www.haleyaldrich.com

REPORT ON
GROUNDWATER FLOW MODELING
ADDENDUM TO CORRECTIVE MEASURES ASSESSMENT
F.B. CULLEY GENERATING STATION
EAST ASH POND
NEWBURGH, INDIANA

by
Haley & Aldrich, Inc.
Cleveland, Ohio

for
Southern Indiana Gas and Electric Company
Evansville, Indiana

File No. 129420-020
September 2019
Issued as CMA Addendum
November 24, 2020

Table of Contents

Page

List of Tables ii
List of Figures ii

1. Groundwater Flow Modeling 1

1.1 MODEL DOMAIN 1
1.2 BOUNDARY CONDITIONS 2
1.2.1 Specified Head Boundaries 2
1.2.2 River Boundaries 2
1.2.3 Recharge Boundaries 3
1.3 HYDRAULIC MODEL PROPERTIES 3
1.3.1 Calibrated Horizontal and Vertical Hydraulic Conductivity 3
1.3.2 Porosity, Storage, and Yield 3
1.4 METHODS OF EVALUATING MODEL CALIBRATION QUALITY 3

2. Fate and Transport Modeling 7

2.1 TRANSPORT MODELING APPROACH 7
2.2 KEY PARAMETERS FOR TRANSPORT MODELING 7
2.2.1 Effective Porosity 8
2.2.2 Dispersivity 8
2.2.3 First-Order Degradation Rate Constant – Lambda (λ) 8
2.2.4 Retardation Effects 8
2.2.6 Source Initial Concentration Data 10
2.3 TRANSPORT MODEL RESULTS - MOLYBDENUM 11

References 12

Tables
Figures

List of Tables

Table No.	Title
1	Groundwater Elevations

List of Figures

Figure No.	Title
1	Site Plan with Model Domain
2	Site Plan with Model Grid
3	Model Layers 1 through 30 with Hydraulic Conductivities and Layer Thicknesses
4	Site Plan with Constant Head Boundary Conditions for Layers 10 through 30
5	Site Plan with River Boundary Conditions for Layers 14 and 15
6	Calibration Scatter Plot (in text)
7	Initial Molybdenum Concentrations for Layers 14 and 15
8	Molybdenum Eh-Ph Diagram (in text)
9	Modeled Molybdenum Concentrations for CMA Options Over Time

\\haleyaldrich\share\CF\Projects\133274\GW_Modeling\Vectren Culley Ash Pond\Model\Groundwater Model Report\Text\2020 0204_Culley EAP GW Flow Modeling_DF.docx

1. Groundwater Flow Modeling

A groundwater flow and solute transport model was constructed to evaluate and compare potential corrective measures in support of the Corrective Measures Assessment (CMA) for the F.B. Culley Generating Station (Site) in Newburgh, Indiana. Molybdenum is the only Appendix IV constituent that exceeds the Groundwater Protection Standard (GWPS) at the Site. Therefore, molybdenum was used for the solute transport portion of the model. The following text describes the model construction, calibration and subsequent simulations of remedy alternatives for molybdenum above the GWPS.

The numerical model MODFLOW-2005 (Harbaugh, 2005) was selected for the modeling effort and is a three-dimensional, finite difference groundwater flow model capable of simulating the groundwater conditions under various scenarios including pumping and changes to infiltration over time. Models were built using available information and for the purpose of aiding decision making in the CMA process. The level of accuracy is directly dependent on the data available to construct the model and should not be construed by the user as a definitive predictor of the future. Instead the CMA alternatives model simulations should be viewed relative to one another to enable the user to determine (when appropriate) favorable, less favorable and least favorable CMA alternatives.

1.1 MODEL DOMAIN

The model domain was established to encompass the Site and surrounding areas that represented model boundaries including the nearby Ohio River located south of the ash pond and landfill.

MODFLOW uses a rectangular grid within the domain and allows for establishing irregular groundwater flow boundary conditions that represent actual and Site-specific features in the study area. The setup is facilitated by assigning boundary types and values to specific grid cells. **Figure 1** depicts the model domain boundary overlain on an aerial photograph of the Site.

Figure 2 depicts the model domain with the grid spacing selected for the model. The three-dimensional finite difference groundwater flow model domain covers a length of 15,000 feet (ft) in the x-direction (west to east), 15,000 ft in the y-direction (north to south), and approximately 160 ft in the z-direction (vertical). The model consists of 191 rows, 216 columns, and 30 layers for a total of 1,237,680 cells covering an approximate area of 378 acres. In MODFLOW, the groundwater-flow system is subdivided laterally and vertically into rectilinear blocks called cells. The hydraulic properties of the material in each cell are assigned and assumed to be uniform within each cell. The row and column dimension of each cell is variable based on proximity to the Site. This variability was created to allow for finer resolution within the vicinity of the primary flow pathway for the Site.

A Digital Elevation Model was obtained from the United States Geological Survey (USGS) website to create the surface of the model for the Site. Lithologic descriptions contained in the boring logs generated during various phases of geo-environmental investigations as well as cross-sections were used to develop formation geometry and hydraulic properties. The Site was divided into two vertical lithologic units to represent geologic conditions underlying the Site and to account for vertical heterogeneities within the model. A summary of each geologic unit is as follows:

- Unconsolidated Ohio River alluvial deposits consisting of silt and clay with discontinuous interbedded layers of sand (Haley & Aldrich, Inc., 2017).

- Shale and sandstone bedrock units underlie the unconsolidated alluvial soil deposits.

Elevations used in the model were determined from digital elevation models for the area. The topography of the ground surface is mimicked in the subsequent lower layers; however, the elevation has been reduced by the layer thickness. Layer thicknesses were determined through the review of the above-mentioned Site geology.

Figure 3 depicts the two-dimensional views of the model layer elevations. The surfaces shown in **Figure 3** represent the model top (i.e., land surface), the flat model bottom, and all the lithologic interfaces between.

1.2 BOUNDARY CONDITIONS

Boundary conditions define the locations and manner in which water enters and exits the active model domain. The conceptual model for the groundwater system that forms the basis for the model boundaries are as follows:

1. The Ohio River is used to estimate southern boundary elevations and is the major groundwater discharge feature.
2. A specified head boundary condition is used to control groundwater flow across the western side of the model.
3. A specified head boundary condition is used to simulate recharge along the topographic high north of East Ash Pond.

The specified boundaries of the model coincide with predicted natural hydrologic boundaries. To recreate observed groundwater flow, two types of model boundaries were used: specified head boundaries, and the Modflow River Package. The locations of these boundary conditions in the model are illustrated in **Figure 3** and **Figure 4**.

1.2.1 Specified Head Boundaries

The MODFLOW Time Variant Specified Head Package (Harbaugh, 2005) also known as the Constant Head Package, was used to simulate boundaries presented in **Figure 4**. The package is used to fix the head values in selected grid cells regardless of the conditions in the surrounding grid cells. The cell with the assigned constant head acts either as a source of water entering or a sink of water leaving the system. Three separate constant head boundaries are used in the model. All constant head boundaries are referenced to datum NAVD 88 and are active in Layer 10 through 30. Constant head boundary one (1) is set to 390 ft. Constant head boundary two (2) is set to 390 ft to the eastern extent and decreases to 370.10 ft at the western extent. Constant head boundary three (3) is to 370.10 ft at the northern extent and decreases to 353.06 ft at the southern extent. These values were estimated based on topography, the depths to water in wells at the Site, the pattern of groundwater flow, elevations of nearby water bodies, and through calibration of the groundwater flow model as described in **Section 1.3** below.

1.2.2 River Boundaries

River boundaries in Modflow are a special form of the head-dependent boundary condition. In a head-dependent boundary, the model computes the difference in head between the boundary and the model cell to calculate the amount of water flowing into or out of the model through the boundary. **Figure 5** represents the river boundary condition representing the Ohio River near the Site. The head assigned to this boundary was 353.00 ft based on the nearby Ohio River USGS gage at Newburgh, Indiana at a time recent to when groundwater elevations used in model calibration were taken at the site.

1.2.3 Recharge Boundaries

Recharge in the model is simulated using constant head boundary one (1) along the topographic high north of East Ash Pond.

1.3 HYDRAULIC MODEL PROPERTIES

Hydraulic properties were initially assigned consistent with observations presented in the 2017 Groundwater Monitoring Program Report (Haley & Aldrich, Inc., 2017). Values were assigned for horizontal hydraulic conductivity and vertical hydraulic conductivity. These parameters were iteratively varied during model calibration to achieve the best fit to observed hydraulic patterns including head elevations, hydraulic gradients, and flow directions.

For calibration, uniform hydraulic properties were applied within discrete model layers. Results of the initial calibration indicated that hydraulic conductivities in the range of those values associated with material described in boring logs were representative with regard to groundwater flow observed at the Site. The hydraulic conductivity values used in the model are presented below for the four hydrogeologic units underlying at the Site:

- Bedrock – 1.0 x 10-1 ft per day (ft/day) or 3.5 x 10-5 centimeters per second (cm/s)
- Fine soils – 1.5 x 10-1 ft/day or 5.3 x 10-5 cm/s
- Sandy soils – 3.7 ft/day or 1.3 x 10-3 cm/s
- Ash pond – 1.5 x 10-1 ft/day or 5.3 x 10-5 cm/s

1.3.1 Calibrated Horizontal and Vertical Hydraulic Conductivity

The calibrated horizontal (K_X and K_Y) and vertical (K_Z) hydraulic conductivity values in Model Layer 1 through Layer 30 were distributed uniformly across the model domain. Vertical hydraulic conductivity values were estimated at $1/10^{th}$ of the horizontal hydraulic conductivity values. This ration between horizontal and vertical conductivities was selected to represent resultant hydraulic conductivity when stratification typical of alluvial sediments is evident.

1.3.2 Porosity, Storage, and Yield

Effective porosity values are needed for particle tracking and solute transport simulations. The effective porosity values were conservatively estimated based on the soil type through the examination of boring logs. For areas that are generally alluvial silty clay, a porosity of 0.25, specific storage of 0.01 ft^{-1} and specific yield of 0.01 were utilized.

1.4 METHODS OF EVALUATING MODEL CALIBRATION QUALITY

Model calibration is the process of refining the model representation of the hydrogeologic framework, hydraulic properties, and boundary conditions to minimize the difference between the simulated heads and fluxes to the measured data. Construction of a complex model with more parameters than the data support may reduce the residuals (difference between measured and simulated values) but does not ensure a more accurate model. Therefore, calibrated model parameters also need to be checked for their validity. Throughout the calibration process, no adjustments were made that conflicted with the general understanding of the groundwater system and previously documented information.

The iterative calibration process of "trial and error" was used for model calibration. It involves making changes to the input values, running MODFLOW, and assessing the impact of the changes. Beside the trial and error approach, a model independent parameter optimization software tool – PEST was used to adjust selected input values to further improve model calibration (Doherty, 2016).

The quality of model fit can be assessed from many statistical and graphical methods. One method is based on the difference between simulated and observed heads and flows, or residuals. The overall magnitude of the residuals is considered, but the distribution of those residuals, both statistically and spatially, can be equally important. The magnitude of residuals can initially point to gross errors in the model, the data (measured quantity), or how the measured quantity is simulated (Hill, 2000). A useful graphical analysis is a simple scatter plot of all simulated values as a function of all observed values.

For the flow calibration, the statistics of the mean error (ME), mean absolute error (MAE), and the root mean square (RMS) error were used to assess the calibration quality. They are defined as follows:

$$ME = \frac{\sum_{i=1}^{n}(O_i - C_i)}{n}$$

$$MAE = \frac{\sum_{i=1}^{n}|O_i - C_i|}{n}$$

$$RMS = \frac{\sum_{i=1}^{n}(O_i - C_i)^2}{n}$$

Where:
Oi = Observed head at observation point i
Ci = Calculated head at observation point i
n = Number of observation points

The mean error is the average of the differences between the observed and calculated heads (or residuals) and can indicate the overall comparison between computed and observed data. Negative and positive residuals can cancel each other out, resulting in a mean error close to zero even when the calibration is not good. The sign of the mean error is an indication of the overall comparison of the model to the data (e.g. a positive mean error indicates the model is generally computing heads that are too high).

The mean absolute error is the average of the absolute values of the residuals. The absolute value prevents positive and negative residuals from canceling each other, providing a clearer picture of the magnitude of errors across the model, without an indication of the direction (high or low) of the errors. The RMS error is the square root of the average of the squares of the residuals. The RMS adds additional weight to points where the residual is greatest. If the residuals at all points are very similar, the RMS will be close to the mean absolute error. Alternatively, a few points with high errors can add significantly to the RMS for an otherwise well calibrated model. For all three of these criteria the optimal value is zero.

The numerical goals for the groundwater flow model calibration are to (1) minimize the ME and MAE errors and (2) achieve the ratio of the RMS error of the head residuals to the range of observed heads (i.e., normalized RMS error) to be at least less than 10 percent (%) (Anderson, M.P., Woessner, WW., 1992).

Groundwater flow field calibration for the Site has been conducted to provide a reasonable representation of the groundwater flow field in the vicinity of the Site, which forms the basis of assessing molybdenum migration potential through the fate and transport process. To accomplish this objective, a MODFLOW numerical model was developed to simulate observed groundwater conditions at the Site through calibrating a representative steady-state flow field. The decision of using a steady-state flow field for the flow model calibration was made through an evaluation of the available groundwater elevation data for the Site. Most importantly is that historical flow patterns have been relatively consistent at the Site; therefore, a steady-state flow model was deemed reasonable to represent average flow conditions.

The evaluation of collected groundwater elevation data resulted in the selection of multiple dates which are considered representative for the Site as the observed heads for the flow model calibration for representing Site conditions (**Table 1**).

Based on the outcome of this quality of model fit evaluation, it is concluded that the numerical calibration goals have been achieved for the Site. The mean error in head was 7.22 ft or 10.0 percent (%) of the head observation range, 72.14 ft. The absolute residual is +6.20 ft. The RMS error for the calibrated model was +0.56 ft and the normalized RMS error was 10.0 percent (%). Presented below is the scatter plot of the observed versus simulated heads, which generally fall along the theoretical slope of 1 to 1. **Table 1** provides the observed heads at the Site for multiple dates, as discussed above, used to generate the plot below. The quality of the flow model calibration meets the calibration goals as described herein. Observed versus computed target values is shown in **Figure 6.**

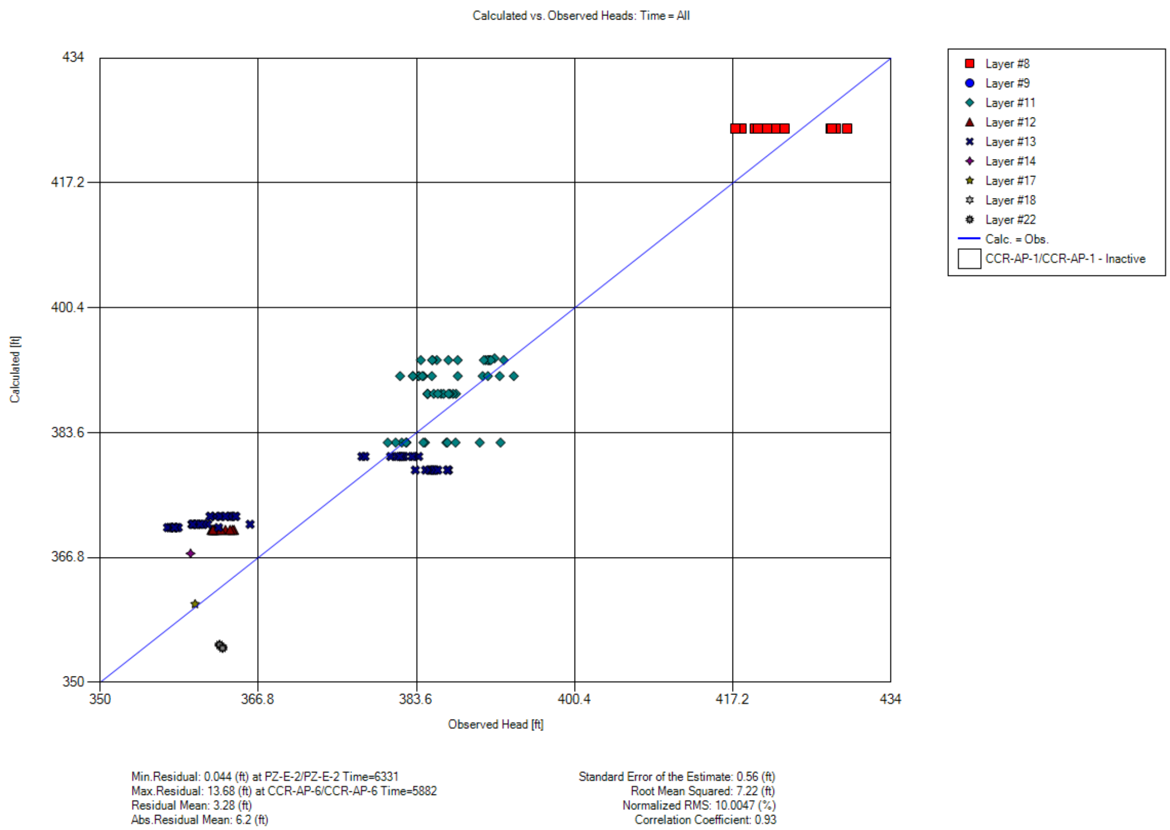


Figure 6: Calibration scatter plot. Values represent steady-state targets.

Furthermore, the calibration assessment has met the acceptable calibration goals, and therefore, the groundwater flow model is considered to be usable for the development of the molybdenum fate and transport models described in **Section 2.**

2. Fate and Transport Modeling

Contaminant fate and transport modeling was conducted utilizing the three-dimensional, numerical model MT3DMS (Version 5 of MT3D) (Zheng, C. and Wang, P.P., 1999). MT3DMS simulates advection, dispersion, adsorption and decay of dissolved constituents in groundwater using a modular structure similar to MODFLOW to permit simulation of transport components independently or jointly. MT3D interfaces directly with MODFLOW for the head solution and supports all the hydrologic and discretization features of MODFLOW. The MT3D code has a comprehensive set of solution options, including the method of characteristics, the modified method of characteristics, a hybrid of these two methods, and the standard finite-difference method. MT3D was originally released in 1990 as a public domain code from the United States Environmental Protection Agency and has been widely used and accepted by federal and state regulatory agencies.

For this modeling effort, the MT3DMS model utilized the flow regime from the steady-state, calibrated Site groundwater flow model presented in **Section 1** to simulate transport of molybdenum. The steady state model was transformed into a transient model so various CMA options could be evaluated with respect to time. The strength and locations of the potential molybdenum sources specified in the transport models were based on surface water concentrations from the Site.

The following describe the adsorption effects on solute transport based on the geochemical properties and published empirical data, as well as the choice of the linear adsorption coefficient for each contaminant used for transport modeling.

2.1 TRANSPORT MODELING APPROACH

The solute transport portion of the modeling effort focused mainly on the future flow pathway for molybdenum at the Site. As such, the initial concentration including the current plume extent and the estimated leachable mass near the ash pond were utilized in place as a constant source. The location and initial concentrations for molybdenum within the model (layers 1 and 2) is presented in **Figure 7**.

The calibrated flow model was allowed to run for 1000 years following implementation of the groundwater remedy. Calibration of the concentrations through time was not performed on the predictive model as the starting conditions were the current conditions at the Site and thus represent a conservative estimate of transport through the Site.

2.2 KEY PARAMETERS FOR TRANSPORT MODELING

The following sections describe the key input parameters of the transport model, and how they were derived. Note that these parameters were selected for the purpose of comparative evaluation of relative benefits of various corrective measures. The parameters and conditions used for the modeling are selected based on the data available to date. Therefore, simulated remedial timeframes using the parameters described in this section should not be construed as absolute predictions of remedial time frames for various corrective measures.

2.2.1 Effective Porosity

The effective porosities used in the model were presented in previous **Section 1.3.2**.

2.2.2 Dispersivity

Dispersion incorporates the effects of fluid mixing that result from heterogeneities within the groundwater system and molecular diffusion, which is the random movement of ions or molecules. If the molecules of water and dissolved constituents traveled at the average seepage velocity, there would be an abrupt interface and dispersion would be negligible. However, in natural systems water molecules and dissolved contaminants do not all travel at the same rate; some travel faster and some slower. Dispersion in the model accounts for the spreading of the dissolved plume. Diffusion is time dependent and is significant at low velocities. In general, dispersion acts to decrease the contaminant concentration on the leading edge of the plume, while increasing the size and rate of transport of the dissolved plume. Longitudinal dispersion occurs in the direction of advective groundwater flow, while transverse dispersion occurs perpendicular to groundwater flow.

The groundwater modeling generally accepted longitudinal dispersity value (α_L) estimate is 1 to 100. The horizontal transverse dispersivity (α_T) can be estimated as approximately one-tenth of the α_L, and vertical transverse (α_v) dispersivity can be estimated as one-hundredth of the α_L. The values utilized for dispersivity values are as follows:

- α_L – 100 ft,
- α_T – 10 ft, and
- α_V – 1 ft

2.2.3 First-Order Degradation Rate Constant – Lambda (λ)

Another input parameter for the fate and transport model is the first order degradation rate constant (λ) for molybdenum. This rate constant only takes into account precipitation of molybdenum during transport due to an in-situ treatment remedy, as it leaves the source. This rate constant does not factor in effects of advection, sorption or dispersivity (dispersion). The field-scale degradation rate constant usually can be expressed as a first order decay constant or as a reaction half-life. A reaction half-life of 0.1 day was specified for the scenario that includes an in-situ remedy. The magnitude of the half-life is based on results of a reported field pilot test that used a redox manipulation approach to remove molybdenum from groundwater through precipitation. Note that this redox manipulation approach can also promote arsenic precipitation.

2.2.4 Retardation Effects

Chemical retardation occurs when a solute (contaminant) reacts with the porous media and its rate of movement is retarded relative the advective groundwater velocity. Retardation can occur by a variety of processes including adsorption and mass transfer in porous media. The effects of retardation are often related to site-specific adsorption isotherms. For this modeling purpose, a liner adsorption isotherm is used to account for the effects of transport retardation that may occur for Site-related contaminants. The effects of retardation on contaminant mobility is usually expressed in terms of a retardation factor (R), which is the ratio of the groundwater velocity to contaminant transport velocity (Bedient, P.B., Rifai, H.S. and Newell, C.J., 1994). When a linear adsorption isotherm is used to characterize contaminant mobility, the linear adsorption coefficient (K_d) can be linked to the retardation factor with the mathematical relationship below:

$$R = \frac{v_{gw}}{v_c} = 1 + \frac{\rho_b}{n} \times K_d$$

Where:

R = Retardation factor
v_{gw} = Groundwater velocity
v_c = Contaminant transport
ρ_b = Aquifer solid bulk density
n = Effective transport porosity of the medium
K_d = Linear adsorption coefficient

The following describe the adsorption effects of molybdenum and arsenic based on their geochemical properties and the published empirical data, as well as the choice of the linear adsorption coefficient for each contaminant used for transport modeling.

2.2.5 Adsorption of Molybdenum on Aquifer Solids

Molybdenum (atomic number 42) is a transition metal in Group VI of the periodic classification of the elements. The affinity for molybdenum to adsorb to the geologic matrix can be affected by factors such as pH, redox conditions, mineral contents of aquifer solids, organic matter abundance, and the presence of organic ligands in the groundwater system.

The aqueous speciation of molybdenum and potential formation of molybdenum-related minerals under a spectrum of the electro-potential (Eh) and pH conditions are shown below (**Figure 8**). Based on Site groundwater monitoring results, the predominant pH values are within the neutral pH range (between 6.5 and 7.5) except at the locations of AP-2 and AP-3. The values of oxidation-reduction potential (Eh) vary widely among locations and sampling events. The main molybdenum species in groundwater is expected to be molybdenum species of a valence state of +6. No molybdenum associated precipitation is expected under the current geochemical conditions.

2.2.5.1 Empirical data on adsorption

The adsorption of molybdenum has been studied on a variety of minerals, sediments, soils, and crushed rock materials. The extent of adsorption is greatly influenced by pH; generally, the degree of adsorption decreases with an increase in pH (Sheppard, S., Long, J., Sanipelli, B. and Sohlenius, G., 2009). Metal oxides (iron, manganese, and aluminum oxides) in aquifer solids are shown to play a major role in molybdenum adsorption; the K_d values reported by Goldberg et al. (1996) for oxide minerals range from 10 to 10^3 liter per kilogram (L/Kg) (Goldberg, S., Forster, H.S. and Godfrey, C.L., 1996). Adsorption on a weight basis of iron oxide minerals increased in the order: hematite< goethite < amorphous Fe oxide < poorly crystalline goethite; adsorption on a weight basis for clay minerals increases in the order: well crystallized kaolinite < poorly crystallized kaolinite < illite < montmorillonite.

2.2.5.2 K_d value used for molybdenum transport modeling

Based on the total iron concentrations found at the Site, a total iron concentration of 24,000 mg/Kg is considered representative. Site aquifer solids likely possess a wide range of redox states and are predominately coarse-grained material. The geometric mean of the published Kd values for iron oxide minerals for more weathered iron oxides (e.g., hematite and goethite) are approximately 100 L/Kg at pH = 7. Assuming that only 10,000 mg/Kg of iron oxide minerals in aquifer solids is available for adsorption, a nominal K_d value of 1 L/Kg for bulk aquifer solids is estimated (= 10,000 mg/Kg x 10^{-6} Kg/mg x 100 L/Kg). This value is considered a representative, yet conservative value for evaluation of molybdenum transport in the saturated zone.

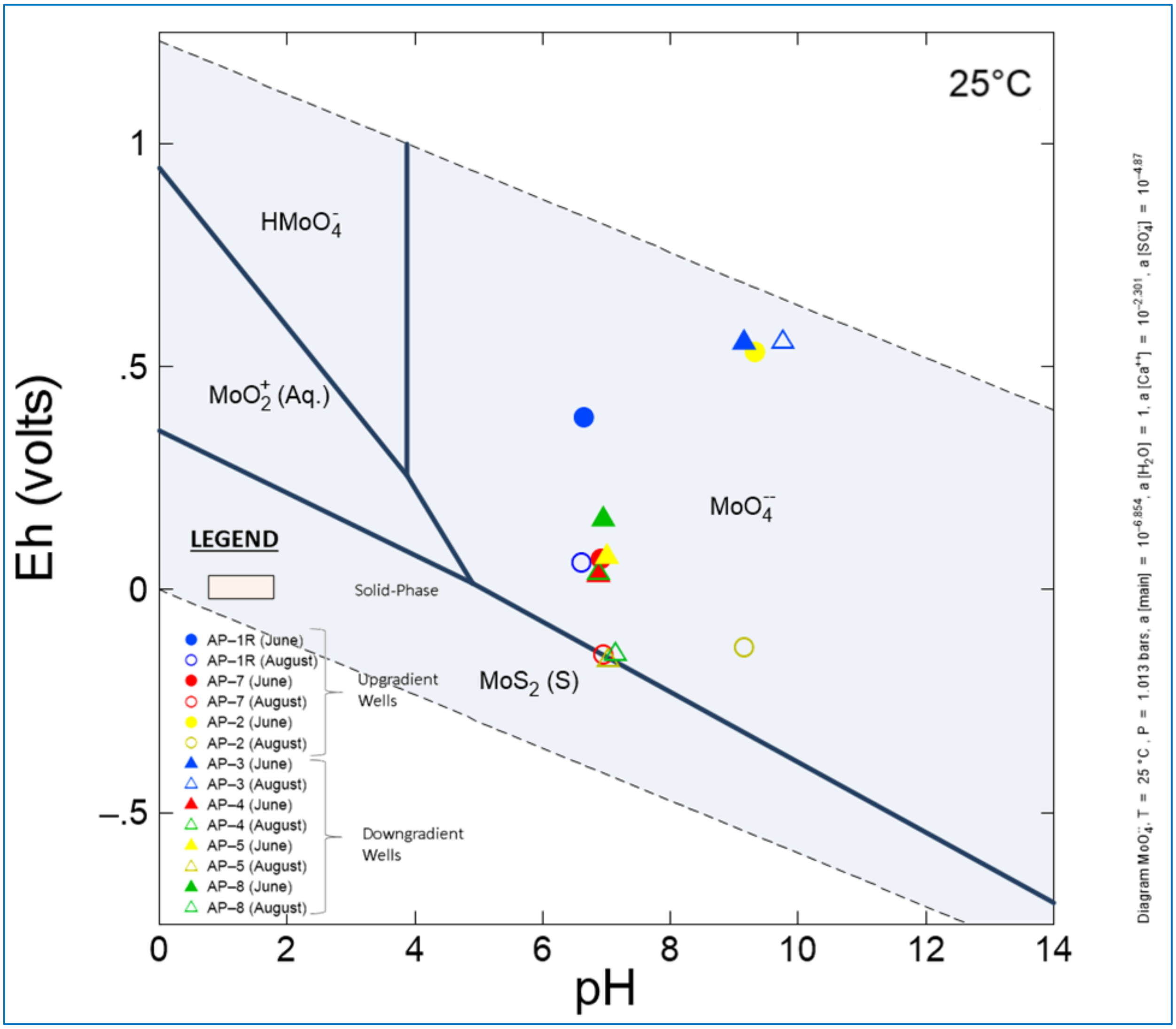


Figure 8: Molybdenum Eh-pH Diagram for a molybdenum-sulfur-oxygen-hydrogen system; groundwater monitoring data collected in June and August 2018 used; field ORP measurements converted to the Standard Hydrogen Electrode (SHE); field pH measurements plotted; assumptions: solute activities = measured concentrations in mols/L; analytical concentrations results for AP-2R used to generate stability diagram. Thermodynamic database used: thermo.com.V8.R6+, fully modified with molybdenum solubility data from Vlek and Lindsay (1977).

2.2.6 Source Initial Concentration Data

To conservatively predict the transport of molybdenum and preserve the mass transported through the Site, the source area was defined utilizing initial concentration and constant sources in the form of recharge. The current extent of the groundwater plume for molybdenum was generated based on groundwater concentrations in the monitoring well network.

Three discrete areas with concentrations of molybdenum above the GWPS are present at the Site within the vicinity of the ash pond. Initial concentrations were created near the following wells at concentrations observed from groundwater sampling events conducted on 28 May 2019 (CCR-AP-5) and 12 June 2019 (CCR-AP-6I and CCR-AP-8I).

- CCR-AP-5 – 0.38 milligram per liter (mg/L)
- CCR-AP-6I – 0.34 mg/L
- CCR-AP-8I – 0.86 mg/L

2.3 TRANSPORT MODEL RESULTS - MOLYBDENUM

Model results for Molybdenum concentrations for each CMA option is shown in **Figure 9**. A detailed discussion of each option is presented in the CMA report (Haley & Aldrich, Inc., 2019).

References

1. Anderson, M.P., Woessner. WW (1992) Applied Groundwater Modeling. Simulation of Flow and Advective Transport.

2. Bedient, P.B., Rifai, H.S. and Newell, C.J., 1994. *Ground water contamination: transport and remediation*. Prentice-Hall International, Inc.

3. Doherty, J., 2016. PEST – Model-Independent Parameter Estimation. Watermark Numerical Computing.

4. Goldberg, S., Forster, H.S. and Godfrey, C.L., 1996. Molybdenum adsorption on oxides, clay minerals, and soils. Soil Science Society of America Journal, 60(2), pp.425-432.

5. Haley & Aldrich, Inc., 2017. CCR Groundwater Monitoring Program Description for the F.B Culley Generating Station East Ash Pond, Warrick County, Indiana, dated 17 October 2017.

6. Harbaugh, A.W., 2005. MODFLOW-2005, the US Geological Survey modular ground-water model: the ground-water flow process (pp. 6-A16). Reston, VA: US Department of the Interior, US Geological Survey.

7. Hill, M.C., 2000. Methods and guidelines for effective model calibration. In Building Partnerships (pp. 1-10).

8. Sheppard, S., Long, J., Sanipelli, B. and Sohlenius, G., 2009. *Solid/liquid partition coefficients (Kd) for selected soils and sediments at Forsmark and Laxemar-Simpevarp* (No. SKB-R--09-27). Swedish Nuclear Fuel and Waste Management Co.

9. Vlek, P.L.G. and Lindsay, W.L., 1977. Thermodynamic Stability and Solubility of Molybdenum Minerals in Soils 1. Soil Science Society of America Journal, 41(1), pp.42-46.

10. Zheng, C. and Wang, P.P., 1999. MT3DMS: a modular three-dimensional multispecies transport model for simulation of advection, dispersion, and chemical reactions of contaminants in groundwater systems; documentation and user's guide. Alabama University.

TABLES

Table 1
Groundwater Elevations
F.B Culley Generating Station
Newburgh, Indiana

Well Location	Easting Feet	Northing Feet	Date Collected	Depth To Water Feet	Groundwater Elevation Feet (NAVD88)
CCR-AP-1	2883429.69	969939.69	6/2/2016	52.66	388.98
			8/12/2016	53.57	388.07
			10/28/2016	54.20	387.44
			12/7/2016	54.71	386.93
			2/8/2017	53.60	388.04
			4/6/2017	53.55	388.09
			6/7/2017	53.58	388.06
			9/28/2017	53.14	388.50
			11/17/2017	54.04	387.60
			6/11/2018	52.20	389.44
			8/28/2018	54.04	387.60
CCR-AP-2	2884168.67	969117.52	6/2/2016	33.16	360.81
			8/12/2016	33.88	360.09
			10/28/2016	34.23	359.74
			12/7/2016	33.68	360.29
			2/8/2017	32.55	361.42
			4/6/2017	28.04	365.93
			6/7/2017	33.69	360.28
			9/28/2017	34.06	359.91
			11/17/2017	33.00	360.97
			6/11/2018	33.35	360.62
			8/28/2018	34.13	359.84
CCR-AP-3	2883542.09	969007.98	6/2/2016	31.23	363.31
			8/12/2016	32.33	362.21
			10/28/2016	32.71	361.83
			12/7/2016	32.62	361.92
			2/8/2017	30.32	364.22
			4/6/2017	30.49	364.05
			6/7/2017	30.74	363.80
			9/28/2017	32.45	362.09
			11/17/2017	32.18	362.36
			6/11/2018	32.55	361.99
			8/28/2018	31.73	362.81

Table 1
Groundwater Elevations
F.B Culley Generating Station
Newburgh, Indiana

Well Location	Easting Feet	Northing Feet	Date Collected	Depth To Water Feet	Groundwater Elevation Feet (NAVD88)
CCR-AP-4	2883281.93	969641.70	6/2/2016	7.92	386.99
			8/12/2016	8.02	386.89
			10/28/2016	10.34	384.57
			12/7/2016	11.43	383.48
			2/8/2017	9.79	385.12
			4/6/2017	9.67	385.24
			6/7/2017	9.98	384.93
			9/28/2017	9.56	385.35
			11/17/2017	9.34	385.57
			6/11/2018	9.39	385.52
			8/28/2018	9.05	385.86
CCR-AP-5	2884016.66	969379.68	6/2/2016	10.49	383.83
			8/12/2016	12.17	382.15
			10/28/2016	16.51	377.81
			12/7/2016	16.18	378.14
			2/8/2017	11.02	383.30
			4/7/2017	11.20	383.12
			6/7/2017	12.04	382.28
			9/28/2017	13.46	380.86
			11/17/2017	12.31	382.01
			6/11/2018	12.78	381.54
			8/28/2018	12.50	381.82
CCR-AP-6	2883285.03	969122.16	6/2/2016	39.27	357.44
			8/12/2016	39.29	357.42
			10/28/2016	38.90	357.81
			12/7/2016	38.87	357.84
			2/8/2017	39.55	357.16
			4/6/2017	34.14	362.57
			6/7/2017	38.94	357.77
			9/28/2017	38.58	358.13
			11/17/2017	38.42	358.29
			6/11/2018	38.80	357.91
			8/28/2018	38.80	357.91

Table 1
Groundwater Elevations
F.B Culley Generating Station
Newburgh, Indiana

Well Location	Easting Feet	Northing Feet	Date Collected	Depth To Water Feet	Groundwater Elevation Feet (NAVD88)
CCR-AP-7	2883090.34	970774.64	6/2/2016	6.54	427.57
			8/12/2016	12.24	421.87
			10/28/2016	15.98	418.13
			12/7/2016	13.27	420.84
			2/8/2017	5.95	428.16
			4/7/2017	4.81	429.30
			6/7/2017	11.46	422.65
			9/28/2017	16.62	417.49
			11/17/2017	14.56	419.55
			6/11/2018	6.45	427.66
			8/28/2018	14.20	419.91
CCR-AP-8	2883846.87	969046.03	3/8/2017	31.59	362.24
			4/6/2017	29.49	364.34
			4/26/2017	29.83	364.00
			5/30/2017	32.11	361.72
			6/7/2017	32.15	361.68
			7/25/2017	30.98	362.85
			8/15/2017	30.01	363.82
			9/28/2017	31.13	362.70
			11/17/2017	30.10	363.73
			6/11/2018	30.49	363.34
			8/28/2018	29.42	364.41
CCR-AP-9	2883998.96	969768.61	3/8/2017	62.48	386.21
			4/7/2017	60.89	387.80
			4/26/2017	61.20	387.49
			5/30/2017	61.53	387.16
			6/7/2017	62.21	386.48
			7/25/2017	63.90	384.79
			8/15/2017	63.93	384.76
			9/28/2017	63.91	384.78
			11/17/2017	63.26	385.43
			6/11/2018	61.69	387.00
			8/28/2018	62.82	385.87

Table 1
Groundwater Elevations
F.B Culley Generating Station
Newburgh, Indiana

Well Location	Easting Feet	Northing Feet	Date Collected	Depth To Water Feet	Groundwater Elevation Feet (NAVD88)
			7/17/2017	20.50	385.76
			7/27/2017	20.95	385.31
			8/15/2017	21.00	385.26
			8/27/2017	22.20	384.06
			1/23/2018	14.97	391.29
			4/2/2018	13.40	392.86
PZ-E-1	2882753.00	971139.68	5/3/2018	14.90	391.36
			5/23/2018	15.30	390.96
			6/14/2018	15.08	391.18
			7/5/2018	14.76	391.50
			7/25/2018	18.28	387.98
			8/16/2018	19.27	386.99
			12/4/2018	15.51	390.75
			7/17/2017	20.10	384.33
			7/27/2017	20.60	383.83
			8/15/2017	20.60	383.83
			8/27/2017	21.20	383.23
			1/23/2018	13.81	390.62
			4/2/2018	10.50	393.93
PZ-E-2	2882682.29	971069.08	5/3/2018	13.25	391.18
			5/23/2018	16.44	387.99
			6/14/2018	22.57	381.86
			7/5/2018	12.00	392.43
			7/25/2018	19.20	385.23
			8/16/2018	21.22	383.21
			12/4/2018	20.22	384.21

Table 1
Groundwater Elevations
F.B Culley Generating Station
Newburgh, Indiana

Well Location	Easting Feet	Northing Feet	Date Collected	Depth To Water Feet	Groundwater Elevation Feet (NAVD88)
PZ-E-3	2882537.49	970928.88	7/17/2017	22.00	382.54
			7/27/2017	22.50	382.04
			8/15/2017	23.15	381.39
			8/27/2017	24.00	380.54
			1/23/2018	20.04	384.50
			4/2/2018	14.22	390.32
			5/3/2018	12.02	392.52
			5/23/2018	17.77	386.77
			6/14/2018	17.66	386.88
			7/5/2018	16.80	387.74
			7/25/2018	20.21	384.33
			8/16/2018	22.05	382.49
WAP-2R	2881511.71	971395.70	4/1/2017	35.69	359.60
WAP-3	2881262.53	971000.02	4/1/2017	33.02	360.08
WAP-4	2881333.33	970405.14	4/1/2017	34.40	362.68
WAP-4I	2881329.18	970408.95	4/1/2017	34.55	362.68
WAP-4D	2881325.08	970412.71	4/1/2017	34.35	362.68
WAP-5	2881521.35	970235.87	4/1/2017	33.41	363.00
WAP-5I	2881524.71	970232.61	4/1/2017	33.35	363.00
WAP-5D	2881528.71	970229.88	4/1/2017	33.35	363.00
WAP-1	2882824.18	971214.17	4/1/2017	11.50	391.89

FIGURES

LEGEND

MONITORING WELL LOCATION

MODEL DOMAIN

EAST ASH POND

WEST ASH POND

NOTES

1. ALL LOCATIONS ARE APPROXIMATE
2. AERIAL IMAGERY SOURCE: ESRI

N

0 500 1,000
SCALE IN FEET

HALEY ALDRICH

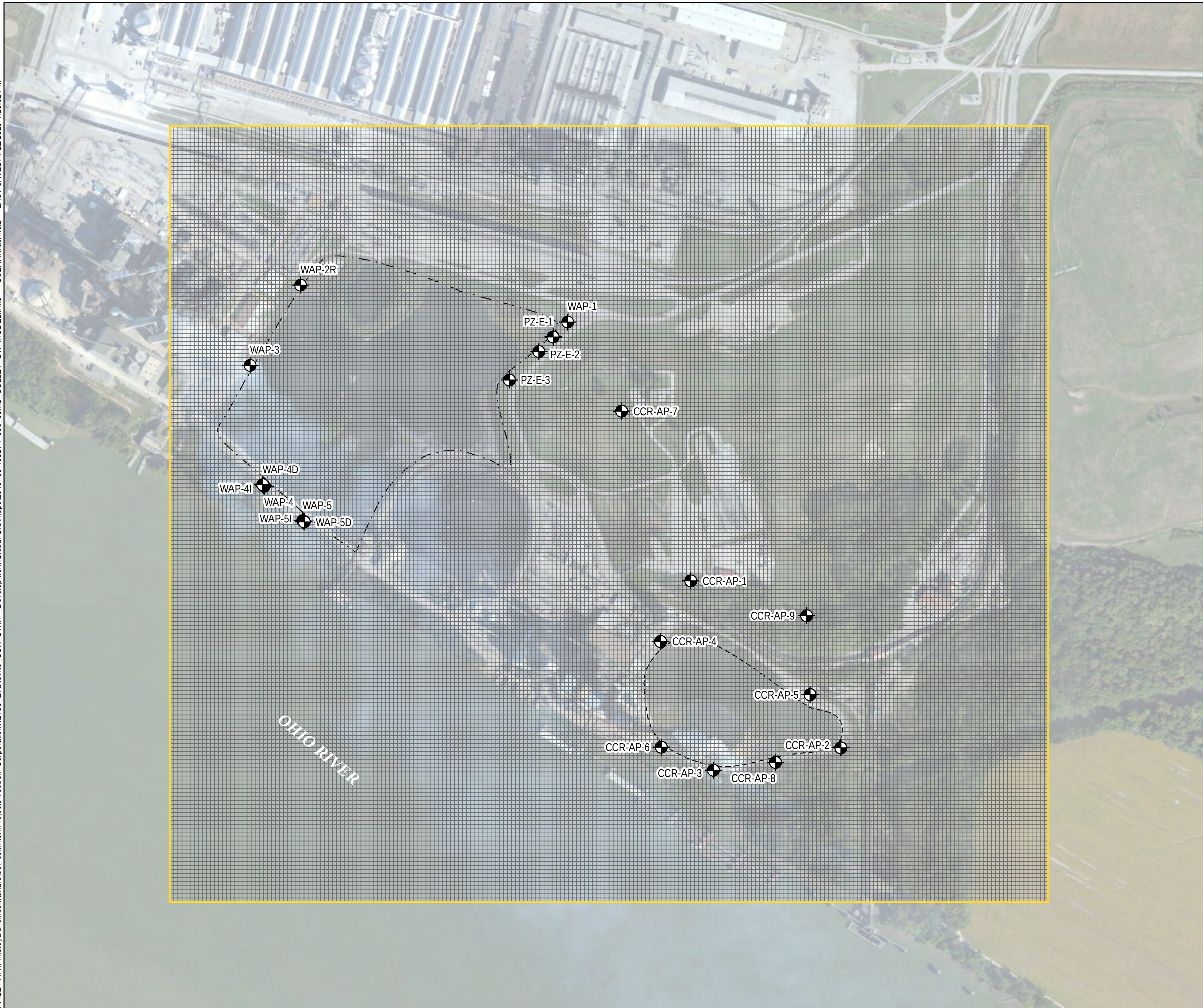
CORRECTIVE MEASURE ASSESSMENT
SOUTHERN INDIANA GAS AND ELECTRIC COMPANY
F.B. CULLEY GENERATING STATION
NEWBURGH, INDIANA

SITE PLAN WITH MODEL DOMAIN

SEPTEMBER 2019

FIGURE 1

GIS FILE PATH: \\haleyaldrich.com\share\boi_common\Projects\Vectren_Corporation\42796_Evansville_CCR_GWMP_Development\Global\GIS\Maps\2019_09\133274_000_00MB_CULLEY_GW_MODEL.mxd — USER: hwachholz — LAST SAVED: 1/22/2020 1:20:02 PM



LEGEND

- MONITORING WELL LOCATION
- MODEL DOMAIN
- GRID
- EAST ASH POND
- WEST ASH POND

NOTES

1. ALL LOCATIONS ARE APPROXIMATE
2. AERIAL IMAGERY SOURCE: ESRI

N

0 500 1,000
SCALE IN FEET

HALEY ALDRICH

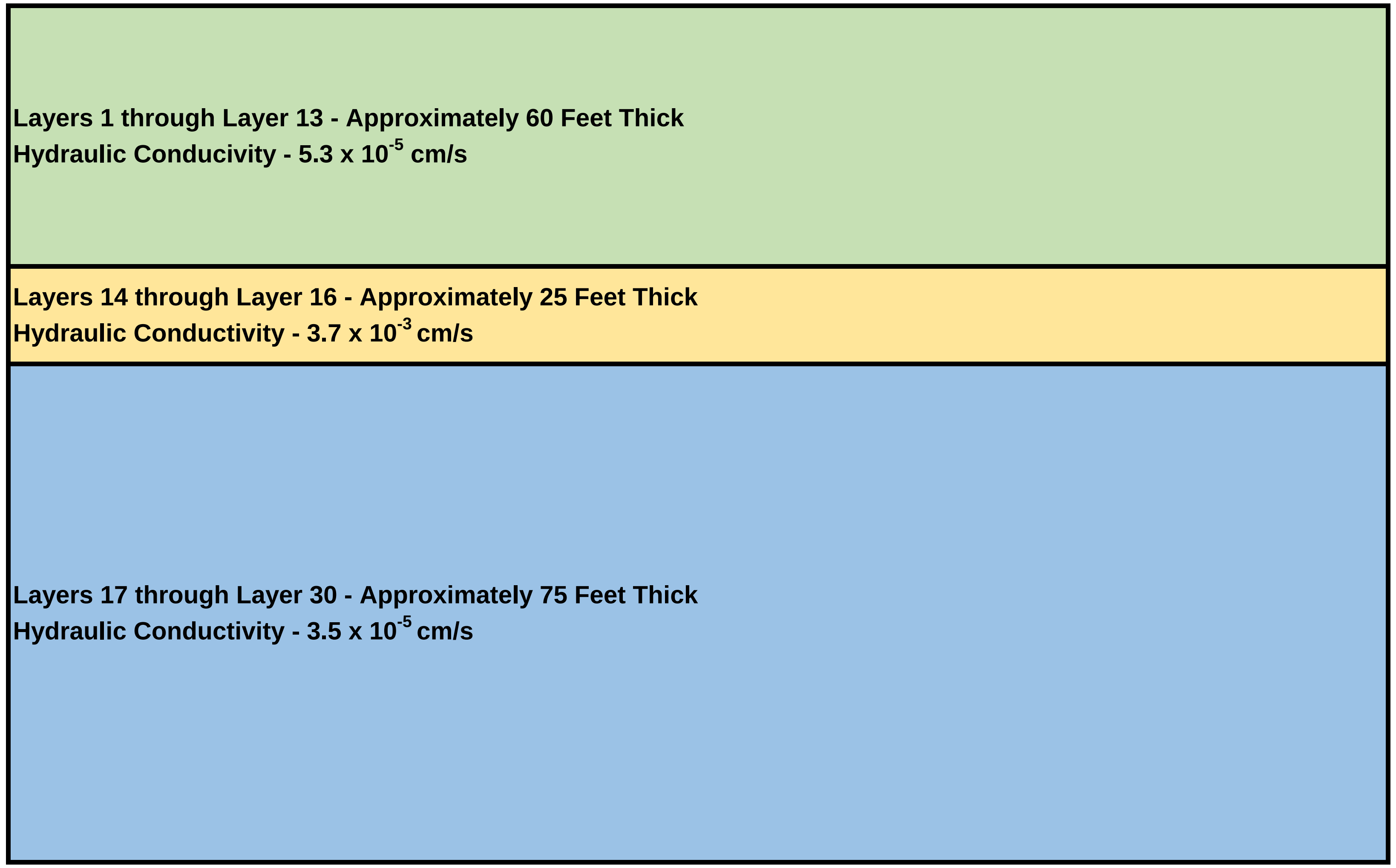
CORRECTIVE MEASURE ASSESSMENT
SOUTHERN INDIANA GAS AND ELECTRIC COMPANY
F.B. CULLEY GENERATING STATION
NEWBURGH, INDIANA

SITE PLAN WITH MODEL GRID

SEPTEMBER 2019

FIGURE 2

GIS FILE PATH: \\haleyaldrich.com\share\boi_common\Projects\Vectren_Corporation\42796_Evansville_CCR_GWMP_Development\Global\GIS\Maps\2019_09\133274_000_00MB_CULLEY_GW_MODEL.mxd — USER: hwachholz — LAST SAVED: 1/22/2020 1:20:02 PM



NOTES:

1. Layer Thicknesses Approximate Due To Variability In Model
2. Layers 1 Through 13 Represent Fine Soils ;
Layers 14 Through 16 Represent Sandy Soils ;
Layers 17 Through 30 Represent Bedrock

VECTREN CORPORATION
F.B CULLEY GENERATING STATION
WARRICK COUNTY, IN

MODEL LAYERS 1 THROUGH 30 WITH HYDRAULIC CONDUCTIVITIES AND LAYER THICKNESSES

SEPTEMBER 2019

FIGURE 3

GIS FILE PATH: \\haleyaldrich.com\share\boi_common\Projects\Vectren_Corporation\42796_Evansville_CCR_GWMP_Development\Global\GIS\Maps\2019_09\133274_000_00MB_CULLEY_GW_MODEL.mxd — USER: hwachholz — LAST SAVED: 1/22/2020 1:20:02 PM

LEGEND

MONITORING WELL LOCATION

MODEL DOMAIN

EAST ASH POND

WEST ASH POND

CONSTANT HEAD BOUNDARY

CONSTANT HEAD BOUNDARY ONE (1) - REACH #10

CONSTANT HEAD BOUNDARY ONE (2) - REACH #11

CONSTANT HEAD BOUNDARY ONE (3) - REACH #12

NOTES

1. ALL LOCATIONS ARE APPROXIMATE

2. AERIAL IMAGERY SOURCE: ESRI

N

0 500 1,000

SCALE IN FEET

HALEY ALDRICH

CORRECTIVE MEASURE ASSESSMENT
SOUTHERN INDIANA GAS AND ELECTRIC COMPANY
F.B. CULLEY GENERATING STATION
NEWBURGH, INDIANA

SITE PLAN WITH CONSTANT HEAD BOUNDARY LAYERS 10 THROUGH 30

SEPTEMBER 2019

FIGURE 4

GIS FILE PATH: \\haleyaldrich.com\share\boi_common\Projects\Vectren_Corporation\42796_Evansville_CCR_GWMP_Development\Global\GIS\Maps\2019_09\133274_000_00MB_CULLEY_GW_MODEL.mxd — USER: hwachholz — LAST SAVED: 1/22/2020 1:20:02 PM

LEGEND

MONITORING WELL LOCATION
MODEL DOMAIN
RIVER
EAST ASH POND
WEST ASH POND

NOTES

1. ALL LOCATIONS ARE APPROXIMATE
2. AERIAL IMAGERY SOURCE: ESRI

N

0 500 1,000
SCALE IN FEET

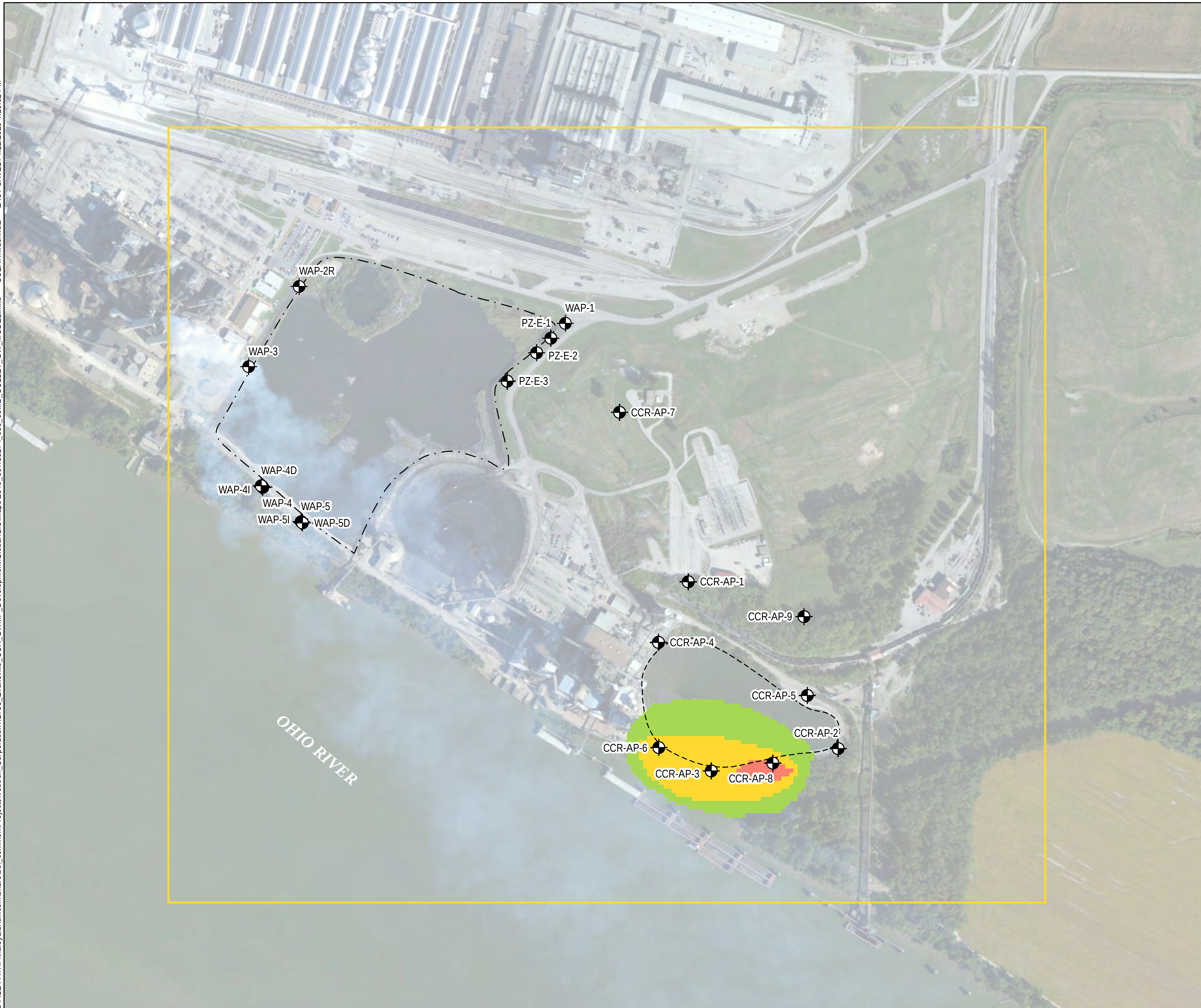
HALEY ALDRICH

CORRECTIVE MEASURE ASSESSMENT
SOUTHERN INDIANA GAS AND ELECTRIC COMPANY
F.B. CULLEY GENERATING STATION
NEWBURGH, INDIANA

SITE PLAN WITH RIVER BOUNDARY CONDITION FOR LAYER 14 AND 15

SEPTEMBER 2019

FIGURE 5



GIS FILE PATH: \\haleyaldrich.com\share\boi_common\Projects\Vectren_Corporation\42796_Evansville_CCR_GWMP_Development\Global\GIS\Maps\2019_09\133274_000_00MB_CULLEY_GW_MODEL.mxd — USER: hwachholz — LAST SAVED: 1/22/2020 1:20:02 PM

LEGEND

MONITORING WELL LOCATION

MODEL DOMAIN

EAST ASH POND

WEST ASH POND

MOLYBDENUM CONCENTRATION

0.1 MICROGRAMS/ LITER

0.3 MICROGRAMS/ LITER

0.8 MICROGRAMS/ LITER

NOTES

1. ALL LOCATIONS ARE APPROXIMATE
2. AERIAL IMAGERY SOURCE: ESRI

N

0 500 1,000

SCALE IN FEET

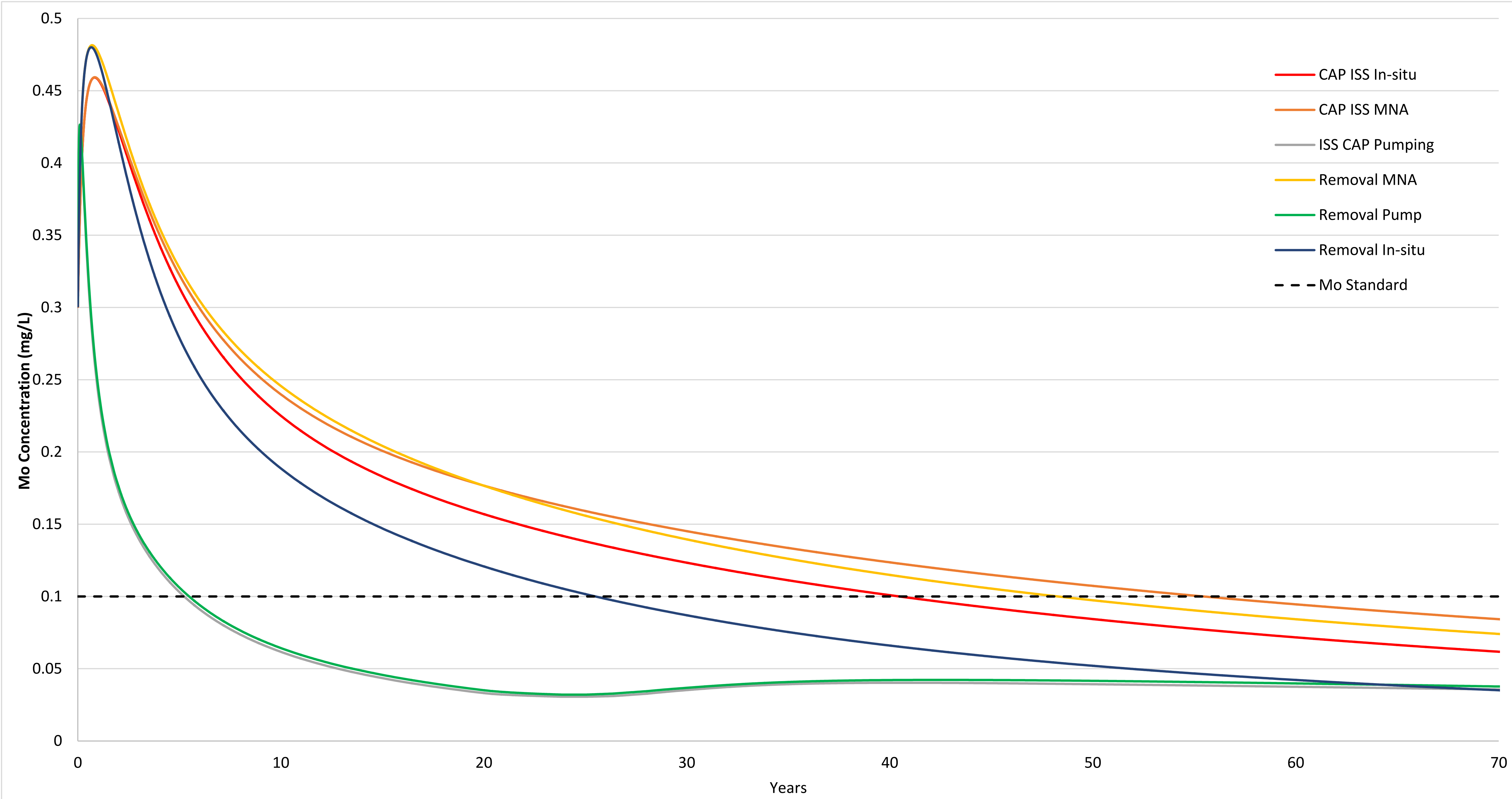
HALEY ALDRICH

CORRECTIVE MEASURE ASSESSMENT
SOUTHERN INDIANA GAS AND ELECTRIC COMPANY
F.B. CULLEY GENERATING STATION
NEWBURGH, INDIANA

INITIAL MOLYBDENUM CONCENTRATION FOR LAYERS 14 AND 15

SEPTEMBER 2019

FIGURE 7



NOTES:

1. Modeled Monitoring Well Located Approximately 200 Feet Downgradient from Pond Toward The River.

HALEY ALDRICH

SOUTHERN INDIANA GAS AND ELECTRIC COMPANY
F.B. CULLEY GENERATING STATION
NEWBURGH, INDIANA

MODELED MOLYBDENUM CONCENTRATIONS FOR CMA OPTIONS OVER TIME

SEPTEMBER 2019

FIGURE 9