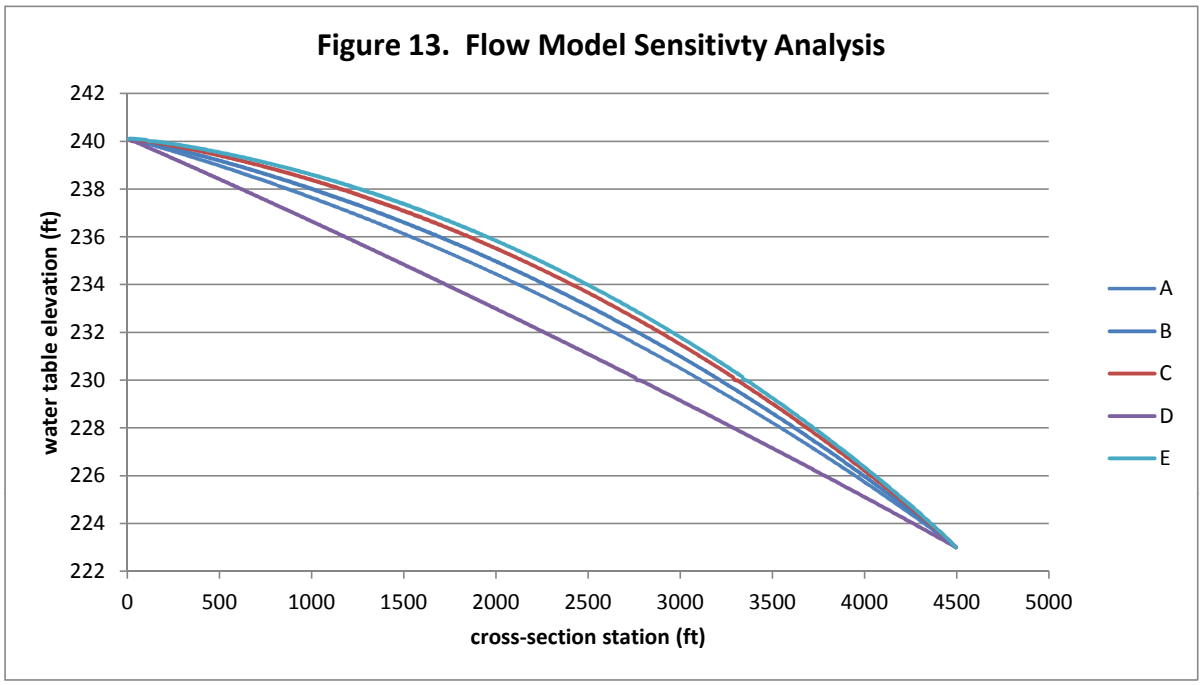
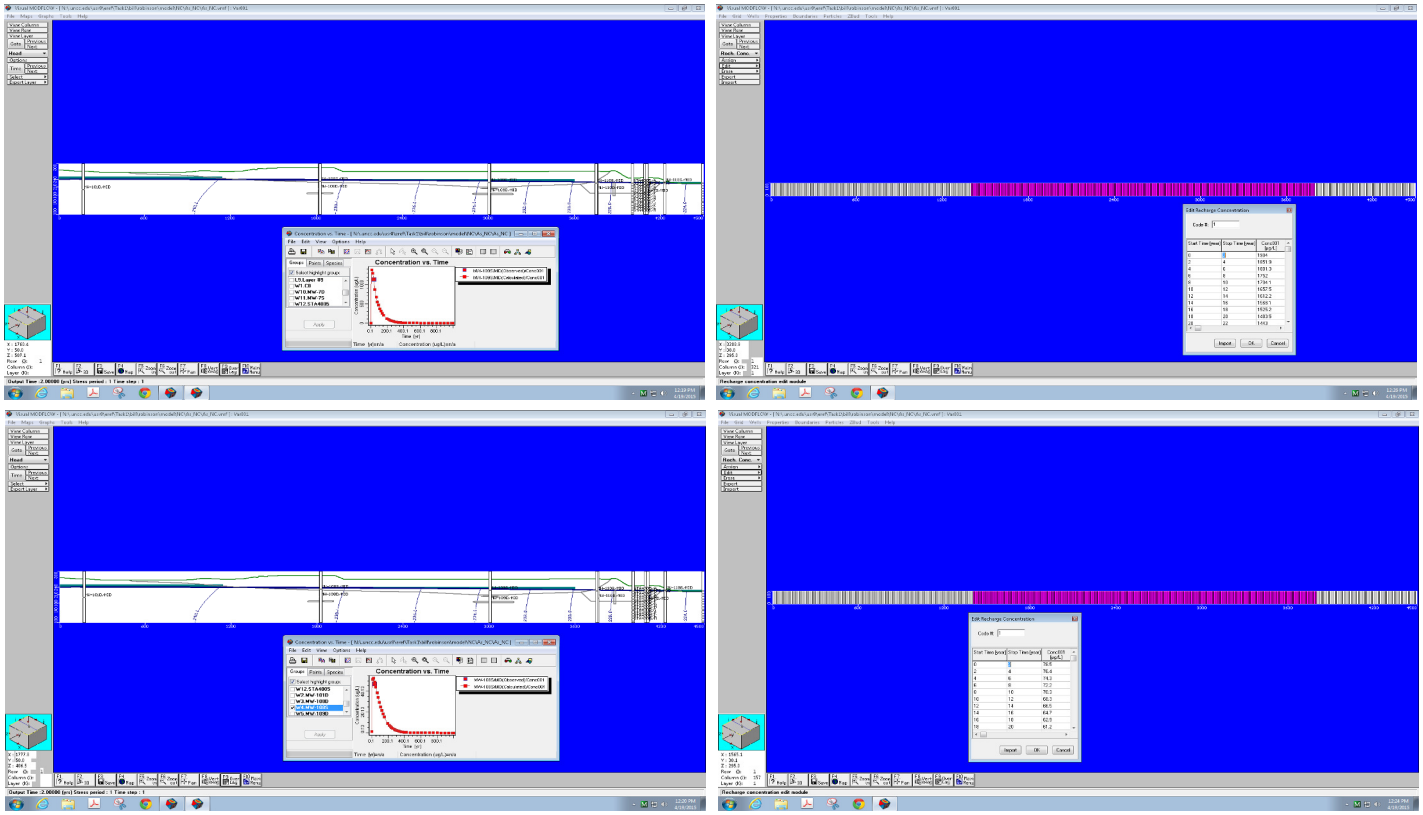


Figure 12. Flow pathlines with 5 year time markers

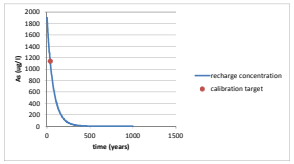


A: recharge 3"/year, Kh 0.0028 cm/sec
B: recharge 4"/year, Kh 0.0028 cm/sec
C: recharge 5"/year, Kh 0.0028 cm/sec
D: recharge 4"/year, Kh 0.028 cm/sec
E: recharge 4"/year, Kh 0.0020 cm/sec



Recharge Concentration for Arsenic:

Cross Section Station:	2400	ft	to	3800	ft			
Calibration Target Location:	MW-109S							
Calibration Target:	1140	ug/l at	37	years		1975	to	2012
Recession Rate Constant:	50	years						
Recharge Concentration Co:	1904	ug/l	C0=C/(exp(-lambda*time)			lambda = ln(2)/thalf		



Recharge Concentration for Arsenic:

Cross Section Station:	1400	ft	to	2400	ft			
Calibration Target Location:	MW-108S							
Calibration Target:	47	ug/l at	37	years		1975	to	2012
Recession Rate Constant:	50	years						
Recharge Concentration Co:	78.5	ug/l	C0=C/(exp(-lambda*time)			lambda = ln(2)/thalf		

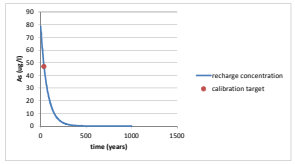


Figure 14. Source Area Model for Arsenic

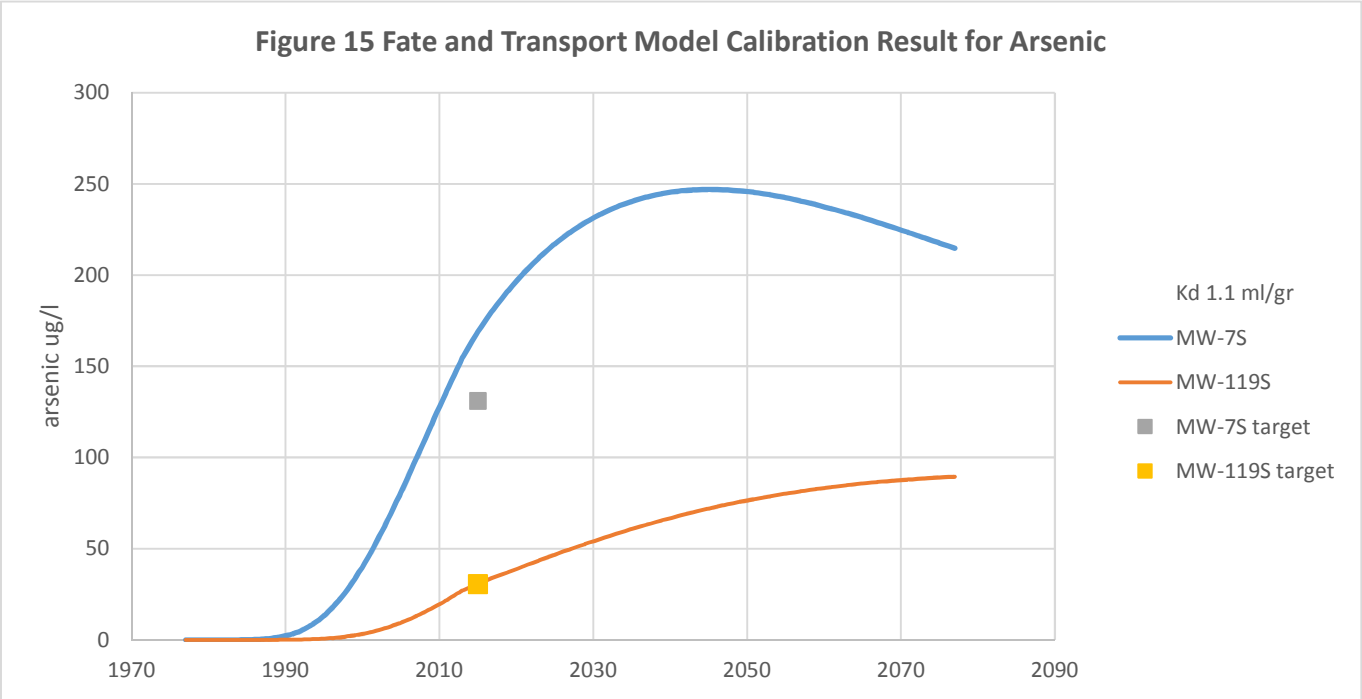


Figure 15 Fate and Transport Model Calibration Result for Arsenic
arsenic ug/l
300
250
200
150
100
50
0
1970
1990
2010
2030
2050
2070
2090
Kd 1.1 ml/gr
MW-7S
MW-119S
MW-7S target
MW-119S target

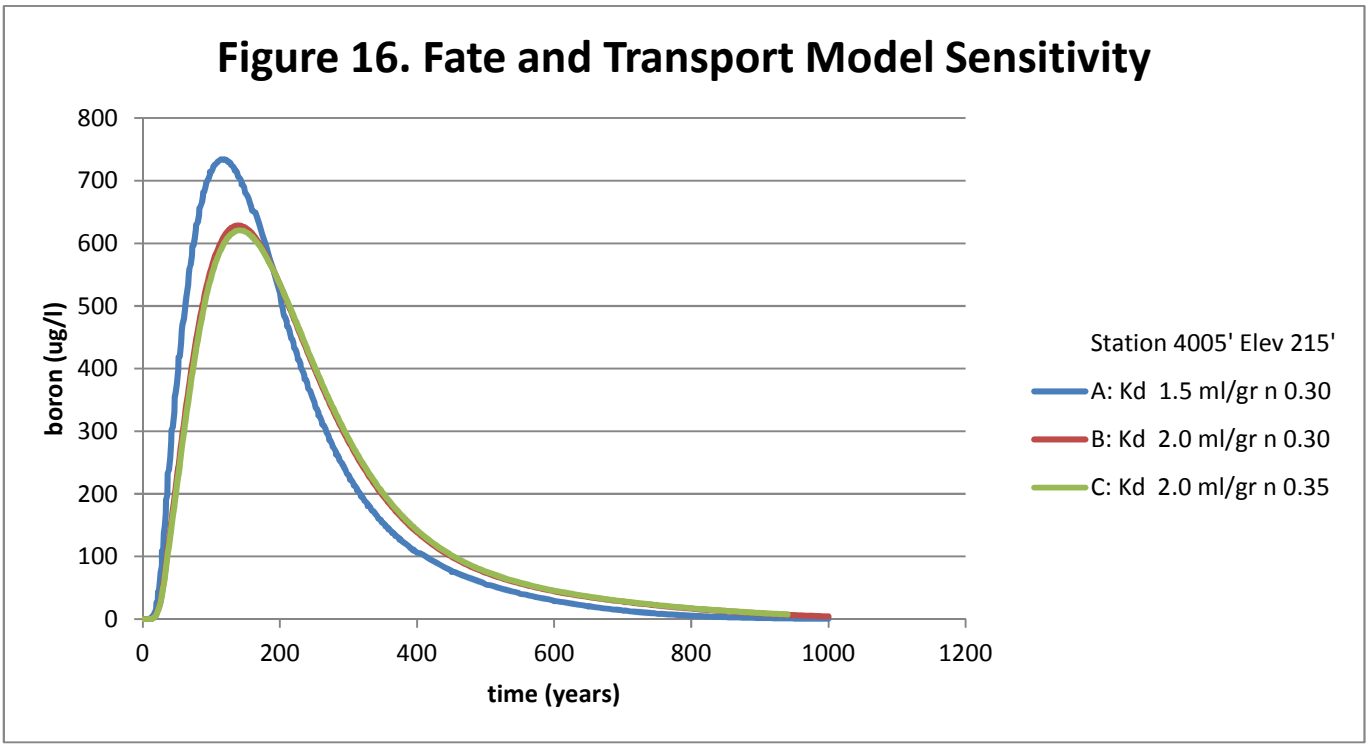


Figure 16. Fate and Transport Model Sensitivity
800
700
600
500
400
300
200
100
0
boron (ug/l)
0
200
400
600
800
1000
1200
time (years)
Station 4005' Elev 215'
A: Kd 1.5 ml/gr n 0.30
B: Kd 2.0 ml/gr n 0.30
C: Kd 2.0 ml/gr n 0.35

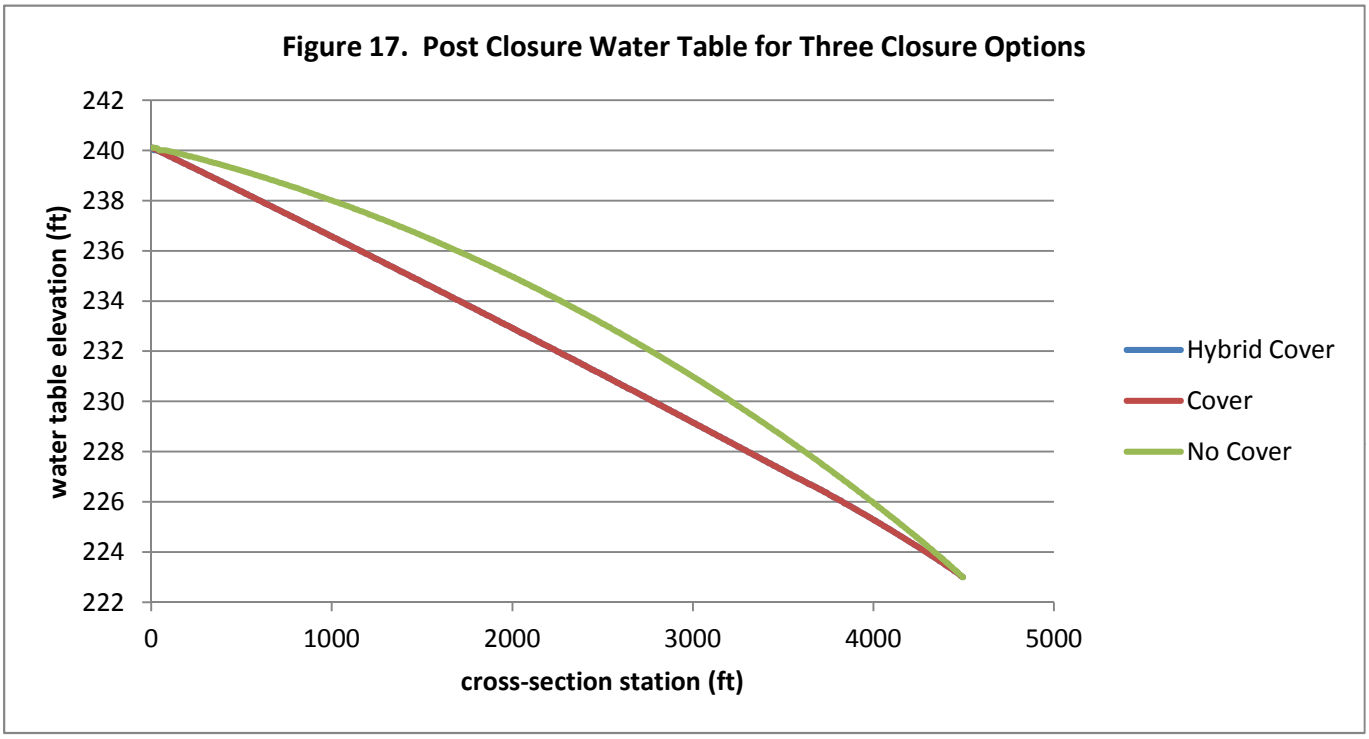


Figure 17. Post Closure Water Table for Three Closure Options
water table elevation (ft)
242
240
238
236
234
232
230
228
226
224
222
0
1000
2000
3000
4000
5000
cross-section station (ft)
Hybrid Cover
Cover
No Cover

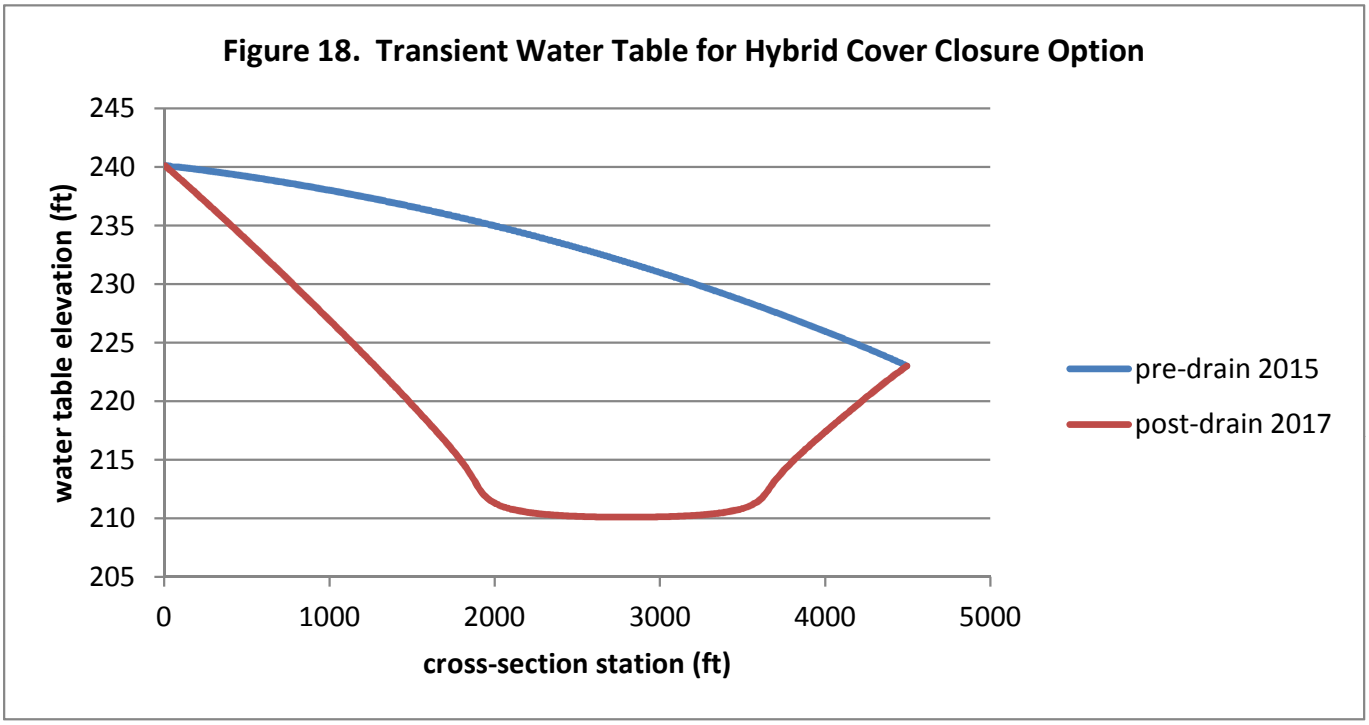


Figure 18. Transient Water Table for Hybrid Cover Closure Option
245
240
235
230
225
220
215
210
205
water table elevation (ft)
0
1000
2000
3000
4000
5000
cross-section station (ft)
pre-drain 2015
post-drain 2017

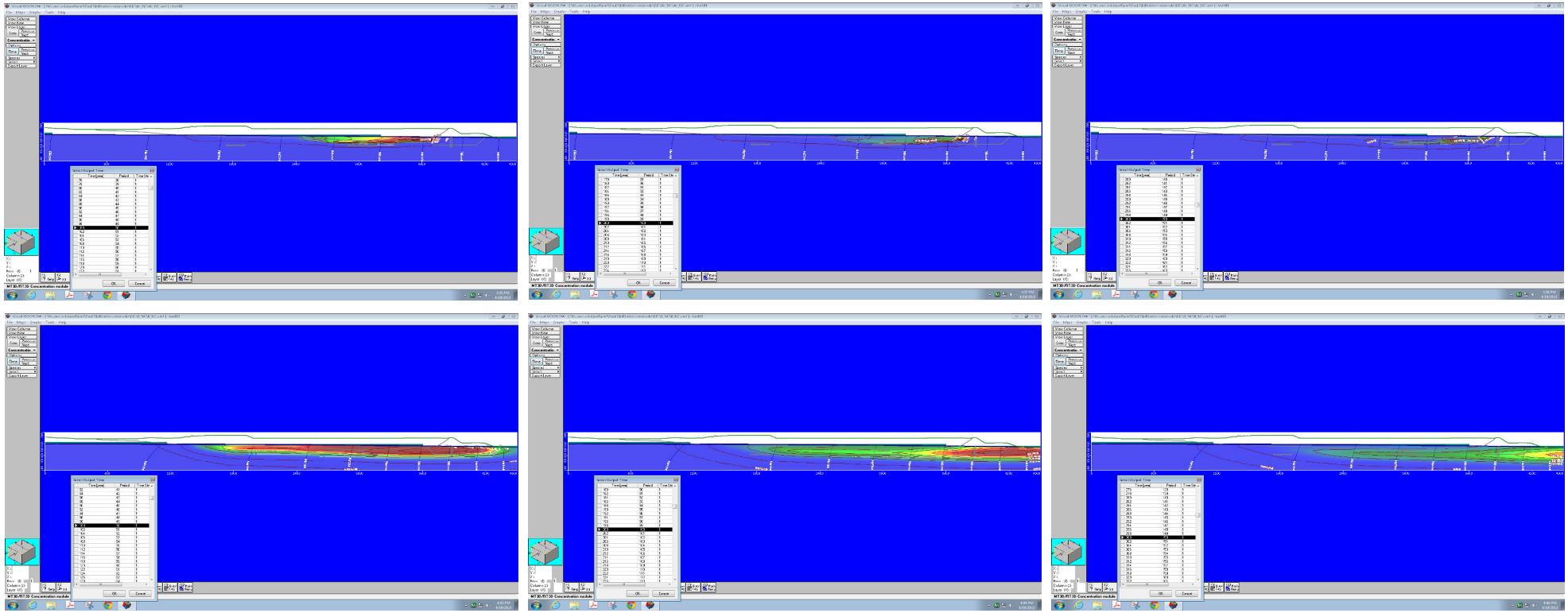


Figure 19. Arsenic and Boron Concentrations over time for the No Action Option
Top row: Arsenic
Botton row: Boron
Left to right: 100, 200, and 300 years post start up

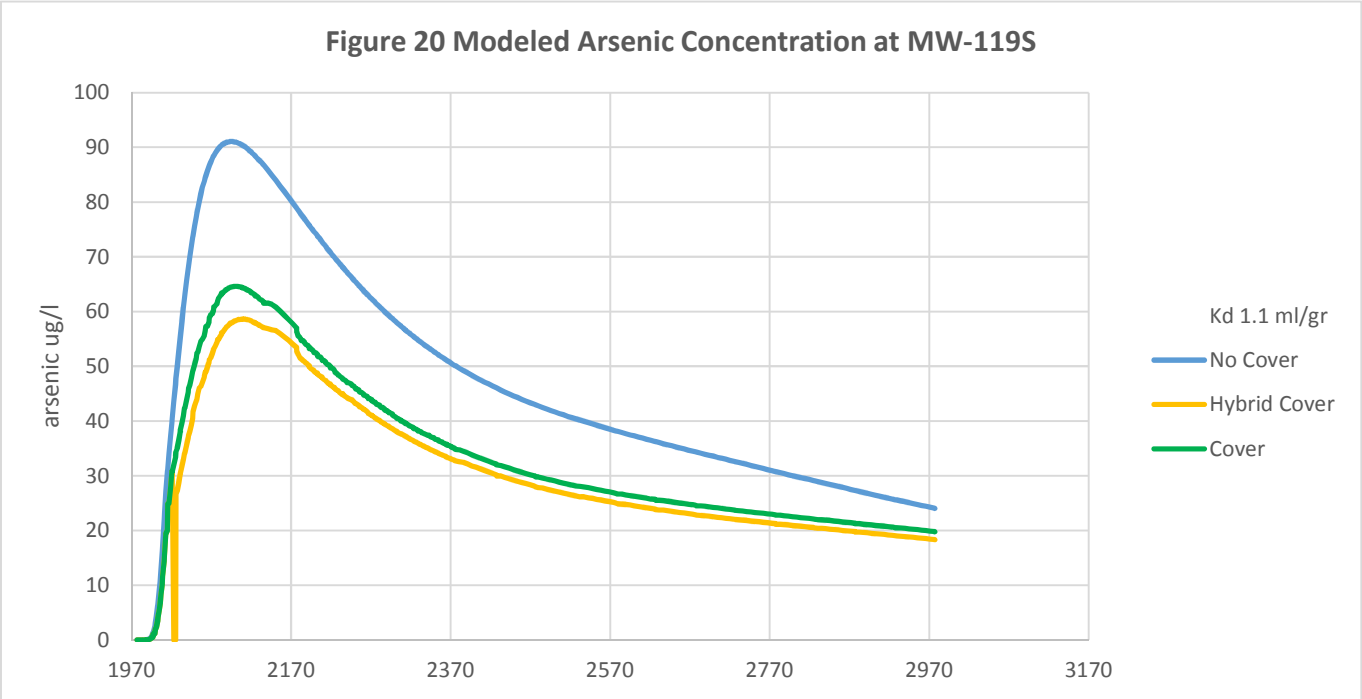


Figure 20 Modeled Arsenic Concentration at MW-119S
arsenic ug/l
100
90
80
70
60
50
40
30
20
10
0
1970
2170
2370
2570
2770
2970
3170
Kd 1.1 ml/gr
No Cover
Hybrid Cover
Cover

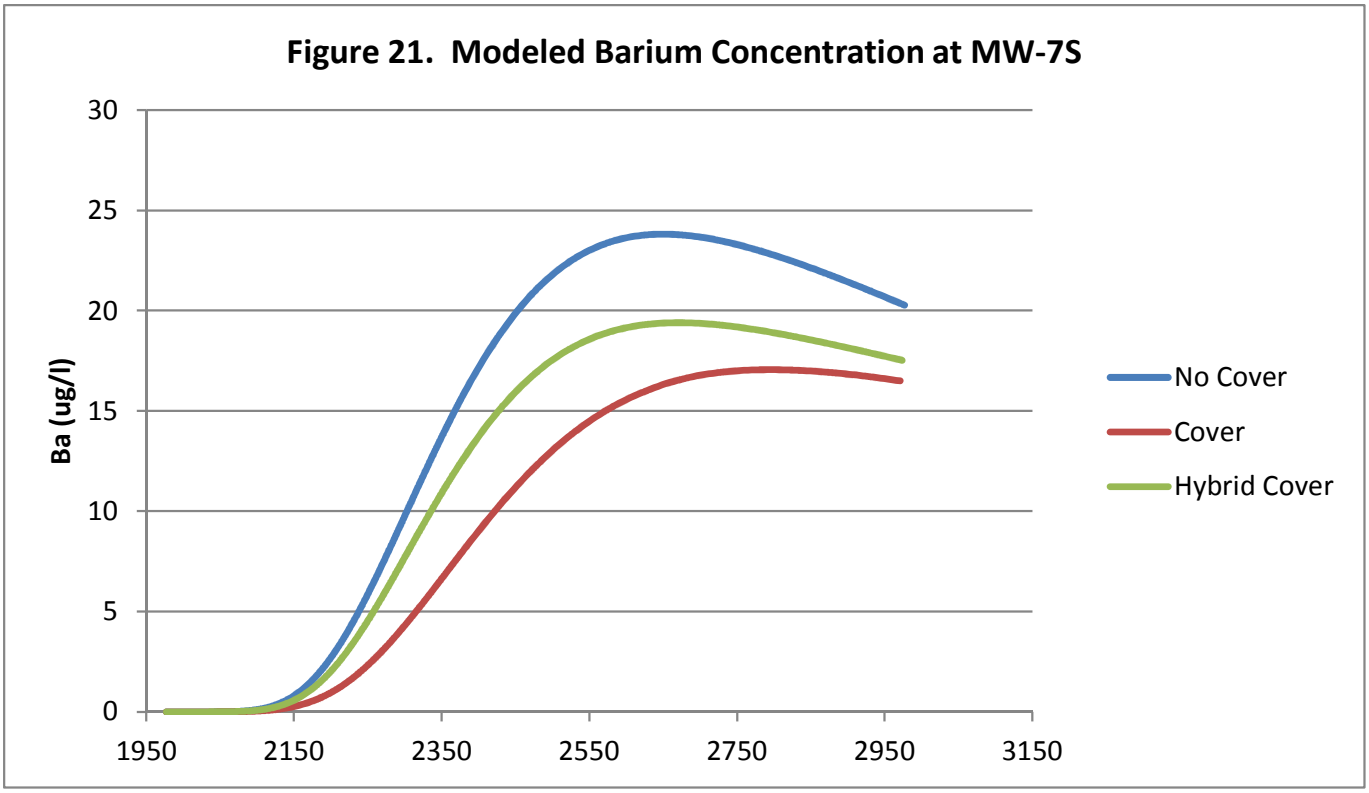


Figure 21. Modeled Barium Concentration at MW-7S
Ba (ug/l)
30
25
20
15
10
5
0
1950
2150
2350
2550
2750
2950
3150
No Cover
Cover
Hybrid Cover

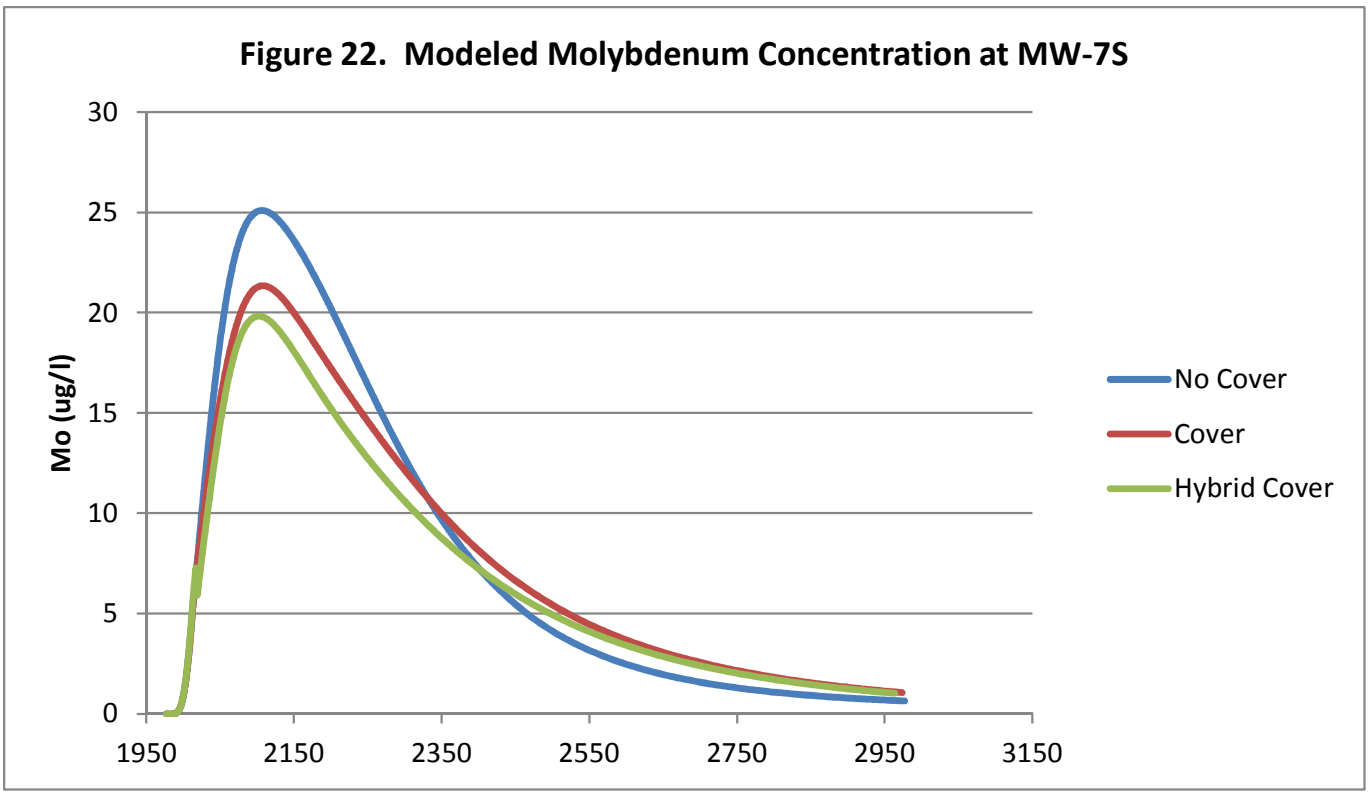


Figure 22. Modeled Molybdenum Concentration at MW-7S
Mo (ug/l)
30
25
20
15
10
5
0
1950
2150
2350
2550
2750
2950
3150
No Cover
Cover
Hybrid Cover

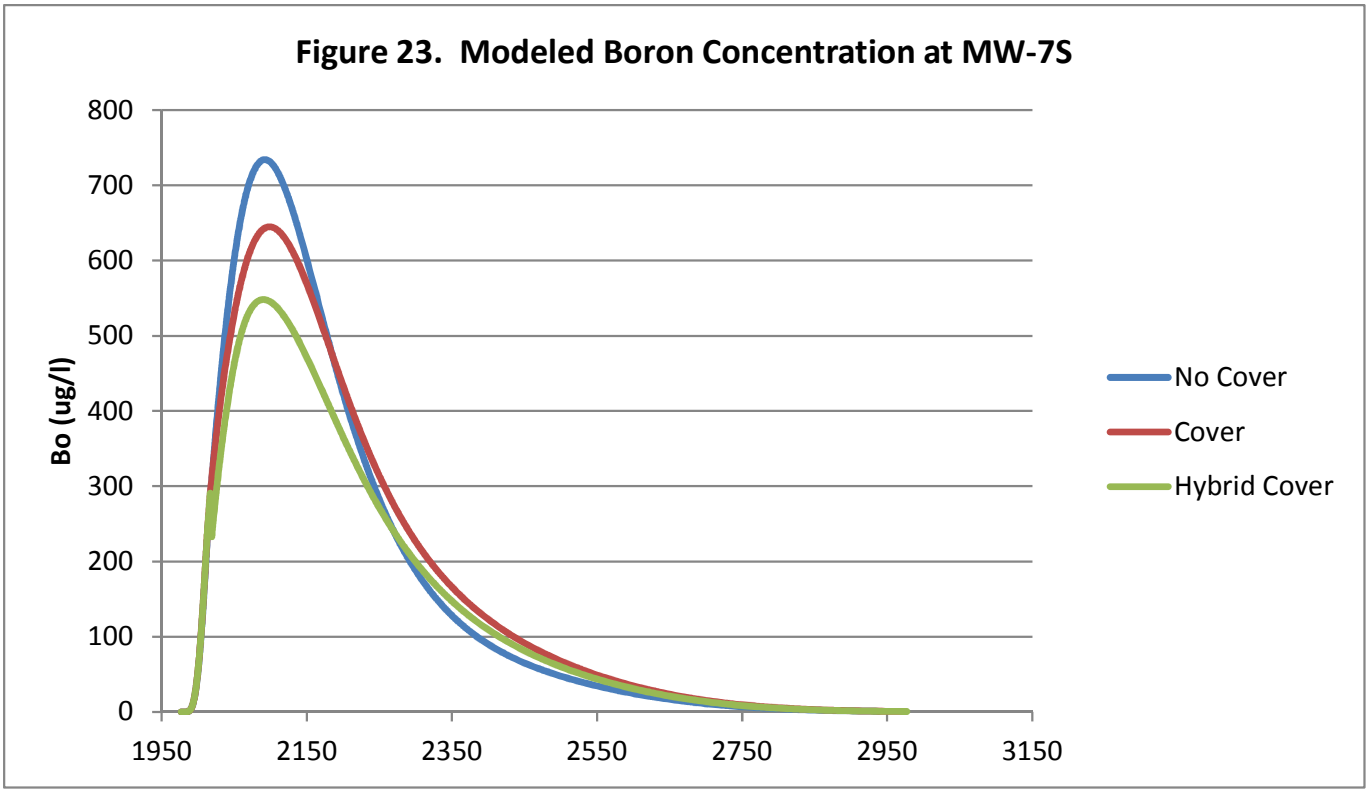


Figure 23. Modeled Boron Concentration at MW-7S
Bo (ug/l)
800
700
600
500
400
300
200
100
0
1950
2150
2350
2550
2750
2950
3150
No Cover
Cover
Hybrid Cover

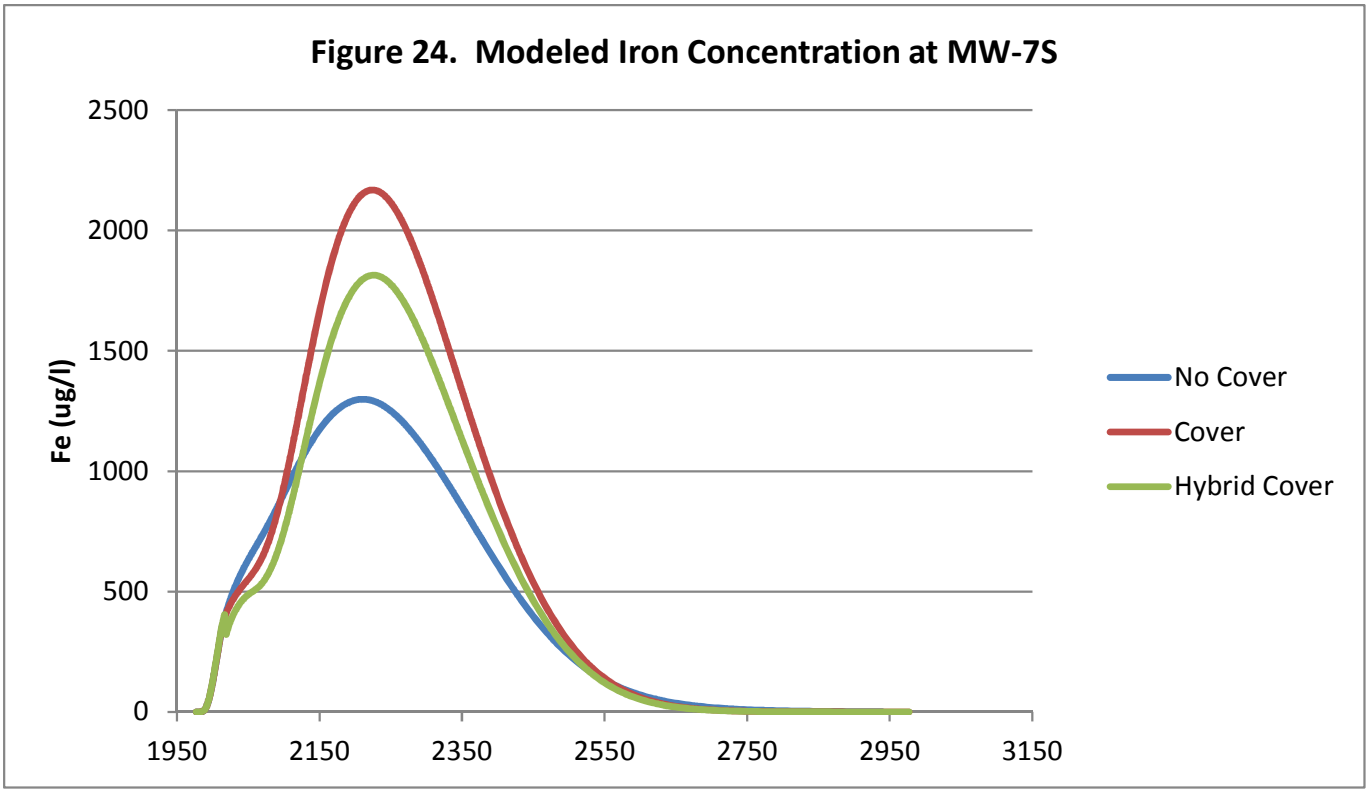


Figure 24. Modeled Iron Concentration at MW-7S
Fe (ug/l)
2500
2000
1500
1000
500
0
1950
2150
2350
2550
2750
2950
3150
No Cover
Cover
Hybrid Cover

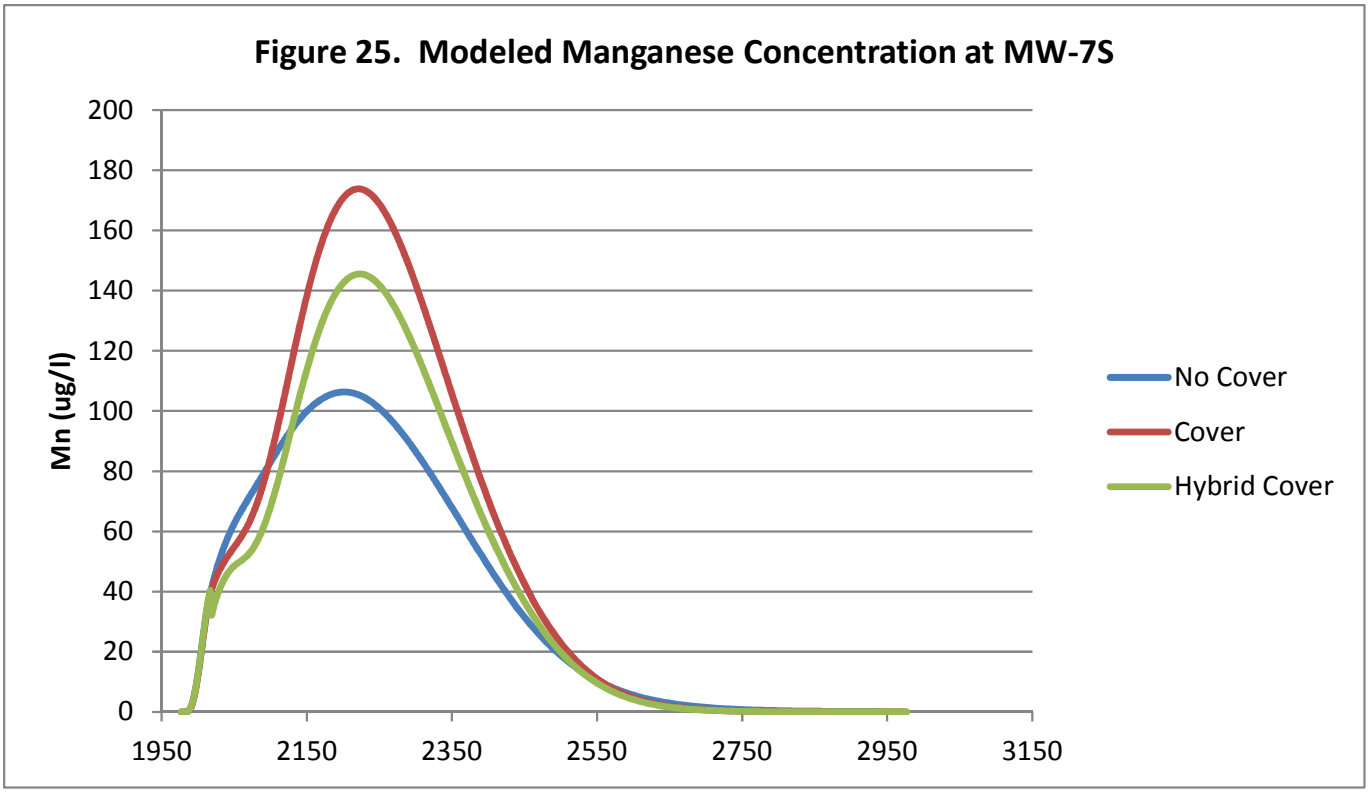


Figure 25. Modeled Manganese Concentration at MW-7S
Mn (ug/l)
200
180
160
140
120
100
80
60
40
20
0
1950
2150
2350
2550
2750
2950
3150
No Cover
Cover
Hybrid Cover

Table 1. Well construction and groundwater elevation data for flow model calibration				
Well ID	Section A-A' station (ft)	Top of screen elevation (ft)	Top of Screen Elevation (ft)	Static Water Elevation (ft)
MW-101D	174	202	197	239.75
MW-108D	1822	206	201	234.85
MW-108S	1825	237	227	235.53
MW-109S	3007	233	223	232.55
MW-109D	3009	191	186	231.42
MW-110S	3751	230	220	227.82
MW-110D	3757	200	195	227.63
MW-7D	4094	190	185	226.37
MW-7	4107	221	211	226.17
MW-119S	4230	233	223	225.61

Table 2. Slug Test Results (HDR 2015b)

Well ID	Static Water Level Measurement (ft bgs)[1]	Screen Depth (ft bgs)	Slug Test Type[2,3]	K (ft/day)[4]	K (cm/sec)
MW-7D	16.53	55-60	Injection	1.2	4.1E-04
			Withdrawal	0.9	3.0E-04
MW-101D	26.04	66-71	Injection	13.2	4.7E-03
			Withdrawal	5.0	1.8E-03
MW-102D	27.61	80-85	Injection	5.8	2.1E-03
			Withdrawal	5.2	1.8E-03
MW-105D	27.30	60-65	Injection	5.8	2.1E-03
			Withdrawal	5.4	1.9E-03
MW-106D	27.25	60-65	Injection1	17.6	6.2E-03
			Withdrawal	15.5	5.5E-03
			Injection2	10.1	3.6E-03
MW-107D	27.18	24-34	Injection	3.3	1.2E-03
			Withdrawal	3.3	1.2E-03
MW-108D	49.15	78-83	Injection	3.9	1.4E-03
			Withdrawal	3.6	1.3E-03
MW-109S	35.28	35-45	Withdrawal	1.1	4.0E-04
MW-109D	36.64	77-82	Injection	3.8	1.3E-03
			Withdrawal	4.1	1.4E-03
MW-110S	42.27	40-50	Withdrawal	2.6	9.2E-04
MW-110D	42.34	70-75	Injection	6.6	2.3E-03
			Withdrawal	6.9	2.4E-03
MW-111D	34.00	68-73	Injection	29.0	1.0E-02
			Withdrawal	34.7	1.2E-02
MW-112S	18.00	15-25	Withdrawal	7.4	2.6E-03
MW-113S	31.19	27-37	Withdrawal	1.7	6.1E-04
MW-113D	31.30	64-69	Injection	14.7	5.2E-03
			Withdrawal	14.8	5.2E-03
MW-114S	29.65	27-37	Withdrawal	0.9	3.3E-04
MW-114D	30.89	63-68	Injection	1.4	4.9E-04
			Withdrawal	15.6	5.5E-03
MW-115D	47.32	72-77	Injection	3.3	1.2E-03
			Withdrawal	1.5	5.2E-04
MW-116D	26.71	60-65	Injection	9.3	3.3E-03
			Withdrawal	7.1	2.5E-03
MW-117S	23.66	22-32	Withdrawal	2.2	7.6E-04
MW-117D	23.97	60-65	Injection	3.7	1.3E-03
			Withdrawal	1.9	6.5E-04
MW-118S	18.66	15-25	Withdrawal	0.9	3.1E-04

Well ID	Static Water Level Measurement (ft bgs)[1]	Screen Depth (ft bgs)	Slug Test Type[2,3]	K (ft/day)[4]	K (cm/sec)
MW-118D	18.75	49-54	Injection	4.7	1.7E-03
			Withdrawal	4.5	1.6E-03
			Injection Test Results	K ft/day3	K cm/sec
			Average	8.1	2.9E-03
			Median	5.8	2.1E-03
			Withdrawal Test Results	K ft/day3	K cm/sec
				D Wells	
			Average	8.1	2.9E-03
			Median	5.1	1.8E-03
				S Wells	
			Average	2.4	8.5E-04
			Median	1.7	6.1E-04

[1]ft bgs = feet below ground surface
[2]Injection = Falling Head Slug Test; Withdrawal = Rising Head Slug Test
[3]Falling Head Test is not valid when the static water level measurement is below the top of the well screen (e.g., S Wells) as outflow occurs above the water table into the unsaturated zone
[4]The Bouwer and Rice Method was used to analyze slug test data and calculate hydraulic conductivity (K):

Bouwer, H. and R.C. Rice. 1976. A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells. Water Resources Research, V.12, pp.423-428.

Bouwer, H. 1989. The Bouwer and Rice Slug Test - An Update. Ground Water, Vol. 27, No.3, May-June, pp. 304-309.

Assumptions:

1. The groundwater zone is infinite in extent, homogeneous and uniform in thickness
2. Groundwater flow can be described by Darcy's Law
3. The water table or piezometric surface is horizontal and extends infinitely in the radial direction
4. At time = 0, the change in head occurs instantly
5. The inertia of the water column in the well and linear/non-linear well losses are considered negligible
6. The well diameter is finite; hence storage in the well is not neglected
7. Groundwater density and viscosity are constant throughout the test

Table 3. COC Source Zone Model Parameters

COC	Initial source zone concentration ug/l		Recession Rate Constant (yrs)
	Station 1400' to 2400'	Station 2400' to 3800'	
As	78.5	1,904.00	50
Ba	217	553	
B	1,523.00	2,622.00	
Mo	36.7	135	
Fe	22,380.00	1,854.00	
Mn	1,770.00	185	

Table 4. Measured versus Model COC Concentrations (ug/l)

	Arsenic			Boron			Barium			Iron			Manganese			Molybdenum		
Well	Measured	Modeled	Residual	Measured	Modeled	Residual	Measured	Modeled	Residual	Measured	Modeled	Residual	Measured	Modeled	Residual	Measured	Modeled	Residual
MW-108D	<10	0.0	-10.0	218	114.6	-103.4	32	0.0	-32.0		3161.0	3151.0	219	250.0	31.0	<10	0.4	-9.6
MW-108S	97.4	26.6	-70.8	912	763.8	-148.2	130	73.7	-56.3	13400	11998.1	-1401.9	1060	949.1	-110.9	22	15.3	-6.7
MW-109D	<10	0.2	-9.8	435	110.1	-324.9	45	0.1	-44.9	1110	355.8	-754.2	361	30.8	-330.2	<10	0.8	-9.2
MW-109S	1140	871.2	-268.8	1570	1390.0	-180.0	331	256.9	-74.1	1110	2165.0	1055.0	111	191.1	80.1	81	66.1	-14.9
MW-110D	<10	22.2	12.2	737	201.5	-535.5	55	0.0	-55.0	8090	294.0	-7796.0	308	29.3	-278.7	<10	2.6	-7.4
MW-110S	11	641.5	630.5	678	1182.9	504.9	163	52.1	-110.9	3030	956.3	-2073.7	224	95.2	-128.8	26	50.6	24.6
MW-119S	30.5	30.8	0.3	10	17.0	7.0	10	0.0	-10.0	10	67.6	57.6	10	6.8	-3.2	<10	0.1	-9.9
MW-7D	<10	1.4	-8.6	852	9.3	-842.7	63	0.0	-63.0	7050	37.7	-7012.3	126	3.8	-122.2	<10	0.0	-10.0
MW-7S	180	168.9	-11.1	774	257	-517	120	0	-120	1510	206.0	-1304.0	180	20.6	-159.4	17.7	5.4	-12.3