An Interactive Process: Evaluating Remediation Systems using Numerical Simulations

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INTRODUCTION

Remedial action may be necessary at Coal Combustion Residual (CCR) sites. Selecting a remedy and evaluating remedial systems are critical steps during the remediation process. In this paper, we present a case study which illustrates how a numerical model was used as an evaluation tool to support decision making during the remediation selection and implementation in an interactive way.

AN INTERACTIVE APPROACH TO REMEDIATON

Figure 1 below outlines the typical steps that comprise the *Remedy Selection* and its implementation. *Remedy Selection* is the process of comparing available remediation options and identifying those that will meet remedial goals in a timely manner. A model can assist in evaluating proposed remedies by looking at effectiveness and time frames.

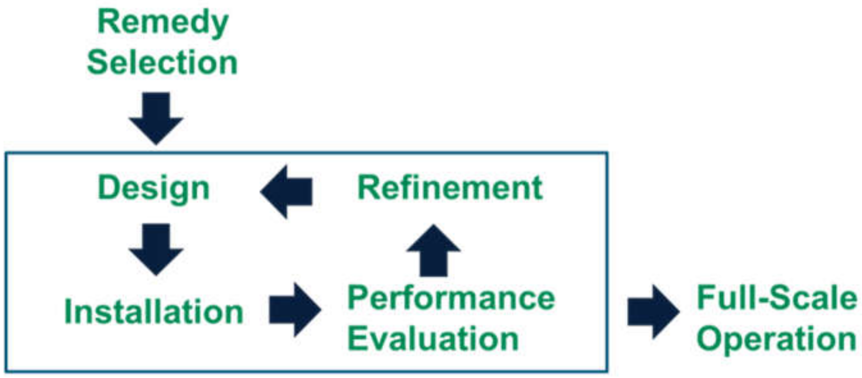


Figure 1. Flow chart of the typical remedy selection and implementation process

The *Design* specifies how the selected remedy will be implemented. A numerical model is especially helpful for estimating quantities and costs. For example, physical layout, flow rates, concentrations, and durations for an extraction and treatment system can be estimated by the model which can be used as inputs for cost estimates. The *Installation* process usually provides additional information about the site which was not available during remedy selection or initial design. This information can be incorporated into model simulations so adjustments to the remedial system can be made, especially if the system is installed in stages. Observations made while the system is operating can be used to evaluate assumptions used in the original design as part of a *Performance Evaluation*. During this step, it can be determined if the system is behaving as expected. If the system is operating differently, then new data can be used to evaluate the original assumptions or properties and help update any site models so that future predictions are improved. Insight gained by the *Performance Evaluation* can be used in *Refinement* of the operation of the system or to adjust the design to improve effectiveness.

The four steps of *Design, Installation, Performance Evaluation,* and *Refinement* do not always unfold in a linear nature, but instead are often more fluid and occur throughout the remediation selection process. These steps can be repeated many times over the course of a remediation project until *Full-Scale Operation* is achieved.

CASE STUDY BACKGROUND

A case study is presented below which provides an example of how numerical flow and transport modeling was used to support groundwater remediation at a CCR site. The numerical simulations discussed in this paper were conducted using MODFLOW-NWT.[1]The transport modeling code used was MT3DMS.[2] Groundwater Modeling System (GMS) version 10.4 was used as the graphical user interface.[3]

The Site is in the Piedmont physiographic region of the eastern US with soils that are weathered in place and underlain by fractured crystalline bedrock. The ash basin was constructed in a stream valley adjacent to a lake. CCR-related constituents of interest (COIs) are persistent and located under the lake, beyond the regulatory boundary (Figure 2). The remedial goal was to contain the COIs within the regulatory boundary within ten years.

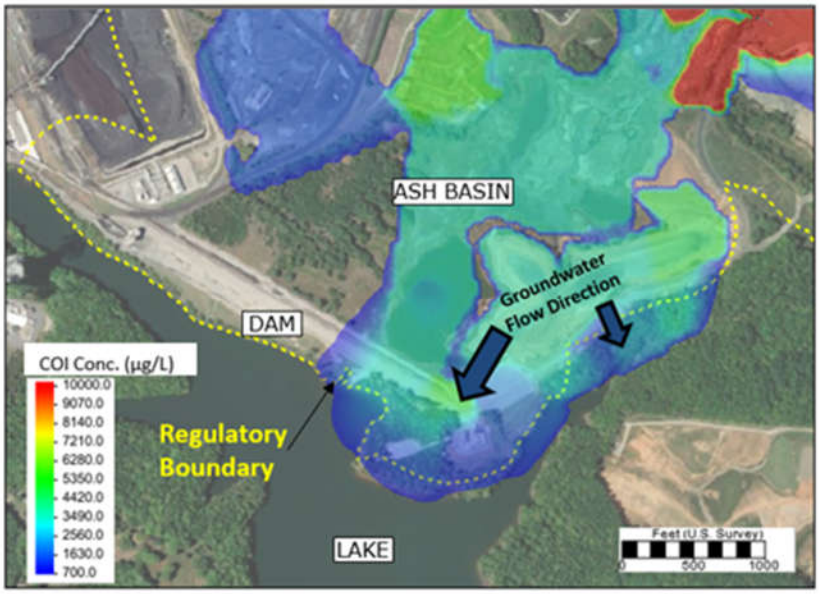


Figure 2. Site map and plume distribution for case study

Challenges encountered at the site when evaluating potential remediation strategies included:

- The remediation goal needed to be met in a short timeframe of 10 years or less, which is atypical compared to typical remediation timelines.
- The regulatory boundary is close to the source area and to the nearby lake, leaving limited room for a remediation system.
- Hydraulic stagnation zones below the lake resulted in areas of persistent COI concentrations below the lake.
- The remediation system needed to remove COI concentrations from the unsaturated zone which were left in place due to decreased groundwater elevations around the CCR unit caused by dewatering.
- Groundwater flow exists in residual soils and fractured bedrock and is controlled by fracture occurrence and interconnections.

FLOW AND TRANSPORT MODEL DEVELOPMENT

Flow and transport models were calibrated prior to conducting modeling for remediation selection. The domain for these models extended beyond the boundaries of the site to great enough distances that boundary effects would not influence model results within the area of interest. The model grid was refined in the area of interest to improve resolution. The models went through several stages of calibration to site data which included hydraulic head data, flow rate, and COI concentration data. During the remediation modeling effort, additional calibration was performed as new data was collected. The initial models used for the remediation design modeling had normalized root mean square errors (NRMSE) of 2.1 percent for the flow model and 1.6 percent for the transport model.

REMEDY SELECTION

Several technologies were initially evaluated to determine their overall suitability as a remedial strategy for the site. These technologies included, but were not limited to, Monitored Natural Attenuation (MNA), in-situ treatment, encapsulation, permeable reactive barriers, and various forms of hydraulic control. After evaluating each of these technologies and their suitability, hydraulic control including groundwater extraction and clean water infiltration was selected. This technology was selected because the primary COI being evaluated is mobile and non-reactive in groundwater, and its primary attenuation mechanisms are adsorption, dilution, or removal from the system at groundwater discharge features. Due to the behavior of the primary COI, hydraulic control is a good option because it can reverse hydraulic gradients and pull the plume back within the regulatory boundary within a reasonable timeframe, remove mass from the system, flush out COIs with clean water from both above and below the water table, and can be effectively implemented at the site.

Flow and transport modelling was conducted to evaluate different methods of hydraulic control to determine which was the most effective to meet the remediation goals. These include groundwater extraction only, groundwater extraction with clean water infiltration galleries, and groundwater extraction with clean water infiltration wells (Figure 3).

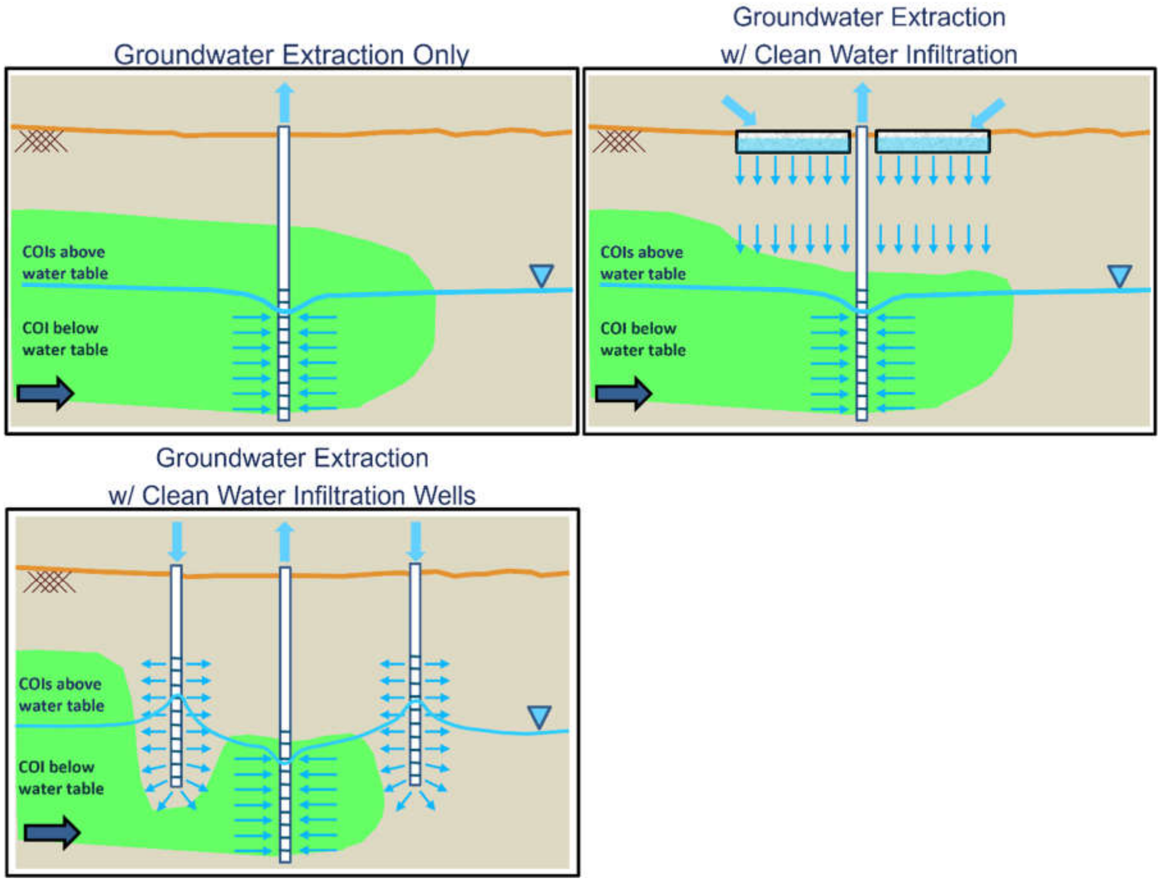


Figure 3. Conceptual illustrations of hydraulic control remedies evaluated with flow and transport modeling

Initial remediation modeling indicated that groundwater extraction alone was generally effective at removing COIs below the water table. It was able to reverse hydraulic gradients and pull the plume back from beyond the regulatory boundary and from below the nearby lake. It was ineffective at removing COIs from unsaturated zones where COIs were stranded due to decreasing water levels caused by dewatering in the CCR unit and may instead exacerbate this issue by further lowering water levels in some areas. COIs stranded in these unsaturated zones could only be removed from the system by natural infiltration and groundwater recharge which was too low of a flux to move enough COI mass within the desired remediation timeframe. Furthermore, with extraction wells alone it was unable to remove COIs from below the water table at a high enough rate to meet the short remedial timeframe of 10 years or less.

Due to the ineffectiveness of extraction alone at meeting the remedial goals, a second design was evaluated that included vertical extraction wells and clean water infiltration galleries. This design had the added benefits of being able to flush COIs from the unsaturated zones in a shorter time because of the increase in infiltration and groundwater recharge. However, two main issues were present with this remedial approach. First is that the infiltration galleries cannot increase the hydraulic gradient enough for a reasonable number of extraction wells to remove COI mass within the desired timeframe. Secondly there were constructability concerns due to the topography at the proposed location of the system based on the model predictions. Constructing the infiltration galleries would require high costs and pose numerous engineering challenges and potential safety concerns.

The third option evaluated involves vertical extraction wells with vertical clean water infiltration wells. Simulations of this third option predicted that it was constructable at the site and would meet the remedial goals. In this option extraction wells reverse the gradient and remove COI mass from the system and the infiltration wells are able to flush COIs out of the unsaturated zones and increase the hydraulic gradients below the water table to remove COIs in groundwater in the desired timeframe.

After positive initial predictions for the option with vertical extraction and clean water infiltration wells, additional simulations were run to determine if the well placement could be improved, and if the number of wells could be reduced. These simulations indicated that with the current understanding of the groundwater system a generally aggressive design may be required to meet the remedial goals (Figure 4). This design included 66 extraction wells and 24 clean water infiltration wells (Table 1).

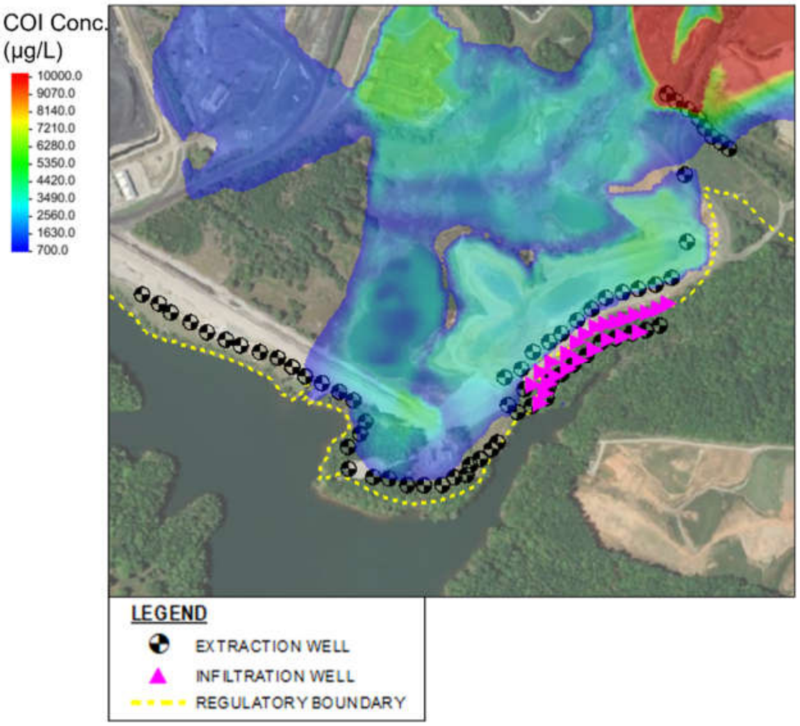


Figure 4. Initial simulated remedial design and predicted COI plume after 10 years of operation

Table 1. General remediation system well summary

Extraction Wells	**Clean Water Infiltration Wells**
Sixty-six (66) wells	Twenty-four (24) wells
Total estimated flow rate of 650 gpm	Total estimated infiltration rate of 290 gpm
Screened through: saprolite, transition zone, and bedrock	Screened through: saprolite and transition zone

This aggressive system was initially predicted to be necessary to meet the short remedial timeframe and to account for data gaps and uncertainties in areas of the remediation system. Extraction wells along the south-southwest portions of the regulatory boundary were screened primarily in bedrock where COIs were observed and/or predicted to occur. Extraction wells along the eastern portion of the regulatory boundary were screened from saprolite to bedrock. Clean water infiltration wells along the eastern side of the regulatory boundary were screened in saprolite and the transition zone.

Along the south region, the proposed system was effective at meeting the remedial goals in the desired timeframe because bedrock wells along the lake created a large cone of depression below the level of the lake that pulled COIs back out from beneath the lake and flushed the fractured bedrock with clean lake water. Along the eastern side, which is located along a topographic ridge (where the unsaturated zones with COIs are encountered), the system was able to flush COIs out of the unsaturated zones and increase the hydraulic gradients to the nearby extraction wells enough to remove mass at a rate that met the remedial timeframe.

PERFORMANCE EVALUATION

After development of the initial design the performance of the system was evaluated using field tests. This was achieved by installing portions of the proposed system and performing hydraulic tests and a pilot test.

Installation of the system started along the southern portion of the regulatory boundary (Figure 5). During installation of these bedrock wells it was discovered that there were a number of highly productive fracture zones in this area that previously were unidentified during the initial model calibration. Initial calibration was performed under steady-state conditions which often can mask such features because the system is unstressed and in equilibrium. When stressed these fracture zones become more obvious as they would have strong influences on the flow and water levels within the fractured bedrock. As a result, several hydraulic tests were performed to determine how well connected and extensive the

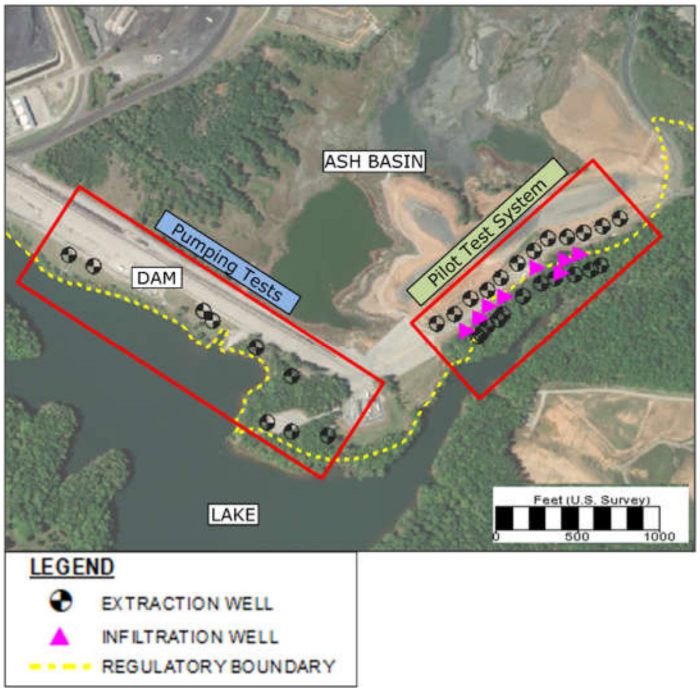
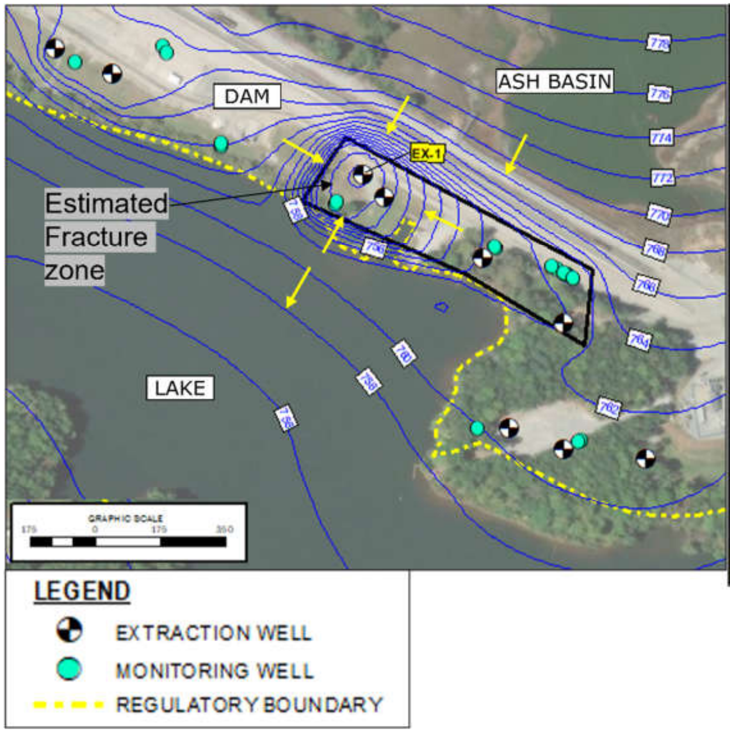


Figure 5. Wells initially installed as part of the remediation system performance evaluation

fracture systems were in this area and if they could be used to reduce the number of extraction wells needed to meet the remedial goals.

The hydraulic tests consisted of one 48-hour pumping test, four 24-hour pumping tests, and nine step-drawdown pumping tests. These tests were conducted by pumping a single well and monitoring water level responses in surrounding wells. These data were then used to update the model calibration for this area to improve the model's ability to predict the performance of the remediation system. Calibration was performed by matching pumping rates in the pumped wells and drawdown in the pumped and observation wells (Figure 6). During calibration the hydraulic conductivity and storage parameters were adjusted to match the observed data.



Well ID	Observed	Simulated
	Drawdown (ft)	
EX-1	12.03	31.81
MW-1	7.24	6.83
MW-2	7.51	4.98
MW-3	8.06	5.81
MW-4	8.20	5.36
MW-5	6.85	1.92
MW-6	0.94	0.92
MW-7	6.74	6.78
MW-8	0.34	0.32
MW-9	1.32	5.32
MW-10	0.41	0.27
MW-11	0.17	0.13
MW-12	-0.28	0.10
	Flow Rate (gpm)	
EX-1	95	95

Figure 6. Calibration results from one of the 24-hour pumping test

Calibration to the hydraulic test data indicated that there were a number of highly permeable fracture zones in the bedrock along the southern portion of the regulatory boundary. These fractures could be utilized to depressurize large portions of the subsurface in this area, resulting in drawdown that could reverse hydraulic gradients back towards the regulatory boundary. This indicated that the number of wells needed to create a sufficient capture zone to pull COIs back from beneath the lake could be reduced and still meet the remedial goals. This demonstrates the value of a phased installation and how data collected during installation and initial evaluation of a remediation system can assist in improving the remedial design.

During installation of wells along the eastern ridge (Figure 5) it was observed that the general behavior of the installed wells appeared to be consistent with the predictions from the initial remediation model. Due to this observation, it was determined that the majority of the wells in this area should be installed because of the short remedial timeframe (Figure 6). Using this portion of the installed system a long-term pilot test was conducted, that is still under way. After six months of operation, data from this pilot test including extraction flow rates and drawdown in extraction wells and observation wells were integrated into the model. The model calibration was updated using this longer-term data. Calibration was conducted by modifying the hydraulic conductivity and storage parameters to match the observed pilot test data. During this calibration it was found that only minimal adjustments to the hydraulic conductivity fields were necessary and that adjustments to the storage parameters were more critical to reproducing the observed data.

The longer-term test data improves the ability to estimate the aquifer storage parameters (i.e., specific yield, storativity) which are critical to understanding how soon the desired capture zone can be achieved and to better predict behavior under full-scale operations. Pumping tests provide a range of reasonable storage values, but long-term stresses, such as long-term pilot tests, help narrow down the range to values that are appropriate for predicting behavior over long-term operation of the system.

Calibration indicated that the storativity values in the original remediation model were close to those needed to match the pilot test data. However, it indicated that a lower value for specific yield in the shallow zones (saprolite and transition zone) were necessary to get a good fit to the data. Through calibration a specific yield of approximately 2 percent (0.02) gave a better match to the observed data than the previously used value of 20 percent (0.2) (Figure 7). This is important because the saprolite and transition zone generally are the primary reservoirs for groundwater in typical fractured rock systems[4] and this stored water is one of the key factors controlling how long a system will take to reach equilibrium and a capture zone will take to fully form.

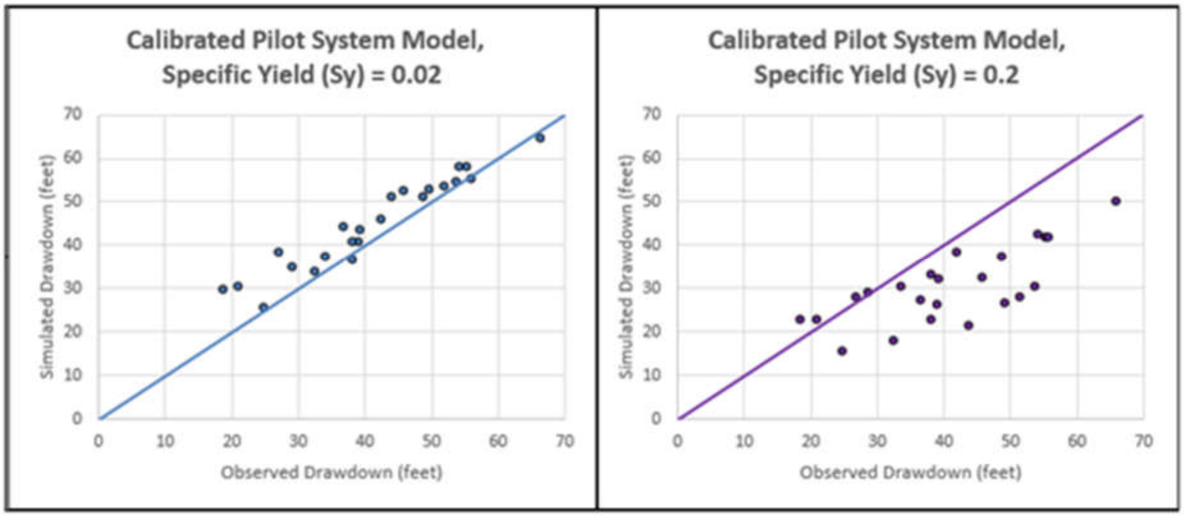


Figure 7. Simulated versus observed drawdowns with a specific yield of 0.02 and 0.2

REMEDIATION SYSTEM REFINEMENT

The initial remediation system design was updated based on the results from the pumping tests, the long-term pilot test, and the updated model calibration. Based on those findings, the number of wells needed to create similar levels of capture could be substantially reduced in areas to the south (Figure 8). Figure 8 shows the capture zone for the initial design, the capture zone for wells installed during the initial evaluation (discussed above), and the capture zone for an updated design. Though the currently installed wells show a good level of capture, additional wells were simulated in key areas (northwest along the lake and between the wells along the lake and the ridge) to determine if they could create additional capture in areas where COIs are predicted, or where COIs that were not modeled have been observed.

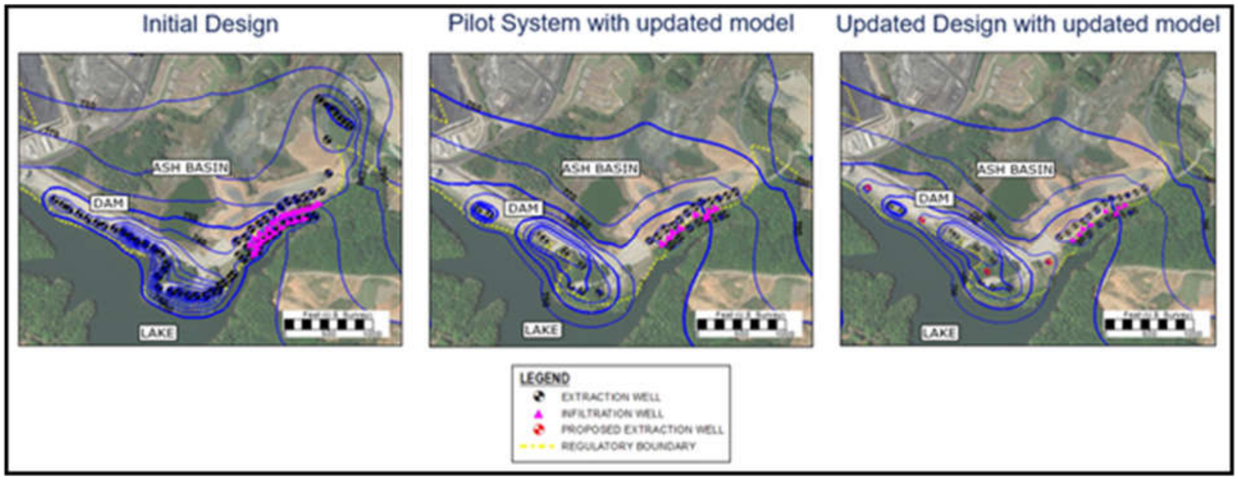


Figure 8. Comparison of capture zones from the initial remedial design, currently installed wells, and updated design based on additional data collected during the performance evaluation

These results were used by remediation engineers to develop an updated design of the remediation system (Figure 10). This updated design utilized the findings from the updated model and included additional wells to account for uncertainty in areas where data had not been collected. Also, the originally proposed wells along the ridge will continue to be installed based on the good level of agreement between the original model predictions and the field observations.

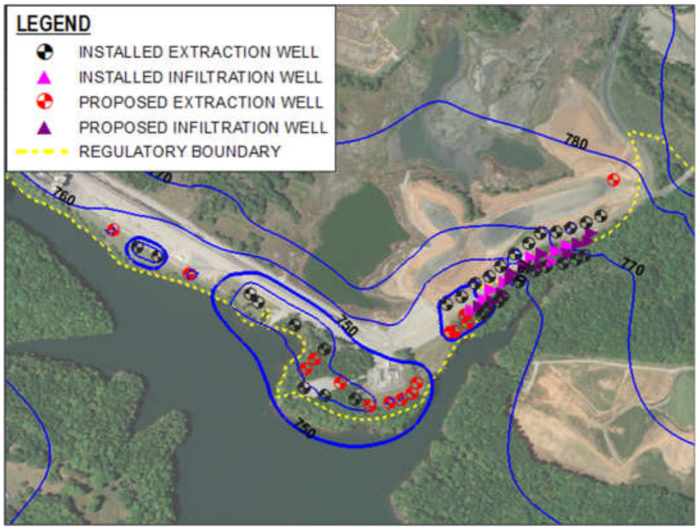
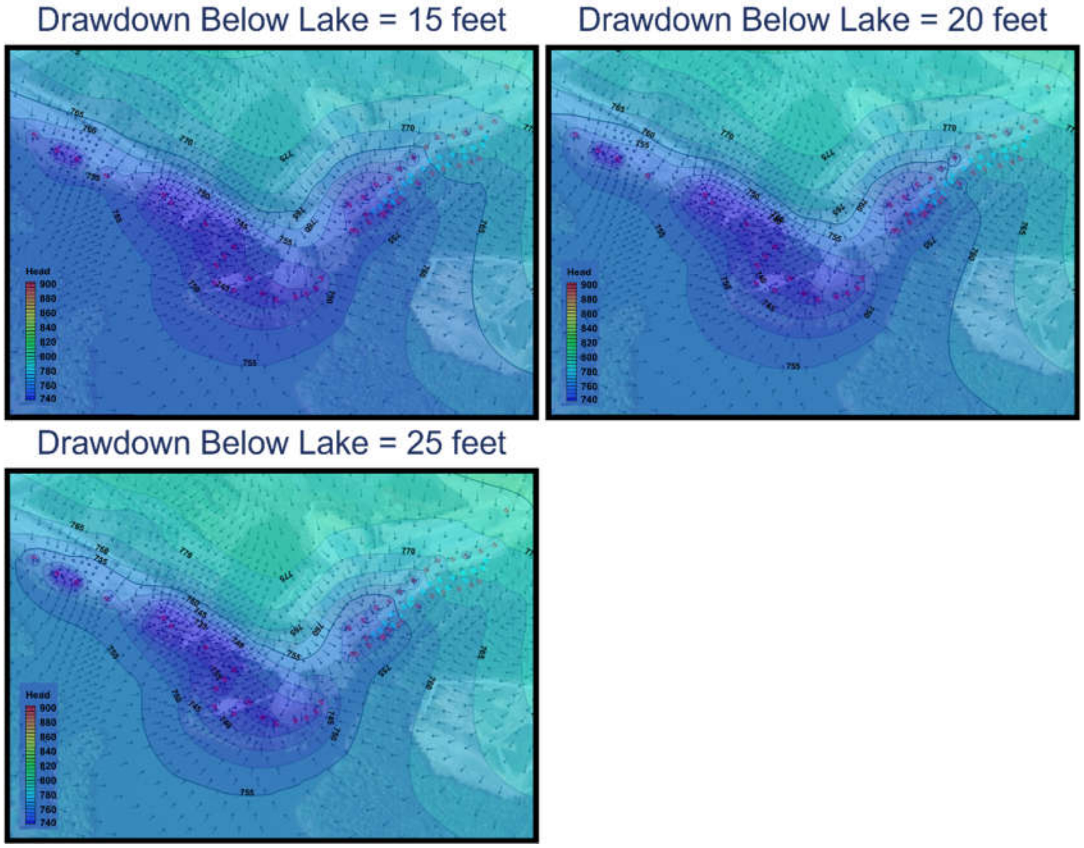


Figure 9. Updated proposed remediation system

The amount of water produced by the remedial system is a key design parameter for the treatment system. Due to this a balance between the effective capture zone and volume of water pumped must be met. To evaluate this, the model was used to estimate the volume of water pumped from the updated remediation system (Figure 10) and the level of drawdown below the lake level in wells along the lake (southern portion of the regulatory boundary). Drawdown below the lake is important because in this area it is the difference between the pumping elevations and the lake level that create the necessary capture zone and hydraulic gradients to pull COIs back from beneath the lake. In these simulations the currently installed wells along the ridge were assumed to continue to operate as they have during the pilot test. Proposed wells along the ridge are assumed to operate similarly to nearby wells currently installed. Wells along the lake were simulated using a constant pumping elevation (*i.e.,* a constant drawdown) and the flow rate was allowed to vary based on the chosen pumping elevation. Drawdown below the lake in those wells was varied from one foot (~0.3 meters) below the lake level to 35 feet (~11 meters) below the lake level and the total flow rate of the entire system was estimated (Figure 10).


Drawdown Below Lake = 15 feet

Drawdown Below Lake = 20 feet

Drawdown Below Lake = 25 feet

Figure 10. Estimated capture zones for the updated remediation system at different levels of drawdown below the lake level in wells along the lake

Based on these simulations it was predicted that a sufficient capture zone would be produced between 15 to 25 feet (~5 to 8 meters) of drawdown below the lake level. This level of drawdown corresponded to a total system flow rate of approximately 370 to 420 gpm (~1,400 to 1,590 liters per minute) which is within the capacity of the currently operating treatment system (Figure 11).

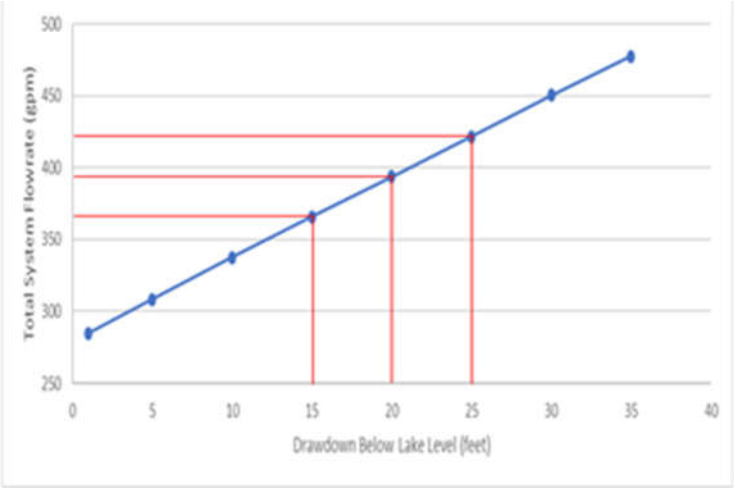


Figure 11. Estimated flow rate from the updated remediation system compared to level of drawdown below the lake level

This remediation system will continue to be installed in a phased approach starting with wells between the southern area and the ridge area. Data collected during additional well installation will continue to be evaluated and changes to the remedial design will be made as necessary until the full-scale design is completed. It is anticipated that additional updates to the model will be made based on these new field observations and that it will be used to evaluate and track the performance of the full-scale system to monitor if remediation goals are being met.

CONCLUSIONS

- Groundwater flow and transport models are powerful decision-making tools.
- The interactive nature of numerical modeling can inform the decision-making process throughout the remediation selection and implementation processes.
- Models are useful for remedial option selection and estimating timeframes to meet regulatory standards.
- Models provide a comparison tool for evaluating different remediation designs under consistent assumptions.
- Models are an effective communication tool and provide multiple ways to communicate information to collaborators and stakeholders.

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