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Revision 3

Evaluation of Potential Hydraulic Capture and Plume Recovery from the Ringold Upper Mud (RUM) in the 100-HR-3 Operable Unit (OU)

Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management

Contractor for the U.S. Department of Energy
under Contract DE-AC06-08RL14788

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Environmental Calculation File

Evaluation of Potential Hydraulic Capture and Plume Recovery from the Ringold Upper Mud (RUM) in the 100-HR-3 Operable Unit (OU)

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Terms

AWLN	automated water level network
AWQC	ambient water quality criteria
bgs	below ground surface
COPC	contaminant of potential concern
Cr(VI)	hexavalent chromium
DOE	Department of Energy
ECF	environmental calculation file
FEPs	Features, Events, and Processes
HEIS	Hanford Environmental Information System
HISI	Hanford Information System Inventory
RI/FS	Remedial Investigation/Feasibility Study
RMS	root mean square
RUM	Ringold Formation upper mud

1 Purpose

The *Comprehensive Environmental Response, Compensation and Liability Act of 1982* (CERCLA) Remedial Investigation (RI)/Feasibility Study (FS) undertaken for 100-D/H area at the Hanford Site was primarily focused on groundwater contamination in the unconfined aquifer (DOE, 2012). Due to the limited extent of hexavalent chromium [Cr(VI)] contamination in the Ringold Formation upper mud (RUM) in the 100-HR-3 groundwater Operable Unit (OU), the uncertainty associated with omitting the semi-confined aquifer from RI/FS models was considered low. However, data collected near the 100-H in the first water bearing unit of the RUM (semi-confined aquifer) indicate there are high concentrations of Cr(VI) in that unit. As a result, there is the possibility of Cr(VI) contamination in the RUM being of significant magnitude so as to prolong aquifer cleanup at 100-H.

The purpose of this calculation is to evaluate possible conceptual models of the fate and transport of Cr(VI) in the semi-confined aquifer including possible sources of contamination and an estimate of cleanup times. However, it should be noted that analytical data collected from the RUM material separating the unconfined and lower water bearing units has not identified any presence of Cr(VI), indicating that a source is not present in that material. As additional data is collected and the site is further characterized, both the conceptual and numerical models of the Cr(VI) in the RUM at the 100-H area will be advanced.

2 Background

The data associated with the semi-confined aquifer at 100-HR-3 OU was evaluated to propose a set of conceptual site models (CSM) for flow and transport of Cr(VI) in the semi-confined aquifer at 100-H. The data evaluated included the hydrostratigraphy of the 100-HR-3, hydraulic head data, pumping rate information, contaminant concentration, and aquifer test data. These data and the CSMs considered in the construction and application of the model are discussed below.

2.1 Hydrostratigraphy of the 100-HR-3 Groundwater Operable Unit

The geologic units in 100 D/H are shown in Figure 1 (DOE/RL-2010-95). Two geologic formations were included in the numerical model for the 100-H area, including the Hanford formation and Ringold Formation. At the 100-H area, the Ringold Formation is represented by two stratigraphic units, unit E and the Ringold upper mud (RUM). The RUM includes a thin aquifer, the first water-bearing unit of the RUM, referred to as the semi-confined aquifer in this ECF (it should be noted however, that it has not been determined if this aquifer is confined or semi-confined). These formations and units are described in the following sub-sections.

2.1.1 Hanford formation

The Hanford formation consists predominantly of unconsolidated sediments that cover a wide range of grain sizes, from boulder-sized gravel to sand, silty sand, and silt. Beneath 100-H, only the gravel and sand dominated facies are present to depths of approximately 17 m below ground surface (bgs). Thicknesses range from 5 to 22 m, with greatest thickness underlying the southwest-central part of 100-D/H (DOE/RL-2010-95).

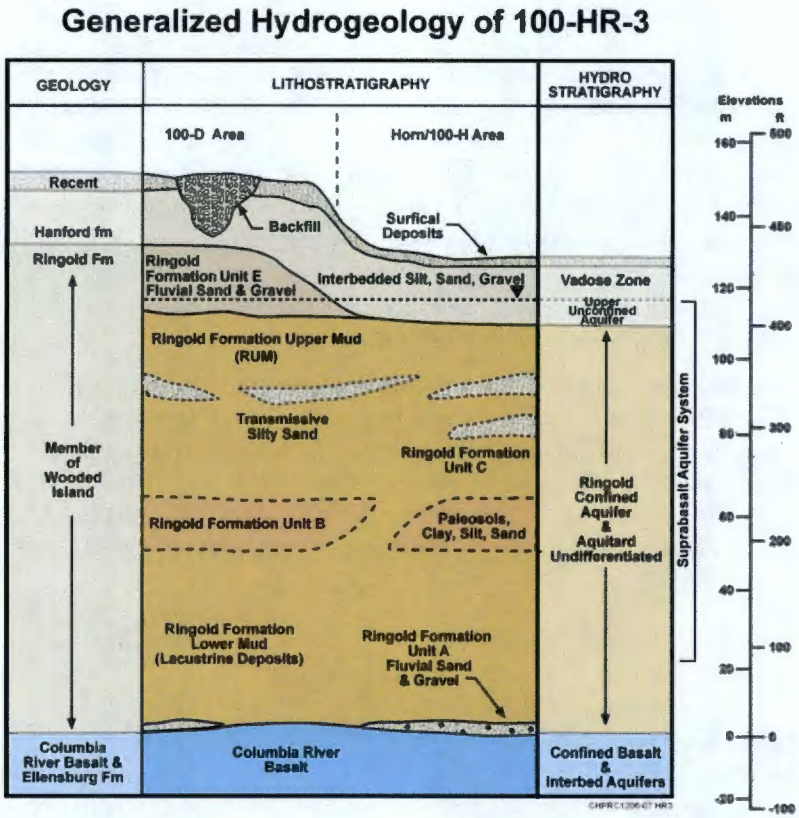


Figure 1. Generalized Hydrostratigraphy of 100-HR-3 Groundwater Operable Unit

2.1.2 Ringold Formation

The typical stratigraphic units within the Ringold Formation are generally identified, from shallowest to deepest, as: unit E, RUM, units B and C, Ringold lower mud, Ringold Formation gravel unit A. Beneath 100-D/H, the Ringold Formation does not contain all of the commonly encountered stratigraphic units found elsewhere across the Hanford Site. Furthermore, the Ringold Unit E is only present over a limited portion of the study area, and is relatively thin in comparison to the Hanford formation and mud unit of the Ringold Formation. The Ringold Formation units evaluated in this calculation include the Ringold unit E and the RUM.

Ringold Formation unit E: The Ringold Formation unit E is composed of fluvial matrix-supported gravels and sands with intercalated fine- to coarse-grained sand 6 and silt layers. In the 100-H Area, the presence of Ringold Formation unit E sediment is limited (DOE/RL-2010-95).

Ringold Formation upper mud unit: The RUM is dominated by a fine-grained overbank paleosol facies association that is up to 61 m thick. Regionally, the RUM appears to be continuous, with an undulating surface with depressions and topographic highs that locally affect aquifer thickness. The RUM surface appears to dip to the north, or to be partly eroded in the most northwestern portion of the Horn area, to the north of the 100-H area. In 100-H, the RUM surface has a regional high point between the river and the Horn, with depressions on either side.

The upper part of the RUM sometimes contains gravel in a silt/clay matrix that represents a transition zone (reworked interval) above the more massive silt or clay. The silt and clay rich RUM has low hydraulic conductivity values relative to the Hanford formation. The RUM is considered an aquitard, and as such, forms the base of the unconfined aquifer. Within the RUM, thin sand-to-gravel layers form zones

with variable hydraulic conductivities that range from low to high and form confined or semi-confined aquifers. Beneath a localized area of 100-H inland from the 105-H reactor, this semi-confined aquifer is potentially hydraulically connected to the unconfined aquifer, which could provide a pathway for contaminants to migrate. The top surface of the RUM ranges from approximately 11m bgs to 20 m bgs in 100-H. The top of the RUM ranges between an elevation of 104.5 and 115 m (DOE/RL-2010-95).

2.2 Hydraulic Head Data

The hydraulic head data collected at sites in 100-H include manual measurements and transducer data collected as part of the Automated Water Level Network (AWLN). Table 1 shows the wells, well types, and type of data (manual or automated) available with hydraulic head information for the semi-confined aquifer. Monitoring wells that are a part of a nested well group with screens in both the unconfined aquifer and the semi-confined aquifer are noted with an asterisk in the Table 1. These data are important to the modeling process for developing initial conditions, boundary conditions, and for evaluating the ability of the model to predict observed hydraulic head. Analysis of data gathered at well 199-H3-2C has indicated that the values may not be reflective of actual conditions within the semi-confined aquifer based on pumping test data (SGW-47776) which indicates leakage between the two aquifers at that location. Therefore, the data point will be excluded from comparison of modeling results and the development of boundary and initial conditions for the numerical modeling.

Evaluation of the nested well data at wells 199-H4-12A, 199-H4-12B, and 199-H4-12C and at the nested wells 199-H4-15B and 199-H4-15CS suggest the existence of a vertical upward gradient during elevated river stage conditions from the semi-confined aquifer to the unconfined aquifer. Manual measurements from these wells and from nested well pairs at 699-97-45 and 699-97-45B, and nested wells 699-97-43B and 699-97-43C are shown in Figure 2. The existence of an upward vertical gradient is not shown in the wells 699-97-45 and 699-97-43 well pairs. In fact, measurements at these wells suggest the existence of a vertical downward gradient. However, none of these data provides proof that excludes the other hypothesis. The maximum downward gradient exists at the well pair 699-97-45 and 699-97-45B on 3/7/2010 at a value of 0.3 m. The maximum upward gradient occurs between well pair 199-H4-15B and 199-H4-15CS on 9/26/2007 at a value of 0.61 m in the semi-confined aquifer.

2.3 Pumping Rate Information

Two extraction wells target contamination in the semi-confined aquifer. The historic extraction rates for these wells, 199-H4-12C and 199-H3-2C, is shown in Figure 3. Pumping records from the wells provide rates between the dates of June 2010 to January 2013. These values will be used as sink terms in the numerical model as recorded below.

2.4 Water Quality Data

Concentration data for the semi-confined aquifer were extracted from the Hanford Environmental Information System (HEIS) database for use in estimate the current distribution of Cr(VI). Table 2 lists the wells where concentration data were available for total chromium and for Cr(VI). Table 2 includes summary information about the amount of information available at each well including number of measurements, number of detections, starting and ending dates, maximum and minimum concentrations. These data will be used in the numerical modeling to establish a distribution of Cr(VI) for the start of the simulation or "initial concentration" and to evaluate the predictive capabilities of the simulation into the future. The complete list of water quality measurements from HEIS for the listed wells is included in Attachment D.

Table 1. Monitoring Wells with Hydraulic Head Measurements in the Semi-confined Aquifer

Well Name	Type of Well	Type of Measurement
199-H2-1	Monitor	Manual
199-H3-10	Monitor	Manual
199-H3-2C*	Extraction	AWLN (System)
199-H3-9	Monitor	Manual
199-H4-12C*	Extraction	AWLN (System)
199-H4-15CS*	Monitor	Manual
199-H4-90	Monitor	Manual
199-H4-91	Monitor	Manual
699-97-43C*	Monitor	Manual
699-97-45B*	Monitor	Manual
H-gauge	River Stage	AWLN (System)

*well is paired with a monitoring well screened in the unconfined aquifer

2.5 Aquifer Test Data

Aquifer tests to estimate hydraulic properties of the semi-confined aquifer have been conducted on extraction wells screened in the semi-confined aquifer. The details of these tests are documented in PNL-6728, *Geohydrologic Characterization of the Area Surrounding the 183-H Solar Evaporation Basins*, and in SGW-47776, *Aquifer Testing and Rebound Study in Support of the 100-H Deep Chromium Investigation*. The aquifer tests detailed in PNL-6728 provided transmissivity estimates for the semi-confined aquifer as 36 and 57 m^2/day, and hydraulic conductivity estimates of 12 and 18 m/day, at wells 199-H3-2C and 199-H4-12C, respectively.

SGW-47776 details step drawdown, constant rate, and rebound testing completed on wells 199-H3-2C, 199-H4-12C, and 199-H4-15CS. Test data analysis concluded that transmissivity of the semi-confined aquifer ranged from 38.3 to 72.3 m^2/day (hydraulic conductivity estimates were that the aquifer exhibits leaky conditions, and that there was minimal rebound of chromium concentration during temporary shutdown of the system). Observation wells for these tests only included those wells that were part of the nested well groups with the extraction well. All of these wells were within 8 m of the extraction wells.

The transmissivity estimates provided in PNL-6728 are similar in magnitude to those reported in SGW-47776. Report SGW-47776 suggests that this discrepancy is likely due to lack of accounting for a positive recharge boundary during testing. Based on this and the increased level of detail in the analysis provided by SGW-47776 the hydraulic properties from SGW-47776 will be used to constrain the hydraulic properties during development of the numerical model.

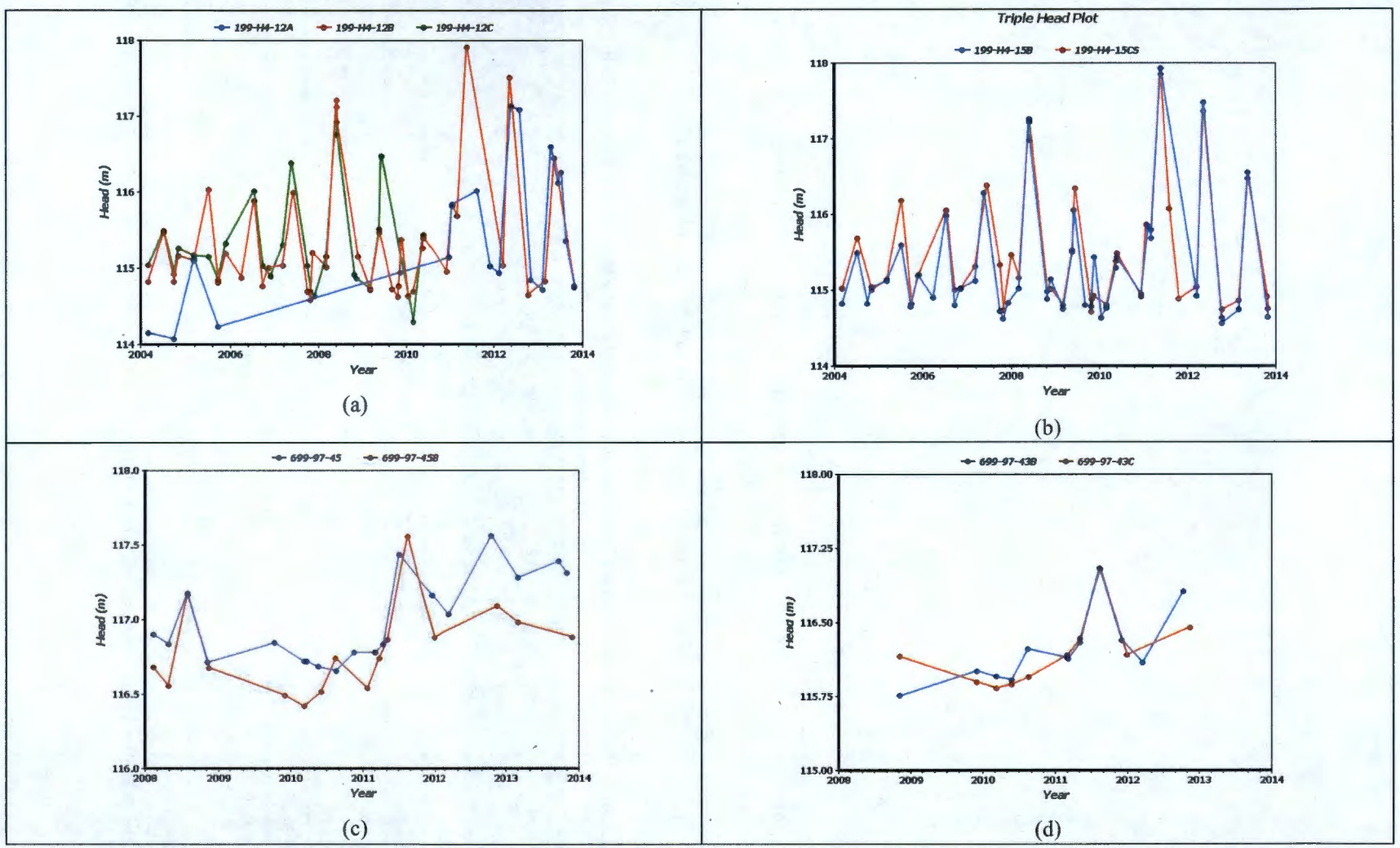


Figure 2. Manual Hydraulic Head Measurements from Nested Well Pairs a) 199-H4-12, b) 199-H4-15, c) 699-97-45, and d) 699-97-43 near the 100-HR-3 Groundwater Operable Unit Semi-confined Aquifer Model Domain

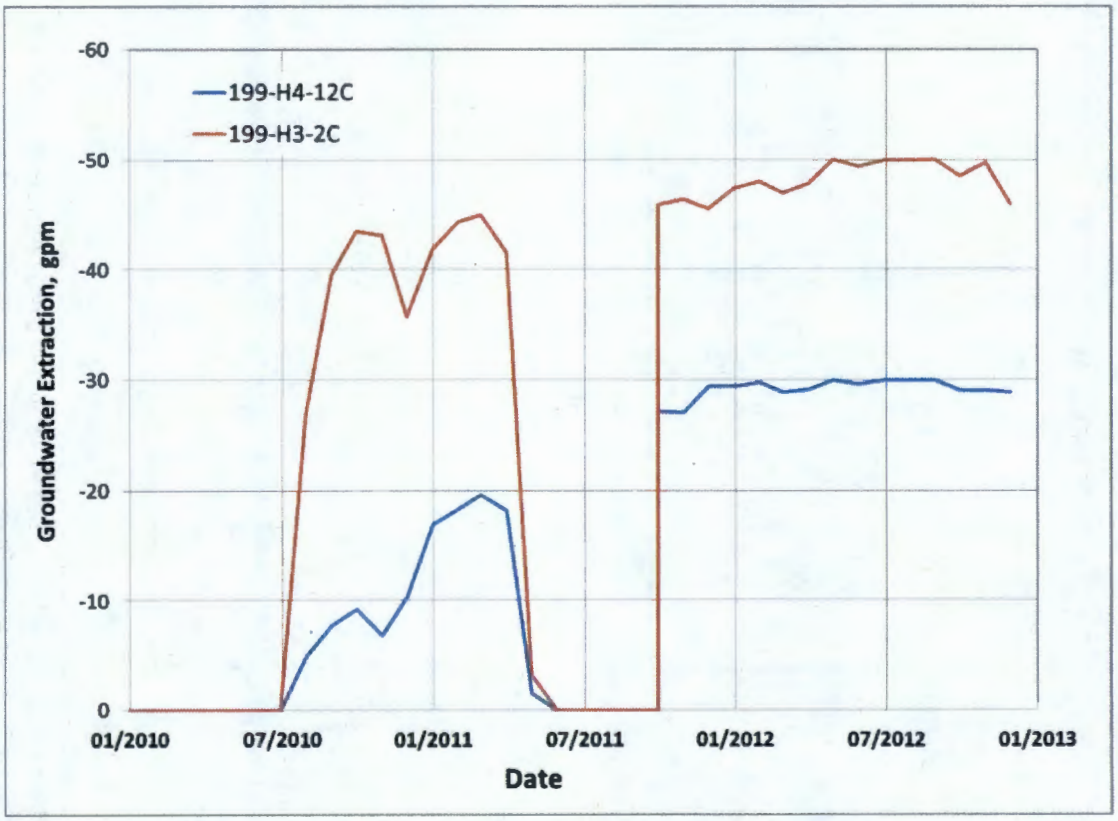


Figure 3. Historic Extraction Rates for Wells 199-H4-12C and 199-H3-2C

Table 2. List of Wells Used to Evaluate Concentration Distribution of Hexavalent Chromium in the Semi-confined Aquifer

Well Name	Number of Measurements	Number of Detections	Sample Dates		Measured Concentration, µg/L	
			Earliest	Latest	Minimum	Maximum
199-H2-1	42	23	Feb-2011	Oct-2013	ND	13.8
199-H3-10	29	20	Mar-2011	Oct-2013	ND	13.8
199-H3-2C	171	140	Dec-1986	Oct-2013	ND	114
199-H3-9	34	30	Jan-2011	Oct-2013	ND	319
199-H4-12C	245	244	Dec-1986	Oct-2013	ND	650
199-H4-15CS	64	64	Jul-1995	Oct-2013	52.3	157
199-H4-90	9	7	Aug-2013	Sep-2013	ND	15
199-H4-91	9	4	Aug-2013	Sep-2013	ND	66.9

Source: Hanford Environmental Information System (HEIS).

2.6 Proposed Conceptual Site Models

One purpose of this ECF is to test a set of conceptual site models (CSM) to evaluate conditions that may or may not exist within the semi-confined aquifer. These include CSMs with respect to the possible source for the Cr(VI) and the groundwater flow field that exists in the semi-confined aquifer. A CSM is an explanation of the features, events, and processes (FEP) that occur within a domain. In general, two CSMs for the same region may have a majority of the FEPs in common with one another. At times, they may be completely different. The FEPs were identified in order to develop a set of CSMs to evaluate as part of the numerical modeling. These were the source of the Cr(VI) contamination and the behavior of the groundwater flow field. These are discussed in the following sub-sections.

2.6.1 Source of Hexavalent Chromium

Two CSMs for the source of Cr(VI) contamination were developed for consideration. One CSM considers only the current distribution of Cr(VI) in the semi-confined aquifer as defined by concentrations observed at wells completed in that unit (RUM aquifer source). The second source model considers possible Cr(VI) sources that persist in the RUM aquitard between the unconfined aquifer and semi-confined aquifer.

According to the available data there is a known distribution of Cr(VI) contamination in groundwater within the semi-confined aquifer. Sediment samples were collected within the RUM material during the RI process at eight well locations (Figure 4). Analytical results from samples collected from the RUM sediments had resulting concentrations of either non-detect or an estimated value below the Cr(VI) cleanup level of 2 mg/kg (DOE/RL-2010-95, Rev.0). These data suggest that during operation the 100-HR-3 facilities (HW-77170) historic high water tables provided the conditions necessary to drive Cr(VI) through the RUM into the semi-confined aquifer. Now that production has ceased, the conditions no longer exist that provide a source of Cr(VI) to the semi-confined aquifer. Simulations based on this CSM simulate the current distribution of Cr(VI) (estimated in ECF-100HR3-13-0040) as the concentration at year zero and predict its fate and transport without considering a continuing source of Cr(VI) from the RUM sediments.

Another CSM considers a possible residual source of Cr(VI) within the RUM sediments that overlie the semi-confined aquifer. The underlying assumption is that downward leakage from trenches, cribs, and other potential release points migrated into the underlying RUM aquitard beneath the unconfined aquifer. Due to the low hydraulic conductivity of the aquitard, the Cr(VI)-enriched groundwater was retained in the aquitard material after leakage from the surface facilities was eliminated. Table 3 shows possible sources of Cr(VI) in the 100-H area that were identified from waste sites known to exist at the 100-H area (Figure 4) that contained Cr(VI).

Estimated Cr(VI) concentrations for waste sites 116-H-1 and 116-H-2 were calculated from reported mass deposited and the volume of the effluent. The estimated Cr(VI) concentration for waste site 116-H-6 was estimated from measured Cr(VI) concentrations in well 199-H4-3 for the 1973-1985 period. Well 199-H4-3 was screened in the unconfined portion of the aquifer. The maximum concentrations observed at this well were approximately 4,000 μg/L. This bounding calculation assumes groundwater with this peak concentration was able to infiltrate into the RUM sediments. Application rates or volumes of effluent for waste sites 116-H-6 and 100-H-46 are unknown. Application rates and concentrations for waste site 116-H-4 are unknown and, due to the small area of the waste site, the contribution from 116-H-4 was assumed insignificant and not included as a Cr(VI) source in the model. Similarly, little information was available describing the extent of Cr(VI) contamination emanating from waste site 118-H-6:3. As a result, waste site 118-H-6:3 was not included as a Cr(VI) source in the model. In this CSM, the concentration of Cr(VI) at year zero of the simulation is the same as the previous simulation. However, for this CSM,

additional Cr(VI) will be applied to the model layer corresponding to the RUM (Layer 3). The final source concentrations applied to the RUM are discussed in Section 4.4.3.

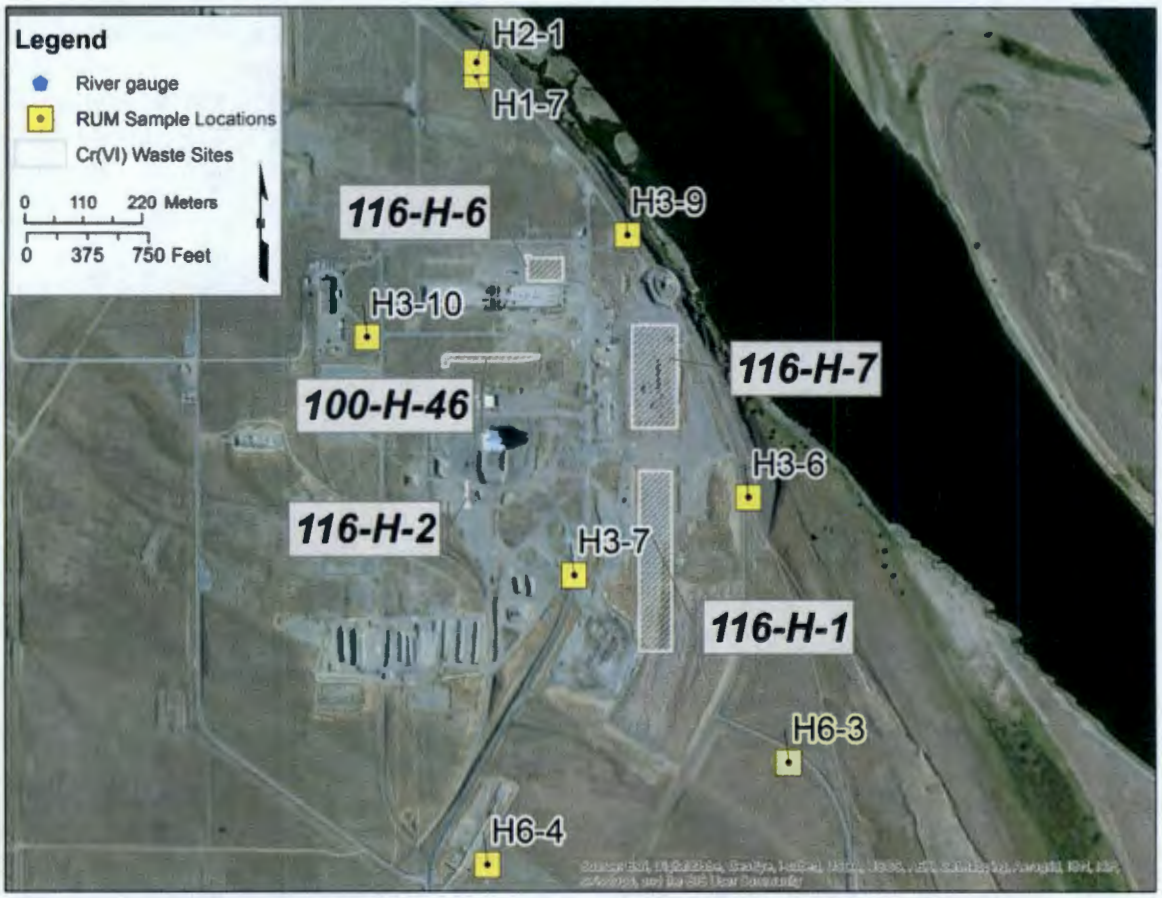


Figure 4. Sample Locations where Ringold Upper Mud Sediments were Collected and Analyzed, and Hexavalent Chromium Source Waste Sites

2.6.2 Groundwater Flow Field

Two processes involving the groundwater flow field will be examined to produce bounding results. These are the presence of vertical gradients and the presence of a dual domain system.

2.6.2.1 Vertical Gradients

Data show the possibility that the semi-confined aquifer is influenced by vertical gradients. Because the trend throughout the site is not definitive, multiple simulations were conducted to evaluate fate and transport of Cr(VI) influenced by vertical upward gradients. In the numerical simulations, boundary conditions will consider the possibility of the existence of no vertical gradient, an upward gradient, and an downward vertical gradients. The range of the gradients will mimic the peak upward gradient for wells demonstrating an upward gradient and the vice versa for the downward gradient presented in Section 2.2.

2.6.2.2 *Dual Domain Flow*

Sediments comprising of the saturated portion of the 100-H subsurface range from coarse to fine. The presence of vary textures in some cases can produce a dual flow domain. The 100 Area numerical groundwater model for the Hanford site, documented in SGW-47629, uses a dual-domain flow system in order to make predictions for fate and transport of Cr(VI) in the Hanford formation. Simulations will be conducted with and without the dual-domain formulation in order to evaluate the effect this has on the results.

Table 3. Possible Sources of Hexavalent Chromium in the Ringold Upper Mud Evaluated in this Study[a]

Facility	Waste Site	Period Active	Cr(VI) Mass Deposited (kg)	Concentration of Effluent (µg/L)	Volume of Effluent (L)	Rate of Effluent Application (L/min)	Approximate Cr(VI) Concentration (µg/L)
107-H Liquid Waste Disposal Trench	116-H-1	1952-58; 1965	90		90×10^6		1,000
1608-H Liquid Waste Disposal Trench	116-H-2	1950-1965	600		600×10^6		1,000
116-H-4 Crib	116-H-4	1950-1952					?
183-H Solar Evaporation Basins	116-H-6	1973-1985					4,000
107-H Retention Basin	116-H-7	1949-1965		350		38,000	
118-H-6 Reactor Fuel Storage Basin	118-H-6:3	1949-1965					?
190-H Sodium Dichromate Handling Facilities	100-H-46	1959-1965		466,000,000			4,000

a. Source: DOE, 2012

3 Methodology

The methodology for this calculation is comprised of the steps involved in the construction and development of a numerical groundwater flow and contaminant fate and transport model developed to evaluate CSMs regarding the remedy for Cr(VI) contamination in the first water bearing unit of the RUM, and its application. The CSMs evaluated in this calculation are enumerated, along with a summary of the data and evaluations that have been completed that provide the basis of these CSMs, in Section 2 of this ECF. The model is used to evaluate the hydraulic containment of the plume and the removal of dissolved contaminants of potential concern (COPCs) for each CSM considered under each remedial scenario evaluated (e.g., pumping and no action). The model is implemented in, and calculations are conducted with qualified installations of software approved for conducting these types of numerical simulation, specifically MODFLOW-2000-MST (Harbaugh et al, 2000; SSPA, 2012a) and MT3DMS-MST (Zheng and Wang, 1999; SSPA, 2012b). Software quality assurance is documented in Section 5 of this ECF.

The steps in the construction, development, and application of the model for this calculation are:

1. Construction: construct a three-dimensional flow and transport model with a domain encompassing the 100-H Area.
    a. Assign the model layering using the defined hydrostratigraphic units documented in ECF-Hanford-13-0020 Rev.0 and a description of the semi-confined aquifer provided by analysis of borehole summaries and geophysical logs screened where sediments. Model layers will be assigned as follows:
        i. Layer 1 – Hanford formation
        ii. Layer 2 – Ringold Unit E where it exists, otherwise RUM
        iii. Layer 3 – RUM
        iv. Layer 4 – first water bearing unit of the RUM
    b. Determine the model domain and cell size based on the radius of influence of the current remedy and the estimated extent of the plume;
    c. Prepare boundary conditions (specified heads) based on available hydraulic head data and the recharge based on current 100 Area groundwater model.
    d. Use model input parameters for flow and transport based on the 100 Area groundwater model and available estimates of transmissivity from PNL-6278 and SGW-47776.
    e. Create model files for pump-and-treat wells in the unconfined aquifer and the semi-confined aquifer based on reported values from ECF-Hanford-13-0008 and DOE/RL-2011-25 for the unconfined aquifer and project pumping data for the wells in the first water bearing unit of the RUM.
    f. Temporal discretization as follows:
        i. Steady state groundwater flow pre-conditioning model representing conditions pre-2010.
        ii. Transient historic flow and transport model from January 2010 to January 2013 will used to compare simulated and observed results.
        iii. Transient predictive flow and transport model from January 2013 to January 2088 will evaluate the current remedy for Cr(VI) in the first water bearing unit of the RUM.
2. Development: define and refine input parameters and contaminant source representations.
    a. Simulated head fields from both the steady state and transient historic simulations will be compared to observed hydraulic head measurements for January 2010 to January 2013 period to evaluate the degree to which the model replicates historic measurements. The results will be used to adjust model input hydraulic conductivity values;
    b. Simulated concentrations from the transient historic simulation will be compared to observed concentration measurements for January 2010 to January 2013 period to evaluate the degree to which the model replicates historic measurements. The results may be used to adjust model input transport parameters;
    c. Evaluate possible Cr(VI) sources including:

i. The Cr(VI) distribution based on available Cr(VI) concentration data from wells completed in the semi-confined aquifer, and

ii. Cr(VI) conceptualized to occupy portions of the RUM aquitard between the unconfined aquifer in the Hanford formation and the semi-confined aquifer; the possible sources are based on information found in reports and available data, and are defined in terms of location, extent, and concentration;

iii. Develop model baseline conditions and sources for Cr(VI) in the RUM

3. Application: apply the numerical flow and transport model to evaluate CSMs.

   a. Run the predictive Cr(VI) transport model for 75 years to calculate the change in groundwater Cr(VI) concentrations over time for both the no action scenario and the selected remedial alternative. Complete the simulation of each of the CSMs listed in Section 2.

4. Post-process the simulation results to produce usable tabular and graphic summary of simulated Cr(VI) concentration for comparison of the remedial scenario and each CSM listed in Section 2.

4 Assumptions and Inputs

This section provides the relevant assumptions made and inputs necessary to perform the calculation. First, the assumptions are discussed. This is followed by a discussion of the inputs used to develop the numerical fate and transport simulation for Cr(VI) in the semi-confined aquifer.

4.1 Assumptions

Several assumptions were made as part of the construction of the numerical model, as listed below. The first three listed assumptions are inherent in the equations used to solve fate and transport. The other assumptions will continue to be refined throughout the life of remediation of the contamination in the semi-confined aquifer as more data are collected. The numerical modeling presented herein represents a range of possible conceptual models for the semi-confined aquifer and give and initial evaluation of possible outcomes of fate and transport and remedial actions regarding the Cr(VI) contamination in the semi-confined aquifer.

1. Water is the only liquid phase flowing through the saturated porous media in the model domain according to the laminar conditions assumed for Darcy's Law and with a constant water density.
2. Flow through the vadose zone is not explicitly considered.
3. Solute fluxes from the vadose zone are negligible.
4. Solute fluxes from the unconfined aquifer (Hanford formation) are negligible.
5. The primary transport processes simulated include advection, and diffusion.
6. For Cr(VI) sources represented by the current distribution of Cr(VI) in the semi-confined aquifer, contouring of available data provides a reasonably accurate representation of the Cr(VI) distribution.

7. For Cr(VI) sources located in the RUM aquitard overlying the semi-confined aquifer, these sources originated from leaks, spills, and discharges that occurred at the surface and were associated with 100-H area facilities.

8. Assessing fate and transport in the unconfined aquifer is beyond the scope of this ECF. Although layer 1 of the model represents flow in the unconfined aquifer, no concentrations will be simulated and any results of the model should not be used to evaluate remedial actions in the unconfined aquifer.

9. Model boundary conditions represent the forces or processes driving water flow and solute transport sufficiently well for the intended use of model results.

10. Boundary conditions on the eastern edge represent flow of water to and from the Columbia River and estimates possible leakage of Cr(VI) to the river.

11. The initial head and solute concentrations values are known sufficiently well for the intended use of the model results.

12. Hydraulic and transport parameter values are known sufficiently well for the intended use of the model results.

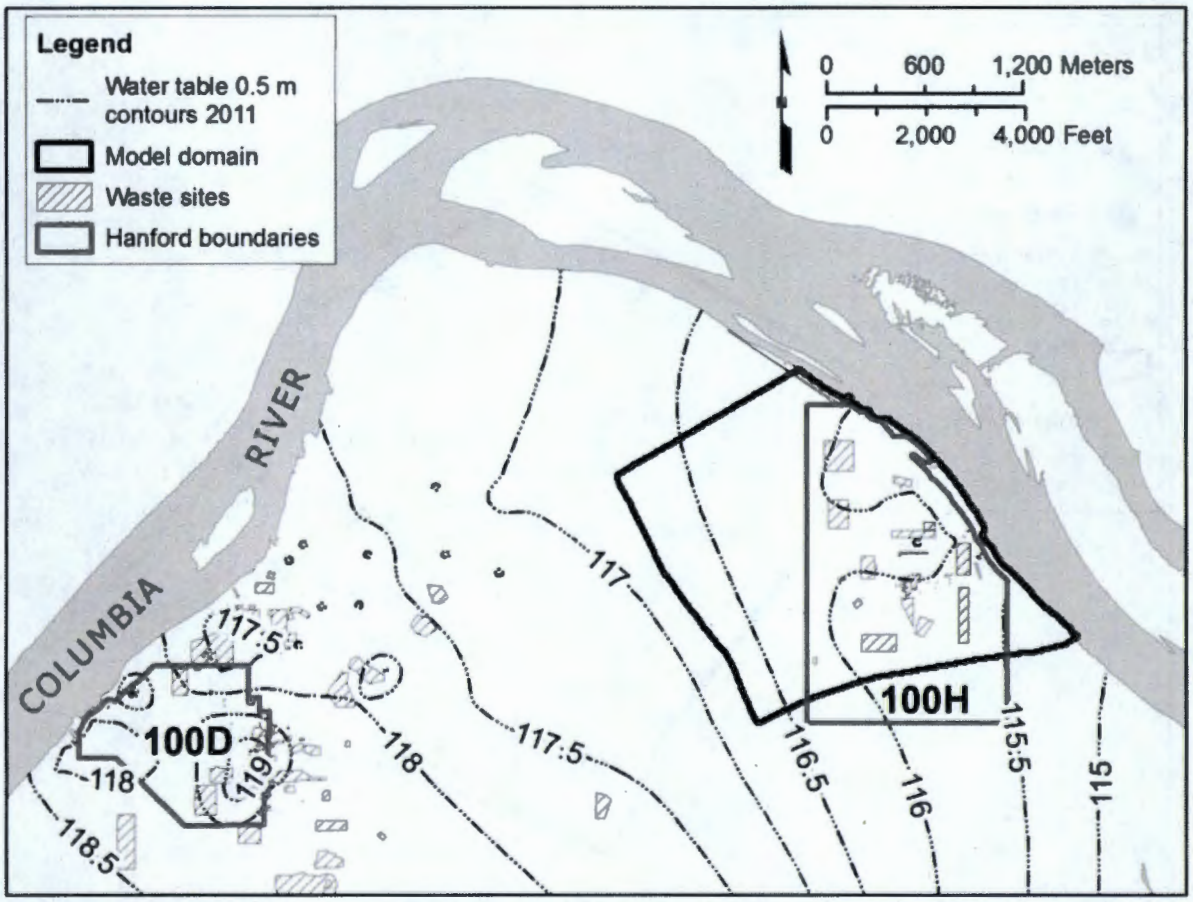
13. The semi-confined aquifer is continuous across the model boundary.

4.2 Model Domain

The model domain is shown in Figure 5 and Figure 6. The northern, southern, and western boundaries were placed far enough from the local area of interest such that the flow and transport solutions were not directly influenced by the boundaries. The western boundary generally runs northwest to the southeast, roughly parallel to the Columbia River to the east. The western boundary was aligned with wells 699-94-43, 699-95-45, and 699-97-45B where hydraulic head measurements were available that could be used in assigning boundary conditions to the model boundary. The northern and southern boundaries extended from the western boundary to the river, generally following a groundwater flow path. The eastern model boundary coincided with the western edge of the Columbia River. The model grid was uniformly discretized with cell dimensions of 10 m by 10 m. The grid origin is at easting and northing coordinates 575730 and 153840 m, respectively in the Washington State Plane South NAD 1983 FIPS 4602 projection. No grid rotation was used in the model grid.

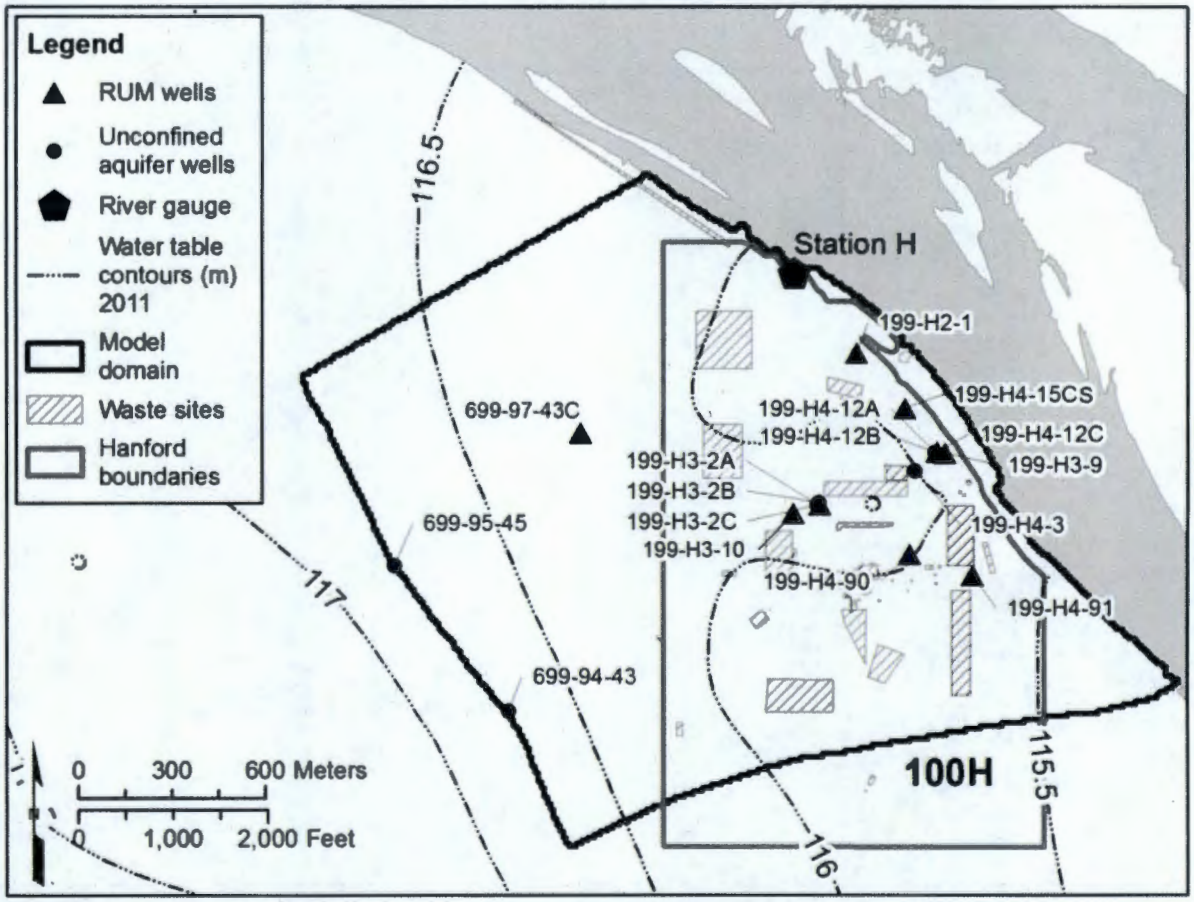
The model was divided into four layers vertically. The top layer represents the unconfined aquifer occupying the Hanford formation. The second and third layers represent the RUM Formation (aquitard) except locally where thin deposits of the Ringold Formation unit E exists (Figure 7) between the RUM and Hanford formation. Layer 4 represents the semi-confined aquifer (first water-bearing unit in the RUM). The base of layer 4 is simulated as a no flow barrier that represents the underlying RUM aquitard.

Thicknesses of the different formations and model layers vary (Figure 7). Thickness of the Hanford formation varied between approximately 14 m and 18 m. The RUM aquitard varies from only a few meters near the Columbia River to over 25 m further inland. There is limited data with which to map out the upper and lower surface of the first water bearing unit of the RUM accurately. As a result, the thickness was made a constant 7 meters based on the average thickness observed in borings that were drilled through the unit (199-H2-1, 199-H3-2C, 199-H3-9, 199-H3-10, 199-H4-12C, 199-H4-15CS, 699-97-43C, 699-97-45B). Based on geologic contacts of the semi-confined aquifer in wells 199-H3-9 and 199-H3-10, the aquifer was assumed to dip 1° to the west south west.



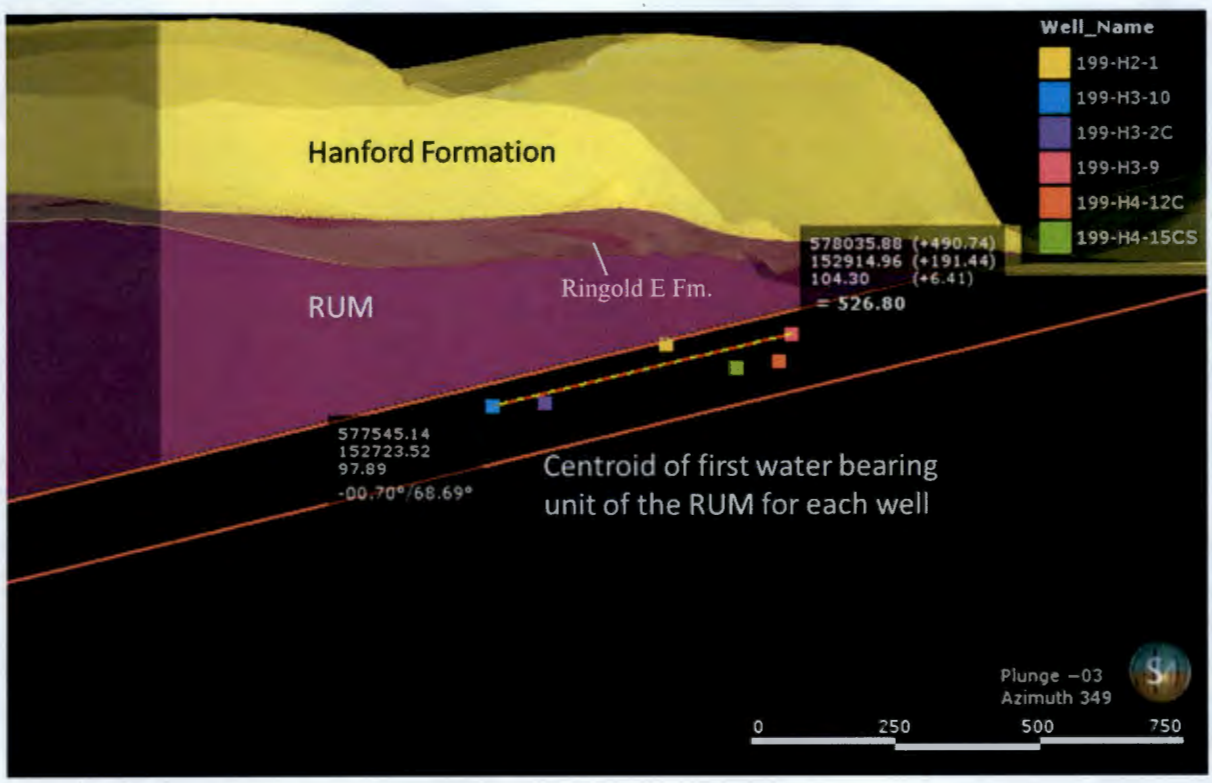
Note: Water table contours represent the unconfined aquifer (DOE/RL-2011-118).

Figure 5. Hanford 100-D and 100-H Areas and 100-H Model Domain



Note: Water table contours represent the unconfined aquifer (DOE/RL-2011-118).

Figure 6. Hanford 100-H Area with Model Domain



Note: vertical exaggeration: 10:1.

Figure 7. East-west Cross Section Through the 100-H Model Domain

4.3 Groundwater Flow

4.3.1 Flow Processes

Groundwater flow in the 100-H area is generally from west to east towards the Columbia River. Saturated flow conditions were modeled. The top layer of the model, representing the aquifer in the Hanford formation, was modeled as an unconfined aquifer. All other layers were modeled as confined layers since it has not been determined if the lower aquifer is confined, semi-confined, or leaky. The models were run in transient mode. The pumping rates of wells in the model are in Attachment B (ECF-100HR3-12-0011, *Analysis of Slug Test Data at the 100-HR-3 OU*).

4.3.2 Boundary Conditions

The four model layers span multiple geologic formations that may introduce significant vertical gradients within the model domain. The possible existence of vertical gradients between units near 100-HR-3 is discussed in Section 2. The western boundary was selected at a location where multiple wells, 699-97-45B, 699-94-43, and 699-95-45, can be used to estimate the hydraulic head for the simulation period of 2010 thru 2012. The heads for these three wells do not provide a definite trend in terms gradient from north to south. Therefore, the boundary will be simulated using the average of the three wells over time. The average heads for each stress period from were used to derive monthly head boundary conditions for the western boundary for the 2010 through 2012 period. Each of these wells is screened in the unconfined aquifer. The possibility of vertical gradients will be simulated by adding and subtracting to the average head condition for each stress period based on the peak gradients as discussed in Section 2. The western boundary for the predictive model will be the three-year average of the three years of data at 117.2 m.

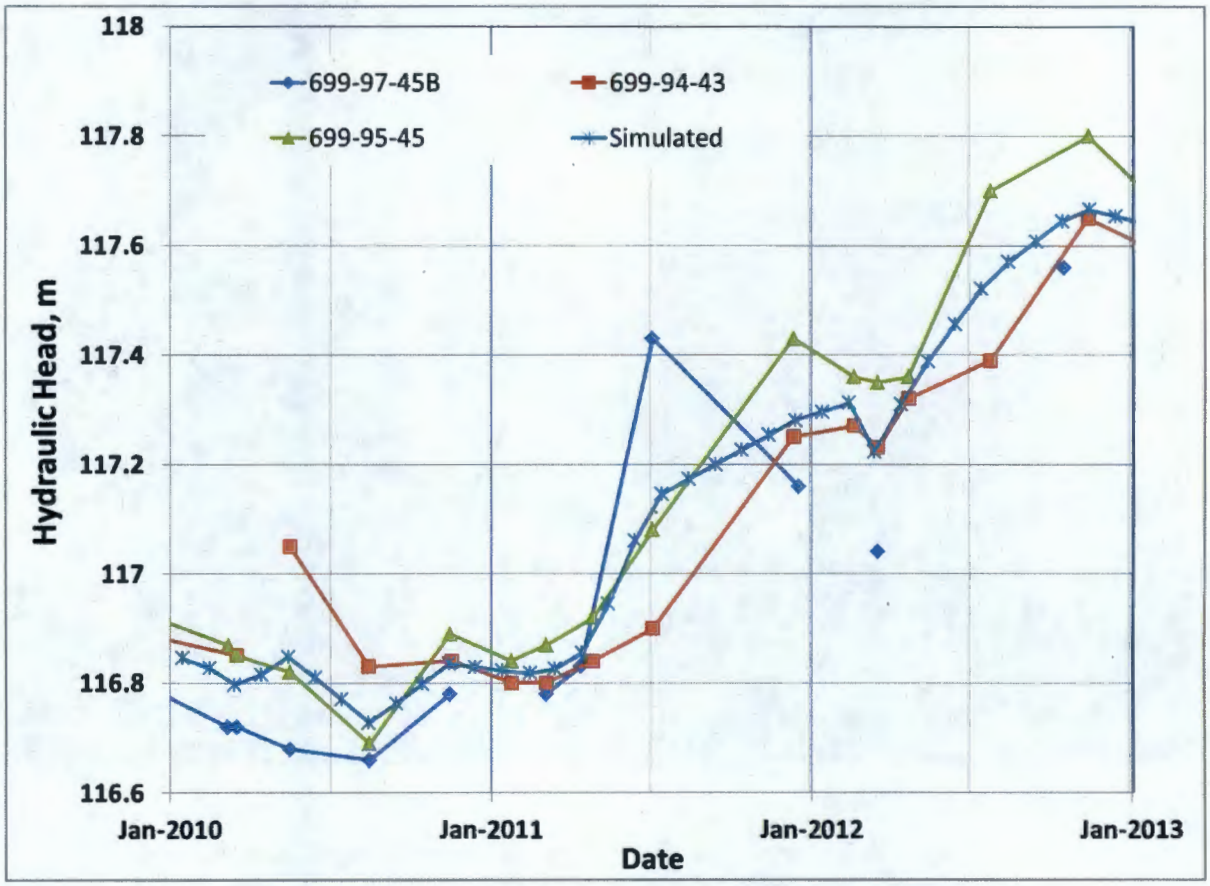


Figure 8. Western Boundary Well Heads Used to Define Transient Boundary Conditions

The northern and southern boundaries were selected to follow approximate groundwater flow paths from the western boundary to the Columbia River based on contours of 2011 head data. These are assumed to be no-flow boundaries.

The eastern boundary was coincident with the Columbia River. For the 2011-2012 model, the FHB package (Harbaugh et al., 2000) was used to specify head-dependent flux boundary conditions at the river. A head dependent flux boundary requires a conductance term and a river stage in order to define the boundary. Riverbed conductance was the same as that used in the 100 Area groundwater model (SGW-42673). The head values representing the river stage were from the automated water level network (AWLN) "H-River Gauge" within a short distance to the north of the 100-H area (Figure 9). As applied in the model the stage assigned to the cell nearest station was equal to the recorded value at H-River Gauge. Model cells to the north and south were H-River Gauge were altered based on the average gradient of the river. The average gradient is consistent with the value used in the 100 Area groundwater model (ECF-100HR3-11-0114, *Modeling of RI/FS Design Alternatives for 100-HR-3*).

Two MODFLOW packages were used to simulate the river condition, the flow and head boundary package (FHB) and river (RIV) packages. The FHB package allowed for implementing daily river stage within the one-month stress periods in the model for the transient historical model. The stages were assigned based on historical daily data downloaded from the AWLN for H-River Gauge for 2010 through 2012 flow models (Figure 7). The RIV package (Harbaugh et al., 2000) was used to specify head-dependent flux boundary conditions at the river in the 75-year predictive model. For the predictive

transport model, the average monthly river stages, derived from daily data at AWLN H-River Gauge for 2010 to 2012, were used for the first 25 years of the 75-year simulation. An average value of 115.6 m at the cell closest to H-River Gauge was used for the remaining 50 years with an applied gradient.

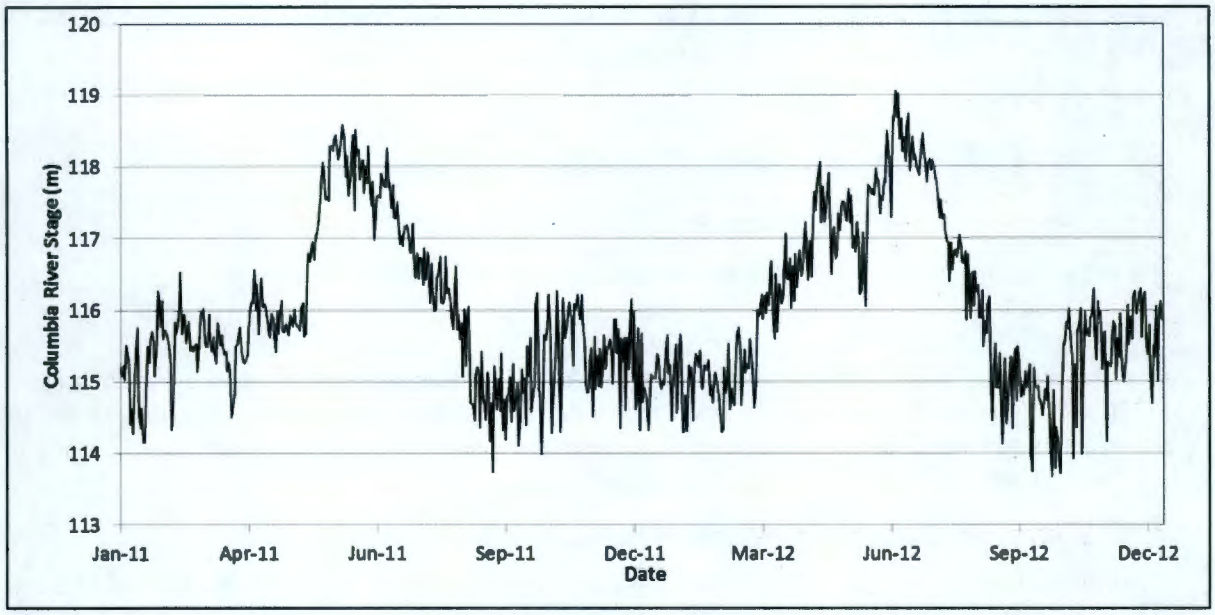


Figure 9. Daily River Stage at Gaging Station H for 2011 and 2012

4.3.3 Flow Parameters

Flow parameters used in the flow model calculation include hydraulic conductivity and specific storage. Initial hydraulic conductivity was assigned as a constant value for each geologic unit based on available data (Table 1) (DOE, 2012; ECF-100HR3-12-0011; SGW-40781, *100-HR-3 Remedial Process Optimization Modeling Data Package*,). Hydraulic conductivity for the Hanford formation and Ringold Formation unit E were similar, ranging between 22.4 m/d and 52.5 m/d. Hydraulic conductivity for the semi-confined aquifer, estimated at 36.6 m/d from aquifer test results, was further calibrated based on hydraulic head measurements at five wells in this unit (see Section 6). Hydraulic conductivity was modeled as anisotropic with $K_v = 0.1 \times K_h$. Specific storage was similar for all four units, ranging between 1.4×10^{-4} m^{-1} and 3.4×10^{-4} m^{-1} (Table 4).

Table 4. Initial Hydraulic Parameters for the Different Units

Geologic Unit	K_h (m/d)	K_v (m/d)	S_s (1/m)
Hanford formation	52.5	5.25	2.4×10^{-4}
Ringold Formation unit E	22.4	2.24	3.4×10^{-4}
RUM aquitard	0.05	0.005	1.4×10^{-4}
Semi-confined aquifer (RUM first water-bearing unit)	36.6	3.66	1.4×10^{-4}

4.4 Contaminant Transport

4.4.1 Transport processes

Processes simulated in the transport model were the same as those modeled in ECF-100HR3-11-0114 for Cr(VI) for the unconfined aquifer. These processes include:

- Advection
- Dual-domain system with mobile and immobile components
- Mass transfer occurs between the mobile and immobile domains
- Equilibrium partitioning of Cr(VI) between the soil and the immobile domain

4.4.2 Boundary Conditions

Simulated transport of contaminants across the model boundary was assigned the default condition for MT3D-MST. Specifically, where water enters the model domain the concentration is assigned a value of zero. Where water leaves the model domain, it is assumed to have the same concentration as the water in the numerical cell where the water exits at the boundary.

4.4.3 Sources and Baseline Conditions for Hexavalent Chromium

Two different CSMs for the Cr(VI) distribution were evaluated in this ECF. These are 1) an estimate for the max concentration of Cr(VI) distribution in the semi-confined aquifer over the time period of 2010 to 2013 where no residual source of Cr(VI) in the RUM is considered and 2) the same maximum concentration distribution in CSM 1 with an additional contribution of Cr(VI) from a residual source in the RUM. The maximum concentration distribution in the semi-confined aquifer was developed as a separate calculation using Cr(VI) sample data at wells screened in the semi-confined aquifer interpolated using the LeapFrog Hydro®[1] software. The concentration distribution shown in Figure 10 is documented in ECF-100HR3-13-0040. The estimated residual source in RUM sediments was developed as part of this ECF, and is discussed further in Section 6.3. Simulation of the fate and transport of the Cr(VI) plumes requires the establishment of the baseline condition for Cr(VI) in the subsurface for each of the source models.

In Section 2.6.1, the CSM describing a possible residual source of Cr(VI) in the RUM sediments was outlined. In order to evaluate this condition an estimate and location of the hypothetical Cr(VI) contamination in the RUM is needed. To estimate a baseline condition for contamination in the RUM, the location of Cr(VI) sources was estimated. The Cr(VI) in these source areas, that may have contributed to Cr(VI) concentrations present in the semi-confined aquifer (first water bearing unit of the RUM), are listed in Table 23. An estimate for effluent concentrations was presented as part of this discussion. These estimates were used to determine a hypothetical concentration that may or may not have migrated into the RUM aquitard. The estimated Cr(VI) concentration is not likely to have migrated at the same concentration as the estimates provided in the table because lateral flow towards the river or extraction wells dominates the advection of Cr(VI) in the unconfined aquifer (SGW-46279). A comparison of lateral flow velocity to vertical flow velocity calculated using Darcy's law shows the ratios of speed of movement vertically to laterally, assuming conditions at present time in the unconfined aquifer and the largest downward gradient as discussed in Section 2, provides a ratio of less than 1% as shown in Table 5. Given the dominance of lateral flow to vertical flow, it was assumed that the concentration that could

[1] LeapFrog Hydro® is a registered trademark of ARANZ, Christchurch, New Zealand.

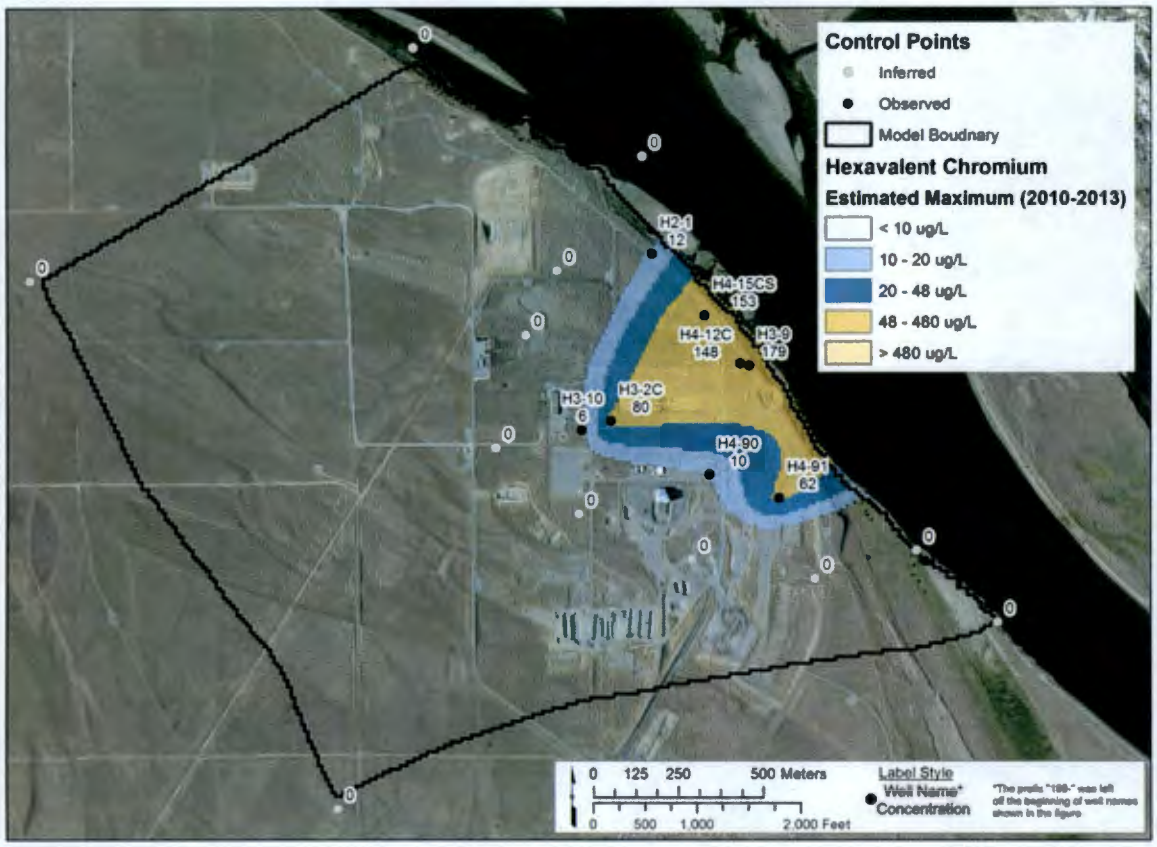


Figure 10. Estimated Concentration of Cr(VI) in the Semi-Confined Aquifer based on Observed and Inferred Control Points Shown

have migrated into the RUM aquitard is low. Therefore, the RUM aquitard source concentration was set to 10% of the estimated effluent concentrations listed in Table 2. This value reflects the dominance of lateral flow while also maintaining a higher ratio than what is expected based on observed hydraulic head data. The estimates for effluent in the unconfined aquifer and final concentration used as a hypothetical RUM source of the various waste site sources that are shown in Table 5. These concentration values were assigned to Layer 3 of the numerical model above the semi-confined aquifer in simulations where a residual source was evaluated. The areal extent of the footprint of waste sites was increased based on the assumption that some lateral spreading as the plume migrated vertically.

Estimated residual source concentrations provided by this ECF are intended to provide a conservatively high concentration in order to perform bookend calculations with the numeric model. As stated in Section 2, no samples collected in the RUM sediments to date indicate concentrations near those listed in Table 6 (DOE/RL-2010-95). This process provides an estimate based on disposal records at waste sites at 100-H and observed data at downgradient wells to these waste site, but it this is unsubstantiated by sample data in the RUM sediments. It is included as a worst-case scenario of possible contamination in the RUM. This analysis is not meant to illustrate that there is or is not a residual source of Cr(VI) in the RUM sediments at this time.

Table 5. Estimated Ratio of Lateral Flow to Vertical Flow Assuming High Downward Vertical Gradient

Parameter	Lateral Hanford formation[1]	Vertical through RUM[2]
Head Change (m)	1	0.3
Distance (m)	1014	10.8
k, (m/day)[3]	52.5	5.00E-03
Velocity (m/day)[4]	5.18E-02	1.39E-04
Percent Ratio	0.27%	

[1]Gradient information is based on contours presented in DOE/RL-2011-118.

[2]Downward gradient is based on maximum of observed wells shown discussed in Section 2 and the average thickness of the RUM within the contaminant plume.

[3]The hydraulic conductivity values are taken from simulated values in this ECF

[4]Velocity is based on Darcy's Law (velocity = hydraulic conductivity * head gradient)

Table 6. Hexavalent Chromium Sources Used in the Transport Model

Facility	Waste Site	Estimated Effluent Concentrations in the unconfined Aquifers (µg/L)	Modeled Cr(VI) Concentration (µg/L)
107-H Liquid Waste Disposal Trench	116-H-1	1,000	100
1608-H Liquid Waste Disposal Trench	116-H-2	1,000	100
116-H-4 Crib	116-H-4	0	0
183-H Solar Evaporation Basins	116-H-6	4,000	400
107-H Retention Basin	116-H-7	350	35
118-H-6 Reactor Fuel Storage Basin	118-H-6:3	0	0
190-H Sodium Dichromate Handling Facilities	100-H-46	4,000	400

4.4.5 Transport Parameters

Parameters in the transport model are shown in Table 7. These were which were obtained from ECF-100HR3-11-0114 which documents the transport of Cr(VI) at 100-HR3 for the unconfined aquifer.

Table 7. Transport Model Parameters

Parameter	Value
Porosity, mobile domain	0.18
Porosity, immobile domain	0.045
Distribution coefficient, mobile domain (mL/g)	0
Distribution coefficient, immobile domain (mL/g)	0.3
Dual-domain mass transfer rate (1/day)	0.01
Dispersivity (m)	0

4.5 Simulation Periods and Remedial Alternatives

Three simulation timeframes were used for this calculation: a historic steady state simulation, a historic transient simulation, and a predictive transient simulation. The steady state historic simulation was used to establish the initial head field for simulation. The boundary conditions for this simulation matched those found in the first stress period of the historic transient simulation. The start and ending dates for the historic transient simulation were January 1, 2010 and December 31, 2012, respectively. This period was selected because it envelopes the time frame where historic pumping records, water levels, and river stage data were available. Simulations for the historic transient runs were executed on a daily time step with monthly stress periods. For the predictive transient simulation, the start and ending dates were January 1, 2013 and December 31, 2087. This simulation was completed using monthly stress periods for the first 25 years and yearly stress periods thereafter, similar to the simulations for the unconfined aquifer at 100-HR-3 documented in SGW-47269.

Two remedial scenarios were evaluated: Scenario A and Scenario B. Scenario A is the No Action Scenario (DOE, 2012). No action here means that remediation would not be implemented to alter the existing conditions. For this scenario, it is assumed that all site remedial activities and interim actions, with the possible exception of backfilling any unsafe open excavations, will be discontinued in December 2012. Scenario B uses pump-and-treat for groundwater remediation at 100-H. The groundwater model simulation for Scenario B expands the interim action pump and-treat system to include additional extraction and injection wells, thus encompassing a larger area of the COC plumes to expedite hydraulic containment and recovery (DOE, 2012).

5 Software Applications

5.1 Approved Software

MODFLOW-2000-MST, MT3D-MST, Excel®, PEST, ArcGIS®[2], and Groundwater Vistas™[3] software programs were used for this calculation. These are CH2M HILL Plateau Remediation Company (CHPRC) approved software, managed and used in compliance with the requirements of PRC-PRO-IRM-309, *Controlled Software Management*. MODFLOW-2000-MST and MT3D-MST are approved calculation software and Excel®, PEST, ArcGIS, and Groundwater Vistas are approved support software (CHPRC-00258).

The Tellus Linux®[4] cluster that is owned by CHPRC and operated by Mission Support Alliance. The Tellus cluster consists of 16 Dell® PowerEdge® M610 blade servers. Each with 2× Intel® Xeon® X5670 CPU's (6 cores/CPU, 2.93 GHz), 96GB of RAM, and 10Gbps Ethernet cards. The management node is a Dell® PowerEdge® M710 blade server with 2x Intel® Xeon® X5550 CPU's (4 cores/CPU, 2.7 GHz, 96 GB of RAM. As given by the command "uname –a", the operating system details are:

```
Linux tellusmgmt.rl.gov 2.6.18-308.4.1.el5 #1 SMP Tue Apr 17
17:08:00 EDT 2012 x86_64 x86_64 x86_64 GNU/Linux
```

Microsoft Excel®[5] spreadsheets were used to tabulate average monthly and long-term hydraulic head and river stage data for model input, and chart modeling results produced by MODFLOW-2000 and MT3D-MST. Groundwater Vistas™ was used in pre-processing some input files and ArcGIS® was used in pre- and post-processing simulation results. These calculations and analysis were performed on a laptop computer with U.S. DOE ID WF16209. The hardware is a Dell® Latitude®[6] E6400 with a 2.26-GHz Intel® Core™ 2 Duo CPU E8200 processor and 3 GB of RAM loaded with the HLAN Windows® XP Image Version 3.0.1.0 operating system.

The results of CHPRC acceptance testing (CHPRC-00261) demonstrate that the MODFLOW-2000/MT3D-MST software is acceptable for its intended use by the CHPRC. Installations of the software are operating correctly, as demonstrated by the RANSAC Linux® cluster system.

5.1.1 Approved Software MODFLOW-2000-MST and MT3D-MST

<u>MODFLOW</u>

- Software Title: MODFLOW-2000-MST
- Software Version: CHPRC Build 6 (executable "mf2k-mst-0006dp.x"), double precision compilation
- Hanford Information System Inventory (HISI) Identification Number: 2517 (Safety Software, Level C)
- Authorized Workstation type and property number: Linux® Cluster, Tellus Modeling Platform

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[2] ArcGIS® is a registered trademark, or service mark, of ESRI in the United States, the European Community, or certain other jurisdictions.

[3] Groundwater Vistas™ is a trademark of Environmental Simulations, Inc.

[4] Linux® is a registered trademark of Linus Torvlads in the United States and other countries.

[5] Excel is a registered trademarks of Microsoft Corporation in the United States and other countries.

[6] Dell® and Latitude® are registered trademarks of Dell, Inc.

- Authorized User: T.J. Budge
- CHPRC Software Control Documents:
  - CHPRC-00257, *MODFLOW and Related Codes Functional Requirements Document*
  - CHPRC-00258, *MODFLOW and Related Codes Software Management Plan*
  - CHPRC-00259, *MODFLOW and Related Codes Software Test Plan*
  - CHPRC-00260, *MODFLOW and Related Codes Requirements Traceability Matrix*
  - CHPRC-00261, *MODFLOW and Related Codes Acceptance Test Report*

MT3D-MST

- Software Title: MT3D-MST
- Software Version: CHPRC Build 0006 (executable name "mt3d-mst-0006dp.x") , double precision compilation
- HISI Identification Number: 2518 [Support Software; CHPRC-00258]
- Authorized Workstation type and property number: Linux® Cluster, Tellus Modeling Platform
- Authorized User: T.J. Budge
- CHPRC Software Control Documents:
  - CHPRC-00257, *MODFLOW and Related Codes Functional Requirements Document*
  - CHPRC-00258, *MODFLOW and Related Codes Software Management Plan*
  - CHPRC-00259, *MODFLOW and Related Codes Software Test Plan*
  - CHPRC-00260, *MODFLOW and Related Codes Requirements Traceability Matrix*
  - CHPRC-00261, *MODFLOW and Related Codes Acceptance Test Report*

5.1.2 MODFLOW & Related Codes Support Software

Groundwater Vistas®: (*Guide to Using Groundwater Vistas* [Rumbaugh and Rumbaugh, 2007].) Provided graphical tools used for model quality assurance and model input/output review.

ArcGIS®[7]: (The ESRI Guide to GIS Analysis, Volume 1: Geographic Patterns and Relationships [Mitchell, 1999].) Provided visualization tool for assessing simulated plume distributions, identifying extraction/injection well coordinates and mapping auxiliary data.

PEST: Pre- and post-processing utilities distributed with the support software PEST were used to facilitate efficient simulation execution.

ARANZ LeapFrog-Hydro®: Used to assign model layers based on current interpretation of geologic units present within the model domain.

Microsoft Excel®: Developed model input files and used to calculate average monthly and daily hydraulic head and river stage estimates.

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[7] ArcGIS® is a registered trademark of ESRI Corporation.

5.1.3 Software Installation and Checkout

Safety Software (MODFLOW-2000-MST and MT3DMS-MST) was checked out in accordance with procedures specified in CHPRC-00259 Rev 2. Executable files were obtained from the Software Owner, installation tests identified in CHPRC-00259 Rev 2 were performed and confirmed, and Software Installation and Checkout Forms were completed and approved for installations used to perform model runs reported in this calculation. Copies of the Software Installation and Checkout Forms for the authorized users and authorized workstations for software used that requires this documentation are provided in Appendix A to this ECF.

5.1.4 Statement of Valid Software Application

The preparers of this calculation attest that the software identified above, and used for the calculations described in this calculation, is appropriate for the application and used within the range of intended uses for which it was tested and accepted by CHPRC. Because MODFLOW 2000-MST and MT3D-MST are graded as Level C software, use of this software is required to be logged in the HISI. Accordingly, this environmental calculation has been logged by the software owner in the HISI under Identification Number 2517 and 2518. The software was used within its limitations.

6 Calculation

6.1 Flow Model

A sensitivity analysis was performed for select parameters to determine if modified parameter values would result in lowering the RMSE of the observed and simulated heads of the five wells shown in Table 8. The hydraulic conductivity and specific storage parameters of layers representing the RUM aquitard and the RUM first water-bear unit were varied one parameter at a time near the original values. Additionally, the conductivity of each head dependent boundary cell representing the Columbia River was varied by a factor of +/- two and three. The mean error (ME) and root mean square error (RMSE) of observed and simulated heads for each well based on the final flow parameter set are shown in Table 8. Comparison of simulated and observed heads is shown in Figure 11. The mean error for all five wells is net-neutral. The hydraulic conductivity of the semi-confined aquifer was altered from 36.6 m/d to 10 m/d, in order to improve the match between the observed and simulated heads.

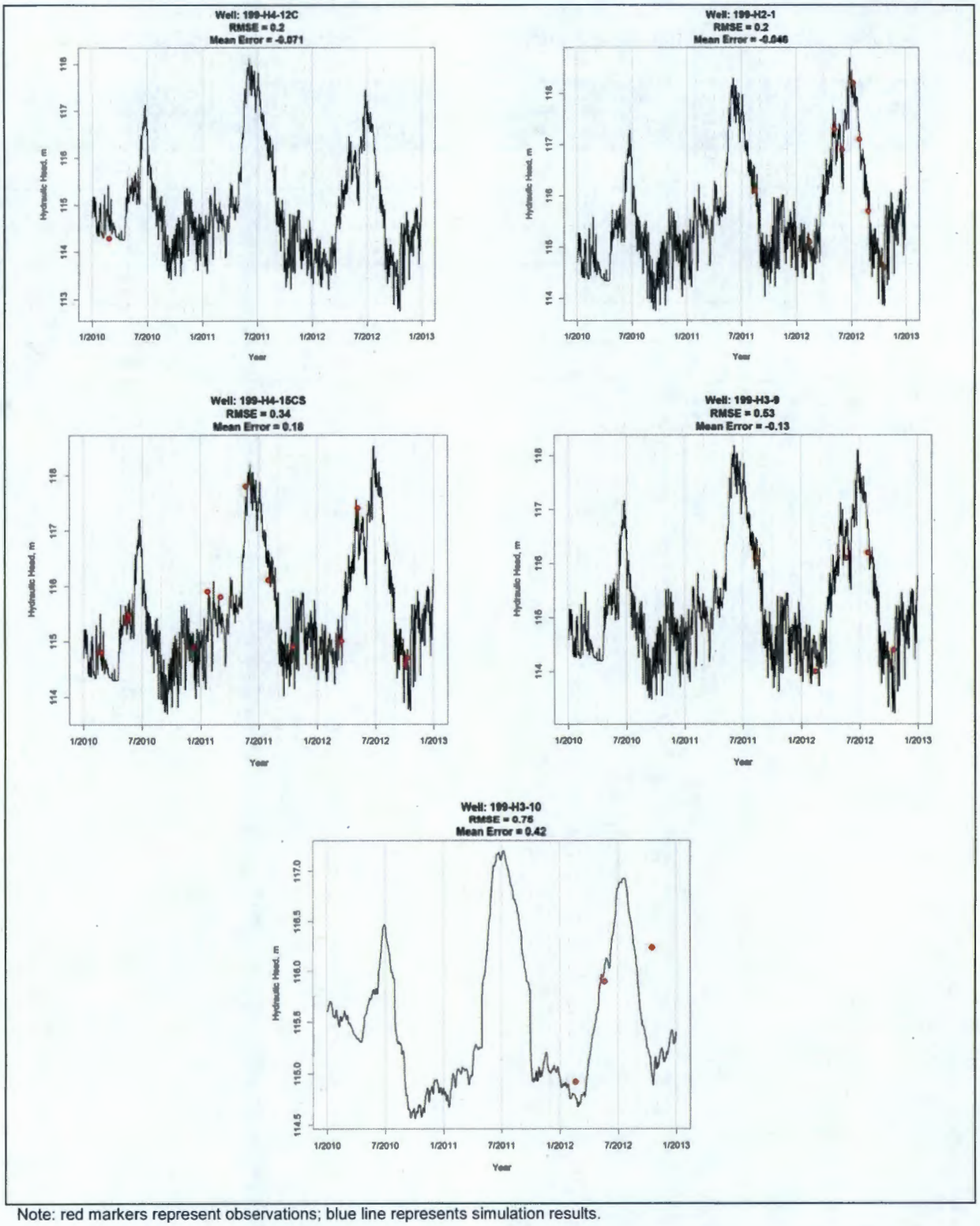
The effect of further changes the hydraulic conductivity and specific yield parameters values on the sum of the RMSE at the five wells of interest was minimal, less than 0.1 % of the sum of the original RMSE values. Changing the conductivity of the head dependent boundary cells representing the Columbia River also had a minimal effect on RMSE of the five wells of interest, changing the sum of the RMSE by less than 0.06% of the original value. Based on the minimal improvement in the sum of the RMSE of the observed and simulated heads at the five well of interest that came at a cost of biasing the mean error of the five wells, only the hydraulic conductivity value for the semi-confined aquifer was altered.

Table 8. Mean Error and Root Mean Square Error for Wells in the Unconfined and Semi-Confined Aquifers

Well	Number of Measurements	ME (m)	RMSE (m)
699-97-43C	2	-0.071	0.2
199-H2-1	8	-0.04	0.2
199-H4-15CS	13	0.17	0.34
199-H3-9	5	-0.13	0.53
199-H3-10	3	0.42	0.75
Average (all well data)		0.08	0.36

ME = mean error

RMSE = root mean square error

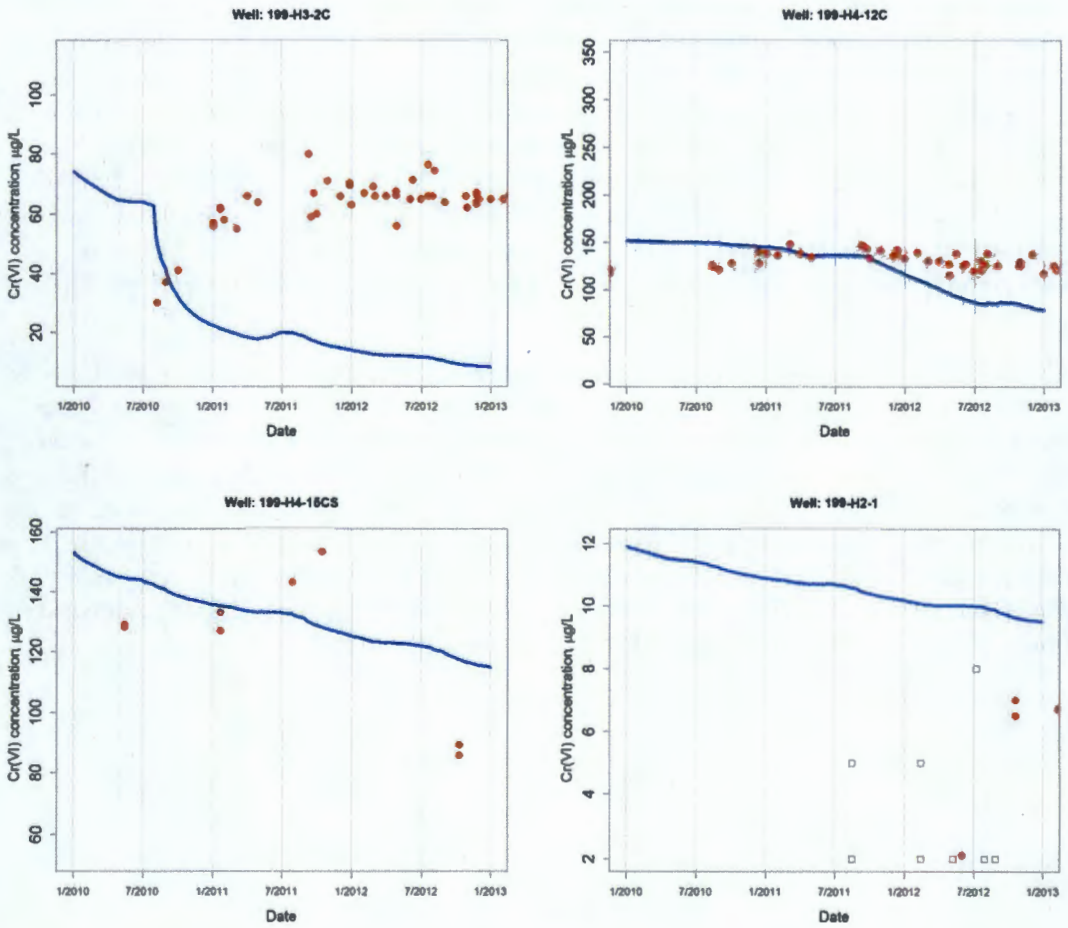


Note: red markers represent observations; blue line represents simulation results.

Figure 11. Simulated and Observed Hydraulic Heads for Wells Screened in the Semi-confined Aquifer

6.2 Transient Historic Fate and Transport

Simulated output from the transient historic fate and transport simulation were compared to the observed data for well screened in the semi-confined aquifer. The simulation consisted of calendar years 2010 through 2012. The initial distribution of Cr(VI) for simulation time zero was the maximum concentration condition documented in ECF-100HR3-13-0040 and shown in Figure 12. No residual source from the RUM was considered as part of this simulation. Figure 12 shows a comparison between the simulated results and the observed concentration data at several wells within the first water bearing unit of the RUM. Well 199-H4-12C shows a relatively good match at initial periods. Towards the end of the simulation, the concentration level declines quicker than observed. Well 199-H4-15CS appears to follow the same trend at the midpoint of the simulation. However, by the end of the simulation the concentration is higher than observed. Well 199-H3-2C shows almost the opposite behavior of what the model predicts. The model predicts a dramatic drop as pumping in the well extracts Cr(VI) from the aquifer. This well is located toward the outer edge of the plume boundary as defined for this simulation. Therefore, the simulated concentrations drop dramatically. One of two things is possible. Either, the plume extent is not sufficient or there is another source of Cr(VI). SGW-47776 indicates that there is communication between 199-H3-2C and the upper aquifer. This communication may be indicative of a FEP that was not accounted for in the model construction.



Note: red markers represent observations; blue line represents simulation results.

Figure 12. Simulated and Observed Cr(VI) Concentrations for Wells in the Semi-confined Aquifer

6.3 Hexavalent Chromium Remedial Scenario Evaluation

A set of 24 simulations were completed to evaluate the range of CSMs presented in Section 2. These include:

- Vertical gradients between geologic units,
- dual domain vs. single domain, and
- residual source in RUM material.

Each of these CSMs was evaluated with respect to remedial Scenario A (no action) and Scenario B (pump-and-treat). In Scenario A, all pumping is turned off at the end of 2012. In Scenario B, remedial pumping continues for 25 years at the rates listed in Table 9. At the end of 25 years, all pumping is ceased under Scenario B and the simulation continues for the remaining 50 years. Table 10 provides a summary of the time (in years) required for the concentration in the first water bearing unit of the RUM to fall below cleanup levels for each of the 24 simulations. Figure 13 and Figure 14 show example time-series charts that summarize the results of each simulation. These particular charts represent the simulation with dual domain, downward gradient, the RUM source, and pumping and single domain, upward gradient, no RUM source, and no pump-and-treat respectively. They represent the extreme estimates for behavior of the Cr(VI) plume. Charts for each simulation are included in Attachment C. Attachment C also provides plan view contours of the simulated plume over time. Table 10 provides a of concentration within the semi-confined aquifer as an arithmetic average, 90th percentile of all model cells with a concentration above 10% of the cleanup level, 10 μg/L, and the simulated peak concentration at any cell within the semi-confined aquifer. A comparison of the times to reach the cleanup level is provided in the following sub-sections split based on the several CSMs evaluated in this ECF. While Table 10 includes the number of years to reach cleanup level, for a screening level model the relative difference in the times can indicate which of the parameters is significant in assessing the predicted effectiveness of the remedial scenario.

All 24 simulations produced a peak, 90th percentile, and mean concentration that fell below cleanup level within the 75-year simulation period. When no source was present in the RUM aquitard and the pump-and-treat system was simulated, the time to attain the cleanup level for the 90th percentile value for the aquifer ranged from 15 to 22 years. These simulations were the ones that attained cleanup levels the fastest. When the source in the RUM aquitard was included and no pump-and-treat system was simulated, and the time to attain the cleanup level ranged from 32 to 58 years. These simulations represent the "book end" calculations reached by these models for evaluating when Cr(VI) concentrations in the aquifer will fall below the cleanup level. The sub-sections that follow discuss the combination of CSMs simulated as part of this ECF and discuss some of the trends that are apparent in the results.

Table 9. Wells and Pumping Rates Used in Scenario B

Well Name	Pumping (-) / Injection Rate (+) (gpm)	Well Name	Pumping (-) / Injection Rate (+) (gpm)
199-H1-1	-14	199-H3-27	50
199-H1-2	-6	199-H3-2C*	-50
199-H1-34	-19	199-H3-4	-56
199-H1-35	-19	199-H4-12C*	-30
199-H1-36	-8	199-H4-14	10
199-H1-37	-19	199-H4-69	-20
199-H1-38	-20	199-H4-71	35
199-H1-39	-21	199-H4-72	35
199-H1-40	-15	199-H4-73	35
199-H1-42	-21	199-H4-74	40
199-H1-43	-21	199-H4-75	-15
199-H1-45	-21	199-H4-76	-14
199-H3-25	50	199-H4-77	-8
199-H3-26	50	199-H6-2	35

* Wells located in semi-confined aquifer (RUM first water-bearing unit); all others in unconfined aquifer.

Table 10. Comparison of Time in Years to Reach Cleanup Levels for Simulations for Each Conceptual Site Model Evaluated for the Semi-Confined Aquifer

Downward Vertical Gradient				
	Dual Domain		Single Domain	
	Action	No Action	Action	No Action
Statistic	Source			
Average	20	41	13	26
90th Percentile	60	58	21	39
Peak	69	69	48	48
	No Source			
Average	13	44	9	28
90th Percentile	22	59	15	39
Peak	25	64	17	43
Neutral Vertical Gradient				
	Dual Domain		Single Domain	
	Action	No Action	Action	No Action
Statistic	Source			
Average	19	38	13	24
90th Percentile	56	53	20	36
Peak	65	63	46	45
	No Source			
Average	13	41	9	26
90th Percentile	22	55	15	37
Peak	25	59	17	40
Upward Vertical Gradient				
	Dual Domain		Single Domain	
	Action	No Action	Action	No Action
Statistic	Source			
Average	18	33	13	21
90th Percentile	46	45	18	32
Peak	57	55	43	41
	No Source			
Average	13	36	9	23
90th Percentile	22	48	15	32
Peak	25	52	17	35

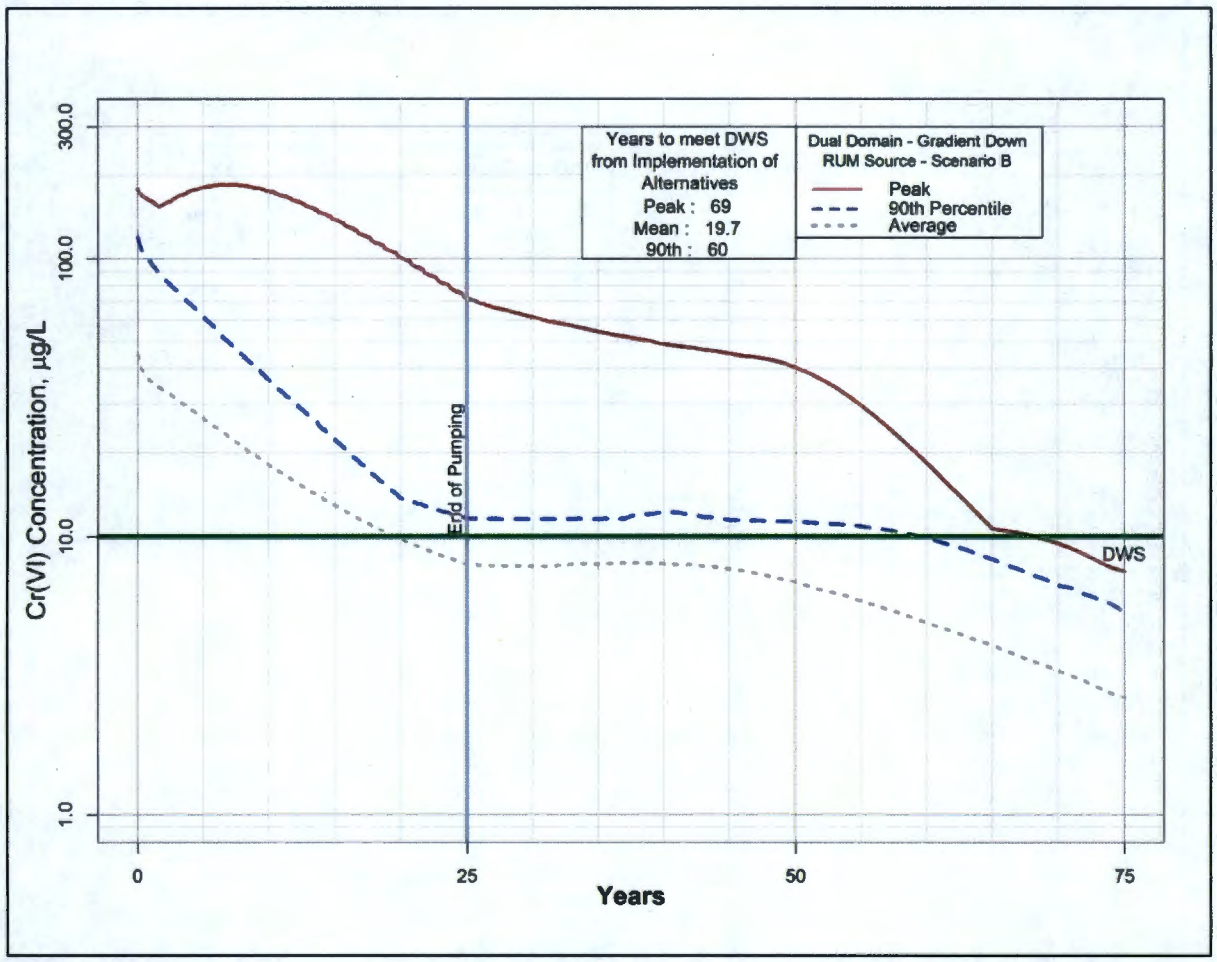


Figure 13. Time Series for Statistical Measure of Simulated Cr(VI) Concentrations within the semi-confined aquifer for Simulation of an Downward Vertical Gradient, Scenario B with Source Simulated in the RUM Aquitard

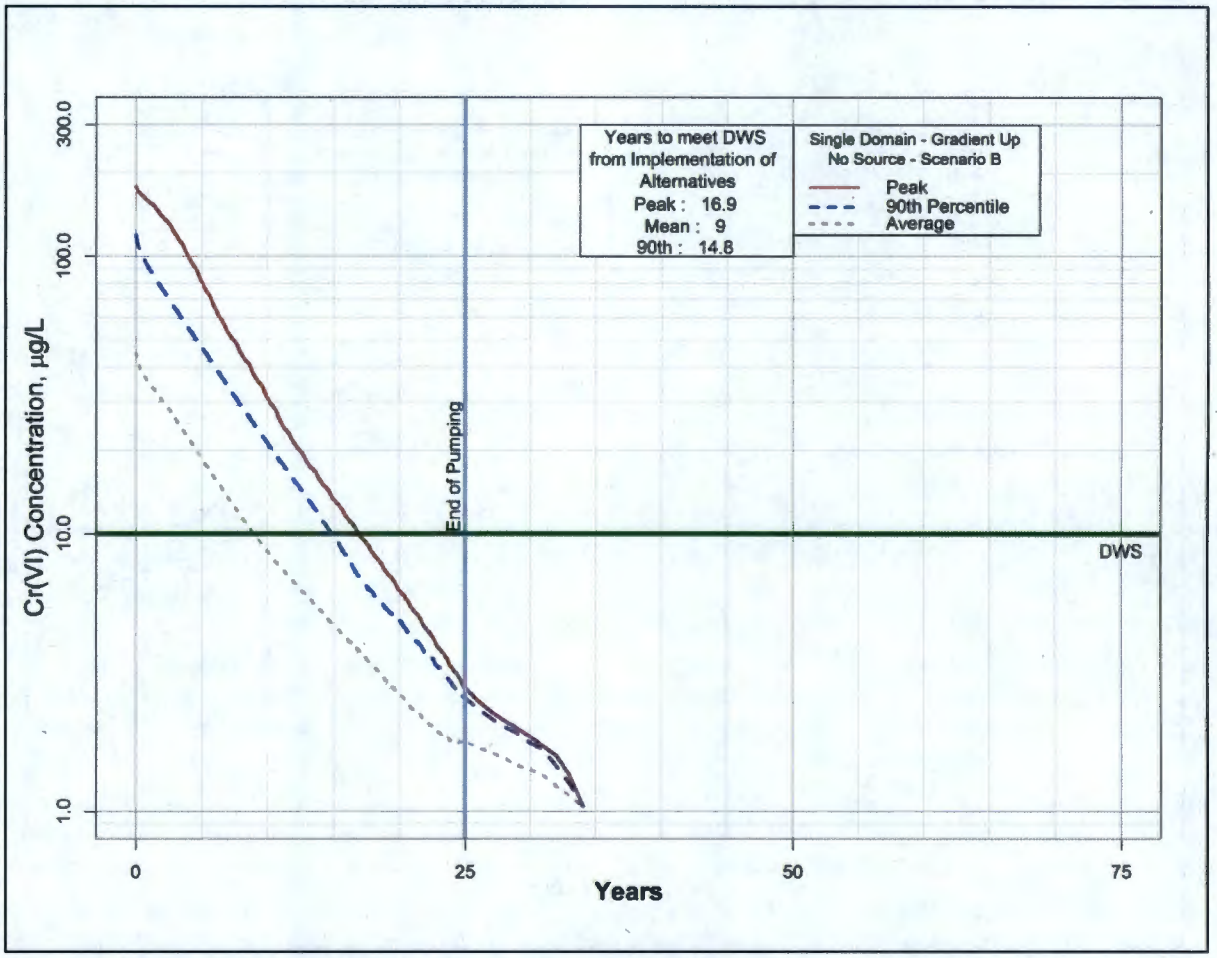


Figure 14. Time Series for Statistical Measure of Simulated Hexavalent Chromium Concentrations within the Semi-confined Aquifer for Simulation of an Upward Vertical Gradient, Single Domain, Scenario B, with Source Simulated in the RUM Aquitard

6.3.1 Vertical Gradients

Vertical gradients were evaluated by applying the maximum upward and downward gradients recorded from nested well groups within the model domain to the western boundary condition of the of the flow model. The magnitude of the upward and downward head difference is 0.61 m and 0.3 m, respectively (discussed in Section 2.2). The effect on simulations for Scenario B where no source is simulated had a no effect on the time to reach cleanup levels for the 90th percentile and peak. The pump-and-treat overcame the effects of the vertical gradients in this case. An effect is observed in the change of time to cleanup between the downward and upward vertical gradient for simulations where no pumping was simulated. In simulations with an upward gradient where a source is simulated the statistical measures of the plume all fall below the cleanup level with an improvement of 7 to 13 years than for simulations with a downward gradient. The downward gradient when a source is present drives increased amounts of Cr(VI) into the semi-confined aquifer and increases the amount of time to reach the cleanup level. This is increased with the introduction of the pump-and-treat that pulls more water from above the semi-confined aquifer.

6.3.2 Dual Domain vs. Single Domain

In general, dual domain simulations produced longer times to attain the cleanup level. This can be attributed to the slight increase in mass, due to partitioning, and the lack of advection in the immobile domain when the dual domain is simulated. When comparing equivalent simulations that only differ due to the dual domain formulation, the 90th percentile statistic shows an improvement of 7 to 40 years when only the single domain is simulated. The simulations that include the source term in the RUM fall at the high value of that range and the simulations without the source in the RUM are at the lower end of that range.

6.3.3 Residual Source in Ringold Upper Mud

The 90th percentile statistic where the RUM source was simulated had a minimum, maximum, and range of cleanup times of 18, 60, and 42 years, respectively. When the source term was not simulated the cleanup time minimum, maximum, and range equaled 15, 59, and 44 years, respectively. In general, when the source term is simulated, the time to reach cleanup levels increases for the pump-and-treat simulations (Scenario B). The opposite is true for the simulations where no source term is simulated. Scenario B shows improvement in the time to reach the cleanup level. This is due to the increased downward gradient caused by the pump-and-treat that pulls increased amounts of Cr(VI) into the first water bearing unit of the RUM from the simulated RUM aquitard source.

These simulations indicate that the source term shows significant influence over the behavior of the plume with respect to cleanup times. In addition, the simulation results seem to indicate that if a source is present employing a pump-and-treat system delays cleanup. Figure 15 and Figure 16 show a comparison of simulated results with plan view Cr(VI) contours in the semi-confined aquifer where the RUM source is, and is not, included in the simulation. In both cases, the simulated contours show that the pump-and-treat is more effective at keeping Cr(VI) from entering the river. Therefore, the time to attain cleanup is not the only consideration for operating, or not operating, a pump-and-treat system. It must be pointed out that the concentration of the RUM source is considered conservative in magnitude and is higher than what would be expected based on currently available data. Therefore, simulations where the RUM source is simulated may not be reflective of the effectiveness of the treatment system because of the tendency to increase concentrations in the interior of the plume due to induced gradients.

The time to reach the cleanup level in the simulations where no source was simulated show an improvement for between simulations of Scenarios A and B from a minimum of 17 years (single domain, upward gradient, no source) to a maximum of 37 years (dual domain, downward gradient, no source). This represents a 20% and 40% improvement for the respective simulations. While these results do carry some uncertainty in the absolute value of time to cleanup, the relative improvement indicates the effectiveness of operating the pump-and-treat system within the first water bearing unit of the RUM. Further, the pump-and-treat prevents Cr(VI) from entering the Columbia River while Scenario A does not prevent migration.

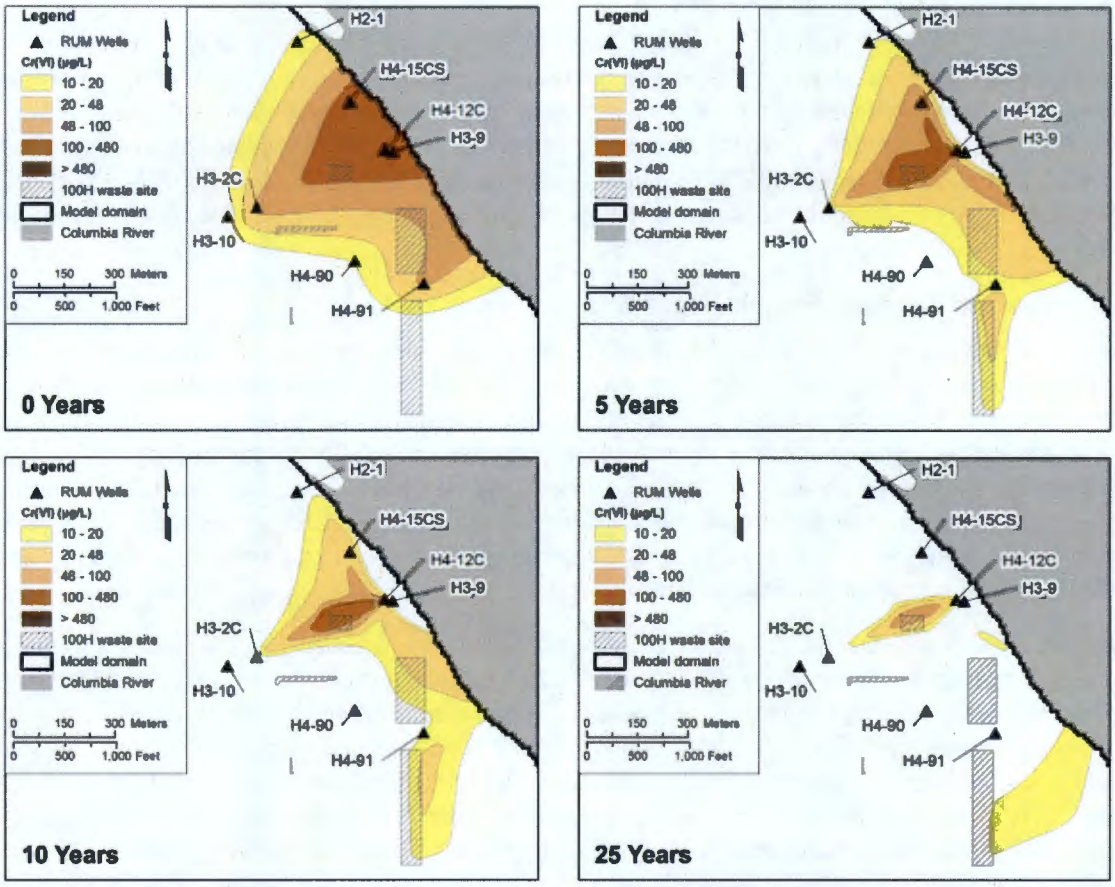


Figure 15. Simulated Hexavalent Chromium Concentrations with a Downward Vertical Gradient for Scenario B with Source Simulated in the RUM Aquitard

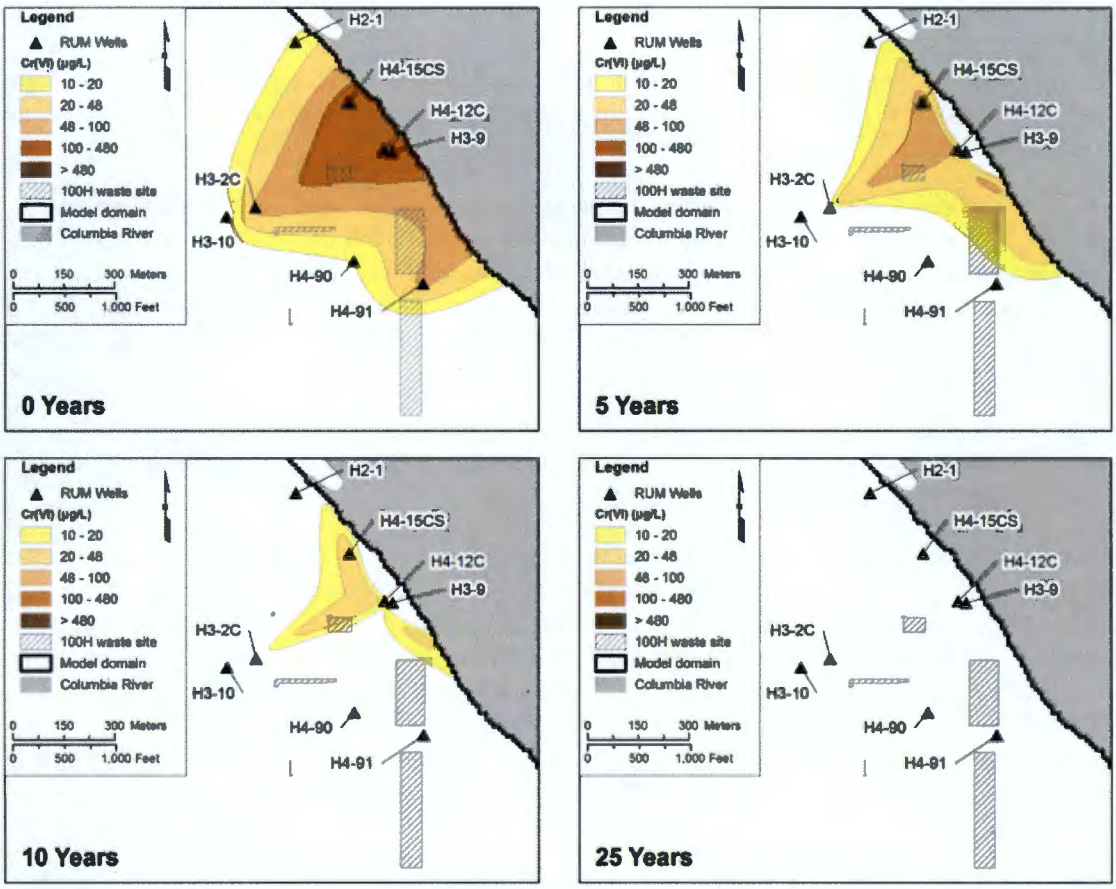


Figure 16. Simulated Hexavalent Chromium Concentrations with a Upward Vertical Gradient for Scenario B with No Source Simulated in the Ringold Upper Mud Aquitard

7 Results/Conclusions

Hexavalent chromium was detected in monitoring wells installed in the semi-confined aquifer (RUM first water-bearing unit) at the Hanford 100-H area. In order to evaluate Remedial Alternatives for cleanup of the Cr(VI) over the next 75 years, a groundwater flow and transport model of the 100-H semi-confined aquifer was developed using the codes MODFLOW-2000-MST and MT3DMS-MST. In order to evaluate a variety of CSMs two different source distributions, two remedial scenarios, the existence of vertical gradients between the geologic units, and the presence of dual domain flow were evaluated in a 75-year simulation. Evaluation of the results of the model construction and application produced the following conclusions.

- Due to the limited data with which to characterize the source of Cr(VI) observed in the semi-confined aquifer, results of the modeling calculation performed above contain significant uncertainty. However, the underlying goal of the calculations provided in this ECF was to develop a screening level model that would envelope bookend calculations for evaluating possible CSMs that may exist in the semi-confined aquifer.

- Results of the simulations indicate that the presence or absence of a source is significant in the time to reach cleanup. No soil samples collected as part of the RI/FS process indicate the presence of a source of Cr(VI) within the RUM sediments. However, an conservatively high source of Cr(VI) in the RUM, as simulated in this ECF, caused significant increase in the time to reach cleanup.

- The pump-and-treat scenarios improved time to reach the cleanup level when no source in the RUM was simulated and simulated contour plots indicated that the remedial system reduced the concentration along the Columbia River for both simulations with and without a source term. Given the uncertainty of a source in the RUM, these simulations indicate a significant improvement (17 to 37 years) in the time for Cr(VI) concentrations in the first water bearing unit of the RUM to reach cleanup levels.

- The range of cleanup times, as represented by the 90th percentile summary statistic of the simulated plume, show a range of times to reach cleanup levels within the first water bearing unit in the RUM as ranging from 15 to 60 years.

These modeling conclusions regarding the timeframe for completing remedial action for the first water-bearing unit of the RUM are made in the context of the two simulated scenarios (Scenario A, no further action, and Scenario B, further remedial action limited to existing wells). Hence, the impact on timeframes noted is indicative of the range of potential cleanup timeframes. However, these timeframe estimates rely heavily on which of the potential conceptual site models evaluated are representative. If monitoring reveals that longer timeframes are likely, a more aggressive remedial design would be included in the remedial design with the objective of matching the remedial timeframe for the first water-bearing unit of the RUM to the remedial timeframe planned for the unconfined aquifer.

8 References

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1

Attachment A

CHPRC Software Installation and Checkout Form for MODFLOW and Related Codes

1

1

CHPRC SOFTWARE INSTALLATION AND CHECKOUT FORM

Software Owner Instructions:
Complete Fields 1-13, then run test cases in Field 14. Compare test case results listed in Field 15 to corresponding Test Report outputs. If results are the same, sign and date Field 19. If not, resolve differences and repeat above steps.

Software Subject Matter Expert Instructions:
Assign test personnel. Approve the installation of the code by signing and dating Field 21, then maintain form as part of the software support documentation.

GENERAL INFORMATION:

1. Software Name: MODFLOW and Related Codes Software Version No.: Bld 6

EXECUTABLE INFORMATION:

2. Executable Name (include path):

Following executable files in directory: _____

MD5 Signature (unique ID)	Executable File Name
C3B75ADEBC7F41F15F006A0A3AED2D21	mf2k-chprc06dp.exe
C3141B0D41E084601DC2C8EB746B189F	mf2k-chprc06sp.exe
4F9E3D4A5ECF0360C8247C4279FE25F1	mf2k-mst-chprc06dp.exe
0E38BD210A582EF42CC79145C14F8E69	mf2k-mst-chprc06sp.exe
EE4D6CE61E07E0218F81822CE54499DE	modpath-mst-chprc06dp.exe
F83D1B16B26887A8C9579373D919DF4F	modpath-mst-chprc06sp.exe
D3337D49ED0AAA92E6FE6A6EB027647A	mt3d-mst-chprc06dp.exe
E6A66025170D441389642CC0A7B59749	mt3d-mst-chprc06sp.exe

3. Executable Size (bytes): MD5 signatures listed above uniquely identify executable files

COMPILATION INFORMATION:

4. Hardware System (i.e., property number or ID):

WC95463; Dell Latitude Laptop

5. Operating System (include version number):

Windows 7 Enterprise Service Pack 1

INSTALLATION AND CHECKOUT INFORMATION:

6. Hardware System (i.e., property number or ID):

INTERA-00568

7. Operating System (include version number):

Windows 7 64-bit Operating System

8. Open Problem Report? ◉ No ○ Yes PR/CR No.

TEST CASE INFORMATION:

9. Directory/Path:

10. Procedure(s):

CHPRC-00259 Rev 2, MODFLOW and Related Codes Software Test Plan

11. Libraries:

N/A (static linking)

12. Input Files:

MF-ITC-1 and MT-ITC-1 inputs

13. Output Files:

MF-ITC-1 and MT-ITC-1 outputs

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2

CHPRC SOFTWARE INSTALLATION AND CHECKOUT FORM (continued)

1. Software Name: MODFLOW and Related Codes — Software Version No.: Bld 6

14. Test Cases:

MF-ITC-1 (both standard and MST versions of MODFLOW)- run for single & double precision
MT-ITC-1 - run for single and double precision

15. Test Case Results:

PASS

16. Test Performed By: Cheng Cheng

17. Test Results: (●) Satisfactory, Accepted for Use ( ) Unsatisfactory

18. Disposition (include HISI update):

Prepared By:

Digitally signed by William E. Nichols
DN: cn=William E. Nichols, o=CHPRC, ou=Risk & Modeling Integration, email=wm_e_nichols@rl.gov, c=US
Date: 2013.08.27 13:52:04 -07'00'

19.	WE Nichols	
Software Owner (Signature)	Print	Date

20. Test Personnel:

Cheng	Cheng Cheng	8/27/13
Sign	Print	Date
Sign	Print	Date
	N/R (CHPRC-00259 Rev 2)	
Sign	Print	Date

Approved By:

21.		
Software SME (Signature)	Print	Date

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Attachment B

Wells and Pumping Rates of the Model (2011 – 2012)

1

Table B-1. Wells and pumping rates of the model, 2011-2012

Well Number	Pumping (-) / Injection (+) Rate (gpm)																							
	Jan-11	Feb-11	Mar-11	Apr-11	May-11	Jun-11	Jul-11	Aug-11	Sep-11	Oct-11	Nov-11	Dec-11	Jan-12	Feb-12	Mar-12	Apr-12	May-12	Jun-12	Jul-12	Aug-12	Sep-12	Oct-12	Nov-12	Dec-12
199-H1-1	-	-	-	-	-	-	-	-	-5	-28	-30	-30	-30	-29	-30	-26	-30	-26	-20	-20	-27	-30	-31	-29
199-H1-2	-	-	-	-	-	-	-	-	-0.4	-3	-3	-2	-2	-2	-2	-2	-5	-6	-7	-6	-4	-3	-3	-3
199-H1-34	-	-	-	-	-	-	-	-	-2	-11	-14	-14	-13	-11	-15	-26	-27	-28	-28	-28	-22	-9	-12	-20
199-H1-35	-	-	-	-	-	-	-	-	-4	-23	-26	-28	-27	-23	-25	-26	-22	-26	-27	-27	-28	-25	-28	-27
199-H1-36	-	-	-	-	-	-	-	-	-1	-8	-7	-7	-6	-5	-5	-8	-9	-9	-9	-9	-9	-8	-7	-8
199-H1-37	-	-	-	-	-	-	-	-	-2	-7	-12	-13	-8	-3	-11	-27	-28	-28	-28	-28	-23	-5	-11	-24
199-H1-38	-	-	-	-	-	-	-	-	-1	-6	-5	-4	-4	-4	-7	-14	-24	-25	-25	-25	-12	-7	-7	-10
199-H1-39	-	-	-	-	-	-	-	-	-0.3	-2	-2	-1	-1	-1	-3	-34	-41	-37	-30	-30	-24	-3	-4	-18
199-H1-40	-	-	-	-	-	-	-	-	-1	-3	-3	-3	-3	-2	-4	-11	-23	-29	-20	-22	-13	-7	-7	-8
199-H1-42	-	-	-	-	-	-	-	-	-4	-26	-28	-29	-28	-29	-28	-28	-29	-28	-28	-28	-29	-28	-29	-28
199-H1-43	-	-	-	-	-	-	-	-	-4	-28	-29	-20	-22	-25	-29	-28	-30	-30	-30	-30	-30	-29	-30	-29
199-H1-45	-	-	-	-	-	-	-	-	-4	-25	-26	-26	-27	-27	-27	-27	-8	-5	-27	-27	-25	-23	-26	-20
199-H3-25	-	-	-	-	-	-	-	-	8	43	51	53	51	50	53	67	91	88	94	78	67	53	57	63
199-H3-26	-	-	-	-	-	-	-	-	7	40	44	45	44	43	46	57	84	84	89	74	63	51	55	60
199-H3-27	-	-	-	-	-	-	-	-	6	34	38	39	38	37	40	56	74	71	75	60	53	44	48	53
199-H3-2C	-42	-44	-45	-42	-3	-	-	-	-	-46	-46	-46	-46	-48	-48	-45	-50	-49	-50	-50	-50	-49	-50	-46
199-H3-4	-	-	-	-	-	-	-	-	-16	-82	-105	-125	-125	-125	-124	-109	-113	-95	-100	-125	-125	-122	-125	-115
199-H4-12C	-17	-18	-20	-18	-2	-	-	-	-	-27	-27	-29	-28	-30	-29	-28	-30	-30	-30	-30	-30	-29	-29	-29
199-H4-14	91	98	96	90	7	-	-	-	3	19	22	15	15	14	16	11	11	9	12	8	7	8	8	12
199-H4-15A	-19	-19	-19	-18	-2	-	-	-	-	-	-	-	-33	-37	-38	-38	-39	-32	-31	-31	-32	-29	-31	-29
199-H4-17	52	51	54	49	11	-	-	-	2	8	11	12	10	10	9	7	6	5	7	6	5	7	9	10
199-H4-18	40	50	46	43	3	-	-	-	2	22	14	13	12	12	13	12	11	9	8	9	9	9	13	8
199-H4-3	-1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
199-H4-4	-	-9	-5	-5	-1	-	-	-	-1	-2	-5	-5	-4	-3	-6	-11	-11	-11	-11	-11	-4	-1	-5	-10
199-H4-63	-24	-24	-23	-21	-2	-	-	-	-4	-25	-25	-26	-26	-26	-26	-26	-27	-27	-27	-27	-27	-26	-26	-25
199-H4-64	-	-	-	-	-	-	-	-	-2	-8	-12	-13	-12	-12	-15	-23	-21	-20	-15	-17	-13	-8	-15	-18
199-H4-69	-	-	-	-	-	-	-	-	-4	-25	-25	-28	-27	-21	-25	-28	-28	-28	-28	-28	-28	-26	-27	-27
199-H4-70	-	-	-	-	-	-	-	-	-4	-22	-23	-24	-24	-24	-24	-23	-21	-22	-23	-24	-25	-24	-24	-23
199-H4-71	-	-	-	-	-	-	-	-	5	27	33	34	32	31	34	44	61	59	63	51	43	35	38	43
199-H4-72	-	-	-	-	-	-	-	-	3	14	21	23	22	21	24	34	59	59	62	51	43	36	39	43
199-H4-73	-	-	-	-	-	-	-	-	4	18	25	26	25	22	26	36	55	54	58	47	39	32	35	39
199-H4-74	-	-	-	-	-	-	-	-	5	33	35	36	35	33	36	46	67	69	75	62	52	43	47	52
199-H4-75	-	-	-	-	-	-	-	-	-3	-18	-19	-20	-20	-20	-18	-19	-19	-19	-20	-20	-20	-19	-19	-19
199-H4-76	-	-	-	-	-	-	-	-	-1	-14	-9	-4	-1	0	0	0	-4	-14	-18	-18	-18	-18	-18	-12
199-H4-77	-	-	-	-	-	-	-	-	-2	-12	-11	-10	-10	-9	-9	-7	-9	-9	-8	-15	-11	-17	-15	-12
199-H6-2	-	-	-	-	-	-	-	-	3	14	19	20	19	18	21	31	50	53	56	41	34	24	30	30

Attachment C

Simulation Results

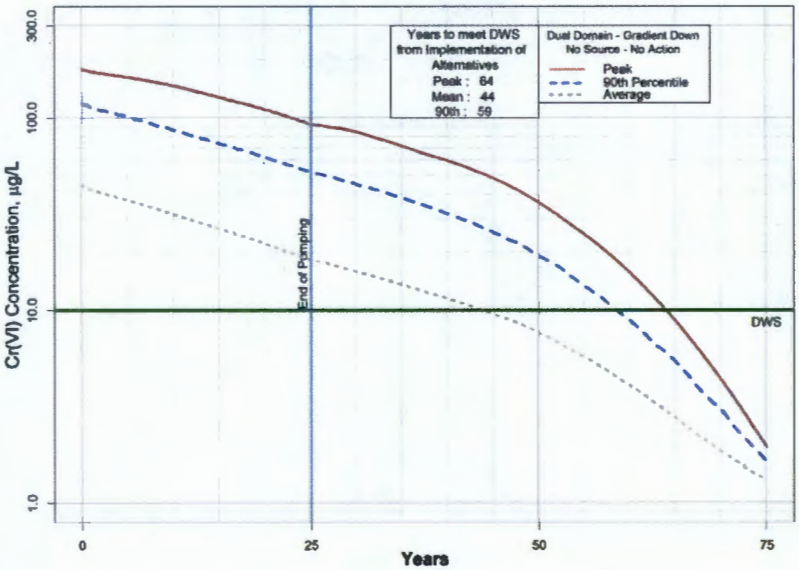

Figure C.1 - Time series for statistical measure of simulated Cr(VI) concentrations within the semi-confined aquifer for simulation of with a dual domain, downward vertical gradient, Scenario A with no source simulated in the RUM aquitard.

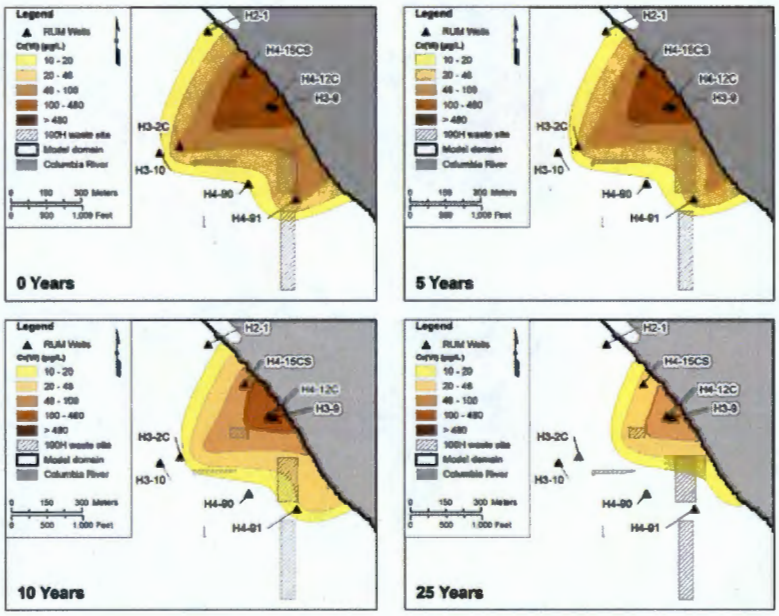

Figure C.2. Simulated Cr(VI) concentrations with a dual domain, downward vertical gradient, Scenario A with no source simulated in the RUM aquitard.

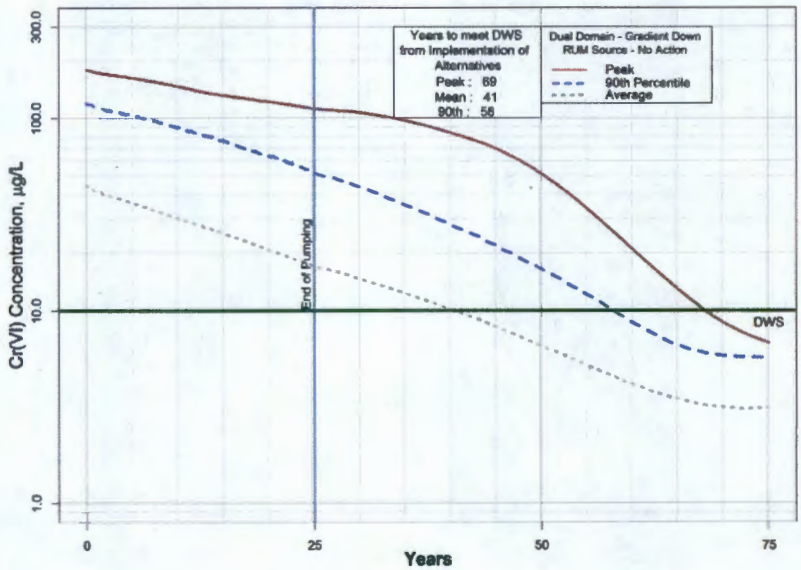

Figure C.3 - Time series for statistical measure of simulated Cr(VI) concentrations within the semi-confined aquifer for simulation of with a dual domain, downward vertical gradient, Scenario A with a source simulated in the RUM aquitard.

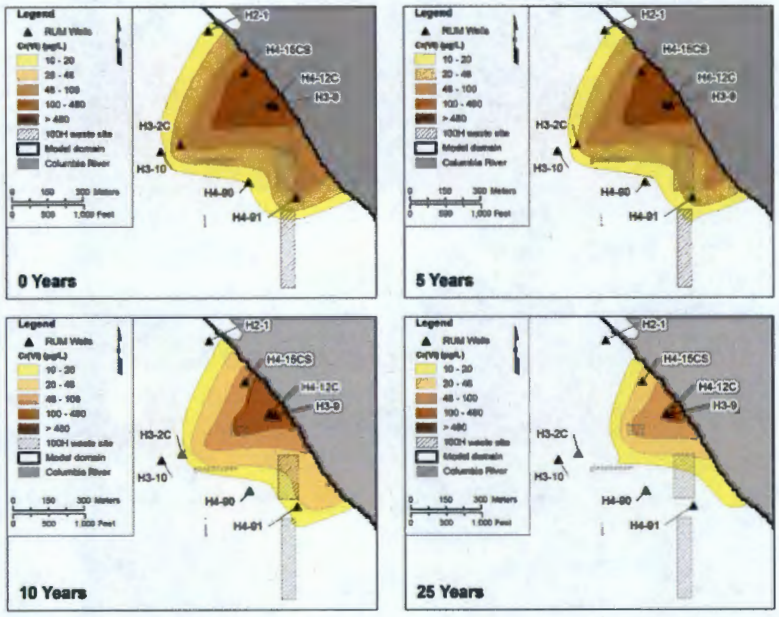

Figure C.4. Simulated Cr(VI) concentrations with a dual domain, downward vertical gradient, Scenario A with a source simulated in the RUM aquitard.

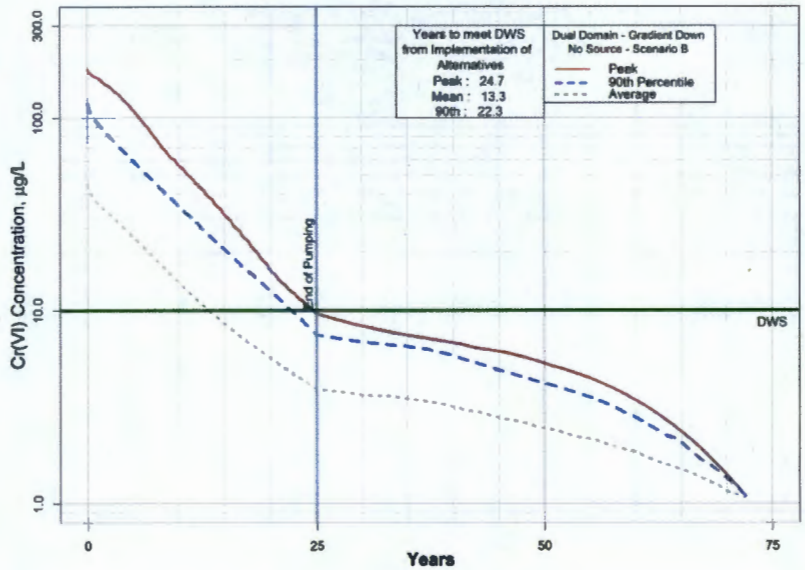

Figure C.5 - Time series for statistical measure of simulated Cr(VI) concentrations within the semi-confined aquifer for simulation of with a dual domain, downward vertical gradient, Scenario B with no source simulated in the RUM aquitard.

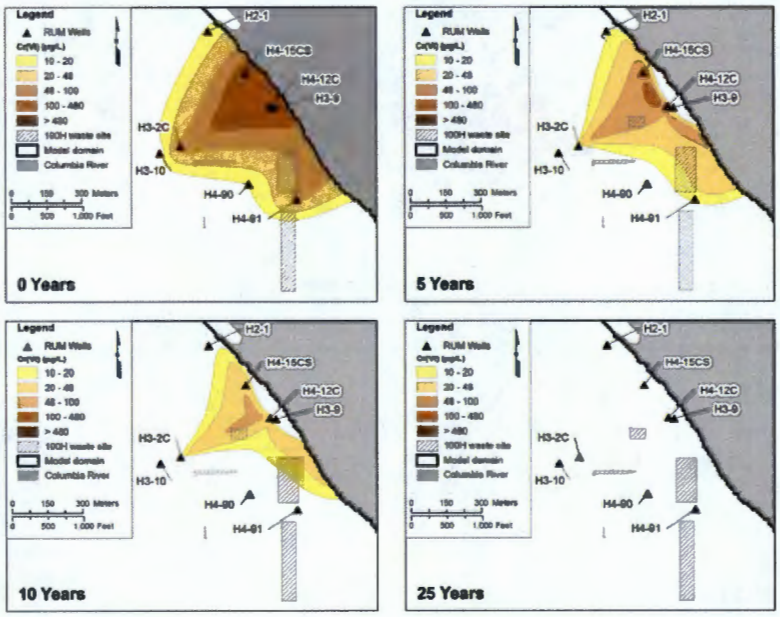

Figure C.6. Simulated Cr(VI) concentrations with a dual domain, downward vertical gradient, Scenario B with no source simulated in the RUM aquitard.

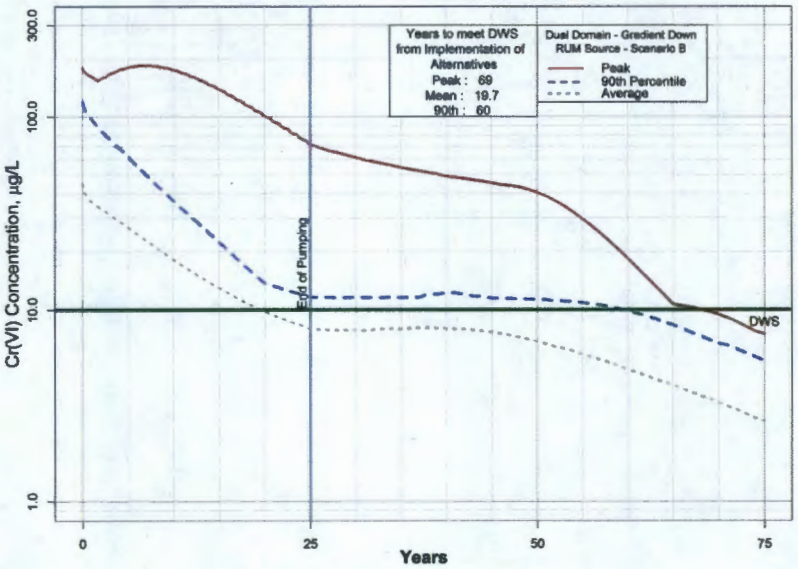

Figure C.7 - Time series for statistical measure of simulated Cr(VI) concentrations within the semi-confined aquifer for simulation of with a dual domain, downward vertical gradient, Scenario B with a source simulated in the RUM aquitard.

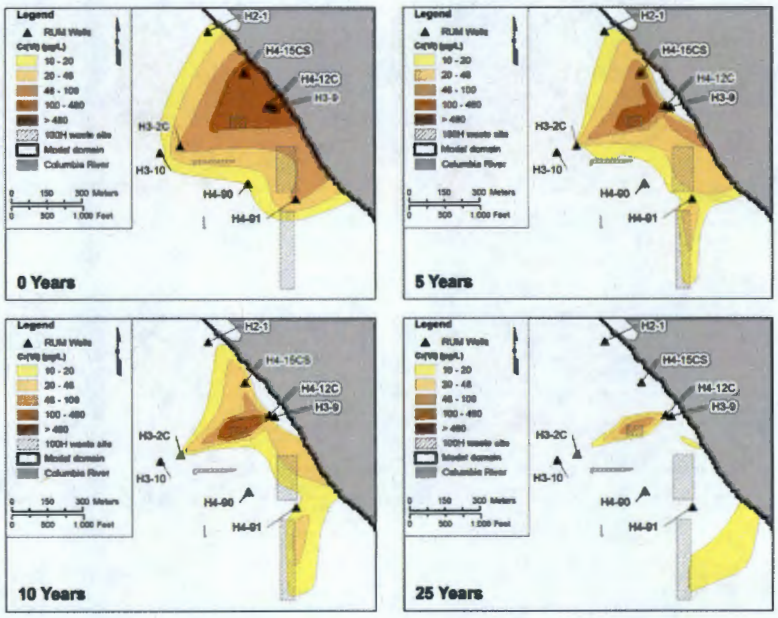

Figure C.8. Simulated Cr(VI) concentrations with a dual domain, downward vertical gradient, Scenario B with a source simulated in the RUM aquitard.

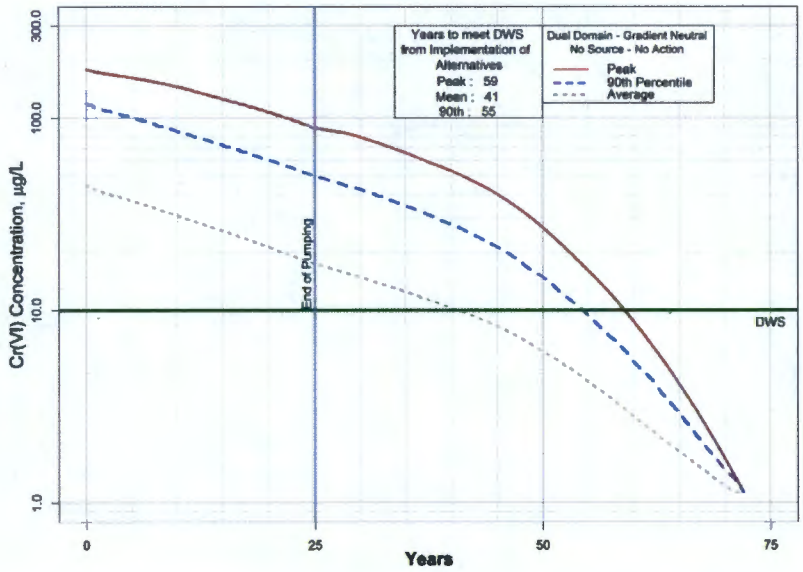

Figure C.9 - Time series for statistical measure of simulated Cr(VI) concentrations within the semi-confined aquifer for simulation of with a dual domain, neutral vertical gradient, Scenario A with no source simulated in the RUM aquitard.

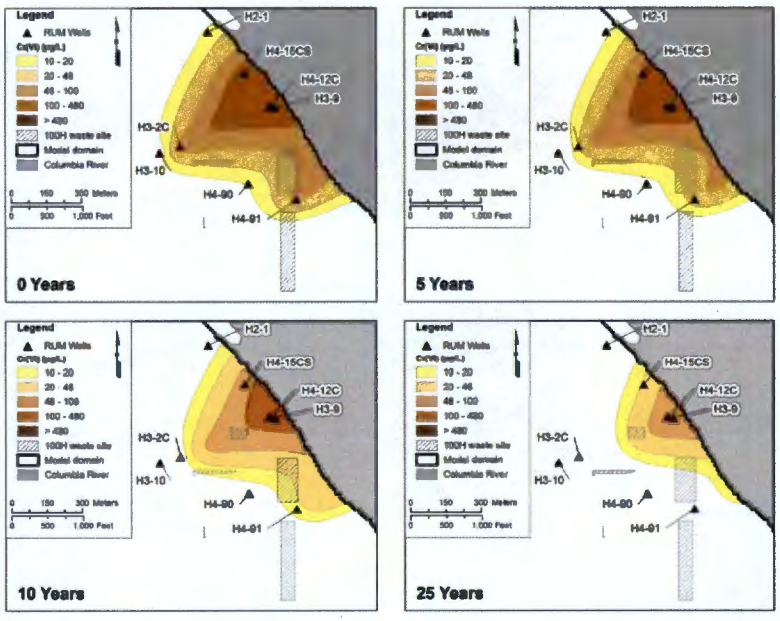

Figure C.10. Simulated Cr(VI) concentrations with a dual domain, neutral vertical gradient, Scenario A with no source simulated in the RUM aquitard.

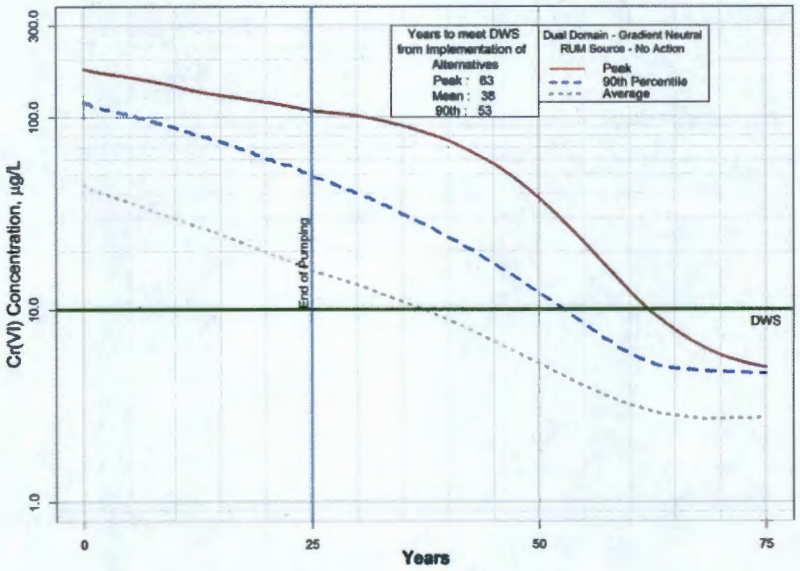

Figure C.11 - Time series for statistical measure of simulated Cr(VI) concentrations within the semi-confined aquifer for simulation of with a dual domain, neutral vertical gradient, Scenario A with a source simulated in the RUM aquitard.

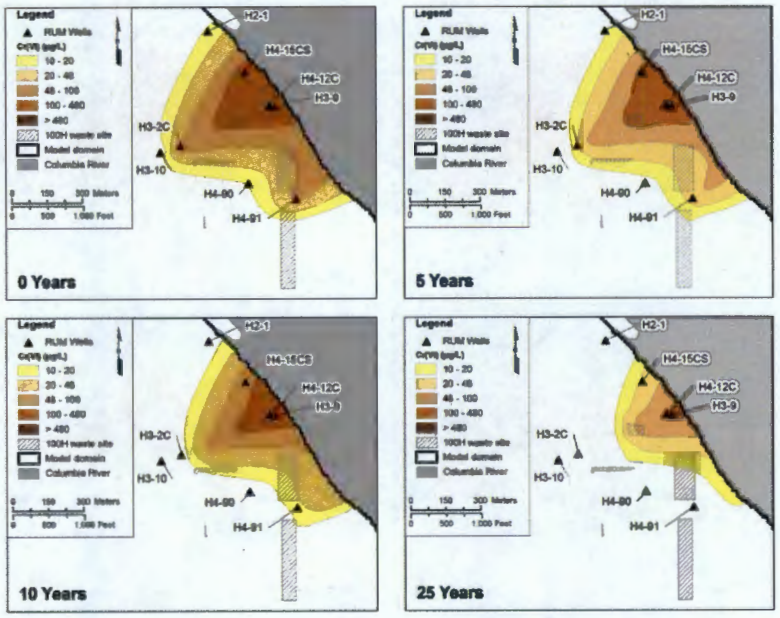

Figure C.12. Simulated Cr(VI) concentrations with a dual domain, neutral vertical gradient, Scenario A with a source simulated in the RUM aquitard.

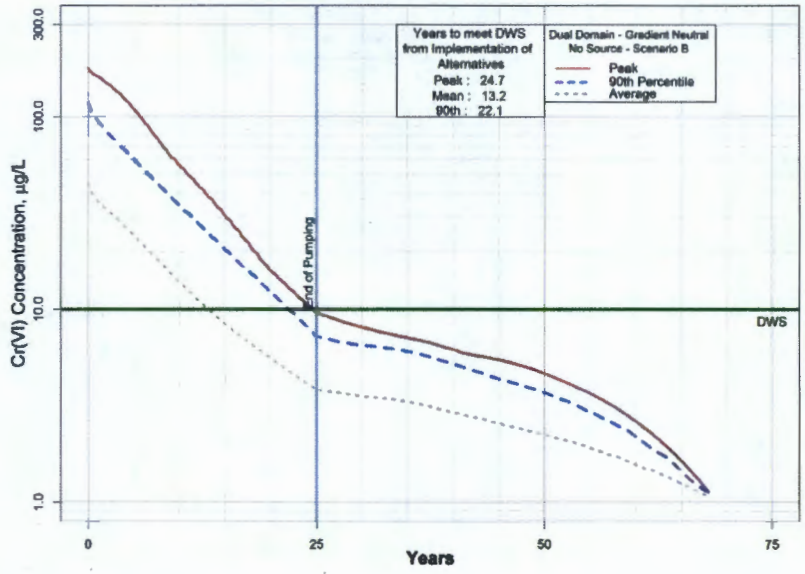

Figure C.13 - Time series for statistical measure of simulated Cr(VI) concentrations within the semi-confined aquifer for simulation of with a dual domain, neutral vertical gradient, Scenario B with no source simulated in the RUM aquitard.

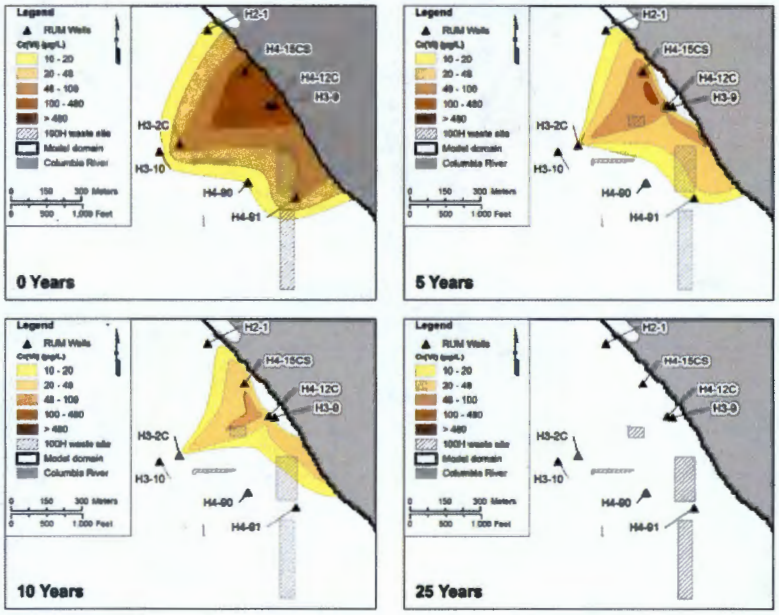

Figure C.14. Simulated Cr(VI) concentrations with a dual domain, neutral vertical gradient, Scenario B with no source simulated in the RUM aquitard.

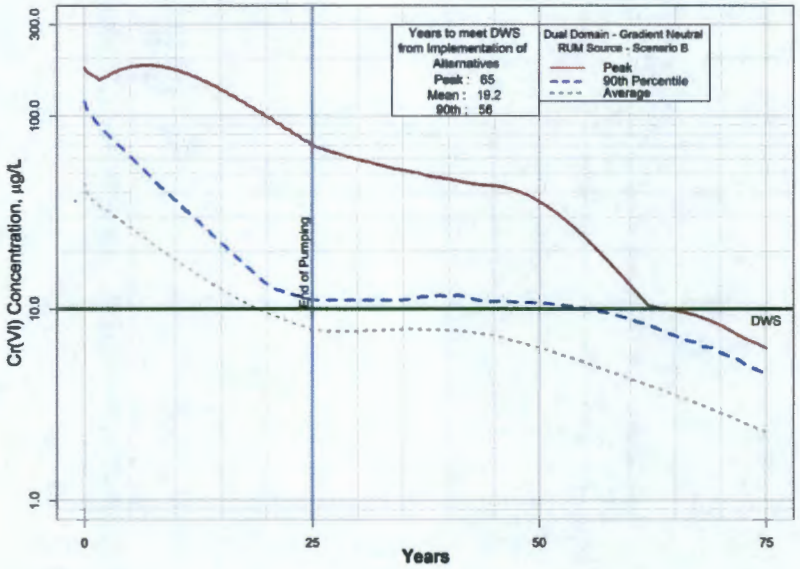

Figure C.15 - Time series for statistical measure of simulated Cr(VI) concentrations within the semi-confined aquifer for simulation of with a dual domain, neutral vertical gradient, Scenario B with a source simulated in the RUM aquitard.

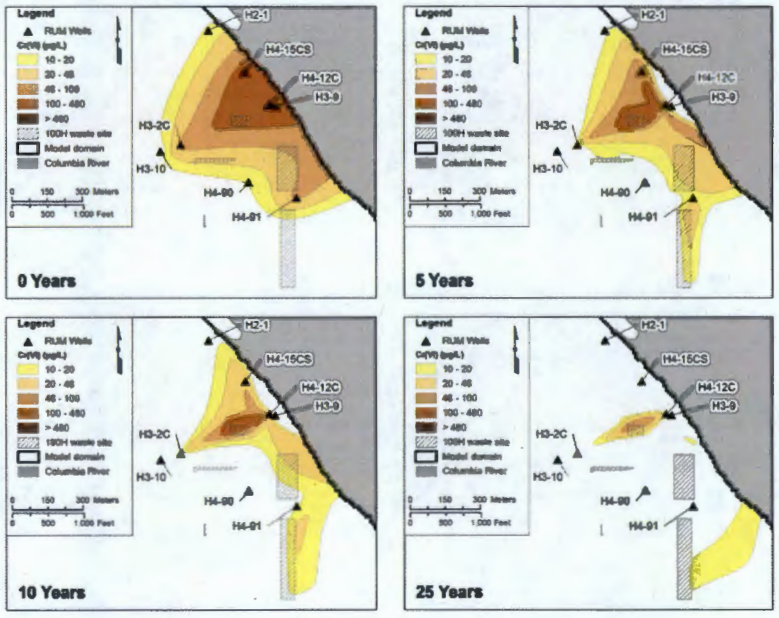

Figure C.16. Simulated Cr(VI) concentrations with a dual domain, neutral vertical gradient, Scenario B with a source simulated in the RUM aquitard.

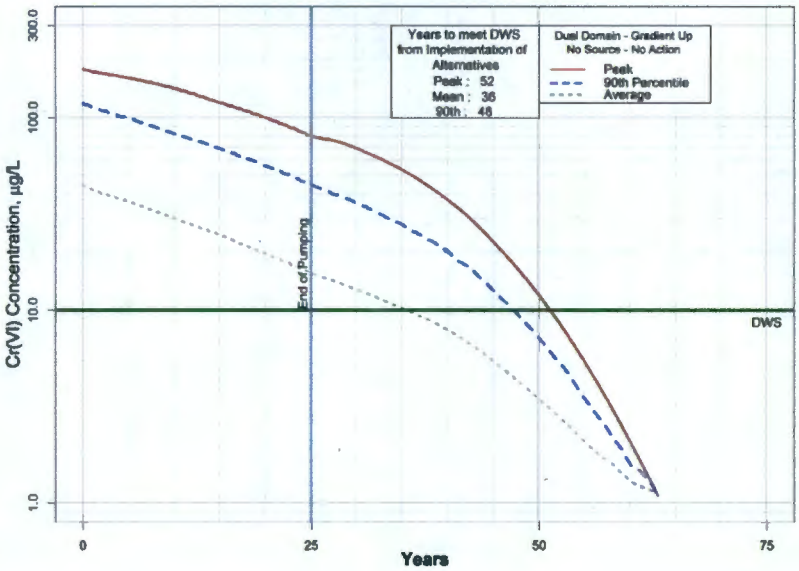

Figure C.17 - Time series for statistical measure of simulated Cr(VI) concentrations within the semi-confined aquifer for simulation of with a dual domain, upward vertical gradient, Scenario A with no source simulated in the RUM aquitard.

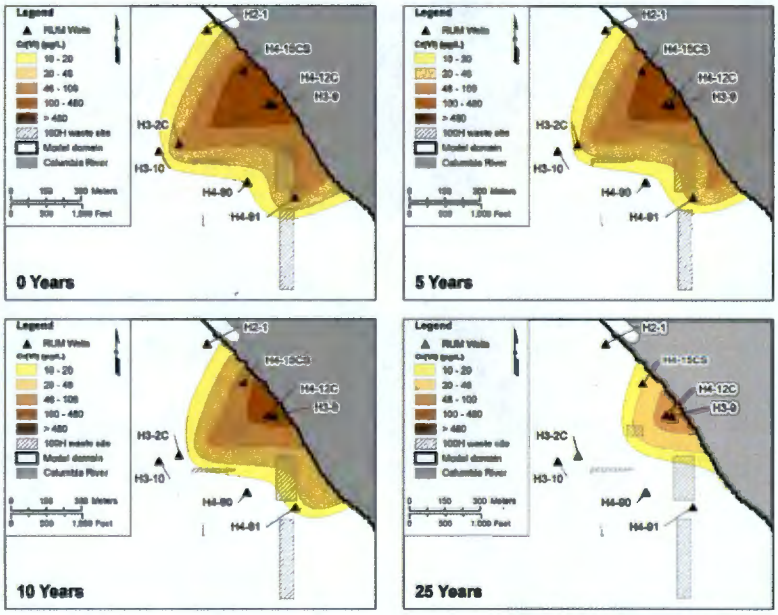

Figure C.18. Simulated Cr(VI) concentrations with a dual domain, upward vertical gradient, Scenario A with no source simulated in the RUM aquitard.

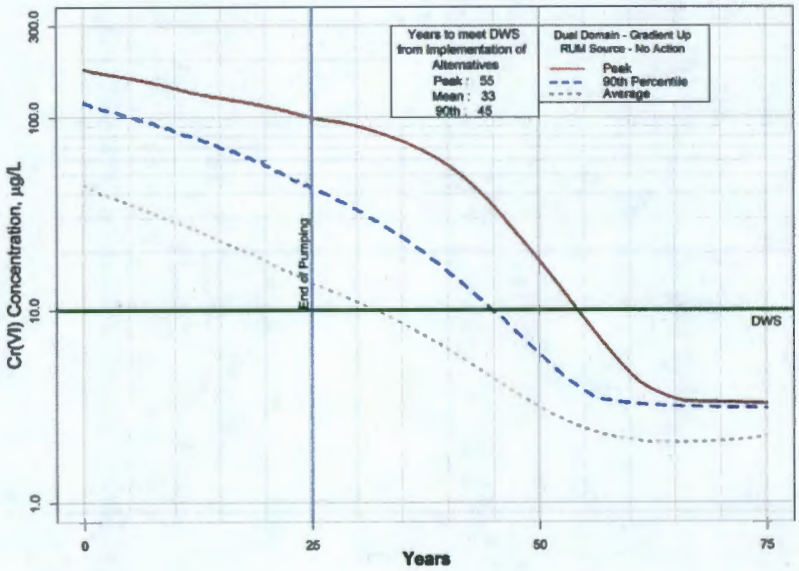

Figure C.19 - Time series for statistical measure of simulated Cr(VI) concentrations within the semi-confined aquifer for simulation of with a dual domain, upward vertical gradient, Scenario A with a source simulated in the RUM aquitard.

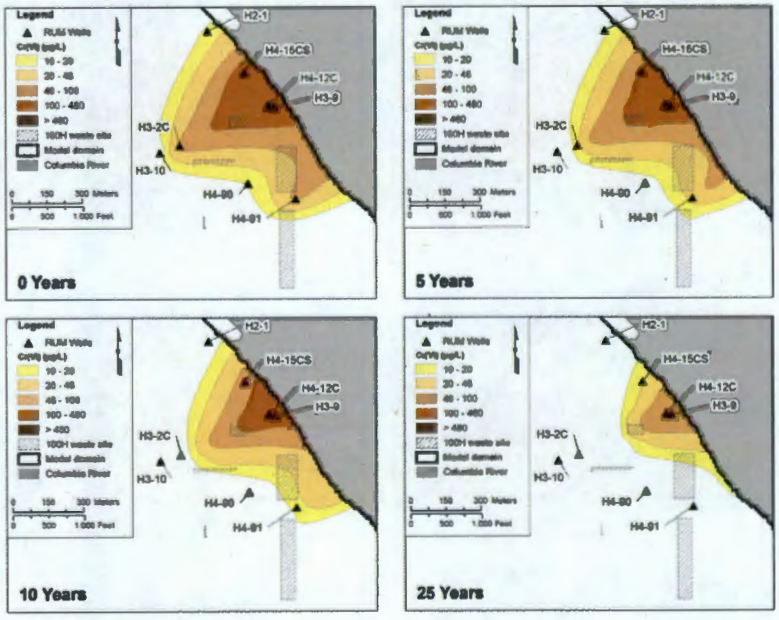

Figure C.20. Simulated Cr(VI) concentrations with a dual domain, upward vertical gradient, Scenario A with a source simulated in the RUM aquitard.

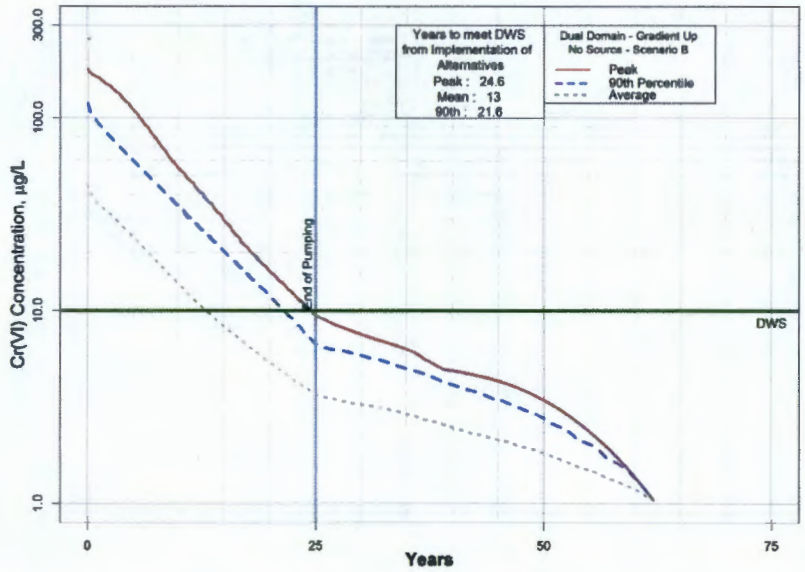

Figure C.21 - Time series for statistical measure of simulated Cr(VI) concentrations within the semi-confined aquifer for simulation of with a dual domain, upward vertical gradient, Scenario B with no source simulated in the RUM aquitard.

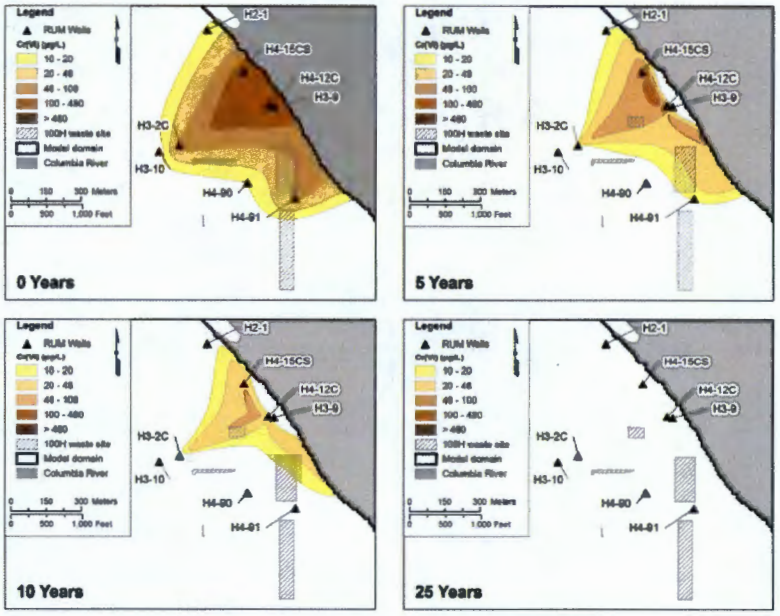

Figure C.22. Simulated Cr(VI) concentrations with a dual domain, upward vertical gradient, Scenario B with no source simulated in the RUM aquitard.

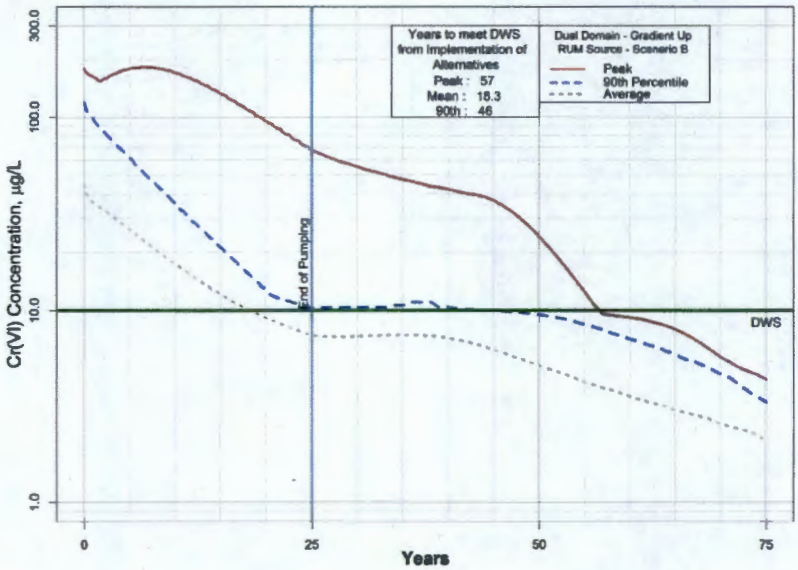

Figure C.23 - Time series for statistical measure of simulated Cr(VI) concentrations within the semi-confined aquifer for simulation of with a dual domain, upward vertical gradient, Scenario B with a source simulated in the RUM aquitard.

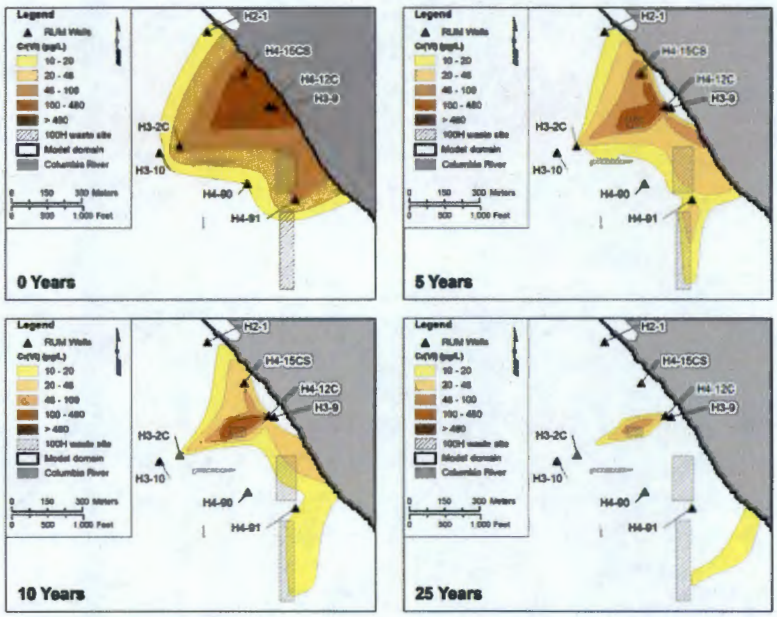

Figure C.24. Simulated Cr(VI) concentrations with a dual domain, upward vertical gradient, Scenario B with a source simulated in the RUM aquitard.

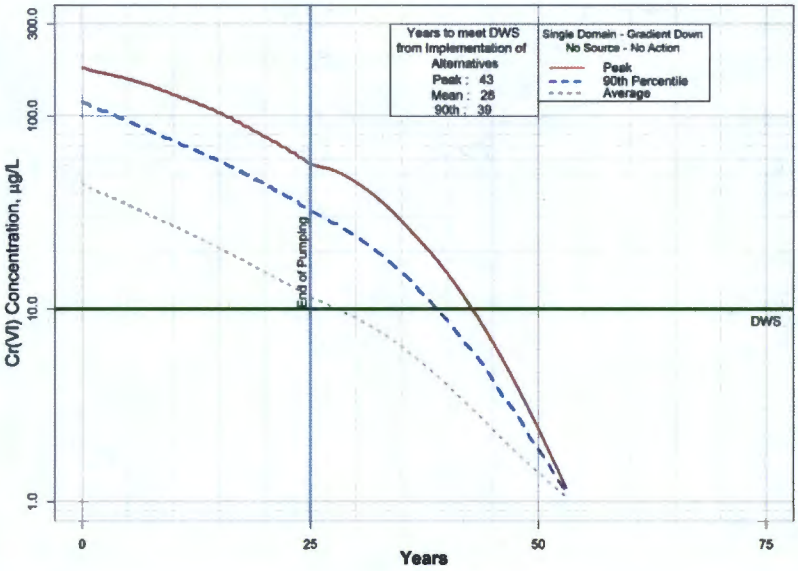

Figure C.25 - Time series for statistical measure of simulated Cr(VI) concentrations within the semi-confined aquifer for simulation of with a single domain, downward vertical gradient, Scenario A with no source simulated in the RUM aquitard.

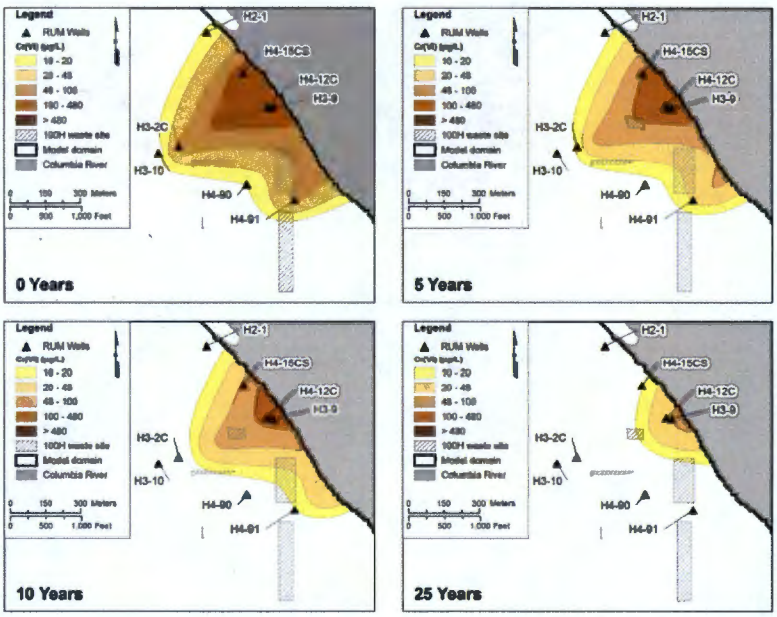

Figure C.26. Simulated Cr(VI) concentrations with a single domain, downward vertical gradient, Scenario A with no source simulated in the RUM aquitard.

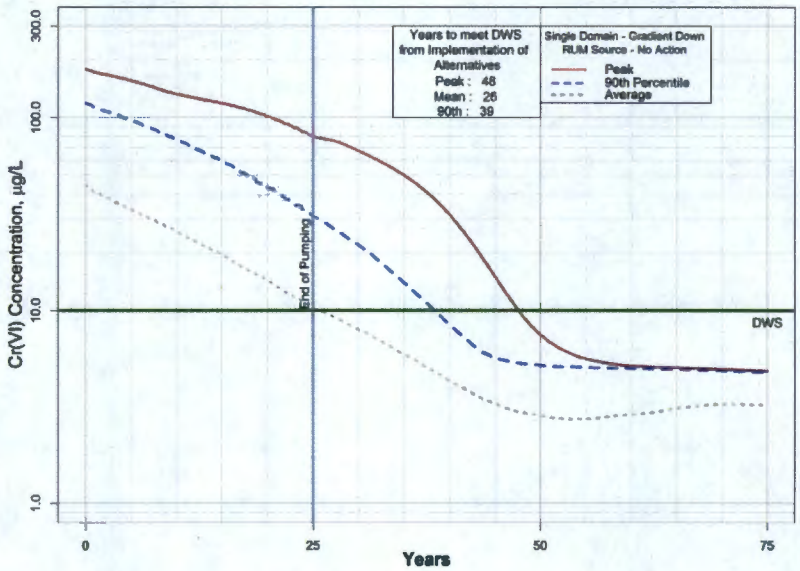

Figure C.27 - Time series for statistical measure of simulated Cr(VI) concentrations within the semi-confined aquifer for simulation of with a single domain, downward vertical gradient, Scenario A with a source simulated in the RUM aquitard.

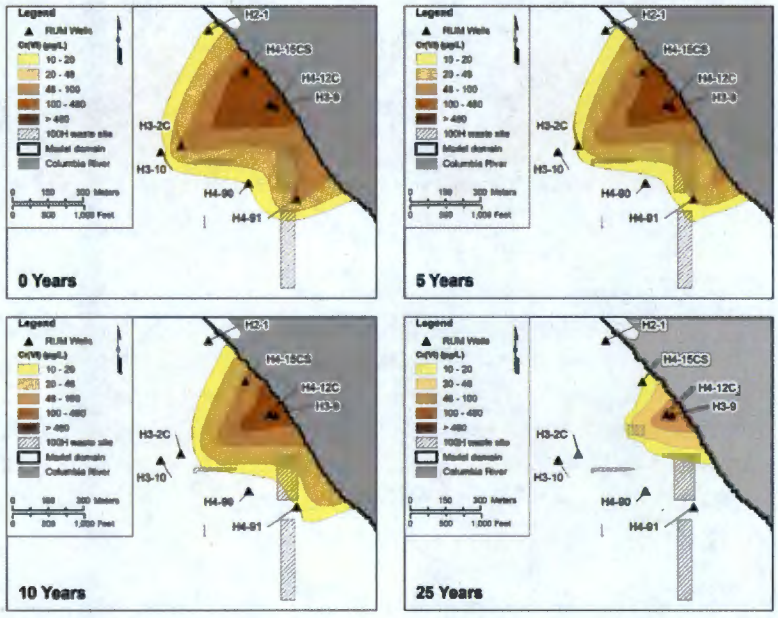

Figure C.28. Simulated Cr(VI) concentrations with a single domain, downward vertical gradient, Scenario A with a source simulated in the RUM aquitard.

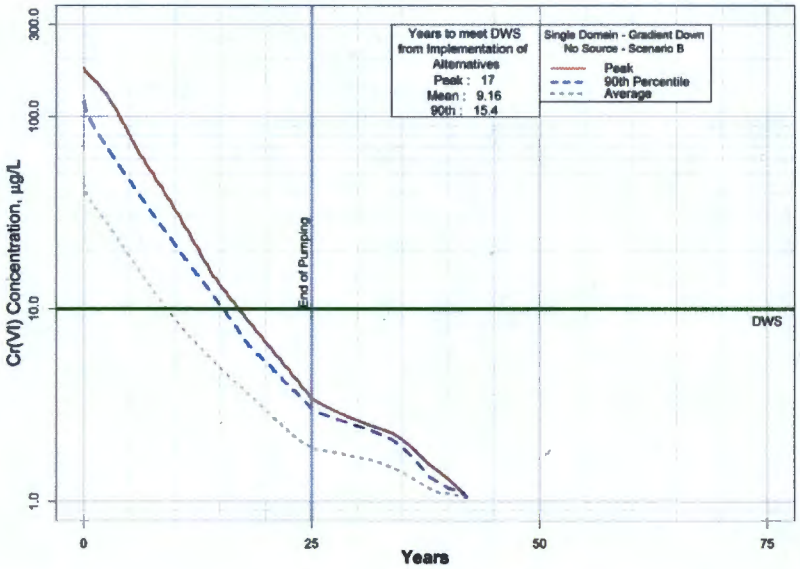

Figure C.29 - Time series for statistical measure of simulated Cr(VI) concentrations within the semi-confined aquifer for simulation of with a single domain, downward vertical gradient, Scenario B with no source simulated in the RUM aquitard.

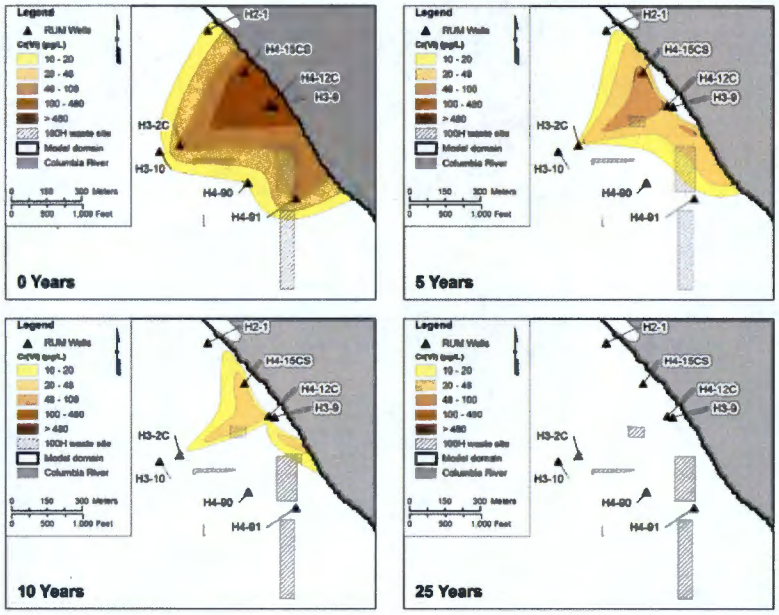

Figure C.30. Simulated Cr(VI) concentrations with a single domain, downward vertical gradient, Scenario B with no source simulated in the RUM aquitard.

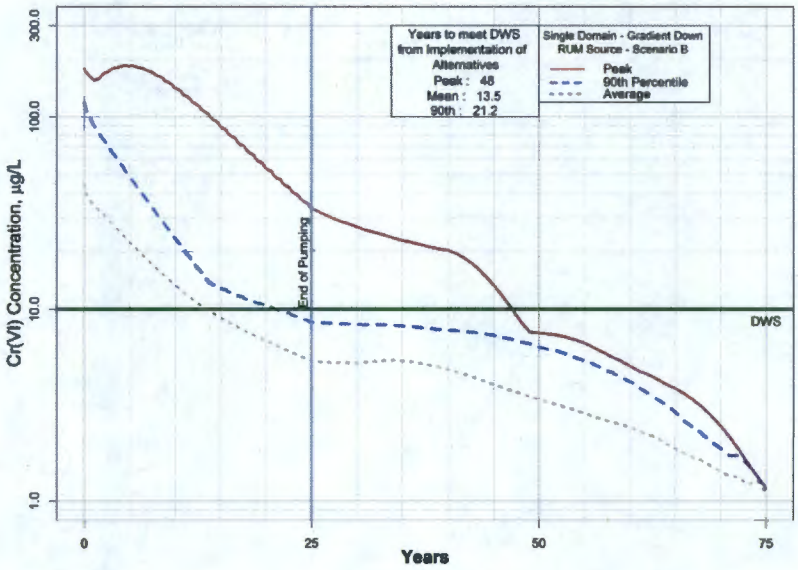

Figure C.31 - Time series for statistical measure of simulated Cr(VI) concentrations within the semi-confined aquifer for simulation of with a single domain, downward vertical gradient, Scenario B with a source simulated in the RUM aquitard.

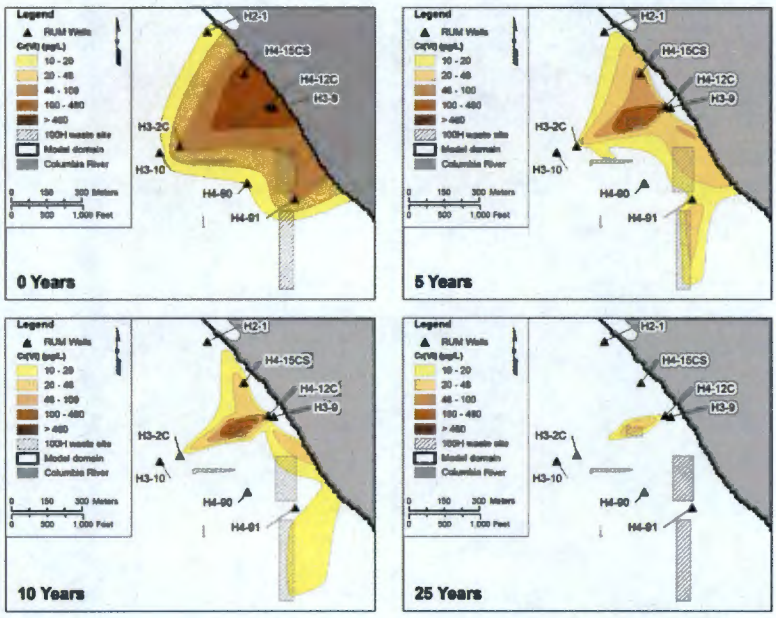

Figure C.32. Simulated Cr(VI) concentrations with a single domain, downward vertical gradient, Scenario B with a source simulated in the RUM aquitard.

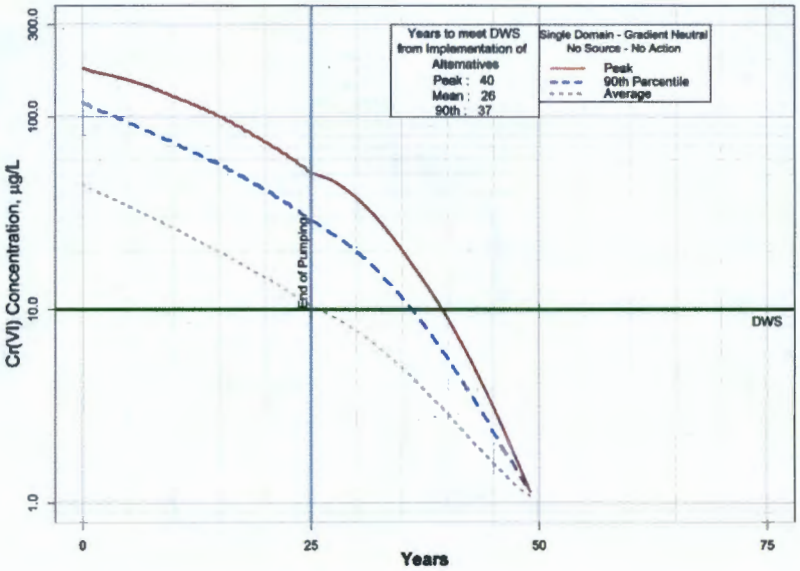

Figure C.33 - Time series for statistical measure of simulated Cr(VI) concentrations within the semi-confined aquifer for simulation of with a single domain, neutral vertical gradient, Scenario A with no source simulated in the RUM aquitard.

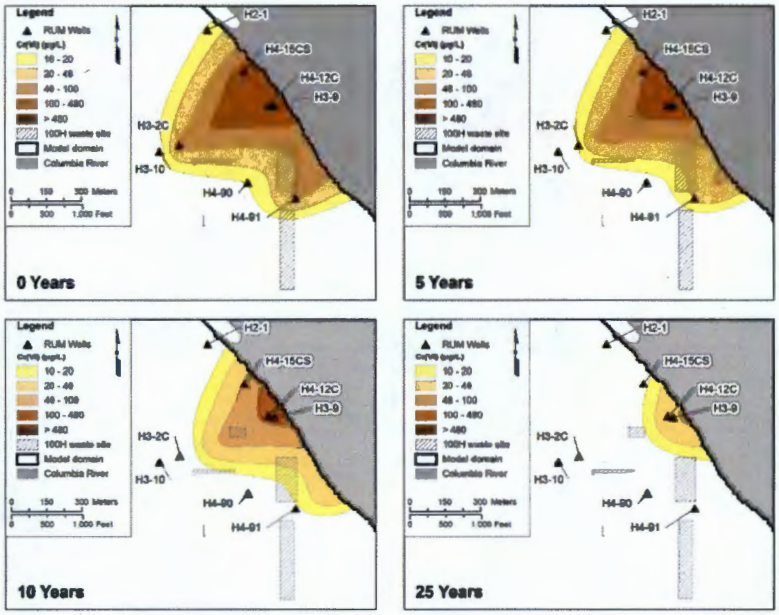

Figure C.34. Simulated Cr(VI) concentrations with a single domain, neutral vertical gradient, Scenario A with no source simulated in the RUM aquitard.

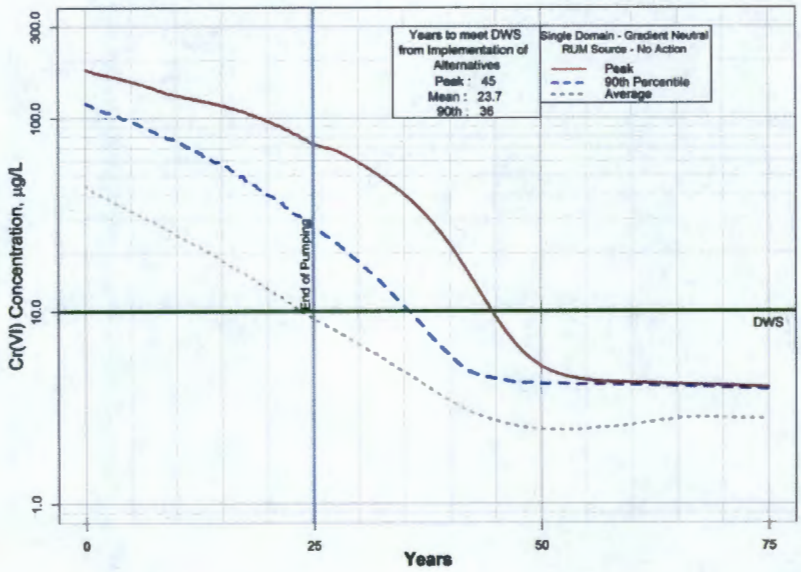

Figure C.35 - Time series for statistical measure of simulated Cr(VI) concentrations within the semi-confined aquifer for simulation of with a single domain, neutral vertical gradient, Scenario A with a source simulated in the RUM aquitard.

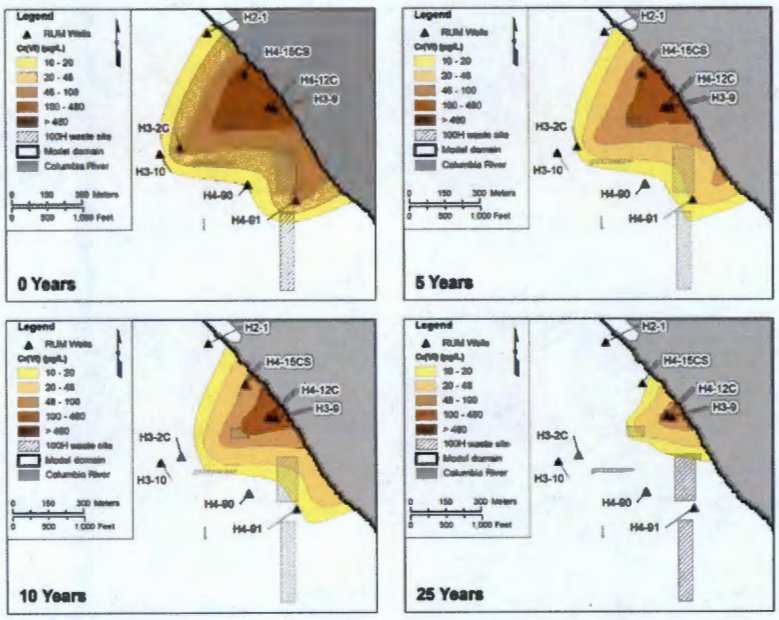

Figure C.36. Simulated Cr(VI) concentrations with a single domain, neutral vertical gradient, Scenario A with a source simulated in the RUM aquitard.

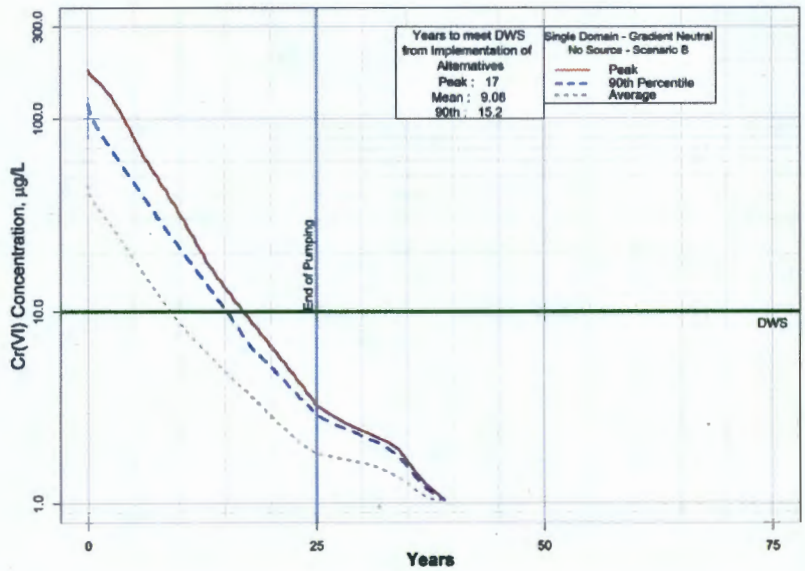

Figure C.37 - Time series for statistical measure of simulated Cr(VI) concentrations within the semi-confined aquifer for simulation of with a single domain, neutral vertical gradient, Scenario B with no source simulated in the RUM aquitard.

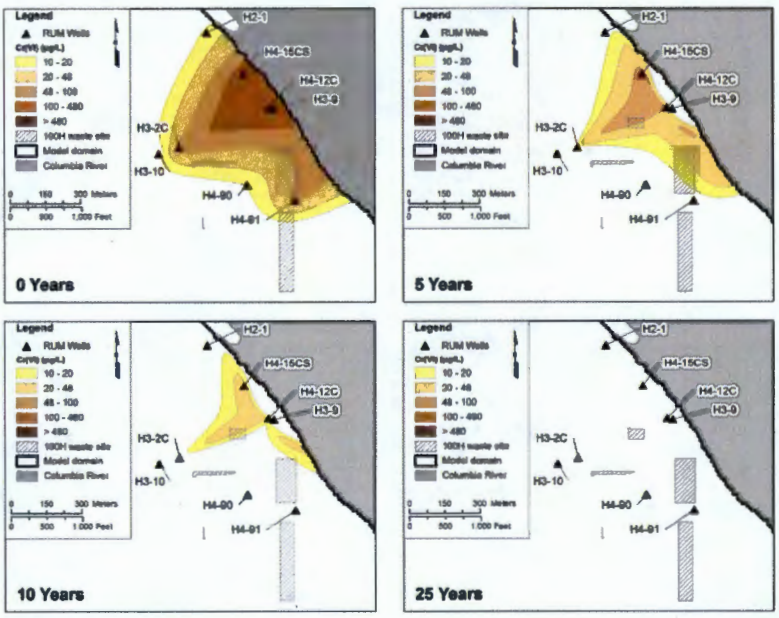

Figure C.38. Simulated Cr(VI) concentrations with a single domain, neutral vertical gradient, Scenario B with no source simulated in the RUM aquitard.

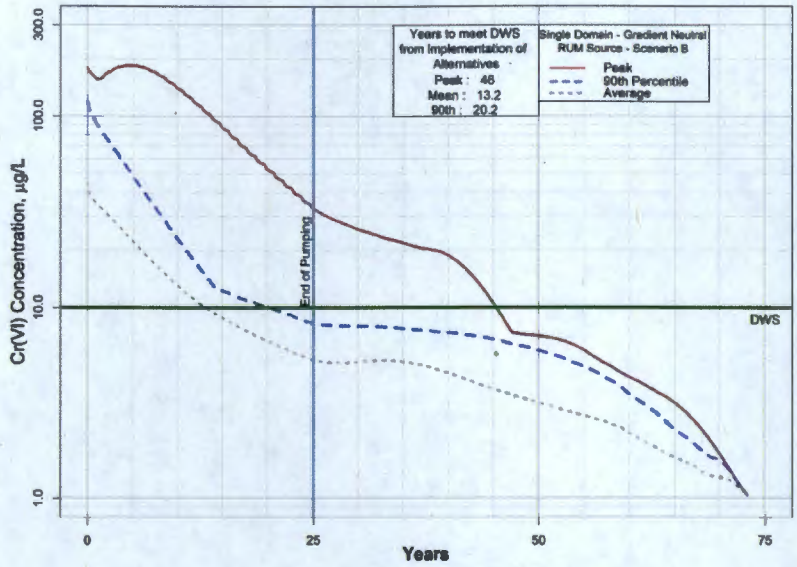

Figure C.39 - Time series for statistical measure of simulated Cr(VI) concentrations within the semi-confined aquifer for simulation of with a single domain, neutral vertical gradient, Scenario B with a source simulated in the RUM aquitard.

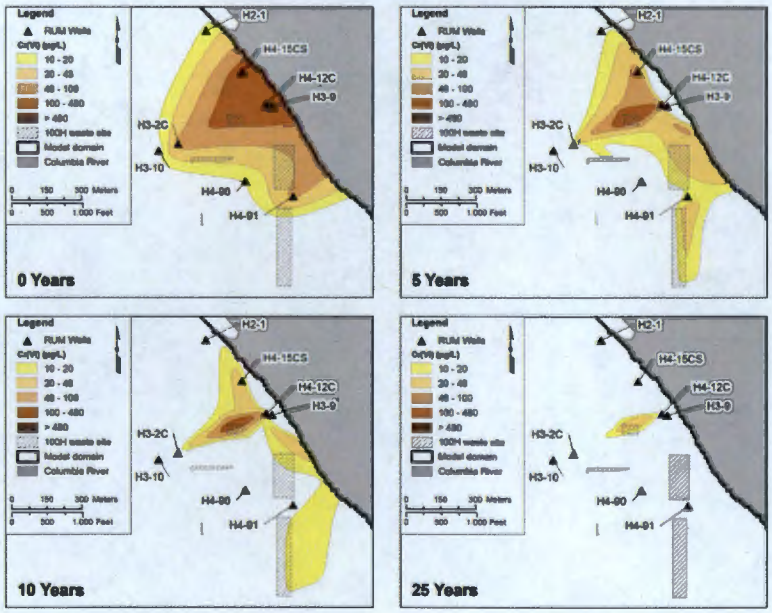

Figure C.40. Simulated Cr(VI) concentrations with a single domain, neutral vertical gradient, Scenario B with a source simulated in the RUM aquitard.

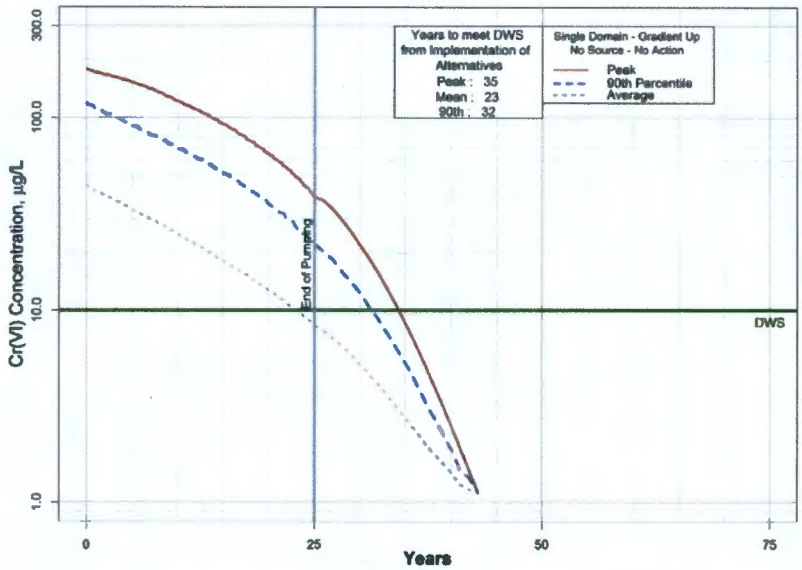

Figure C.41 - Time series for statistical measure of simulated Cr(VI) concentrations within the semi-confined aquifer for simulation of with a single domain, upward vertical gradient, Scenario A with no source simulated in the RUM aquitard.

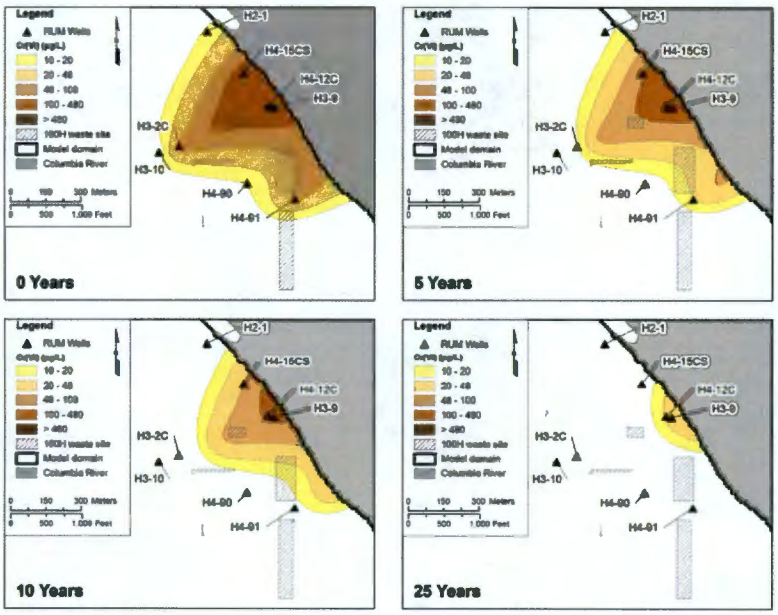

Figure C.42. Simulated Cr(VI) concentrations with a single domain, upward vertical gradient, Scenario A with no source simulated in the RUM aquitard.

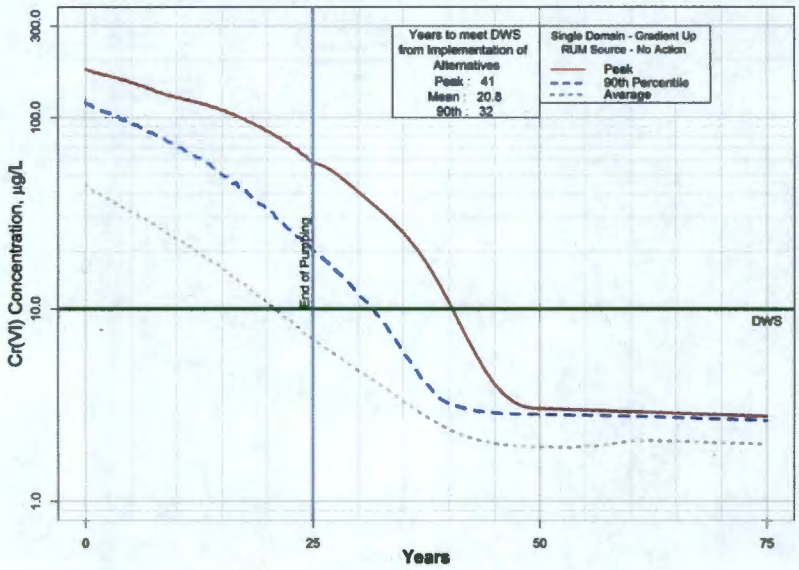

Figure C.43 - Time series for statistical measure of simulated Cr(VI) concentrations within the semi-confined aquifer for simulation of with a single domain, upward vertical gradient, Scenario A with a source simulated in the RUM aquitard.

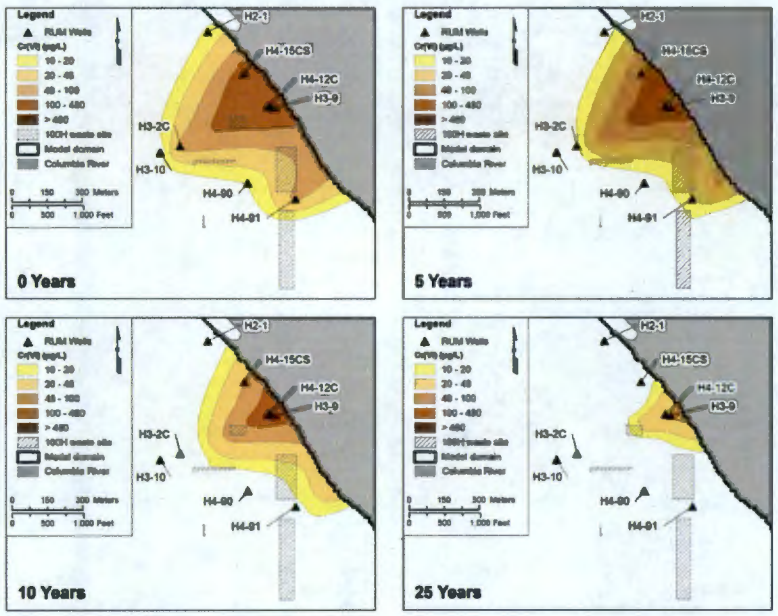

Figure C.44. Simulated Cr(VI) concentrations with a single domain, upward vertical gradient, Scenario A with a source simulated in the RUM aquitard.

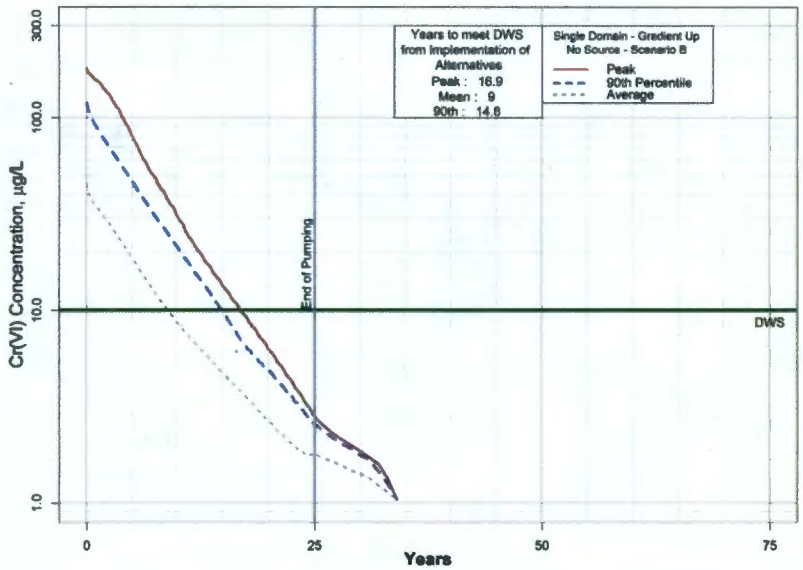

Figure C.45 - Time series for statistical measure of simulated Cr(VI) concentrations within the semi-confined aquifer for simulation of with a single domain, upward vertical gradient, Scenario B with no source simulated in the RUM aquitard.

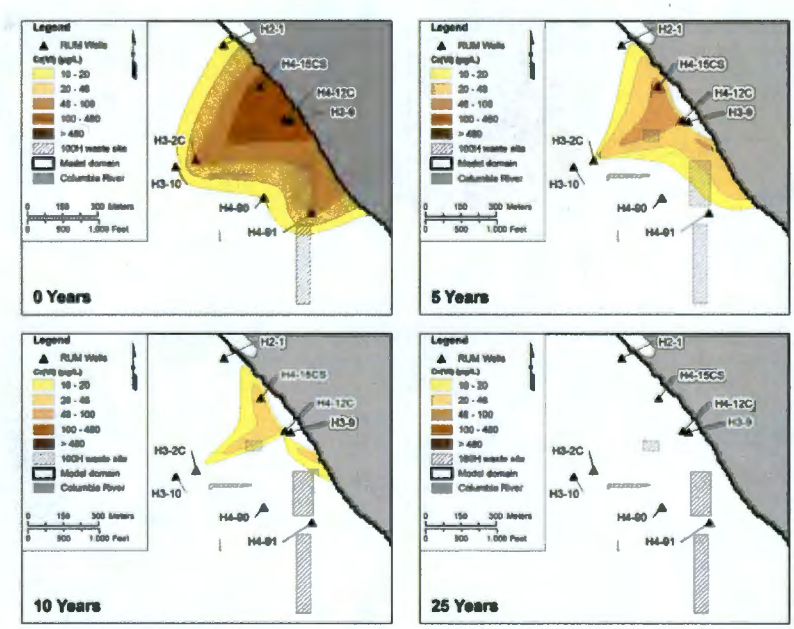

Figure C.46. Simulated Cr(VI) concentrations with a single domain, upward vertical gradient, Scenario B with no source simulated in the RUM aquitard.

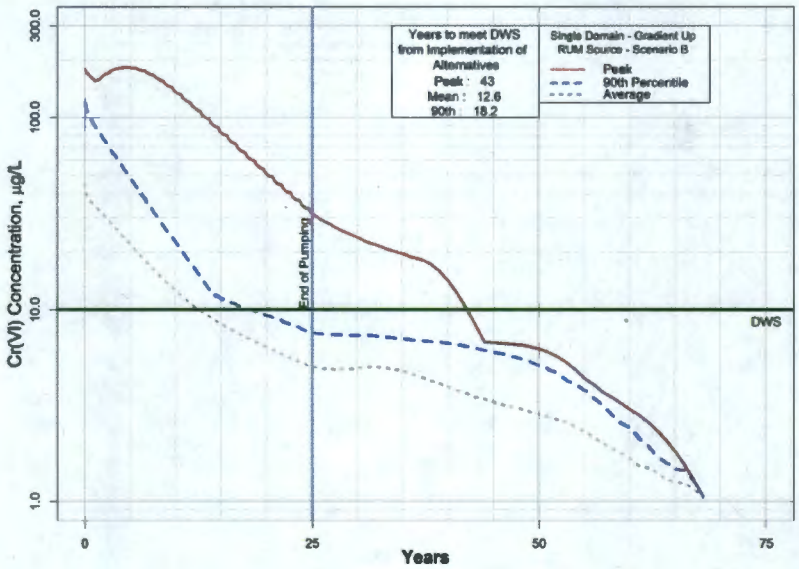

Figure C.47 - Time series for statistical measure of simulated Cr(VI) concentrations within the semi-confined aquifer for simulation of with a single domain, upward vertical gradient, Scenario B with a source simulated in the RUM aquitard.

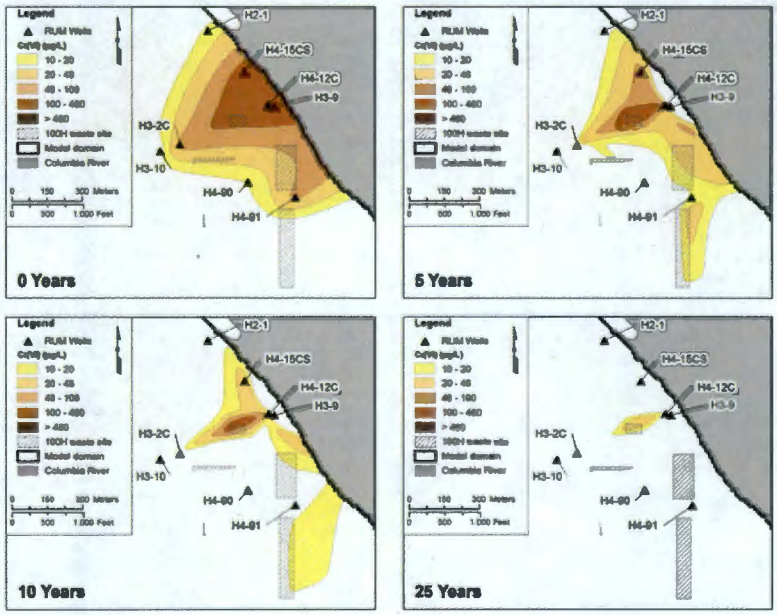

Figure C.48. Simulated Cr(VI) concentrations with a single domain, upward vertical gradient, Scenario B with a source simulated in the RUM aquitard.

Attachment D

Water Quality Measurements from HEIS for Wells Completed in the Semi-Confined Aquifer (First Water-bearing Unit of the Ringold Upper Mud)

Well Name	Date	Simulation Time (days)	Cr(VI) Concentration	Units	Lab Qualifier
199-H2-1	8/17/2011	593	5	µg/L	U
199-H2-1	8/17/2011	593	5	µg/L	U
199-H2-1	8/17/2011	593	2	µg/L	U
199-H2-1	8/17/2011	593	2	µg/L	U
199-H2-1	2/15/2012	775	5	µg/L	U
199-H2-1	2/15/2012	775	2	µg/L	U
199-H2-1	5/9/2012	860	2	µg/L	U
199-H2-1	6/4/2012	885	2.1	µg/L	B
199-H2-1	7/11/2012	922	8	µg/L	U
199-H2-1	7/31/2012	943	2	µg/L	U
199-H2-1	8/29/2012	972	2	µg/L	U
199-H2-1	10/22/2012	1025	7	µg/L	B
199-H2-1	10/22/2012	1025	6.5	µg/L	
199-H2-1	2/12/2013	1138	6.7	µg/L	
199-H2-1	4/17/2013	1203	6.4	µg/L	
199-H2-1	9/13/2013	1351	12.1	µg/L	
199-H2-1	10/25/2013	1394	11.9	µg/L	DCN
199-H2-1	10/25/2013	1394	9.1	µg/L	
199-H3-10	2/21/2012	782	5	µg/L	U
199-H3-10	2/21/2012	782	2	µg/L	U
199-H3-10	5/23/2012	874	2	µg/L	U
199-H3-10	10/19/2012	1023	5	µg/L	U
199-H3-10	10/19/2012	1023	2.2	µg/L	B
199-H3-10	2/4/2013	1131	5.5	µg/L	
199-H3-10	4/22/2013	1208	2.3	µg/L	B
199-H3-10	9/13/2013	1352	3.8	µg/L	B
199-H3-10	10/25/2013	1393	1.23	µg/L	BD
199-H3-10	10/25/2013	1393	2.6	µg/L	B
199-H3-2C	8/9/2010	221	30	µg/L	
199-H3-2C	9/2/2010	244	37	µg/L	
199-H3-2C	10/4/2010	277	41	µg/L	
199-H3-2C	1/5/2011	369	56	µg/L	
199-H3-2C	1/5/2011	369	57	µg/L	
199-H3-2C	1/24/2011	388	61.6	µg/L	
199-H3-2C	1/24/2011	388	62.1	µg/L	
199-H3-2C	2/3/2011	398	58	µg/L	
199-H3-2C	3/7/2011	430	55	µg/L	
199-H3-2C	4/4/2011	458	66	µg/L	
199-H3-2C	5/2/2011	486	64	µg/L	
199-H3-2C	9/12/2011	619	80	µg/L	

Well Name	Date	Simulation Time (days)	Cr(VI) Concentration	Units	Lab Qualifier
199-H3-2C	9/19/2011	626	59	µg/L	
199-H3-2C	9/26/2011	633	67	µg/L	
199-H3-2C	10/3/2011	641	60	µg/L	
199-H3-2C	11/1/2011	669	71	µg/L	
199-H3-2C	12/5/2011	703	66	µg/L	
199-H3-2C	12/29/2011	727	69.6	µg/L	
199-H3-2C	12/29/2011	727	70.3	µg/L	
199-H3-2C	1/3/2012	732	63	µg/L	
199-H3-2C	2/6/2012	766	67	µg/L	
199-H3-2C	2/29/2012	789	69.2	µg/L	
199-H3-2C	3/5/2012	794	66	µg/L	
199-H3-2C	4/2/2012	823	66	µg/L	
199-H3-2C	4/29/2012	849	67.6	µg/L	
199-H3-2C	4/29/2012	849	66.2	µg/L	
199-H3-2C	4/29/2012	850	56	µg/L	
199-H3-2C	6/4/2012	886	65	µg/L	
199-H3-2C	6/11/2012	893	71.3	µg/L	
199-H3-2C	7/3/2012	914	65	µg/L	
199-H3-2C	7/22/2012	933	66	µg/L	
199-H3-2C	7/22/2012	933	76.5	µg/L	
199-H3-2C	8/1/2012	944	66	µg/L	
199-H3-2C	8/8/2012	950	74.5	µg/L	
199-H3-2C	9/4/2012	977	64	µg/L	
199-H3-2C	10/28/2012	1032	66	µg/L	
199-H3-2C	11/1/2012	1036	62	µg/L	
199-H3-2C	11/26/2012	1060	66.5	µg/L	
199-H3-2C	11/26/2012	1060	67.1	µg/L	
199-H3-2C	11/26/2012	1060	63.4	µg/L	
199-H3-2C	11/26/2012	1060	64	µg/L	
199-H3-2C	12/3/2012	1067	65	µg/L	
199-H3-2C	1/2/2013	1097	65	µg/L	
199-H3-2C	2/4/2013	1131	65	µg/L	
199-H3-2C	2/20/2013	1146	66.2	µg/L	
199-H3-2C	3/4/2013	1158	65	µg/L	
199-H3-2C	4/1/2013	1186	66	µg/L	
199-H3-2C	5/1/2013	1217	65	µg/L	
199-H3-2C	5/29/2013	1244	63.4	µg/L	
199-H3-2C	6/3/2013	1249	64	µg/L	
199-H3-2C	7/2/2013	1278	63	µg/L	
199-H3-2C	8/1/2013	1308	62	µg/L	

Well Name	Date	Simulation Time (days)	Cr(VI) Concentration	Units	Lab Qualifier
199-H3-2C	8/13/2013	1320	62.4	µg/L	
199-H3-2C	9/3/2013	1341	60	µg/L	
199-H3-2C	10/8/2013	1377	61	µg/L	
199-H3-9	2/1/2011	397	2	µg/L	U
199-H3-9	8/17/2011	594	104	µg/L	
199-H3-9	8/17/2011	594	115	µg/L	
199-H3-9	2/15/2012	775	158	µg/L	
199-H3-9	2/15/2012	775	170	µg/L	
199-H3-9	5/23/2012	873	162	µg/L	
199-H3-9	7/30/2012	941	179	µg/L	
199-H3-9	10/19/2012	1022	153	µg/L	
199-H3-9	10/19/2012	1022	146	µg/L	
199-H3-9	2/4/2013	1131	129	µg/L	
199-H3-9	4/17/2013	1202	133	µg/L	
199-H3-9	9/13/2013	1351	114	µg/L	
199-H3-9	9/13/2013	1351	115	µg/L	
199-H3-9	10/25/2013	1393	103	µg/L	N
199-H3-9	10/25/2013	1393	116	µg/L	
199-H4-12C	8/16/2010	227	124	µg/L	
199-H4-12C	8/16/2010	227	126	µg/L	
199-H4-12C	9/2/2010	244	121	µg/L	
199-H4-12C	10/4/2010	277	128	µg/L	
199-H4-12C	12/16/2010	349	128	µg/L	
199-H4-12C	12/16/2010	349	139	µg/L	
199-H4-12C	12/16/2010	349	140	µg/L	
199-H4-12C	1/5/2011	369	138	µg/L	
199-H4-12C	2/3/2011	398	136	µg/L	
199-H4-12C	3/7/2011	430	148	µg/L	
199-H4-12C	4/4/2011	458	138	µg/L	
199-H4-12C	5/2/2011	486	134	µg/L	
199-H4-12C	9/12/2011	619	147	µg/L	
199-H4-12C	9/19/2011	626	145	µg/L	
199-H4-12C	9/26/2011	633	143	µg/L	
199-H4-12C	10/3/2011	641	133	µg/L	
199-H4-12C	11/1/2011	669	141	µg/L	
199-H4-12C	12/5/2011	703	135	µg/L	
199-H4-12C	12/14/2011	713	142	µg/L	
199-H4-12C	12/14/2011	713	137	µg/L	
199-H4-12C	1/3/2012	732	133	µg/L	
199-H4-12C	2/6/2012	766	139	µg/L	

Well Name	Date	Simulation Time (days)	Cr(VI) Concentration	Units	Lab Qualifier
199-H4-12C	3/5/2012	794	130	µg/L	
199-H4-12C	4/2/2012	823	130	µg/L	
199-H4-12C	4/29/2012	849	127	µg/L	
199-H4-12C	4/29/2012	850	115	µg/L	
199-H4-12C	5/17/2012	868	138	µg/L	
199-H4-12C	6/4/2012	886	125	µg/L	
199-H4-12C	6/11/2012	893	127	µg/L	
199-H4-12C	7/3/2012	914	119	µg/L	
199-H4-12C	7/22/2012	933	120	µg/L	
199-H4-12C	7/22/2012	933	130	µg/L	
199-H4-12C	8/1/2012	944	126	µg/L	
199-H4-12C	8/8/2012	950	138	µg/L	
199-H4-12C	9/4/2012	977	125	µg/L	
199-H4-12C	10/28/2012	1032	125	µg/L	
199-H4-12C	11/1/2012	1036	129	µg/L	
199-H4-12C	11/1/2012	1036	127	µg/L	
199-H4-12C	11/1/2012	1036	125	µg/L	
199-H4-12C	12/3/2012	1067	137	µg/L	
199-H4-12C	1/2/2013	1097	117	µg/L	
199-H4-12C	1/28/2013	1124	125	µg/L	
199-H4-12C	2/4/2013	1131	121	µg/L	
199-H4-12C	3/4/2013	1158	122	µg/L	
199-H4-12C	4/1/2013	1186	120	µg/L	
199-H4-12C	4/10/2013	1195	120	µg/L	
199-H4-12C	5/1/2013	1217	116	µg/L	
199-H4-12C	6/3/2013	1249	117	µg/L	
199-H4-12C	7/2/2013	1278	113	µg/L	
199-H4-12C	7/31/2013	1308	114	µg/L	
199-H4-12C	8/1/2013	1308	113	µg/L	
199-H4-12C	9/3/2013	1341	116	µg/L	
199-H4-12C	10/8/2013	1377	120	µg/L	
199-H4-15CS	7/7/1995	-5292	85.7	µg/L	
199-H4-15CS	10/28/1996	-4812	100	µg/L	
199-H4-15CS	10/28/1996	-4812	100	µg/L	
199-H4-15CS	4/3/1997	-4656	100	µg/L	
199-H4-15CS	7/2/1997	-4565	63	µg/L	
199-H4-15CS	11/23/1997	-4422	99.2	µg/L	
199-H4-15CS	11/23/1997	-4422	93	µg/L	
199-H4-15CS	7/8/1998	-4195	95	µg/L	
199-H4-15CS	11/10/1998	-4070	90.8	µg/L	

Well Name	Date	Simulation Time (days)	Cr(VI) Concentration	Units	Lab Qualifier
199-H4-15CS	7/1/1999	-3837	98	µg/L	
199-H4-15CS	7/1/1999	-3837	101	µg/L	
199-H4-15CS	11/3/1999	-3712	99	µg/L	
199-H4-15CS	7/12/2000	-3459	104	µg/L	
199-H4-15CS	11/14/2000	-3335	110	µg/L	
199-H4-15CS	7/3/2001	-3104	113	µg/L	
199-H4-15CS	11/5/2001	-2979	105	µg/L	
199-H4-15CS	11/5/2001	-2979	115	µg/L	
199-H4-15CS	7/18/2002	-2724	115	µg/L	
199-H4-15CS	10/29/2002	-2621	118	µg/L	
199-H4-15CS	7/1/2003	-2376	109	µg/L	
199-H4-15CS	11/17/2003	-2237	105	µg/L	
199-H4-15CS	7/6/2004	-2005	92	µg/L	
199-H4-15CS	11/3/2004	-1884	84.1	µg/L	
199-H4-15CS	11/3/2004	-1884	89	µg/L	
199-H4-15CS	11/3/2004	-1884	82	µg/L	
199-H4-15CS	7/8/2005	-1638	74	µg/L	
199-H4-15CS	7/8/2005	-1638	75	µg/L	
199-H4-15CS	11/29/2005	-1494	95	µg/L	
199-H4-15CS	7/12/2006	-1269	95	µg/L	
199-H4-15CS	11/9/2006	-1149	105	µg/L	
199-H4-15CS	11/9/2006	-1149	98.6	µg/L	
199-H4-15CS	6/14/2007	-932	102	µg/L	
199-H4-15CS	1/3/2008	-729	100	µg/L	
199-H4-15CS	1/3/2008	-729	157	µg/L	
199-H4-15CS	5/29/2008	-582	95	µg/L	
199-H4-15CS	11/24/2008	-403	97.3	µg/L	
199-H4-15CS	11/24/2008	-403	98.7	µg/L	
199-H4-15CS	6/10/2009	-205	94.9	µg/L	
199-H4-15CS	6/10/2009	-205	95.2	µg/L	
199-H4-15CS	10/27/2009	-66	102	µg/L	
199-H4-15CS	10/27/2009	-66	102	µg/L	
199-H4-15CS	10/27/2009	-65	99.6	µg/L	
199-H4-15CS	10/27/2009	-65	101	µg/L	
199-H4-15CS	10/27/2009	-65	102	µg/L	
199-H4-15CS	10/28/2009	-65	101	µg/L	
199-H4-15CS	11/9/2009	-52	115	µg/L	
199-H4-15CS	11/9/2009	-52	113	µg/L	
199-H4-15CS	5/16/2010	135	129	µg/L	
199-H4-15CS	5/16/2010	135	128	µg/L	

Well Name	Date	Simulation Time (days)	Cr(VI) Concentration	Units	Lab Qualifier
199-H4-15CS	1/24/2011	388	127	µg/L	
199-H4-15CS	1/24/2011	388	133	µg/L	
199-H4-15CS	1/24/2011	388	133	µg/L	
199-H4-15CS	8/2/2011	578	143	µg/L	
199-H4-15CS	10/18/2011	655	153	µg/L	
199-H4-15CS	10/12/2012	1015	89.2	µg/L	
199-H4-15CS	10/12/2012	1015	85.7	µg/L	
199-H4-15CS	10/17/2013	1385	54.2	µg/L	
199-H4-15CS	10/17/2013	1385	52.3	µg/L	
199-H4-90	9/12/2013	1351	10.4	µg/L	
199-H4-91	9/9/2013	1347	62.2	µg/L	