Appendix H

Mass Removal and Contaminant Transport Modeling

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H.1 Introduction

Analytical modeling was undertaken for the Cabot portion of the Site to understand plume behavior and evaluate the performance of viable remedial configurations. Contaminant transport models can be useful tools to enhance the understanding of plume evolution, inform predictions of future plume behavior, and estimate the relative outcomes of different remedial actions to assist in decision-making.

H.2 Contaminant Transport Modeling

An analytical contaminant transport model, REMChlor (Falta *et al.*, 2007), was used as part of the remedy evaluation described in this report. The objective of the modeling was to enhance the understanding of plume evolution in the Upper Hawthorn Group (UHG) formation and to inform remedial action decision-making. The rationale for the model and analyte selection is provided below:

 REMChlor simulates a contaminant source of finite mass and resulting downgradient plume in a steady, uniform groundwater flow field. Fractional source removal, source decay, and source mass dissolution can affect the source material. Advection, dispersion, and first-order decay processes can affect the downgradient plume. A power function governs the relationship between the source material and the plume, as follows:

$$\left(\frac{M}{M_0}\right)^{\Gamma} = \frac{C}{C_0}$$

where M is the time-dependent source mass, M_0 is the original source mass, C is the timedependent source groundwater concentration, C_0 is the original source groundwater concentration, and Γ (gamma) is a site-specific factor that determines the shape of the source discharge response to changing mass (additional discussion regarding Γ , including the basis for the input value used in this evaluation, is presented in Section H.2.1, below). The ability of REMChlor to simulate the time-dependent depletion of source mass makes it a model that is well suited for understanding the fate and transport of a groundwater plume associated with potential non-aqueous phase liquid (NAPL) sources. The model has its limitations, including assuming a uniform flow field in the entire model domain, but it is capable of capturing the important contaminant transport processes taking place in the UHG.

3,4-methylphenol was selected as the primary modeling compound of interest because it is a key pine tar constituent and remedy-driver at the Site, with relatively high mobility, a large plume footprint, relatively high concentrations, and a relatively low cleanup goal. Phenol, which is another key pine tar constituent, was also evaluated, but not used in the model, since it has a smaller plume footprint and higher cleanup goal in comparison to 3,4-methylphenol. Other detected compounds, including 2,4-dimethylphenol and benzene were not simulated since they have other sources, such as the Koppers Site, that would confound the analysis.

Model simulations were undertaken first, to calibrate the model (*i.e.*, to ensure that model predictions matched measured values of 3,4-methylphenol concentrations at multiple downgradient plume locations). A sensitivity evaluation was then performed to evaluate the uniqueness of the calibration, and a conservative calibrated model was selected. Finally, plume evolution was modeled under a no-action scenario and under three different remedial scenarios.

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H.2.1 Calibration and Sensitivity Analysis

Inputs for the calibrated model were assembled as listed in Table H.1. Site-specific data, where available, were the primary resource to determine appropriate input parameter values. For model parameters where ranges of values were plausible, the parameters were adjusted within reasonable limits to obtain good model agreement with measured values.

The exponent gamma on the concentration vs. mass discharge curve is a site-specific and calibrated value that is a function of the contaminant source characteristics and aquifer hydrogeologic properties. The value is generally between 0.5 and 2, with lower values being more representative of a younger site (*i.e.*, a site with a relatively recent contaminant release) and high values being more representative of an older site (Falta *et al.*, 2007). At sites with relatively old releases (*i.e.*, gamma > 1), as the source mass declines,¹ the mass flux to the downgradient plume decreases at an accelerated rate. For the Cabot Carbon portion of the Site, a value of 2 resulted in a good match between modeled and measured concentrations and is consistent with the relatively old age (more than 60 years) of the source material.

An anaerobic biodegradation rate well below the lowest reported literature values was used in the calibrated model. Anaerobic decay rates recommended in the literature range from 0.00029/day (or a half-life of 7 years) to 0.048/day (or a half-life of 14 days) (Syracuse Research Corp., 1997). The value used in the calibrated model was 0.0001/day (or a half life of 20 years). Use of a decay rate lower than literature values is justified, however, because biodegradation is inhibited by the high contaminant concentrations detected in the source area and the concentrated portion of the plume (*i.e.*, within and downgradient of the Former Lagoon Area, extending to monitoring well HG-28S).

Groundwater sampling results indicate that 3,4-methylphenol has been detected in groundwater at seven sample locations (listed in Table H.2) directly downgradient of the former lagoons and within the main plume footprint in the UHG since the HG investigation was initiated in 2011. For permanent monitoring wells where multiple data sets were available, an average of the detected values was used as the representative concentration for that location.

Results from the final selected model calibration are shown in Figures H.1-H.4.

- Figure H.1 shows the modeled plume contours for 3,4-methylphenol on the Site map. The modeled source area is shown as a solid line, perpendicular to the predominant groundwater flow direction, depicting how the REMChlor model is aligned. Data from the model are posted at locations with measured analytical data. The modeled values are in good agreement with measured data, including the low-level concentrations downgradient of the leading edge of the plume (for example, concentrations on the order of tens of micrograms per liter at WS-18 and non-detect values at HG-37S).
- Figure H.2 shows a concentration profile of a transect along the plume centerline, with measured data from nearby locations projected onto the profile. The figure shows good agreement between modeled and measured concentrations at the three permanent monitoring wells, and the plume profile is consistent with the conceptual site model (Section 3.4). The profile shows that the peak concentration along the plume centerline is located immediately upgradient of HG-28S rather than near the source (the Former Lagoon Area). This is attributable to the declining mass flux associated with source decay in the Former Lagoon Area, which controls the concentration

¹At sites with older NAPL sources, contaminant mass flux from source areas typically declines due to the depletion of soluble contaminants from the NAPL surface or the formation of crusts on the NAPL surface that limit further dissolution of mass (Falta *et al.*, 2007).

profile, whereas the low anaerobic biodegradation decay rate simulated in the model has a relatively small effect (*e.g.*, at HG-28S).

- Figure H.3 directly compares modeled and measured concentrations and shows good agreement between the two. The model conservatively over-predicts concentrations at WS-17, which is the only significant outlier.
- Figure H.4 compares modeled and measured concentrations at HG-28S through time and shows good agreement between the temporal trends (*i.e.*, increasing concentrations at HG-28S in recent years).

During the model calibration, an analysis was conducted to determine how sensitive the model was to key input parameters. Figure H.5 presents the centerline profiles from several of the sensitivity analysis results, along with the profile of the selected calibration for comparison.

- The gamma parameter in REMChlor governs the source discharge relationship and primarily affects the concentration-distance profile of the plume. The value of gamma in the selected calibration (2.0) is the recommended value for older sites (Falta *et al.*, 2007) and produces the best match with measured concentrations at the Site in comparison to other values of gamma.
- Effective porosity strongly influences the position of the plume, since it plays an important role in contaminant travel times. The selected calibration value results in a good match of the plume position and other characteristics.
- Halving the initial source concentration produced low concentrations at the downgradient plume edge that did not provide a good match to measured values.
- An alternative calibrated model, created by adjusting several factors (source concentration, source mass, porosity, dispersion, and background decay rate) in conjunction, is also shown in Figures H.5 and H.6. This alternative calibration has a peak concentration more consistent with measured Site data and more closely approximates concentrations at WS-17; however, it underestimates concentrations at HG-29S.

Recognizing that a calibrated model is non-unique, the selected model calibration is a conservative choice: it may over-predict the plume peak concentration and concentrations at isolated locations, but it provides a representation of the plume that is conservative and consistent with both measured data and the site conceptual model (Section 3.4).

H.2.2 Model Predictions

The calibrated model was run for longer times to predict plume evolution under a no-action scenario. Additionally, three potential remedial scenarios were modeled: the installation of a slurry wall encompassing the former Cabot lagoons and the concentrated portion of the plume combined with MNA of the downgradient plume, the installation of a slurry wall combined with a pumping well point system in the vicinity of well HG-28S, and the installation of a slurry wall combined with a pumping trench in the vicinity of well HG-28S (see Figure 4.2).

The effect of remedial actions was modeled as follows:

• For the slurry wall configuration, the effect of containment of the source area on the downgradient plume was simulated using the source removal term. An artificially high first-order

decay rate coefficient was used to remove 99% of the source mass from within the contained concentrated plume in one simulation time-step.

- Pumping wells cannot be directly simulated in REMChlor; hence, the effect of contaminant mass removal associated with the pumping systems was modeled by specifying an exponential mass decay rate in the area of the potential pumping systems. The decay rates for the two potential pumping systems were estimated using an iterative calculation procedure for estimating the temporal decline in contaminant mass removal rates. As part of this procedure, the total 3,4-methylphenol mass within the region of influence of the pumping system was estimated and the average groundwater concentration within this zone was calculated (see Attachment H-1). The pumping rate of the potential system and the mass removed were then computed using an incremental time-step. The mass remaining was calculated by subtracting the mass removed by the pumping system from the total mass accessible to the system.
 - For the well point system, the radius of influence of the system and mass removal efficacy were calculated, as discussed in Attachment H-1. An equivalent decay half life was calculated by fitting an exponential decay curve to the mass removal estimates for the well point system. The system was modeled in REMChlor by applying the decay rate from the downgradient edge of the slurry wall to one radius of influence downgradient of the well point system.
 - For the pumping trench, the radius of influence of the trench and mass removal efficacy were determined, as discussed in Attachment H-1. An equivalent decay half life was calculated by fitting an exponential decay curve to the mass removal estimates for the pumping trench. The trench was modeled in REMChlor by applying the decay rate from the downgradient edge of the slurry wall to one radius of influence downgradient of the pumping trench.

The parameters modified from the calibrated model for each scenario are given in Tables H.3 through H.5.

The evolution of the centerline profile of the plume over the long-term (*i.e.*, 100 years) for the no-action scenario and the three containment-based remedial alternatives are presented in Figures H.7 through H.10. The no-action scenario (Figure H.7) shows that plume migration is extremely slow, and that with no remedial action, a continuous plume is expected to stretch outward from the source area to hundreds of meters downgradient in future decades. For this scenario, the model predicts that the leading edge of the plume exceeding the updated GCTL of 640 ug/L for 3.4-methylphenol would reach the Superfund Site boundary, just east of monitoring well HG-36S, in approximately 100 years. Figure H.8 shows that a slurry wall will effectively limit the extent of the plume by containing most of the mass within its footprint and eliminating contaminant mass flux from the contained area to the downgradient plume. The slurry wall also reduces the plume longevity, relative to the no action scenario, because it captures the most concentrated portion of the contaminant plume. The operation of a well point system outside the slurry wall for 10 years (Figure H.9) effectively reduces peak concentrations by about 50% relative to the slurry wall with MNA scenario (Figure H.8). In comparison, the operation of the pumping trench for 5 years (Figure H.10) effectively reduces the peak concentration outside the slurry wall by more than 70% relative to the slurry wall with MNA scenario. However, the observed mass removal and corresponding decrease in contaminant concentration is limited to the portion of the plume that is accessible to the pumping system, *i.e.*, in the vicinity of HG-28S. The observed concentrations in the leading edge of the plume (*i.e.*, beyond HG-28S) are unaffected by any of the modeled scenarios, since this portion of the plume has already migrated beneath the auto dealership building and is inaccessible to any remedial system.

The effect of the biodegradation rate on downgradient plume evolution was evaluated for each of the remedial alternatives. The biodegradation rate in the model (half-life of 20 years) was based on achieving good matches between modeled and measured concentrations during model calibration, and is conservatively low relative to literature values for anaerobic degradation of 3,4-methylphenol (Syracuse Research Corp., 1997).² The difference in UHG chemistry (*e.g.*, lower COC concentrations and more neutral pH; Tables 3.5 and 3.6) in the downgradient or far-field area of the plume (*i.e.*, downgradient of HG-28) in comparison to the more concentrated portion of the plume that would be contained suggest that conditions may be more amenable to the anaerobic biodegradation of pine tar constituents in the far-field portion of the plume. Thus, the sensitivity of long-term concentrations at the Superfund Site boundary to the biodegradation decay rate was evaluated by increasing the 3,4-methylphenol decay rate in this far-field portion of the plume to the lower end of the range of values reported in the literature (*i.e.*, decay rate of 0.00029/day or a half life of 7-years). Under these conditions, the model-predicted concentration for 3,4-methylphenol at the Superfund Site boundary is less than 640 µg/L for all of the modeled scenarios (Figures H.11 through H.13).

H.2.3 Conclusions

A conservative, well-calibrated analytical model of 3,4-methylphenol source material and downgradient plume evolution was developed to guide remedial decision-making. The results indicate that containment can significantly mitigate the extent of the downgradient plume, and that targeted groundwater pumping for relatively short time periods (5 to 10 years) downgradient of the slurry wall can reduce plume longevity. Modeling predictions indicate that the installation of the slurry wall in combination with MNA of the downgradient plume will reduce 3,4-methylphenol concentrations to below 640 μ g/L at the Superfund Site boundary using the lower-bound literature-reported decay rate value in the far-field portion of the plume. Modeling predictions also show that the magnitude and longevity of the plume can be further reduced through the operation of a pump and treat system (*via* either multiple pumping wells or a pumping trench) in the vicinity of highest observed concentrations downgradient of the containment system.

² Literature values for anaerobic biodegradation of 3,4-methylphenol range from 0.00029/day (half-life of 7 years) to 0.033/day (half-life of 21 days; Syracuse Research Corp., 1997).

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Tables

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REMChlor Input Parameter	Value	Source/Explanation	
Source Parameters			
Concentration (g/L)	0.6834	Site-specific effective solubility of 3,4-methylphenol	
Mass (kg)	9,000	Calibrated parameter; consistent with estimated values of plume mass	
Mass (lb)	19,845		
Gamma (-)	2	Recommended value for older sites (Falta et al., 2007)	
Time of source origin	1950	Assumed that release occurred shortly after the former Cabot lagoons were	
		constructed	
Source Dimensions			
Source Width (m)	110	Approximate width of the central and eastern lagoon projected into the	
		groundwater flow direction (see Figure H.1)	
Source Depth (m)	9.14	Approximate thickness of the UHG (30 ft)	
Hydraulic conductivity (cm/s)	$2.3 \cdot 10^{-4}$	Geometric mean of estimated hydraulic conductivities from Site purge logs	
		(method from Robbins <i>et al</i> ., 2009)	
Hydraulic gradient (-)	0.01	Average hydraulic gradient in the UHG (Gradient, 2012)	
Porewater Velocity (m/yr)	3.6	Calculated from Darcy velocity and effective porosity.	
Darcy Velocity (m/yr)	0.725	Calculated from hydraulic conductivity and gradient	
Effective Porosity (-)	0.2	Calibrated parameter; approximately consistent with previous Site models	
		(WHI, 2005)	
Source Remediation			
Fraction removed (-)	0	No source material removed in calibrated model	
Source Decay (1/yr)	0	No source decay other than mass dissolution was assumed	
Transport Parameters			
Sorption coefficient, K _{oc} (L/kg)	300	US EPA (2015)	
Fraction organic carbon, f _{oc} (%)	0.048	Minimum f_{oc} measurement recorded in the UHG (see Table 3.3)	
Bulk density (g/cm ³)	1.4	Professional judgment; based on the soil in the UHG	
Retardation factor (-)	2	Calculated from effective porosity (n _e), sorption coefficient (K _{oc}), fraction	
		organic carbon (f_{oc}), and bulk density (ρ_b): 1 + $\rho_b K_{oc} f_{oc} / n_e$	
Sigma v (-)	0.2	Calibrated parameter, equivalent to a longitudinal dispersivity of travel	
		distance divided by 50	
v Min (-)	0.2	Set equal to 2 - v Max, as recommended in Falta et al. (2007)	
v_Max (-)	1.8	Set equal to 1 + 4*Sigma v, as recommended in Falta et al. (2007)	
alpha_y (m)	0.3	Equal to about 1/10 th the longitudinal dispersivity value	
alpha_z (m)	0.03	Equal to 1/10 th the transverse dispersivity value	
Decay			
Background decay half-life (yr)	19.8	Calibrated parameter; conservative for anaerobic conditions (Syracuse	
		Research Corp., 1997)	

Table H.1 Model Calibration Assumptions, Inputs, and Sources

Well Location	Target Concentration		
	(µg/L)		
HG-29S	35,000		
WS-17	21,000		
HG-28S	50,000		
WS-27	700		
WS-19	17,000		
WS-18	9.5		
WS-20	260		

Table H.2 Calibration Wells andTarget Concentrations

Notes:

Temporary well target concentrations were based on data from the mid-UHG (40-50 ft bgs) (Table 3.5).

Permanent monitoring well target

concentrations were the average of

detections from 2011-2014 (Table 3.5), with the exception of a 2011 sample at HG-29S that was biased low due to a well cap leak.

REMChlor Input Parameter Val		Source/Explanation
Source Remediation		
Fraction removed (-)	0.99	Conservatively assumed slurry wall was effective at containing 99% of the
		remaining source mass
Start time (yr)	66	Assume slurry wall construction initiated in 2016
End time (yr)	68	Assume slurry wall construction completed in 2018
Source decay (1/yr)	0	No source decay other than mass dissolution was assumed
Decay		
Background decay half-life (yr)	19.8	Calibrated parameter; conservative for anaerobic conditions (Syracuse
		Research Corp., 1997)
Slurry wall extent distance from	107.5	Distance from edge of lagoons to NE 28 th Pl.
source (m)		
Simulated decay begins	2017	Assume decay occurs rapidly to mimic slurry wall containment
Simulated decay ends	2018	Assume slurry wall construction completed in 2018
Decay half-life to simulate mass	5	High decay rate used to rapidly remove mass from model to simulate
containment (d)		containment effects on downgradient plume

Table H.3 Slurry Wall + MNA Key Assumptions and Input Modifications

REMChlor Input Parameter	Value	Source/Explanation	
Source Remediation			
Fraction removed (-)	0.99	Conservatively assumed slurry wall was effective at containing 99% of the	
		remaining source mass	
Start time (yr)	66	Assume slurry wall construction initiated in 2016	
End time (yr)	68	Assume slurry wall construction completed in 2018	
Source decay (1/yr)	0	No source decay other than mass dissolution was assumed	
Decay			
Background decay half-life (yr)	19.8	Calibrated parameter; conservative for anaerobic conditions (Syracuse	
		Research Corp., 1997)	
Slurry wall extent distance from	107.5	Distance from edge of lagoons to NE 28 th Pl.	
source (m)			
Downgradient limit of well	138	One system radius of influence (8 m) downgradient of HG-28S.	
system influence			
Simulated decay begins	2017	Assume decay occurs rapidly to mimic large slurry wall containment.	
Simulated decay ends	2027	Assume wells pump for 10 years.	
Decay half-life to simulate	2	Calculated by fitting an exponential decay coefficient to the mass removal	
pumping well effects (yr)		estimates for a well point system pumping at 2.5 gpm.	
Decay half-life to simulate mass	37	High decay rate used to rapidly remove mass from model to simulate	
containment (d)		containment effects on downgradient plume	

Table H.4 Slurry Wall + Well Point System Key Assumptions and Input Modifications

REMChlor Input Parameter	Value	Source/Explanation	
Source Remediation			
Fraction removed (-)	0.99	Conservatively assumed slurry wall was effective at containing 99% of the	
		remaining source mass	
Start time (yr)	66	Assume slurry wall construction initiated in 2016	
End time (yr)	68	Assume slurry wall construction completed in 2018	
Source decay (1/yr)	0	No source decay other than mass dissolution was assumed	
Decay			
Background decay half-life (yr)	19.8	Calibrated parameter; conservative for anaerobic conditions (Syracuse	
		Research Corp., 1997)	
Slurry wall extent distance from	107.5	Distance from edge of lagoons to NE 28 th Pl.	
source (m)			
Trench length (m)	61	Assumed parameter (200 ft); to be refined in pre-remedy design.	
Downgradient limit of trench	146	One pumping trench radius of influence (26 m) downgradient of the trench	
influence (m)		center (see Figure 4.2).	
Simulated decay begins	2017	Assume decay occurs rapidly to mimic slurry wall containment.	
Simulated decay ends	2022	Assume trench pumping for 5 years.	
Decay half-life to simulate	0.9	Calculated by fitting an exponential decay coefficient to the mass removal	
pumping trench effects (yr)		estimates.	
Decay half-life to simulate mass	37	High decay rate used to rapidly remove mass from model to simulate	
containment (d)		containment effects on downgradient plume	

Table H.5 Slurry Wall + Pumping Trench Key Assumptions and Input Modifications

Figures

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Well Location	Target Concentration (µg/L)			1		
HG-295	35,000					
WS-17	21,000		March Stephen ve	- Contraction		Real and a second
HG-28S	50,000					
WS-27	700	Contraction of the		The land	สารบาทเสียบการการการการการการการการการการการการการก	G
WS-19	17,000	1 2 2 2 2 2		5 E	al marken to all	
WS-18	9.5		and a set of the fact	1.50		
WS-20	260	Same - All	AN A STATE	E		
			AL D		WS-18:	HG-37S:
Lend C .	SIE					
一種			• WS-19: 22,000	HG-28S: 49,000 •		
			HG-29S: 34,000	WS-17: 57,000	WS 97	S-20: 0
				•	WS-27: 70	
			1000	L'UNITED OF		





Figure H.2 3,4-Methylphenol Plume Calibrated Centerline Profile. (1) Temporary well target concentrations were based on data from the mid-UHG (40-50 ft bgs) (Table 3.5). (2) Permanent monitoring well target concentrations were the average of detections from 2011-2014 (Table 3.5), with the exception of a 2011 sample at HG-29S that was biased low due to a well cap leak.



Figure H.3 3,4-Methylphenol Calibration. (1) Temporary well target concentrations were based on data from the mid-UHG (40-50 ft bgs) (Table 3.5). (2) Permanent monitoring well target concentrations were the average of detections from 2011-2014 (Table 3.5), with the exception of a 2011 sample at HG-29S that was biased low due to a well cap leak.



Figure H.4 3,4-Methylphenol: Modeled and Measured Trends at HG-28S. SVOC analyses from April 2014 were of poor quality, leading to resampling in June 2014. April 2014 data are not shown.



Figure H.5 3,4-Methylphenol Plume Calibrated Centerline Profile Sensitivity Analysis. (1) Temporary well target concentrations were based on data from the mid-UHG (40-50 ft bgs) (Table 3.5). (2) Permanent monitoring well target concentrations were the average of detections from 2011-2014 (Table 3.5), with the exception of a 2011 sample at HG-29S that was biased low due to a well cap leak.



Figure H.6 3,4-Methylphenol Plume Alternative Calibrated Centerline Profile. (1) Temporary well target concentrations were based on data from the mid-UHG (40-50 ft bgs) (Table 3.5). (2) Permanent monitoring well target concentrations were the average of detections from 2011-2014 (Table 3.5), with the exception of a 2011 sample at HG-29S that was biased low due to a well cap leak.



Distance Along Plume Centerline, Starting from the Former Lagoons (m)





Figure H.8 3,4-Methylphenol Plume Evolution – Slurry Wall + MNA



Figure H.9 3,4-Methylphenol Plume Evolution – Slurry Wall + Well Point System. Well point pumping system rate assumed to be equal to 2.5 gpm.



Figure H.10 3,4-Methylphenol Plume Evolution – Slurry Wall + Pumping Trench. Pumping trench pumping rate assumed to be equal to 7.5 gpm.



Figure H.11 3,4-Methylphenol Plume Evolution – Slurry Wall + MNA, Higher Far-Field Decay Rate. 3,4-methylphenol half-life set equal to 7 years starting halfway between HG-28S and HG-37S.



Figure H.12 3,4-Methylphenol Plume Evolution – Slurry Wall + Well Point System, Higher Far-Field Decay Rate. 3,4-methylphenol half-life set equal to 7 years starting at the downgradient end of the region influenced by the pumping system (138 m), beginning after pumping completed (2026).



Figure H.13 3,4-Methylphenol Plume Evolution – Slurry Wall + Pumping Trench, Higher Far-Field Decay Rate. 3,4-methylphenol half-life set equal to 7 years starting at the downgradient end of the region influenced by the pumping system (146 m), beginning after pumping completed (2021). All concentrations in the 100-year plume were below $100 \mu g/L$.

AH.1 Mass Removal Estimates

AH.1.1 Mass Estimation

The dissolved mass within a given zone of interest for the two pumping systems was estimated using the plume contour map for 3,4-methylphenol presented in Figure 3.9, using the average of the lower and upper bounds of each contour interval as a representative concentration for that area.¹ The average concentration, interval area, average thickness, and effective porosity of the UHG were used to determine the total dissolved mass. The total mass (dissolved and sorbed) was calculated by multiplying the dissolved mass by the retardation factor for 3,4-methylphenol. The zone of influence for each pumping system was assumed to be an area extending from the downgradient edge of the slurry wall to one radius of influence downgradient² of the pumping system (Figure 4.2).

AH.1.2 Radius of Influence Calculation

The radius of influence was calculated for the well point pumping system using the analytical formulation for radial flow to a well from Muskat (1937):

$$Q = \frac{2\pi L K H}{ln \left(\frac{R_e}{R}\right)}$$
(Eqn. 1)

where Q is the volumetric flow rate into the well, L is the length of the screened interval, K is the hydraulic conductivity of the aquifer surrounding the well, H is the drawdown at the well, R_e is the radius of influence of the well, and R is the radius of the well. Using a Site-specific value for the hydraulic conductivity and design assumptions for the flow rate, length of screened interval, drawdown, and radius of the pumping system, the radius of influence was computed. Data from low flow sampling events that were conducted between 2011 and 2015 were used to estimate the Site-specific hydraulic conductivity values using the method outlined in Robbins *et al.* (2009) (Table AH.1). The values used for the radius of influence calculation are provided in Table AH.2. The downgradient capture zone of the trench system was assumed to be approximately three times the radius of influence of the well point system as a simplifying assumption to facilitate the modeling.¹ Pumping rates were assumed for the two pumping configurations based on the reasonableness of the values for the radius of influence of each system. These estimated pumping rates and capture zones will be refined based on additional data collection and analyses to be undertaken as part of the design, including a pump test and numerical groundwater flow modeling. The two pumping systems were assumed to operate until mass removal rates reached an asymptote, which occurred at 5 years for the pumping trench and at 10 years for the well point system.

 $^{^1}$ For the highest contour interval, 70,000 $\mu\text{g/L}$ was used as the upper-bound concentration.

 $^{^{2}}$ The definition of the capture zone of a pumping system can require detailed analysis (see US EPA, 2008) and will be refined as part of a pre-design investigation.

Aquifer	Well ID	Date	Screen Interval (ft)	Steady State Drawdown (ft)	Intake Hole Diameter (cm)	Steady State Discharge (L/min)	Calculated K – Half Ellipsoid (cm/s)	Calculated K — Half Ellipsoid (ft/day)
SA	SA-29	3/22/2012	5	0.27	5.08	0.26	2.68E-03	7.61
	SA-29	4/23/2013	5	0.14	5.08	0.10	1.95E-03	5.54
	SA-30	11/15/2011	5	1.12	5.08	0.42	1.02E-03	2.88
	SA-30	4/25/2013	5	0.45	5.08	0.15	9.11E-04	2.58
	SA-31	3/21/2012	5	0.1	5.08	0.38	1.04E-02	29.3
	SA-32	3/21/2012	5	0.2	5.08	2.84	3.88E-02	110
	SA-33	3/21/2012	5	0.6	5.08	0.30	1.38E-03	3.91
	SA-33	4/23/2013	5	0.6	5.08	0.10	4.56E-04	1.29
UHG	HG-26S	11/18/2011	10	2.24	5.08	0.30	2.12E-04	0.60
	HG-28S	11/17/2011	10	5.1	5.08	0.11	3.49E-05	0.10
	HG-28S	3/29/2012	10	5.65	5.08	0.30	8.39E-05	0.24
	HG-29S	3/27/2012	10	3.8	5.08	1.14	4.68E-04	1.33
	HG-30S	11/19/2011	10	0.72	5.08	0.15	3.29E-04	0.93
	HG-30S	3/27/2012	10	8.48	5.08	0.42	7.69E-05	0.22
	HG-30S	3/29/2012	10	1.6	5.08	0.15	1.48E-04	0.42
	HG-30S	11/16/2011	10	0.72	5.08	0.15	3.29E-04	0.93
	HG-36S	5/21/2015	10	22.65	5.08	4.54	3.14E-04	0.89
	HG-37S	5/12/2015	10	23.43	5.08	2.27	1.52E-04	0.43
	HG-37S	5/13/2015	10	23.43	5.08	3.03	2.02E-04	0.57
	HG-38S	5/13/2015	10	0.35	5.08	0.11	5.08E-04	1.44
	HG-38S	5/5/2015	10	6.07	5.08	4.54	1.17E-03	3.32
	HG-38S	5/6/2015	10	12.64	5.08	2.42	3.00E-04	0.85
	HG-38S	5/6/2015	10	12.64	5.08	2.27	2.81E-04	0.80
	HG-38S	5/7/2015	10	14.62	5.08	2.27	2.43E-04	0.69
LHG	HG-30D	11/16/2011	10	1.73	5.08	0.19	1.71E-04	0.49
	HG-30D	3/26/2012	10	0.9	5.08	7.57	1.32E-02	37.3
	HG-36D	5/22/2015	10	1.1	5.08	3.79	5.39E-03	15.3
	HG-37D	5/18/2015	10	8.27	5.08	1.89	3.58E-04	1.02
	HG-38D	5/14/2015	10	2.2	5.08	0.95	6.73E-04	1.91
	HG-38D	5/11/2015	10	9.19	5.08	5.68	9.67E-04	2.74

Table AH1.1 Hydraulic Conductivity Calculations^a

Notes:

SA = Surficial Aquifer; UHG = Upper Hawthorn Group; LHG = Lower Hawthorn Group.

Hydraulic conductivity was calculated from the purge rate data using the following equation:

$$Q = \frac{2\pi L K H}{2.303 \log \left[\frac{L}{R} + \sqrt{1 + \left(\frac{L}{R}\right)^2}\right]}$$

where Q = Steady-State Flow Rate; L = Intake Length; K = Hydraulic Conductivity; H = Steady-State Drawdown; and R = Intake Radius.

(a) Calculated using the methods outlined in Robbins et al. (2009).

Parameter	Value for Well Point System ^a	Value for Pumping Trench
Pumping rate (gpm)	2.5/3	7.5
Length of screened interval (ft)	10	30
Hydraulic conductivity (cm/s)	2.3 × 10 ⁻⁴	2.3×10^{-4}
Drawdown (ft)	20	20
Well Radius (in)	2	NA
Radius of Influence (m)	8.4	25.7

Table AH.2 Radius of Influence Calculations

Notes:

NA = Not Applicable.

(a) It is assumed that three wells will be utilized, with a combined sustainable yield of 2.5 gpm.

AH.1.3 Containment Area Mass Removal Estimates

Mass removal from within the containment area was calculated similarly to the mass removal rates for the downgradient pumping systems. The initial total and dissolved mass contained within the slurry wall was determined by applying the mass estimation technique described in Section AH.1.1 to the extent of the containment area shown on Figure 4.2. The lower and upper bounds of each contour interval were averaged to determine a representative concentration for each enclosed interval.³ The average concentration of each interval, the interval area (square footage), the average thickness, and the effective porosity of the mid-UHG and base-UHG were used to determine the total dissolved mass. The dissolved mass of 3,4-methylphenol contained by the slurry wall was calculated to be approximately 2,300 lbs. The total mass (dissolved and sorbed) was then calculated by multiplying the dissolved mass by the retardation factor for 3,4-methylphenol. Note that the total mass estimate does not account for the potential presence of NAPL. Using the 3,4-methylphenol retardation factor of 2 from Table H.1, it was estimated that approximately 4,600 lbs of total (dissolved and sorbed) 3,4-methylphenol mass are A total phenolics (including phenol and 3.4-methylphenol) to contained by the slurry wall. 3,4-methylphenol ratio of 2.1, based on data from HG-29S, was used to scale the 3,4-methylphenol mass to an equivalent total phenolics mass of 9,700 lbs.

An initial average dissolved 3,4-methylphenol concentration of 26,000 μ g/L for the containment area was computed by dividing the dissolved mass by the total volume of groundwater within the extent of the containment area. The initial mass and initial average concentration were used as the starting conditions for the mass removal model.

The mass removed by pumping was calculated using the pumping rate and the average dissolved concentration over an incremental time-step. A time-step of 3-4 months was used in the model. In the 2 gpm pumping scenario, for example, the mass removed in the first incremental time-step was computed by multiplying the pumping rate (2 gpm), the time-step (0.3 yr), and the initial average concentration (about 26,000 μ g/L). Note, the calculations assume idealized operational conditions for the pumping system (*e.g.*, complete mixing within the containment area) and do not account for the potential presence of NAPL or matrix diffusion effects in the UHG. The mass removed by pumping was subtracted from the initial total mass (*i.e.*, partitioning between sorbed and dissolved phases was assumed). The new total mass was used to compute a dissolved mass and a new average concentration. This process was iterated until the time-step reached 30 yrs, when the mass removed by pumping at 2 gpm was 7,560 lbs and the mass removed by pumping at 4 gpm was 9,300 lbs; the mass removed by pumping within the slurry wall is plotted in Figure 4.4.

 $^{^3}$ For the highest contour interval, 70,000 µg/L was used as the upper-bound concentration.