ECF-200UP1-14-0031
Revision 0

Optimization of 200-UP-1 Uranium Pump-and-Treat Well Locations with Resultant Contaminant Effluent Concentrations

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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INTERA, Inc.

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ENVIRONMENTAL CALCULATION COVER PAGE

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ENVIRONMENTAL CALCULATION COVER PAGE (CONTINUED)

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Contents

1 Purpose

The purpose of this environmental calculation file (ECF) is to document the design of two extraction well (EW) locations, with resultant contaminant effluent concentration, for the uranium plume at the U-Plant Zone (Area) of the 200-UP-1 Groundwater Operable Unit (OU) in the U.S. Department of Energy's (DOE's) Hanford Site (**Figure B-1**). The locations were determined using a heuristic optimization method. Uranium was considered the primary contaminant of interest (COI). Nitrate, technetium-99, and iodine-129 were the secondary COIs.

This ECF was completed in four steps.

1. The effectiveness of cut-off levels (CLs) and injection wells (IWs) in remediating the uranium plume was assessed.
2. The evolution of the EW locations for the uranium plume is discussed. An initial selection of locations was evolved to the final selection for remediating the plume.
3. The effectiveness of the EW locations in remediating the other plumes was assessed.
4. The effluent concentration of each COI was assessed.

This ECF was completed using groundwater flow and transport modeling. The Central Plateau Groundwater (CPGW) model was used for the modeling.

2 Methodology

2.1 Cut-Off Level and Injection Well

A set of scenarios to remediate multiple plumes at the 200-UP-1 OU was presented in ECF-200UP1-10-0374, 2012, *Development and Evaluation of Pumping Scenarios for Iodine, Uranium, Nitrate, Technetium-99, Tritium, and Chromium Plumes in the 200-UP-1 Operable Unit Using Central Plateau Groundwater Model Version 3*, Rev. 2. Of these, Scenario 3 was selected for this ECF (**Figure B-2**). This scenario included two EWs and two IWs to remediate the uranium plume at the U-Plant Zone. Each of these IWs/EWs was operated at 75 gallons per minute (gpm). In this ECF, the fate of the plume over time was summarized using statistical analysis. A cut-off level (CL) was used to define the plume boundary. A sensitivity analysis (SA) was conducted to select the cut-off level for the plume (Section 7.1.1). Thereafter, another SA was conducted to assess the effectiveness of IWs in remediating the plume (Section 7.1.2).

2.2 Extraction Well

An optimization (evolutionary) method was used to select the two EWs (Section 1). Below, the method is discussed (Section 2.3). In summary, the method guided an initial selection through an evolutionary (improvement) path of improved selections to the final selection. Groundwater modeling was conducted for the guidance (Section 2.4). An initial set of nine EWs covering the uranium plume at the U-Plant Zone was evolved over a simulation period (Section 5.4.1). In this ECF, the evolutionary method itself is not documented. Only, the final selection is documented (Table A-1). In addition, the impact of this selection on the uranium and other plumes is documented.

2.3 Optimization Modeling

Optimization may refer to efforts for improving the effectiveness, efficiency, and speed of a remedy (USEPA 2007). Simulation (groundwater modeling) optimization is a tool to support the effort. The optimization attempts to minimize cost or time in achieving a remedial objective using mathematical models of subsurface processes.

Theoretically, the optimal solution is defined as the best solution (the minimum cost or time in achieving the remedial objective). However, finding this solution is difficult (Morshed and Kaluarachchi, 2000). Alternatively, an evolutionary method may be used to find a sub-optimal solution given computational resources. The method evolves from an initial solution to increasingly improved solutions along an evolutionary path. The method is terminated after evolving to a sub-optimal solution given the resources. As the optimal solution remains unknown, this sub-optimal solution inherits a tentative definition. The solutions (from the initial to the sub-optimal) found along the path are studied to assess the acceptability.

In this ECF, optimization is limited to finding an improved (not the optimal) solution. As such, the evolutionary method was used. The method was not compared with other methods. The method evolved an initial selection to the final selection along an evolutionary path scenario-by-scenario. The final selection is sub-optimal. It was considered workable. Its objective was to select two EW locations from a set of nine locations. Each EW were assigned a maximum extraction rate. The actual rate was adjusted based on a minimum concentration. Noted, the drinking water standard (DWS) of uranium is 30 μg/L.

Scenario 1 included the initial selection: a set of nine EWs (including the selected two EWs) covering the uranium plume at the U-Plant Zone. The wells were screened given the initial concentration (IC) of the plume (Section 5.2.2). One well was screened in Layer 2, while the others were screened in Layers 2 and 3. Initially, a well was assigned a maximum extraction rate of 75 gpm. The rate was distributed to the screens of the well based on the IC and a minimum concentration (15 μg/L). If the IC was above the minimum concentration, the screen was turned on. Otherwise, the screen was turned off. These wells, together with other wells (already present as part of model definition) in the model domain, formed a configuration. Groundwater modeling was conducted to predict fate of the plume and to adjust extraction rates over time given the configuration. The modeling was conducted in 2-year increments over 7 cycles, leading to a simulation period of 14 years (Section 5.4.1). The operation of the wells was adjusted based on the IC and the minimum concentration at the end of each 2-year increment. This scenario identified three wells with higher acceptability. These wells remained turned-on for most of the simulation period and, hence, had higher acceptability.

Scenario 2 was similar to Scenario 1 with a different basis. The rate of a well was distributed to the screens of the well based on the IC, and the rates of the wells were based on a maximum total rate (150 gpm). This scenario identified three wells with higher acceptability. These are same three wells identified in Scenario 1.

Scenario 3 included another configuration of nine wells. Six wells were place near the three wells identified in Scenario 2. The extraction rates of these wells were adjusted similar to Scenario 2. This scenario identified four adjacent wells with higher acceptability. One had the highest acceptability, while the remaining three had next higher acceptability. The well with the highest acceptability and a well with the next higher acceptability were selected as the two EWs (Table A-1). The selection matched the recommendation provided in ECF-200UP1-10-0374 (2012).

2.4 Groundwater Modeling

Given an EW selection (Section 2.2), groundwater flow was simulated using the CPGW model (CP-47631, 2014, *Model Package Report: Central Plateau Groundwater Model Version 6.3.3*). The simulation began from an initial head (IH) of the groundwater (Section 5.2.1). The hydraulic head and groundwater flow over time were predicted by the simulation. Given the flow, contaminant transport of a COI (Section 1) was simulated re-using the CPGW model. The simulation began from an IC of the COI. The predictions helped to assess the effectiveness of the EW selection on concentration attenuation and, hence, mass removal of the COI.

The CPGW model was used for the groundwater modeling. The model was implemented using the MODFLOW-2000-MST and MT3DMS-MST software packages for the flow and transport, respectively. A description of the model is provided in CP-47631 (2014). The key features are presented in Section 4.

2.5 Summary Statistics

Human health and ecological risk assessments are discussed in River Corridor Baseline Risk Assessment (RCBRA), 2008. These assessments assume receptors to be exposed to contaminants of potential concern (COPCs) over a specified space-time domain given various media/pathways. An exposure point is a location (along a pathway in a medium) of potential contact with a receptor. The exposure point concentration (EPC) is the COPC concentration at the exposure point over time. To quantify EPC, the assessments include the central tendency exposure (CTE) and the reasonable maximum exposure (RME). A CTE scenario assesses risk to an average member of the population. An RME scenario assesses risk to a non-average member, whose behavior may subject itself to higher-than-average risk. The CTE and RME present a probabilistic risk assessment. They provide an estimate of the mean and upper percentile for EPC.

Generally, the RME and CTE are based on representative concentrations (RCs). Means (averages) are used to calculate RC as CTE. 95% upper confidence limit (UCL) is used to calculate RC as RME. An overview of the technical approach for calculating RCs for the RCBRA is discussed in DOE (2011). In addition, the Washington Administrative Code (WAC) provides methods for calculating RCs (WAC 173-340-740). The code permits use of "other statistical methods approved by the department." Furthermore, Oregon Administrative Rule (OAR) specifies 90% UCL on the arithmetic mean to estimate RME, unless a different estimate is acceptable to Department of Environmental Quality (DEQ) (OAR 340-122-0084, 2014).

In this ECF, groundwater modeling was conducted over an appropriate time period given the final selection (Section 2.2). A summary statistics of the resulting contaminant concentrations were used to quantify EPC. The statistics were predicted in three steps.

1. The operation of the selected configuration was operated over a time sufficient to lower the 90th percentile concentration (C_{90}) below the DWS of the uranium plume (Section 2.5.1).
2. The effectiveness of the selected configuration in lowering the maximum concentration (C_{max}) of the uranium plume (Section 2.5.2) was studied.
3. The effectiveness of the selected configuration in lowering C_{90} and C_{max} of the other COIs was studied.

2.5.1 90th Percentile Concentration

RME is calculated using 95% upper confidence limit (UCL) (Section 2.5). Furthermore,

1. WAC provides permits use of other statistical methods (WAC 173-340-740).
2. OAR specifies 90% UCL on the arithmetic mean to estimate RME (OAR 340-122-0084, 2014).

In this ECF, 90% UCL is used to widen the range between RME and C_{max}.

The concentration of a COI plume was predicted over time using groundwater modeling (Section 2.4). The predicted concentrations were sampled at all cells in the model domain at a time. The concentrations above a cut-off level (CL) were selected. The level used was 1% of the DWS (Section 7.1). In general, the DWS was taken as the maximum contaminant level (MCL). The mean (μ) and standard deviation (σ) of the selected concentration were predicted. Assuming a statistical distribution (Section 3.1), a one-sided C_{90} for the time was predicted: $C_{90} = \mu + 1.282\sigma$. Repeating, C_{90} over time was predicted.

2.5.2 Maximum Concentration

The selected concentration was re-used (Section 2.5.1). C_{max} at a time was predicted as the maximum of the sample at the time. Repeating, C_{max} over time was predicted.

2.6 System Modeling

The two selected EWs (Section 2.3) and the other wells in the model domain were used to define the well configuration for further analysis. In addition, a simulation period was defined to simulate pump-and-treat (PT) followed by monitored natural attenuation (MNA) (Section 5.4.2).

2.7 Resultant Effluent Concentration

Given the groundwater modeling (Section 2.5.1), the resultant effluent concentrations (C_es) of all COIs were predicted. C_e was predicted using a mixing method. First, the effluent concentration of an EW (C_{ei}) was predicted. In general, the EW was screened in multiple layers of the model domain. Each screen received a distinct set of extraction rate and contaminant concentration over time. The resulting mass rates from all the screens mixed to produce the total mass rate of the EW. Thus, C_{ei} was predicted as the total mass rate divided by the total flow rate of the EW. Second, the resultant effluent concentration (C_e itself) after mixing the effluents of the two EWs was predicted. Each EW contributed a distinct set of extraction rate and effluent concentration to the mix over time. The resulting mass rates from all the EWs mixed to produce the total mass rate to the mix. Thus, C_e was predicted as the total mass rate divided by the total flow rate of the EWs. In short, C_e was predicted as:

$$C_{ei} = \frac{\sum_{j=1}^{S} Q_j C_j}{\sum_{j=1}^{S} Q_j} \qquad Q_i = \sum_{j=1}^{S} Q_j \tag{1}$$

$$C_e = \frac{\sum_{i=1}^{N} Q_i C_{ei}}{\sum_{i=1}^{N} Q_i} \qquad Q = \sum_{i=1}^{N} Q_i \qquad (N = 2) \tag{2}$$

Here, Q_j = extraction rate at the j-th screen of the i-th well; C_j = concentration at the j-th screen; S = number of screens in the i-th well; Q_i = extraction rate at the i-th well; N = number of wells, and Q = total extraction rate.

3 Assumptions and Limitations

3.1 Assumptions

The assumptions of this ECF are the same as those of the CPGW model (CP-47631, 2014). The groundwater flow solution of this model is implemented in the MODFLOW-2000 software (USGS, 2000, *MODFLOW-2000, the U.S. Geological Survey Modular Ground-water Model – User Guide to Modularization Concepts and the Ground-Water Flow Process*). The solution is used to solve the governing equation for groundwater flow in the model domain. The contaminant transport solution is implemented in the MT3DMS software (SERDP-99-1, 1999, *MT3DMS: A Modular Three-Dimensional Multi-Species Transport Model for Simulation of Advection, Dispersion and Chemical Reactions of Contaminants in Groundwater Systems, Documentation and User's Guide*). The solution is used to solve the governing equation for contaminant transport in the domain. The solution uses the MODFLOW-generated solution. Thus, these two approved software packages together with certain assumptions are used for groundwater modeling. The key assumptions are:

1. Water is the only liquid phase flowing through the saturated porous media in the domain.
   - The flow occurs with constant density
   - The flow occurs under a laminar condition that follows Darcy's Law.
2. Transport processes include advection, dispersion, linear sorption, and first-order decay.
   - The reactions between COIs are negligible.
3. Flow boundary conditions (BCs) represent the flow-driving processes adequately.
   - Recharge arrives directly in the uppermost saturated layer.
   - Flow through the basalt bedrock is negligible.
4. Transport BCs represent the transport- driving processes adequately.
   - Contaminant fluxes from the overlying vadose zone are negligible.
5. Flow IC is known adequately.

6. Transport IC is known adequately.

7. Each plume of a COI is independent. It does not impact other plumes.

8. Each hydrostratigraphic unit (HSU) is homogeneous both regionally and vertically (Section 4.3)

9. Flow parameters are representative of the hydrogeologic properties near vicinity of each COI plume.

10. Transport parameters are representative of the material hydrogeochemical properties near vicinity of each COI plume.

11. A normal distribution was assumed for the predicted concentration.

3.2 Limitations

The limitations of this ECF are those arising from the use of the CPGW model (CP-47631, 2014). The model is limited in intent and purpose to the simulation of saturated flow in the unconsolidated aquifer above the underlying basalts. The model is suitable for predicting water levels, hydraulic gradients, and groundwater flow directions and rates throughout the Central Plateau. The key limitations are:

1. The flow model is regional in nature. Hydraulic property variation is generally recognized at the scale (1 km to 10 km horizontally) of HSUs.

2. The model grid represents the model domain with cells of dimension 100 m by 100 m. The model is suitable for making predictions of heads, hydraulic gradients, and groundwater flow rates over areas that comprise many model cells. The model is not suitable for making predictions of these quantities on scales smaller than 100 m, except in circumstances of uniform hydraulic gradients.

3. Fluid flow and contaminant transport in the overlying vadose zone are not explicitly simulated.

4. The application of recharge derived from deep percolation of precipitation at the land surface implicitly represents the effects of vadose zone migration and storage. The rates used represent a best practice combination of empirical data and model simulations of vadose zone migration characteristics at the Hanford Site.

5. Attenuation of facility discharges to the ground surface, crib, trench, well, pond, ditch, and other infiltration areas is indirectly accounted following Nichols et al (2007). The predicted attenuation (delay of arrival and reduction of peak) of recharge to the water table is included as input data for the model. At present, the limitations of this method include:

    a. The method simulates the vadose zone for each liquid discharge site as a quasi-two-dimensional cross section model using local hydraulic stratigraphy, scaling the horizontal dimension to achieve unit gradient conditions in the lowest conductivity layer during the highest artificial discharge period. Further, some calibration is applied for certain sites where more detailed three-dimensional modeling studies are available.

    b. This method may not be suitable where perching of water on fine-grained layers, followed by lateral redistribution of moisture in the vadose zone, occurs.

However, this method provides an improvement, compared to ignoring the presence of the considerable vadose zone, for incorporating artificial discharges.

6. Perching is believed to have been a significant vadose zone process in the 200-West Area, including the 200-UP-1 OU. Perching is suspected for the failure of the calibration to date in matching predictive and measured water levels in these locales. However, the large discharges to the surface that occurred in the historic period are expected not to occur in the future. Perching is not expected to be a significant process in future.
7. Flow through the bedrock is not explicitly simulated. If there are sources and/or sinks of water associated with this bedrock, the model is limited to this exclusion.
8. The calibration used weighting to emphasize early and late hydraulic head data. The weighting was used to ensure a better match for periods closer to the future period, where the unconfined aquifer is not strongly influenced by high operational liquid discharges. The model is limited to poorer match of hydraulic heads during the peak of the historic operational period.
9. There remain considerable areas with limited well control in the Central Plateau. Consequently, the assignment of HSUs is subject to continued refinement, as more information becomes available for such areas.
10. The selection of the EWs was subjected to some restrictions.
    a. These EWs function within the facility engineering design lifetime.
    b. These EWs is limited by the capacity of the 200 West Groundwater Treatment Facility (GTF).
    c. These EWs will provide decision support to groundwater management for the U-Plant Zone. The final decision shall include additional factors like data limitation, model uncertainty, cost considerations, and others.
    d. An approximate reference for time is used. The exact time will depend on the actual start of remediation in/around the 200-UP-1 OU.

4 Key Feature

4.1 Domain

- Shape (Rectangular, **Figure B-3)**
    - Length (east-west extent): 25.6 km
    - Width (north-south extent): 13.4 km
- Datum
    - Horizontal: Washington State Plane, NAD 1983
    - Vertical: NAVD 1988
- Origin (lower-left corner)
    - Easting: 555650 m
    - Northing: 129850 m

- Coordinate System
  - x-axis: horizontal (east-west) direction
  - y-axis: horizontal (north-south) direction
  - z-axis: vertical direction

4.2 Discretization

- Domain: 134 rows, 256 columns, and 7 layers
  - Each cell: 100 m by 100 m
  - Each layer: non-uniform thickness

4.3 Hydrostratigraphic Unit

HSUs are used to define the model domain. They are:

1. Hanford coarse-grained
2. Hanford fine-grained
3. Cold Creek
4. Ringold E
5. Ringold mud
6. Ringold A

The key properties of the HSUs are presented in **Table A-2** and **Figure B-3** to **Figure B-4**. Each HSU is tagged to a distinct hydraulic conductivity (K_x) value (**Table A-2**). Thus, the delineation of the HSU in Layer 2 may be conceived from the distribution of (K_x) in the layer (**Figure B-3**). A discussion of the HSUs and their hydraulic conductivity (K_x, K_y, K_z) is provided in CP-47631 (2014).

4.4 Initial Time

- Beginning of 2014 (**Table A-3**)

5 Inputs

This section specifies the model inputs used for the groundwater modeling. Inputs include BC, IC, model parameter, and simulation period. Flow inputs, except the EWs for optimization, were obtained from CP-47631 (2014) (Section 2.3). The EWs for optimization were selected through the evolutionary method. Transport inputs, except initial concentration, were obtained from the CPGW model CP-47631 (2011 and 2013). The initial concentration was obtained from ECF-200UP1-14-0019, 2014, *Initial Groundwater Plume Development (Uranium, Technetium-99, Nitrate, and Iodine-129) to Support Fate and Transport Modeling for Remedial Design in the 200-UP-1 Groundwater Operable Unit.*

5.1 Boundary Condition

5.1.1 Flow Boundary Condition

Inflows to the model domain include recharge from areal precipitation, leakage through the beds of Cold Creek and Dry Creek, injection (subsurface discharge) from Treated Effluent Disposal Facility (TEDF) and State-Approved Land Disposal Site (SALDS), and groundwater inflow through lateral boundaries (Nichols et al, 2007). The domain is constricted by basalt sub-crops above the water table to the north, south, and west. Where present, these sub-crops are assumed to be no-flow boundaries. They are treated as inactive cells in the model. There are two gaps in the basalt sub-crops along the northern boundary, where the water table is above the basalt. The western-most region is referred to as the western gap, and the eastern region is referred to as the Gable Gap. The water table is above the basalt along the eastern boundary and the eastern-most part of the southern boundary. Cold Creek is located in the gap along the western boundary. This creek is a source of inflow to the domain. Dry Creek is the gap in the basalt sub-crops in the southwest corner. This creek is another source of inflow to the domain.

Outflows are restricted to groundwater flow across lateral boundaries and extraction wells. The low permeability basalt underlying the domain is assumed to experience negligible flow crossing it. Thus, it is treated as a no-flow boundary.

The key boundary conditions are:

- **Recharge**: In general, the recharge rate is varied spatially.
- **Constant Head:** Two gaps where the water table is above the top of Gable Ridge/Mountain Gap are set to constant head (CH) boundary condition.
- **General Head**: Eastern boundary below Gable Mountain is set to general head boundary (GHB) condition. The conductance for the GHB condition is determined through calibration of the model. In addition, a part of the southeastern boundary is set to a GHB condition.
- **Sources/Sinks:** Multiple extraction and injection wells (e.g. those in 200-ZP-1 OU), are included in the model. In addition, the selected EWs are included (Section 2.2).
- **No-Flow**: A part of the southeastern boundary, north of the Rattlesnake Ridge sub-crop, is set to no-flow boundary condition. In addition, the bottom boundary of the domain follows the contact between the overlying sediments and the underlying basalt. This boundary is set to no-flow boundary condition.

5.1.2 Transport Boundary Condition

The key boundary condition is:

- **Advective Mass Flux:** The advective mass flux at a boundary is determined internally in the model using the flow rate and contaminant concentration across the boundary (SERDP-99-1). Inflow concentration is zero by default.

5.2 Initial Conditions

5.2.1 Initial Head

The IH is the predicted head for the initial time (Section 5) at the beginning of the simulation. This head delineates the hydraulic head and groundwater flow distribution at the said time. The head is set to the predicted head at the end of the historic model simulation (CP-47631, 2014).

5.2.2 Initial Concentration

The IC is the predicted concentration of a COI for the initial time (Section 5). This concentration delineates the COI concentration distribution at the said time. The IC was based on data till 2013 (ECF-200UP1-14-0019). The IC included multiple parts of the COI plume in the model domain. Often, these parts overlap. A CL may be used to separate the parts.

In this ECF, a CL was used to separate the parts of a plume into separate plumes. Starting from a small value, the CL was gradually increased until the separation became visually distinct. Then, the plume at

U-Plant Zone was kept. The plumes away from the zone were discarded. Given the COIs, the CLs are presented in **Table A-4**. The horizontal extents in Layer 2 are presented in **Figure B-5** to **Figure B-8**. The vertical extents are presented in **Table A-4**.

5.3 Model Parameters

5.3.1 Flow Parameter

The hydraulic conductivities for the HSUs are presented in **Table A-2**. The hydraulic conductivity along the x-axis (K_x) in Layer 2 is presented in **Figure B-3** (Section 4.1). Given K_x=K_y, the hydraulic conductivity along the y-axis (K_y) in the layer is also presented in **Figure B-3**.

5.3.2 Transport Parameter

The bulk density of soil is presented in **Table A-2**. The distribution coefficient, half-life, and decay rate of the COIs are presented in **Table A-5**.

5.4 Simulation Period

5.4.1 Optimization Modeling

The simulation period for the optimization modeling (Section 2.3) was discretized using seven stress periods.

1. The first period is 2 year for 2014 to 2015. This period presents the present condition (PT1).
2. The second period is 2 years from 2016 to 2017. This period includes the EWs to be optimized.
3. The second period is 2 years from 2018 to 2019. This period includes the EWs to be optimized.
4. The second period is 2 years from 2020 to 2021. This period includes the EWs to be optimized.
5. The second period is 2 years from 2022 to 2023. This period includes the EWs to be optimized.
6. The second period is 2 years from 2024 to 2025. This period includes the EWs to be optimized.
7. The second period is 2 years from 2026 to 2027. This period includes the EWs to be optimized.

Thus, the first period defines the time before the EWs to be optimized begin operation. The second through seventh periods define the time over which the EWs to be optimized operate.

5.4.2 System Modeling

The simulation period for the system modeling (Section 2.6) was discretized using seven stress periods (**Table A-3**).

8. The first period is 1 year for 2014. This period presents PT1.
9. The second period is 5 years from 2015 to 2019. This period includes the operation of the two selected EWs (PT2). At the beginning of this period, the selection begins operation.

10. The third period is 5 years from 2020 to 2024. This period includes the operation of the two selected EWs.
11. The fourth period is 5 years from 2025 to 2029. This period includes the operation of the two selected EWs.
12. The fifth period is 5 years from 2030 to 2034. This period includes the operation of the two selected EWs.
13. The sixth period is 2 years from 2034 to 2036. This period includes the operation of the two selected EWs. At the end of this period, the selection ends operation.
14. The seventh period is 100 years from 2037 to 2136. This period presents the future condition (MNA) after the selection ends operation.

Thus, the first period defines the time before the two selected EWs begin operation. The second through sixth periods define the time over which the selection operates. The seventh stress period defines the time after the selection ends operation.

6 Software Application

Software is used in accordance with PRC-PRO-IRM-309, 2013, *Controlled Software Management.*

6.1 Approved Software

Approved software used is managed under the following software quality assurance documents of CH2M HILL Plateau Remediation Company (CHPRC) consistent with the requirements in PRC-PRO-IRM-309:

- 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 Acceptance Test Report*
- CHPRC-00261, *MODFLOW and Related Codes Requirements Traceability Matrix*

The safety software and support software are distinguished in CHPRC-00259. Safety software predicts reportable results. Support software supports run, visualization, or similar functions.

6.2 Description

Approved software packages were used.

1. **MODFLOW-2000-MST** (USGS, 2000)
    - HISI Entry: #2157
    - Rated: Safety Software (Graded Level C)
    - Function: Simulate groundwater flow under saturated conditions

- Application: Solve the three-dimensional groundwater flow equation using the finite difference method for both steady state and transient systems in the CPGW model
- Vendor: U.S. Geological Survey, with modifications by S. S. Papadopoulos and Associates
- Version: Build 6 with Minimum Saturated Thickness (MST)
- CHPRC approved executable file: mf2k-mst-chprc06dp.exe (CHPRC Build 6)

2. **MT3DMS-2000-MST** (SERDP-99-1)
   - Rated: Safety Software (Graded Level C)
   - HISI Entry: #2158
   - Function: Simulate contaminant transport under saturated conditions
   - Application: Solves the three-dimensional transient advection dispersion equations using the several different methods.
   - Vendor: U.S. Environmental Protection Agency, with modifications by S. S. Papadopoulos and Associates
   - Version: Build 6 with MST
   - CHPRC approved executable file: mt3d-mst-chprc06dp.exe (CHPRC Build 6)
3. **Groundwater Vistas™**[1]
   - Rated: Support Software
   - HISI Entry: N/A
   - Function: Provides a graphical user interface to construct, run, and depict MODFLOW and MT3DMS model and results
   - Application: Construct, run, and depict CPGW model
   - Vendor: Environmental Simulations, Inc. (Rumbaugh and Rumbaugh, 2011)
   - Version: 6

6.3 Software Installation and Checkout

Approved Safety Software (MODFLOW and MT3DMS) packages were checked out in accordance with procedures specified in CHPRC-00258. Executable files were obtained from the Software Owner who maintains the configuration-managed copies in MKS Integrity™[2]. Installation tests identified in CHPRC-00259 were performed, and successful installation was confirmed. Software Installation and Checkout Forms were completed and approved. Copies of the Software Installation and Checkout Forms for approved users and installations are provided in Appendix C.

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

[2] MKS Integrity™ is a trademark of MKS, Incorporated.

6.4 Statement of Valid Software Application

The software is used consistent with its intended use for the CHPRC. The use is identified in CHPRC-00257. The use is valid.

7 Prediction

7.1 Effectiveness of Cut-Off Level and Injection Well

7.1.1 Cut-Off Level

A SA was conducted to assess the effectiveness of CL in remediating the uranium plume at the U-Plant Zone (Section 2.1). The scenario (with IWs) was considered. The predicted concentration of this scenario was compared for three CLs based on three fractions (0.001, 0.01, and 0.10) of the DWS (**Table A-6**). C_{90} for these CLs are presented in **Figure B-9**. The time C_{90} takes to attain DWS increases as CL increases. The times are about 11, 14, and 19 yr for CL of 0.03, 0.3, and 3 respectively. The times change by a few years when the CL changes by orders of magnitude. Thus, the sensitivity of the time to a CL was expected low.

> Given this expectation, a tentative CL of 1% (or 0.01) DWS was selected to provide a lower bound of the time (C_{90} takes to attain DWS). The upper bound is provided by C_{max}. These two bounds are expected to provide a workable range for decision making.

Thus, the 1% DWS was selected for further analysis (**Table A-7**).

7.1.2 Injection Well

A SA was conducted to assess the effectiveness of injection in remediating the uranium plume at the U-Plant Zone (Section 2.1). Two scenarios (with/without IWs) were considered. (1) The scenario with IWs included two IWs and two EWs. Each well operated at 75 gpm. (2) The scenario without IWs included two EWs. Again, each well operated at 75 gpm. Their C_{90} and C_{max} are presented in **Figure B-10** to **Figure B-11**. The conclusion was:

> The injection wells do not provide a significant improvement of the remediation system in meeting the remediation objective (RAO) for clean-up of uranium.

Thus, the IWs were excluded in further analysis.

7.2 Selection of Extraction Well

In this ECF, two EWs are selected to remediate the uranium plume at the U-Plant Zone. The EW locations are presented in **Table A-1** and **Figure B-5**.

7.3 Effectiveness of Extraction Well

The effectiveness of the two EW locations in remediating the COI plumes was assessed. Flow simulation with these wells was conducted. Then, transport simulation of each COI plume was conducted. The predicted concentration of the COI was used to predict C_{90} and C_{max} over time. In addition, the concentration was used to predict C_e over time.

8 Result

8.1 Summary Statistics

1. **Uranium**: C_{90} and C_{max} are presented in **Figure B-12** to **Figure B-13**. C_{90} is expected to attain DWS after 20 years approximately. C_{max} is expected to remain above DWS after 123 years, or at the end of simulation period.

2. **Nitrate**: C_{90} and C_{max} are presented in **Figure B-14** to **Figure B-15**. C_{90} is expected to attain DWS after 50 years approximately. C_{max} is expected to remain above DWS after 123 years.

3. **Iodine-129**: C_{90} and C_{max} are presented in **Figure B-16** to **Figure B-17**. C_{90} is expected not to attain DWS within 123 years. C_{max} is expected to remain above DWS after 123 years.

4. **Technetium-99**: C_{90} and C_{max} are presented in **Figure B-18** to **Figure B-19**. C_{90} is expected to remain below DWS after 1 year approximately. It is expected to be below the DWS since the beginning of the simulation. C_{max} is expected to attain DWS after 8 years.

8.2 Resultant Effluent Concentration

1. **Uranium**: The effluent concentration in EW-1-U is presented in **Figure B-20**. The effluent concentration in EW-2-U is presented in **Figure B-21**. The resultant effluent concentration is presented in **Figure B-22**. The resultant concentration is expected to attain DWS after 15 years approximately.

2. **Nitrate**: The effluent concentration in EW-1-U is presented in **Figure B-23**. The effluent concentration in EW-2-U is presented in **Figure B-24**. The resultant effluent concentration is presented in **Figure B-25**. The resultant concentration is expected to attain DWS after 3 years approximately.

3. **Iodine-129**: The effluent concentration in EW-1-U is presented in **Figure B-26**. The effluent concentration in EW-2-U is presented in **Figure B-27**. The resultant effluent concentration is presented in **Figure B-28**. The resultant concentration is expected to attain DWS after 1 year approximately. It is expected to be below the DWS since the beginning of the simulation.

4. **Technetium-99**: The effluent concentration in EW-1-U is presented in **Figure B-29**. The effluent concentration in EW-2-U is presented in **Figure B-30**. The resultant effluent concentration is presented in **Figure B-31**. The resultant concentration is expected to attain DWS after 2 years approximately.

9 Conclusion

1. The assumptions and limitations of the ECF should be noted in interpreting the results.

2. C_{90} is based on a CL. As C_{90} is sensitive to the CL, C_{90} should be interpreted with caution.

3. C_{90} is significantly different from the C_{max}. C_{90} and C_{max} may be used as tentative and upper bounds respectively for groundwater management.

4. C_e attains DWS earlier than C_{90}. The treatment of groundwater extracted by the two EWs (final selection) may be stopped before the groundwater itself attains C_{90}.

5. The final solution obtained using the evolutionary method is the final solution obtained earlier using a trial-and-error method. In this first application, the evolutionary method did as well as the trial-and-error method. The only advantage is: the evolutionary method is computer intensive, while the trial-and-error method is labor intensive. Additional applications of the evolutionary method are needed to assess its potential in solving groundwater problems.

10 Reference

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Appendix A

Tables

Table A-1. Grid Coordinates of the Extraction Wells

Well (Name)	Row (#)	Column (#)	Top Layer (#)	Bottom Layer (#)
EW-1-U	83	121	2	2
EW-2-U	83	123	2	3

Table A-2. Hydrogeological Properties

CP (Order)	HSU (Name)	PNNL (Name)	K_x (m/day)	K_y (m/day)	K_z (m/day)	ρ_b (kg/L)
1	Hanford coarse-grained	HSU 1	17000	17000	1200	1.93
2	Hanford fine-grained	HSU 1	40	40	5	1.93
3	Cold Creek	HSU 3	400	400	20	1.93
4	Ringold E	HSU 5	5	5	0.5	1.90
5	Ringold mud	HSU 8	0.008	0.008	0.0008	1.90
6	Ringold A	HSU 9	4.8	4.8	0.48	1.90

HSU : Hydrostratigraphic unit
CP : Listing order in Section 4.3
PNNL : HSU number in PNNL-14898 (CP-47631)
K_i : Hydraulic conductivity along i-th direction
x-axis : Horizontal (east-west) direction
y-axis : Horizontal (north-south) direction
z-axis : Vertical direction
ρ_b : Bulk density of soil

Table A-3. Design of Stress Periods

Stress Period (#)	Period Length (yr)	Begin (Year)	End (Year)	Condition (Type)
1	1	2014	2014	PT1
2	5	2015	2019	PT2
3	5	2020	2024	PT2
4	5	2025	2029	PT2
5	5	2030	2034	PT2
6	2	2035	2036	PT2
7	100	2037	2136	MNA

PT1 : Pump-and-treat with present condition
PT2 : Pump-and-treat with the selected extraction wells (EWs) turned-on
MNA : Monitored natural attenuation with the selected EWs turned-off

Table A-4. Vertical Extent and Cut-Off Levels for Initial Concentration

Contaminant	VE Top Layer (#)	VE Bottom Layer (#)	CL (µg/L or pCi/L)
Uranium	2	4	10
Nitrate	2	5	35,000
Iodine-129	2	5	0.2
Technetium-99	2	5	180

VE : Vertical extent
CL : Cut-off level

Table A-5. Transport Properties

Contaminant	K_d (L/kg)	Half-Life (yr)	Half-Life (day)	Decay Rate (1/day)
Uranium	0.4	4.47E+09	1.63E+12	4.25E-13
Nitrate	0			
Iodine-129	0.1	1.57E+07	5.73E+09	1.21E-10
Technetium-99	0	2.11E+5	7.71E+07	8.99E-09

K_d: Distribution coefficient

Table A-6. Cut-Off Levels for Sensitivity Analysis

Contaminant	DWS (µg/L)	Fraction	CL (µg/L)
Uranium	30	0.001	0.03
Uranium	30	0.010	0.30
Uranium	30	0.100	3.00

DWS : Drinking water standard
CL : Cut-off level

Table A-7. Cut-Off Levels for Summary Statistics

Contaminant	DWS (µg/L or pCi/L)	Fraction	CL (µg/L or pCi/L)
Uranium	30	0.01	0.3
Nitrate	45,000	0.01	450
Iodine-129	1	0.01	0.01
Technetium-99	900	0.01	9

DWS : Drinking water standard
CL : Cut-off level

Appendix B

Figures

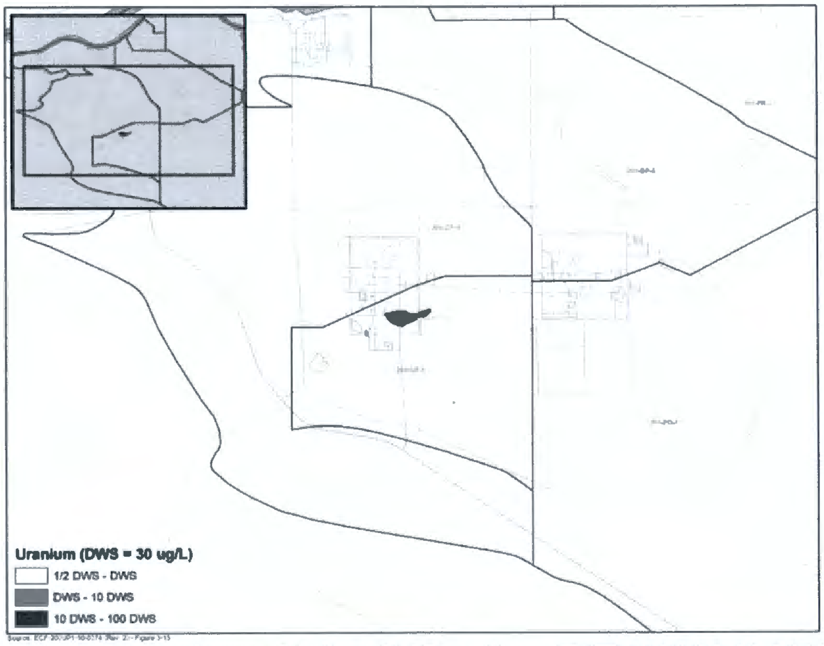

Figure B-1: Uranium Plume (2012) at U-Plant Zone (ECF-200UP1-10-0374, 2012)

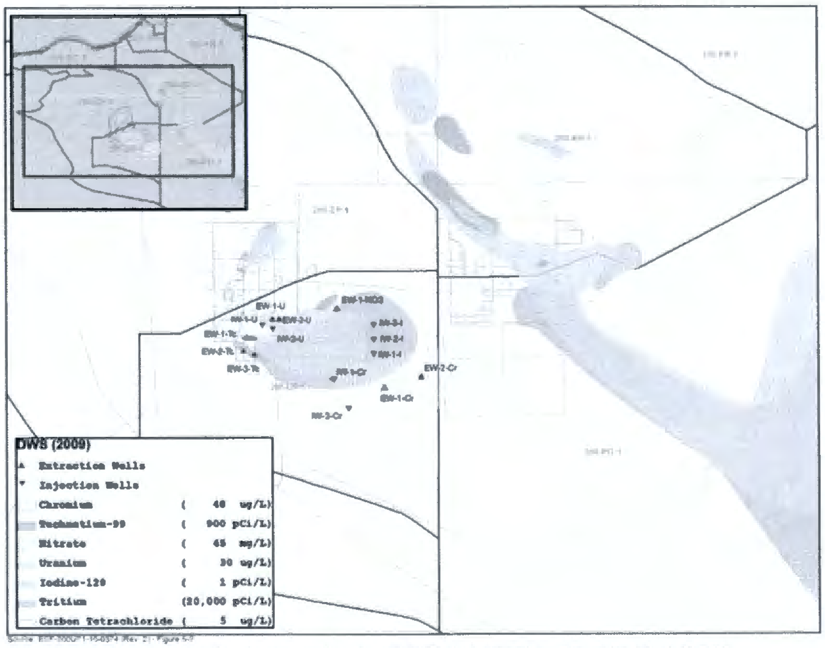

Figure B-2: Scenario 3 (ECF-200UP1-10-0374, 2012)

Figure B-3: Hydraulic Conductivity (K_x) of Soil in Layer 2 (m/day)

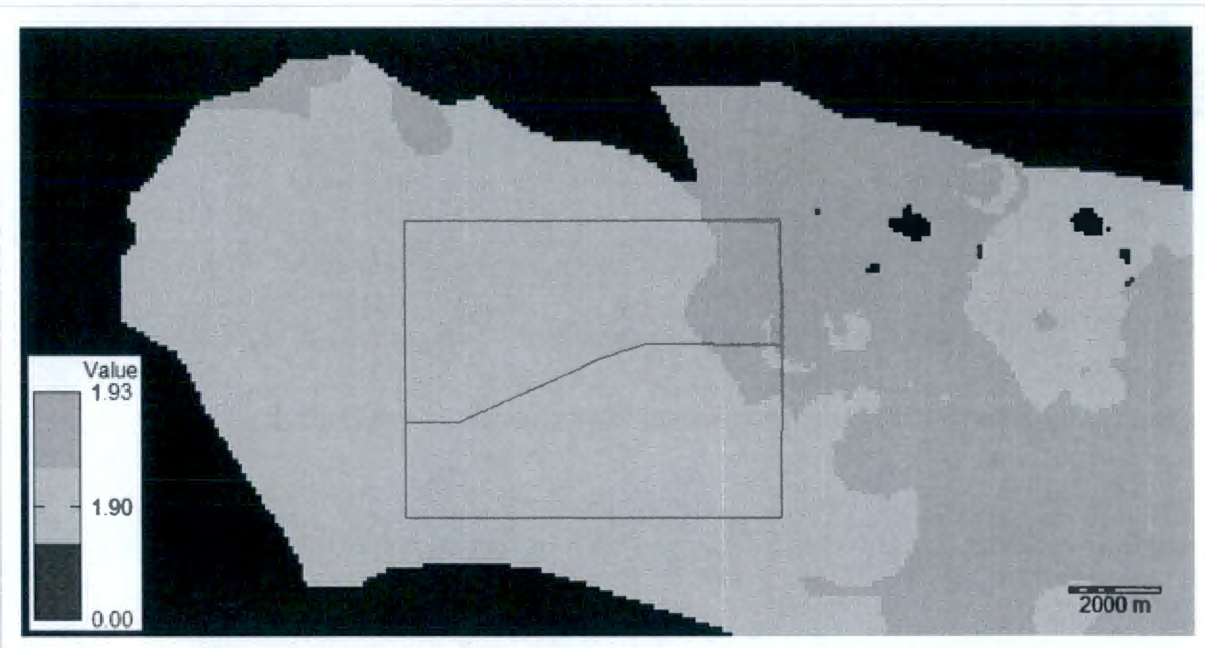

Figure B-4: Bulk Density of Soil in Layer 2 (kg/L)

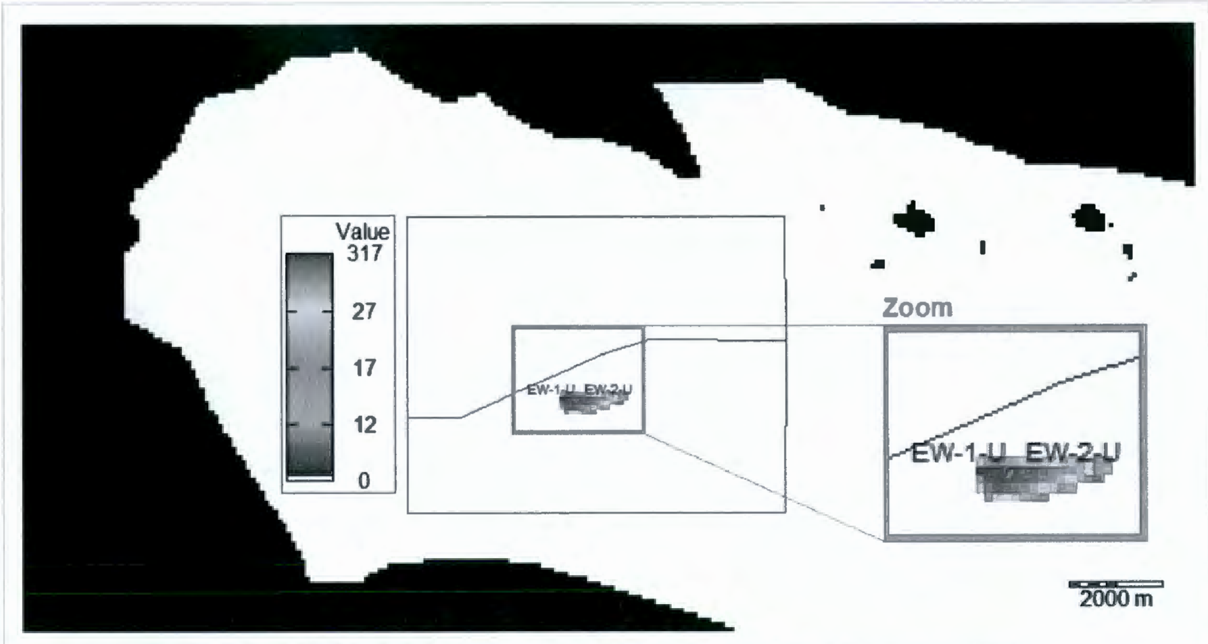

Figure B-5: Initial Concentration (µg/L) of Uranium in Layer 2 (2013)

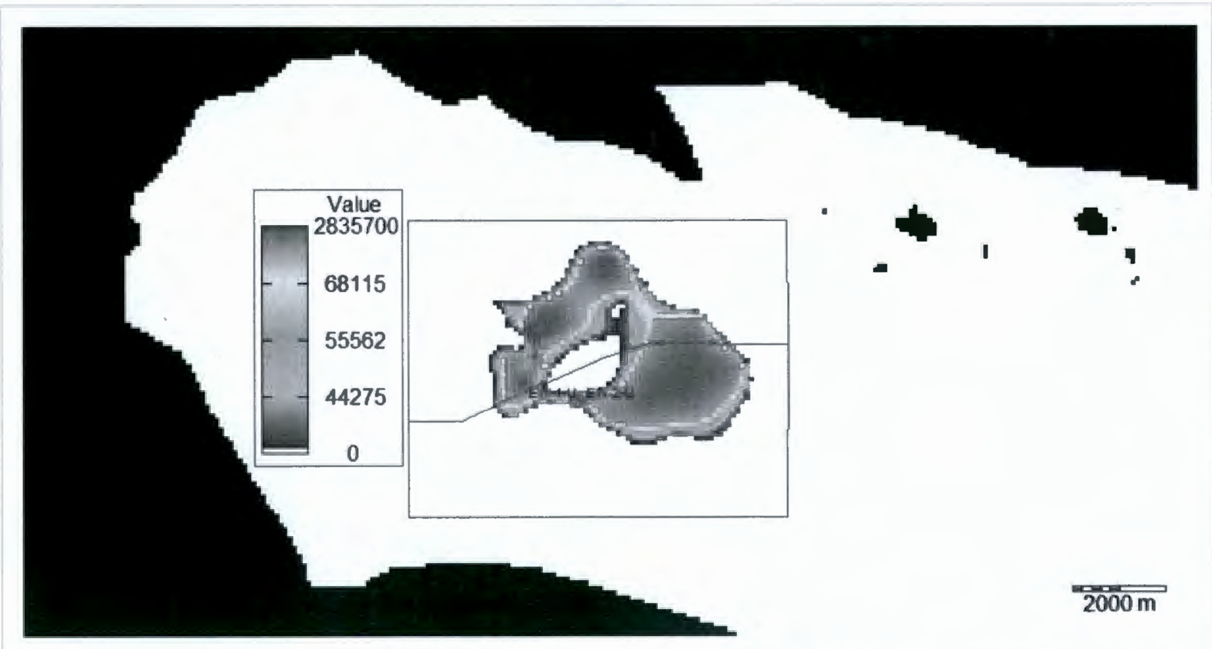

Figure B-6: Initial Concentration (µg/L) of Nitrate in Layer 2 (2013)

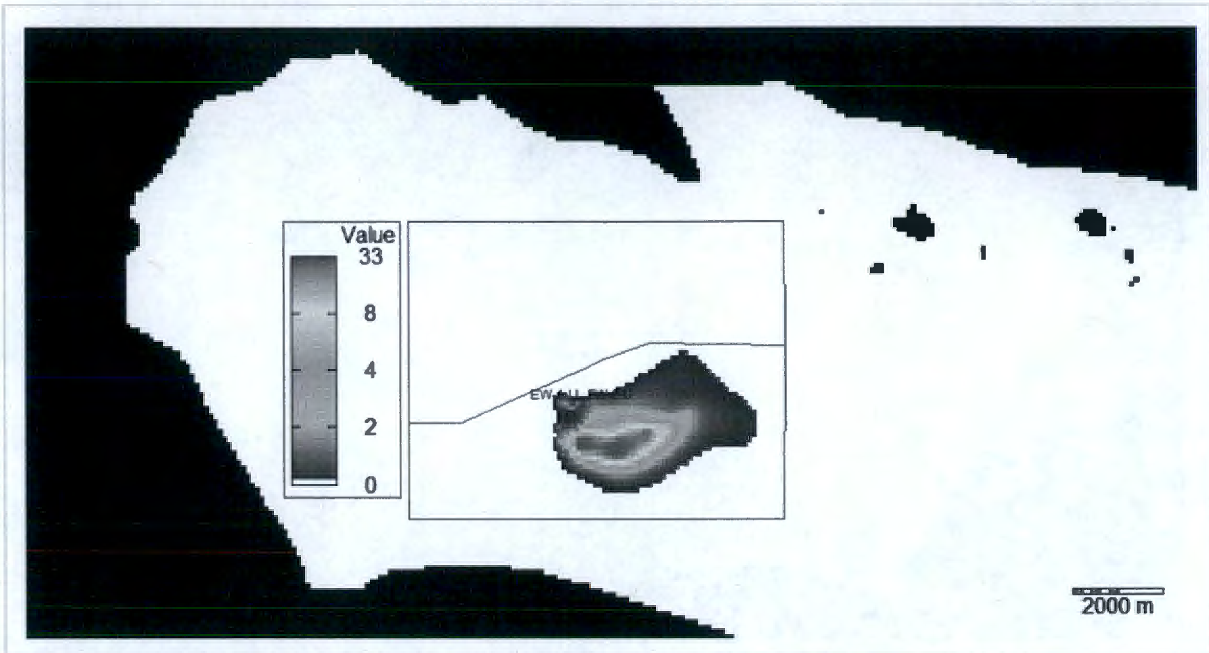

Figure B-7: Initial Concentration (pCi/L) of Iodine-129 in Layer 2 (2013)

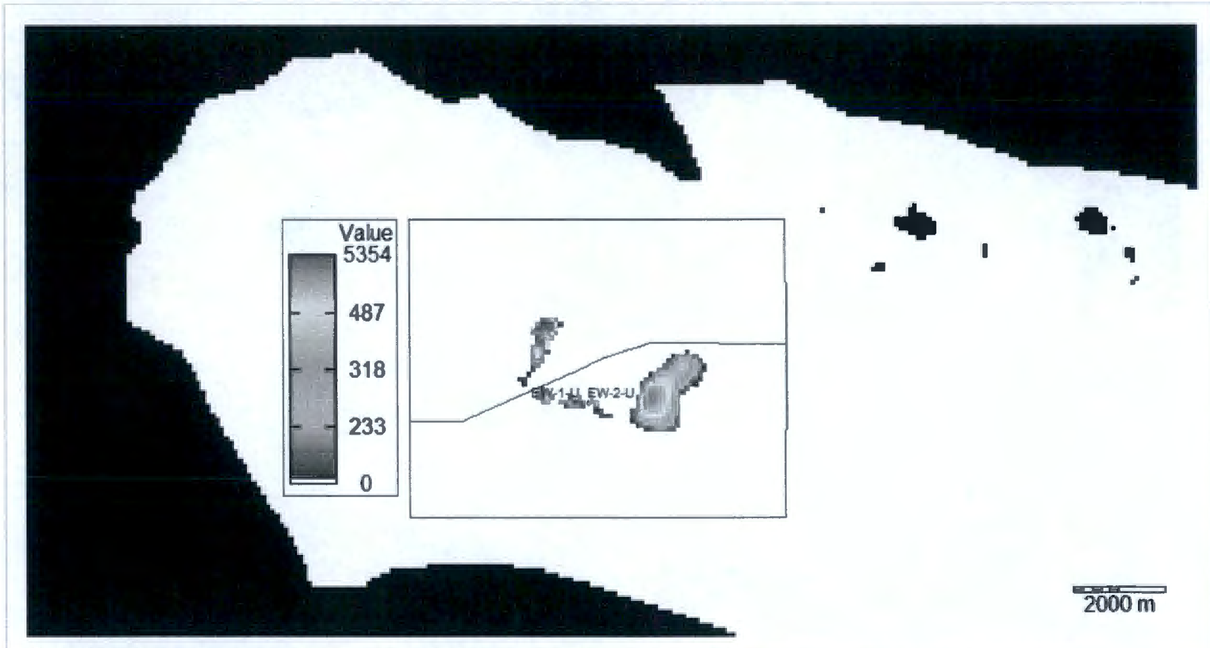

Figure B-8: Initial Concentration (pCi/L) of Technetium-99 in Layer 2 (2013)

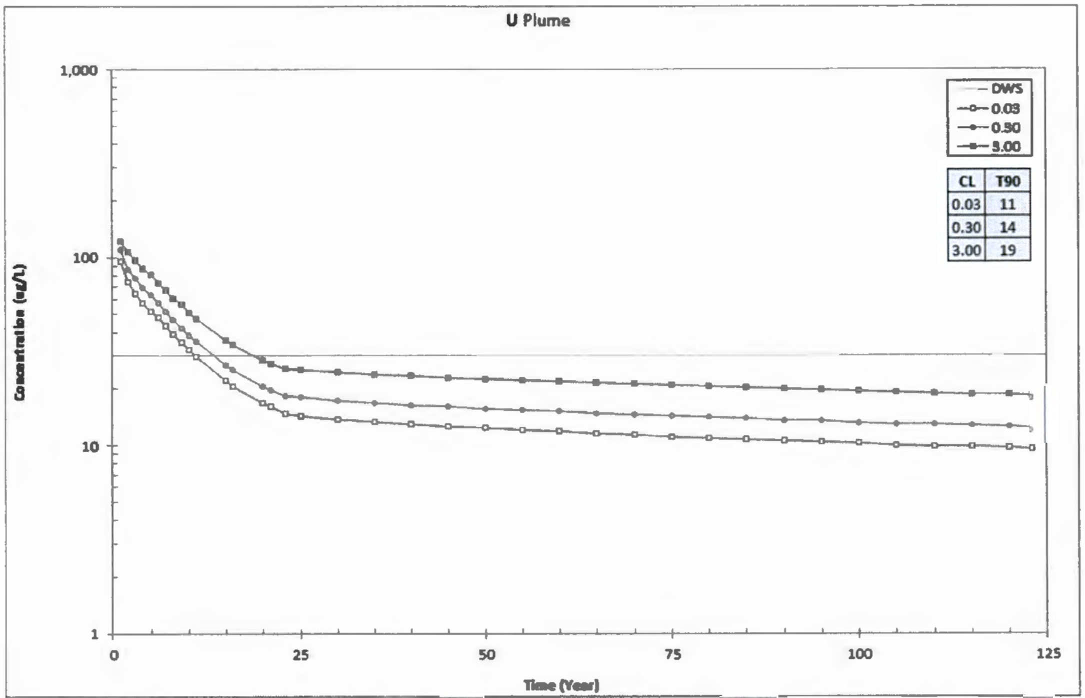

Figure B-9: Sensitivity of 90th Percentile Concentration (C_{90}) for Uranium to Cut-Off Level (CL)

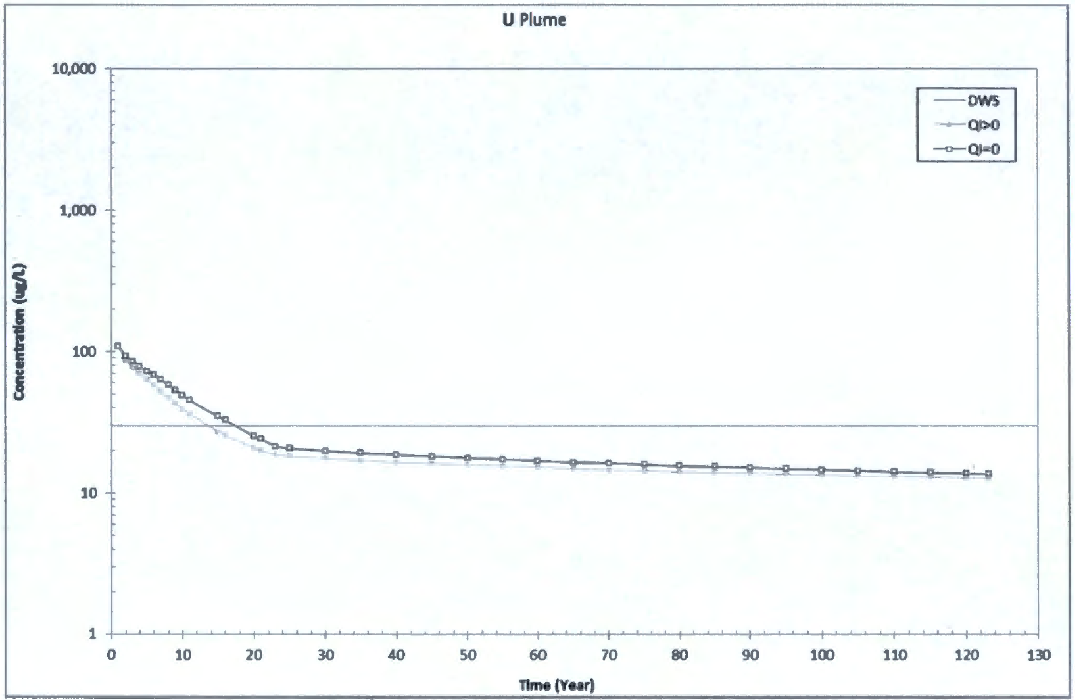

Figure B-10: Sensitivity of 90[th] Percentile Concentration (C_{90}) for Uranium to Injection

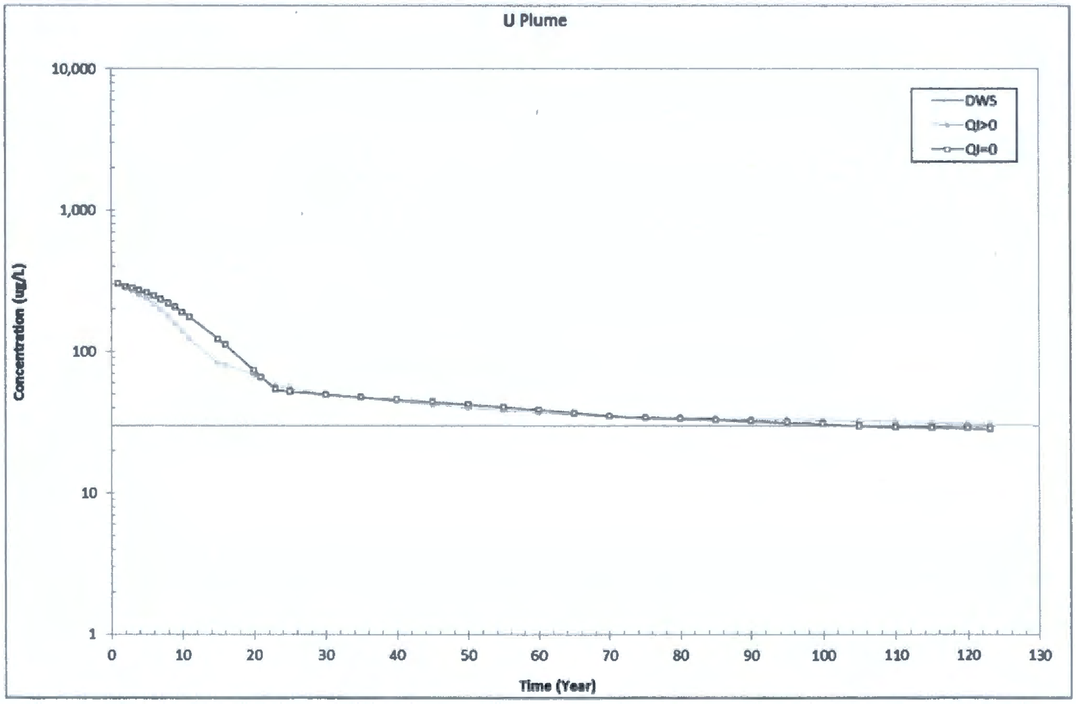

Figure B-11: Sensitivity of Maximum Concentration (C_{max}) for Uranium to Injection

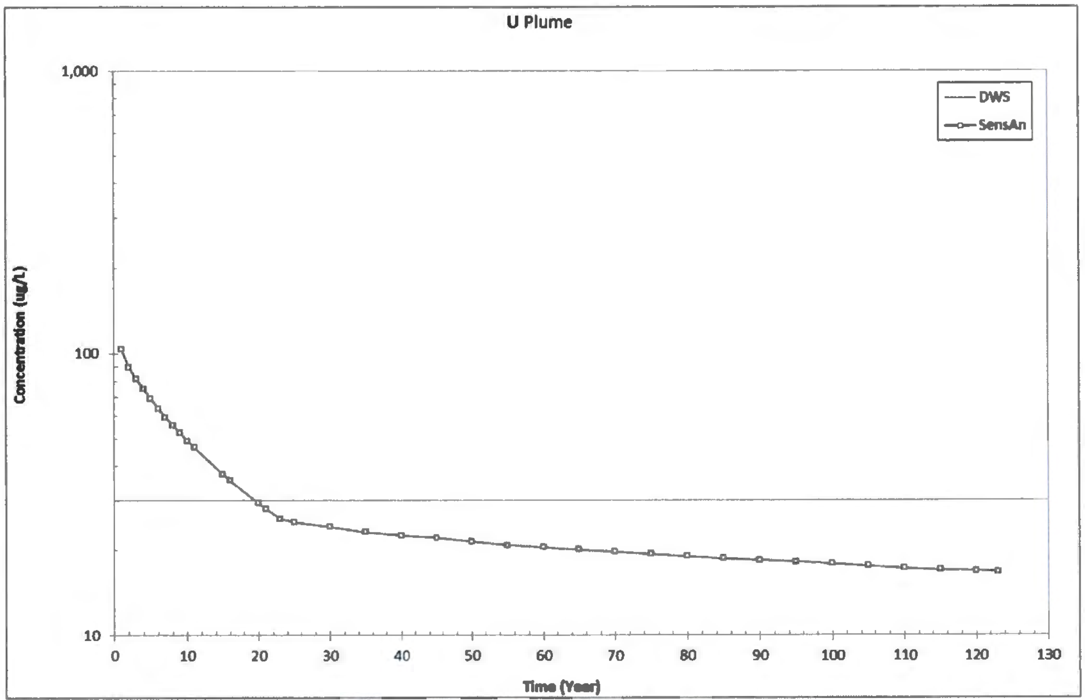

Figure B-12: 90th Percentile Concentration (C_{90}) for Uranium

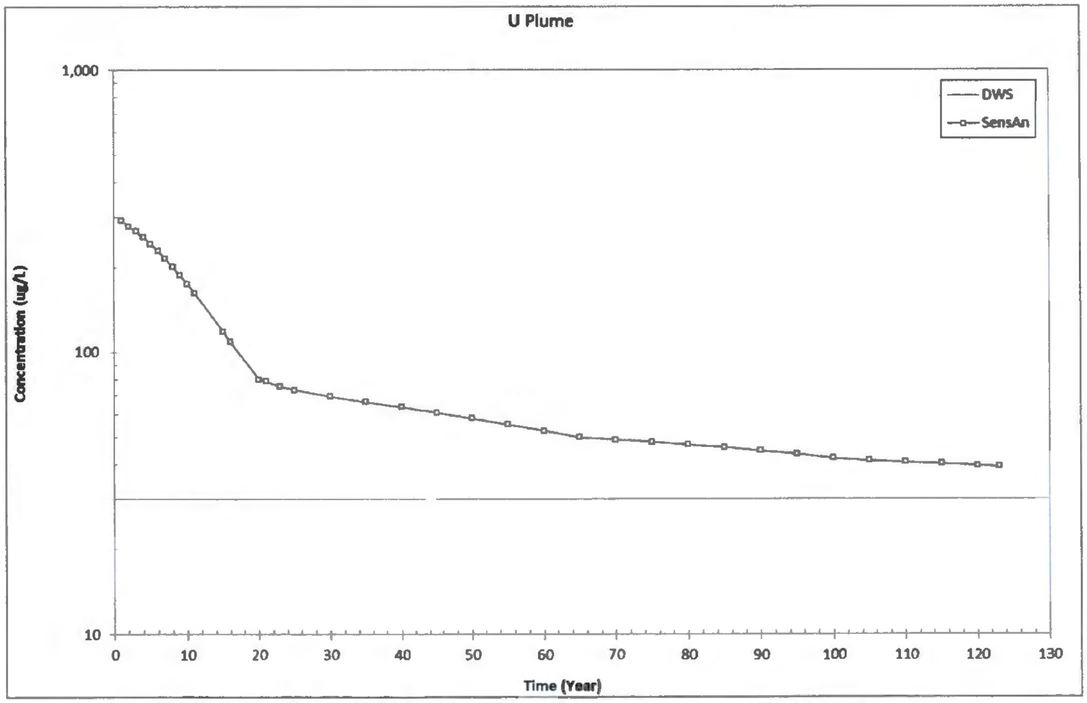

Figure B-13: Maximum Concentration (C_{max}) for Uranium

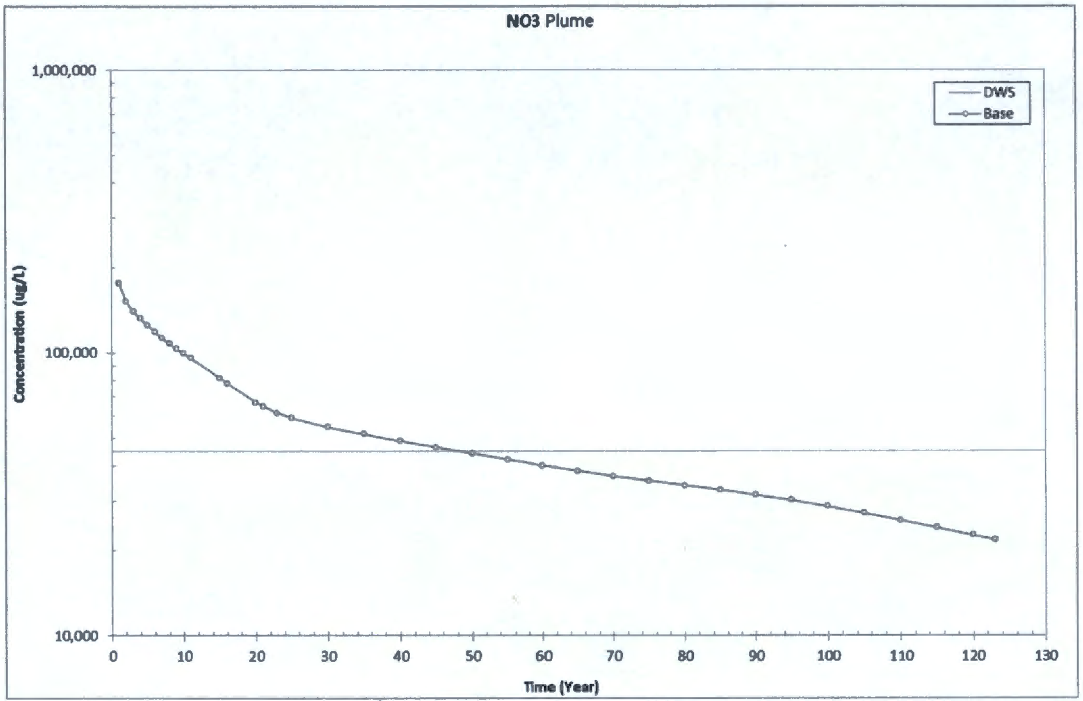

Figure B-14: 90th Percentile Concentration (C_{90}) for Nitrate

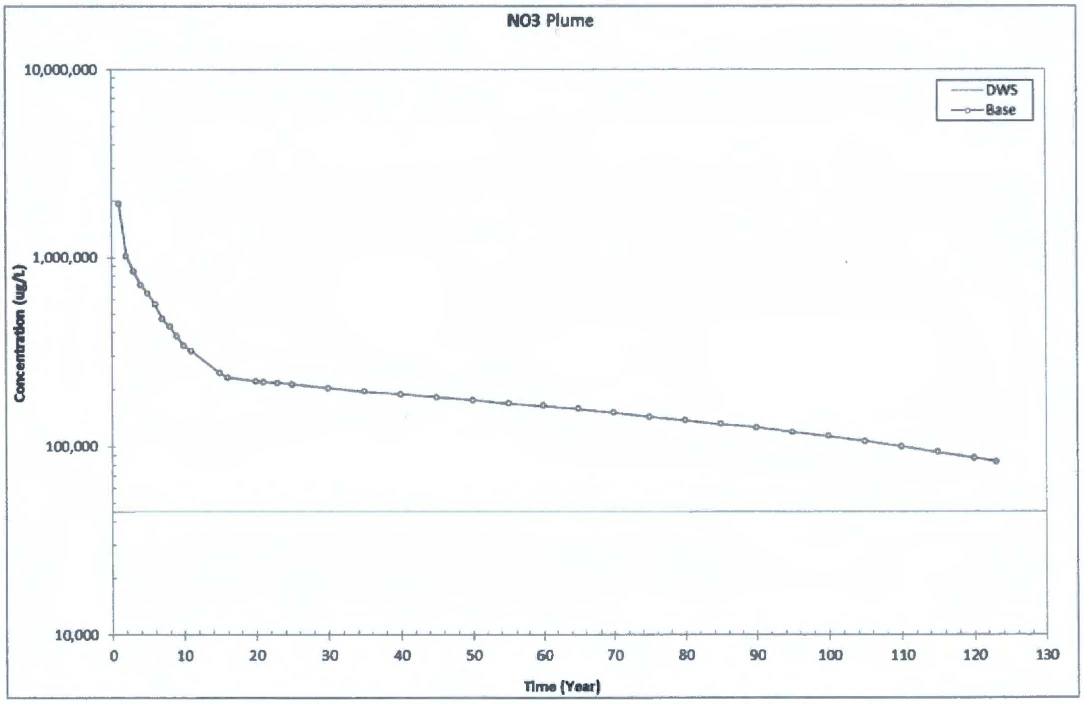

Figure B-15: Maximum Concentration (C_{max}) for Nitrate

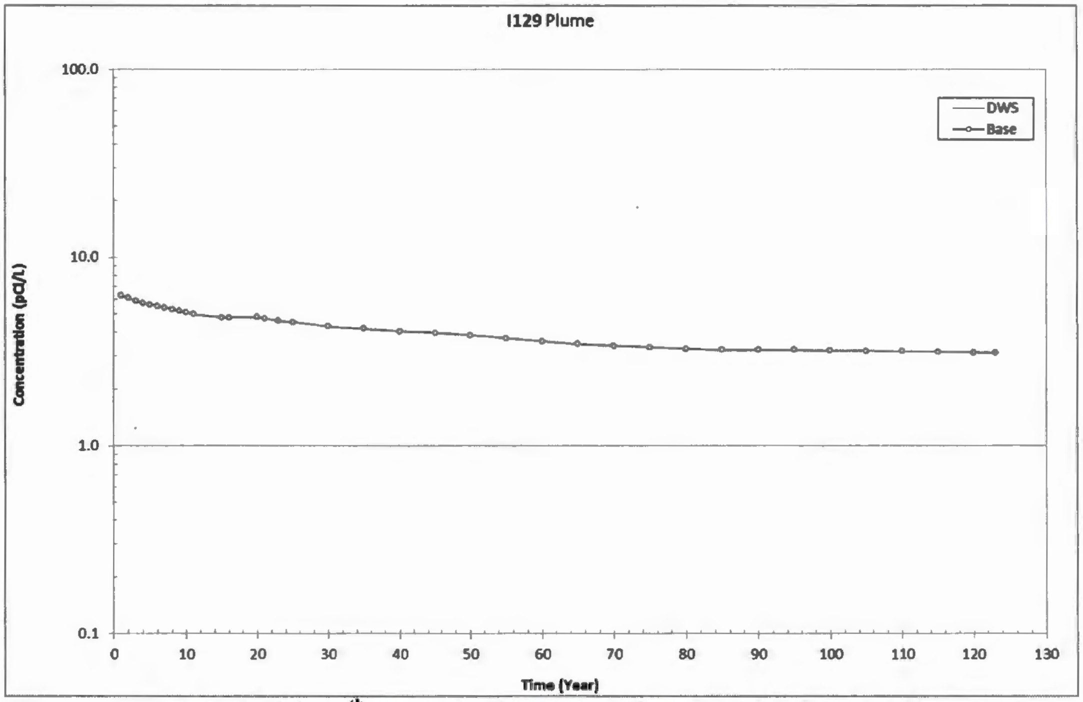

Figure B-16: 90th Percentile Concentration (C_{90}) for Iodine-129

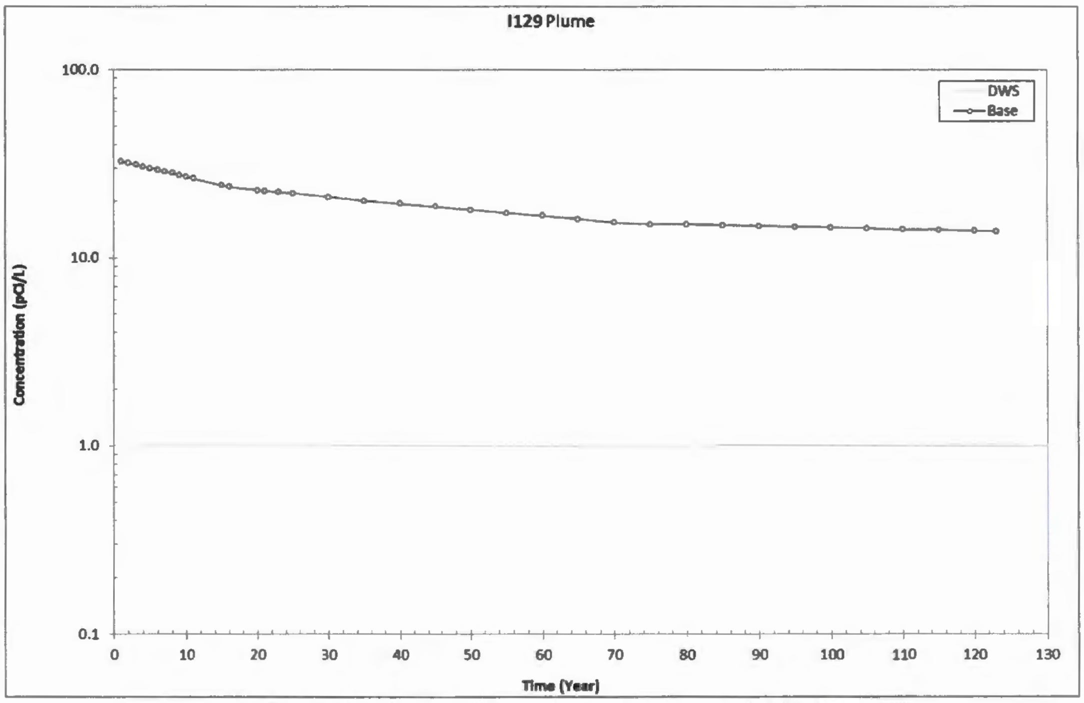

Figure B-17: Maximum Concentration (C_{max}) for Iodine-129

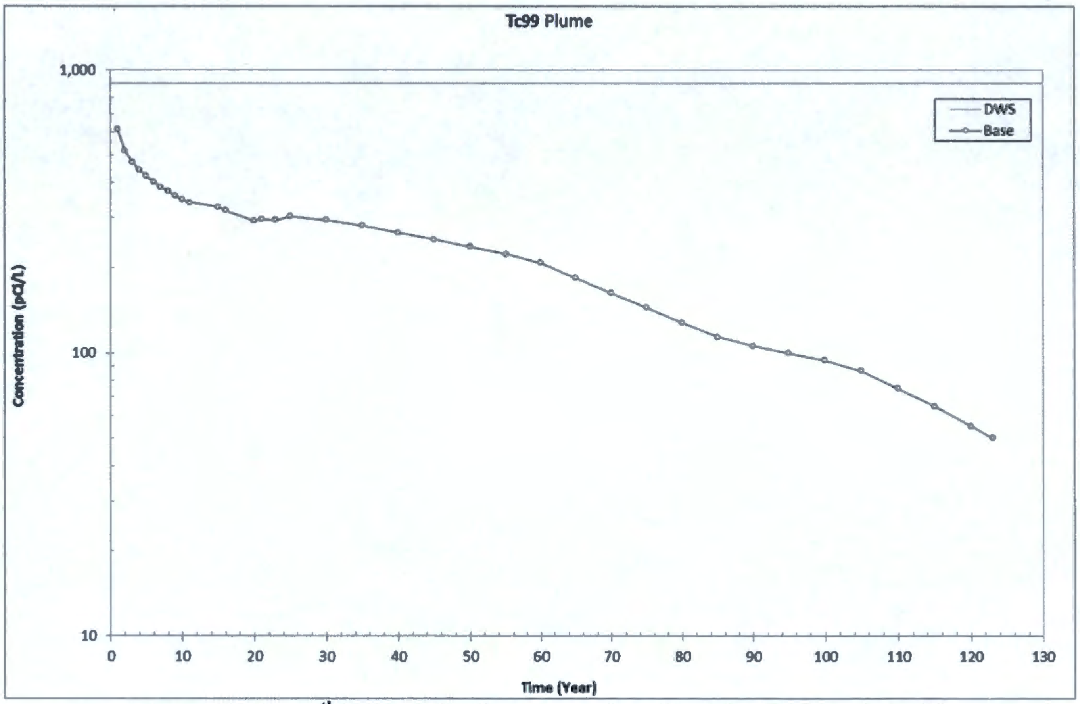

Figure B-18: 90th Percentile Concentration (C_{90}) for Technetium-99

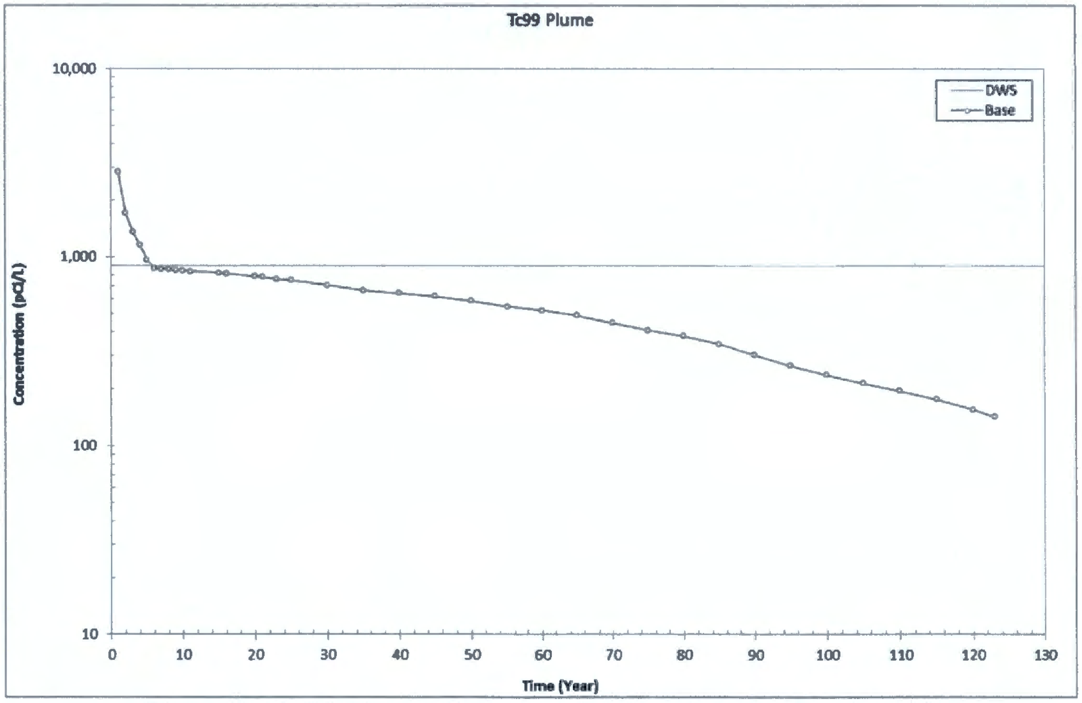

Figure B-19: Maximum Concentration (C_{max}) for Technetium-99

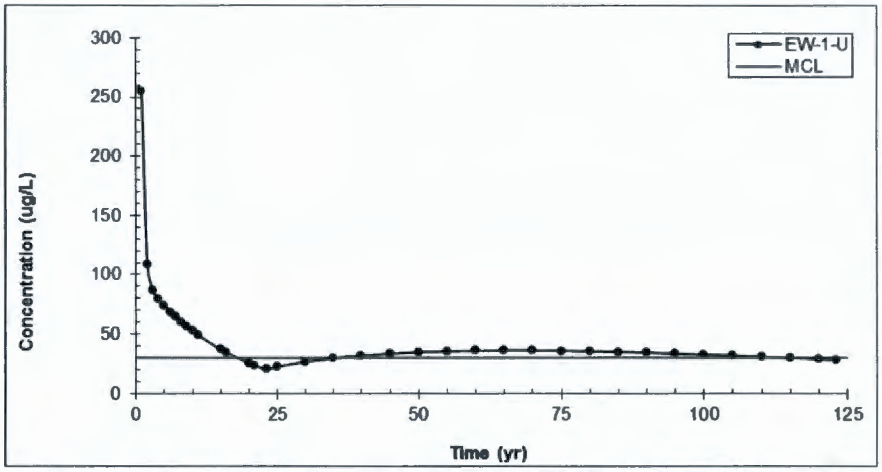

Figure B-20: Effluent Concentration (C_{e1}) of Uranium in EW-1-U

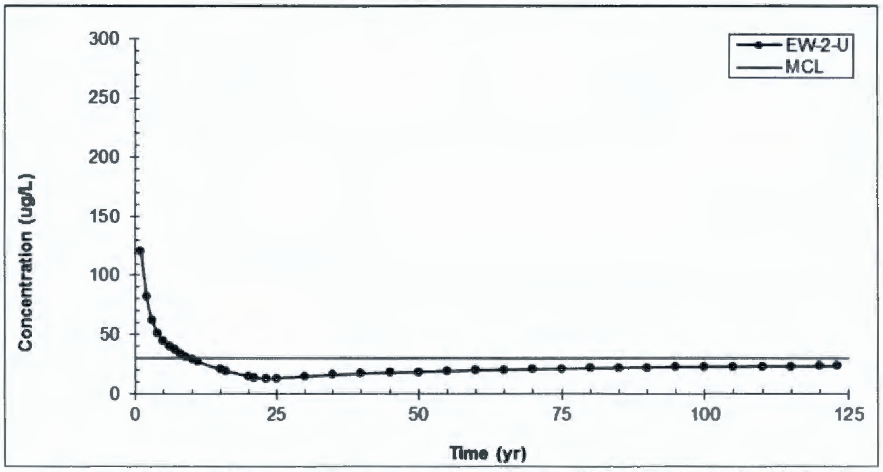

Figure B-21: Effluent Concentration (C_{e2}) of Uranium in EW-2-U

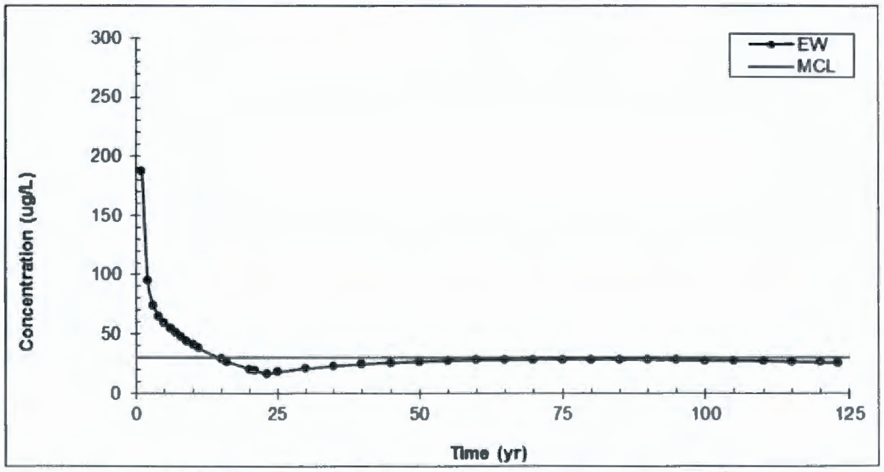

Figure B-22: Resultant Effluent Concentration (C_e) of Uranium

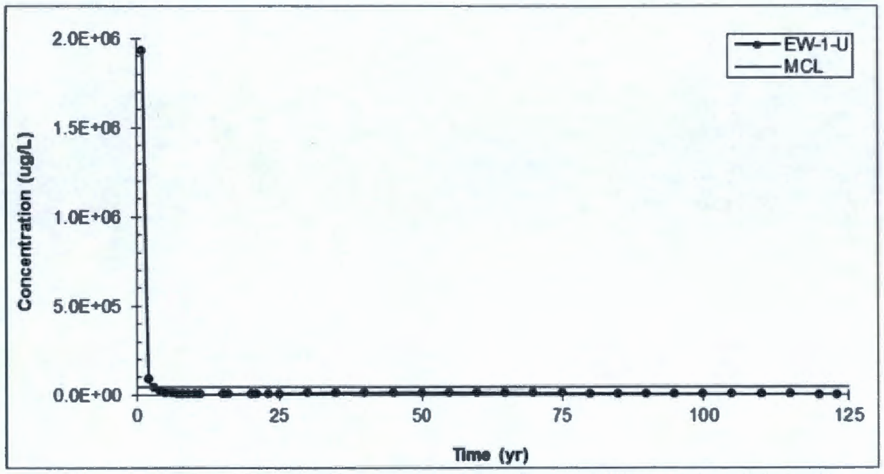

Figure B-23: Effluent Concentration (C_{e1}) of Nitrate in EW-1-U

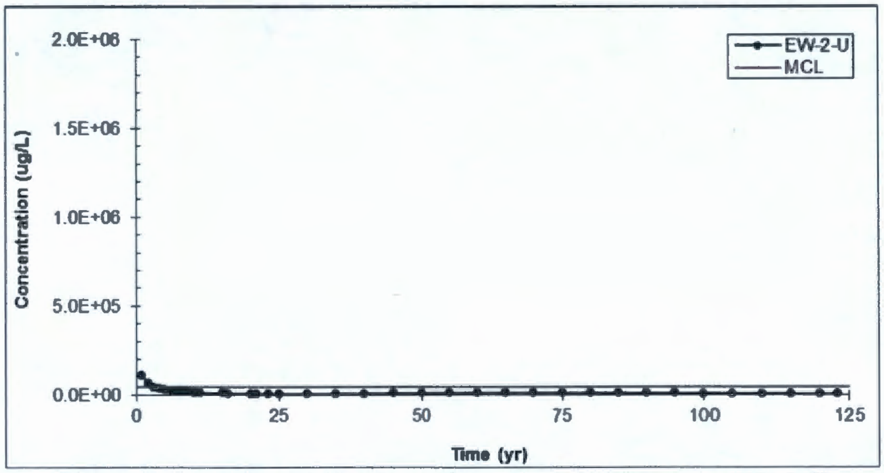

Figure B-24: Effluent Concentration (C_{e2}) of Nitrate in EW-2-U

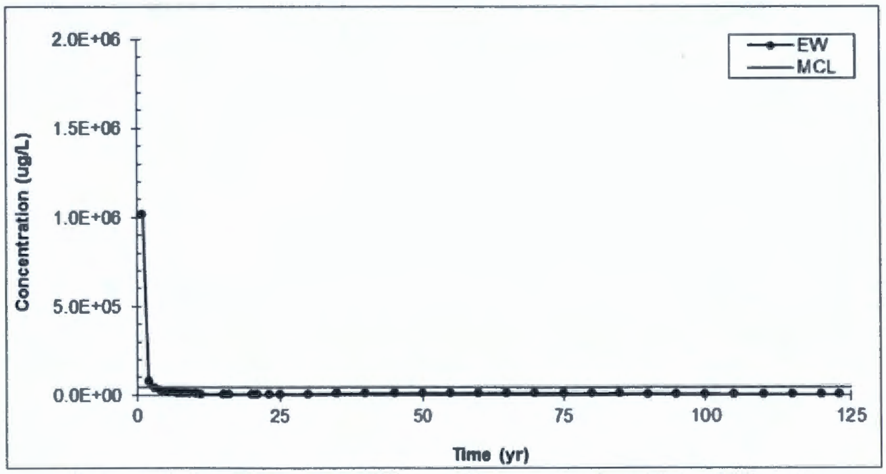

Figure B-25: Resultant Effluent Concentration (C_e) of Nitrate

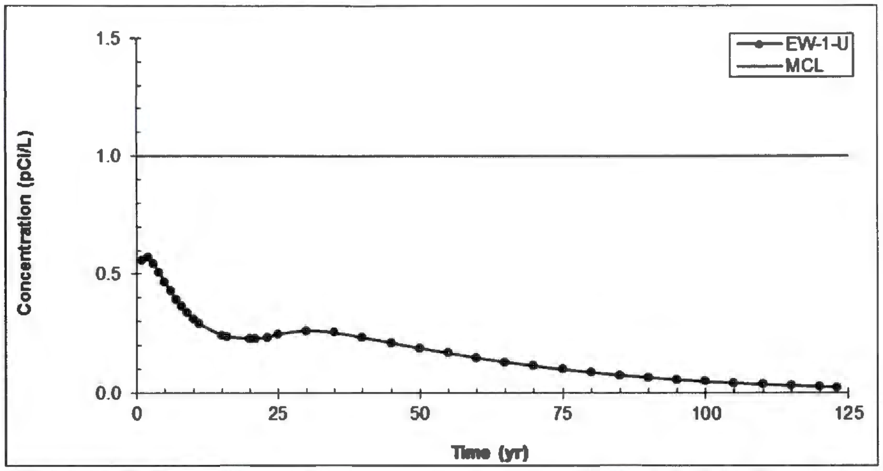

Figure B-26: Effluent Concentration (C_{e1}) of Iodine-129 in EW-1-U

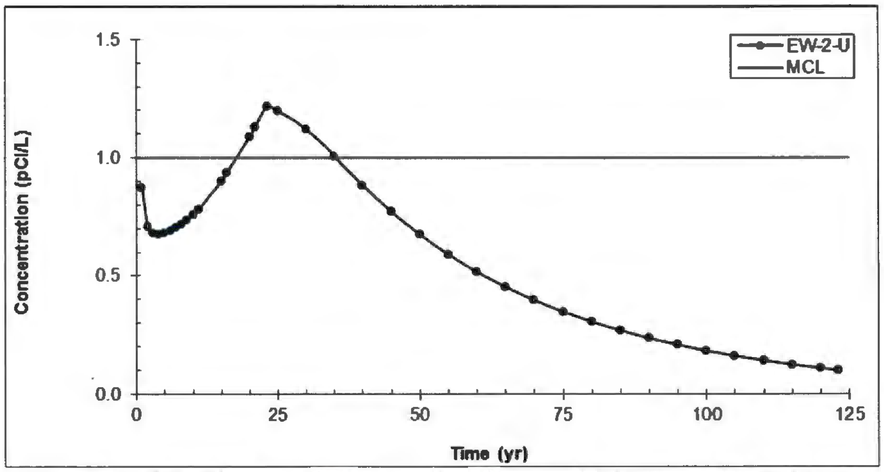

Figure B-27: Effluent Concentration (C_{e2}) of Iodine-129 in EW-2-U

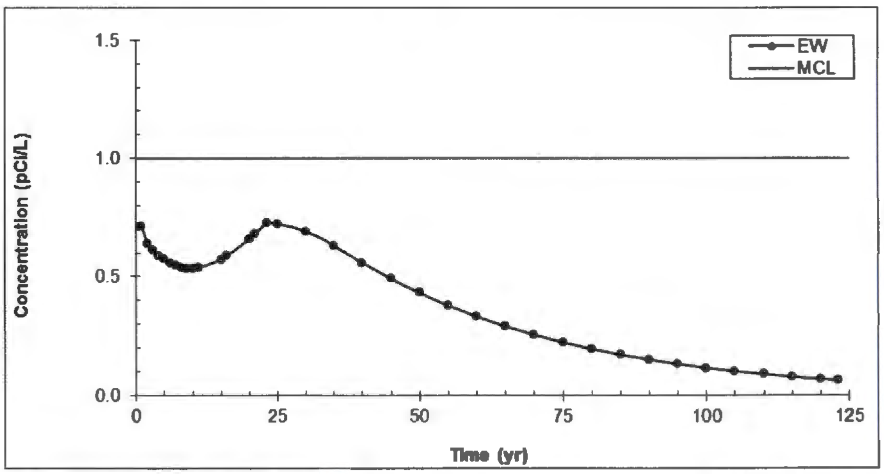

Figure B-28: Resultant Effluent Concentration (C_e) of Iodine-129

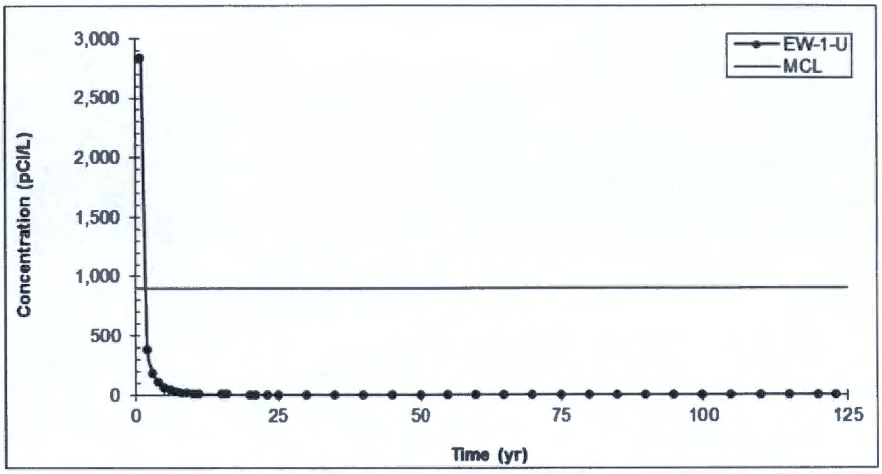

Figure B-29: Effluent Concentration (C_{e1}) of Technetium-99 in EW-1-U

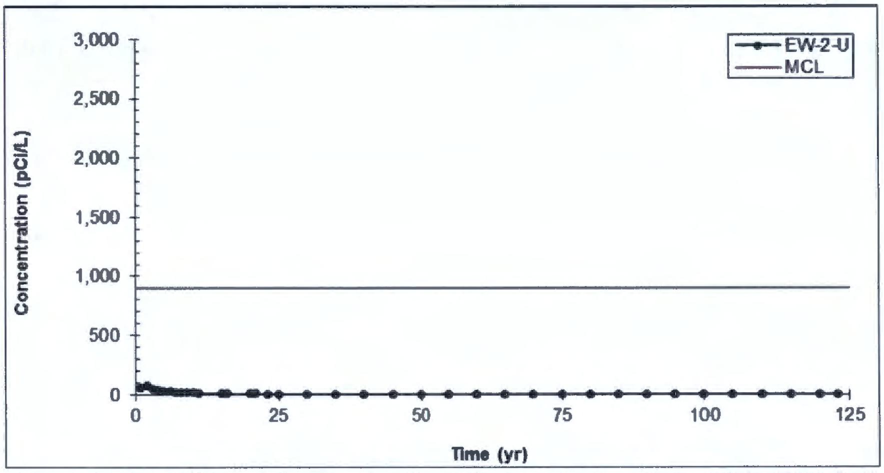

Figure B-30: Effluent Concentration (C_{e2}) of Technetium-99 in EW-2-U

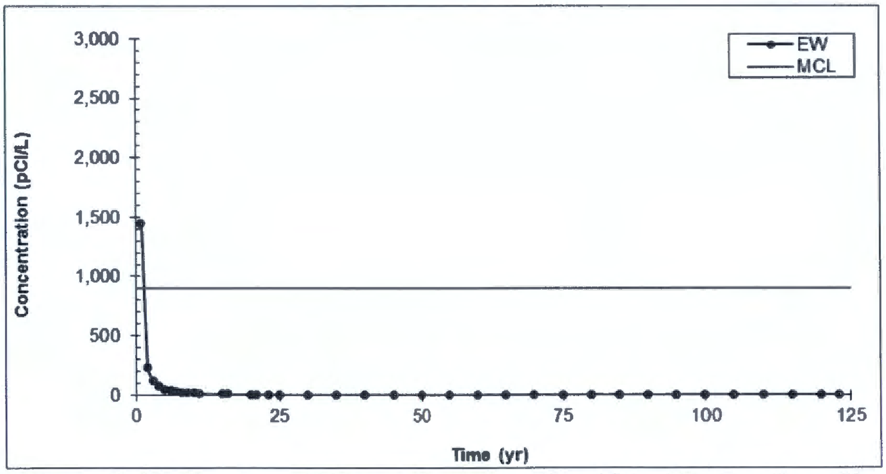

Figure B-31: Resultant Effluent Concentration (C_e) of Technetium-99

Appendix C

Software Installation and Checkout Form

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: [redacted]

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):

Dell Precision Laptop (INTERA 00590)

7. Operating System (include version number):

Windows 7 Professional Service Pack 1

8. Open Problem Report? (●) No ( ) Yes PR/CR No.

TEST CASE INFORMATION:

9. Directory/Path:

[redacted]

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

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:

All tests return identical result as base cases.

16. Test Performed By: Jahangir Morshed

17. Test Results: ◉ Satisfactory, Accepted for Use ○ Unsatisfactory

18. Disposition (include HISI update): ADDED TO HISI ENTRIES # 2157 (MODFLOW) + # 2158 (MT3DMS)

Prepared By:

19.	[signature] Software Owner (Signature)	WE Nichols Print	20 AUG 2012 Date
20. Test Personnel:	J. Morshed Sign	J Morshed Print	26. Jul. 12 Date
	Sign	Print	Date
	Sign	N/R (CHPRC-00259 Rev 2) Print	Date
Approved By: 21.	Software SME (Signature)	N/R (CHPRC-00259 Rev. 2) Print	Date

A-6005-149 (REV 0)