Numerical Modeling to Evaluate Hydrological Dynamics and Risk Assessment of Bottom Ash Ponds at a Former Coal-Fired Electric Power Plant

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ABSTRACT

Leaching and transport of ash-related inorganic constituents from bottom ash ponds (BAPs) at a former coal-fired electric power plant (Site) adjacent to a river system in southwest Virginia were modeled to understand subsurface flow dynamics at the Site and to identify an effective management strategy for the BAPs under the recent Coal Combustion Residuals (CCR) legislation. Modeling was conducted assuming baseline (uncapped) and closure (capped) conditions. Subsequently, predicted concentrations of site-related constituents in nearby surface water bodies were evaluated to assess the potential for ecological and human health effects under both conditions.

The numerical model was used to examine Site hydrological dynamics and groundwater interaction with nearby surface water bodies. Pathline analyses were performed using MODPATH to evaluate potential surface water receptors under baseline and closure conditions. Dilution attenuation factors (DAFs) were calculated and subsequently used in combination with site-related constituent concentration data as well as ambient up-gradient background surface water concentrations to predict mixed surface water concentrations in the water bodies adjacent to the BAPs, which were then used to assess potential risk to human and ecological receptors.

Results from the risk analyses indicated that predicted surface water concentrations for ash-related constituents were all below applicable risk based screening levels, indicating that risk to human and ecological health is not expected under either capped or uncapped conditions. This approach of numerical modeling followed by risk evaluation has been found to be an effective management strategy for BAP closure under the CCR legislation.

INTRODUCTION

CCR management facilities are generally found to be located in close proximity of large water bodies, and thus have the potential to pose risks to human and ecological receptors from leaching and transport of CCR-related constituents. The current study was carried out for a former coal-fired electric power plant (Site) to evaluate the subsurface flow dynamics, assess constituent migration potential, and to identify an effective management strategy for closure under the federal CCR legislation.

CONCEPTUAL SITE MODEL

The conceptual site model (CSM) is a narrative description of Site conditions that summarizes important geologic, hydrologic, and hydraulic features of the groundwater system. The CSM provides the framework of essential input parameters required by a mathematical model, and is developed from regional, local, and site specific data.

Site Setting and Operation

The Site is located in south-western Virginia along the south bank of the Big River and the east bank of the Small River (**Figure 1**). The climate in this area is characterized as humid continental with an average rainfall of approximately 36 inches annually. Topography across the Site has high topographic relief within the Valley and Ridge Province. The ridge maximum elevation in the area reach over 2,300 feet above mean sea level (amsl) to the northeast and over 3,400 feet amsl to the south of the Site.

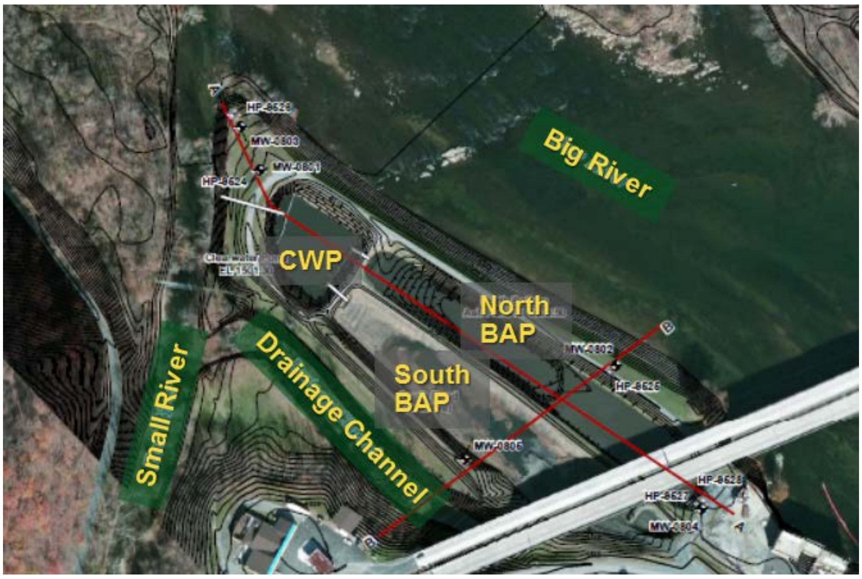

Figure 1: Site setting

The Site contains two Bottom Ash Ponds (BAPs), namely North BAP and South BAP, and also a Clear Water Pond (CWP) that is separated by two splitter dikes. The South BAP has not been used in recent years and the North BAP received sluiced bottom ash until plant shut-down in 2015. The recently active North BAP covers an area of approximately 2.20 acres at an elevation of 1,505.05 feet amsl. Overflow from the two ponds is routed through a corrugated 18-inch diameter metal pipe to the CWP that is approximately 0.52 acres with a pool elevation of 1,501.3 feet amsl. Ultimate discharge from the CWP to the Small River occurs by a skimmer and decant tower.

<u>Geology and Hydrogeology</u>

Within the Valley and Ridge Province in the vicinity of the Site, the varied distribution of unconsolidated deposits consists of Quaternary age alluvial strata (floodplain, levee, terrace and channel deposits – silts, clays, sands and gravels) within the stream channels and paleo stream channel deposition (McDowell and Schultz, 1990). There are also areas of colluvium. The principal rock units at the Site consist of the Mauch Chunk Group (Hinton and Bluefield Formations), the Green Brier Limestone and the Maccrady and Price Formations; all Mississippian in age (youngest to oldest, respectively). These sedimentary rocks were deposited in a variety of depositional environments.

Figures 2 and 3 depict annotated cross-sections of shallow geology and the BAPs; locations of the cross-sections shown on **Figure 1**.

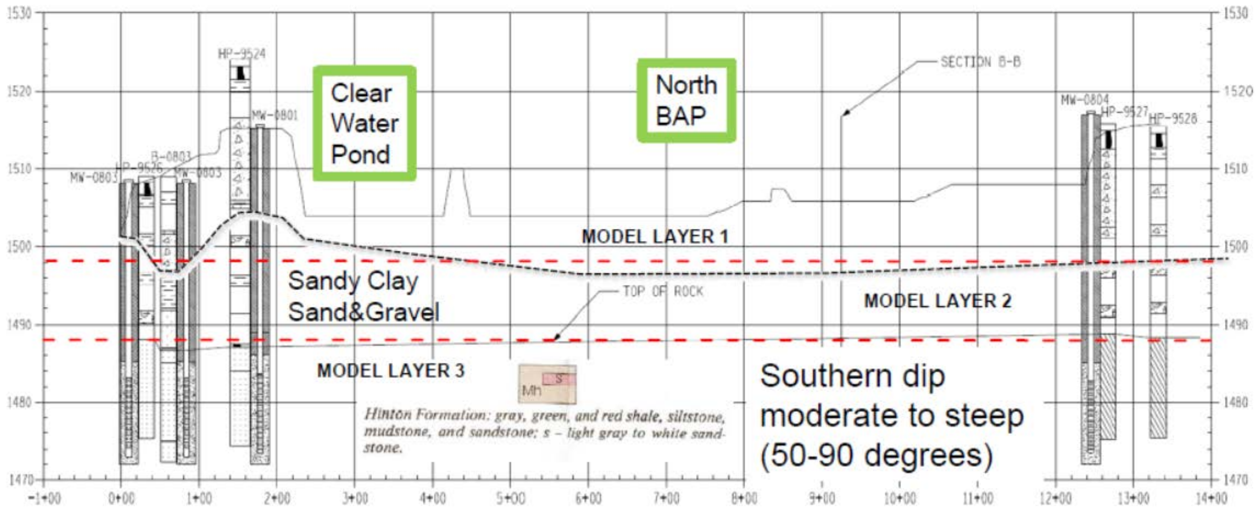

Figure 2: Cross-section A-A’

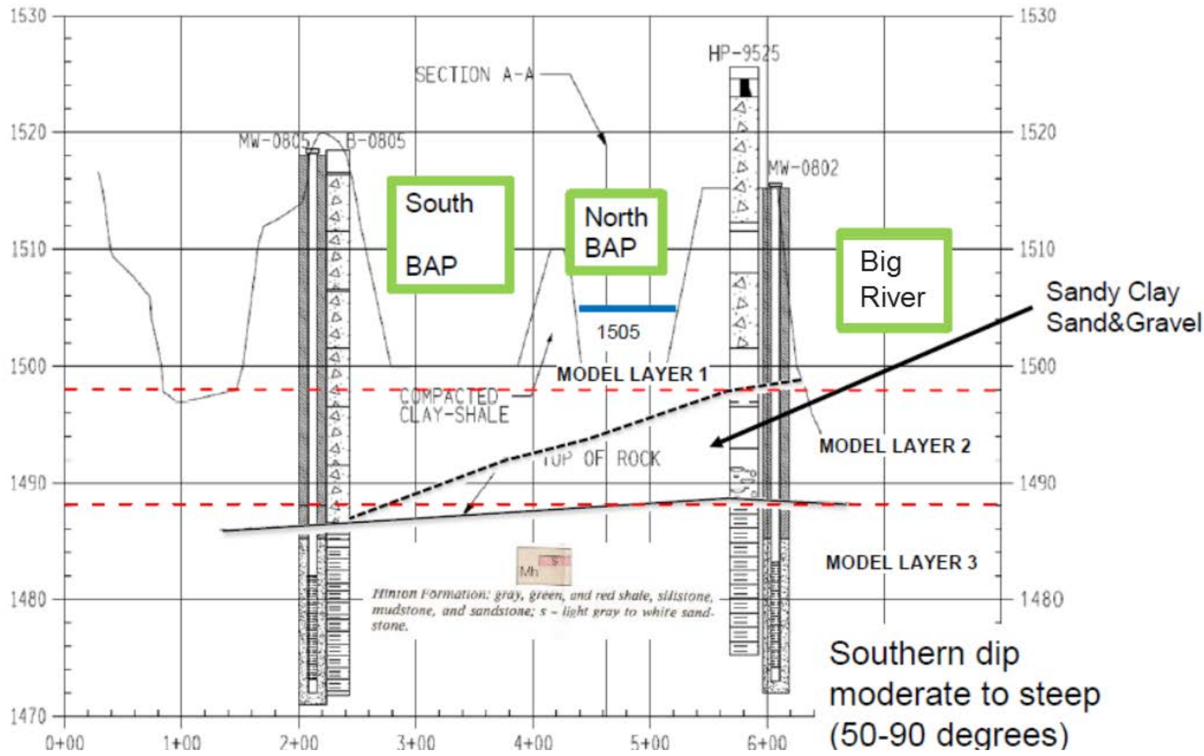

Figure 3: Cross-section B-B'

Recharge to the groundwater system is from precipitation infiltration that occurs between the topographic highs and valleys. Recharging water infiltrates into unconsolidated deposits and shallow rock across the basin and ultimately flows downslope to discharge into nearby surface water bodies.

Shallow groundwater likely occurs in the unconsolidated deposits and bedrock units in the upland areas. Site wells have been completed in the shallow bedrock zone of the Hinton Formation (weathered and competent shale). Preferential bedrock groundwater flow is within the fracture system and is also local to the shallow alluvial systems produced by perennial stream flow deposition. In addition, stress-relief fracturing may occur at erosional portions of the rock units along hillsides. This fracture system introduces additional secondary permeability in these areas.

There are two main surface water features, namely the Big River and the Small River present across the Site along with a drainage channel south of the BAPs.

GROUNDWATER FLOW MODEL DEVELOPMENT

A numerical groundwater flow model was developed and calibrated to observed Site conditions to evaluate groundwater flow paths from the BAPs to adjacent surface water bodies and to estimate dilution attenuation factors (DAFs) for risk assessment purposes. The numerical code selected for this model was MODFLOW (McDonald and Harbaugh, 1988). MODFLOW was selected because it is widely used in both academia and industry, is familiar to and accepted by regulatory agencies, and has the flexibility to simulate the hydrologic and hydrogeologic stresses and boundary conditions.

Model Discretization

The numerical model domain is three-dimensional, consisting of 273 rows, 275 columns, and 4 layers, and covers an area of approximately 802 acres (**Figure 4**). In the vicinity of the Site, grid cell size is as small as 10 feet by 10 feet. The grid spacing increases up to 100 feet at model extent. The model grid axes are rotated 23 degrees counter-clockwise to align the major axes of the model with major flow directions in the pond area. The model is vertically discretized into four layers. The bottom of layer 1 is set to the bottom of the BAPs in the active model domain, approximately 1,498 feet amsl (**Figures 2 and 3**). Model layer 2 corresponds to the unconsolidated material near the Site. Model layers 3 and 4 correspond to bedrock unit, specifically the Hinton Formation. The bedrock unit was split into two model layers to more accurately simulate flow in the shallow bedrock beneath the BAPs where the monitoring wells at the Site are installed.

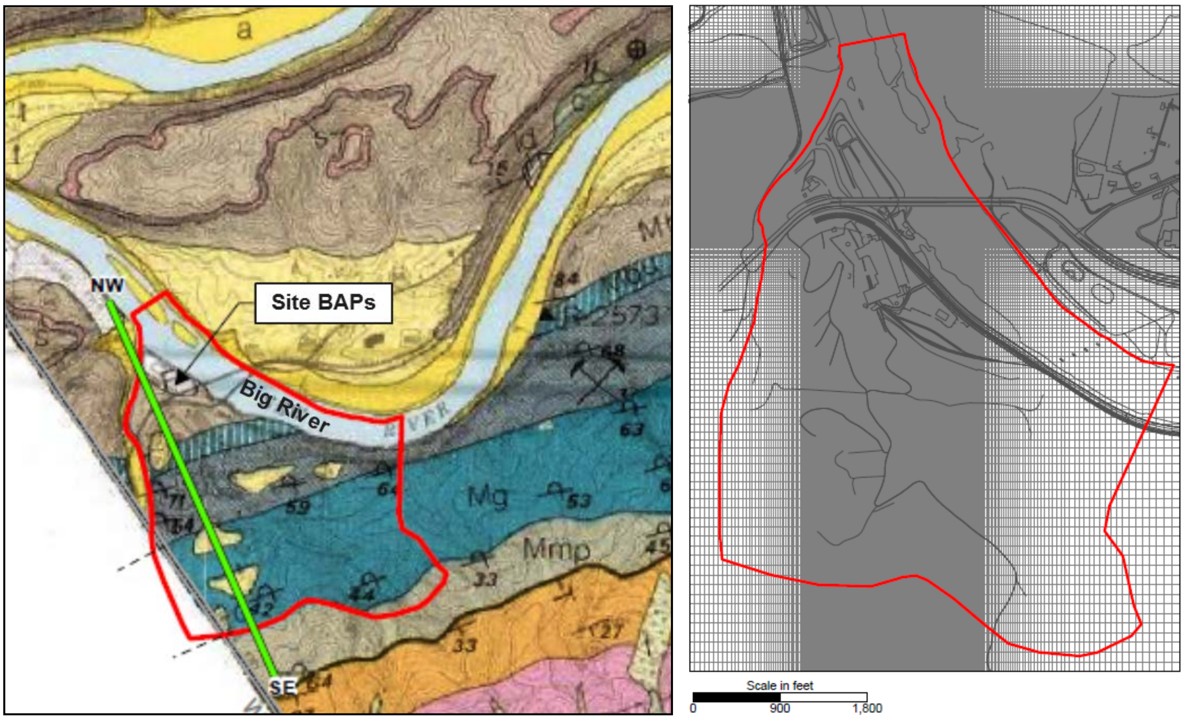

Figure 4: Model extent and finite difference grid

Boundary Conditions

The groundwater flow model features four types of boundary conditions: no-flow boundary cells, constant-head cells, river cells, and pumping wells. No-flow boundary cells were used to delineate the spatial extents of the model within each layer. For the model layers representing high elevations, no-flow boundaries represent the outcrop of each geologic unit as the base layer elevation intersects ground surface. No-flow boundaries in the lower-elevation model layers were selected based on natural topographic groundwater divides, and local and regional discharge features. **Figure 5** presents the horizontal extents and boundary conditions of the active areas for each model layer.

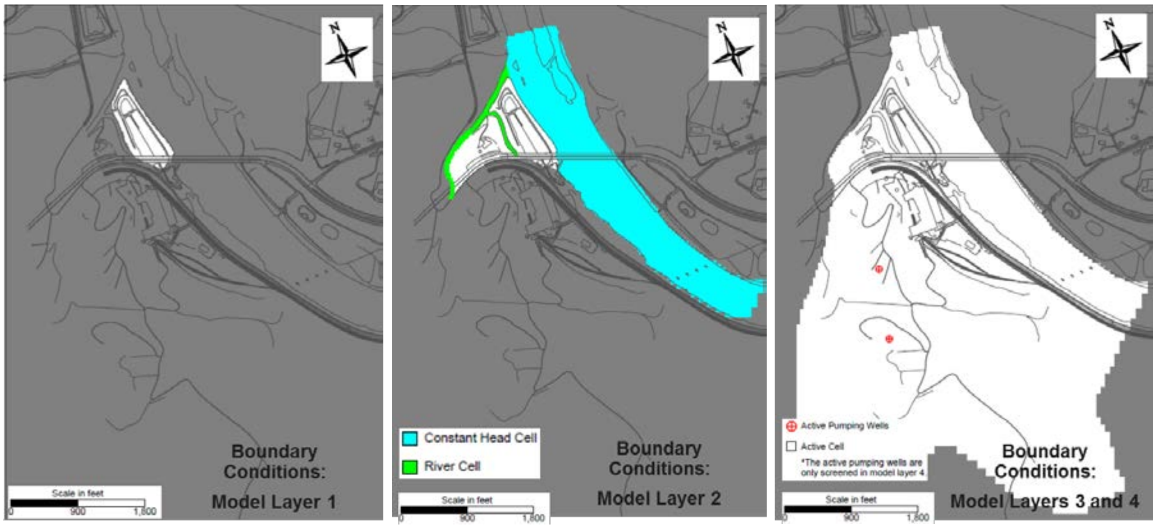

Figure 5: Simulated boundary conditions

Model layer 1 contains only active cells and no-flow boundary conditions. The active model domain represents the area covering the three ponds (i.e., two BAPs and CWP) as well as the berm surrounding the three ponds. Model layer 2 has no-flow cells, constant head cells, and river cells. Constant-head cells were used to simulate the Big River as a regional head boundary in model layer 2. The river cells represent the Small River and the drainage channel adjacent to the South BAP. Model Layers 3 and 4 have only active cells and no-flow boundary conditions. The active model domain in Layer 3 and 4 is bounded by the Big River to the north, the Small River to the west, and a hydrologic divide to the east and south. Model Layer 4 includes two municipal pumping wells: PW-1 and PW-2.

<u>Hydraulic Parameters</u>

Hydraulic conductivity values were assigned using hydrogeologic zones in the groundwater flow model (**Figure 6**). Hydrogeologic zones are areas where hydraulic parameters are set to a constant value. Values of horizontal and vertical hydraulic conductivity for each of the model zones and layers are generally based upon hydraulic conductivity estimates for the appropriate material types, and were varied during model calibration. The berm area surrounding the ponds is represented by a low conductivity zone of 0.2 feet per day (ft/day). Since the South BAP is inactive and mostly filled with ash, it was represented with an estimated hydraulic conductivity of 1 ft/day. On the contrary, both the CWP and the North BAP are mostly filled with water; therefore, these two ponds have been assigned a high conductivity value of 400 ft/day. The hydraulic conductivity distribution in model layer 2 has two zones representing the alluvium (2 ft/day) and the bedrock (10 ft/day). Model layers 3 and 4 had similar zonation: a zone of low hydraulic conductivity of 0.25 ft/day where steep gradient in surface elevation is observed, and a higher conductivity zone of 10 ft/day where the bedrock surface is relatively flat.

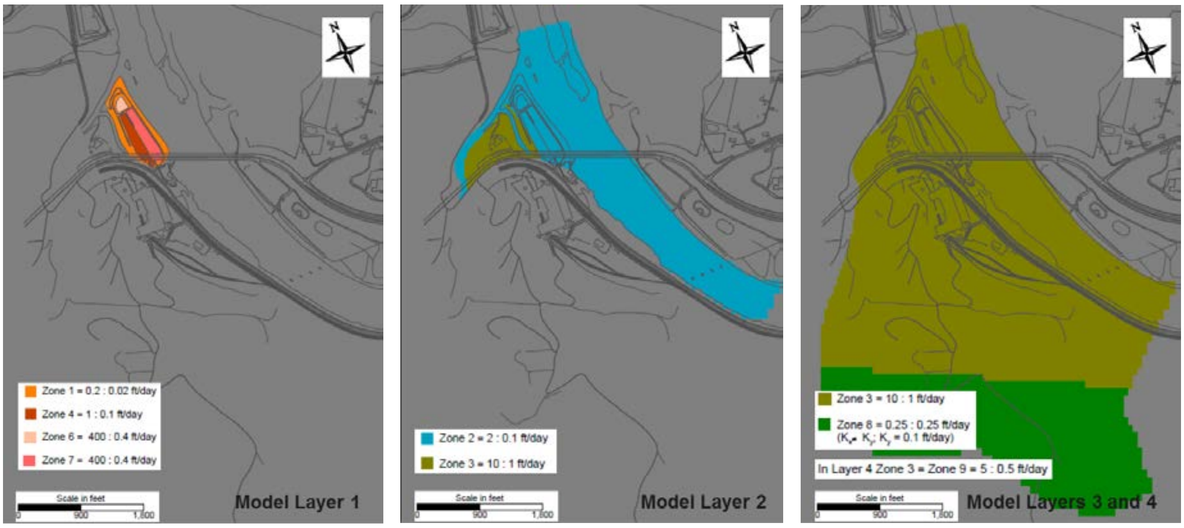

Figure 6: Simulated hydraulic conductivity distributions

A uniform recharge rate of 5.25 inches per year (in/yr) was applied to most of the model domain. Due to the reduced spatial extents of the uppermost model layers (model layers 1 and 2), recharge was assigned to the highest active model layer for any particular point within the model domain. A much higher net recharge rate of approximately 315.74 in/yr was applied to the CWP and North BAP. The net recharge rate was primarily estimated from inflow and outflow data for the ponds, and was adjusted during model calibration.

<u>Model Calibration</u>

Model calibration is an iterative procedure that involves adjustment of hydraulic properties and/or boundary conditions to achieve the best match between observed and simulated water levels. The steady-state flow calibration process for the numerical model consisted of 7 water-level targets, which included groundwater elevations at five monitoring wells, and water level measurements in the CWP and the North BAP.

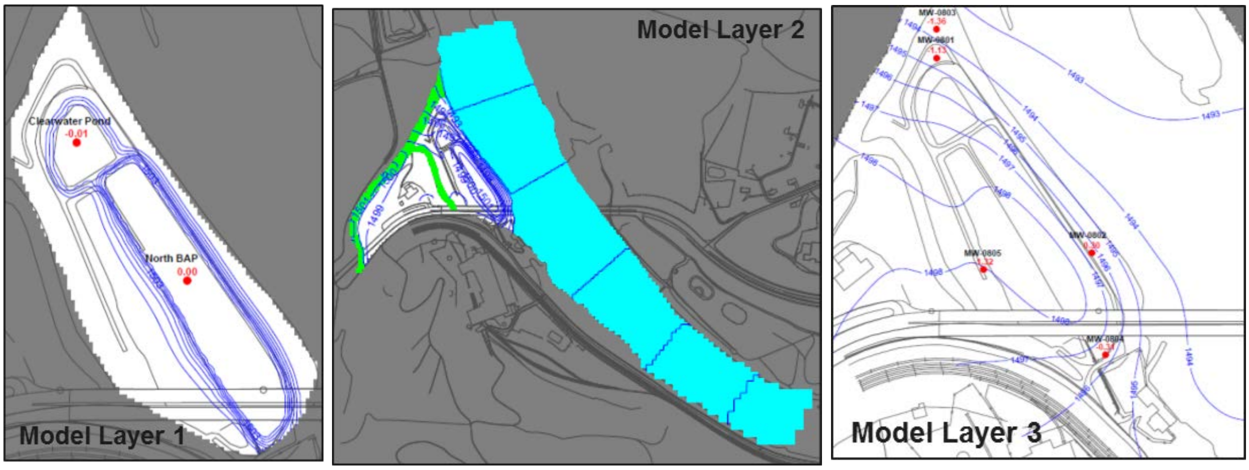

Figure 7: Simulated water levels and residual distributions

The quality of the model calibration can be determined by a statistical analysis of the residuals, which are defined as the difference between the model-simulated heads and the observed values. Positive residual values indicate that the model-simulated values are lower than the measured values, and negative residual values indicate that the model-simulated values are higher than the measured values. **Figure 7** illustrates simulated water levels and residual distributions across various model layers. The figures also suggest that observed water levels match closely with simulated water levels across various hydrogeologic units. The residual mean, residual standard deviation, and sum of squared residuals were calculated to be -0.55 feet, 0.65 feet, and 5.05 square feet, respectively. The residual standard deviation is less than 5% of the range in observed water levels. These statistics along with simulated head and residual distributions indicate a satisfactory degree of model calibration has been achieved.

GROUNDWATER FLOW EVALUATION

As depicted on **Figure 7**, groundwater elevations are generally higher at the pond area within each layer, and decrease radially towards surface water bodies, particularly to the Big River.

Pathline Analysis

Pathline analysis was performed to evaluate groundwater flow path using MODPATH (Pollock, 1989) simulation code. Particles were simulated in model layer 1 surrounding the BAPs and CWP. Particles were also simulated longitudinally in each pond in model layer 1. Forward path line analysis for the calibrated flow model (i.e., baseline condition) indicates that all the simulated particles originating from the BAP area eventually terminate either at or below the Big River (**Figure 8**) suggesting that all the water from the pond area discharge to the Big River.

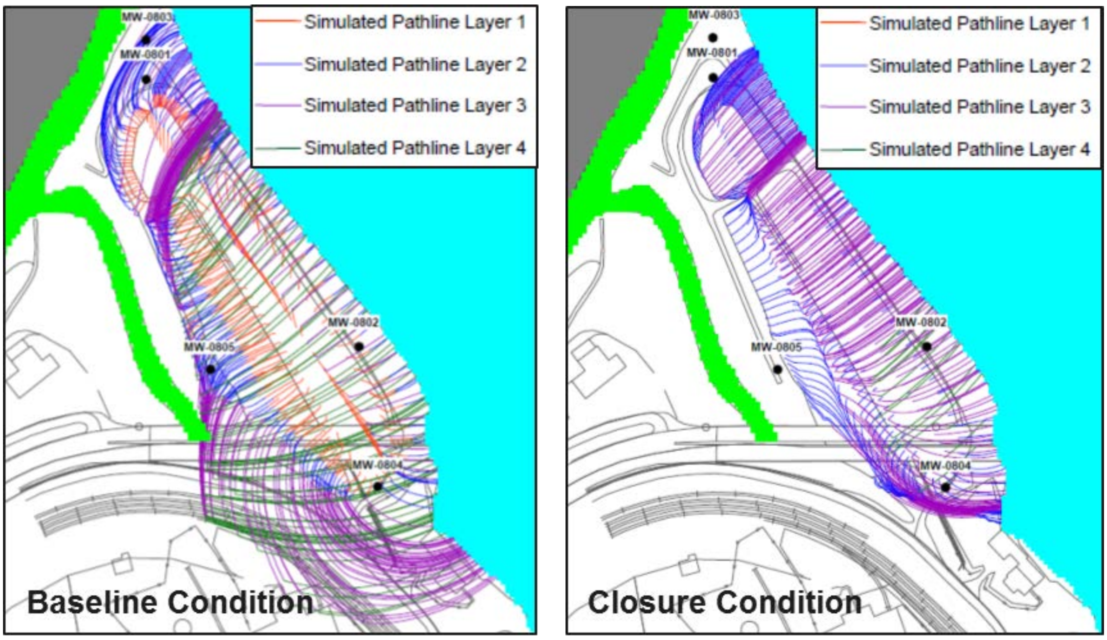

Figure 8: Simulated pathlines under baseline and closure conditions

Pathline analysis was also performed for a closure scenario with the North BAP assumed to be closed. For this scenario, recharge to the CWP and the North BAP was reduced to 30% of the baseline condition. All other parameter values in the model remained same to the calibrated flow model. Forward pathline analysis (**Figure 8**) indicate that similar to the baseline condition, all the simulated particles originating from the BAP area eventually terminate either at or below the Big River suggesting that all the water from the pond area will continue to discharging albeit at a substantially lower rate to the Big River when the North BAP is closed.

Dilution Attenuation Factors

The DAFs were calculated for the baseline (i.e., current) condition as well as the closure scenario with the North BAP being closed. The DAF is calculated by dividing the measured flow in the surface water body (i.e., the Big River) by the model simulated groundwater discharge from the ponds (i.e., CWP, and the two BAPs). Flow data for the Big River was obtained from a nearby USGS Stream Gauge, where the minimum of the recorded flow value over the last 20 years was utilized as conservative DAF estimate. **Table 1** presents the simulated and measured flows as well as the calculated DAF values for the two scenarios.

Table 1: Calculated DAFs under baseline and closure scenarios

Scenario	Simulated Flow from Ponds (cfd)	Minimum Flow in Big River (1995-2015) (cfd)	Dilution Attenuation Factor
Baseline Scenario	9916	58,752,000	5,925
Closure Scenario	2946	58,752,000	19,941

cfd = cubic feet per day

Table 1 indicates that the DAF under closure scenario is expected to be 3.4 times higher compared to baseline condition, which in turn, suggests more dilution of the discharging groundwater and accompanying site-related constituents would occur under the North BAP closure condition.

RISK EVALUATION

A screening level risk evaluation was conducted to assess the potential for exposure of human and aquatic ecological receptors to constituents associated with the BAPs potentially migrating to the Big River in the vicinity of the Site. The approach for this evaluation was conservative in nature so that the results will be protective of human and ecological receptors.

Exposure Conceptual Site Model

The Exposure CSM provides the framework of the screening level risk evaluation. It identifies the primary and secondary potential sources and release mechanisms as well as the media of interest (exposure points), potential receptors, and their potential exposure routes. Exposure points are places or "points" where exposure could potentially occur, and exposure routes are the means by which constituents of interest may be taken up by the receptor (ingestion, inhalation, and dermal contact).

As discussed earlier, constituents in the BAPs could potentially migrate to groundwater which flows towards the Big River in the vicinity of the Site. Exposure to constituents in surface water could occur during recreational use (e.g., wadding, swimming, and/or fishing) or through use of surface water as a potable water supply. Exposure to constituents in groundwater could also occur through use of groundwater as a potable water supply. To identify potential exposure pathway, both groundwater and surface water use in the vicinity of the Site were considered as well as the source of potable water in the area.

A water well survey was conducted for the area within 0.5 mile of the Site that identified two municipal wells (namely PW-1 and PW-2), though both of them were located at cross-gradient from the Site. No downgradient wells were identified during the survey.

Surface water in the vicinity of the Site is not used for potable use. However, surface water was evaluated for recreational use.

Predicted Surface Water Concentrations

Surface water concentrations were predicted using constituent concentrations detected in water samples obtained at the bottom of the BAPs and from monitoring wells and the estimated DAFs. A total of 13 samples taken between 2010 and 2014 were available for pond water from the BAPs and a total of 17 groundwater samples per well sampled between 2009 and 2014 were available for the monitoring well network. For the preliminary screening evaluation, maximum detected concentrations from both the pond water and groundwater were used to estimate surface water concentrations. The DAF for BAP water to surface water based on the baseline scenario was conservatively used to estimate the surface water concentrations because the model simulation indicated that most of the flux comes from the BAPs and not from up-gradient groundwater. Since maximum concentrations for some constituents were higher in groundwater than pond water, using the greater maximum concentration of the pond water or groundwater was a conservative assumption. Further, using the DAF based on baseline scenario is conservative because the DAF derived based on the closure scenario is predicted to be much higher. In summary, predicted surface water concentrations are conservatively reflective of the baseline scenario and protective of the future closure scenario.

Screening Levels

Screening levels are concentrations below which risk to human or ecological receptors is not expected. Screening levels are conservative in nature because they are derived based on protection of the most sensitive receptor. Concentrations exceeding screening levels do not necessarily imply that risk exists, rather that further evaluation is warranted.

Screening levels were identified from a variety of sources for this evaluation. Methods used in the screening evaluation were consistent with those recommended by the Commonwealth of Virginia (Virginia Department of Environmental Quality [VDEQ]) and the U.S. Environmental Protection Agency (USEPA) agencies, that included:

- VDEQ Voluntary Remediation Program Tier II Screening Levels
- USEPA Drinking Water Maximum Contaminant Levels and Tap Water Regional Screening Levels
- Water Quality Criteria for water & organisms and organisms only
- USEPA Regions 3, 4, and 5 freshwater screening levels

Results

Comparison of predicted surface water concentrations and all identified screening levels indicated that the predicted maximum surface water concentrations were all below the applicable screening levels for all site-related constituents, indicating that risk to human and ecological health is not expected.

In addition, upstream and downstream surface water samples were collected from the Big River in December 2014. Duplicate samples were collected and the greater of the two results was selected as the point of comparison to the predicted contribution to surface water concentrations and are summarized in **Table 2** below. Upstream background data were available only for arsenic, chromium, lead, mercury, and selenium. Although selenium was not detected in the upstream surface water samples, the contribution from groundwater to the Big River would also not be detectable following groundwater discharge. As seen in **Table 2**, none of the predicted contributions to surface water exceed upstream sample data and the predicted contributions to surface water relative to upstream data are minimal as they range from 0.024% to 2.4%. Thus, it is unlikely that the contribution of the groundwater discharging to the Big River will have a significant impact on the river, and any impacts to the Big River due to discharge of groundwater into the river is not expected to adversely affect the river.

Table 2: Predicted surface water and background concentrations

Constituent	Maximum Background Concentration		Maximum Predicted Concentration Contribution to Surface Water	Percent of Predicted Contribution to Surface Water
	Upstream (µg/L)	Downstream (µg/L)	(µg/L)	(%)
Inorganics				
Arsenic	0.18	0.25	0.00425	2.4
Chromium	0.3	0.3	0.000186	0.062
Lead	0.45	0.481	0.000473	0.11
Mercury	0.21	0.20	0.0000506	0.024
Selenium	<0.1	0.1	0.000527	0.53

µg/L = micrograms per liter

SUMMARY AND CONCLUSIONS

A three-dimensional groundwater flow model was developed to evaluate groundwater flow conditions and groundwater flux to surface water bodies in the vicinity of a CCR management facility with BAPs. The model was used to estimate DAFs to the adjacent Big River. A screening level risk evaluation used the estimated DAFs and concentration data to assess the potential for adverse effects to human and aquatic ecological health from exposure to constituents associated with the BAPs and potentially migrating to the Big River in the vicinity of the study area. The predicted maximum contribution to surface water concentrations were all below the background surface water concentrations measured in the Big River. The predicted maximum surface water concentrations were all below the applicable screening levels, indicating that risk to human and ecological health is not expected. This approach of numerical modeling followed by risk evaluation has been found to be an effective management strategy for BAP closure under the CCR legislation.

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