Cap or Excavation, and What Happens Next? Numerical Flow and Transport Modeling as a Decision-Making Tool for Ash Basin Closure

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ABSTRACT

Driven by the U.S. Environmental Protection Agency (USEPA) Coal Combustion Residuals (CCR) Rule, closure of ash basins has become necessary at many power facilities across the United States. Common closure alternatives include capping the ash in place (closure-in-place), excavation of ash for disposal (closure-by-removal), or a hybrid of both. Choosing a closure alternative is a complicated decision considering the economic, hydrologic, and ecologic relationship between a CCR unit and the surrounding facilities, residents, and ecosystem. Finding a balance between costs and closure goals can be especially challenging when multiple stakeholders are involved.

This paper uses examples in the Piedmont region of the southeastern United States to demonstrate how numerical flow and transport models can be used as a tool to support decision-making throughout a closure project. By integrating geological, hydrological, and other site characterization information into one model, the investigator can screen different options on a fair and objective basis. A suite of commercially available programs permits detailed evaluations of various closure system designs. Model results can reveal crucial but not readily understandable factors in a project, thereby providing the opportunity to address problems proactively and cost-effectively. Furthermore, model output can be easily visualized at different spatial and temporal scales, which promotes effective communication among all stakeholders.

INTRODUCTION

According to the Global Energy Monitor website,[1] about 240 coal-fired power plants are in operation in the United States as of January 2022 and approximately 300 coal-fired power plants have been retired since 2000. The U.S. Energy Information Administration website[2] summarizes the historical distribution of coal-fired power plants from 2008 through 2021 (**Figure 1**) and indicates an overall decreasing trend in the number of plants over time.

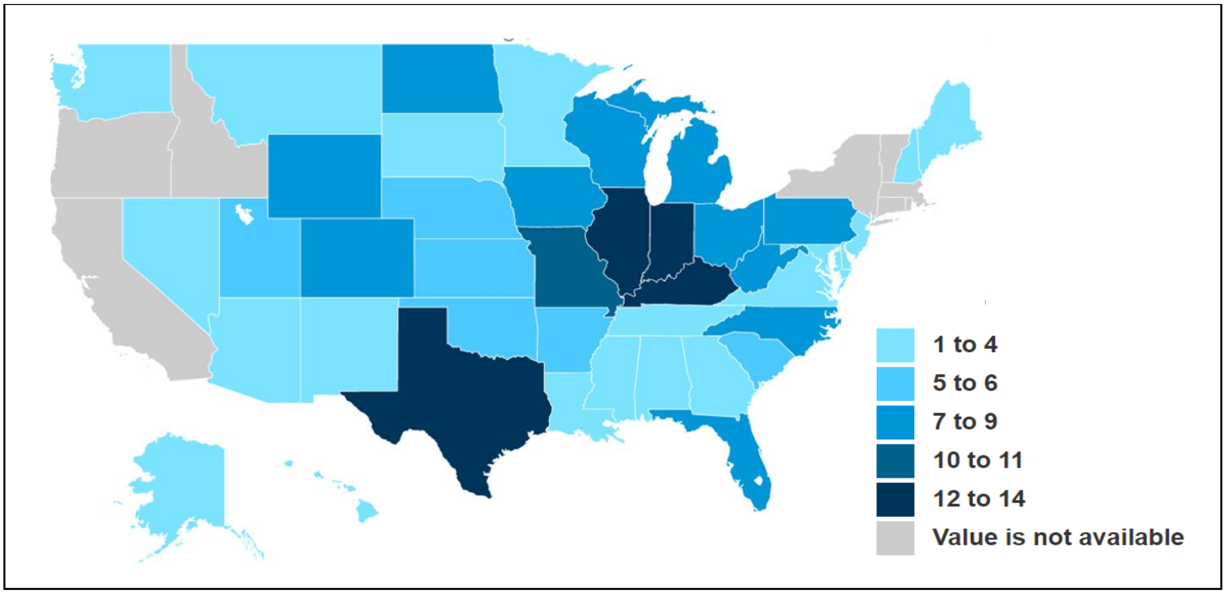


Figure 1. Coal-fired power plants in operation in the US in 2021[2]

CCR has been historically managed on-site, either in landfills (dry storage) or ash basins (wet storage). The majority of the older ash basins were built without a liner. In 2015, USEPA rolled out the CCR Rule that set up minimum requirements for CCR management in ash basins and landfills. Although this rule does not explicitly prohibit wet storage of CCR, ash basins without a liner are required to be retrofitted or closed. The CCR Rule combined with the retirement of many older coal-fired power plants greatly accelerates the transition from wet to dry storage. Many ash basins are expected to be closed in the next decade.

Closure of an ash basin can involve a myriad of tasks that may differ from site to site (**Figure 2**):

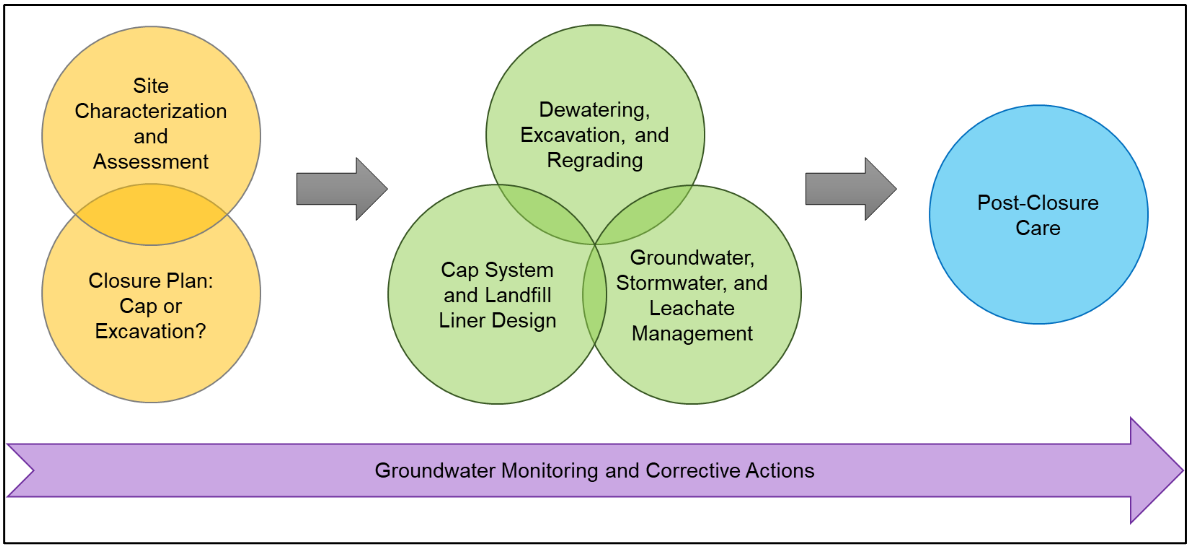


Figure 2. Common decision-making process for a closure project

A closure project normally starts with a comprehensive site characterization and assessment. Based on the site characterization and assessment a master closure plan may be determined, which can either be capping the ash in place, excavating ash for disposal, or a combination of the two options.

After selecting the overall closure approach, closure engineers need to work on detailed designs and implementation plans, including but not limited to:

- How to dewater, grade, or excavate ash
- Design of a final cap system or a landfill liner system
- Management of stormwater, groundwater, or landfill leachate

If the ash basin is capped in-place, once closure is completed, post-closure care must be conducted after closure for a minimum of 30 years according to the CCR Rule. In addition to above closure activities, the CCR Rule also requires groundwater monitoring throughout the closure project which can lead to more extensive corrective actions.

Because of the unique characteristics of ash basins, making good decisions during closure can be challenging. First, unlike landfills, ash basins can vary greatly in many aspects such as basin configuration, size and shape, property of ash and containment material, percent of water content, proximity to community, etc. All factors could affect the closure decision to some degree and there is no single “playbook” to follow. Secondly, many older ash basins have accumulated a large amount of operational and monitoring data, which are not necessarily coherent and organized due to historical changes in analytical methods, regulatory criteria, and plant personnel. These data are like pieces of a jigsaw puzzle that need to be put together to reveal the big picture. Last, there is a need to balance costs, schedule, compliance goals, and plant operational goals, just like many other projects.

A numerical flow and transport model is a mathematical representation of a real-world system. The processes in this system are often simplified in the model so that they can be effectively analyzed by computational methods with reasonable accuracy. Modeling presents several advantages in addressing concerns related to a complicated groundwater system that includes one or more CCR units:

- A model can be customized based on the site-specific need to focus on important or urgent questions during closure
- A model can offer the framework to structure and integrate a large amount of data and is efficient at identifying data gaps
- A model can be used to evaluate multiple closure alternatives on an equal and objective basis

This paper presents several case studies to demonstrate how numerical flow and transport models can be used through all stages of an ash basin closure project. This paper will discuss major challenges during closure including site characterization, closure option selection, closure system design, and remedial system design, and viable numerical modeling methods to overcome these challenges both efficiently and defensively.

MODELING METHODS

The numerical groundwater flow models discussed in this paper were developed using MODFLOW,[3] a three-dimensional (3D) finite difference groundwater model created by the United States Geological Survey (USGS). The chemical transport model is the Modular 3-D Transport Multi-Species (MT3DMS) model.[4] MODFLOW and MT3DMS are widely used in industry and government and are considered industry standards. The models were assembled using the Aquaveo GMS 10.4 graphical user interface (http://www.aquaveo.com/).

MODFLOW uses Darcy's law and the conservation of mass to derive water balance equations for each finite difference cell. This study uses the MODFLOW-NWT version.[5] The NWT version of MODFLOW provides improved numerical stability and accuracy for modeling problems with variable water tables. The improved capability is helpful in the present work where the position of the water table in the ash basin can fluctuate depending on the conditions under which the basin is operated and on closure activities.

MT3DMS uses the groundwater flow field from MODFLOW to simulate 3D advection and dispersion of the dissolved CCR constituents, including the effects of retardation due to adsorption of constituents to the soil matrix.

Common steps in building a numerical flow and transport model include:

- Develop a site conceptual model according to preliminary knowledge of the site geology and hydrology
- Define the model domain and appropriate grid spacing
- Populate the model domain with hydrogeological features and aquifer properties, such as groundwater sources and sink, recharge rate, hydraulic parameters, etc.
- Define the key processes which commonly involve groundwater flow and chemical transport
- Run the model to provide initial estimates for hydraulic head distributions, groundwater flow, and chemical transport
- Perform model calibration (a vital step for the model to be robust and reliable), primarily by adjusting model configuration and parameter values, so that the modeling results reasonably match field observations
- Run comparison or predictive simulations to answer site-specific questions
- Refine models to incorporate updated information and recalibrate to match new observations when new data that is likely to influence the studied processes become available

What makes a flow and transport model particularly useful is that it is not a static tool. Instead, it can be constantly updated and improved as a project moves forward, and then be used to provide more accurate and specific answers to questions of the site owners and regulators.

CASE STUDIES

Figure 3. Aerial photo of the coal-fired power plant

The subject of the case studies is a coal-fired power plant located in the southeastern United States (**Figure 3**). In the middle of the last century, an ash basin was built within a perennial stream valley near the coal-fired unit to sluice and store CCR material. Two decades after the commencement of the ash basin operation, a lined landfill was built above the ash grade partially within this basin. Groundwater samples from this site indicated that several CCR constituents of interest (COIs) had migrated below and downgradient of the ash basin. The coal-fired unit is currently in operation but is expected to be decommissioned soon.

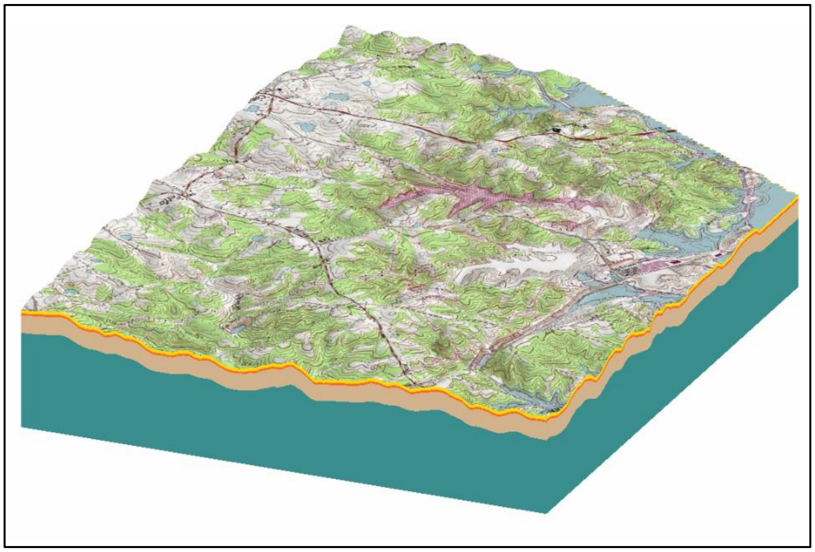


Figure 4. 3D view of the numerical model for the CCR site

A numerical flow and transport model was developed to represent the groundwater flow system that includes this ash basin and the surrounding aquifer (**Figure 4**).

Four examples of applications of flow and transport modeling during the ash basin closure project are presented below. These examples include applications of modeling in site characterization, predicting post-closure groundwater quality in support of closure option analysis, facilitating closure system design, and informing remedial system design through characterization of a preferential chemical migration pathway.

APPLICATION OF NUMERICAL MODELING IN SITE CHARACTERIZATION

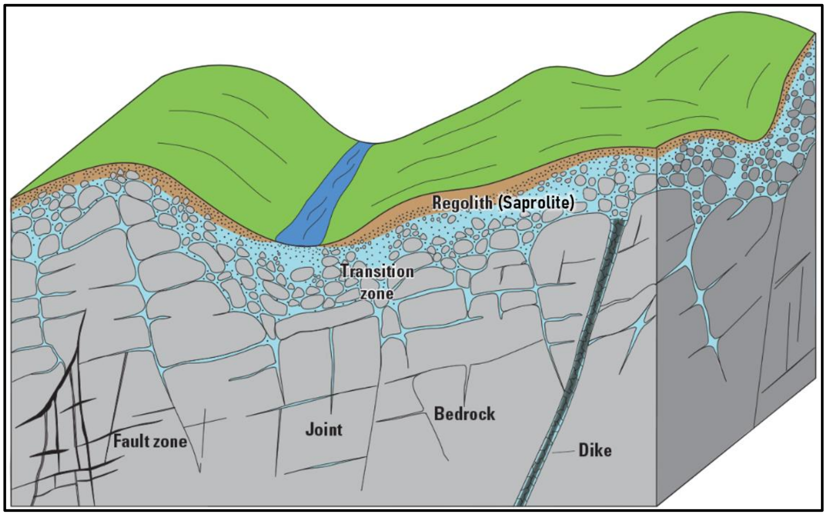


Figure 5. Schematic of a typical Piedmont geologic system (modified from Freeze and Cherry, 1979)[6]

Site characterization often begins with the development of a conceptual site model with some basic knowledge of the site geology and hydrology. This site is located in the Piedmont geological region in the southeastern United States. It is characterized by gently rolling topography, underlain by a thick layer of regolith, a highly weathered transition zone, and crystalline rocks that are often fractured (**Figure 5**). Regolith, in some cases referred to as saprolite, is where the groundwater table normally occurs. The transition zone is often the most permeable zone for groundwater flow. And fractures in the bedrock can serve as additional flow pathways.

This ash basin at the site was created in a perennial stream valley via construction of an earthen dam on the lower end of the valley (**Figure 6**).

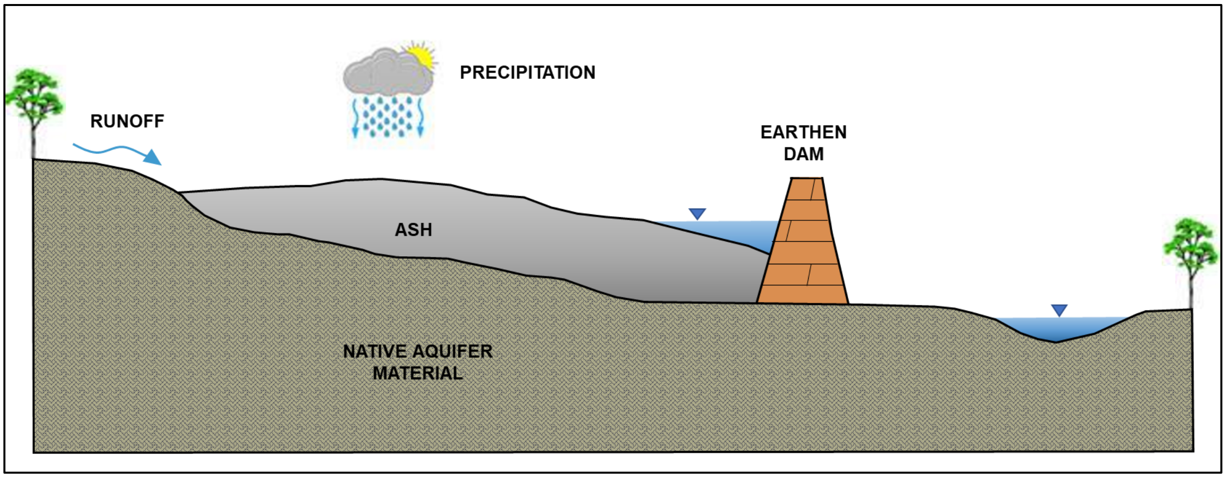


Figure 6. Cross-section through the ash basin within a perennial stream valley

A numerical model was developed based on the above conceptual model as well as site-specific data from field investigations, lab tests, and literature data review. **Figure 7** shows the model grids through the ash basin area with a 4-time vertical exaggeration, along with key hydraulic features such as the dam, the lined landfill above the ash, and a drainage feature downgradient of the dam.

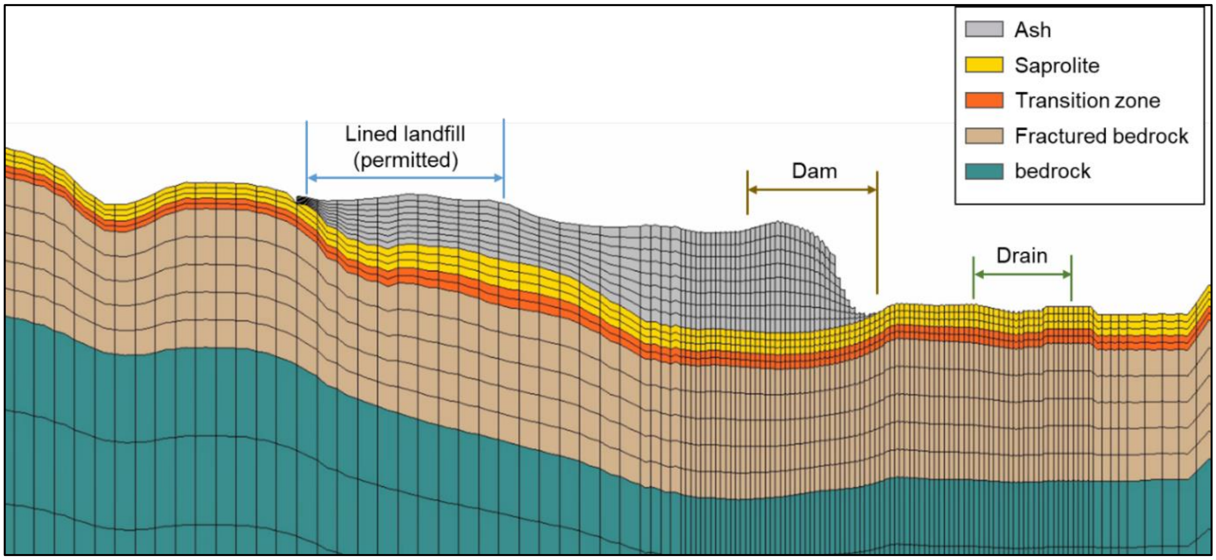


Figure 7. Cross-section of the numerical model grid through the ash basin

A steady-state MODFLOW simulation was run with the numerical grid shown above. The flow simulation was calibrated to site-wide water-level data from more than 170 monitoring wells. Flow calibration resulted in a total normalized root mean square error (NRMSE) of 2.3 percent. The typical industry standard for a good fit to the data is a NRMSE of 10 percent or less. Simulated water table elevations and hydraulic head contour distribution for this cross-section are shown in **Figure 8**.

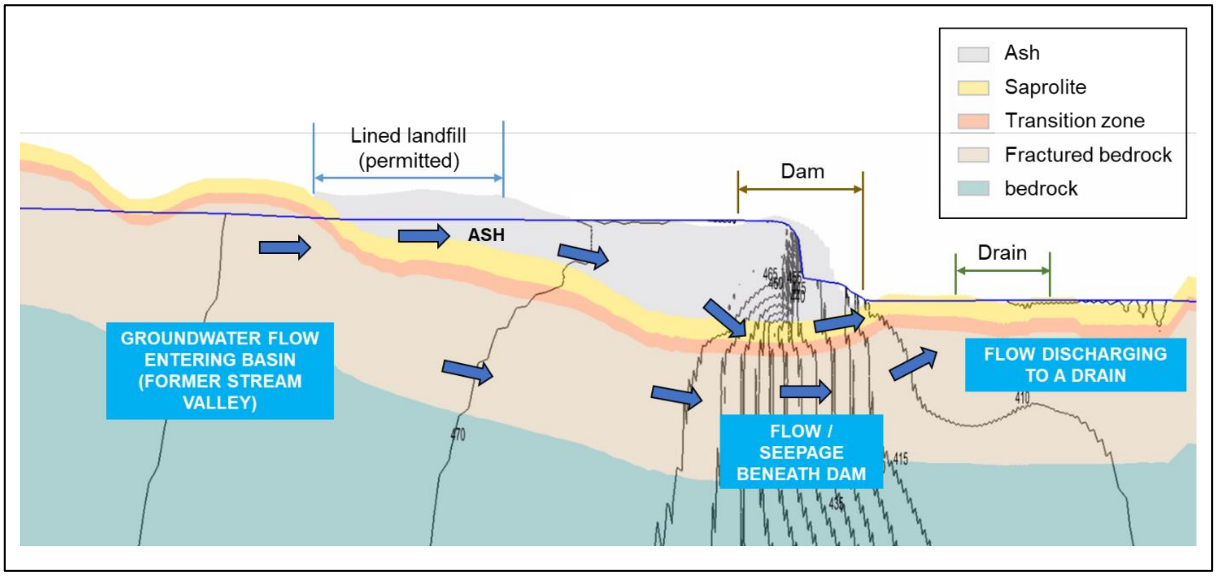


Figure 8. Cross-section through the ash basin showing model-simulated flow field

One major task during site characterization was to understand the local groundwater flow system that drives CCR COIs into groundwater, which is the primary concern under the CCR Rule. The calibrated model revealed an important phenomenon about this flow system. The ash basin acts as a flow-through system where groundwater in the shallow flow zones enters the basin from the upland area, travels through the main body of the basin, moves downward upgradient of the dam (which is a feature of lower hydraulic conductivity compared to surrounding material), and ultimately discharges to a drainage feature downgradient of the dam.

The model was then configured to simulate constituent transport, which was calibrated to measured current groundwater concentrations for several COIs. The transient transport model used a sequence of steady-state MODFLOW simulations to provide the time-dependent groundwater velocity field. Necessary assumptions were made about source zone distribution and historical site operation that were not readily available. The transient transport simulation was then run in MT3DMS to reproduce the observed plume. Transport model calibration resulted in a total NRMSE of 3.6 percent. The simulated COI plumes from 1966 to 2020 along the same cross-section are shown in **Figure 9**.

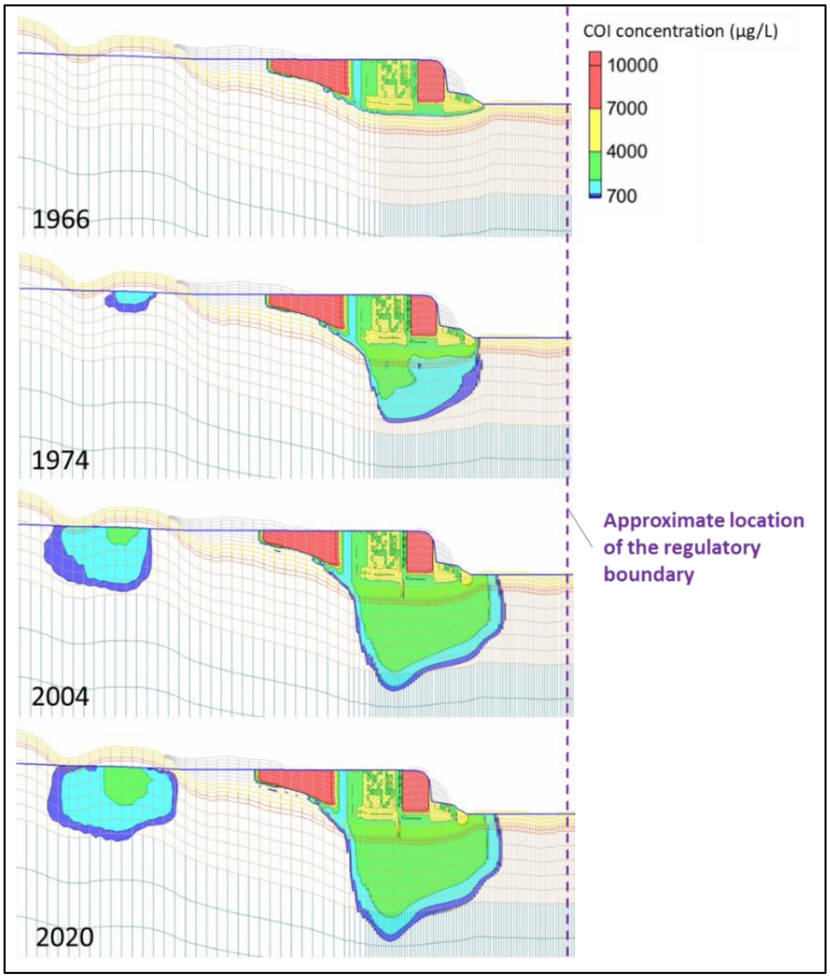


Figure 9. Cross-section through the ash basin showing simulated COI migration

The COI plume from the ash basin is predicted to gradually migrate from the source zone (*i.e.*, the ash basin) into groundwater over time with its impact essentially limited to a zone surrounding the dam. This is consistent with the simulated flow field in **Figure 8** where a downward hydraulic gradient primarily existed upgradient of the dam. However, without the use of the groundwater model, it might be intuitive to assume that CCR COIs would migrate into the environment everywhere beneath the basin, which is not necessarily true.

What may appear unexplainable in **Figure 9** is the development of an additional COI plume to the left of the ash basin around 1974. This area appears to be located upgradient of the ash basin and is unlikely to be affected by COIs from the basin according to the flow field in **Figure 8**. The actual source of this COI plume is a different area containing CCR material that is not visible on the displayed cross-section. This highlights the complexity of COI distributions that are often encountered at CCR sites where multiple sources may be present.

Modeling results from 2004 to 2020 indicated that the leading edge of the plume has been nearly stable for the past two decades (**Figure 9**). One possible reason for this is that the drain feature downgradient of the dam acts as a discharge location for shallow groundwater and prevents the plume from further migration. Another explanation is that COI concentrations along the leading edge of the plume have reach equilibration with natural attenuation mechanisms, which prevents the plume from expanding further. Model predictions indicate that CCR-related COIs never crossed the regulatory boundary along the cross-section shown in **Figure 9**.

Figure 10 presents a different scenario in another area of the ash basin where COIs were found beyond the regulatory boundary. The ash basin (a CCR unit) is located to the left of the regulatory boundary; a non-CCR unit is located to the right (**Figure 10**). It was suspected that plumes to the right are primarily associated with the non-CCR unit rather than the ash basin. To evaluate this hypothesis, a parallel model was constructed with everything identical to the original model except that the non-CCR unit source zone was omitted to estimate the extent of COI plumes solely related to the ash basin.

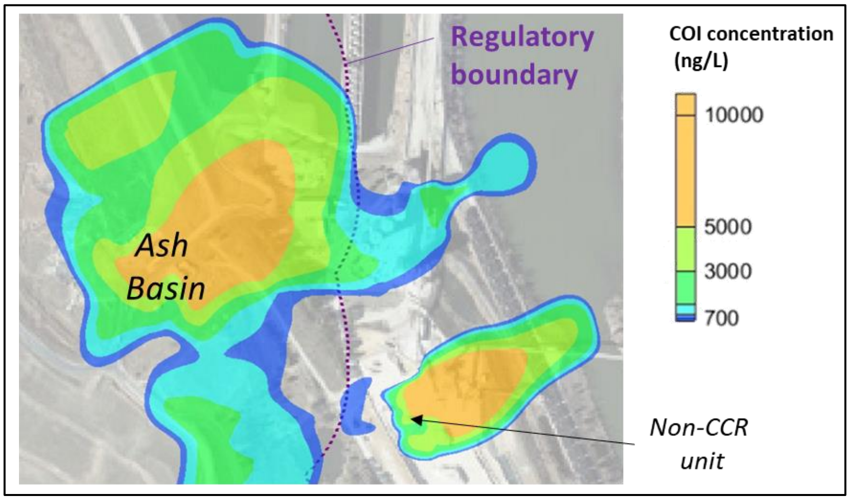


Figure 10. Plan view of model-predicted COI plume extents along the ash basin regulatory boundary

Results from the model with both CCR and non-CCR units (left panel of **Figure 11**) versus the model without the non-CCR unit (right panel of **Figure 11**) suggested that the majority of COI plumes to the right side of the regulatory boundary (circled by black dotted lines) are likely associated with the non-CCR unit. This is a meaningful finding for the ash basin closure and groundwater remediation because the non-CCR unit is regulated under a different program from the CCR Rule and has different compliance requirements. With the demonstration of this alternative source, site owners were able to apply different remedial methods to address each group of COI plumes and have greater flexibility in the remedial design to best meet the goal of each program.

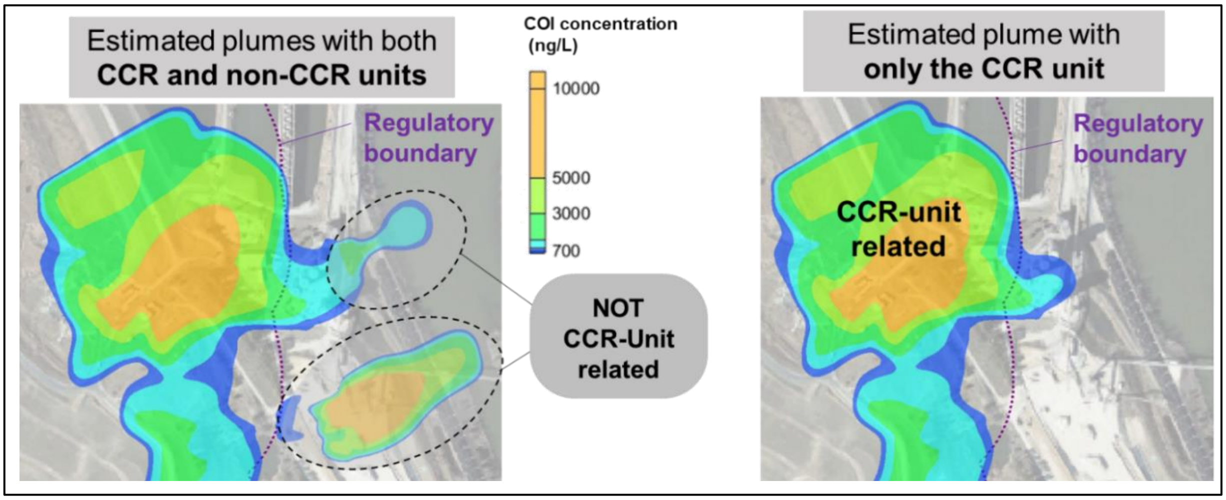
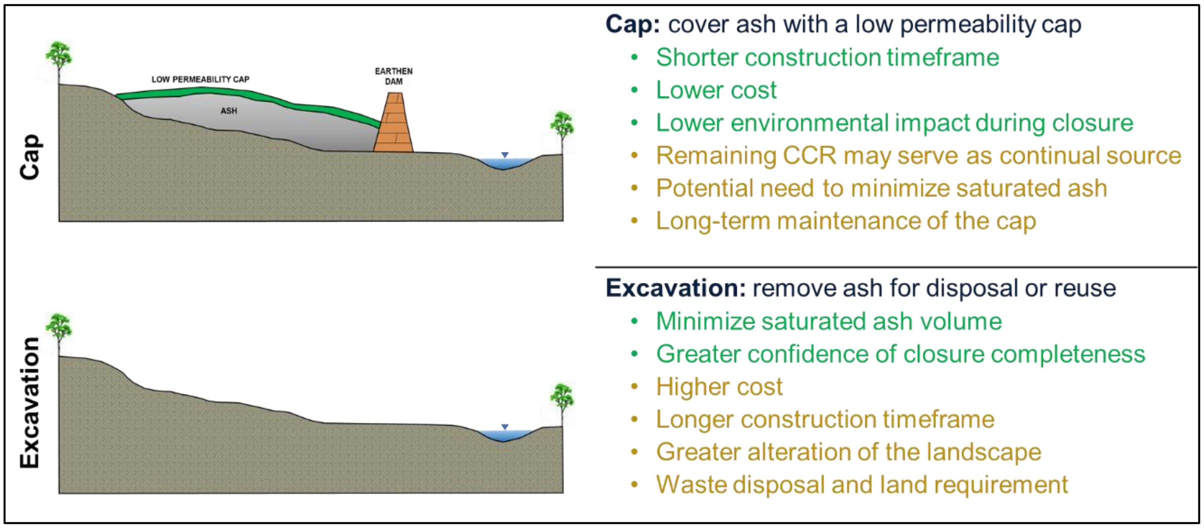


Figure 11. Plan view of model-predicted COI plume extents along the ash basin regulatory boundary

APPLICATION OF NUMERICAL MODELING IN CLOSURE OPTION ANALYSIS

“Cap” and “excavation” are the two primarily ash basin closures options. Cap, sometimes referred to as “cap-in-place” or “closure-in-place”, involves covering ash with a lower permeability cap in conjunction with minimum to no ash removal. Excavation, also known as “clean closure” or “closure-by-removal,” involves removing CCR and affected soil for disposal or beneficial reuse.

Each option has its advantage and disadvantages (**Figure 12**). Cap is often the preferred option due to less time and effort, but it may leave saturated ash in place that could potentially leach into groundwater. Excavation is more costly and lengthy but may be desired or required to reduce long-term liability.



Cap: cover ash with a low permeability cap
- Shorter construction timeframe
- Lower cost
- Lower environmental impact during closure
- Remaining CCR may serve as continual source
- Potential need to minimize saturated ash
- Long-term maintenance of the cap

Excavation: remove ash for disposal or reuse
- Minimize saturated ash volume
- Greater confidence of closure completeness
- Higher cost
- Longer construction timeframe
- Greater alteration of the landscape
- Waste disposal and land requirement

Figure 12. Advantages and disadvantages of Cap and Excavation closure options

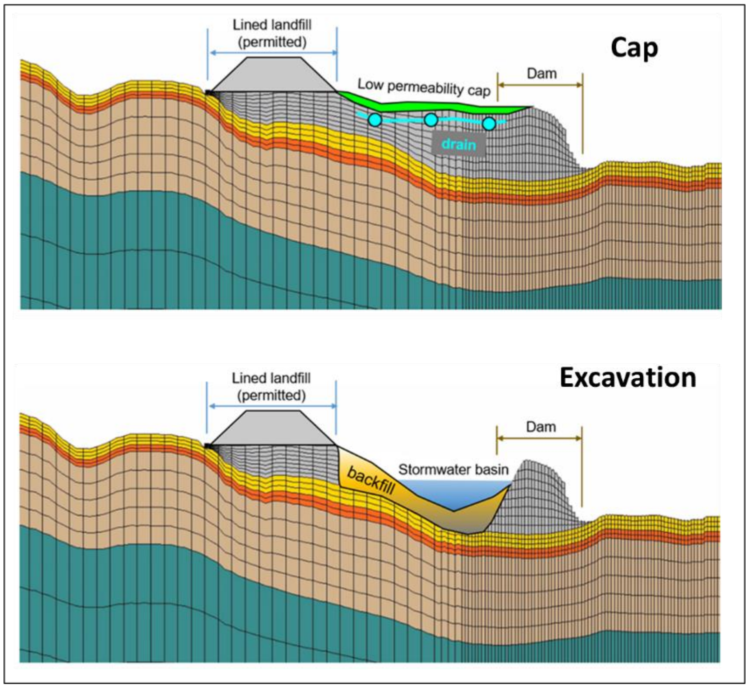


Figure 13. Site-specific closure options

A closure plan for a specific site needs to factor in site-specific conditions and constraints and can vary significantly from the schematics shown in **Figure 12**. The proposed cap option for the ash basin in question includes a low permeable cover with an under-cap swale drain system to keep the ash pore water below the cap (**Figure 13** top panel). The proposed excavation option involves excavation of ash outside of the dam and existing landfill area. Removed ash will be placed in a new landfill that is partially within the footprint of the excavated ash basin (not shown on this cross-section) and the rest of the area will be backfilled to create a stormwater basin (**Figure 13** bottom panel).

The calibrated flow and transport model was updated to represent the two closure designs. Changes include reducing recharge rate for capped areas, increasing hydraulic conductivity to large values to represent excavated material, and inclusion of head boundaries to simulate proposed drains and basins. **Figure 14** shows the simulated responses of the flow system to each closure option. Elevations of the water table in the ash basin are predicted to decrease in both cases, and the final water level is slightly lower in the cap option. However, neither option changes the fact that the ash basin still acts as a flow-through system and the downward flow still occurs near the dam, suggesting that the primary groundwater impact by CCR constituents would likely still occur near the dam area.

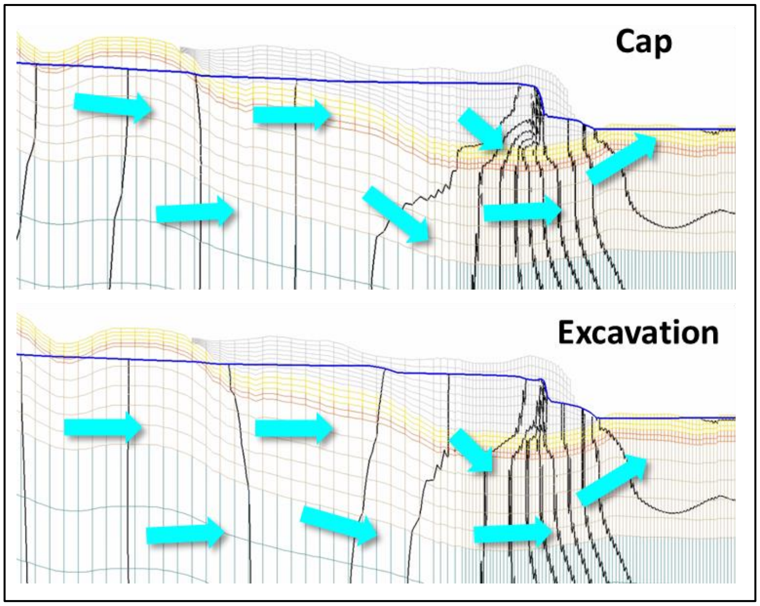


Figure 14. Model-predicted hydraulic head distributions under each closure scenario

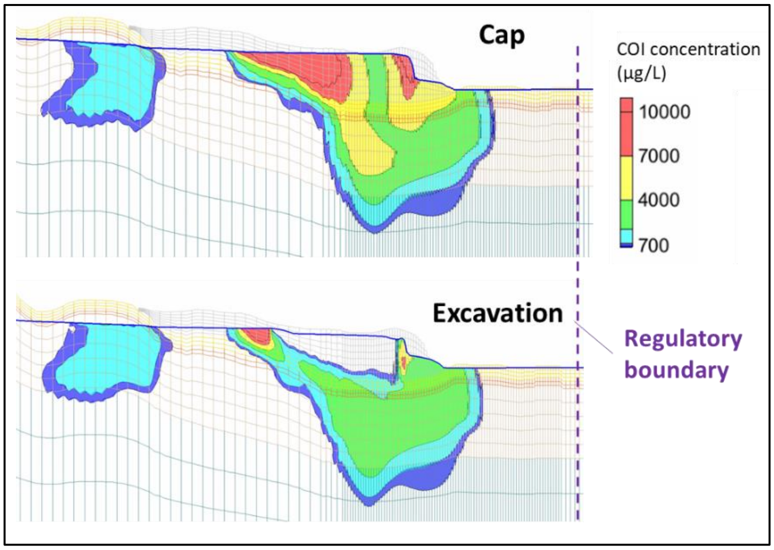


Figure 15. Model-predicted COI plume distribution after 30 years

With the simulated groundwater flow field, the transport model was able to predict future changes in groundwater quality using simulated COI distribution under current conditions as the starting conditions. Model-predicted COI plumes approximately 30 years from now are shown in **Figure 15**. It appears that the excavation option leads to immediate improvement in groundwater quality near the dam, whereas the cap option allows COIs to continuously leach out of the remaining ash that's still partially saturated. However, the difference is limited to the area beneath and downgradient of the dam. At the regulatory boundary, which is closer to the leading edge of the plume, the two options are predicted to cause little difference in groundwater quality.

After reviewing modeling results at several other locations around this ash basin, it was concluded that cap and excavation options are predicted to result in a similar flow field below and downgradient of the ash basin, and more importantly, very similar constituent distribution at the regulatory boundary.

Findings from the model were evaluated along with many other pieces of evidence during the closure decision-making process. In the end, several other factors, including the preference of the regulatory agency and public acceptance, pushed the final decision in the direction of excavation and disposal into an on-site landfill.

APPLICATION OF NUMERICAL MODELING IN DETAILED CLOSURE DESIGN

Several detailed closure designs were developed after a master closure plan was selected (*i.e.*, excavation of the ash basin and placement of CCR material into a proposed on-site landfill). The new landfill, together with a proposed stormwater basin, will be built within the footprint of the current ash basin next to the existing landfill (**Figure 16**).

As required by the CCR Rule, all new CCR landfills shall maintain a vertical separation no less than 5 feet (1.5 meters) between the landfill subgrade and the groundwater table. A preliminary water-level assessment near the landfill footprint suggested that an underdrain below the landfill would be needed to achieve this goal.

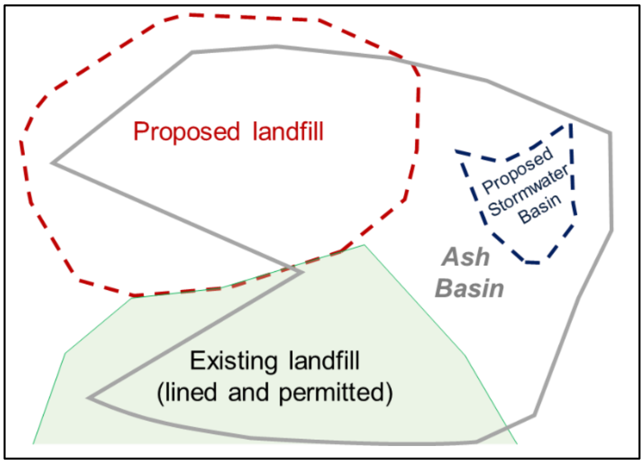


Figure 16. Approximate location of the proposed landfill

The design of this underdrain system faced several uncertainties. First, it is difficult to predict the water table elevations after ash removal using water-level measurements collected with ash in place. Secondly, the water table is likely to fluctuate because of seasonal changes in the recharge rate, which needs to be accounted for with a proper factor of safety.

When it's not practical to obtain all necessary design parameters via field investigation, the regulators often accept the use of flow and transport modeling results as a surrogate to field data to support preliminary designs. The modeling work was done interactively with the underdrain design engineers. Design engineers provided an initial design that was simulated in the model to predict water table elevations; predicted water table elevations were then given to the engineers to compare with the proposed subgrade elevation to identify areas without sufficient separation (left panel of **Figure 17**). The design was subsequently modified to address the issue and re-evaluated in the model. Eventually, the evaluation landed on a design that provides sufficient vertical separation everywhere under the landfill (right panel of **Figure 17**).

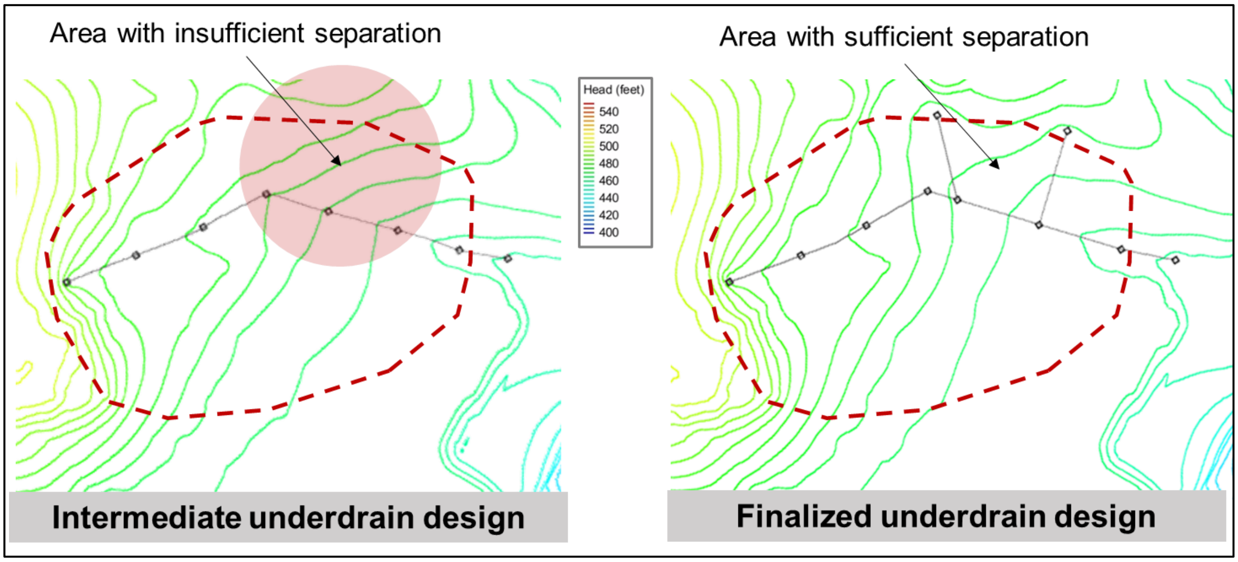
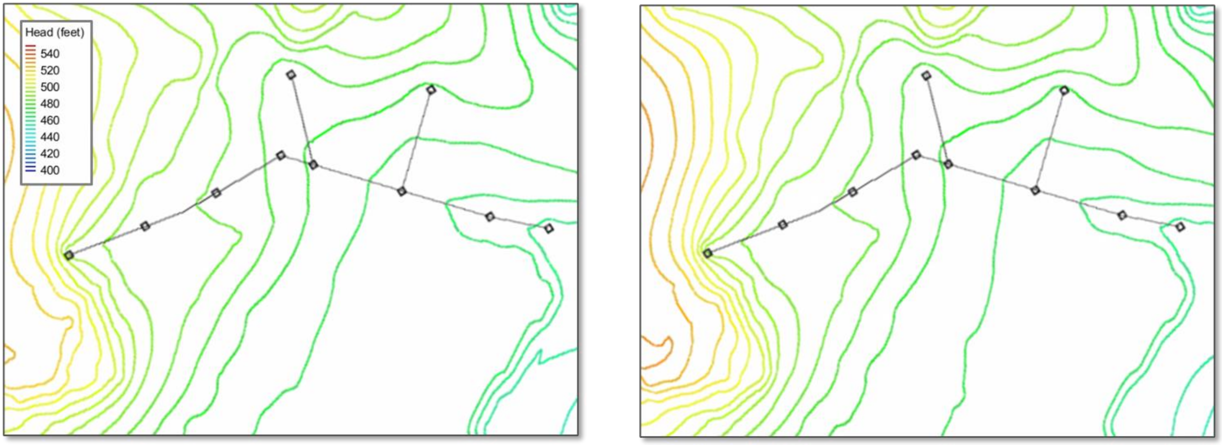


Figure 17. Simulated hydraulic head distribution with different underdrain designs

To address the uncertainty in water table elevations due to seasonal recharge rate fluctuation, a sensitivity analysis was run assuming either an averaged site recharge rate or a "seasonal-high" recharge rate that was determined based on historical data and statistical analyses. The differences in water table elevations between the two scenarios are small but notable on **Figure 18**. The predicted flow rates into the underdrain differ by about 7 gallons per minute (~ 27 liters per minute). The model with the seasonal-high recharge rate represents the worst-case scenario for groundwater separation, but the drain was predicted to achieve sufficient vertical separation under both conditions.



Model estimated total flow rate = **25.2 gpm**

Average recharge

Model estimated total flow rate = **32.1 gpm**

Seasonal-high recharge

Figure 18. Sensitivity analysis of recharge on water table elevations and flow rates

The above modeling results allowed the engineers to complete their preliminary landfill design and the permit application, which would have required lengthy and possibly costly field investigation work without the model.

APPLICATION OF NUMERICAL MODELING IN REMEDIAL DESIGN

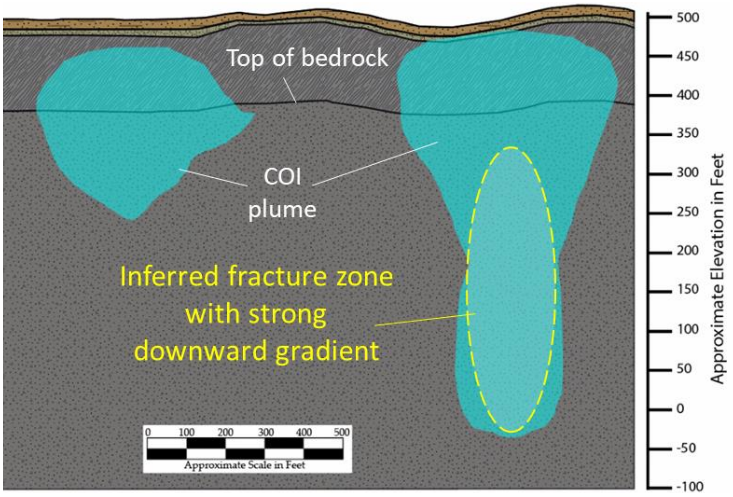


Figure 19. Simulated COI plumes and model-inferred fracture zone

CCR COIs were found at several locations beyond the regulatory boundary and need to be remediated under both the CCR Rule and the state regulations. **Figure 19** shows the model-predicted COI plume distribution along one cross-section outside of the ash basin footprint.

Model-predicted plumes are consistent with field observations where the plume to the right appears to extend to a much greater depth than the one to the left (by approximately 250 feet, or 75 meters). It is challenging to determine the cause of this difference just by looking at the plume distribution because it can result from various reasons such as different source zones or different flow paths. Several hypotheses were tested in the flow and transport model to help answer this question, and it was found that assuming a fractured zone with a vertical downward gradient in bedrock where this deeper plume existed would provide the best match to both hydraulic heads and concentration data. The model was also used to evaluate the reason for the strong downward gradient. The results indicated that an engineered drainage feature that has been operating for several decades downgradient of the ash basin may serve as the discharge feature for the predicted downward groundwater flow.

A pump-and-treat system was designed to target both the shallow and deep plumes (**Figure 20**). Water levels in extraction wells were specified to be no higher than the elevation of the outlet drainage feature during system operation in order to reverse the hydraulic gradient and pull the plume back into the ash basin regulatory boundary. This design was tested and refined in the model until the predicted performance met the remediation goal in a reasonable time frame.

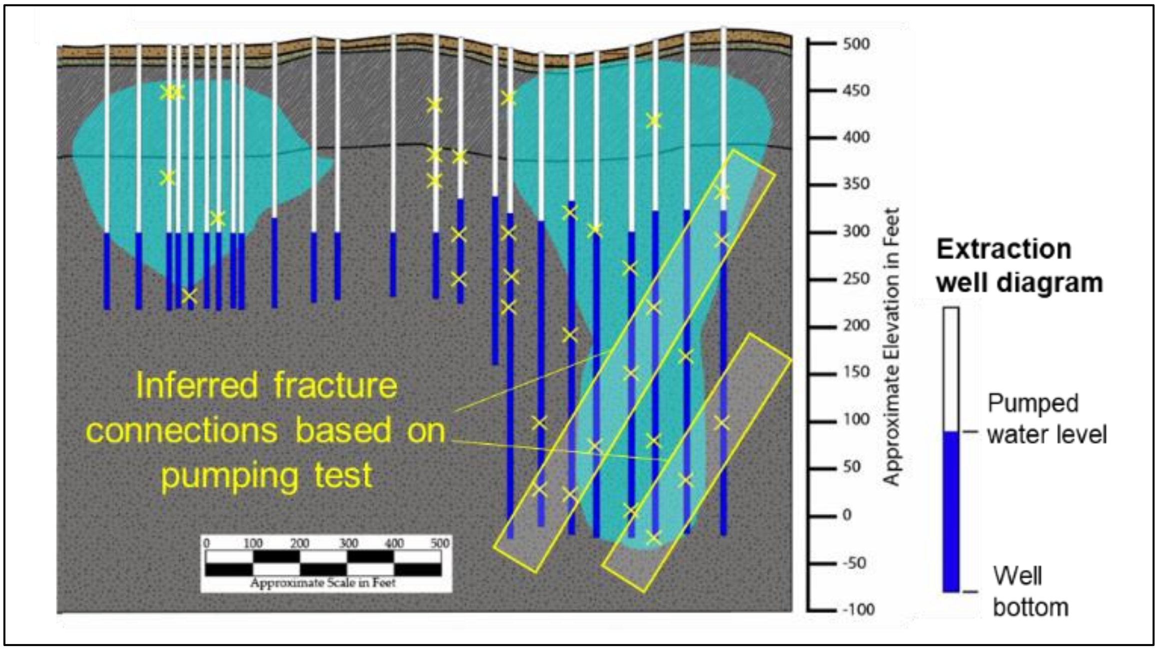


Figure 20. Geological and hydrological information obtained from geophysical logs and pumping test of the pump-and-treat system

During remedial well installation, geophysical logs were obtained that confirmed the presence of extensive fractures in bedrock. Pumping tests were later conducted and revealed several hydraulic connections between these fractures and indicated a likely connection with the downgradient drain feature (**Figure 20**), confirming the previous hypothesis made based on modeling. The model was subsequently updated based on these new data and the remedial system was re-evaluated for its performance. This example demonstrates the advantage of using a model throughout a project which allows continuous input for decision making.

APPLICATION OF NUMERICAL MODELING IN PROJECT COMMUNICATION

A flow and transport model can also serve as an effective communication tool. Just like any other project, ash basin closure often involves multiple collaborators who may come from different departments, have diverse professional backgrounds, and hold various responsibilities. Making sure everyone is on the same page is critical for a project to move forward smoothly.

A model is a powerful tool to promote effective communication. First, modeling results can be visualized in numerous ways such as figures, tables, diagrams, and even animations, to support specific project needs. A picture is worth a thousand words, which is especially true for complicated 3D systems. Modeling outputs usually are compatible with other software such as AutoCAD, ArcGIS, and other modeling software, making them readily usable by collaborators in their designs and decision-making process.

CONCLUSIONS

Closure of ash basins has become necessary at many power facilities across the United States. Due to the large variations in ash basin configurations and properties, closure is often a complicated task without a one-size-fits-all solution.

Numerical flow and transport modeling is a powerful tool to support sound decision-making during a closure project, because:

- A model can be customized to answer site-specific questions
- A model can structure and integrate data into one organized framework, which is particularly challenging for large basins with long histories
- A calibrated model can serve as a surrogate for field investigations that are potentially lengthy, costly, or impractical
- A model can provide an objective platform for the comparison of different closure and remedial alternatives using consistent assumptions
- A model often reveals crucial unknowns that are not readily understandable, such as flow and COI transport patterns between the ash basin and the aquifer, the existence of alternative sources, and causes for unusual COI plume distributions, allowing investigators to make sound and proactive decisions
- Modeling outputs can be easily visualized to promote effective communication among all stakeholders

This paper presents several case studies from an ash basin closure project and shows the strength of numerical flow and transport modeling in solving complicated problems in a heterogeneous groundwater system. Numerical flow and transport modeling can serve as a powerful evaluation tool at other CCR sites to support decision-making, provided that data and methodologies used to develop the model are appropriate and defensible.

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