

Groundwater Modeling in Support of Remedial Process Optimization: Implementing a Developing Conceptual Site Model into Comparative Remedy Analyses – 10319.

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ABSTRACT

In recent months remediation activities at Hanford 100 Area sites – located along the shores of the Columbia River near Richland, Washington – have accelerated in order to protect aquatic species from discharges of hexavalent chromium (CrVI). These activities have focused on expanding existing groundwater pump-and-treat remedies, together with pilot-testing complementary in situ technologies. Comparative analyses of remedial alternatives within the context of remedial process optimization led by CH2M HILL Plateau Remediation Company (CHPRC) employed groundwater flow, particle tracking, and transport modeling using MODFLOW, MODPATH, and MT3DMS, respectively. As the conceptual site models for each of the groundwater operable units have developed, so too has the representation of the key features and processes within the numerical model. Herein the initial model construction and calibration are described and then the stepwise integration of several features and processes are presented, including multi-scale hydraulic conductivity heterogeneity and dual-domain transport of CrVI. Finally, examples of graphics constructed to communicate data and results to stakeholders and decision makers are presented.

INTRODUCTION

CHPRC is currently operating five groundwater pump-and-treat systems across the 100 Areas of the Hanford Site, which include two systems to treat Cr(VI) in the 100-HR-3 Operable Unit (OU); two systems to treat Cr(VI) in the 100-KR-4 OU; and the 100-NR-2 system, which treats strontium-90 and is in cold-standby status.

The interim remedial actions chosen for the 100-HR-3 and 100-KR-4 OUs are pump-and-treat systems that use an ion-exchange (IX) medium for contaminant removal. The systems were designed to achieve three remedial action objectives (RAOs), as well as specific operational and aquifer performance criteria described in the interim remedial action Record of Decision (ROD), Declaration of the Record of Decision for the 100-HR-3 and 100-KR-4 Operable Units at the Hanford Site (Interim Remedial Actions) [5]. The three RAOs are identified as follows:

- RAO #1: Protect aquatic receptors in the river bottom substrate from contaminants in groundwater entering the Columbia River.
- RAO #2: Protect human health by preventing exposure to contaminants in the groundwater.
- RAO #3: Provide information that will lead to a final remedy.

In recent months, remedial process optimization efforts have focused on the expansion of the remedial systems in order to achieve these RAOs within specified timeframes [16]. The primary objectives for the remedial process optimization design are: (a) to prevent the discharge of Cr(VI) to the Columbia River substrate at concentrations exceeding those considered protective of aquatic life in the river and riverbed

sediments by the year 2012; and (b) aquifer restoration by attaining target cleanup levels in the by the year 2020. The objectives related to achieving river protection by 2012 and target cleanup levels by 2020 will be met, at a minimum, by pumping groundwater from existing and proposed extraction wells located within and around the contaminated areas and removing Cr(VI) from the groundwater by treatment at an ex situ facility.

Groundwater flow and contaminant transport modeling was performed to support the calculation of appropriate pumping rates for injection and extraction wells to achieve the remedial process optimization objectives. Groundwater flow models have been used at the 100-K, 100-N, 100-D, and 100-H Areas to support design of pump-and-treat interim remedies and to evaluate the performance of the pump-and-treat systems. These groundwater flow models were constructed to simulate patterns of groundwater flow and other hydraulic features local to each operable unit (OU) and, as such, the domains of these models were of limited spatial extent. Because the size and influence of the various 100 Area groundwater pump-and-treat remedies have increased over time, recent efforts have focused on developing a single groundwater flow model that encompasses the various pump-and-treat remedies and that can be used to support decisions at each of the 100-K, 100-N, 100-D, and 100-H Areas.

The groundwater flow model was developed to simulate the operations of the current pump-and-treat systems at the OUs. Model development was based on various sources of information including the Model Data Package [15] developed for that reason by CHPRC for each OU. The model was calibrated using continuous water level data from monitoring wells in the 100-K, 100-D, and 100-H Areas during calendar year 2008 (CY2008). Particle tracking was implemented to develop capture efficiency maps as a means to evaluate system performance by estimating hydraulic capture extent under transient conditions. A contaminant transport model was then developed to simulate the temporal and spatial migration of Cr(VI) at the 100 Areas, based on a dual-domain approach that describes advective transport in the mobile domain and mass-transfer between the immobile and mobile domain. The model timeframe was then extended to facilitate comparative predictive simulations for the evaluation of various remedial alternatives for each OU.

MODEL DEVELOPMENT AND CALIBRATION

Simulation Codes

The groundwater flow model is constructed using the U.S. Geological Survey (USGS) three-dimensional modular groundwater flow model, MODFLOW [7]. The MODFLOW code was selected because it has the necessary simulation capabilities, is relatively simple to use, and can be executed on a variety of computers and operating systems without modification. The USGS program MODPATH [12] is a particle-tracking, post-processing program developed for MODFLOW. MODPATH was used to evaluate the approximate directions of groundwater flow and the approximate extent of hydraulic capture developed by current and proposed pump-and-treat configurations. MT3DMS [17] is the second generation of the modular, three-dimensional transport model MT3D with significantly expanded capabilities. It was used to simulate the contaminant plume migration under advective conditions, and MT3DMS Version 5.2b was used in this work. PEST [4] was used to assist in the groundwater flow model calibration. PEST is an advanced software package for model calibration, parameter estimation, and predictive uncertainty analysis.

Groundwater Flow Model Structure

The model grid encompasses the 100-K, 100-D, and 100-H OUs. The 100-HR-3 OU encompasses the 100-D and 100-H Areas, which are treated as a single groundwater OU for the purposes of the remedy design and remedial process optimization activities. The model finite-difference grid is rotated 50 degrees from east, so the northwest and northeast boundaries of the flow model parallel and are next to the Columbia River. The model extends southward, toward Gable Butte and Gable Mountain. The model

grid spacing is relatively coarse (about 50 m) throughout much of the model domain, but it is refined (about 12 m) in the area of the 100-K, 100-D, and 100-H Areas in support of remedy evaluations. The model grid is shown in Figure 1.

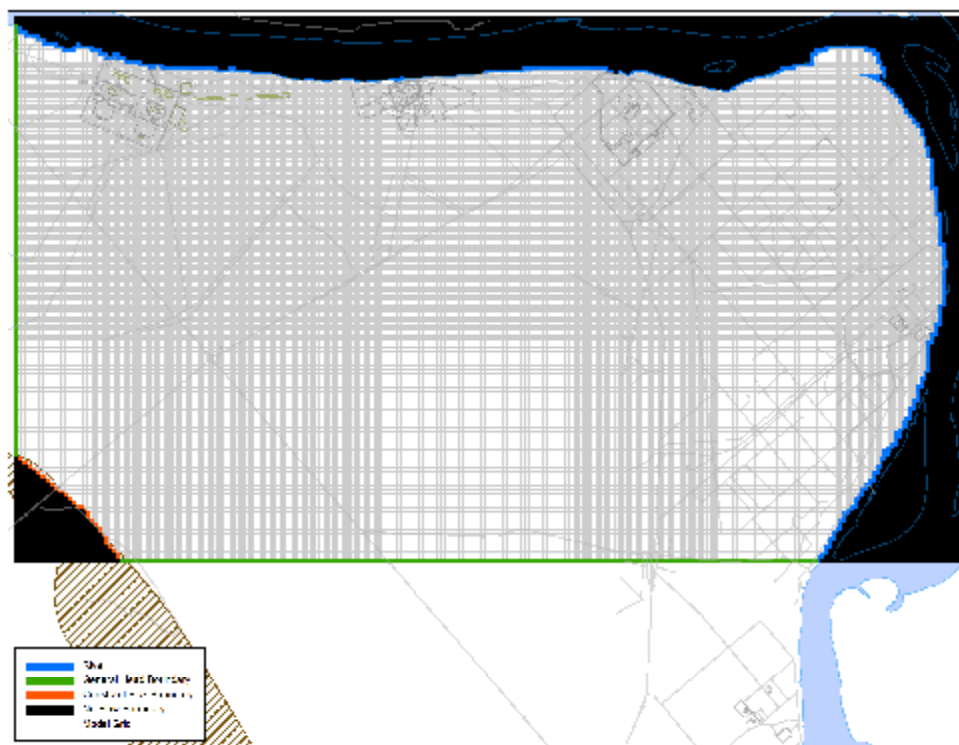


Fig. 1. Model Grid, Distribution of Active and Inactive Cells, and Boundary Conditions.

At the present time, groundwater flow is simulated as two-dimensional using one layer. The base of the model is assumed to be the top of the Ringold Upper Mud (RUM) Unit where present and the top of the basalt where the RUM is absent. This typically occurs in the southern portions of the model approaching Gable Butte. A single model layer is used because the majority of the extraction wells penetrate most of the saturated thickness of the aquifer materials lying above the RUM. Throughout much of the western half of the modeled area (including 100-KR-4 and 100-HR-3), the water table lies within the Ringold Unit E sands, whereas toward the east and north of the modeled area, the water table lies within the Hanford formation sands and gravels. The lateral transition between these areas is reasonably abrupt. The assumption of two-dimensional flow is also supported by the large horizontal-to-vertical dimension ratio throughout the model domain and the small saturated thickness in the areas of interest.

The calculation for the model bottom elevation (representing the top of the RUM, or the top of the basalt where the RUM is absent) was based on information from (1) digitized elevation contours near the 100-KR-4 OU; (2) digitized elevation contours for 100-HR-3 as presented in the 100-HR-3 Remedial Process Optimization Model Data Package [15]; and (3) point-data for the RUM top elevation, in electronic form and hardcopy. Additional available information, including well logs from several wells within the 100 Areas, was not considered in this analysis because it refers to wells drilled more than three decades ago, and the absence of detailed documentation of the geologic description of the sediments prevents a reliable geologic interpretation.

The model simulates transient-state (i.e., time-varying) conditions in the aquifer that reflect water-level changes due to river-stage variations over time. The modeling timeframe corresponds to a 2-year period, consisting of monthly stress periods and three time steps per stress period, repeated in the same sequence over the model time horizon. The stress periods correspond to monthly average river stages, representing

the time-varying river stage for the period of January 1, 2008, through December 31, 2008 (CY2008). It is assumed that these conditions are representative of the typical conditions in the field and that future conditions will not vary significantly. All other model inputs are assumed to be constant over time.

Figure 1 illustrates the distribution of active and inactive cells in the 100 Areas MODFLOW model. In general, the inactive cells are located beyond the shores of the Columbia River that form the lateral extents of the model to the northwest and northeast, and also in the area of Gable Butte to the south. Figure 1 also illustrates the lateral boundaries specified for the 100 Areas MODFLOW model:

- Along the northwest and northeast boundaries of the model, the river package is used to represent the flow of water to and from the Columbia River. The river stage specified for the river package was calculated using river-stage data for CY2008, as included in Hanford Environmental Information System database. The riverbed conductance was estimated through the model calibration process.
- Along the southwest and southeast boundaries of the model, the general head boundary package is used to represent the flow of groundwater into and out of the model domain through the aquifer. The head specified for the general head boundary package was calculated on the basis of a map of Sitewide groundwater elevations provided by Pacific Northwest National Laboratory (PNNL) representing average water-level conditions. The hydraulic conductance along the boundary was determined through the model calibration process.
- Along the model south boundary next to Gable Mountain, the well package is used to represent specified fluxes, reflecting limited aquifer recharge in the unconfined aquifer from the sub-cropping basalt.

Parameter Values - Model Calibration

As part of the modeling effort in support of the evaluation of remedy alternatives, the groundwater flow model was calibrated to data included in the model data package. In particular, values for some of the boundary conditions and aquifer parameters were estimated through a combined manual and automated calibration process.

The model calibration process was facilitated by the use of PEST and post-processing programs that were developed to calculate water-level response to stresses. The model was calibrated to data from throughout CY2008. No formal calibration statistics were calculated to determine the goodness of fit of the model results to the measured data. The model calibration process was focused on the transient response of water levels to changing stresses and how they compared to the measured values at all the locations if continuous data were available at the 100-K, 100-D, and 100-H Areas. In addition, maps of water-level contours calculated by the model were compared to contours included in published reports to ensure that the simulated hydraulic gradient magnitude and direction in those areas is in agreement with measured values.

The principal aquifer property that is specified in the model is the spatially varying hydraulic conductivity of the saturated aquifer materials. The transmissivity that is calculated when this hydraulic conductivity is multiplied by the model's calculated saturated thickness should correspond with independent sources of information. The hydraulic conductivity distribution in the model was developed based on the information included in the model data package. The following stepwise approach was used to construct a spatially varying hydraulic conductivity distribution for the 100 Areas groundwater flow model:

1. The geologic characterization compiled as part of the model data package depicts the lateral transition from the Ringold Unit E in the west and south of the model domain, to the Hanford formation sands and gravels in the east and north of the model domain. The secondary separation of zones within Ringold Unit E reflects the difference in measured hydraulic conductivity values between the 100-K and 100-N Areas and the 100-D Area. This geologic characterization was used to define three independent areas for evaluating aquifer properties, on the assumption that the mean

and standard deviation should be expected to be relatively constant within each of these areas and to differ between each of the areas.

2. Estimates of hydraulic conductivity compiled as part of the model data package were tabulated and assigned to their corresponding aquifer unit (i.e., Ringold Unit E east of the 100-N Area, Ringold Unit E west and south of the 100-D Area and east of the 100-N Area, and the Hanford formation sands and gravels to the east and north). When multiple hydraulic conductivity estimates were available for the same location, the average value of those estimates was used.
3. A spherical variogram was defined for each of these three areas. Because the aquifer testing data are relatively local to each of the OUs while at some distance from each OU, aquifer testing data are limited. The following approach was used to define the three variables of the variogram:
 1. Nugget (near-field [semi-]variance): Estimated using test data where estimates of hydraulic conductivity were available from two or more co-located aquifer tests:
 - i. If the co-located estimates were similar, the (semi-)variance was estimated directly from these measurements.
 - ii. If the co-located estimates were wide-ranging, the (semi-)variance was estimated by assuming that the upper and lower bounds represent upper and lower 95th confidence levels on the mean, such that their difference represents 4 standard deviations, from which a (semi-)variance could be determined.
 2. Sill (total [semi-]variance): Estimated directly as the (semi-)variance of the data.
 3. Range (correlation length): Estimated visually by plotting the empirical variogram.
4. Simple kriging was used to interpolate the measured values within each of the three areas independently, and the resulting hydraulic conductivity fields within the Ringold Unit E and Hanford formation sands and gravels were merged along the transition zones using a smooth, local averaging interpolation scheme.

The initial mean values for the aquifer hydraulic conductivity within the two regions of the Ringold Unit E and the Hanford formation sands and gravels, respectively, required for simple kriging were estimated directly from the aquifer test data. These values were then updated through the calibration process. This approach provides a hydraulic conductivity field that respects the geologic structure described in the model data package, generally respects the existing aquifer test data, and results in area-wide hydraulic properties to calibrate the groundwater flow model.

The mean values for the aquifer hydraulic conductivity that resulted from the model calibration process are as follows:

- 7 m/day for Ringold Unit E in the 100-K and 100-N Area region of the aquifer.
- 18 m/day for Ringold Unit E in the 100-D Area region of the aquifer.
- 50 m/day for the Hanford formation.

The resulting hydraulic conductivity distribution across the model domain is shown in Figure 2.

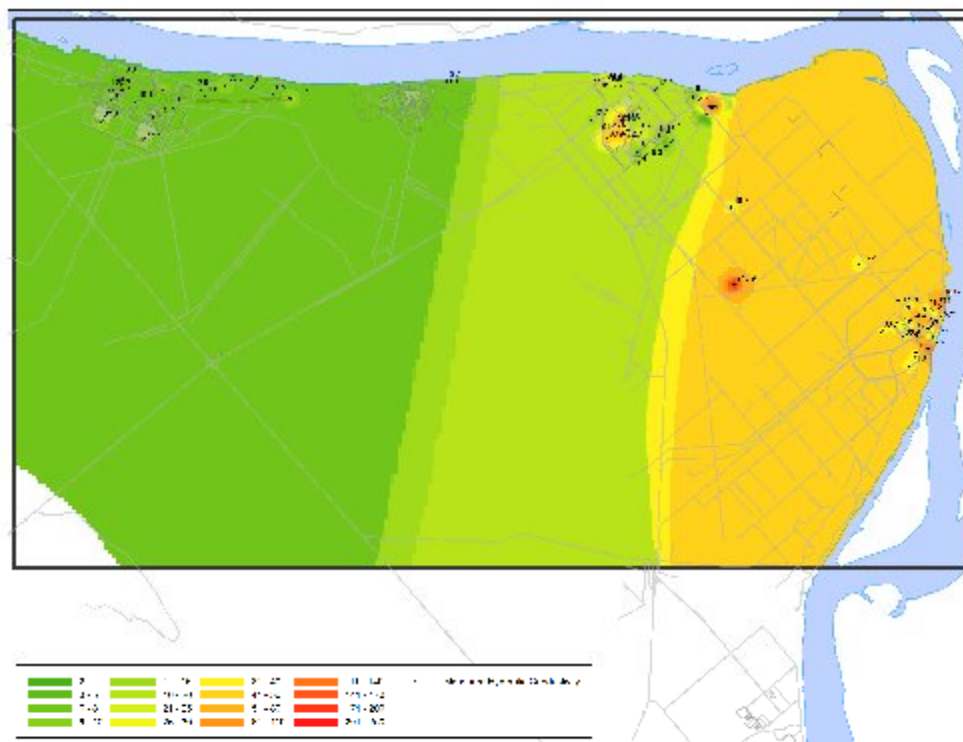


Fig. 2. Model Hydraulic Conductivity Distribution.

In addition to hydraulic conductivity, areal recharge from precipitation was specified based on information included in the Groundwater Data Package for Hanford Assessments [10]. An electronic version of the recharge package developed in the PNNL report was obtained, and the data were spatially distributed to the model grid cells. Based on the results of the model calibration, the recharge value specified in the 100 Areas MODFLOW model domain was equal to 12 mm/yr throughout most of the model domain. Higher recharge values of up to 100 mm/yr were assigned in parts of the model, depending on parameters identified in the report. A recharge value of approximately 2.5 m/yr was assigned to the 182-D reservoir in the 100 D Area. This rate is equivalent to 98 L/min leakage rate calculated for the 182-D reservoir during the first quarter of fiscal year 2007 (FY2007) (October through December 2006). This leakage rate is significantly lower than rates calculated for previous years (up to 401 L/min during the first quarter of FY06); however, it is reported that no leakage occurred during the remainder of FY07. The assigned recharge rate for the 182-D reservoir should be considered as an upper limit for the purposes of this model simulation [2].

Effective porosity and specific yield values for the entire aquifer were determined from the model calibration and are equal to 18% and 10%, respectively. Both values are within the range of values documented in previous investigations for Hanford [9].

Contaminant Transport Model

The migration of Cr(VI) in response to current and projected well operations in the 100-HR-3 Area was simulated to support the remedial process optimization (RPO) design for attaining the 2012 and 2020 river protection and aquifer cleanup goals, respectively. Transport simulations were based on the transient flow fields calculated by the groundwater flow model; an initial distribution for the Cr(VI) in groundwater; and a dual-domain formulation representing plume migration in a dual-porosity continuum with mass transfer between the mobile and immobile domains.

Initial Conditions

The initial conditions for the Cr(VI) in groundwater reflect the distribution that is obtained using maximum Cr(VI) concentrations at each monitoring location during 2008. Calculation of the initial distribution was performed using Quantile Kriging. Quantile Kriging is a variation of Kriging, and is considered one of the more robust methods for the interpolation of non-stationary data like contaminant concentrations. Quantile Kriging is based on ranking the concentration values in ascending order and dividing these ranks by one plus the total number of data points, resulting in a standardized rank transformation equivalent to a cumulative distribution function [13]. Each data point is then assigned the corresponding standardized rank and the new dataset is interpolated using Kriging. The interpolated distribution is then back-transformed using the constructed cumulative distribution function, resulting in the desired contaminant distribution.

A stepwise procedure was used to obtain initial conditions. First, Quantile Kriging was used to obtain contours of Cr(VI). Next, these contours were digitized and manually adjusted to reflect institutional knowledge of the historical plume migration and the local conditions affecting the actual Cr(VI) distribution in the aquifer. These adjusted contours were then converted to a point data set to supplement the measurements obtained from wells. Finally, the augmented dataset, including the maximum Cr(VI) concentrations at each monitoring location plus the interpreted contour data, were interpolated using Kriging to develop the initial conditions used in the transport model.

Dual-Domain Transport Processes

Recent studies by PNNL [11] suggest that the Cr(VI) within soils of the 100 Areas exhibits migration characteristics that may be more complex than can be represented using simple advection. According to these tests, although the majority of the mass is highly mobile and migrates by advection, Cr(VI) mass can be held in heterogeneous parts of the aquifer of low hydraulic conductivity. This immobile Cr(VI) constitutes a longer-term continuing source of chromium to the mobile domain facilitated by mass transfer between the domains. Based on these observations, the migration of Cr(VI) could be described by a dual-domain (or dual-porosity) approach that divides the aquifer into two domains, the mobile and immobile. Advective transport occurs predominantly in the mobile domain while mass transfer occurs between the mobile and immobile domain.

MT3DMS supports the use of a dual-domain formulation to simulate the transport of a contaminant in groundwater. To do so, the following parameters must be defined for the dual domain formulation: the fraction of mobile and immobile domains; the mass transfer coefficient between the mobile and immobile domains; and distribution coefficients describing sorption within the mobile and immobile domains. For the 100 Area transport modeling, it was assumed that sorption occurs only within the immobile domain so that the K_d in the mobile domain is zero.

To develop initial parameters for the MT3DMS dual-domain formulation, benchmark calculations evaluating migration in a soil under single- and dual-domain conditions were performed using MPNE1D [8], an analytical solution for one-dimensional solute transport with multi-process non-equilibrium. The analytical solution describes the following transport processes: advection; dispersion; dual-porosity mobile-immobile mass transfer; combined equilibrium and kinetic sorption; and first-order transformation reactions. The following are the principal assumptions that underlie the use of the MPNE1D code to develop initial parameters for the MT3DMS dual-domain formulation with the 100-Area model:

- The domain is represented as dual porosity continuum, with mass transferred between the mobile and immobile domains modeled as first-order mass transfer.
- Sorption occurs at both equilibrium and rate-limited sites.
- Transformation reactions are modeled as first-order decay processes.
- The material properties are spatially uniform and temporally constant.
- The Darcy flux is steady, one-dimensional and spatially uniform.

- Longitudinal dispersion is assumed to be a Fickian process, characterized by a constant dispersion coefficient.
- The initial concentrations in each domain are specified and assumed in equilibrium.

The conceptual model developed to evaluate appropriate parameters for the 100-Area dual-domain simulations consisted of a one-dimensional soil column of 50 cm in length. Uniform hydraulic and transport parameters were assumed throughout the soil column. A steady-state flow field was assumed with a Darcy Flux of 1.319 cm/day under confined conditions. Contaminant transport was simulated for a period of 40 days for a conservative solute with no dispersion or decay. The initial concentration in the soil column was assumed equal to zero. The boundary condition at the top of the soil column represented a contaminant flux of 1 gm/cc from the start of simulation to 17.6 days. From 17.6 days to 40 days, the influx of mass dropped to zero and no additional mass was introduced into the system. Breakthrough curves were calculated at a distance of 30 cm from the top of the soil column. Numerical simulation of the conditions described in the conceptual model using the same parameter values were performed using MT3DMS and the results were compared to the analytical solution.

A single-domain model that simulates the movement of a conservative plume through a soil column was developed first to provide a basis for understanding the effect of each individual process that influences the movement of contaminants under dual-domain conditions. Corresponding breakthrough curves suggest excellent agreement between the analytical and numerical solutions.

Dual-domain simulations were performed assuming 20% immobile water fraction. This results in an immobile water content of 4.5% and mobile water content of 18% for a total water content of 22.5%. Adsorption was also simulated in the form of instantaneous linear adsorption in the immobile domain. A value of 0.3 cc/g, was used for the distribution coefficient K_d . Two cases were examined, for different values of the first-order mass transfer coefficient α : (a) α equal to zero, reducing the system to a single-domain; (b) α equal to 0.01, representing a dual-domain system.

When the mass transfer coefficient α is set to 0.01, solute mass is able to enter and leave the immobile domain generating a characteristic “tailing” of the contaminant plume migration. When compared to the single-domain simulation, lower solute concentrations are initially observed in the mobile phase. This can be attributed to mass transfer from the mobile domain into the immobile domain when the immobile dissolved concentration is lower than the mobile domain concentration. Subsequently, mass in the immobile domain is slowly released into the mobile domain, as mobile domain concentrations decrease. The corresponding breakthrough curves indicate additional retardation of the plume migration due to adsorption.

Table I shows the solute mass introduced to, recovered from, and remaining in the system at the end of the simulation timeframe under single-domain conditions; dual-domain conditions; and dual-domain conditions with adsorption considered. Although the entire solute mass was flushed out of the system within the 40-day simulation period, up to 6% of the mass introduced into the system remains in the soil column under dual-domain conditions including adsorption. This suggests that small-scale heterogeneities in the aquifer could result in significant amounts of mass slowly migrating and prolonging the necessary time to cleanup. Such effects of small-scale heterogeneity were incorporated in the numerical model for the simulation of the Cr(VI) fate and transport under the RPO design.

Table I: Mass Balance of Solute for each Scenario after 40 days.

Scenario	Total IN (g)	Mass Remaining (g)	Total Out (g)
Base Case - single domain	23.264	0.000	23.264
Dual Domain - no sorption	23.264	0.118	23.147
Dual Domain - sorption in immobile phase	23.264	1.395	21.870

Model Assumptions and Limitations

The principal assumptions and limitations of the modeling analyses are described below:

- The model simulates 2D groundwater flow. This assumes that the effects of 3D flow, such as occurs near partially-penetrating wells, are negligible. This assumption is considered reasonable since most extraction wells penetrate almost the full saturated thickness of aquifer.
- The Ringold Upper Mud Formation, where present, is currently considered a vertical no-flow boundary for the model. However, sensitivity analysis should be performed to examine the effects, if any, of possible vertical gradients across the bottom of the model on plume migration and on the effectiveness of the proposed remedies.
- The initial hexavalent chrome distribution is based on currently available data from a finite number of sampling points. Acquisition of new data (including new sampling locations) could lead to different plume distributions and, therefore, different projections of plume migration and mass recovery.
- Small-scale heterogeneity and its effect on hexavalent chrome transport are incorporated in the model through the dual-domain formulation. However, the parameters that describe mass transfer between the mobile and immobile phases are calculated based on limited prior information from soil column experiments. Actual field-scale values could vary significantly and should be evaluated through model calibration when pump-and-treat mass recovery data are collected.
- The model does not include any continuing sources in the vadoze zone or the RUM. The presence of such sources could significantly prolong aquifer cleanup times.

Model Simulations

Current Conditions, Hydraulic Capture and Capture Efficiency

The interim pump-and-treat system consisted of 18 extraction and injection wells operating in 100-HR-3 Area for the period of January 1, 2008, to December 31, 2008. A total of approximately 120 gallons per minute (gpm) and 70 gpm are extracted from wells in the 100-D and 100-H Areas, respectively. About 70 gpm of the groundwater extracted from the 100-D Area is transferred to the 100-H Area in support of current pump-and-treat operations in that area.

The flow model can simulate quasi-steady-state conditions, assuming average conditions, or it can simulate transient (time-varying) conditions that incorporate changing pumping rates and changing river stage. To evaluate the approximate extent of capture of each 100 Area pump-and-treat remedy during CY2008, the groundwater flow model was used to simulate aquifer conditions based on monthly stress periods, with monthly average river stage and pumping rate values for each stress period. The extent of hydraulic capture in transient systems differs from that depicted assuming quasi-steady-state conditions [6]. When simulating quasi-steady-state conditions, a single depiction of the extent of capture is delineated by releasing particles from all model cells encompassing the operable unit recording those particles that are ultimately recovered by an extraction well. Since the model is quasi-steady-state, the resulting depiction assumes that the simulated conditions will persist until the particles are captured. When simulating transient conditions, it is acknowledged that conditions change over time in response to

time-varying stresses and, as such, a different method is required to prepare a single map of capture using the transient model.

To accomplish this, particle tracking was conducted by releasing particles at the commencement of each of the 12 monthly model stress periods and simulating their migration using a very low effective porosity (1.0×10^{-9}). This ensures that particle travel times are essentially instantaneous, so the fate of each particle during each stress period is recorded without regard for the actual groundwater velocity. As a result, a capture zone is calculated for each stress period based on a “snapshot” of aquifer conditions at the time of the particle release. This approach provides a depiction of well capture based on 12 discrete snapshots of the aquifer conditions during CY2008. A capture efficiency map is then prepared by counting the number of times a particle originating from a location was captured by a well, and then dividing this number by the total number of releases (in this case, 12). This approach is similar to those described by Festger [6] and Reilly [14] and focuses on the evaluation of the temporal variation in capture due to changing flow patterns and hydraulic gradients in response to the principal time-varying stresses on the system.

In the 100 Area operable units using the 100 Area groundwater model, the sole causes for efficiencies ranging between zero and 1.0 are changing pumping rates and the effects of the changing river stage. Inference from a capture efficiency map should focus on the relative extents and distribution of the low and high efficiencies. Figure 3 illustrates the simulated capture efficiency map for 100-HR-3 during CY2008 [1].

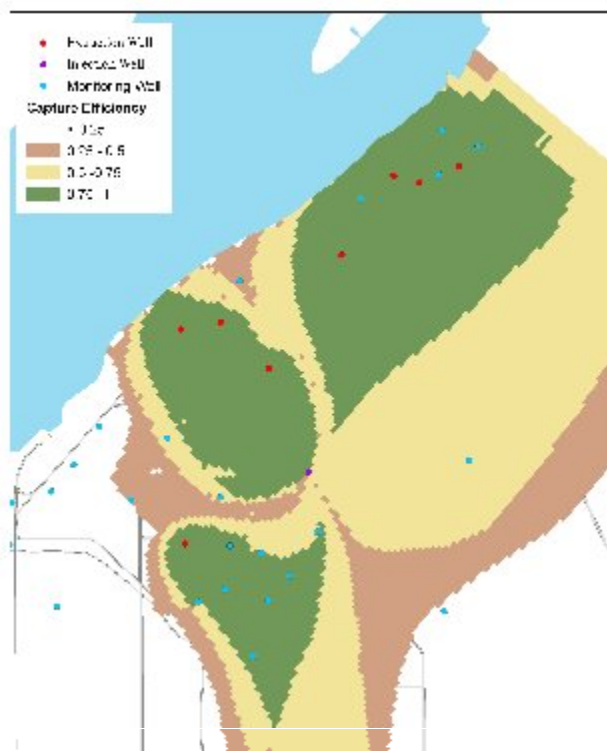


Fig. 3. 100-D Area Capture Efficiency Map (Modeled).

Optimized Well Field Design: 2012 and 2020 Objectives

Remedy simulations were performed by an iterative process where proposed extraction and injection wells were considered in various combinations. The model was executed, and the outputs of the model simulation were processed to provide calculated groundwater elevations and Cr(VI) concentration distributions.

The results of the RPO effort suggest that the following well field design modifications are necessary to accomplish the 2012 cleanup goal:

- Install new extraction and injection wells to increase hydraulic capture of the dissolved Cr(VI) plume to prevent discharge of Cr(VI) to the Columbia River substrate at concentrations exceeding those that are considered protective of aquatic life in the river and riverbed sediments.
- Modify some of the existing monitoring wells to act as dual-purpose wells, and allow additional extraction and/or injection in order to assist in achieving the 2012 and 2020 cleanup goals. These wells were identified based on their location relative to existing pump-and-treat wells, and their expected capacity is based on information from limited tests performed at selected monitoring wells in the 100-D Area (e.g., well 199-D4-39).
- Install new extraction and injection wells to establish hydraulic containment and subsequent recovery of the dissolved Cr(VI) plume at locations within and around the plume footprint to assist in achieving the 2020 cleanup goal.

Results and Discussion

The proposed design for attainment of the 2012 and 2020 goals consists of the following, as a minimum:

- Eight existing extraction/injection wells in the 100-D Area.
- Thirty new extraction/injection wells in the 100-D Area.
- Nine existing monitoring wells used as dual-purpose wells in the 100-D Area.
- Thirteen existing extraction/injection wells in the 100-H Area.
- Forty new extraction/injection wells in the 100-H Area.
- One existing monitoring well used as a dual-purpose well in the 100-H Area.

Figure 4 illustrates the approximate distribution of Cr(VI) in the 100-HR-3 Area in 2012, as developed by the proposed RPO design and estimated by the numerical model using the proposed extraction and injection well locations and rates.

The proposed remedy well layout and corresponding pumping rates provide (a) hydraulic control in the targeted area for the 100-D Area, which is sufficient to achieve the 2012 goal of protecting the Columbia River; and (b) recovery of the Cr(VI) plume toward attainment of the 2020 cleanup goal. The existing extraction/injection wells provide limited plume containment, so additional wells are necessary. In order to minimize the number of new wells to be drilled and expedite the process of system configuration, existing monitoring wells will be implemented in the system by modifying their specifications and operation as extraction and/or injection wells, as necessary. Preliminary tests for existing monitoring well capacity were performed at well 199-D4-39, and a pumping rate of approximately 15 gpm was sustained for approximately 24 hours. Thus, the proposed design assumed that all of the selected monitoring wells could produce similar quantities of groundwater

In the 100-H Area, the current pump-and-treat wells are located in areas of low Cr(VI) concentrations. The current extent of the plume in the 100-H Area identified during recent investigations [4] requires the installation of new extraction/injection wells. The placement and installation of these wells must follow guidelines and constraints related to historical and natural significance of portions of the 100-H Area. Thus, the system was designed so the maximum possible plume containment and recovery could be achieved.

Given the modeling assumptions and limitations, the calculated Cr(VI) distribution at different times in the future should be considered relative estimates and not absolute predictions of the actual plume migration patterns that will prevail. Upon implementation of the remedy design, short- and longer-term monitoring data should be compiled and analyzed in order to further improve the estimation of the

parameters associated with the contaminant transport as implemented in the numerical model. The numerical model should then be updated and redeployed in order to provide new estimates of the pump-and-treat system performance.

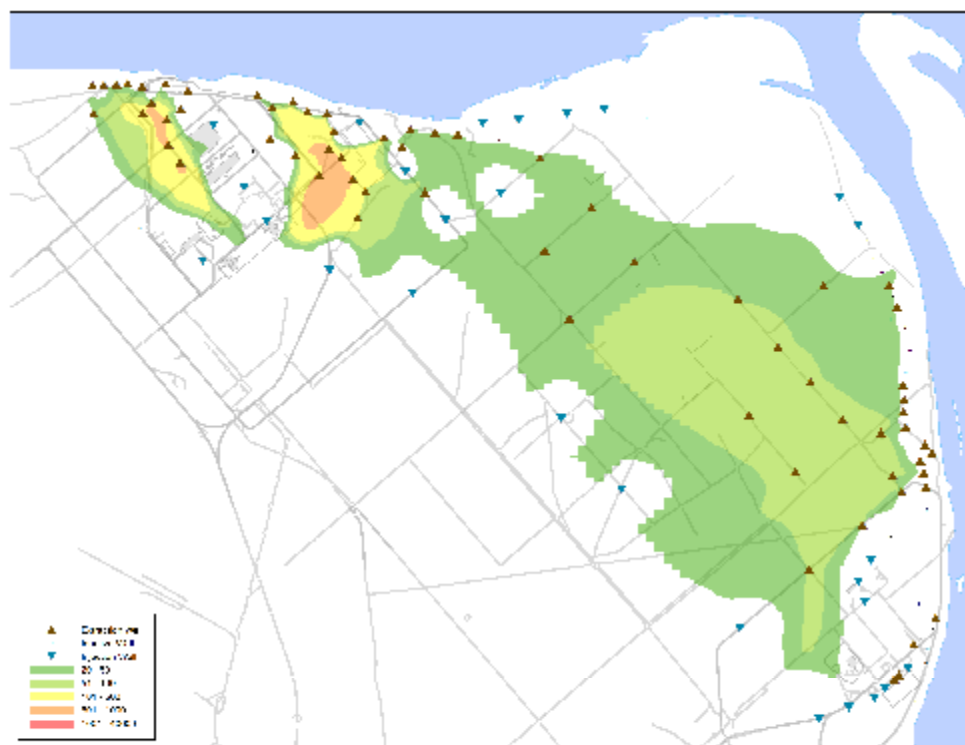


Fig. 4. Simulated Distribution of Dissolved Cr(VI) in the 100-HR-3 Area in 2012.

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