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Draft A

Cumulative Impact Evaluation Technical Approach Document

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

Richland Operations Office

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Terms

200 West P&T	200 West Area Pump and Treat
CCU	Cold Creek unit
CCUc	Cold Creek unit caliche
CCUg	Cold Creek unit gravel
CERCLA	*Comprehensive Environmental Response, Compensation, and Liability Act of 1980*
CIE	cumulative impact evaluation
COC	contaminant of concern
COPC	contaminant of potential concern
CPVZ GFM	Central Plateau Vadose Zone Geoframework Model
CRBG	Columbia River Basalt Group
CSM	conceptual site model
EHM	equivalent homogeneous media
EPA	U.S. Environmental Protection Agency
GIS	geographic information system
HEIS	Hanford Environmental Information System
Hf1	Hanford formation unit 1
Hf2	Hanford formation unit 2
Hf3	Hanford formation unit 3
HSGF	Hanford South Geoframework
HSS	hydrocarbon spill source (package)
HSU	hydrostratigraphic unit
ICF	Integrated Computational Framework
K_d	distribution coefficient
LLBG	low-level burial ground
MCL	maximum contaminant level
OU	operable unit
P&T	pump and treat
P2R	plateau to river (model)

PA	performance assessment
PA-TCT	power-averaging tensorial connectivity-tortuosity
PFP	Plutonium Finishing Plant
PUREX	Plutonium Uranium Extraction Plant
QA	quality assurance
QAP	quality assurance plan
QC	quality control
RCRA	*Resource Conservation and Recovery Act of 1976*
Redox	reduction-oxidation
Rlm	Ringold Formation member of Wooded Island – lower mud unit
RTD	removal, treatment, and disposal
Rtf	Ringold Formation member of Taylor Flat
Rwia	Ringold Formation member of Wooded Island – unit A
Rwie	Ringold Formation member of Wooded Island – unit E
SALDS	State-Approved Land Disposal Site
SIM	Soil Inventory Model
SIM-v2	Soil Inventory Model SIM v.2
STOMP	Subsurface Transport Over Multiple Phases (code)
TC & WM EIS	*Final Tank Closure and Waste Management Environmental Impact Statement (TC & WM EIS)*
TCE	trichloroethene
USGS	U.S. Geological Survey
WMA	waste management area

1 Introduction

This document presents the technical approach for developing a set of tools to perform a cumulative impact evaluation (CIE) on the effects of cleanup decisions regarding groundwater quality in the Hanford Site Central Plateau. Due to the complexity and large number of waste sites in noncontiguous source operable units (OUs), the computational tools used for the CIE must be capable of representing a range of site conditions and source terms in the vadose zone while also efficiently computing the impact that cleanup decisions have on the underlying aquifer. These tools will support remedial and closure decisions across the Central Plateau by providing cumulative information, but without replacing or displacing any part of those decision processes. The objective of this document is to describe the major components required for the CIE, the approach for developing these tools, and the plan for implementation.

The Central Plateau has more than 1,300 waste sites, active and inactive burial grounds, and active and inactive waste processing facilities that are regulated under a combination of the *Comprehensive Environmental Response, Compensation, and Liability Act of 1980* (CERCLA); the *Resource Conservation and Recovery Act of 1976* (RCRA); and other waste disposal regulatory frameworks. Figure 1-1 shows the source OUs on the Central Plateau and illustrates the geographical intermixing of sites within different source OUs. Groundwater OUs have several overlying source OUs, and actions taken within source OUs may affect groundwater across the entire Central Plateau.

Waste site proximity between and within source OUs has resulted in contaminants commingling in the vadose and saturated zones in complex ways (Figure 1-2). Plume commingling requires cleanup decisions to be evaluated considering the surrounding waste sites and existing groundwater contamination, therefore demonstrating the need to evaluate cumulative impacts from the vadose zone to groundwater.

Soil (vadose zone) and groundwater (saturated zone) contamination across the Central Plateau is undergoing investigation and remediation, and decisions need to be made regarding how to most efficiently disposition and remediate sites. Because contaminants intermingle among the OUs, decisions should be evaluated considering the context of the surrounding sites and facilities and not in isolation. Thus, the CIE of Central Plateau groundwater contamination should consider the integrated effects of numerous contaminant sources and prospective remedies. For this CIE, cumulative impacts of an action (e.g., groundwater remediation or placement of an evapotranspiration barrier over a waste site) will be viewed as the total effects on groundwater from that action, considering all other activities or likely future activities for source or groundwater OUs.

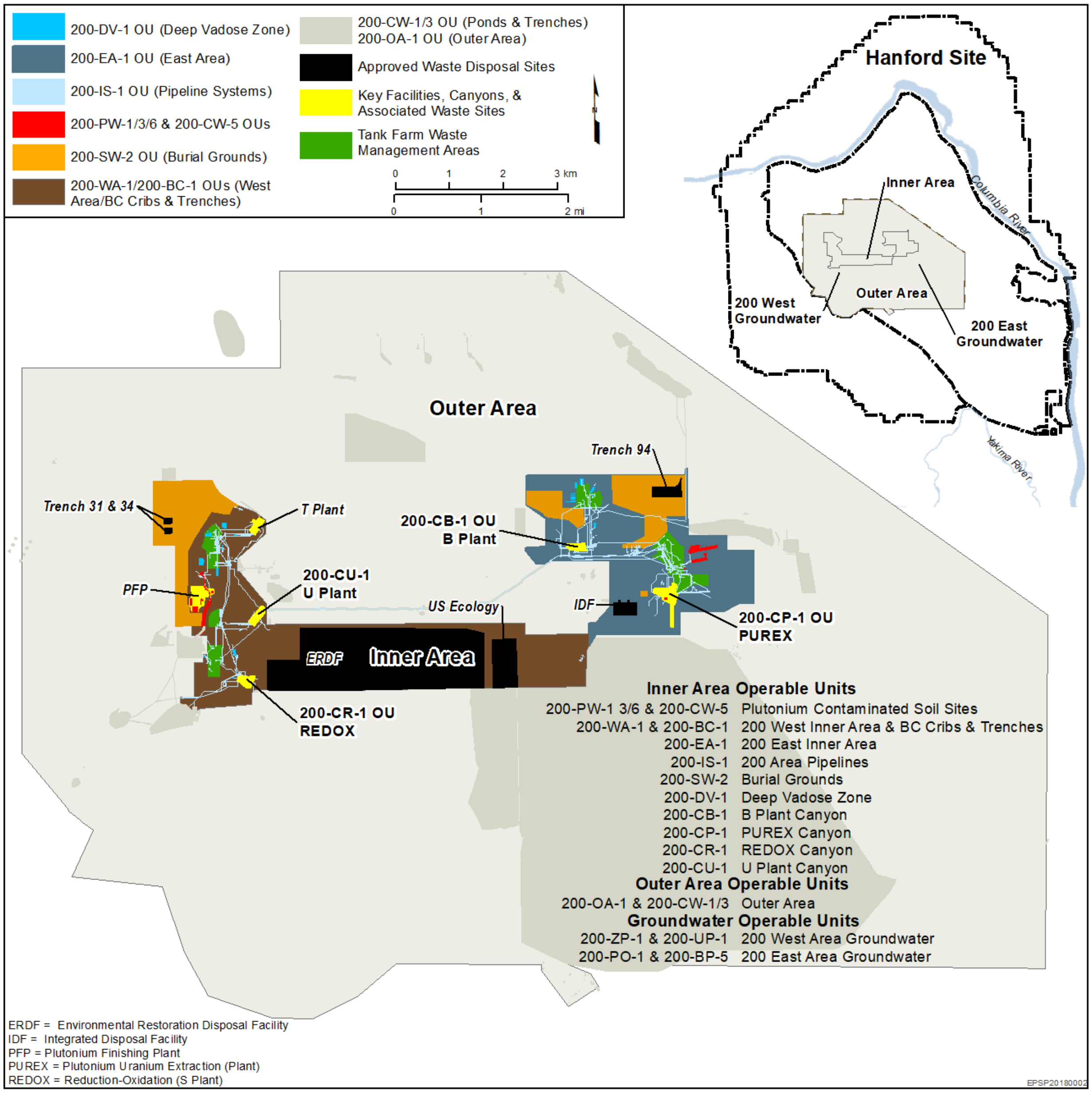


Figure 1-1. Central Plateau OUs

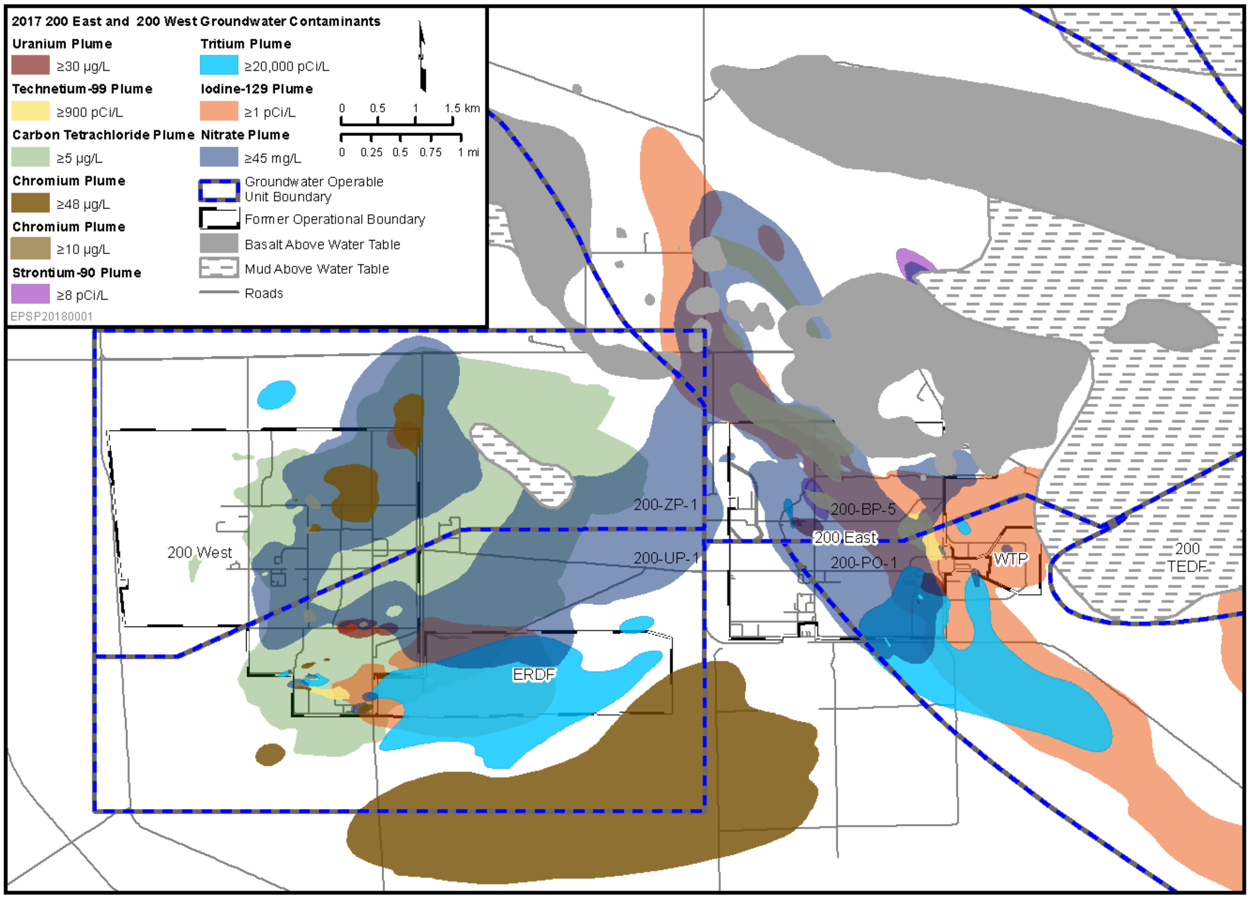


Figure 1-2. Central Plateau Groundwater Plumes

The CIE will be implemented as a dynamic set of tools used to support remediation and closure decisions for both source and groundwater OUs on the Central Plateau. A large volume of information has been collected, and will continue to be collected for potentially decades, that must be managed. The information has been organized using technical aspects or facets of inventory, vadose zone, and saturated zone (Figure 1-3). The facets will be implemented in the CIE as inputs from existing information sources to computational tools, which will result in simulations of future groundwater impacts. Therefore, the CIE requires integrating and linking the facets in order to efficiently propagate information from one facet to another. Figure 1-4 illustrates the flow of information into and between facets. Many of the information sources shown in the figure are existing products being used to support investigation and remediation activities. For example, the Soil Inventory Model (SIM) was developed in 2005 (RPP-26744, *Hanford Soil Inventory Model, Rev. 1*) to quantify the sources of contaminated soil inventories associated with liquid waste disposal sites.

The CIE is intended to be a flexible toolset that can be systematically used to inform the decision-making process. It is expected to be updated as additional source and groundwater information is obtained through characterization and remediation efforts and as waste sites advance through the regulatory process.

The CIE will consist of a number of software tools and databases. Some of those software tools and databases are well established and have been in use for years or decades for a variety of applications. The inventory facet will use the most recent version of the SIM software (and associated databases).

The Subsurface Transport Over Multiple Phases (STOMP)[1] software will be used for the vadose zone facet, and the MODFLOW[2] family of codes will be used for the saturated zone facet. The existing plateau-to-river (P2R) saturated zone flow and transport model (CP-57037, *Model Package Report: Plateau to River Groundwater Model, Version 8.2*) will be part of the initial CIE implementation. In addition to these software tools, an Integrated Computation Framework (ICF) will develop other tools and databases to automate routine tasks, link different models, perform quality assurance tasks, increase efficiency and quality, create standard reports and figures, and manage inputs and outputs of the different tools. Chapters 2 through 4 provide descriptions of these tools and how they will be used to implement all CIE facets.

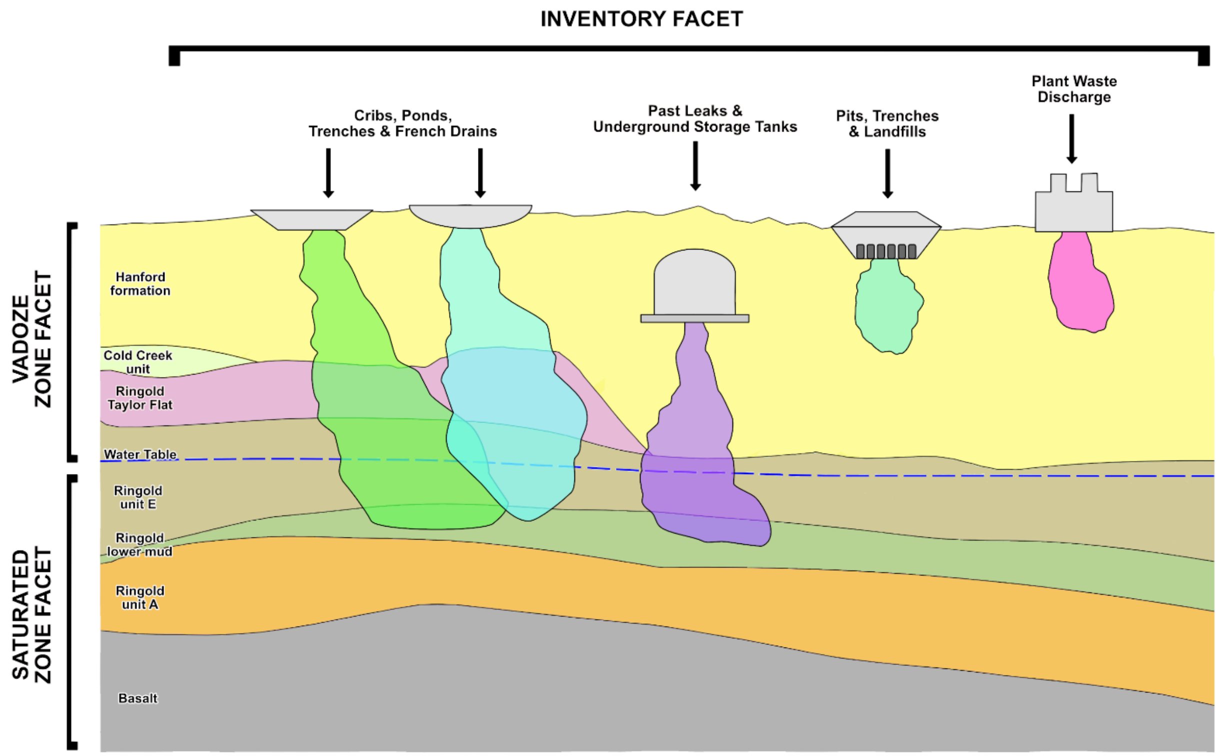


Figure 1-3. Conceptual Facet Diagram

[1] STOMP is a copyright of Battelle Memorial Institute, Columbus, Ohio, and used under the Limited Government License.
[2] MODFLOW a product of the U.S. Geological Survey, Reston, Virginia.

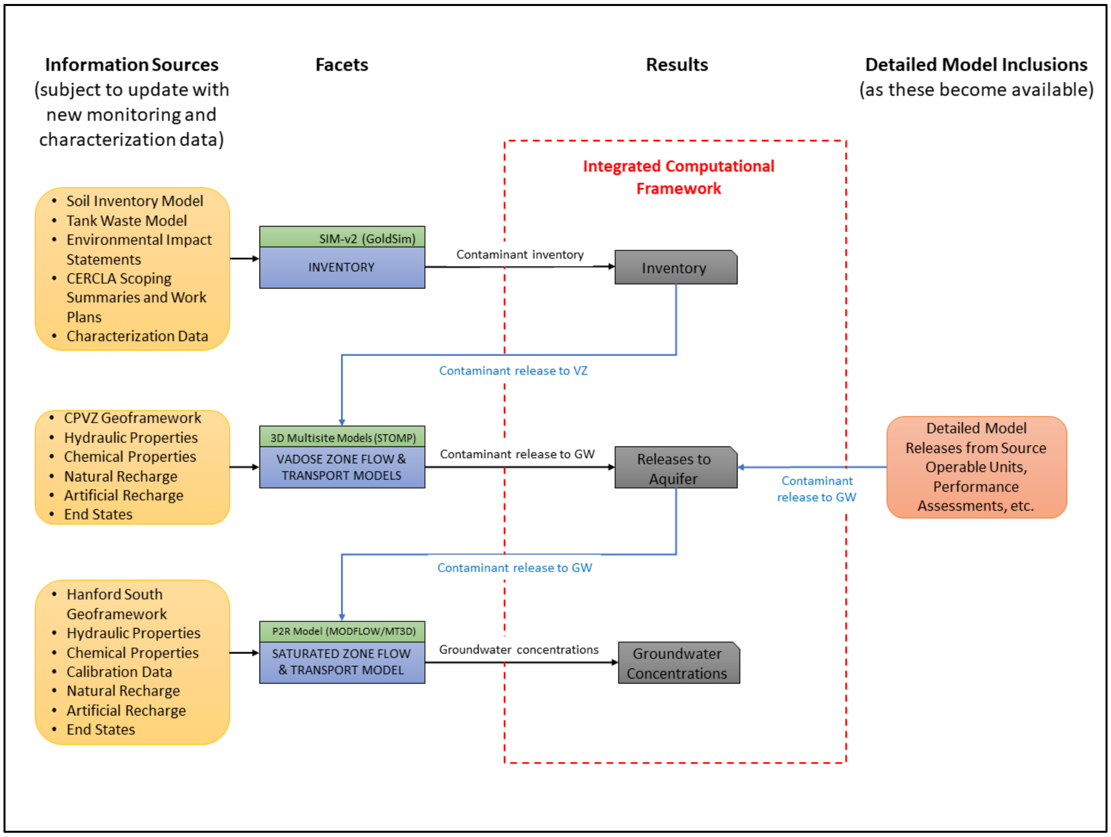
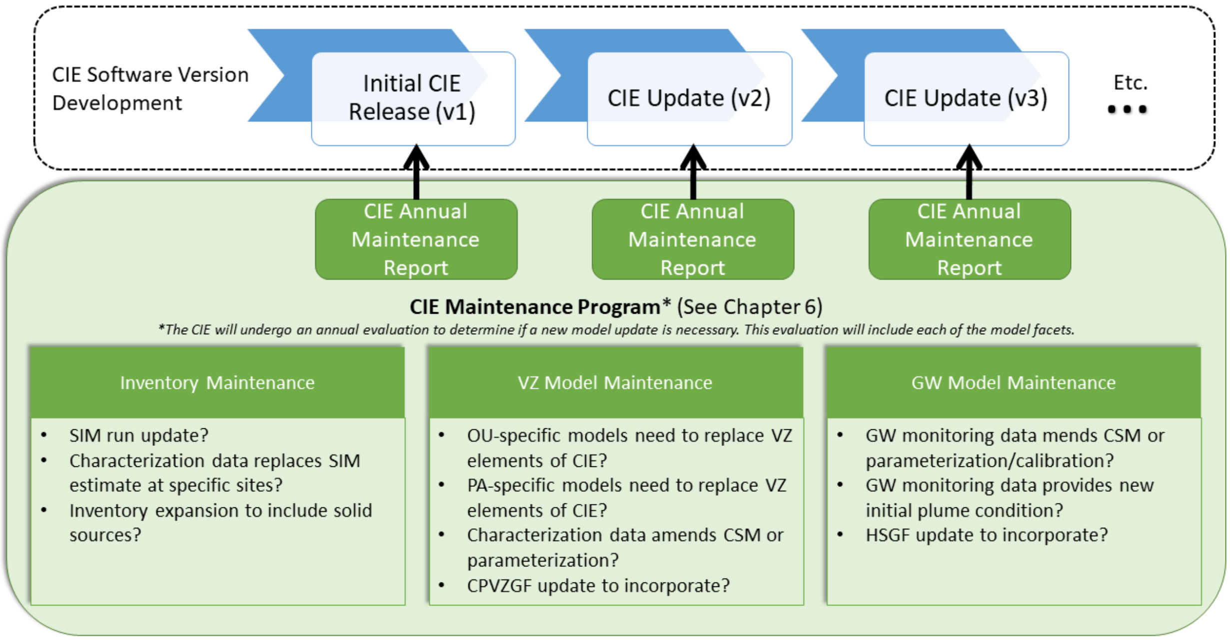


Figure 1-4. CIE Wiring Diagram

Given the dynamic nature of the CIE tools and databases, software updates are expected and planned for under the Maintenance activity for the models (Chapter 6). As the Central Plateau OUs and waste management areas (WMAs) go through their regulatory decision-making processes, characterization information will be collected and analyzed to inform cleanup decisions. Characterization data will inform all facets of the CIE, including inventory estimates, geoframeworks for the vadose and saturated zones, as well as the groundwater plume configuration. More importantly, as regulatory decisions are made for surface contamination of the vadose zone and groundwater, these decisions can also impact several facets of the CIE and will require updating one or more of the facets.

The technical approach presented in this document focuses on the initial software development. In each of the subsequent chapters where individual model facets are discussed in depth, efforts are made to indicate what may be considered for a future update given the dynamic nature of the Central Plateau. Figure 1-5 is a conceptual flow chart that illustrates the types of information that will be considered during the maintenance activity and is not intended to be comprehensive model update considerations.



CIE = cumulative impact evaluation; GW = groundwater; OU = operable unit; PA = performance assessment; VZ = vadose zone; v1, v2 = version 1, version 2

Figure 1-5. CIE Development and Maintenance

1.1 Summary and Organization

This technical approach document includes in the following chapters:

- Chapter 1, "Introduction," provides introductory information regarding the purpose of the CIE.
- Chapter 2, "Contaminant Sources, Inventory, and Waste Release Model Facet," discusses contaminant sources and the inventory modeling approach.
- Chapter 3, "Vadose Zone Flow and Transport Models," discusses the vadose zone (soil) flow and transport modeling approach.
- Chapter 4, "Saturated Zone Fate and Transport Models," discusses the saturated zone (groundwater) flow and transport modeling approach.
- Chapter 5, "Quality Assurance," provides quality assurance (QA) information.
- Chapter 6, "Maintenance," discusses the CIE maintenance plan.
- Chapter 7, "References," includes the references cited in this document.

2 Contaminant Sources, Inventory, and Waste Release Model Facet

Information is needed about contaminant sources and waste form releases to provide necessary inputs for the vadose zone facet of the CIE. This information will enable an evaluation of potential effects of future remedial actions and their impact on groundwater. As discussed in Chapter 1, liquid and solid waste disposal resulting from Hanford Site operations has resulted in soil and groundwater contamination. Significant liquid waste releases have contaminated the underlying groundwater aquifers and have resulted in several commingled contaminant plumes within the Central Plateau (Figure 1-2). The objective of the contaminant sources, inventory, and waste release facet is to provide the radionuclide activity and mass of chemicals in liquid and solid waste within the vadose zone soil for input into the vadose zone model facet, which then evaluates the fate and transport of these contaminants through the vadose zone until reaching groundwater. This chapter describes the approach for selecting the significant vadose zone inventory sources and developing the vadose zone inventory estimates for the initial version of the CIE, including the approach to revising the inventory for subsequent model updates. Chapter 3 describes how this inventory is used in the vadose zone facet. Chapter 4 describes how existing groundwater plumes will be implemented separately from the vadose zone inventory in the saturated zone facet.

To address how the CIE will account for contaminant source and inventory for selected contaminants, the CIE will initially use CP-59798, *Model Package Report: Hanford Soil Inventory Model SIM v.2: Build 1* (hereinafter called SIM-v2 and further discussed in Section 2.1), to represent liquid waste disposal sites, including leaks from single-shell tanks and other unplanned releases. Solid waste release models will be added as a feature for consideration in a later version of the CIE. The initial model setup will focus on the liquid waste disposal sites because current groundwater contamination shows that past liquid waste disposal moved mobile contaminants through the vadose zone to the water table. This is evident based on the existing plumes in the Central Plateau. Current analytical measurements of groundwater contaminants indicate that a limited number of contaminants are found in groundwater as plumes. This implies that the CIE can focus on contaminants for cumulative impacts on a subset most likely to impact groundwater quality (Section 2.3). Vadose zone sources of these mobile contaminants that will initially be implemented include the following chemical and radionuclide contaminants: cyanide, hexavalent chromium (Cr(VI)), iodine-129, nitrate, strontium-90, technetium-99, tritium, and uranium (Section 2.3).

The CIE is a dynamic toolset that will be updated as Central Plateau OUs and WMAs undergo the regulatory decision-making processes. The initial contaminant sources and inventory may be replaced in the future as characterization data are collected and evaluated in the OU-specific remedial investigations and similar documents (particularly if the investigations identify additional contaminants or waste sites that could impact groundwater). These evaluations will need to determine if the CIE model data sets are consistent with the conceptual site models (CSMs) or if an OU-specific vadose zone source model needs to be developed.

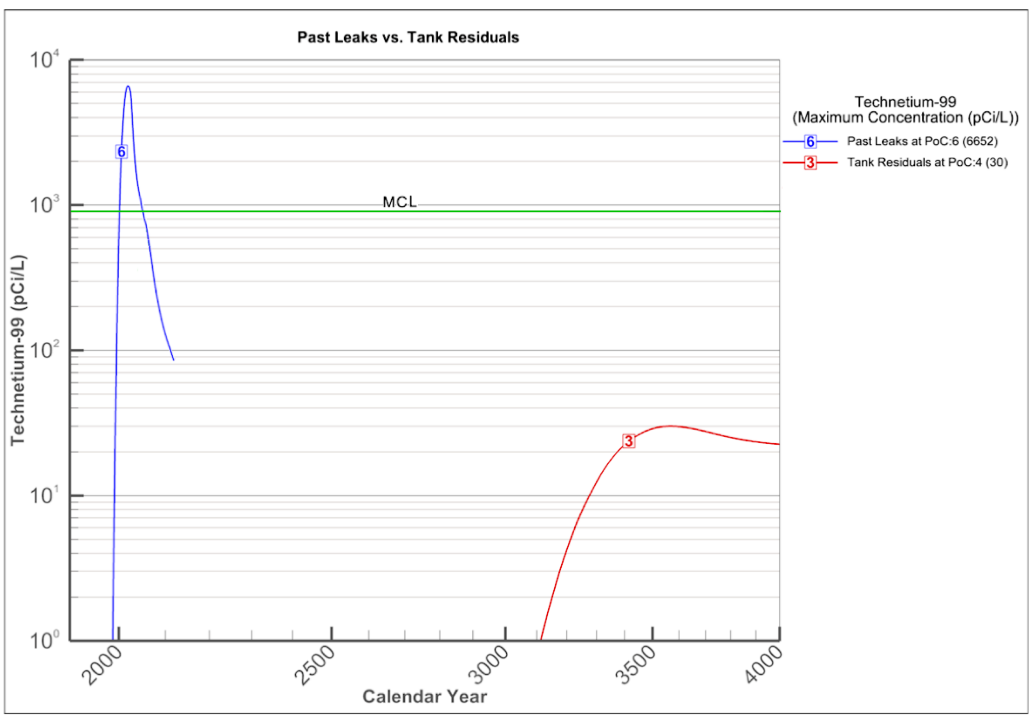
2.1 Contaminant Sources for Cumulative Evaluation

Two historical waste form types are known to provide contaminant sources that may contribute to groundwater contamination under the Central Plateau:

- Liquids (e.g., past leaks, disposal to cribs, and unplanned releases)
- Solids (e.g., grouted waste and soil debris)

Previous analyses have shown that liquid and solid waste affect groundwater at different times and at different concentrations (Appendix M of DOE/EIS-0391, *Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington (TC & WM EIS)* [hereinafter called the TC & WM EIS]; and RPP-RPT-59197, *Analysis of Past Waste Tank Leaks and Losses in the Vicinity of Waste Management Area C, Hanford Site, Washington*). While liquid waste is immediately available to migrate in the subsurface, contaminants within solid waste forms must be leached from or diffuse out of the solid waste into the aqueous phase before it can migrate to groundwater, which takes a longer time and results in lower contaminant concentrations.

A specific contaminant illustration for the timing of waste releases and the peak concentration is provided in the modeled results for technetium-99 in WMA C (RPP-RPT-59197). As shown in Figure 2-1, the first arrival time of technetium-99 from past liquid releases (the "Past Leaks at PoC" curve; the PoC is 100 m downgradient of WMA C) is about 1,000 years earlier as compared to the first arrival time of technetium-99 mobilized from grouted tank residuals (the "Tank Residuals at PoC" curve) at WMA C. The peak technetium-99 concentration associated with past liquid leaks is about 200 times higher (6,000 pCi/L versus 30 pCi/L) than for tank residual wastes. Additionally, the liquid waste impact is above the maximum contaminant level (MCL); when the solid waste release arrives at the groundwater, the resulting concentrations are below the MCL. The two sources of technetium-99 do not commingle in the aquifer because their arrival times at the water table are separated by more than 1,000 years. Nitrate shows a similar breakthrough and peak concentration behavior.



Source: RPP-RPT-59197, *Analysis of Past Waste Tank Leaks and Losses in the Vicinity of Waste Management Area C, Hanford Site, Washington.*

Figure 2-1. WMA C Past Leaks and Tank Residuals Simulated Future Impacts to Groundwater

The difference in peak concentration and the timing between liquid and solid waste releases is further discussed in the long-term environmental consequences analysis (Chapter 5 of the TC & WM EIS [DOE/EIS-0391]). Table 2-1 summarizes the contaminants of potential concern (COPCs), source, peak concentration, and peak arrival for the B Barrier presented in the TC & WM EIS. Peak liquid source concentrations range from about 50 to 1,000 times greater than those from solid sources. Peak concentrations from liquid sources have already arrived (e.g., technetium-99 in 1956), are currently arriving (e.g., tritium in 2011), or will arrive no later than year 2104 (chromium). In contrast, releases from solid sources do not begin until 2873, which is a delay of at least 700 years. This pattern is consistent with the previous example discussed for WMA C (RPP-RPT-59197).

Table 2-1. Summary of TC & WM EIS Selected Contaminant Peak Concentration and Time from Liquid and Solid Sources for the B Barrier

COPC (MCL)	Liquid Sources Peak Concentration (year)		Solid Source Peak Concentration (year)
	Cribs and Trenches	Past Leaks	Tank Residuals
Tritium (20,000 pCi/L)	672,000 (1956)	41 (2011)	Not reported
Technetium-99 (900 pCi/L)	33,700 (1956)	1,550 (2084)	617 (2965)
Iodine-129 (1 pCi/L)	42.3 (1956)	2.8 (2085)	0.7 (3533)
Nitrate (45,000 µg/L)	2,120,000 (1956)	3,030 (2095)	1,700 (2966)
Chromium (100 µg/L)	6,150 (1955)	58 (2104)	19 (2873)
Total uranium (30 µg/L)	0 (11,835)	4 (11,913)	Not reported
TC & WM EIS table	Table 5-3	Table 5-4	Table 5-6

Reference: DOE/EIS-0391, *Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington (TC & WM EIS).*

COPC = contaminant of potential concern

MCL = maximum contaminant level

The WMA C (RPP-RPT-59197) and TC & WM EIS (DOE/EIS-0391) examples show that liquid waste sources will dominate current and predicted groundwater concentrations for the next several hundred years. It is also likely that solid waste forms will impact groundwater quality at much lower concentrations than liquid waste releases 1,000 years or more in the future. Therefore, liquid waste release models will be implemented in the initial version of the CIE, with the solid waste release models being added as an optional feature in future runs of the CIE to assist in certain sensitivity cases.

2.2 Inventory Basis

To provide inventory inputs for the vadose zone facet, inventory must either be known or estimated. The technical approach for providing vadose zone facet inventory quantities for the initial CIE will use inventory information from the SIM-v2 (RPP-26744). This model provides an estimated history of liquid waste inventory, as well as uncertainty information for those estimates. The SIM-v2 is based on historical records and data from various Hanford Site process facilities that extracted plutonium and uranium from spent nuclear fuel. The SIM-v2 considers waste streams from the chemical separations conducted in the canyon buildings that were discharged directly to waste sites (e.g., ditches, cribs, ponds, and chemical sewers). Data from the Waste Information Data System were evaluated to determine which sites were appropriate to include in the SIM-v2. Unplanned releases and tank leaks are also included. The SIM-v2 combines the above information to estimate the liquid volume and inventory of many radionuclides and chemicals at many of the Central Plateau waste sites.

As characterization data are collected by source OUs and WMAs, the inventory will be updated as necessary using data from characterization and analyses efforts across the Central Plateau. It is anticipated that contaminants of concern (COCs) could be added that are not accounted for in the SIM-v2 (RPP-26744), or contaminant quantities could change. Where OU-specific information indicates differences from SIM-v2 estimates, these values will be updated in future CIE updates. Chapter 3 further describes how the SIM-v2 inventory will be used and updated in vadose zone modeling.

2.3 Contaminant Screening Process

Previous work has been performed at the Hanford Site to evaluate key contributors to groundwater contamination and develop vadose zone inventories. The CIE will use the evaluations from previous studies as the basis for which contaminants will be included in the initial version of the CIE. For example, the TC & WM EIS cumulative impact analysis alternatives (Chapter 6 in DOE/EIS-0391) determined that, out of a larger list of contaminants that have impacted (or are likely to impact) groundwater, the radiological contaminants were tritium, iodine-129, technetium-99, and uranium-238; and the chemical contaminants were carbon tetrachloride, Cr(VI), nitrate, and uranium (a total of eight contaminants).

To ensure that the CIE captures all the contaminants that could be impacting groundwater, the Central Plateau groundwater OUs were also evaluated. Key contaminants for groundwater protection were further identified by reviewing the following Central Plateau documents:

- DOE/RL-2009-127, *Remedial Investigation Report 200-BP-5 Groundwater Operable Unit*
- DOE/RL-2009-85 ADD1, *Remedial Investigation Report for the 200-PO-1 Groundwater Operable Unit*
- EPA et al., 2008, *Record of Decision Hanford 200 Area 200-ZP-1 Superfund Site, Benton County, Washington*
- EPA et al., 2012, *Record of Decision for Interim Remedial Action Hanford 200 Area Superfund Site 200-UP-1 Operable Unit*

Review of the groundwater OU COCs and COPCs identified three additional contaminants that were not identified in the TC & WM EIS (DOE/EIS-0391): cyanide, strontium-90, and trichloroethene (TCE). All of the 11 (eight from the TC & WM EIS) contaminants were then further evaluated for inclusion in the initial CIE based on SIM-v2 inventory (RPP-26744) and OU decisions.

Four of the contaminants (Cr(VI), cyanide, carbon tetrachloride, and TCE) require special consideration. The SIM-v2 (RPP-26744) considers total (not hexavalent) chromium; therefore, further analysis will be performed to refine the chromium inventory. Cyanide will require development of an inventory estimate since SIM-v2 was selected as the inventory information source for input into the vadose zone model. Cyanide is not included in the SIM-v2 chemical inventory because the SIM-v2 assumed that ferrocyanide used in scavenging cesium-137 from tanks was completely used up. Since cyanide is currently found in groundwater (with increasing trends in some locations), this upward trend in groundwater concentrations implies there is inventory in the vadose zone that must be included in the cumulative evaluation.

Carbon tetrachloride will also not rely on the SIM-v2 inventory estimate (RPP-26744). The SIM-v2 does not account for remedial actions that have taken place or are ongoing for the Central Plateau to date. A soil vapor extraction system operated to reduce carbon tetrachloride soil concentrations in the 200-PW-1 OU from 1992 to 2015. Because of this cleanup effort, it has been determined that vadose zone carbon tetrachloride soil concentrations no longer contribute a substantial source of the contaminant to groundwater (DOE/RL-2014-48, *Response Action Report for the 200-PW-1 Operable Unit Soil Vapor Extraction Remediation*). Therefore, the carbon tetrachloride vadose zone inventory will not be considered from the SIM-v2 for input into the vadose zone model.

A process stream has not been identified to contain TCE, a waste site disposal for TCE has not been identified, and no source term has been evaluated. TCE will not have a source term in the initial CIE. However, the known carbon tetrachloride and TCE groundwater plumes will be represented in the groundwater model facet (as described in Chapter 4). Similar to other contaminants, if a source unit or a waste management area identifies the presence of TCE in the vadose zone, this information will be used in future CIE updates.

As information is collected for source OUs and WMAs, the contaminant list will be revised as necessary based on information from remedial investigations and tank closure performance assessments (PAs). For example, preliminary characterization data from waste sites within the 200-DV-1 OU have identified considerable levels of methyl isobutyl ketone in the vadose zone. Therefore, it is possible that as the characterization effort is completed and documented, the CIE will add methyl isobutyl ketone to its list of contaminants.

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3 Vadose Zone Flow and Transport Models

The objective of the CIE vadose zone facet is to provide Central Plateau vadose zone models to numerically evaluate fate and transport of contaminants in the vadose zone and mass/activity fluxes into the aquifer. The development of such vadose zone models faces some unique challenges due to the size of the area with several hundred disposal sites, large disposal volumes and contaminant inventory, considerable thickness of the vadose zone, sediment heterogeneity, variable hydraulic and transport properties, and spatial and temporal variation in recharge.

Waste site proximity has resulted in contaminants commingling in the vadose and saturated zones, requiring cleanup decisions considering the effects of vadose zone sources, resulting from waste site disposal and past leaks, on existing groundwater contamination. Groundwater sample results indicate that ongoing releases from continuing sources are causing concentrations above cleanup levels in the Central Plateau. An example is shown in Figure 3-1 (adapted from ECF-200W-17-0030, *Calculation of Source Terms for the 200 West Pump-and-Treat System Optimization Modeling, FY 2017*) for selected contaminants, showing groundwater plumes in 200 West and associated waste sites from which continuing sources have likely developed. Analyses like ECF-200W-17-0030 are based on relatively simple control volume approaches, and computed source terms are considered screening-level estimates due to uncertainties in inventories and groundwater flow and by not considering vadose zone hydraulic processes. It is expected that the CIE will yield improved relations between groundwater plumes and continuing source terms as vadose zone flow and transport processes are incorporated in the analysis.

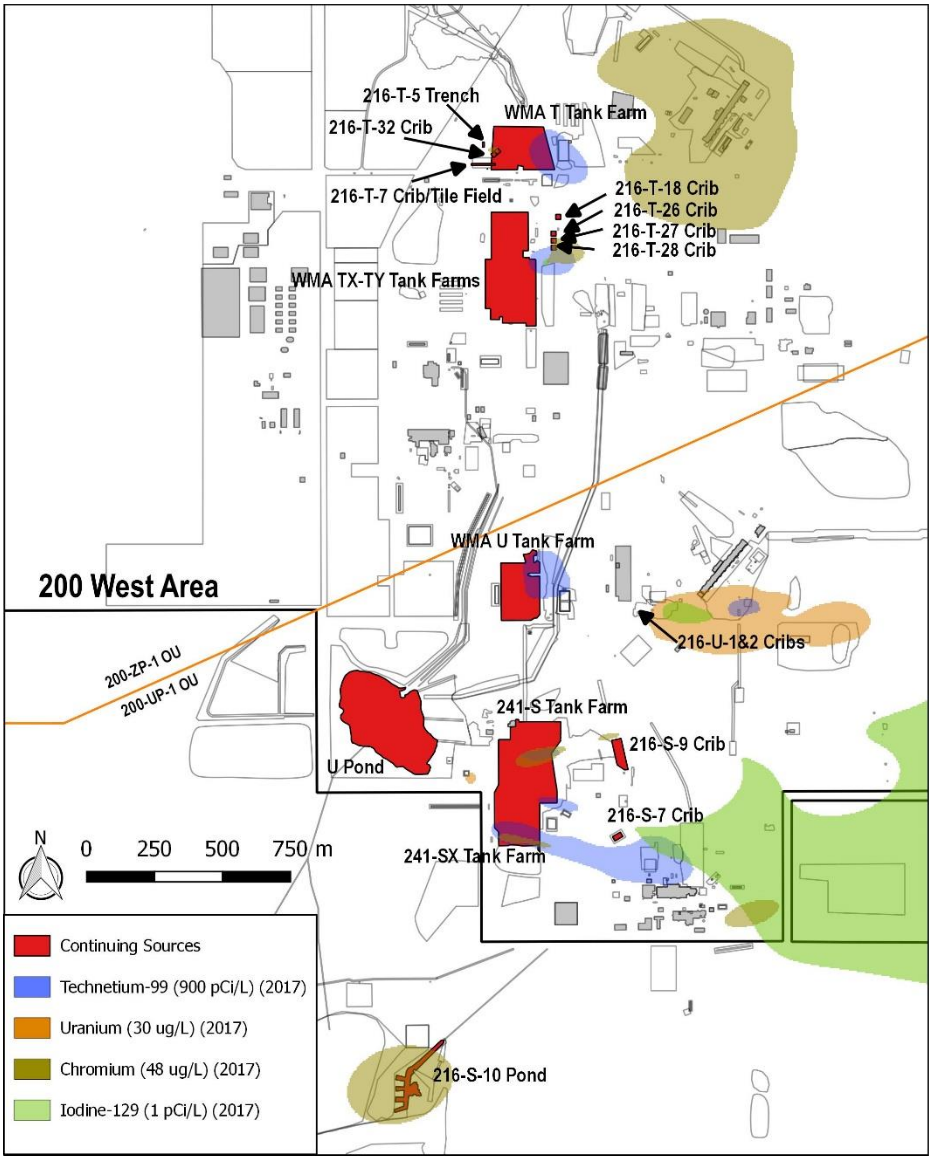
The vadose zone models must be representative of the Central Plateau unsaturated zone conditions so the predictions of future contaminant flux to the water table will approximate expected behavior. Model configuration and parameter values are selected with reasonable ranges. Developing representative vadose zone flow and transport models requires that the models be consistent with the following:

- Existing geologic interpretation of hydrostratigraphic units (HSUs) in the Central Plateau
- Available vadose zone characterization data (e.g., hydraulic parameters and soil moisture content)
- Observed vadose zone concentrations of contaminants
- Estimates of flux to groundwater for contaminants

Large-scale models that can be used to predict contaminant transport from contaminant waste sites to the water table will be constructed, considering the following components:

- **Subsurface geology:** The use of the Central Plateau Vadose Zone Geoframework Model (CPVZ GFM) (CP-60925, *Model Package Report: Central Plateau Vadose Zone Geoframework Version 1.0*) to obtain HSUs (Section 3.1).

- **Impacts of subsurface heterogeneity on fluid flow and contaminant transport:** The selection of the equivalent homogeneous media (EHM) modeling approach accounting for heterogeneity using soil moisture-dependent anisotropy (Section 3.2).



Modified from Figure 1 in ECF-200W-17-0030, *Calculation of Source Terms for the 200 West Pump-and-Treat System Optimization Modeling, FY 2017.*

Figure 3-1. Selected 2017 Central Plateau 200 West Groundwater Plumes (Technitium-99, Uranium, Chromium, and Iodine-129) with Associated Continuing Vadose Zone Source Locations

- **Computational domain and spatial extent:** An important factor complicating selection of the spatial extent of the modeling domains is that many liquid discharge sources on the Central Plateau are near other liquid sources, potentially leading to commingled contaminant plumes within the vadose zone as the discharged fluids migrate through the vadose zone to the groundwater. Section 3.3 discusses the technical approach to develop representative models considering the potential for commingling of contaminant plumes.

- **Hydraulic and transport properties for anisotropic EHMs:** Section 3.4 presents an overview of the hydraulic and transport properties that need to be specified in the CIE vadose zone models, including upscaling methods that will be used to yield field-scale properties accounting for directional-dependent flow and transport.

- **Impacts of model boundary conditions and contaminant disposal characteristics on flow and contaminant transport:** Section 3.5 discusses the technical approach to account for time- and spatially-variable natural and anthropogenic recharge and waste site contaminant disposal.

Section 3.6 discusses the representativeness evaluation of the CIE vadose zone models, defined as the process used to generate information to determine if a model and its results are sufficient to serve as a basis for decisions. The process is designed to evaluate representativeness in several ways, including using the CPVZ GFM, accounting for effects of sediment heterogeneity on contaminant transport, employing spatial model domains large enough to account for subsurface interference (commingling) of liquid waste disposal, and applying time- and spatially-variable liquid disposal and recharge.

The vadose zone models will include the flexibility to incorporate output (i.e., activity/mass fluxes from the vadose zone to groundwater) from detailed site modeling activities in facility-specific or OU-specific analyses or characterization data obtained for specific decision-supporting purposes in the CIE framework. Section 3.7 outlines the two distinctive ways to include model output and characterization information into the CIE tools.

Section 3.8 discusses the computational tools, in particular the subsurface flow and transport simulator STOMP (PNNL-12030, *STOMP Subsurface Transport Over Multiple Phases Version 2.0, Theory Guide*; PNNL-15782, *STOMP Subsurface Transport Over Multiple Phases Version 4.0, User's Guide*; PNNL-11216, *STOMP Subsurface Transport Over Multiple Phases, Application Guide*) which was selected to implement the detailed flow and solute transport models in the CIE vadose zone facet. Section 3.9 presents the key technical approach assumption of the vadose zone facet.

3.1 Central Plateau Vadose Zone Geoframework and Hydrostratigraphic Units

The hydrostratigraphy of the vadose zone models will be derived from the CPVZ GFM (CP-60925 and future revisions). The CPVZ GFM provides a three-dimensional representation of the vadose zone beneath the Central Plateau. The model is constructed based on the most up-to-date, three-dimensional interpretations of the Hanford Site's extensive geologic database. In the future, as source units and WMAs advance through the regulatory decision-making process, it is expected that additional information will become available to update the CPVZ GFM and, subsequently, the vadose zone models described in this chapter. The CPVZ GFM represents the subsurface geologic structure vertically extending from the ground surface to the top of the Columbia River Basalt Group, covering an area shown in Figure 3-2. The CPVZ GFM will be used to populate and assemble CIE numerical model architectures, thus providing three-dimensional grids of the vadose zone geology consistent with the CPVZ GFM.

The CPVZ GFM is built using a hydrostratigraphic approach, which is a combination of lithologic and sequence stratigraphic interpretations (EPA/600/R-17/293, *Best Practices for Environmental Site Management: A Practical Guide for Applying Environmental Sequence Stratigraphy to Improve Conceptual Site Models*), leading to the definition of a series of HSUs. This approach maps broadly correlated hydraulically significant units in the subsurface while still representing lithologically heterogeneous features. The geologic unit interpretations used in the CPVZ GFM are based on subsurface borehole records, geophysical measurements, and related information. Approximately 1,200 boreholes were selected for the detailed vadose zone geologic interpretation. The HSUs identified by the CPVZ GFM are as follows:

- Backfill/surface deposits (Backfill)
- Hanford formation unit 1 (Hf1)

- Hanford formation unit 2 (Hf2)
- Hanford formation unit 3 (Hf3)
- Cold Creek unit upper silt and sand (CCU)
- Cold Creek unit caliche (CCUc)
- Cold Creek unit gravel (CCUg)
- Ringold Formation member of Taylor Flat (Rtf)
- Ringold Formation member of Wooded Island – unit E (Rwie)
- Ringold Formation member of Wooded Island – lower mud unit (Rlm)
- Ringold Formation member of Wooded Island – unit A (Rwia)

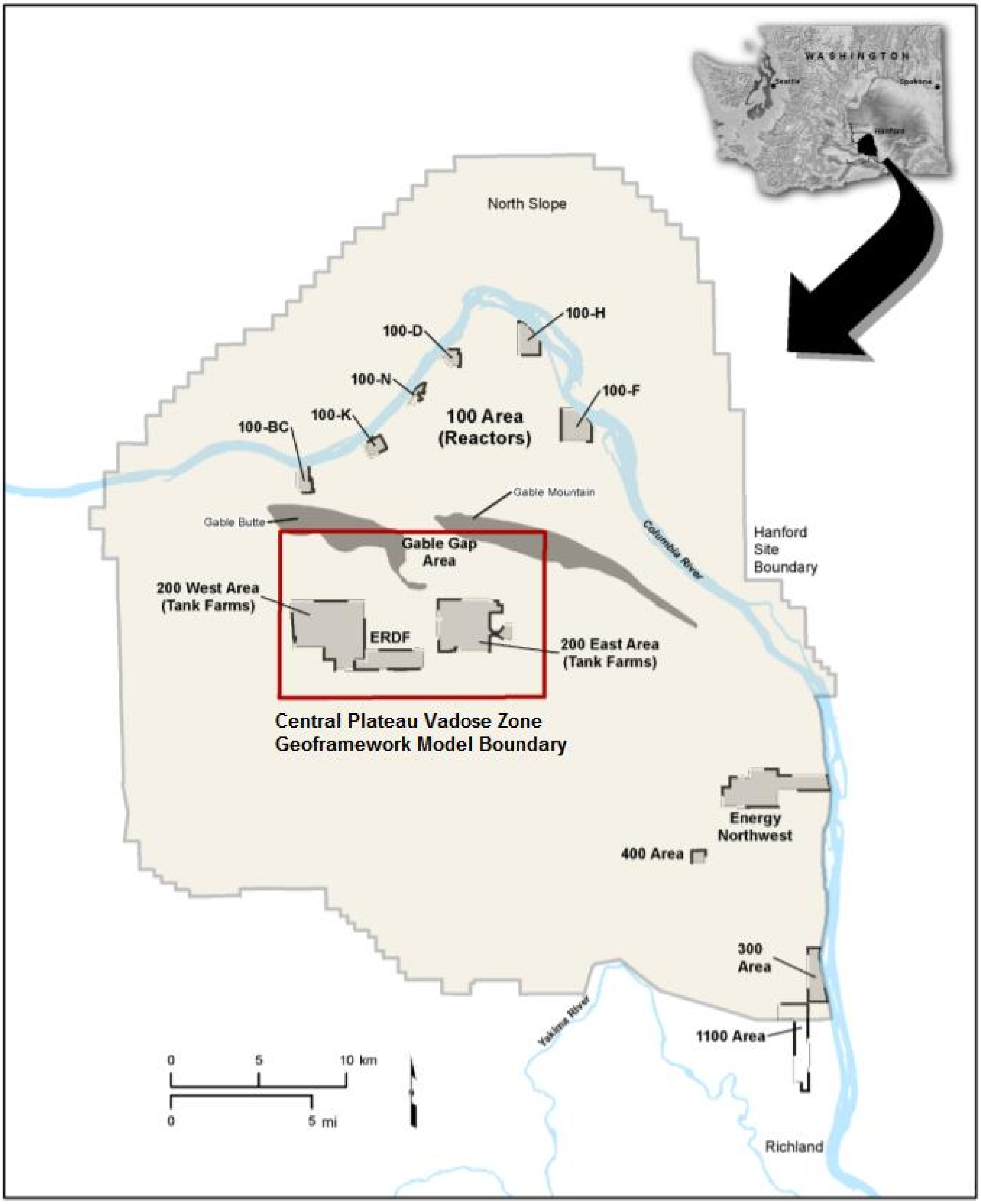
Figures 3-3 and 3-4 show example borehole logs for 200 West and 200 East with formation top selections, respectively. Figure 3-5 provides an example of a vadose zone model in 200 West, with Backfill, Hf1, Hf2, Hf3, CCU, CCUc, Rtf, and Rwie HSUs.

The CPVZ GFM provides an efficient, modular way to construct consistent and maintainable geologic interpretations for vadose zone flow and transport models. This approach allows for the inclusion of controlling geological features in vadose zone domains, depending on additional data availability from WMA or OU characterization.

3.2 Anisotropic Equivalent Homogeneous Media Approach to Represent Heterogeneous Hydrostratigraphic Units

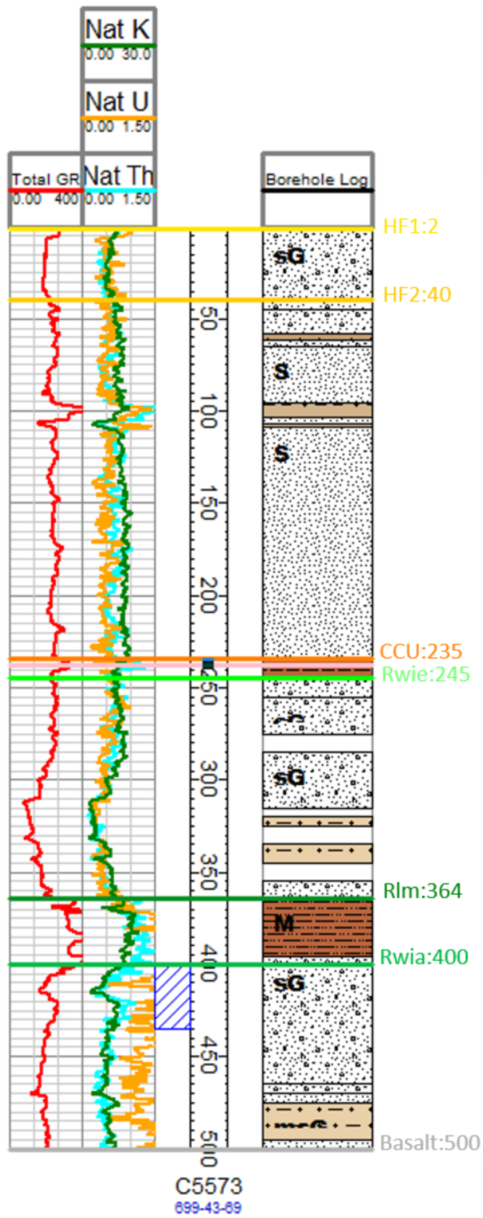
Within HSUs, the vadose zone sediments are heterogeneous at a variety of scales. Figure 3-6 provides an example of Hanford Site subsurface heterogeneity at the core and field scales for the upper Ringold Formation with laminated sand and silt layers (Mayes et al., 2003, "Transport of multiple tracers in variably saturated humid region structured soils and semi-arid region laminated sediments"). The stratigraphy of these sediments typically causes more water flow and contaminant spreading to occur laterally than vertically. The directional dependence of flow and transport prevalent in Hanford Site sediments is typically referred to as subsurface anisotropy (e.g., Yeh et al., 2005, "Estimation of effective unsaturated hydraulic conductivity tensor using spatial moments of observed moisture plume").

The CIE will use the anisotropic EHM approach to model flow and transport in the heterogeneous HSUs. The approach, recommended by Yeh et al., 2015, *Flow Through Heterogeneous Geologic Media*, for systems with large-scale HSUs, is based on two major assumptions: each HSU has representative hydraulic property and parameter values that are equivalently homogeneous (constant) in space, and (2) the effects of heterogeneity on flow are described using an anisotropic unsaturated hydraulic conductivity (i.e., the ratio of the effective unsaturated conductivity parallel to geologic bedding to the effective unsaturated conductivity perpendicular to geologic bedding). Figure 3-7 illustrates the consistency of the anisotropic EHM approach with a subsurface consisting of several HSUs. The heterogeneous outcrop (inset a in Figure 3-7) is mapped into three distinct, large-scale HSUs based on a facies distribution (inset b in Figure 3-7). Each of these heterogeneous HSUs is then represented by an anisotropic-equivalent homogeneous medium with upscaled (from core to field-scale) effective macroscopic flow and transport properties.



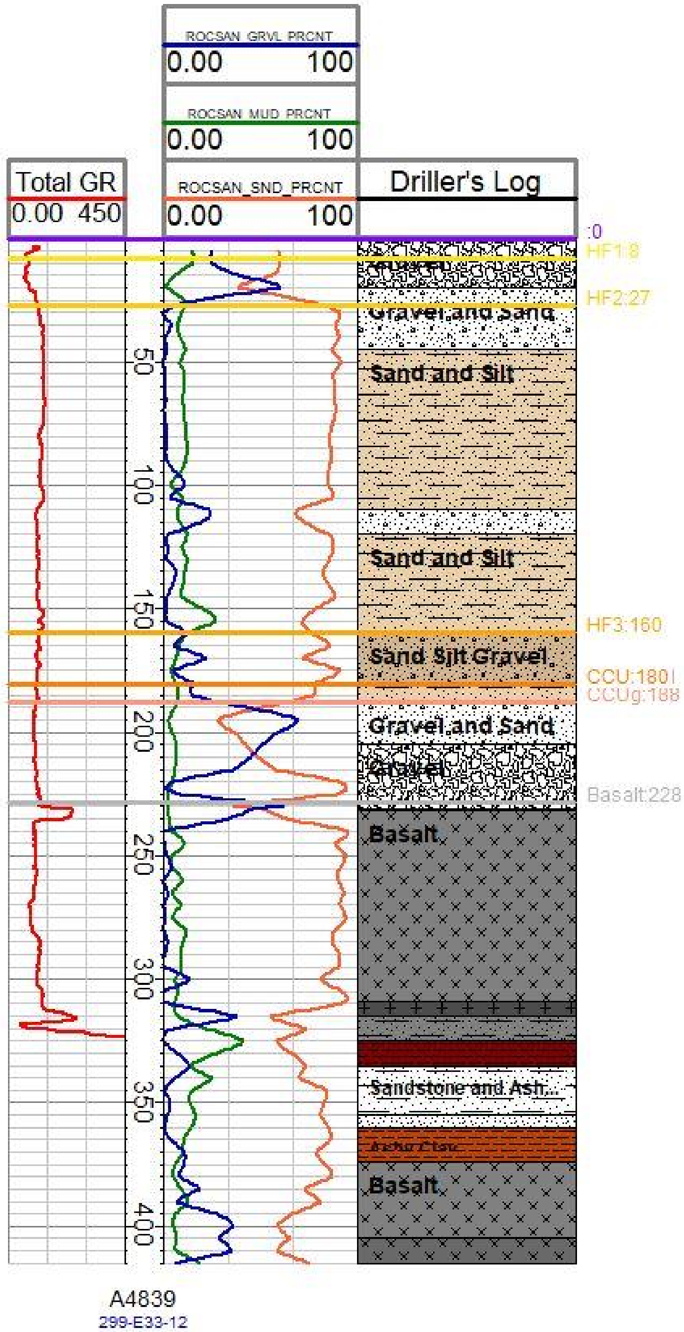
Source: Figure 1 in CP-60925, *Model Package Report: Central Plateau Vadose Zone Geoframework Version 1.0*.

Figure 3-2. CPVZ GFM Location and Model Boundary



Source: Figure B-730 in CP-60925, *Model Package Report: Central Plateau Vadose Zone Geoframework Version 1.0*.

Figure 3-3. Example Borehole Log for 200 West (699-43-69) with Formation Tops for Hf1, Hf2, CCU, Rwie, Rlm, Rwia, and Basalt



Source: Figure B-75 in CP-60925, *Model Package Report: Central Plateau Vadose Zone Geoframework Version 1.0*.

Figure 3-4. Example Borehole Log for 200 East (299-E33-12) with Selected Formation Tops for Hf1, Hf2, Hf3, CCU, CCUg, and Basalt

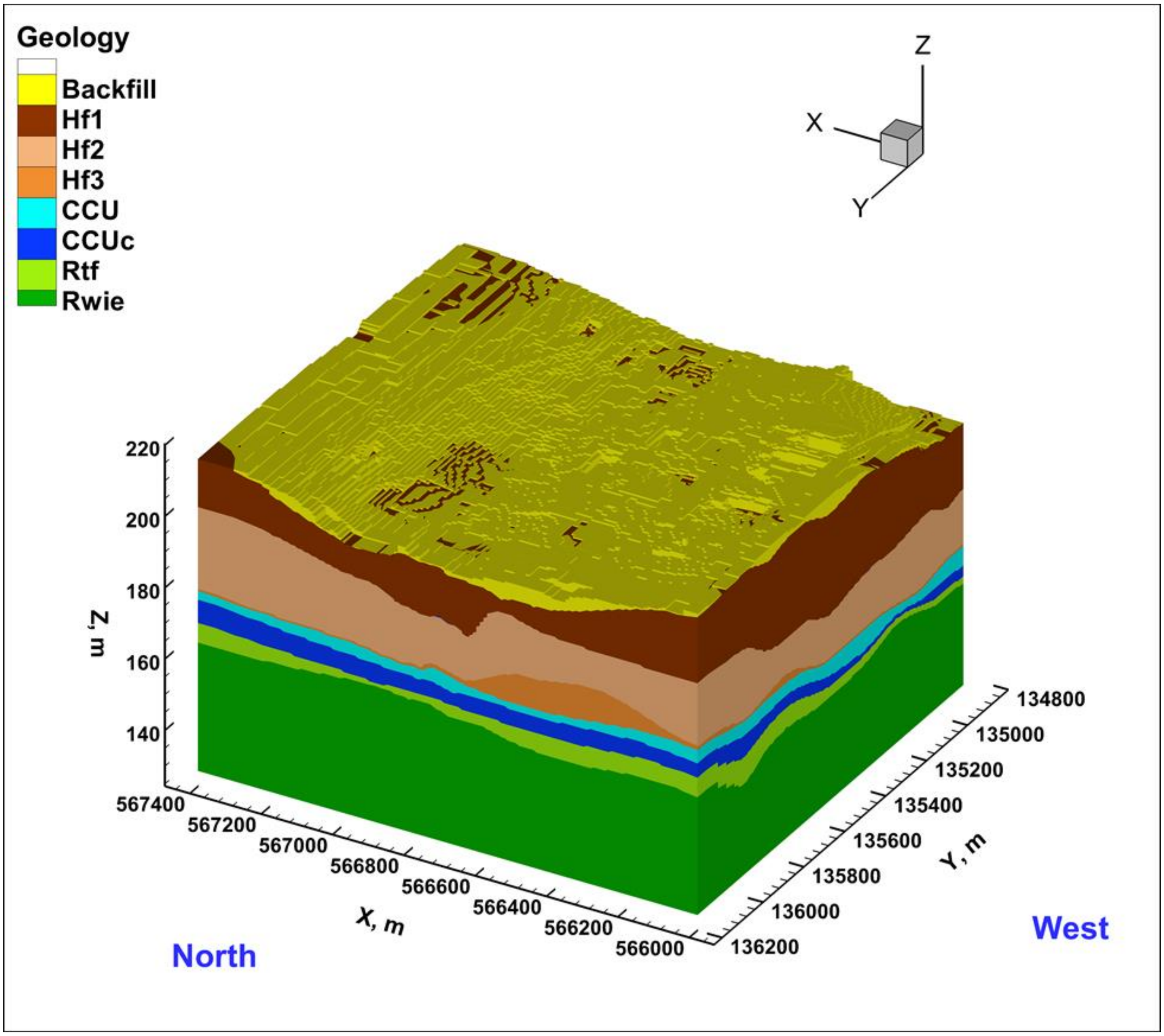
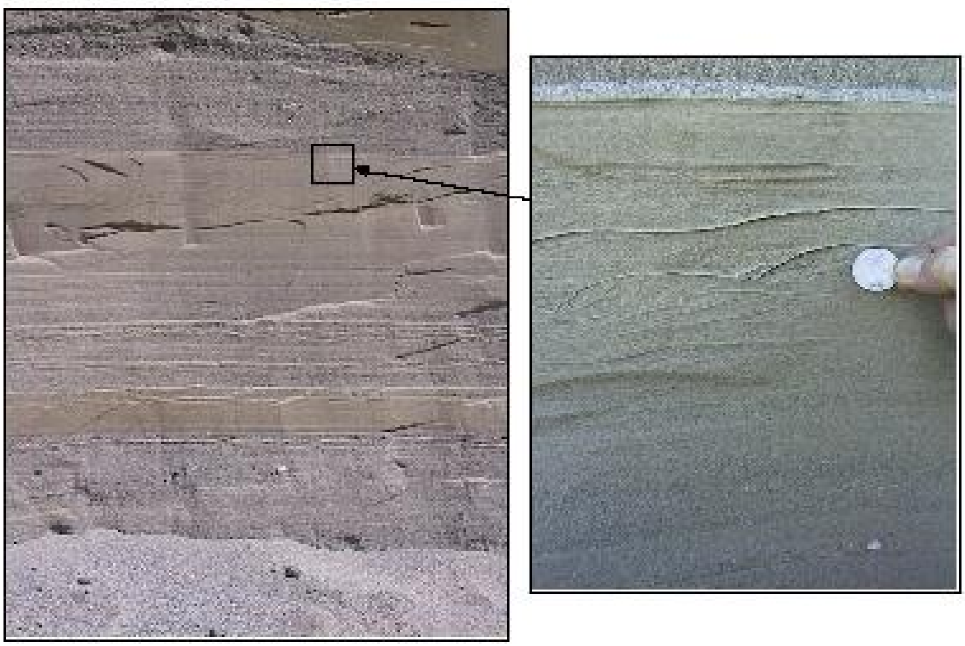


Figure 3-5. Detail of a Three-Dimensional Vadose Zone Model Domain in 200 West with HSUs Obtained from the CPVZ GFM

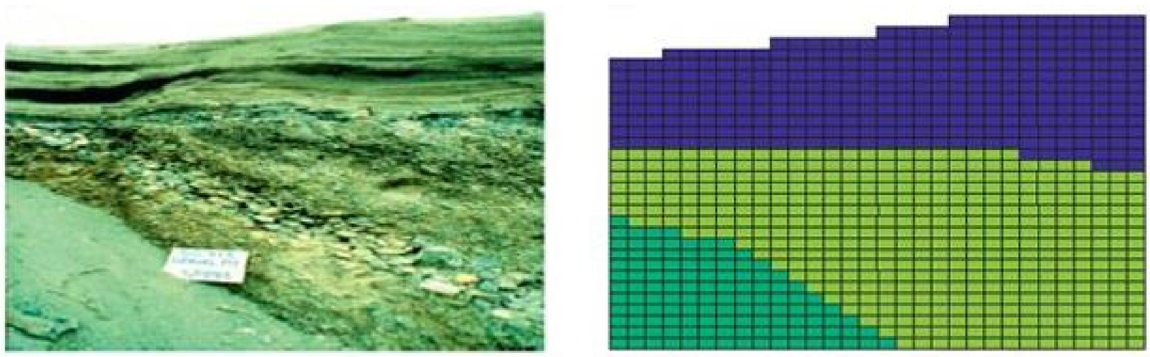
(a)



(b)

Source: Mayes et al., 2003, "Transport of multiple tracers in variably saturated humid region structured soils and semi-arid region laminated sediments."

Figure 3-6. Hanford Site Heterogeneity at the (a) Core and (b) Field Scale



(a) (b)

Source: Yeh et al., 2005, Estimation of effective unsaturated hydraulic conductivity tensor using spatial moments of observed moisture plume.”

Note: The function of this figure is *only* to demonstrate the mechanism of EHM representation of geologic features. The grid blocks shown in (b) are smaller than the grid blocks that will be used in the CIE vadose zone model.

Figure 3-7. Ilustration of (a) a Geologic Outcrop and (b) its EHM Representation

Anisotropy in the vadose zone is largely determined by the moisture content (Zhang et al., 2003, “A Tensorial Connectivity–Tortuosity Concept to Describe the Unsaturated Hydraulic Properties of Anisotropic Soils”) and typically increases with dryer conditions. The concept of moisture-dependent anisotropy was introduced in Yeh et al., 1985, “Stochastic Analysis of Unsaturated Flow in Heterogeneous Soils, 2. Statistically Anisotropic Media with Variable α.” Under this concept, anisotropy increases as the medium becomes less saturated. The anisotropic behavior explains the lateral spreading of observed moisture plumes in stratified sediments (e.g., Yeh et al., 2005).

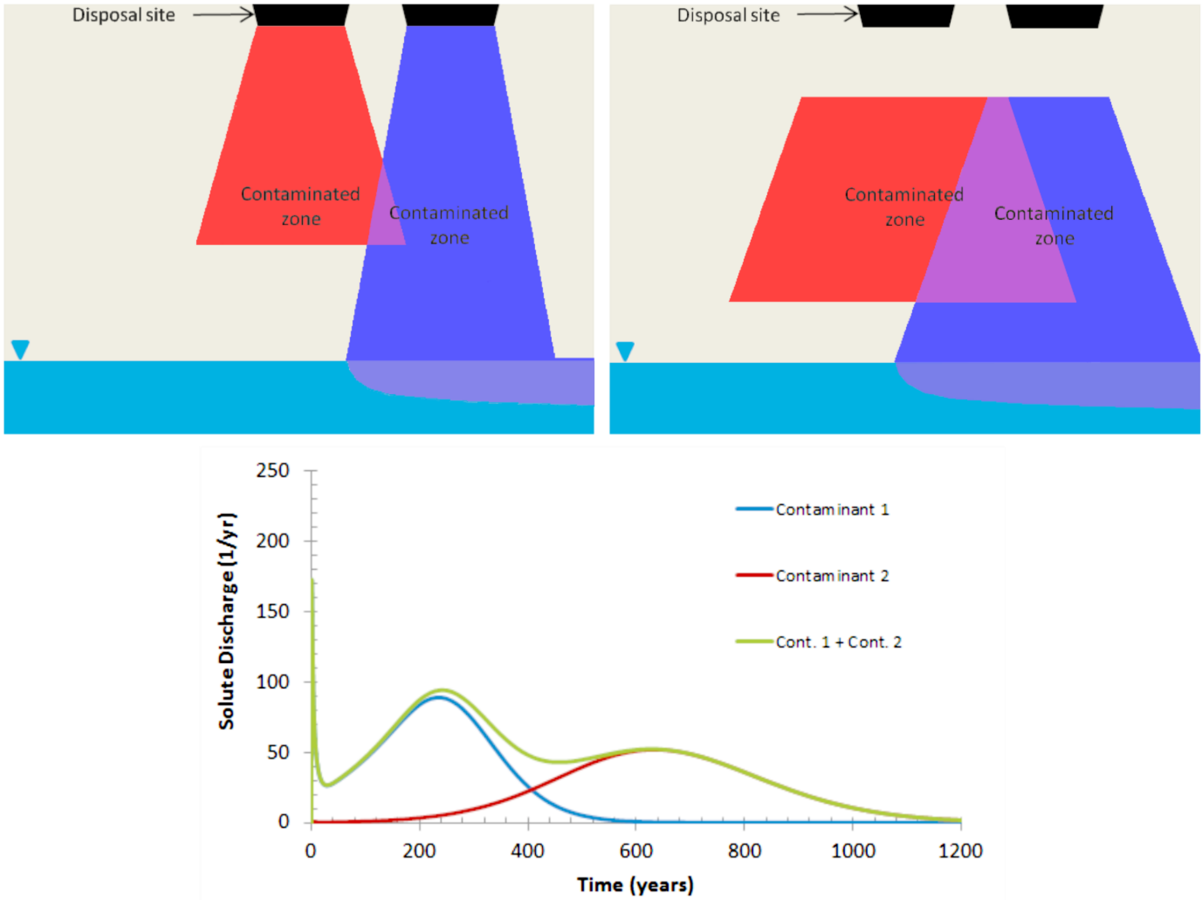
For the heterogeneous stratified sediments at the Central Plateau, upscaled hydraulic properties based on small-scale laboratory measurements will be used to simulate the large, field-scale behavior. Each heterogeneous HSU is replaced by an anisotropic EHM with upscaled or effective flow properties. The upscaling process, discussed in Section 3.4, honors the underlying flow dynamics. An important feature of an anisotropic EHM model representation is that it does capture the mean or the bulk flow characteristics of the vadose zone moisture plumes, as demonstrated by Yeh et al. (2005) and Zhang and Khaleel, 2010, “Simulating field-scale moisture flow using a combined power-averaging and tensorial connectivity-tortuosity approach.” For example, the upscaled, effective unsaturated hydraulic conductivity is the hydraulic conductivity of an anisotropic EHM that produces the same volumetric water flux as the heterogeneous media under the same boundary conditions. Following Yeh et al. (2005), the contaminant peak arrival time under recharge-dominated flow conditions is adequately captured by an anisotropic EHM model representation.

The anisotropic EHM approach is commonly used to model flow and transport at the Hanford Site. For instance, recent PA vadose models for the Integrated Disposal Facility (RPP-RPT-59344, *Integrated Disposal Facility Model Package Report: Vadose and Saturated Zone Flow and Transport*) and WMA C (RPP-ENV-58782, *Performance Assessment of Waste Management Area C, Hanford Site, Washington*) used some form of soil moisture-dependent anisotropy to simulate subsurface flow.

3.3 Vadose Zone Model Domains, Grid Discretization, and Activity/Mass Transfer to the Saturated Zone Model

The approach to address the scale and distribution of contaminant sources in the CIE vadose zone model facet is to subdivide the Central Plateau into individual geographic areas (i.e., model domains) that contain contaminant sources and liquid discharges likely to commingle during flow and transport through the vadose zone to the water table. The potential for commingling occurs when liquid discharge sources are near other liquid sources and is related to disposal characteristics (e.g., volumes, duration, rate, and time period), hydrological properties (e.g., unsaturated hydraulic conductivity anisotropy), and the distance between waste sites and other release areas (Oostrom et al., 2017, "Deep Vadose Zone Contaminant Flux Evaluation at the Hanford BY-Cribs Site Using Forward and Imposed Concentration Modeling Approaches").

Figure 3-8 provides an example of the effects of vadose zone plume commingling on contaminant flux to groundwater (PNNL-24731, *Evaluating Transport and Attenuation of Inorganic Contaminants in the Vadose Zone for Aqueous Waste Disposal Sites*). In this example, a waste site with a large liquid disposal volume and an adjacent waste site with a much smaller liquid volume are assumed to have introduced the same contaminant into the vadose zone. After some time, the two plumes start to commingle, followed by transport into groundwater. Some activity/mass from the high-volume liquid site reaches the groundwater quickly, resulting in an initial peak (shown in Figure 3-8 by a blue line). A second peak forms when the remaining contaminant travels through the vadose zone with the prevailing recharge. The activity/mass from the adjacent low-volume liquid waste site travels much slower (shown in Figure 3-8 by a red line) and the flux peak arrival is primarily determined by recharge. When the two flux plots are superimposed (shown in Figure 3-8 by a green line), the resulting flux relation shows contaminant transport into the groundwater over a long time period with three distinct peaks. This example shows that when a contaminant emanating from multiple waste sites commingles, complex flux behavior might develop with multiple peak arrival times. This complex behavior can only be captured when waste sites creating commingled plumes are evaluated in the same vadose zone model. The compounding effect of adjacent waste sites would not be apparent using models representing a single waste site. This example illustrates that plume commingling may affect the spatial and temporal distribution of contaminant flux to groundwater. Therefore, a representative modeling approach needs to capture plume commingling resulting in contaminant mixing.



Source: PNNL-24731, *Evaluating Transport and Attenuation of Inorganic Contaminants in the Vadose Zone for Aqueous Waste Disposal Sites.*

Note: Contaminant disposal is shown at adjacent sites during disposal (top left) and at the time of transport evaluation (top right). The high and low volume waste sites are blue and red, respectively. A typical groundwater mass flux example for this scenario is shown in the bottom graph.

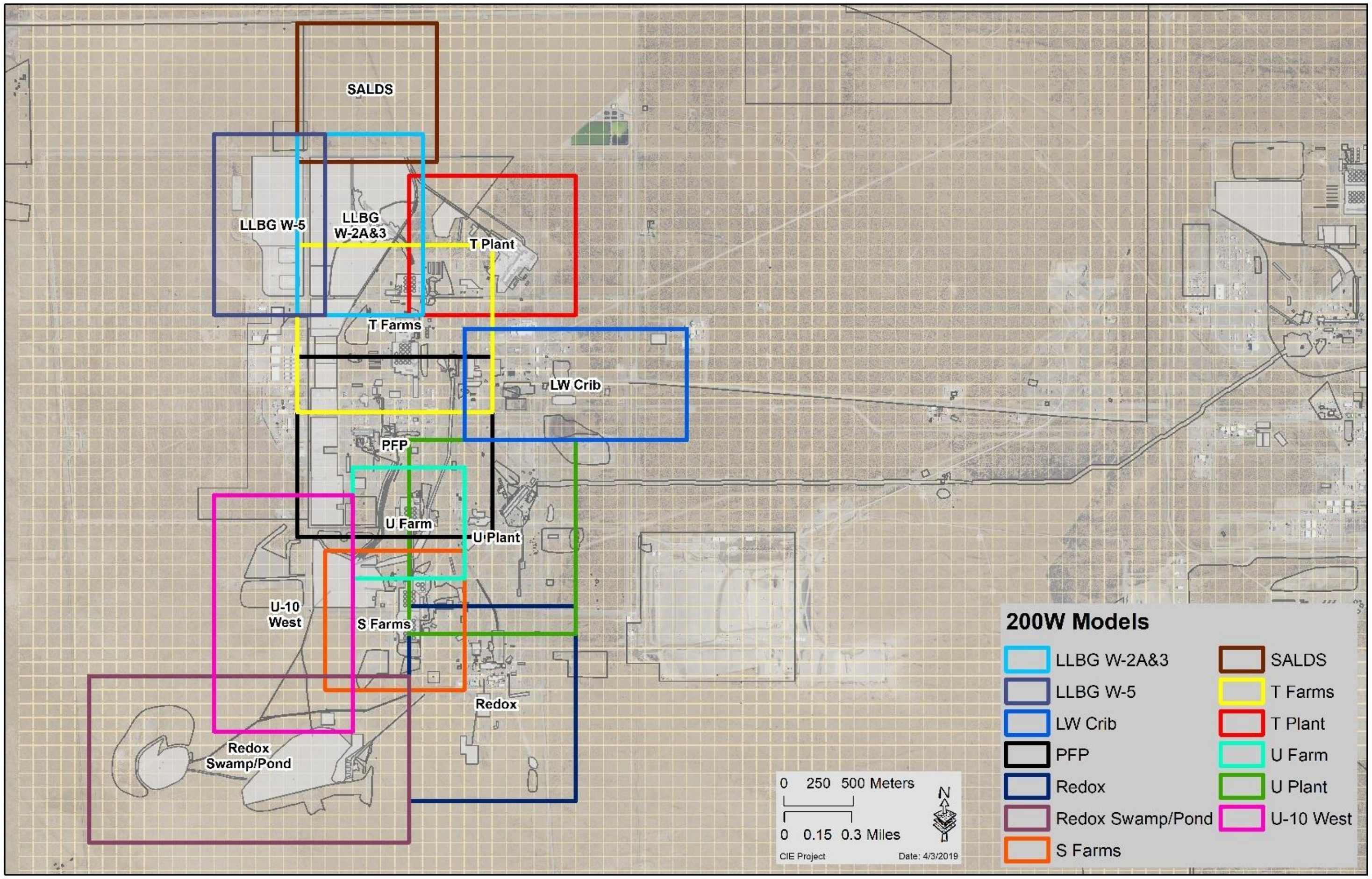
Figure 3-8. Schematic of Vadose Zone Plume Commingling Process and the Effects on Contaminant Fluxes to Groundwater

The scale of the individual CIE vadose zone models must strike a balance between the need to evaluate the potential extent of commingled plumes originating from multiple adjacent waste sites and computational efficiency. The model domains will be chosen to be large enough to ensure that disposal from waste sites that may be expected to result in commingled plumes is simulated in the same vadose zone model, and the lateral boundaries do not affect water flow and contaminant transport. However, the model domains will be chosen to be small enough to ensure that there will be sufficient horizontal grid resolution that individual contaminant sources can be represented at a minimum scale of 5 to 10 m (16.4 to 32.8 ft), and sufficient vertical grid resolution that individual HSUs can be represented vertically at a scale of 0.1 to 1 m (1.6 to 3.3 ft).

The 200 West and 200 East Areas of the Central Plateau will be subdivided into three-dimensional vadose zone models, each containing multiple waste sites. Figures 3-9 and 3-10 provide examples of vadose zone models that could be created for the 200 West and East Areas, respectively. To encompass all of the waste sites and to account for plume commingling, some overlapping models will be needed. However, the contaminant inventory of a waste site will only be included in one of the models to maintain a modular approach and avoid double-counting releases to the saturated zone. The selection of the individual model boundaries will be an iterative process to ensure that contaminant migration and fluxes into the groundwater model will not be affected. Based on the initial representation of vadose zone models shown in Figures 3-9 and 3-10, it is anticipated that approximately 25 large-scale models will need to be constructed to represent all SIM-v2 (CP-59798) waste sites, tank leaks, and unplanned releases on the Central Plateau.

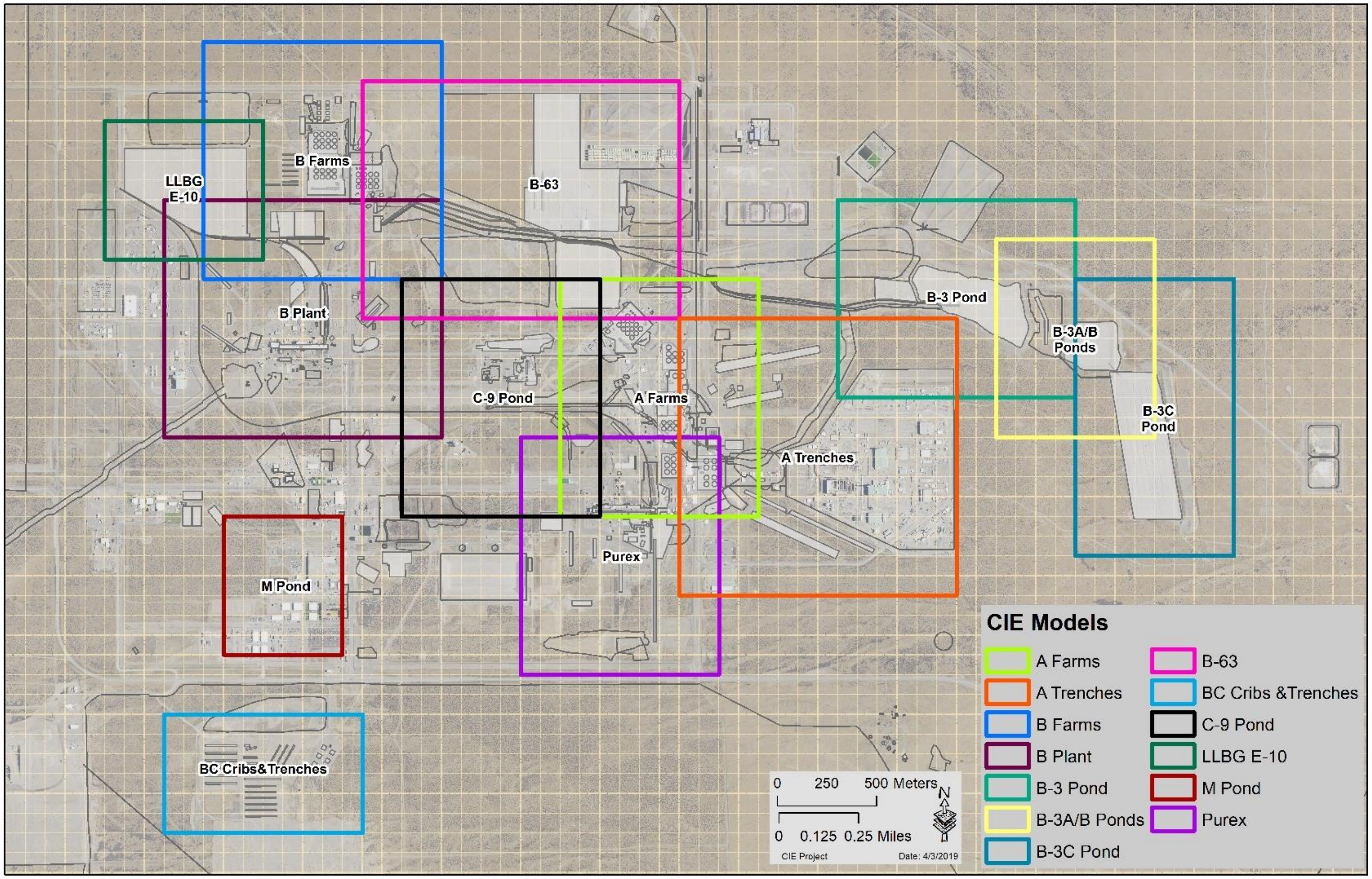
Waste site shapes will be assigned to vadose zone model surfaces using geometry information. Water volumes and SIM-v2 contaminant inventories will be assigned to the model grid surfaces for each of the site footprints. An example of how waste site footprints will be assigned to model grid surfaces is illustrated in Figure 3-11 for the BC Cribs area shown in Figure 3-10. In Figure 3-11, the model grid surfaces are colored to show their relation to the waste site footprints, which are the pink lines. Grid refinement was applied in some areas to provide good correspondence between waste sites and model grid surfaces for the relatively narrow cribs B-23 through B-28, and the slanted cribs B-20, B-21, and B-22.

The total yearly contaminant activity/mass passed on to the groundwater model will be the combined activity/mass emanating from all the waste sites in all vadose zone models shown in Figures 3-9 and 3-10. The yearly contaminant fluxes are used as boundary conditions for the saturated zone model. Water fluxes are not passed on to this model. Instead, the groundwater model will use a geographic information system (GIS)-based recharge tool, described in Section 3.5.2.2, for its upper boundary conditions. To help facilitate the computation of contaminant fluxes into the groundwater model, the corners of the large-scale vadose zone models will coincide with corners of the saturated zone 100 by 100 m (328.1 by 328.1 ft) model grid cells, as illustrated in Figures 3-9 and 3-10. In addition, the horizontal discretization of the vadose zone models will be such that the corners of each of the saturated zone model grid cells coincide with corners of the vadose zone grid cells. To demonstrate this configuration, an example of the horizontal vadose zone model and saturated zone model grids of a 300 by 300 m (984 by 984 ft) area near BY Cribs is shown in Figure 3-12. In this example, a total of 100 vadose zone model grid cells, with dimensions of 10 by 10 m (33 by 33 ft), fit into one saturated zone 100 by 100 m (328.1 by 328.1 ft) model grid cell. For each of the Central Plateau saturated zone grid cells, the vadose zone model sums the fluxes over the 100 vadose zone grid cells and passes on a yearly flux to the saturated zone model for each of the contaminants starting in 2018. An example of the mass transfer process is shown in Figure 3-13 (inset a) for simulated technetium-99 fluxes from the vadose zone near B Farms into groundwater during the year 2070. The figure shows the yearly fluxes per vadose zone model grid cell. For each of the saturated zone grid cells (light blue squares), the individual vadose zone fluxes are summed and then transferred to the top of the aquifer. The summed 2070 activity transferred in the aquifer for each of the saturated zone model surfaces is shown in Figure 3-13 (inset b). Further details on the interaction between the vadose and saturated zone facets are presented in Section 4.4.4, “Vadose Zone Contaminant Sources.”



Note: The grid lines represent the 100 by 100 m (328.1 by 328.1 ft) finite-difference mesh used in the saturated zone transport model (Chapter 4). Some vadose zone model domains have overlapping extents to ensure that the lateral boundaries are sufficiently far from the liquid contaminant sources so that lateral spreading of contaminant migration is not impacted.

Figure 3-9. Example of Vadose Zone Models in the 200 West Area of the Central Plateau



Note: The grid lines represent the 100 by 100 m (328.1 by 328.1 ft) finite-difference mesh used in saturated zone model (Chapter 4). Some vadose zone model domains have overlapping extents to ensure that the lateral boundaries are sufficiently far from the liquid contaminant sources so that lateral spreading of contaminant migration is not impacted.

Figure 3-10. Example of Vadose Zone Models in the 200 East Area of the Central Plateau

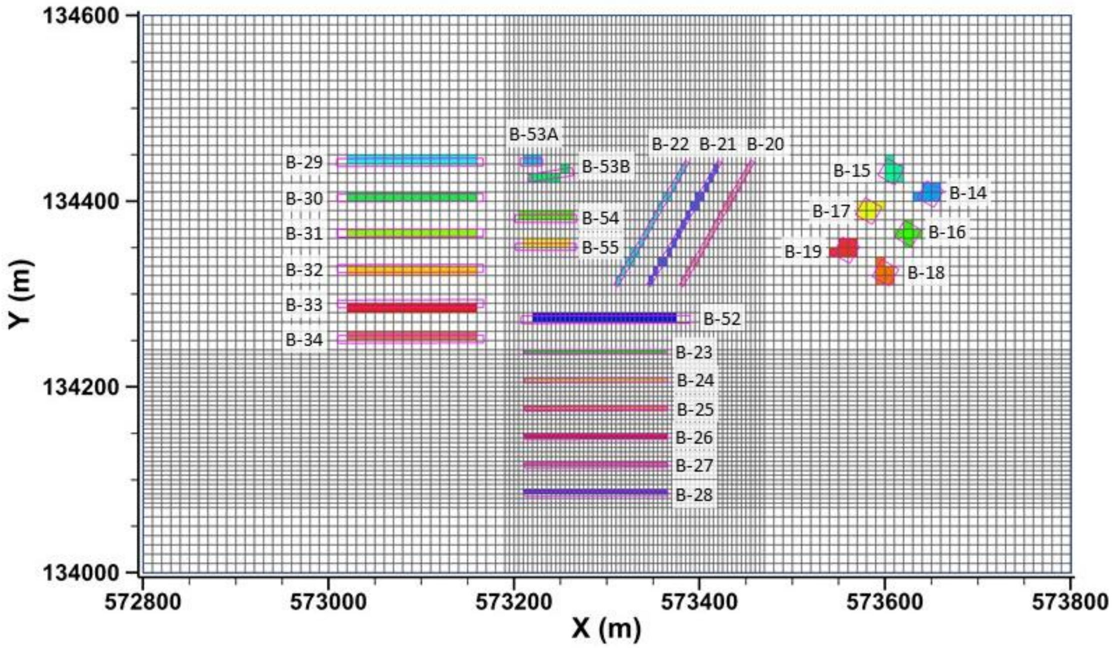


Figure 3-11. Grid Size Resolution and Source Allocations for the BC Cribs Area

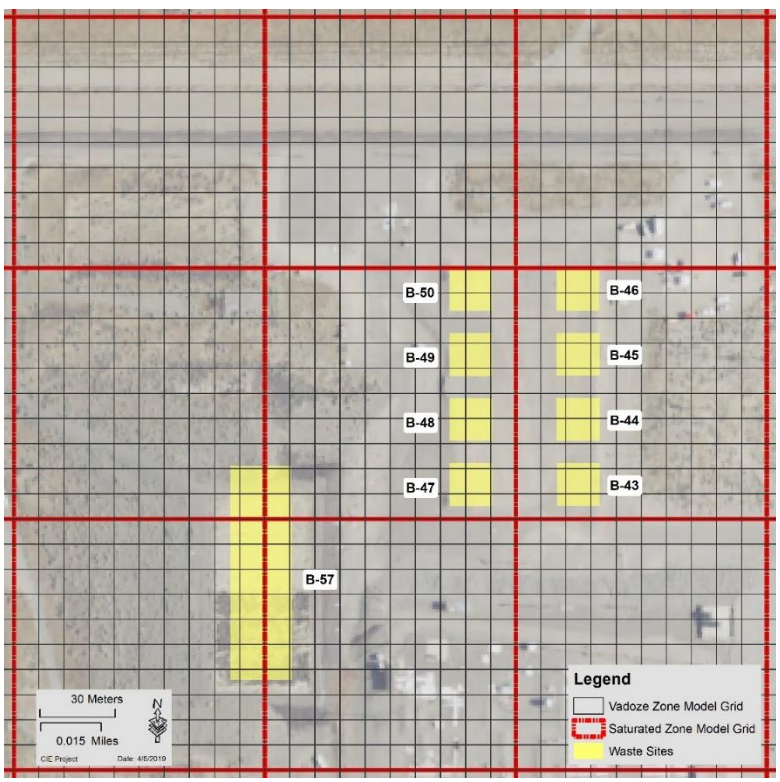
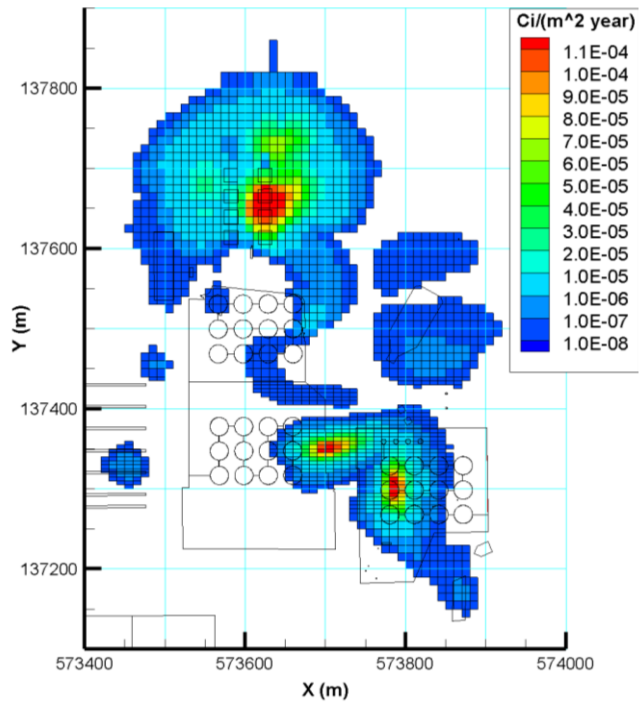
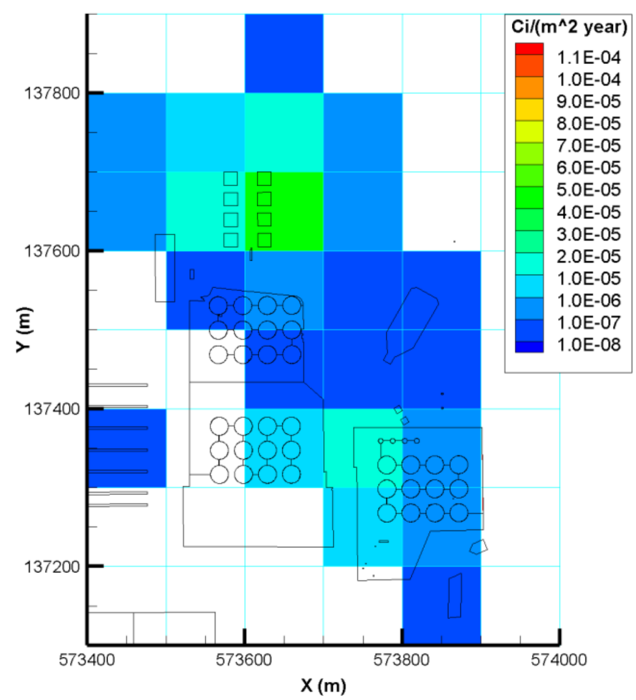


Figure 3-12. Vadose Zone Model and Saturated Zone Model Grids for a 300 by 300 m (984.3 by 984.3 ft) Area Near the BY Cribs in 200 East



(a)



(b)

Note: Light blue lines represent the 100 by 100 m (328.1 by 328.1 ft) saturated zone model grid.

a. From the vadose zone near B Farms into groundwater.

b. Into the top of the aquifer for the saturated zone model surfaces.

Figure 3-13. Simulated 2070 Technetium-99 Activity Flux

3.4 Parametrization of Hydraulic and Transport Properties

Vadose zone flow and transport numerical models solve the water conservation equation and the mass/activity conservation equation for each of the contaminants. The water and activity/mass conservation equations need the specification of hydraulic and transport property values for each grid block in the computational domain. Sections 3.4.1 and 3.4.2 discuss the CIE approach to parameterize hydraulic and transport properties. Table 3-1 lists the parameter values or methods to obtain values.

Table 3-1. Summary of Hydraulic and Transport Input Parameter Values or Methods to Obtain Values for CIE Vadose Zone Models

Input Parameter (Units)	Input Parameter Value
Hydraulic Parameters	
Hydraulic parameters will be developed for the following hydrostratigraphic units (Section 3.1): Backfill, Hf1, Hf2, Hf3, CCU, CCUc, CCUg, Rtf, Rwie, Rlm, Rwia	
Van Genuchten (1980) soil water retention parameters (Eq. 3-1): • θ_r: residual moisture content (-) • θ_s: saturated moisture content (-) • α: fitting parameter (L^{-1}) • n: fitting parameter (-)	From Green et al. (1996) upscaling method using Hanford core data
m: Mualem (1976) relative permeability function fitting parameter (-)	$m = (n-1)/n$
L: Mualem (1976) connectivity-tortuosity term (Eq. 3-4; -)	From power-averaging tensorial connectivity-tortuosity (PA-TCT) upscaling method (Zhang et al., 2003; Zhang and Khaleel, 2010) using Hanford core data
K_{sat}: hydraulic conductivity (Eq. 3-4; L/T)	From PA-TCT upscaling method (Zhang et al., 2003; Zhang and Khaleel, 2010) using Hanford core data
ρ_p: particle density (M/L^3)	Calculated from bulk density and porosity; $\rho_p = \rho_d / (1- \varphi)$
φ: porosity (-)	Saturated moisture content from Green et al. (1996) upscaling procedure.
Transport Parameters	
D_m: molecular diffusion (L^2/T)	From the *CRC Handbook of Chemistry and Physics* (2018).
α_L: longitudinal dispersivity (L)	From Hanford Site literature on field-scale numerical simulations, stochastic solutions, and field experiments
α_T/α_L: dispersivity anisotropy ratio (-)	1/10
K_d: distribution coefficient (L^3/M)	K_d selection will be developed based on values specified in DOE/RL-2011-50 and other Hanford Site literature
$T_{1/2}$: radioactive half-life (T)	Specified for each radionuclide using values from ICRP Publication 107

Note: Complete reference citations are provided in Chapter 7.

Backfill = backfill/surface deposits
CCU = Cold Creek unit upper silt and sand
CCUc = Cold Creek unit caliche
CCUg = Cold Creek unit gravel
CIE = cumulative impact evaluation
Hf1 = Hanford formation unit 1
Hf2 = Hanford formation unit 2
Hf3 = Hanford formation unit 3
Rtf = Ringold Formation member of Taylor Flat
Rwie = Ringold Formation member of Wooded Island – unit E
Rlm = Ringold Formation member of Wooded Island – lower mud unit
Rwia = Ringold Formation member of Wooded Island – unit A

3.4.1 Hydraulic Properties

Hydraulic properties include soil water retention, unsaturated hydraulic conductivity (the product of the saturated hydraulic conductivity and relative permeability), porosity, and bulk density. To simulate fluid flow and contaminant transport, these property values need to be specified for each discretized grid block. The hydraulic properties used in the CIE model will be on a grid-block scale (Section 3.3), which will be much larger than the cores that are typically analyzed in the laboratory. The grid-block scale properties are obtained by applying averaging procedures to core-scale data. The process of defining effective, representative, large-scale hydraulic properties from small-scale measurements is referred to as "upscaling." A comprehensive query will be conducted of Hanford Site literature and databases to ensure that available core hydraulic data that have passed QA/quality control (QC) requirements, will be used in the upscaling procedures.

3.4.1.1 Soil Water Retention

The soil water retention relation provides the soil moisture content, θ (-), as a function of water pressure head, h (L), and therefore quantifies the moisture storage in vadose zone sediments. The soil water retention will be described for each HSU using the van Genuchten relation (van Genuchten, 1980, "A Closed-Form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils").

$$\theta(h) = \theta_r + (\theta_s - \theta_r)\{1 + [\alpha h]^n\}^{-m} \quad \textbf{(Eq. 3-1)}$$

where:

θ_r = the residual moisture content (-)

θ_s = the saturated moisture content (-)

α = a fitting parameter (L^{-1}) approximating the inverse of the air entry head

n = a fitting parameter (-)

m = 1 - 1/n.

A widely used linear upscaling scheme (Green et al., 1996, "Upscaled Soil-Water Retention Using Van Genuchten's Function") will be applied to obtain the grid-block scale parameter values for the soil-water relations applied to each HSU.

3.4.1.2 Unsaturated Hydraulic Conductivity

The unsaturated hydraulic conductivity is a measure of how water flows in sediments not saturated with water. The highly-nonlinear property is the proportionality coefficient between the unsaturated Darcy velocity and the head gradient, given by:

$$q = -K_u(\theta)\nabla H \quad \textbf{(Eq. 3-2)}$$

where:

q = the unsaturated Darcy velocity (L/T)

$K_u(\theta)$ = the unsaturated hydraulic conductivity (L/T) as a function of moisture content θ

∇H (-) = the hydraulic head gradient.

Equation 3-2 indicates that unsaturated water flow through sediments in response to a hydraulic pressure (head) gradient is dependent on the water content. The unsaturated hydraulic conductivity, $K_u(\theta)$, is the product of the saturated hydraulic conductivity, K_s (L/T), and the relative permeability, $k_r(\theta)$:

$$K_u(\theta) = K_s k_r(\theta)$$ **(Eq. 3-3)**

Allowing for a principal direction dependence (subscript *i*) of the unsaturated hydraulic conductivity and adopting the Mualem pore-distribution model for the relative permeability term (Mualem, 1976, "New Model for Predicting the Hydraulic Conductivity of Unsaturated Porous-Media"), Equation 3-3 becomes:

$$K_{ui}(S_e) = K_{si} S_e^{L_i} \left\{1 - \left(1 - S_e^{(1/m)}\right)^m\right\}^2 \quad i = 1,2,3$$ **(Eq. 3-4)**

where:

K_u = dependent on the effective saturation

S_e, L (-) = the connectivity-tortuosity coefficient

m has been defined for Equation 3-1

S_e = defined as $S_e = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r}$.

In Equation 3-4, the connectivity-tortuosity coefficient L is the exponent in the connectivity-tortuosity term $S_e^{L_i}$. Mualem (1976) estimated $L = 0.5$ based on an average of 45 disturbed and undisturbed samples and this value has become a default for most isotropic unsaturated flow modeling applications. However, for the CIE HSUs, both K_s and L are directionally dependent and will result in anisotropic unsaturated flow.

To estimate the effective upscaled K_{ui} values (Equation 3-4), the power-averaging tensorial connectivity-tortuosity (PA-TCT) method (Zhang et al., 2003; Zhang and Khaleel, 2010) will be used to determine directionally-dependent K_{si} and L_i values. The PA-TCT method uses small-scale core data to compute upscaled K_{si} and L_i values for each of the HSUs identified in Section 3.2. As Equation 3-4 indicates, the use of directionally-dependent K_{si} and L_i values will lead to upscaled K_{ui} values that are different in each of the principal directions and are functions of the moisture content (or water saturation). In essence, the PA-TCT upscaling method leads to a soil-moisture-dependent K_{ui} anisotropy (i.e., the ratio of the effective unsaturated conductivity parallel to geologic bedding to the unsaturated conductivity perpendicular to bedding varies in space). Applying the method allows for an assessment of the effects of heterogeneity on lateral flow and contaminant spreading, including plume commingling at the HSU scale.

The PA-TCT method has been successfully applied to evaluate various water infiltration tests performed at the Sisson and Lu field experiment site in the 200 East Area (Ye et al., 2005, "Stochastic Analysis of Moisture Plume Dynamics of a Field Injection Experiment"; Zhang and Khaleel, 2010). The good match between observed and predicted moisture contents supports the notion that the PA-TCT method provides representativeness of flow behavior in heterogeneous media. The field application of the upscaled vadose zone property values based on the PA-TCT method suggests that it provides a reasonable framework for upscaling core-scale measurements, as well as an accurate simulation of moisture flow in the heterogeneous vadose zone under the Central Plateau.

3.4.1.3 Porosity and Bulk Density

Porosity, φ (-), is the volume of voids in a sample (i.e., the air- and water-filled volume) divided by the total volume. In many hydraulic property data sets, the porosity is equal to the saturated moisture content determined in the water retention relation. The dry bulk density, ρ_d (M/L^3), is the mass of solids in a sample divided by the total (bulk) volume of the sample. The effective, large-scale estimates for bulk density and porosity are assumed to be the average of the small-scale laboratory measurements for each of the HSUs (Zhang and Khaleel, 2010). The simple averaging of these properties for vadose zone applications is common because of their limited ranges.

3.4.2 Transport Properties

Contaminant mass/activity is transported in the vadose zone by advection and hydrodynamic dispersion. Advective transport is computed using the flow field obtained when solving the water conservation equation and no additional parameters are needed beyond the ones described in Section 3.4.1. To compute hydrodynamic dispersion of the contaminants, parameter values are needed for the effective diffusion coefficient and dispersivity (Section 3.4.2.1). Migration may be retarded due to sorption to the solid phase. Contaminant sorption is evaluated using a linear distribution coefficient (K_d) and is discussed in Section 3.4.2.2. The source for radionuclide half-live data is presented in Section 3.4.2.3.

3.4.2.1 Hydrodynamic Dispersion

For vadose zone transport modeling applications, hydrodynamic dispersion is considered to be the sum of molecular diffusion and mechanical dispersion. To compute molecular diffusion and mechanical dispersivity, values of the effective diffusion coefficient, D_e (L^2/T), and dispersivity, α (L), need to be provided, respectively.

Effective Diffusion Coefficient

For Hanford Site vadose zone modeling, the effective, large-scale diffusion coefficients for an HSU are a function of volumetric moisture content and can be estimated based on an empirical relation that is the product of a computed tortuosity and the diffusion coefficient in free water (Millington and Quirk, 1961, "Permeability of Porous Solids"). The diffusion coefficient values in free water will be obtained from the *CRC Handbook of Chemistry and Physics* (2018).

Dispersivity

Field observations indicate that the dispersion coefficients required to describe field-scale transport processes are much different from those observed in small-scale laboratory experiments (PNNL-23711, *Physical, Hydraulic, and Transport Properties of Sediments and Engineered Materials Associated with Hanford Immobilized Low-Activity Waste*). Field-scale dispersivities, typically referred to as macrodispersivities (e.g., Russo, 1993, "Stochastic Modeling of Macrodispersion for Solute Transport in a Heterogeneous Unsaturated Porous Formation"), may often be orders of magnitude larger than those observed in the laboratory. Consequently, laboratory-scale dispersivities (which are typically <1 cm [0.39 in.]) are not used to estimate macrodispersivities. Macrodispersivities increase with time and distance, until they tend to converge on their unique asymptotic (large-time) values. This well-known asymptotic behavior is usually attributed to heterogeneity-induced spreading until dispersion becomes constant. Therefore, the use of a constant (asymptotic) macrodispersivity for large-scale vadose zone CIE modeling is considered appropriate (NUREG/CR-6114, *Auxiliary Analyses in Support of Performance Assessment of a Hypothetical Low-Level Waste Facility: Groundwater Flow and Transport Simulation*, Vol. 3; NUREG/CR-5965, *Modeling Field Scale Unsaturated Flow and Transport Processes*).

To obtain macrodispersivity values for the HSUs in the longitudinal direction, α_L (L), available data from Hanford Site literature on field-scale numerical simulations, stochastic solutions, and field experiments related to dispersivity will be evaluated to determine the values for sandy, gravelly, and fine-textured media. Hanford Site-specific data sets include Khaleel et al., 2002, "Upscaled flow and transport properties for heterogeneous unsaturated media"; PNNL-23711; and PNNL-25146, *Scale-Dependent Solute Dispersion in Variably Saturated Porous Media*. In the absence of unsaturated media experimental data, the CIE transport models will use a transverse macrodispersivity, α_T (L), 1/10th of the obtained longitudinal macrodispersivity values.

3.4.2.2 Contaminant Sorption

For the CIE vadose zone simulations, sorption of radionuclides and chemicals will be simulated using a reversible linear sorption isotherm with a linear K_d (L^3/M). In most circumstances, the linear sorption model approach will be adequate for modeling transport at the Hanford Site (PNNL-13895, *Hanford Contaminant Distribution Coefficient Database and Users Guide*). An important benefit of the linear adsorption approach is that a relatively extensive database of K_d values applicable to Hanford sediments is available for the contaminants of most concern over a broad range of conditions (e.g., PNNL-13037, *Geochemical Data Package for the 2005 Hanford Integrated Disposal Facility Performance Assessment*; PNNL-13895; PNNL-16663, *Geochemical Processes Data Package for the Vadose Zone in the Single-Shell Tank Waste Management Areas at the Hanford Site*; and PNNL-17154, *Geochemical Characterization Data Package for the Vadose Zone in the Single-Shell Tank Waste Management Areas at the Hanford Site*). Information from Hanford Site literature, in particular DOE/RL-2011-50, *Regulatory Basis and Implementation of a Graded Approach to Evaluation of Groundwater Protection*, will be used to develop conceptual models involving reversible linear K_d isotherms and will consider dominant sediment textures, gravel percentage, mineralogy, waste chemistry, and the extent of interaction between waste releases and the natural sediments.

While single K_d values for each radionuclide will be used for most models, values may be changed in certain areas near a source where the discharge chemistry could significantly impact these values and, therefore, transport behavior. Recognizing that experimental K_d values are mostly determined using sediment grain sizes <2 mm (PNNL-13895), corrections for gravel content using equations provided in PNNL-17154 will be used to adjust measured values for the finer fraction applicable to HSUs with considerable gravel content.

3.4.2.3 Radionuclide Half-Lives

The radionuclide half-lives will be obtained from ICRP Publication 107, *Nuclear Decay Data for Dosimetric Calculations*.

3.5 Initial Conditions, Boundary Conditions, and Contaminant Sources

Vadose zone flow and transport numerical models solve the water conservation equation and the contaminant activity/mass conservation equation, respectively. For both the water and activity/mass conservation equations, considered to be the governing equations for flow and transport, initial and boundary conditions need to specified. The initial conditions of the water conservation equation prescribe the water pressures (or heads) in the unsaturated system at the start of a simulation. For the activity/mass conservation equation, the initial conditions prescribe the concentration distribution at that time. Section 3.5.1 describes the initial conditions for the vadose zone models. The model boundary conditions provide the conditions at the model domain boundaries as a function of time, after initiating the flow and transport simulation. Boundary conditions for the water conservation equation include natural and anthropogenic recharge at the top of the vadose zone models and specification of a water table location at the bottom. For the contaminant conservation equation, boundary conditions include the emplacement of inventory in the model domain through specified fluxes at waste site footprints. Section 3.5.2 describes the boundary conditions for the vadose zone models.

Disposed liquid volumes and contaminant activity/mass will be treated as site-specific sources in the vadose zone models. Section 3.5.3 describes the treatment of liquid and waste disposal in the models.

The CIE vadose zone models will use a "forward" modeling approach for contaminant transport in the subsurface. Using this approach, model transport simulations initiate at a time when contamination is not present in the subsurface, and the contaminant activity/mass is introduced in the models as sources or boundary conditions over time. After introduction, the contaminant is transported by advection and hydrodynamic dispersion, with potential retardation due to sorption. This approach has been used to simulate Hanford Site contaminant transport resulting from liquid waste disposal (e.g., Oostrom et al., 2017) and past WMA C tank leaks (RPP-RPT-59197). Alternatively, three-dimensional representations of contaminant distribution and concentrations in the vadose zone could be used as initial conditions for contaminant transport simulations. However, at most locations in the Central Plateau, characterization data are currently not sufficient to produce comprehensive representations. Site-specific analyses (provided by source OU investigations), PAs, and similar analyses may produce updated models based on characterization data. When such models become available, these will replace the CIE vadose zone models.

The forward modeling approach consists of four successive time periods:

1. Prior to 1943
2. From 1943 to 2018
3. From 2018 to the end of remediation activities
4. From the end of remediation activities to the end of transport simulation.

Contaminant transport is simulated during periods 2, 3, and 4. The activity/mass fluxes computed in periods 3 and 4 are transferred to the saturated zone model. The four periods are further described as follows:

1. **Prior to 1943:** Prior to commencing Hanford Site operations, it is assumed that the vadose zone hydrologic conditions at the Central Plateau are in a steady state with water that infiltrates the surface, percolating through the vadose zone and becoming recharged to the underlying saturated zone. The steady-state moisture content and water pressure distributions in 1943 (determined by the hydraulic properties of the vadose zone and the preoperational net infiltration rates) denote the initial conditions for the subsequent flow and transport simulations. The preoperational net infiltration rates are assumed to be controlled by the undisturbed soil distribution in the Central Plateau and the associated native vegetation.

2. **From 1943 to 2018:** This period includes Hanford Site operations when discharges of uncontaminated and contaminated liquids occurred at numerous Central Plateau waste disposal sites. The waste inventory and water discharges during operations are being developed for the CIE under the waste inventory and contaminant sources model facet, described in Chapter 2. In addition to the direct discharge of uncontaminated and contaminated liquids to the ground surface, operations at the Hanford Site disturbed the native soils and vegetation over large areas of the Central Plateau, which increased the permeability of the native soil and reduced the transpiration (by removing the native vegetation), therefore increasing net infiltration over the disturbed areas.

3. **From 2018 to the end of remediation activities:** The dates of planned remediation activities vary across the Central Plateau. A range of remediation activities are foreseen for the different liquid contaminant sources that could affect the source concentration or the rate of transport of contaminants in the vadose zone. The potential remediation activities include removal, treatment, and disposal (RTD) and reducing water flow by returning the surface to its undisturbed conditions or by placing a surface barrier to reduce the net infiltration. To assess the effects on these activities, the CIE will develop disposition baselines, which are collections of decisions and actions regarding surface condition changes affecting recharge.

4. **From the end of remediation activities to the end of transport simulation:** After all remediation actions are completed, the surface of the Hanford Site is expected to be either returned to conditions similar to the pre-1944 native vegetation in areas covered by native soil with net infiltration rates the same as the assumed pre-1944 values, or covered by surface barriers designed to reduce the amount of net infiltration to values less than those assumed in the pre-1944 conditions. These assumptions are consistent with the land-cover scenarios given in three approved work plans (DOE/RL-2011-102, *Remedial Investigation/Feasibility Study and RCRA Facility Investigation/Corrective Measures Study Work Plan for the 200-DV-1 Operable Unit*; DOE/RL-2010-49, *Remedial Investigation/Feasibility Study Work Plan for the 200-WA-1 AND 200-BC-1 Operable Unit*; and DOE/RL-2004-60, *200-SW-2 Radioactive Landfills Group Operable Unit RCRA Facility Investigation/Corrective Measures Study/Remedial Investigation/Feasibility Study Work Plan*). The surface barriers are assumed to degrade after a period of 500 years, at which point it is assumed that the net infiltration rate for the entire Central Plateau returns to the pre-1944 steady-state conditions. Continued contaminant transport through the vadose zone to the water table during this time period will be calculated by the vadose zone flow and transport models described in this chapter.

The vadose zone contaminant transport simulations begin in 1943 and continue through the time when contaminant flux from the vadose zone to the groundwater diminishes to insignificant amounts. The time it takes to reach an "insignificant" release rate is dependent on the:

- Contaminant
- Contaminant source release amount
- Contaminant concentrations in the saturated zon
- Type of remediation action related to the contaminant

The duration of the CIE vadose zone flow and transport simulations is assumed to be 1,000 years after the end of the last remediation action on the Central Plateau. Predictions may be extended if warranted to evaluate the potential long-term impacts associated with less mobile contaminants.

The cumulative contaminant flux predicted to occur from the vadose zone to the saturated zone from 1943 to 2018 will be compared to the observed contaminant activity or mass currently residing in the saturated zone (for the first CIE runs) to determine the representativeness of the vadose zone model results. From the present time onward, the predicted contaminant flux from the vadose zone to the water table will be used as boundary conditions for the saturated zone flow and transport models.

For the forward CIE vadose zone flow and transport models, initial and time-variable boundary conditions need to be provided for the periods after 1943. Section 3.5.1 discusses the initial conditions at 1943, and Section 3.5.2 discusses the boundary conditions related to natural and anthropogenic recharge and the water table location. Section 3.5.3 provides the technical approach for implementing contaminant and liquid fluxes emanating from waste sites and liquids from noncontaminant sources.

3.5.1 Initial Conditions

The CIE vadose zone models will use a long-term solution with preoperational Hanford average recharge rates to establish initial hydraulic conditions for the flow and transport simulations starting in 1943. By simulating a sufficiently long time with unchanging boundary conditions (primarily the recharge rate at the top boundary), the pressures and moisture contents in the model domain will stabilize to steady-state conditions at 1943. These conditions will be verified by evaluating nodal fluxes throughout the domain, which will be uniform and unchanging when this steady-state condition is attained. At 1943, it is assumed that no contaminant is present in the vadose zone models.

3.5.2 Boundary Conditions

The boundary conditions for the model water conservation equation include the specification of the water table location at the bottom, and the natural and anthropogenic recharge at the top of the vadose zone models. This section specifies the technical approach for addressing boundary conditions, consistent with the needs of this facet.

3.5.2.1 Lower Boundary Condition

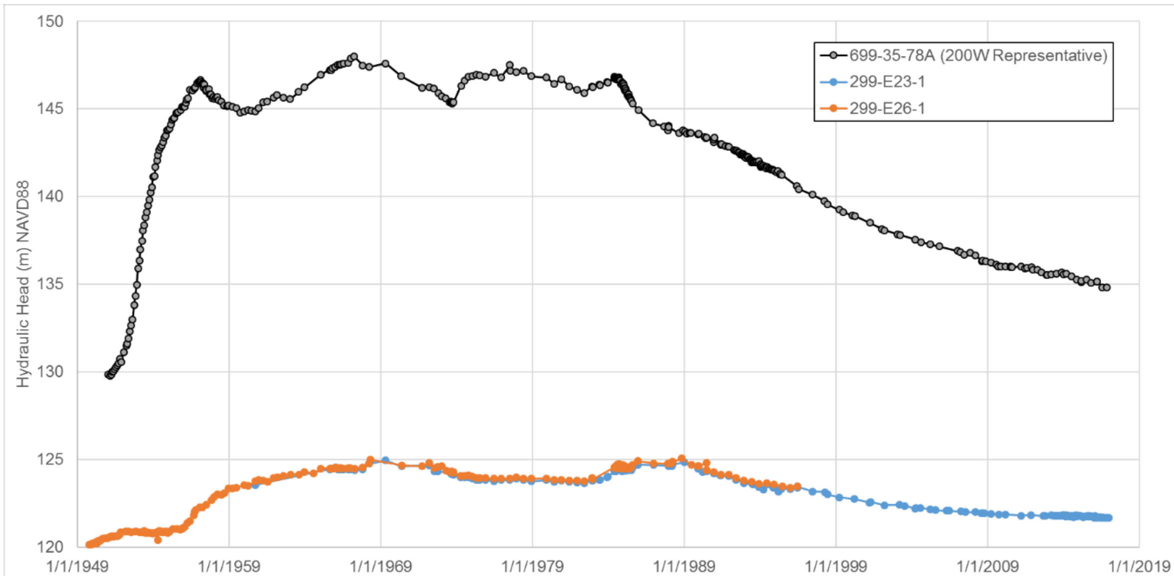
The lower boundary of each vadose zone model is the water table, representing the interface between the vadose and the saturated zone. At this boundary, the computed contaminant fluxes out of the vadose zone into the aquifer are passed on to the groundwater model. As discussed in Section 3.3, water fluxes at the water table boundary are not passed on to the groundwater model. Because of the influence of effluent discharges during and following the Hanford Site operational period, the location of the water table changes over time (Figure 3-14). As the water table increased in response to the effluent discharges during the operational period, the vadose zone thickness was reduced. Conversely, as the water table has receded since cessation of large-scale discharges, the vadose zone thickness has increased. The amount of change in the vertical location of the water is variable, depending on the geologic media under the effluent discharge locations and the proximity to those locations. Given that water table fluctuations occurred mostly during Hanford operations and immediately thereafter, the effects on activity/mass transport after 2018, when activity/mass fluxes will be passed on to the groundwater model, are likely relatively small. To increase efficiency and reduce complexity during initial implementation of the vadose zone models, the simulations will use a fixed water table representing current conditions. However, the effects of the transient water table on contaminant transfer to the aquifer after 2018 will be evaluated to determine if a time-variant water table is necessary. Simulations for selected vadose zone models with continuing sources will be conducted to determine the need for fluctuating water table boundary conditions. If the simulated fluxes after 2018 differ considerably, a time-variant water table will be used for the models.

3.5.2.2 Natural and Anthropogenic Recharge Upper Boundary Condition

The upper boundary of the vadose zone models is defined by the natural recharge rate (arising from meteoric water) and any additional anthropogenic recharge rate (associated with liquid discharges to ground). This section discusses the approach for accounting for the natural recharge rate, as well as the approach for accounting for anthropogenic recharge.

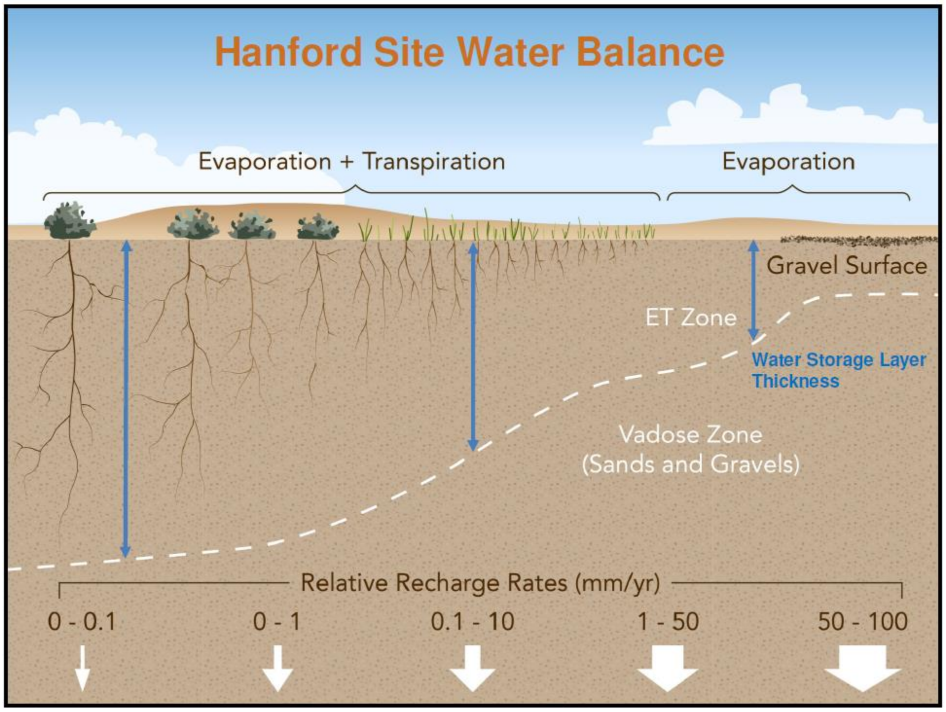
The natural recharge rate is a term applied to define the net infiltration that ultimately flows through the vadose zone to reach the water table. At the Hanford Site, this rate is primarily a function of two factors: surface soil type and type/density of vegetative cover (Figure 3-15). These factors vary in space and time and are directly altered by land use and management. The recharge rates that pertain to surface soil type and type/density of vegetation cover will draw from those identified in DOE/RL-2011-50.

Anthropogenic recharge is an additional flux that must be specified for the upper boundary of the vadose zone models. This recharge refers to the effluent disposal associated with other liquid discharges to ground. This will be handled separately from natural recharge because these two types of recharge have different spatial extents and temporal variability. Anthropogenic recharge will be applied directly to vadose zone models using the documented discharge extents at the applicable waste sites or other effluent areas for the durations and quantities in the record (or projected, for future estimated liquid discharges to ground).



Note: 200 West Area groundwater elevations are shown in black. 200 East Area groundwater elevations are shown in blue and orange.

Figure 3-14. Groundwater Elevation During Hanford Site Operational and Post-Operational Era at Selected Wells in the 200 West and 200 East Areas Showing Representative Transient Change in Vadose Zone Model Lower Boundary Position



Note: Factors that determine natural recharge (net infiltration) rates at the Hanford Site are surface soil type and the degree and type of vegetative cover.

Figure 3-15. Range of Recharge Rates at the Hanford Site

For purposes of the CIE, anthropogenic recharge includes the following categories:

- **Effluent discharges:** Usually associated with process waste disposal. The volumes and timing of these discharges were often measured and recorded and are available for inclusion in vadose zone models.
- **Storm water management:** Results in redistribution of meteoric water and localized increased infiltration. Effects of this category have not been well characterized to date for the purpose of input to subsurface modeling.
- **Dust suppression water:** Water applied most often in conjunction with remedial or construction activities to impede windborne redistribution of soil when vegetative cover is disturbed. The quantities applied and application timing have not been well characterized to date for the purpose of input to subsurface modeling.
- **Other potential discharges:** May include pipeline leaks, water line testing, historical surface water applications, septic systems, etc. The effects of this category have not been well characterized to date for the purpose of input to subsurface modeling.

The first of the above categories (effluent discharge) is well characterized for input to flow and transport models based on process records for contaminated waste streams, but the other categories are not. During development of the CIE models, a task will be defined to better characterize these other categories for potential inclusion in the vadose zone (and groundwater) models, including reviewing water system management plans and reports, and calculations to estimate net infiltration quantities for dust suppression water or stormwater management systems. Work will be prioritized by ranking the liquid volume magnitude to emphasize the most impactful quantities.

Figure 3-16 provides an example of spatial and temporal variability in recharge rates as a function of land use and management for a hypothetical waste site. In this example, the hypothetical waste site was cleared for use as an effluent disposal location in 1943, covered with clean sand, and maintained vegetation-free until 2015. The site is then remediated over a 5-year period, during which it continues to be maintained vegetation-free. This site is subsequently revegetated to a young shrub-steppe condition that takes 3 decades to progress to a shrub-steppe vegetation density. In this example, the waste site would be characterized as starting from an initial condition that represents native soil with mature shrub-steppe vegetation density, with an associated recharge rate of 4 mm/yr. The rate changes in 1943 when the site begins operation and the recharge increases to 63 mm/yr, which is much higher because removal of vegetation results in a higher net infiltration rate. This rate would apply for 77 years (assuming remediation activities at this waste site will be completed by 2020) before beginning to decline in 2020 to 8 mm/yr, which is the rate for disturbed sand with young shrub-steppe vegetation density. The rate would decrease again to 4 mm/yr in 2050 and would remain at that rate thereafter. This example shows the temporal variability at a single location. In this analysis, large multi-site models (as proposed for the CIE) will cover other surrounding area waste sites and other areas that are not waste sites. All of these sites may have land-use and management changes on different time schedules. Therefore, the recharge rate at the upper boundary is both temporally and spatially variable.

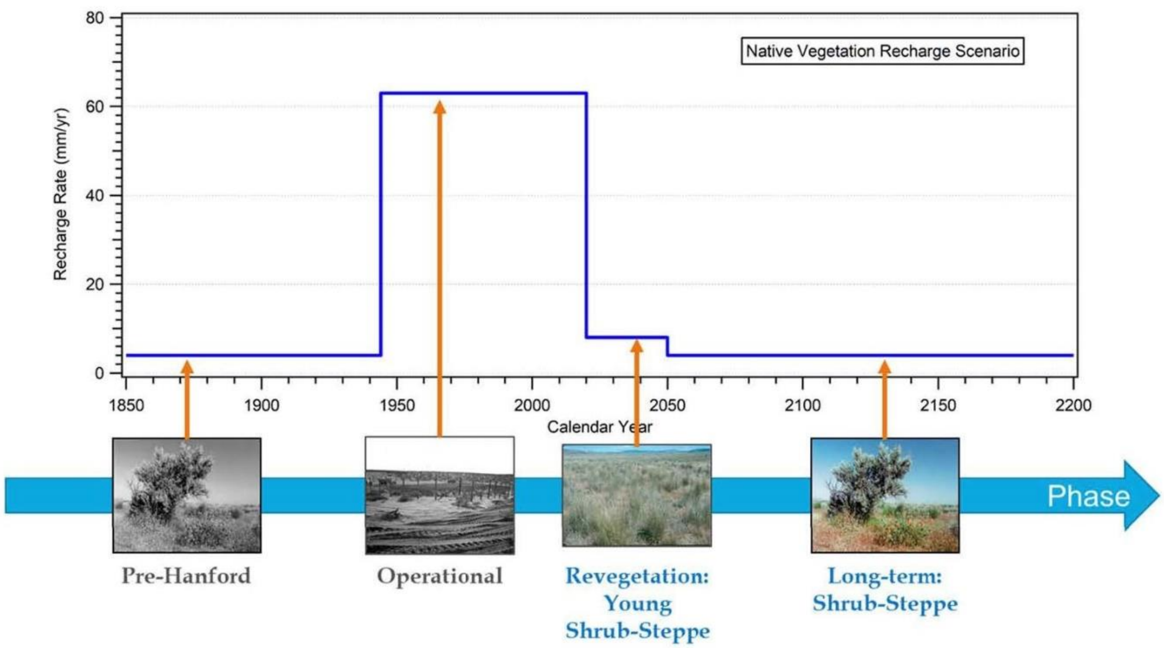


Figure 3-16. Example of Recharge Over Time for a Hypothetical Waste Site

Accounting for spatial and temporal variability recharge rates is complicated because of change due to future remedial decisions that may occur; therefore, the CIE must allow for different disposition baselines. The term "disposition baseline" is used to denote the collection of decisions already made, actions already taken, and projected future actions to account for upper (surface) boundary condition changes. To the degree that future decisions may vary, alternative disposition baselines can be developed. Alternative disposition baselines will be maintained using a database that reflects potential future paths to site closure and end states at closure. The database will provide the information for the development of a disposition baseline scenario generator tool to construct and review alternative scenarios for future remedial decisions. The functionality of this tool will include assigning a unique scenario identification tag for each alternative scenario for tracking purposes. Functionality will also include the ability to export a scenario summary report to provide support documentation and review needs for each alternative scenario. The GIS-based tool will export scenario information in a format that can be used within the CIE modeling framework to specify the alternative disposition baseline for CIE simulations.

The disposition scenario generator tool will maintain the following information:

- Identification of waste sites and their respective associated OUs or WMAs
- Indication of whether each waste site has a completed remedial action or decision (in which case, the disposition of such a waste site is "locked" for all scenarios)
- A range of alternative dispositions that may be selected for sites that do not yet have a final remedial decision, with options including the least and most energetic plausible alternatives from the U.S. Department of Energy, Richland Operations Office lifecycle report (DOE/RL-2015-10, *Hanford Lifecycle Scope, Schedule and Cost Report*), no further action, and an option to directly specify a remedial action
- The key dates associated with changes in site conditions in conjunction with the disposition selected
- If applicable, depth of soil removed for RTD remedies

Accounting for spatial and temporal recharge variability across the upper boundaries of the vadose zone models will be a complex task. To illustrate the complexity involved, consider Figure 3-17, which shows two hypothetical waste sites (labeled XYZ-1 and XYZ-2) and their surrounding area. Hypothetical waste site XYZ-1 has the same recharge scenario shown in Figure 3-16 for a site that is subject to remediation in 2015 and revegetation in 2020. In contrast, hypothetical waste site XYZ-2 receives an evapotranspiration barrier in 2050, so the recharge rate scenario for this site differs accordingly. An operational area that is never contaminated, but which does have changes in surface conditions that impact recharge, has a different recharge scenario. Finally, the surrounding undisturbed area remains at a constant native vegetation recharge rate throughout. Tracking these changes in recharge over just these four areas evolving independently in time for a simple example illustrates the need for a tool to manage the recharge information for inclusion as boundary conditions in flow and transport models. Actual conditions at Hanford exhibit much greater complexity and cannot be managed efficiently without a tool for this purpose. A new GIS-based tool will be developed to meet this need. The new tool will be able to accept alternative disposition baselines and prepare boundary condition specifications for inclusion in input files for the vadose zone flow and transport code that are reflective of the spatial and temporal variability of natural recharge for each disposition baseline.

3.5.3 Liquid and Contaminant Sources

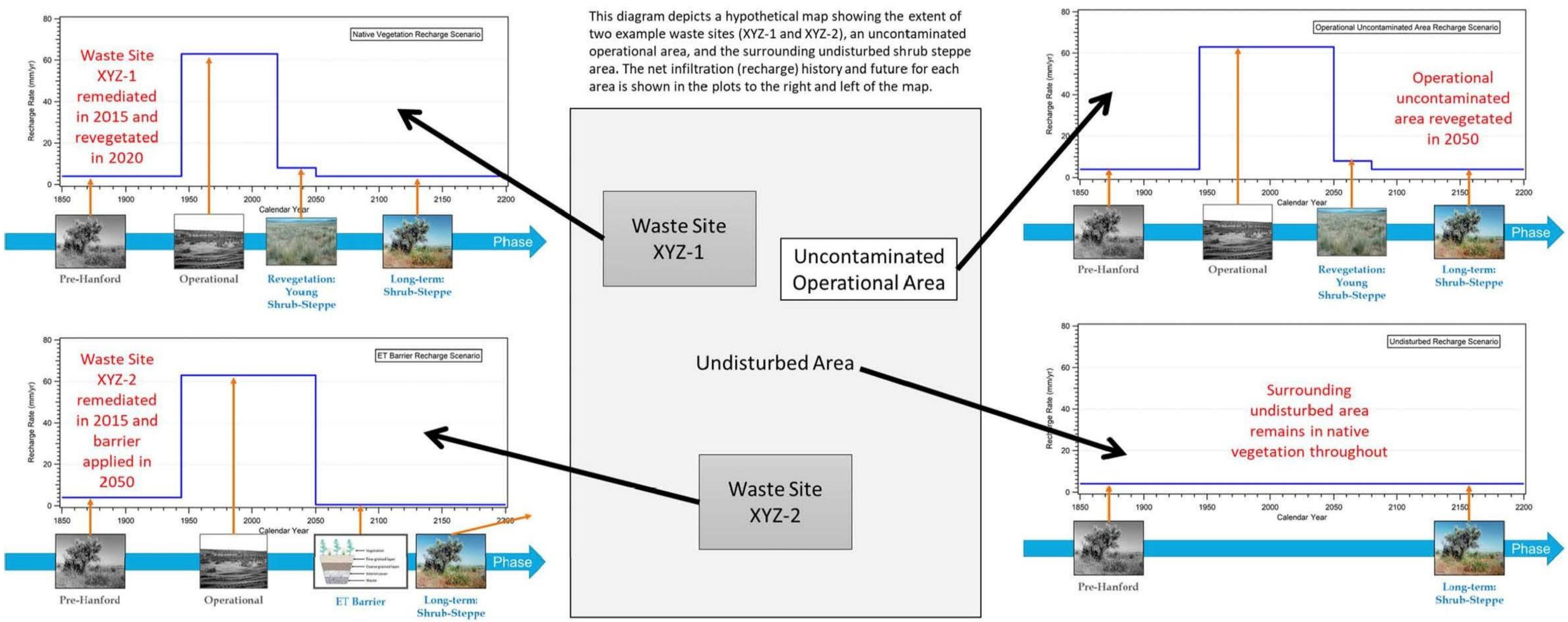
The liquid volumes and waste site inventories will be obtained from SIM-v2 (CP-59798), as discussed in Chapter 2. Nonradiological site liquid volumes will be obtained from site-specific literature (e.g., quarterly discharge monitoring reports for the Treated Effluent Disposal Facility and State-Approved Land Disposal Site). Using geometry information, waste and nonradiological site shapes will be assigned to vadose zone model grid surfaces. Water volumes and SIM-v2 contaminant inventories will be assigned to the model grid cells coinciding with the bottom of the sites within the footprints. Assumptions will be made to specify the minimum area of unplanned releases that do not have a defined footprint. An example of how waste site footprints from DOE/RL-2017-66, *Hanford Site Groundwater Monitoring Report for 2017*, will be assigned to model grid surfaces is shown in Figure 3-11 in Section 3.2.

The SIM-v2 data provides the total and yearly inventories when waste sites were active. Figure 3-18 provides examples of total liquid and technetium-99 inventory over all disposal years for 200-DV-1 OU B Complex waste sites. The chemical and radionuclide inventories, as well as liquid volumes, will be distributed with a constant rate per calendar year, as shown for the liquid volumes of waste site 216-B-57 in Figure 3-19. For this site, the total waste volume of 84,311 m^3 (Figure 3-18) will be disposed over a total of 6 years (1968 to 1973), with the highest rate of 20,000 m^3/year in 1969 and the lowest rate of 5,130 m^3/year in 1973.

Modeled releases from the vadose zone to the aquifer that have already been documented in existing PAs (e.g., Integrated Disposal Facility, Environmental Restoration Disposal Facility, and WMA C), will be mapped directly to the CIE groundwater model. These PAs focused on detailed analysis of long-term future releases from waste disposal systems, which will only reach the deep vadose zone and aquifer in the distant future when the water table is effectively receded to the long-term steady-state level. An exception is the analysis of past leaks for WMA C. For that analysis, an analysis was performed to represent the transition of the aquifer gradient over time. Thus, all existing PAs are explicitly accounting for activity/mass migrating from the vadose zone into groundwater. When activity/mass releases become available in the future from other PAs or other detailed modeling activities, they will also be transferred directly into the groundwater model, as discussed in Section 3.7.

3.6 Vadose Zone Model Evaluation

The purpose of the CIE vadose zone models is to provide forecasts of the effects of potential remediation decisions on contaminant transport into the aquifer. Subsurface flow and transport models will always be constrained by computational and data limitations, and they are best viewed as tools that approximate reality to help inform decisions rather than as machines to generate truth (NRC, 2007, *Models in Environmental Regulatory Decision Making*). The approximation of reality occurs through model evaluation, defined as the process used to generate information to determine if a model and its results are sufficient to serve as a basis for decisions. Model evaluation occurs over the entire lifecycle of a modeling project and consists of several components, including QA planning and data quality assessment (Section 5.2), objective peer review (Section 5.3), sensitivity and uncertainty analysis, and accounting for representativeness (EPA/100/K-09/003, *Guidance on the Development, Evaluation, and Application of Environmental Models*). For the initial CIE simulations, the number of sensitivity and uncertainty analyses will be limited due to computational limitations. However, such analyses may be included in the future to support OU and WMA investigations, for instance, in cases where Conceptual Site Model (CSM) modifications are developed.



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2 **Figure 3-17. Representation Illustrating the GIS Application Concept Needed for Managing Spatial and Temporal Variability of Natural Recharge at Hypothetical Waste Sites XYZ-1 and XYZ-2 and Surrounding Area**

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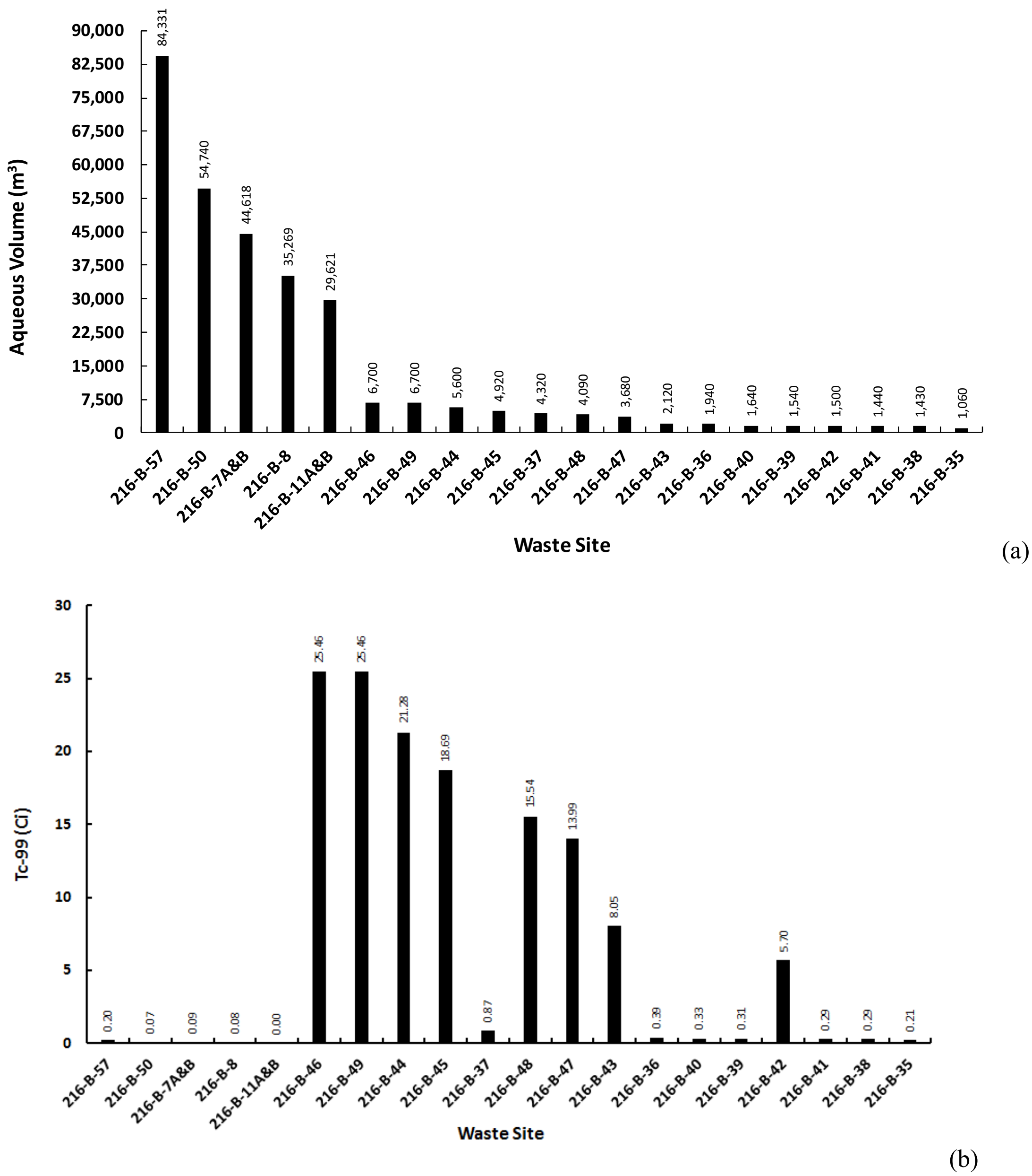

Figure 3-18. Example of Total Liquid Volumes and Technetium-99 Inventory to be Applied as Sources for 200-DV-1 OU and B Complex Waste Sites

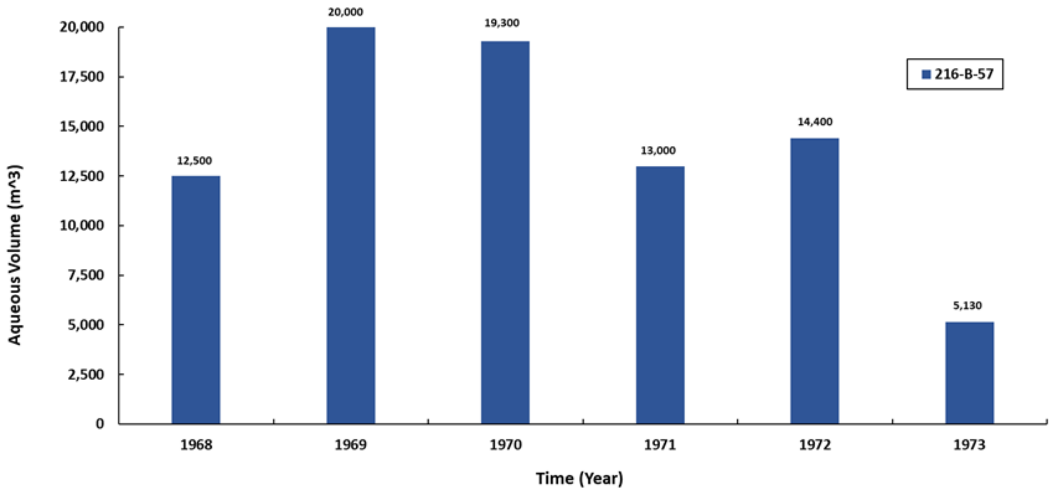

Figure 3-19. Example of Liquid Volume Distribution per Year for Waste Site 216-B-57

The approach to construct the CIE vadose zone models is designed to account for representativeness in several ways, including:

- Using the Central Plateau Vadose Zone Geoframework (CP-60925 and future revisions)
- Consideration of the effects of heterogeneity on flow and transport using the anisotropic Equivalent Homogeneous Media parametrization approach
- Employing a spatial model domain large enough to account for subsurface interference (commingling) of liquid waste disposal
- Applying time- and spatially-variable liquid disposal and recharge

As simulation results become available, they will be assessed against field data in a variety of ways, including:

- Examining simulated and field moisture content profiles and trends (e.g., are simulated moisture contents change consistent with hydrogeologic changes?)
- Inspecting simulated and field concentration distribution and trends for consistency
- Comparing integrated vadose zone fluxes with activity/mass in past and current known groundwater plumes

If simulated results do not compare suitably with field data, a review of model inputs would be conducted, considering the historical discharge records, SIM-v2 (CP-59798) inventory confidence limits, quality of data supporting flux estimates, moisture content data, contaminant concentration data, and hydraulic/transport property parameterization.

EPA, 2009, suggests that qualitative and quantitative measures can be used to evaluate model outcomes. Qualitative measures include expert judgement if model-predicted behavior agrees with best-available understanding and may be useful at sparsely characterized sites. Quantitative measures range in complexity from descriptive statistics up to multiple alternative models. In the sparsely characterized subsurface, typical on the Central Plateau, qualitative measures may be better suited than quantitative ones. Care will be taken to not make unreasonable parameter adjustments and introduce additional model parameters to prevent compensating errors; using different types of data and respecting the principle of parsimony will help build confidence in model parameters and results. Parameter changes made solely to improve model comparison will not be made and may represent irreducible uncertainty.

3.7 Inclusion of Information from Other Modeling Activities, Conceptual Site Model Updates, and Characterization Data

The CIE tools will include the flexibility to incorporate output (i.e., activity/mass fluxes from the vadose zone to groundwater) from detailed site modeling activities in facility-specific or OU-specific analyses or information developed for specific decision-supporting purposes in the CIE framework. There are two distinctive ways in which this will happen:

1. Replacement of activity/mass fluxes obtained for the initial CIE simulations with activity/mass fluxes obtained from other detailed model simulations
2. Updates to CIE vadose zone models based on CSM modifications and characterization data

The replacement of activity/mass fluxes refers to the replacement of fluxes computed with the initial CIE models with computed fluxes of more refined models. This was shown in the CIE Wiring Diagram (Chapter 1, Figure 1-4) in the “Detailed Model Inclusions” column to illustrate that detailed model releases from source OUs, PAs, etc., could be used to provide releases to the aquifer in place of the initial CIE vadose zone facet model releases. For example, PAs generate refined, facility-specific models of disposal systems with high resolution and robust case analysis. Rather than continue to simulate the same disposal systems with the CIE model developed for plateau-scale purposes, the PA model results will be directly used by the CIE framework to represent that specific facility. This approach ensures consistency with PAs by integrating the results of future PAs directly into the CIE tools. Take as an example the WMA C PA past leak analysis results (RPP-ENV-58782). Rather than creating a duplicative CIE model for the purposes of simulating future releases resulting from this closure system for residual tank waste, the PA model results will be directly used in the CIE groundwater model. It is possible that CERCLA source OUs may also produce detailed models whose results could be incorporated into the CIE in the same manner.

CSM modifications and characterization data obtained by source OUs and other programs may also be used to improve CIE vadose zone models. In this case, the foundation of the CIE models, as shown in “Information Sources” column of the CIE Wiring Diagram (Chapter 1, Figure 1-4), includes many sources of information and supporting facet tools that are subject to revision as new information becomes available. In turn, the updated information can then be used to update supported CIE facet models. For example, a vadose zone facet model is developed using a representation of the geology in the CPVZ GFM (CP-60925 and future revisions). Where new characterization data are collected by, for instance, a source OU, additional information is produced on the location of geologic formation “tops.” These data will then be incorporated into a new version of the CPVZ GFM. Subsequently, the new version may then be used to revise the grid of vadose zone STOMP numerical flow and transport models, resulting in a new vadose zone facet model version for use in the CIE tools. The same is true of any of the information sources in the CIE wiring diagram discussed in Chapters 2, 3, and 4. These sources may be updated with new information to support updating CIE facet models based on CSM updates and new characterization data.

Another way in which characterization data can be used to update CIE vadose zone models is through replacement of waste site inventory data by characterization data to establish initial soil contamination distributions for vadose zone flow and transport simulations. The source of inventory estimates, as discussed in Chapter 2, is provided using SIM-v2 (CP-59798). The SIM-v2 is a model that estimates inventory, with associated uncertainty, based on process knowledge at waste sites rather than direct measurement. This approach is appropriate where characterization data are unavailable or limited. However, where characterization data for soil contamination levels are adequate to define a three-dimensional subsurface plume to fully account for inventory in the vadose zone, these data are to be used in place of forward modeling of inventory estimates provided by SIM-v2. The process in this case will be to use these data with an appropriate geostatistical tool to develop the three-dimensional representation of present-day contamination in the vadose zone. Then that representation will be imposed as an initial condition at the corresponding time in the STOMP model input files. The STOMP model may then be run in a predictive mode from the present forward in time to simulate the continuing source of contamination to the aquifer resulting from the initial condition provided by characterization data. The new initial condition would then replace the forward simulation that initiates from the past introduction of contamination estimated by SIM-v2.

Chapter 6 describes the CIE Maintenance Program. The program includes periodic review and reporting of specific information sources for changes that might be used to update the CIE tools, and assesses the importance of those changes. This will support a work planning process to prioritize CIE maintenance activities.

3.8 Computational Tools

The simulation code STOMP (PNNL-12030, PNNL-15782, and PNNL-11216) was selected to implement the detailed models of flow and solute transport in the CIE vadose zone facet. STOMP was selected for the following reasons:

- The STOMP code is the modeling software managed for use at the Hanford Site for vadose zone and near-field groundwater modeling.
- The available parallel implementation of STOMP is well suited to the challenges of modeling at the scale that results from the need to simulate multi-site models (on the order of 2 to 3 million computational nodes) to account for potential commingling of waste site effluent discharges.
- The regulatory basis for using the STOMP code for the applications planned in the CIE are established in DOE/RL-2011-50.

The STOMP code was developed by Pacific Northwest National Laboratory to simulate flow and transport over multiple phases in a subsurface environment. The code uses numerical approximation techniques to solve partial differential equations that describe the conservation of a component mass, thermal energy, and solute mass in variably saturated porous media. These governing conservation equations, along with a corresponding set of constitutive relations that relate variables within the conservation equations, are solved numerically by using integrated-volume, finite-difference discretization to the physical domain and first- or second-order Euler discretization[1] to the time domain. The resulting equations are nonlinear, coupled algebraic equations that are solved using the Newton-Raphson iteration.[2] The STOMP code has been executed on a variety of platforms at national laboratories, government agencies, private companies, and universities.

The documentation for the STOMP code is comprehensive. The theoretical and numerical approaches applied in the STOMP code are documented in a published theory guide (PNNL-12030). The code has

[1] Euler's method is a numerical method to solve first-order, first-degree differential equation with a given initial value. It is the most basic explicit method for numerical integration of ordinary differential equations.

[2] The Newton–Raphson method is a numerical analysis method for finding successively better approximations to the roots (or zeroes) of a real-valued function. It is an example of a root-finding algorithm.

undergone a rigorous verification procedure against analytical solutions, laboratory-scale experiments, and field-scale demonstrations. The application guide (PNNL-11216) provides instructive examples in the application of the code to classical groundwater problems. The user’s guide (PNNL-15782) describes the general use, input file formatting, compilation, and execution of the code.

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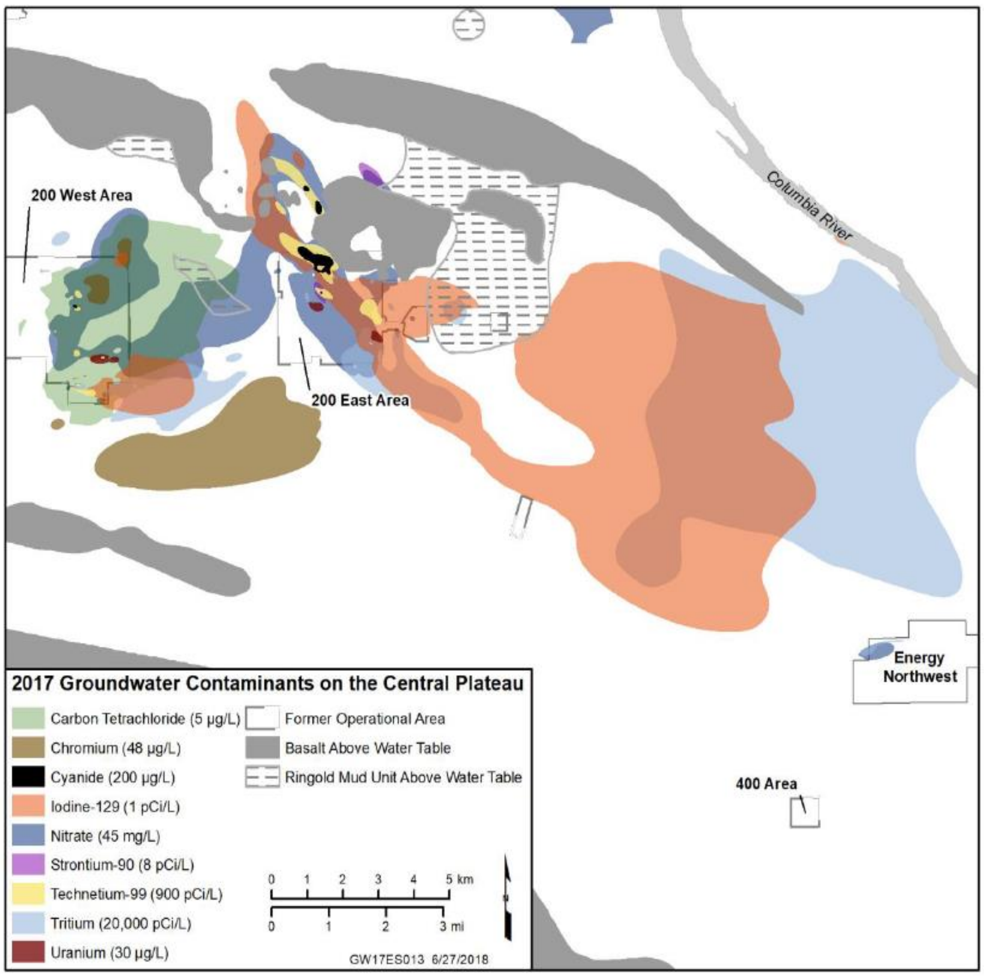
4 Saturated Zone Fate and Transport Models

The CIE saturated zone facet provides the tools necessary to evaluate contaminant fate and transport in the aquifer and is the final step in the modeling element that provides the spatial location and concentrations of contaminants. The objective of the saturated zone facet is to forecast future contaminant concentrations in the aquifer by simulating the fate and transport of groundwater plumes beneath and downgradient from the Central Plateau. The facet will use the current distribution of plumes (Figure 4-1) as the starting conditions and incorporate estimates of future source contaminant releases to the aquifer provided by the vadose zone facet as described in Chapter 3. The saturated zone facet will consist of a groundwater flow and contaminant fate and transport model capable of simulating the movement of groundwater contaminants under a variety of future scenarios. These scenarios will simulate implementation of integrated vadose and saturated zone actions identified in remedial action decision documents for the Central Plateau source and groundwater OUs. The groundwater flow and contaminant fate and transport model will enable the simulation of existing groundwater contamination, with additional contamination resulting from multiple vadose zone sources. This information will allow evaluation of groundwater and source OUs together and support a comprehensive evaluation of contaminants from the comingled vadose and saturated zone plumes as they migrate through the aquifer.



Source: DOE/RL-2017-66, *Hanford Site Groundwater Monitoring Report for 2017*.

Figure 4-1. Groundwater Contaminant Plumes in the Central Plateau, 2017

The model used for the saturated zone facet must be representative of Hanford Site groundwater conditions. This is achieved through a two-step process. First, the model is constructed consistent with the conceptual understanding of the hydrogeological environment. Thousands of wells have been drilled at Hanford and information on groundwater conditions has been collected for over 75 years. Thus, there is a large body of data available to inform the conceptual understanding of the Hanford Site environment. Second, historical simulations from Hanford Site operations support model calibration, the process of adjusting input parameters within the constraints imposed by the conceptual model to achieve an acceptable match of model results to field data.

The P2R Model v. 8.2 is a groundwater flow and contaminant fate and transport model used to meet the objectives for the CIE saturated zone facet. Developed to simulate groundwater flow and contaminant fate and transport from the Central Plateau groundwater OUs (CP-57037, Rev. 1), the model encompasses the 200 East and 200 West Areas and extends east and southeast to the Columbia River where contaminant plumes from the Central Plateau migrate. The model is implemented using software that meets all applicable quality assurance requirements.

The organization of this chapter reflects the process of developing a calibrated saturated zone model. This begins from the conceptual basis (discussed in Section 4.1). This is followed by the translation of that conceptual basis into a numerical groundwater flow and fate and transport model, namely the P2R Model (Section 4.2). Next, the P2R Model is calibrated using historical data (Section 4.3). Then, the model is configured for predictive use (Section 4.4) where model boundary conditions and well pumping rates are set based on projected future conditions that may differ from that of the period of historic data.

This chapter's organization requires that certain model parameters will be discussed several times throughout this chapter because their treatment can vary for each aspect of the model development and application process. To illustrate, consider the example of anthropogenic recharge. The nature and influence of this parameter is described with respect to the model conceptualization in Section 4.1. Anthropogenic recharge is discussed again for the historic model in Section 4.2 because there are a specific set of effluent discharge locations, magnitudes, and durations to account for in the period simulated by the historical model. Then, this historic model is used in the model calibration process described in Section 4.3. Finally, for the predictive use of the P2R Model discussed in Section 4.4, the effluent discharge locations, magnitudes, and durations will be different from those in the past, so the treatment of these is presented for projected discharges in the future. So, in this example, the same parameter (anthropogenic recharge) is discussed in multiple places in this chapter as it pertains to the model development stage being presented.

The section on predictive simulations (Section 4.4) is followed by an explanation of the simulation results provided by the P2R Model in Section 4.5. Then future updates planned for the model are discussed in Section 4.6, and a summary of key assumptions and supporting information is provided in Section 4.7.

4.1 Saturated Zone Conceptual Model

This section describes features of groundwater flow and contaminant transport for the suprabasalt aquifer, i.e., the groundwater system above basalt bedrock at the Hanford Site. The focus of the discussion is the Central Plateau in the southern Hanford Site, where waste sites included in the CIE are located, and the region east and hydrologically downgradient toward the Columbia River. The features of the Central Plateau region east and downgradient toward the Columbia River include the geology and hydrostratigraphy of the aquifer, hydraulic properties, groundwater flow direction, aquifer recharge, pump and treat (P&T) operations on the Central Plateau, interaction with the Columbia River, and groundwater flow uncertainty. This section provides the conceptual understanding of the hydrogeological environment that is represented in the numerical P2R Model.

4.1.1 Geology

The geology of the southern Hanford Site consists of alluvial deposits overlying Miocene bedrock of the Columbia River Basalt Group (CRBG) (Figure 4-2). Regional subsidence and uplift of the Pasco Basin has led to depositional and erosional periods, with depositional features influenced by structural deformation of the basalt. Major flooding events (i.e., the Missoula floods) caused deep erosion and deposition during the last ice age.

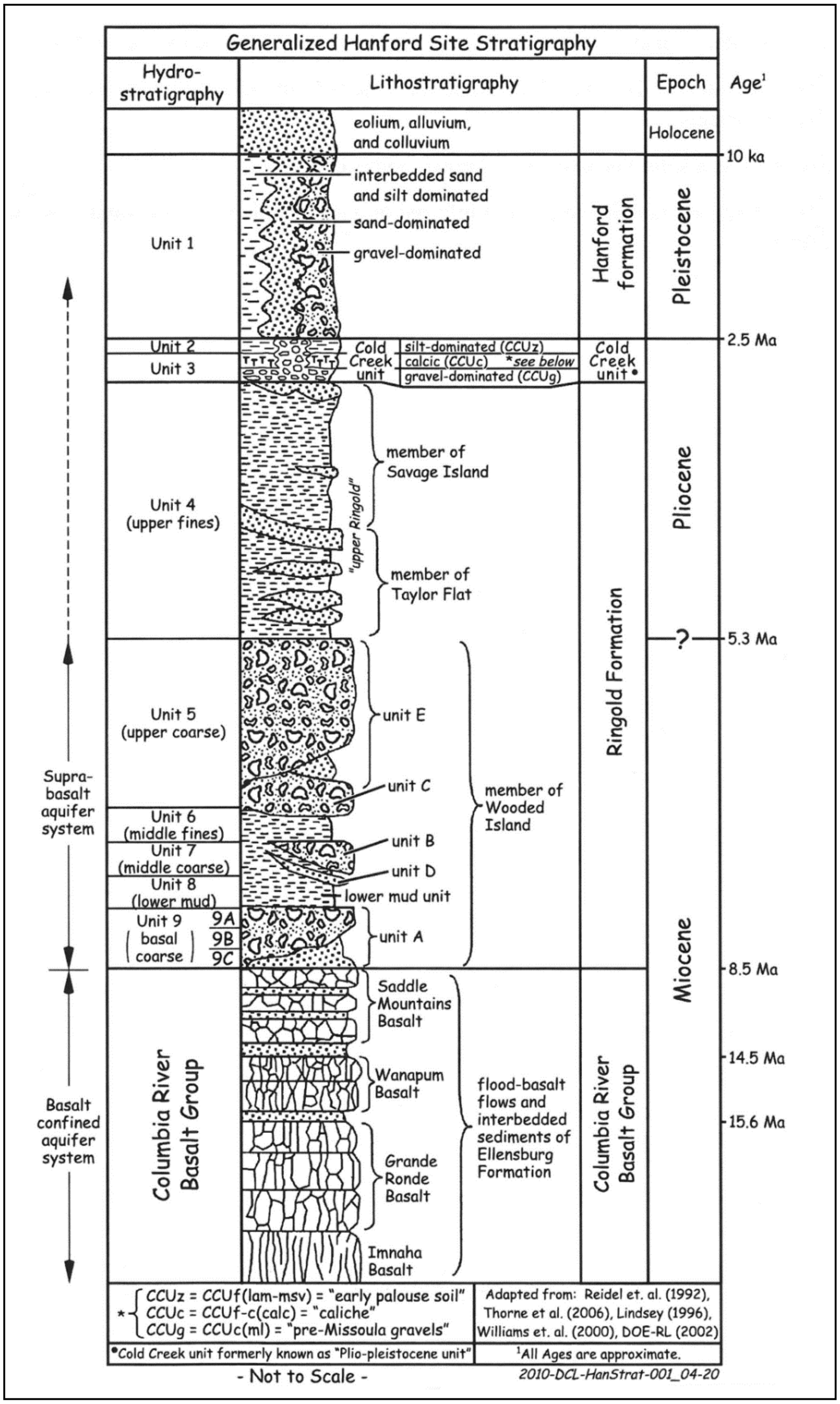
The Miocene-Pliocene Ringold Formation consists of unconsolidated to semi-consolidated silt, sand, and gravel overlying basalt bedrock (BHI-00184, *Miocene- to Pliocene-Aged Suprabasalt Sediments of the Hanford Site, South-Central Washington*). The Ringold Formation has been divided into three informal members in ascending sequence: Wooded Island, Taylor Flat, and Savage Island (Figure 4-2). The lowermost unit of the member of Wooded Island, Rwia, is composed of extensive gravel with interbedded sand deposited in a braided plain setting overlain by the fine-grained paleosol and overbank deposits of the Rlm. The lower mud is laterally extensive beneath the Hanford Site, although it is absent in portions of the 200 East and 200 West Areas and to the north of both areas (BHI-00184).

Overlying the lower mud unit are the fluvial gravels of the member of Rwie. Locally, unit E contains fine-grained lenses that may have lower permeability. Much of the member of Taylor Flat (Rtf) (alluvial sand and overbank fines) and all members of Savage Island (lacustrine deposits) have been removed from the Hanford Site by erosion, with only remnants of the member of Taylor Flat remaining.

Overlying the Ringold Formation is the CCU that was deposited by the ancestral Columbia River following a period of erosion of the Ringold consisting of alluvium within and southeast of the 200 East Area and fine-grained overbank and paleosols near the 200 West Area. Much of the CCU is above the water table in the western part of the site, but CCU gravels occur below the water table in the eastern part, including the 200 East Area.

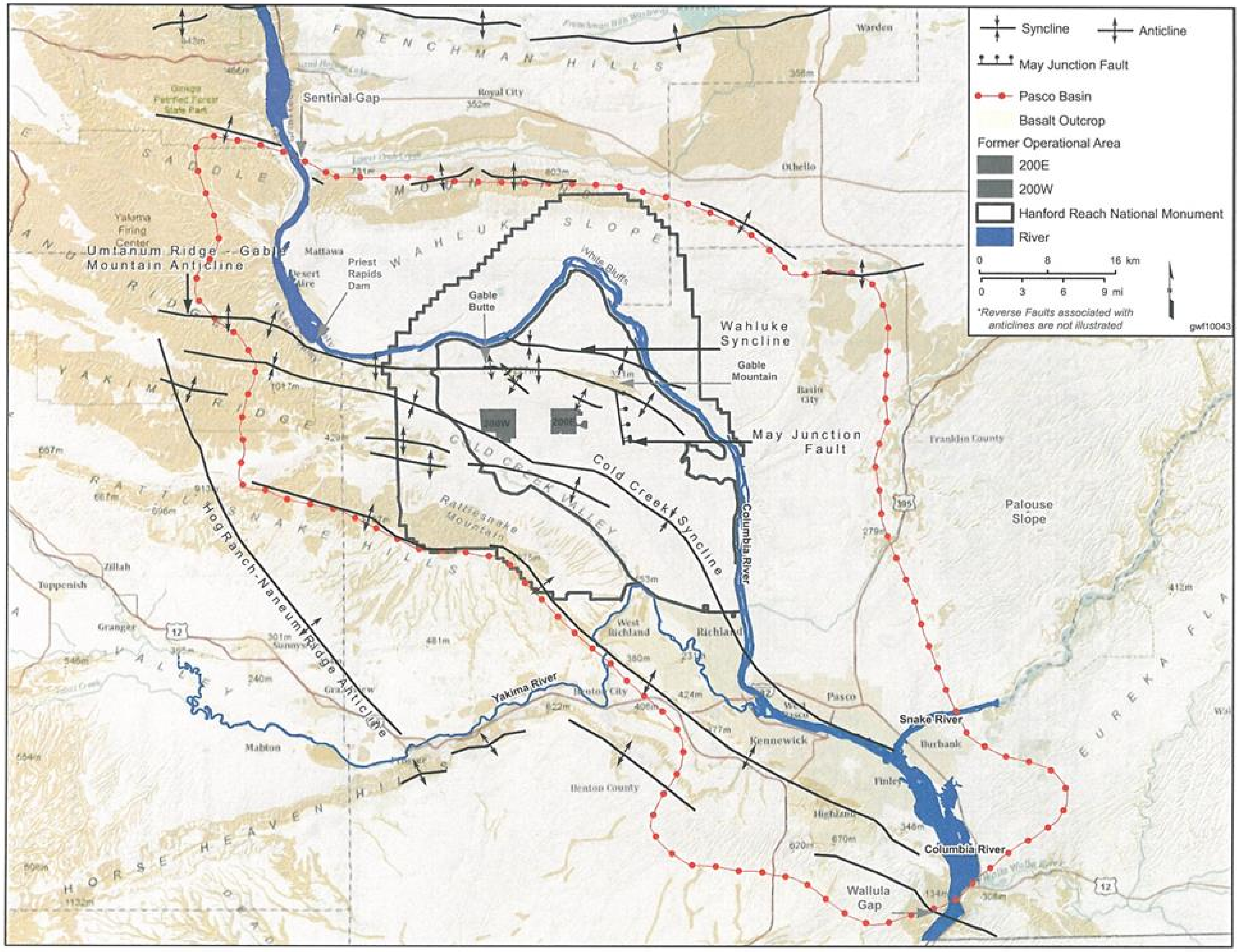
The cataclysmic outburst Missoula floods caused repeated large erosional and depositional events that significantly shaped Central Plateau geology. The many large floods left a series of overprinted features, including scour channels in the basalt, deep erosion of the CCU and Ringold Formation, highly transmissive channel fill deposits in the central part of the Hanford Site, and relatively lower energy deposits across the western portion of the Central Plateau. Collectively, the flood deposits are informally referred to as the Hanford formation. As would be expected of deposits formed from multiple erosive and depositional flood events, large vertical and horizontal variations range from fine sand to open-framework gravel.

The geologic units beneath the Hanford Site, most notably the CRBG, have been locally deformed into a series of west to east trending asymmetric anticlines and synclines (Figure 4-3) that dip steeply to the north and more gently to the south. North of the 200 East and 200 West Areas, the Umtanum Ridge-Gable Mountain anticline trends west to east. The Gable Gap cuts through this anticline between Gable Butte and Gable Mountain north of the 200 East Area. Bounded to the south by the Yakima Ridge and Rattlesnake Hills anticlines, the Cold Creek syncline contains thick accumulated deposits of Ringold Formation and Hanford formation sediments.



Source: PNNL-14898, *Results of Groundwater Modeling for Tritium Tracking at the Hanford Site 200 Area State-Approved Land Disposal Site – 2004*.

Figure 4-2. Stratigraphic Column for the Hanford Site



Source: SGW-54165, *Evaluation of the Unconfined Aquifer Hydraulic Gradient Beneath the 200 East Area, Hanford Site.*

Figure 4-3. Generalized Geologic Structure of the Pasco Basin and the Hanford Site

4.1.2 Hydrostratigraphy

HSUs are used to describe the main geologic sediment groups that control the flow of groundwater in the aquifer. Sediments are grouped based on similar hydraulic properties, similar depositional history, and abundance throughout the aquifer. The three-dimensional extent and thickness of the HSUs are estimated and documented in the Hanford South Geoframework (HSGF) spatial model (ECF-HANFORD-13-0029, *Development of the Hanford South Geologic Framework Model, Hanford Site, Washington*). The following HSUs have been defined for the suprabasalt aquifer in the southern Hanford Site:

- Ringold Formation unit A member of Wooded Island (unit 9)
- Ringold Formation lower mud unit member of Wooded Island (unit 8)
- Ringold Formation unit E member of Wooded Island (unit 5)
- Ringold Formation member of Taylor Flat (unit 4)
- Cold Creek unit (unit 3)
- Hanford formation (unit 1)

The HSGF represents the presence of the HSUs within the southern portion of the Hanford Site. Vertically, the HSGF provides an estimate of the thickness of sediments from ground surface to the top of basalt. The HSGF is periodically updated to reflect the most recent well data collected at the site. Section 4.2.2.1 discusses application of the HSGF to develop the structure of the P2R Model.

4.1.2.1 Aquifer Properties

Estimates of hydraulic conductivity, specific yield, and specific storage of the HSUs have been made by aquifer testing. Summaries of hydraulic property estimates (PNL-10886, *Development of a Three-Dimensional Groundwater Model of the Hanford Site Unconfined Aquifer System: FY 1995 Status Report*; PNNL-13641, *Uncertainty Analysis Framework – Hanford Site-Wide Groundwater Flow and Transport Model*) provide synthesized interpretations of data from hydraulic testing of the suprabasalt aquifer at the Hanford Site. Table 4-1 presents ranges of hydraulic conductivity interpretations from the summary estimates and other sources.

Table 4-1. Summary of HSU Aquifer Test Results (Horizontal Hydraulic Conductivity)

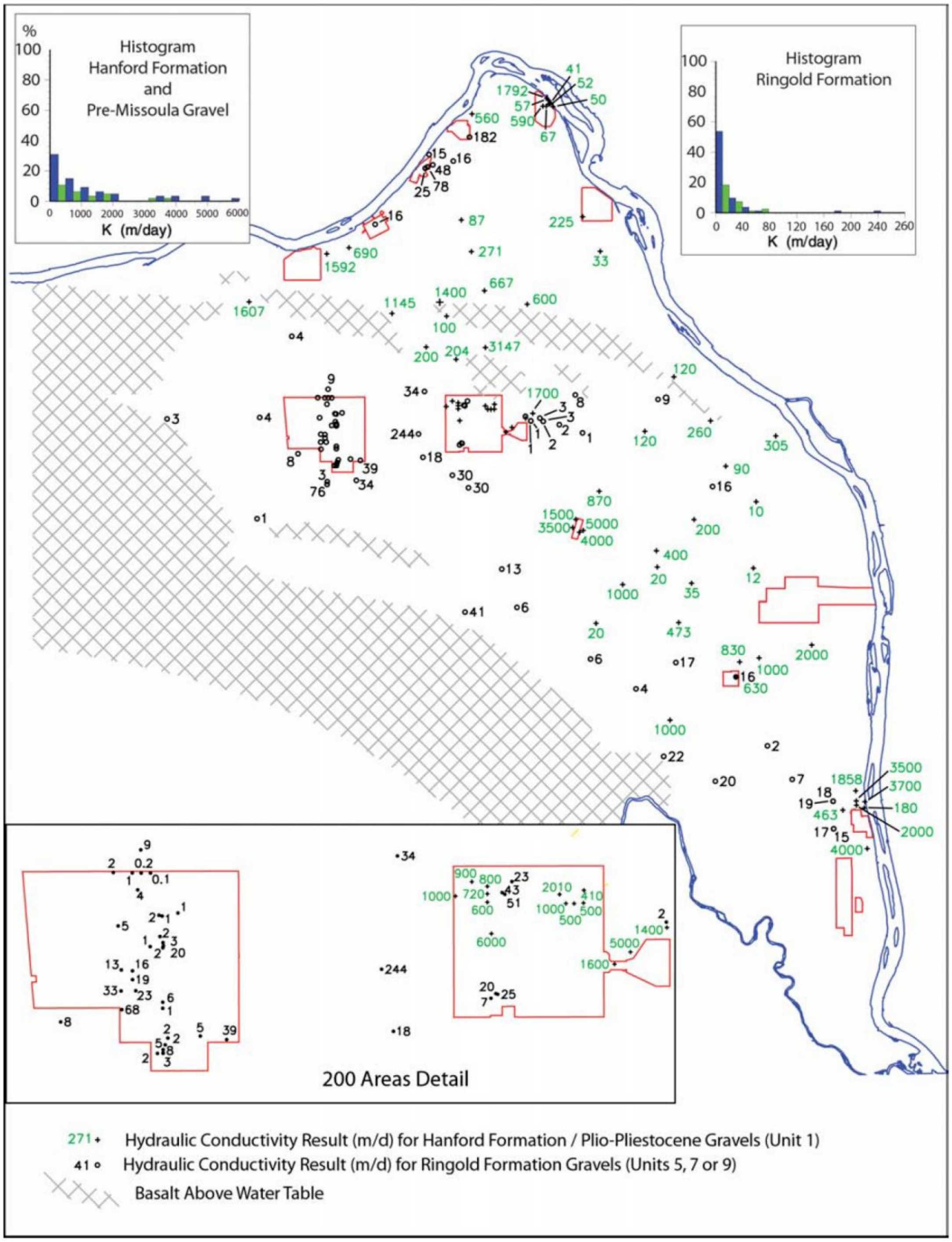
	Hydraulic Test Data (m/d)				Dye-Tracer Test (m/d)
Unit	PNL-10886	PNNL-13641	DOE/RL-2015-75	PNNL-18732	SGW-62323
Hanford formation	1–10,000	10–>3,500	18,200	--	30,000(?)*
Cold Creek unit	--	--		--	--
Ringold unit E	0.1–200	0.1–244	--	7.91	--
Ringold lower mud unit	0.03–<0.06 (unit 6)	0.002–0.03 (unit 6)	--	--	--
Ringold unit A	0.1–200	8	--	--	--

Note: Complete reference citations are provided in Chapter 7.

*SGW-62323 indicates that hydraulic conductivity values could be as high as 30,000 m/d (98,400 ft/d) to replicate observed breakthrough of dye in the tracer test, although there is uncertainty regarding the observed tracer concentration peaks.

Figure 4-4 illustrates the variable nature of hydraulic conductivity over the Hanford Site both by location and sediment type. As shown, the conductivity values for the Hanford formation and CCU (referred to as "Plio-Pleistocene Gravels") vary locally but tend to be higher in magnitude than the hydraulic conductivity values estimated from hydraulic testing of the Ringold Formation. Hanford formation and

CCU sediment hydraulic test results ranged from 10 to 10,000 m/d (33 to 32,800 ft/d) based on PNNL-13641 and PNL-10886. Hydraulic conductivity values for Ringold Formation sediments generally range from 1 to 50 m/d (3.2 to 160 ft/d) (PNNL-13641).



Source: PNNL-13641, *Uncertainty Analysis Framework – Hanford Site-Wide Groundwater Flow and Transport Model*.

Figure 4-4. Map of Hydraulic Testing Results for the Hanford Suprabasalt Aquifer

Several pumping tests have been conducted in the Central Plateau and vicinity. In 2015, a pumping test was performed in the 200-East Area at the B Complex (DOE/RL-2015-75, *Aquifer Treatability Test Report for the 200-BP-5 Groundwater Operable Unit*) that indicated an average hydraulic conductivity of 18,200 m/d (59,700 ft/d) for the Hanford formation and CCU combined. In 2009, a large-scale constant rate discharge test in the 200 West Area provided hydraulic property information for design of the 200 West Pump and Treat (200 West P&T) system (PNNL-18732, *Field Test Report: Preliminary Aquifer Test Characterization Results for Well 299-W15-225: Supporting Phase I of the 200-ZP-1 Groundwater Operable Unit Remedial Design*). The HSU tested was the Ringold unit E, and the best estimate hydraulic conductivity value was 7.91 m/d (26.0 ft/d).

A 2018 evaluation of historic dye-tracer tests conducted in deposits near the Non-Radioactive Dangerous Waste Landfill indicate relatively high values of hydraulic conductivity. SGW-62323, *Central Plateau Groundwater Tracer Study Phase I Report*, indicated that hydraulic conductivity values could be as high as 30,000 m/d (98,400 ft/d) to replicate observed breakthrough of dye in the historic experiments, although there is uncertainty regarding the observed tracer concentration peaks.

Specific yield has been estimated from tests of the Hanford formation and Ringold Formation, as presented in Table 4-2 (Ringold units A and E are jointly described in PNL-10886). Values range from 0.1 to 0.37 for the Hanford formation and 0.05 to 0.37 for the Ringold units A and E. A value of 0.21 was estimated for the 2015 aquifer test conducted in the 200 East Area (DOE/RL-2015-75), and 0.096 was estimated for the large-scale aquifer test in 200 West Area (PNNL-18732).

Table 4-2. Summary of HSU Aquifer Test Results (Specific Yield)

Unit	Hydraulic Test Data (dimensionless)			
	PNL-10886	**PNNL-13641**	**DOE/RL-2015-75**	**PNNL-18732**
Hanford formation	0.1–0 .3	0.2–0.37	0.21	--
Cold Creek unit	--	--		--
Ringold unit E	0.05–0.2	0.05–0.37	--	0.096
Ringold unit A		0.15	--	--

Note: Complete reference citations are provided in Chapter 7.

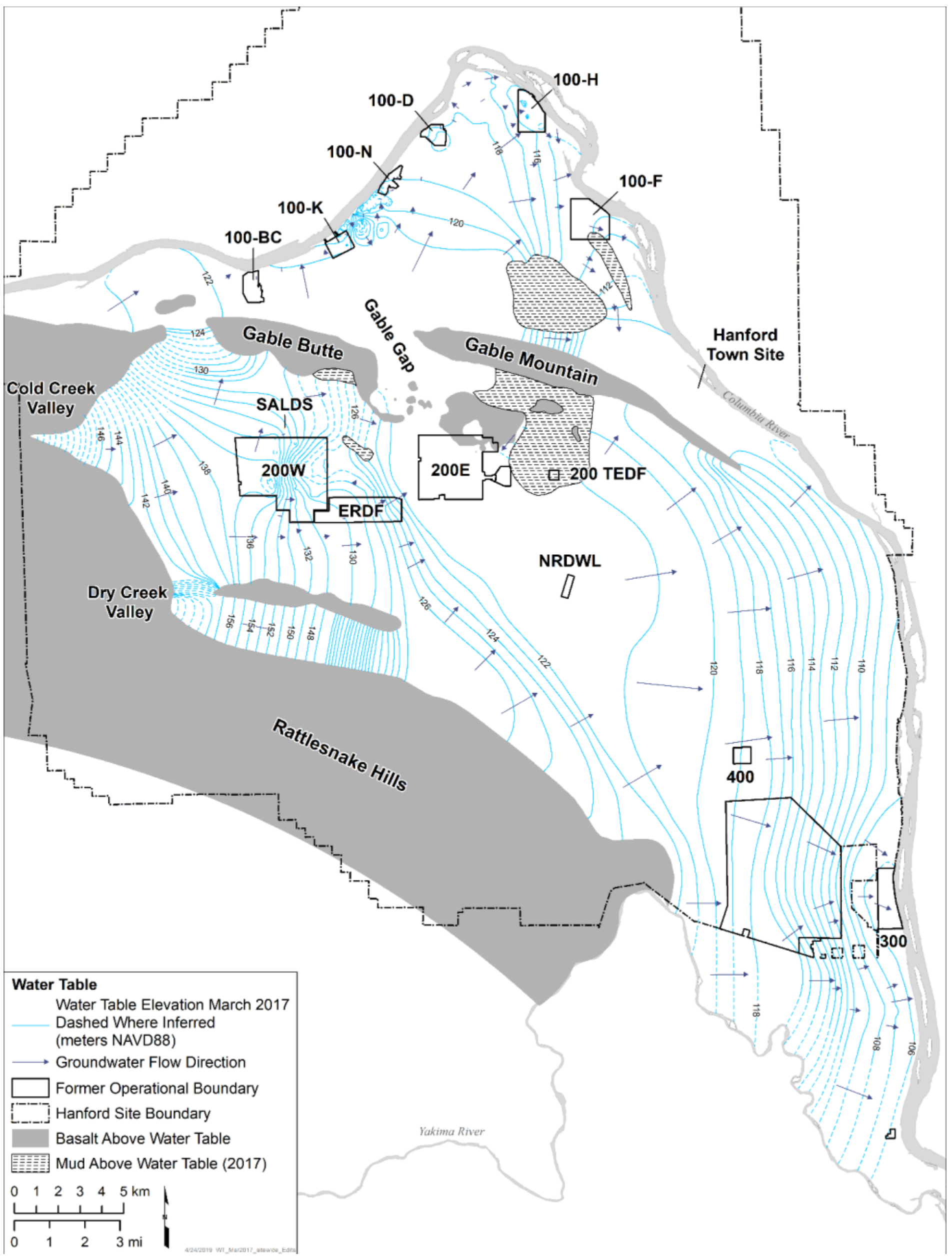
HSU = hydrostratigraphic unit

An analysis of 43 estimated values of storativity (available in the references cited in EMDT-HP-0010[1]), (Appendix G in CP-57037, Rev. 1), accompanied by an estimate for saturated thickness indicated that the geometric mean of the specific storage values calculated from the storativity data was 0.000019 m^{-1}. PNNL-18732 provides a recent analysis of storage coefficients within the 200-ZP-1 OU located in the 200 West Area. The results of the analysis of a 3-day constant rate discharge test were a storativity value of 0.00097 (dimensionless). The reported saturated thickness of 55.4 m produces a specific storage of 0.000017 m^{-1}. The geometric mean of specific storage data for the 2015 pumping test in the 200 East Area (DOE/RL-2015-75) yields a specific storage value of 0.000026 m^{-1}.

[1] EMDT-HP-0010, 2016, *Hydraulic and Transport Parameters for Site-wide Models*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington. This is a data transmittal; a copy is provided in the appendices of CP-57037.

4.1.3 Groundwater Flow

Water flow in the suprabasalt aquifer is influenced by the locations of recharge and discharge areas, hydraulic properties of the HSUs, the presence of structural and stratigraphic controls, and historical anthropogenic recharge. Groundwater flow beneath the southern Hanford Site is generally from recharge areas in the west toward the regional discharge area east along the Columbia River (Figure 4-5). Steep hydraulic gradients occur in the west and near the Columbia River, while a low-gradient region extends from the 100-B/C Area through Gable Gap and the 200 East Area and into the central portion of the Hanford Site. The steep gradients are due to lower permeability sediments of the Ringold Formation at the water table, whereas the low-gradient region is due to the occurrence of high permeability sediments of the Hanford formation and CCU.



Source: Modified from DOE/RL-2017-66, *Hanford Site Groundwater Monitoring Report for 2017*.

Figure 4-5. Hanford Site Water Table Map, March 2017

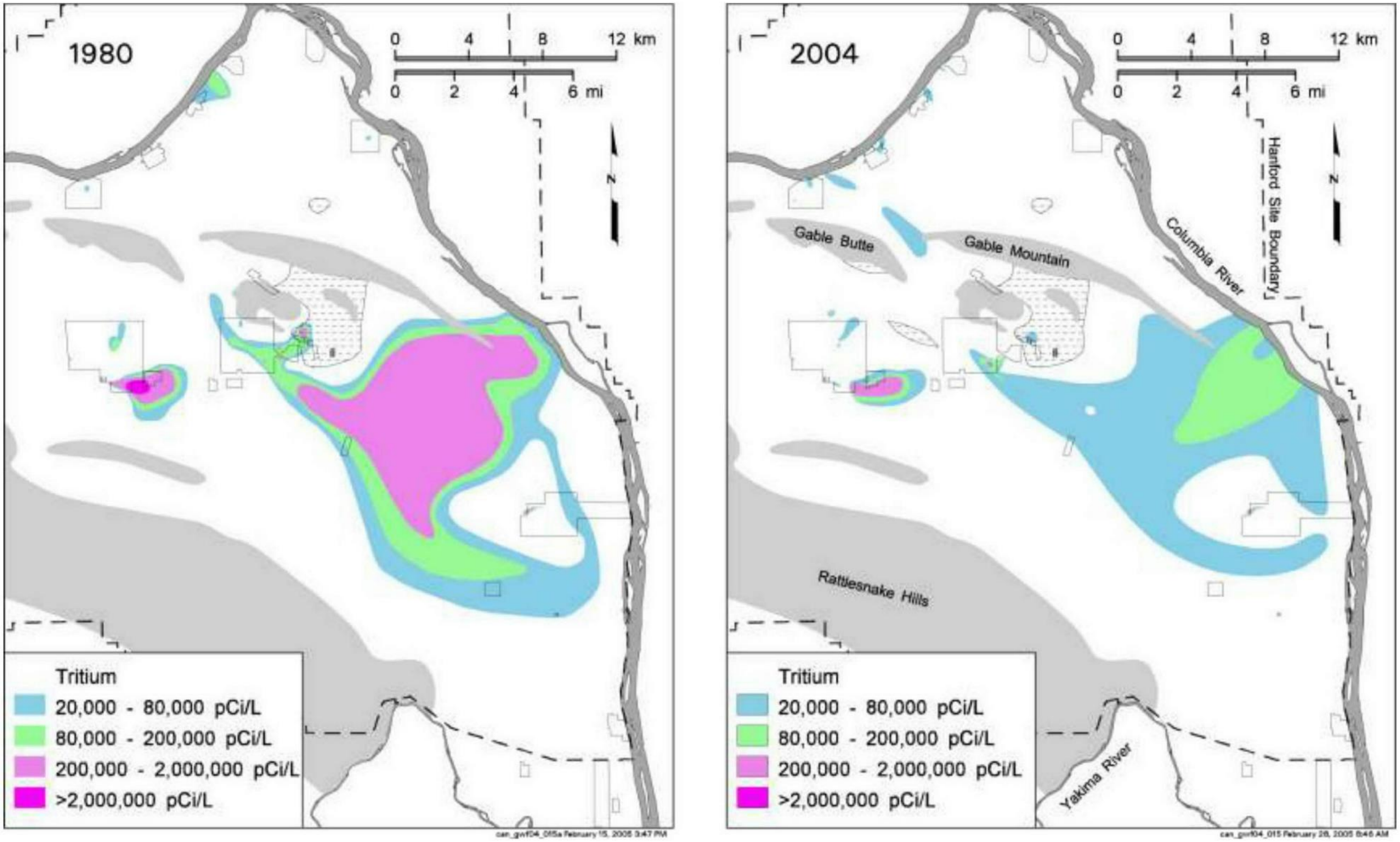
The highly permeable sediments in the low-gradient region were deposited by the ancestral Columbia River (CCU) and the Missoula floods (Hanford formation), forming a paleochannel. The occurrence of the basalt anticlinal ridges north of the 200 East Area constrained the flow to a narrow region resulting in high energy, coarse-grained deposits, particularly through Gable Gap and the 200 East Area. Hydraulic gradients in the paleochannel region of the 200 East Area are currently low (10^{-6} m/m; DOE/RL-2017-66), resulting in a nearly flat water table.

The flow directions shown in Figure 4-5 indicate that water follows an east-northeast flow path to the Columbia River south of the Hanford Townsite. Historically, this location is where the highest concentrations of tritium from the Central Plateau reached the river in the 1980s, confirming the flow path. Tritium occurs as tritiated water, which does not sorb to aquifer sediments and is a good indicator of groundwater flow directions. Tritium from the 200 East Area originated predominantly from effluent releases in the 1960s to cribs associated with the Plutonium Uranium Extraction Plant (PUREX) in the southeast part of the area. Figure 4-6 shows the tritium plume in 1980 and 2004. The plume from the PUREX cribs migrated southeast from the 200 East Area along the paleochannel. Most of the plume then turned toward the east-northeast, consistent with the flow directions in Figure 4-5, although portions of the plume continued to migrate to the southeast.

Groundwater is present in unconfined and confined conditions beneath the Central Plateau. The unconfined aquifer occurs mostly in the Ringold Formation unit E, CCU, and Hanford formation. Where present, the Ringold lower mud unit forms the base of the unconfined aquifer. Beneath the mud, groundwater in Ringold unit A occurs under confined conditions. The lower mud has been eroded from much of the 200 East Area, and water from Ringold unit A discharges to the overlying unconfined aquifer in this region (PNNL-12261, *Revised Hydrogeology for the Suprabasalt Aquifer System, 200-East Area and Vicinity, Hanford Site, Washington*). Basalt bedrock generally constitutes a barrier to groundwater flow and serves as the lower confining layer for the Ringold unit A in most places. Where the lower mud is absent, the top of basalt is the base of the unconfined aquifer. Exceptions occur where the basalt flow top is present or the basalt dense interior has been substantially thinned by erosion.

Typical simple basalt flow top (i.e., the top of a basalt flow not substantially affected by erosion) is highly vesicular, but the vesicles are normally not interconnected and do not contribute to effective porosity. The low effective porosity that does occur in a simple flow top is due to the presence of tensional cooling joints. Flow top breccias are occasionally present and consist of vesicular, pebble- to cobble-sized clast deposits. In contrast to simple flow tops, flow top breccias can exhibit moderate to high effective porosity. In locations where the flow top breccias have formed, these sediments are considered part of the suprabasalt aquifer (SGW-41072, *Liquid Effluent Retention Facility Engineering Evaluation and Characterization Report*). In some places, the uppermost basalt flow has had much if not all of its flow top and dense flow interior removed by erosion resulting in a reduction or elimination of its confining properties, allowing for communication between aquifers. This scenario has been interpreted to occur north of the 200 East Area, where the basalt was eroded by the ancestral Columbia River and Missoula floods (RHO-RE-ST-12P, *An Assessment of Aquifer Intercommunication in the B Pond-Gable Mountain Pond Area of the Hanford Site*; PNNL-19702, *Hydrogeologic Model for the Gable Gap Area, Hanford Site*).

A north to south trending normal fault May Junction occurs east of the 200 East Area (Figure 4-3). The eastern portion of the fault is the downthrown side, and maximum displacement has been estimated at 56 m (185 ft) (PNNL-12261). The water chemistry in Ringold unit A (tritium and major ion chemistry) west of the May Junction fault indicates that the water pre-dates Hanford Site operations and has not been displaced or diluted by waste water discharges particularly from B Pond (PNNL-12261). This history shows that the May Junction fault is a barrier to groundwater flow in Ringold unit A.



Source: DOE/RL-2009-85, *Remedial Investigation Report for the 200-PO-1 Groundwater Operable Unit*.

Figure 4-6. Comparison of the 1980 and 2004 Tritium Plumes

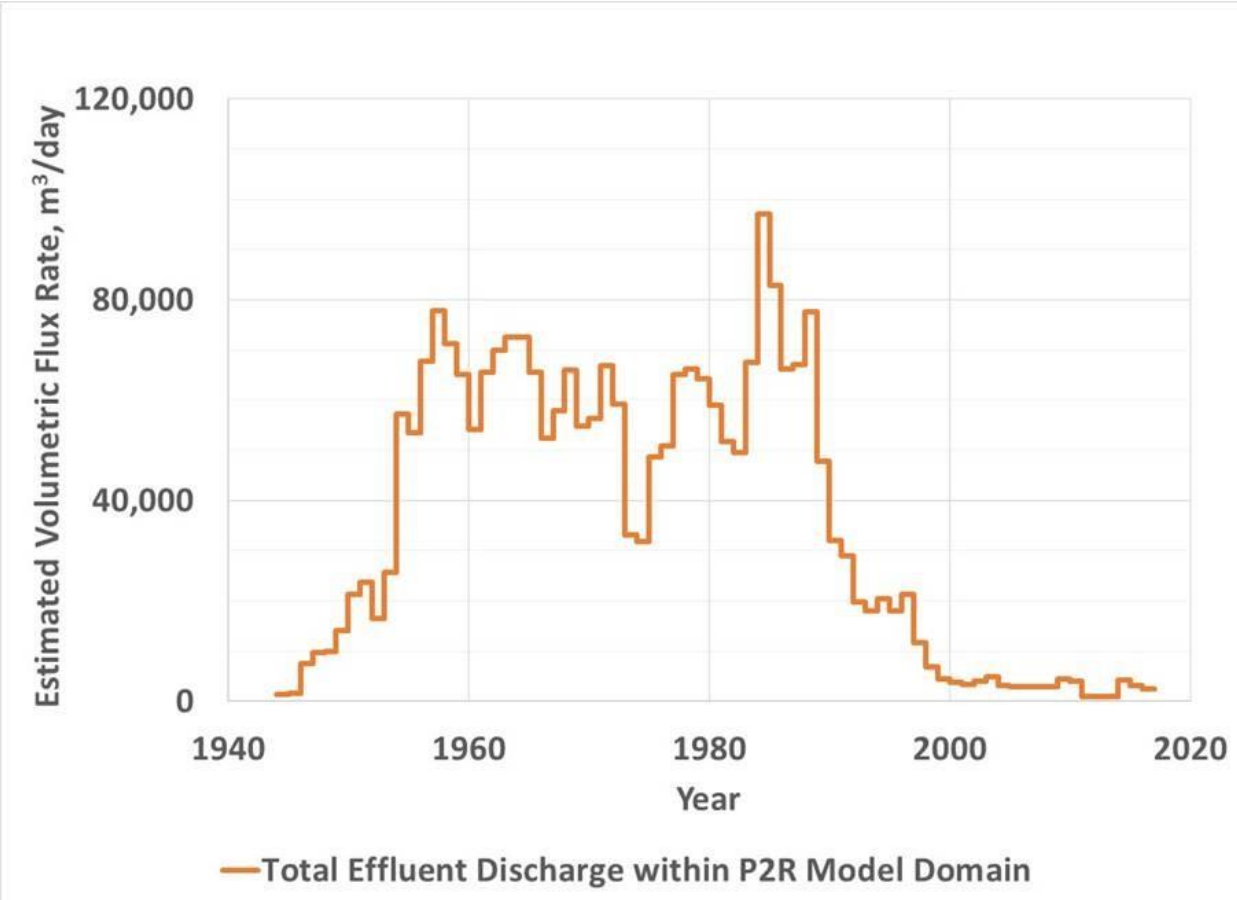
4.1.3.1 Natural and Anthropogenic Recharge

Natural recharge includes percolation of net precipitation to the water table, mountain-front recharge arising from infiltration of snowmelt, agricultural return-flows from irrigation, and runoff from elevated areas. On the Hanford Site, this natural recharge is highly variable both spatially and temporally, ranging from near zero for fine-textured silt loam soils with shrub-steppe vegetation to more than 100 mm/yr for gravel-covered areas maintained vegetation free, with the variability depending on climate, vegetation, and soil texture (Gee et al., 1992, "Variations in Recharge at the Hanford Site"; PNL-10285, *Estimated Recharge Rates at the Hanford Site*). As noted in Chapter 3, vegetative areas and fine-texture, soil-like silt loams tend to have lower recharge rates, while areas with little vegetation and coarse-texture soil (e.g., dune sands) tend to have higher recharge rates. Rattlesnake Mountain is the primary source of mountain-front recharge. The Cold Creek and Dry Creek Valleys (Figure 4-5) are the primary locations where agricultural return-flows from irrigation occur.

Natural recharge from percolation of net precipitation is applied as an upper boundary condition for both vadose zone models described in Chapter 3 and the saturated zone model described in this chapter. Note that while the CIE tools will pass contaminant mass or activity flux from vadose zone models to the saturated zone model, water flux is not passed between these models. The land areas simulated by vadose zone models is limited to waste sites and surrounding areas, whereas the saturated zone covers a much larger area. Because of the scale difference, and the need to define natural recharge over the full extent of the saturated zone model domain, the vadose zone models will not be coupled for the purpose of passing natural recharge. Instead, the GIS-based tool called for in Chapter 3 to manage the spatial and temporal variability of natural recharge will be constructed at a scale and resolution sufficient to support both the vadose models described in Chapter 3 and the saturated zone model described in this chapter. Using this new GIS-based tool to specify boundary conditions in both model facets will ensure consistency in natural recharge rates applied in these models.

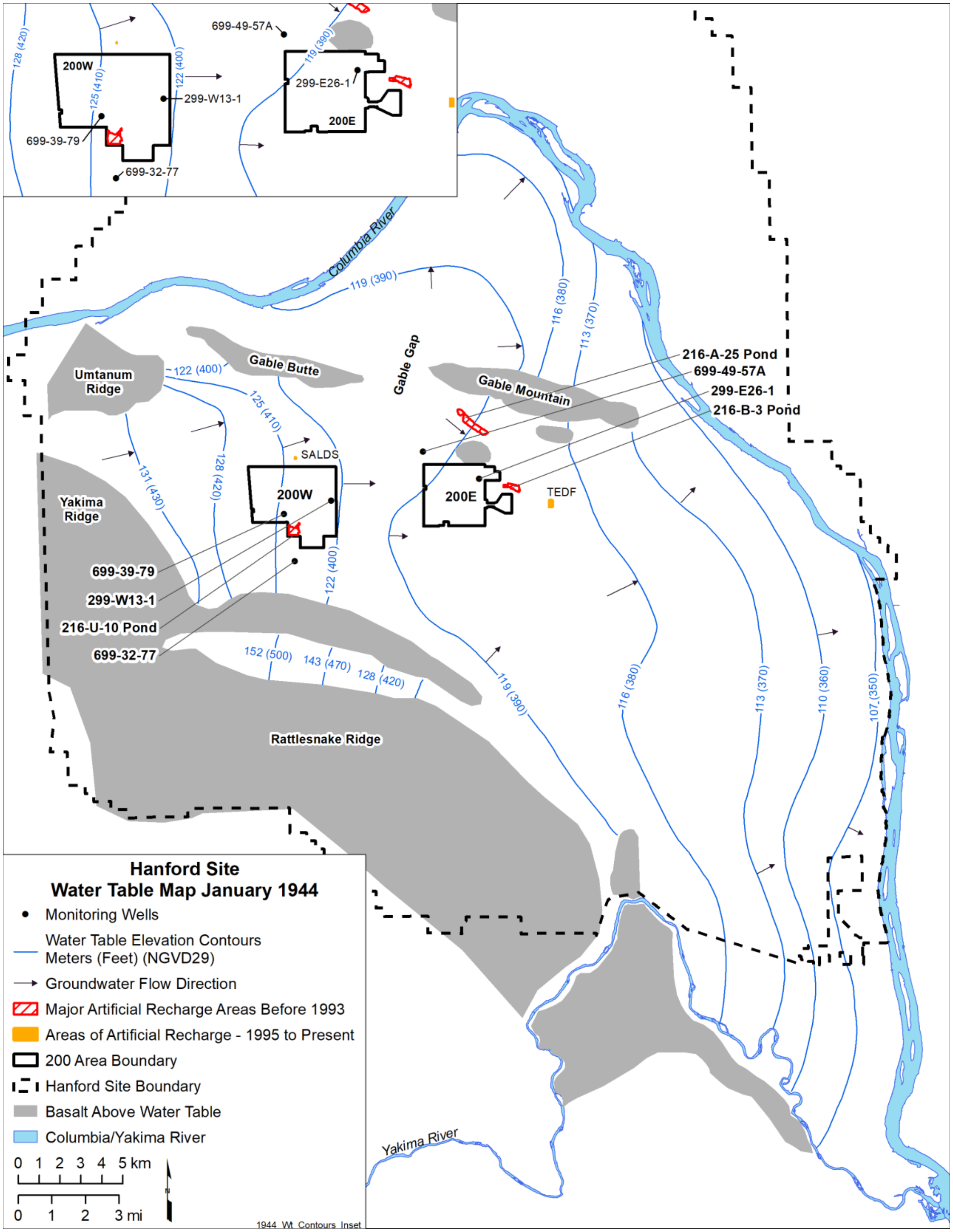
Anthropogenic recharge is comprised of effluent discharges to ground associated with Hanford Site operations. The water source for all facilities on the Central Plateau operations was and remains Columbia River water imported to the Central Plateau through the Hanford Site water supply system. Wastewater discharges associated with production activities at the Hanford Site were significant sources of water to the subsurface historically, at times exceeding 100,000 m^3/d. Figure 4-7 shows the annual total discharge summed over all recorded radiologically contaminated discharges and other effluent discharges since 1943 for the Central Plateau. It is known that this discharge record is incomplete because there were additional unmeasured effluent discharges as discussed in Section 3.5.2.2.

The water table elevation and hydraulic gradients on the Hanford Site were affected by these large volume wastewater discharges (SGW-60338, *Historical Changes in Water Table Elevation and Groundwater Flow Direction at Hanford: 1944 to 2014*). Some of the largest sources of process-related water to the subsurface until 1995 included U Pond (216-U-10), B Pond (216-B-3), and Gable Mountain Pond (216-A-25), which caused increases in the water table elevation and exerted control on the rates and directions of groundwater flow. The estimated pre-Hanford Site water table is shown in Figure 4-8 (water table map for 1944), while the alteration of the water table from wastewater discharges can be seen in Figure 4-9 (water table map for 1973). Effluent discharges (most of which concluded by 1995) caused the formation of substantial groundwater mounds in the 200 East and 200 West Areas. Two permitted effluent disposal facilities continue to operate since that time: the State Approved Land Disposal Site north of the 200 West Area and the 200 Area Treated Effluent Disposal Facility east of the 200 East Area (Figure 4-5). The effects of the historical effluent releases continue to exert influence on the water table and flow directions because water levels have not yet receded to equilibrium conditions.



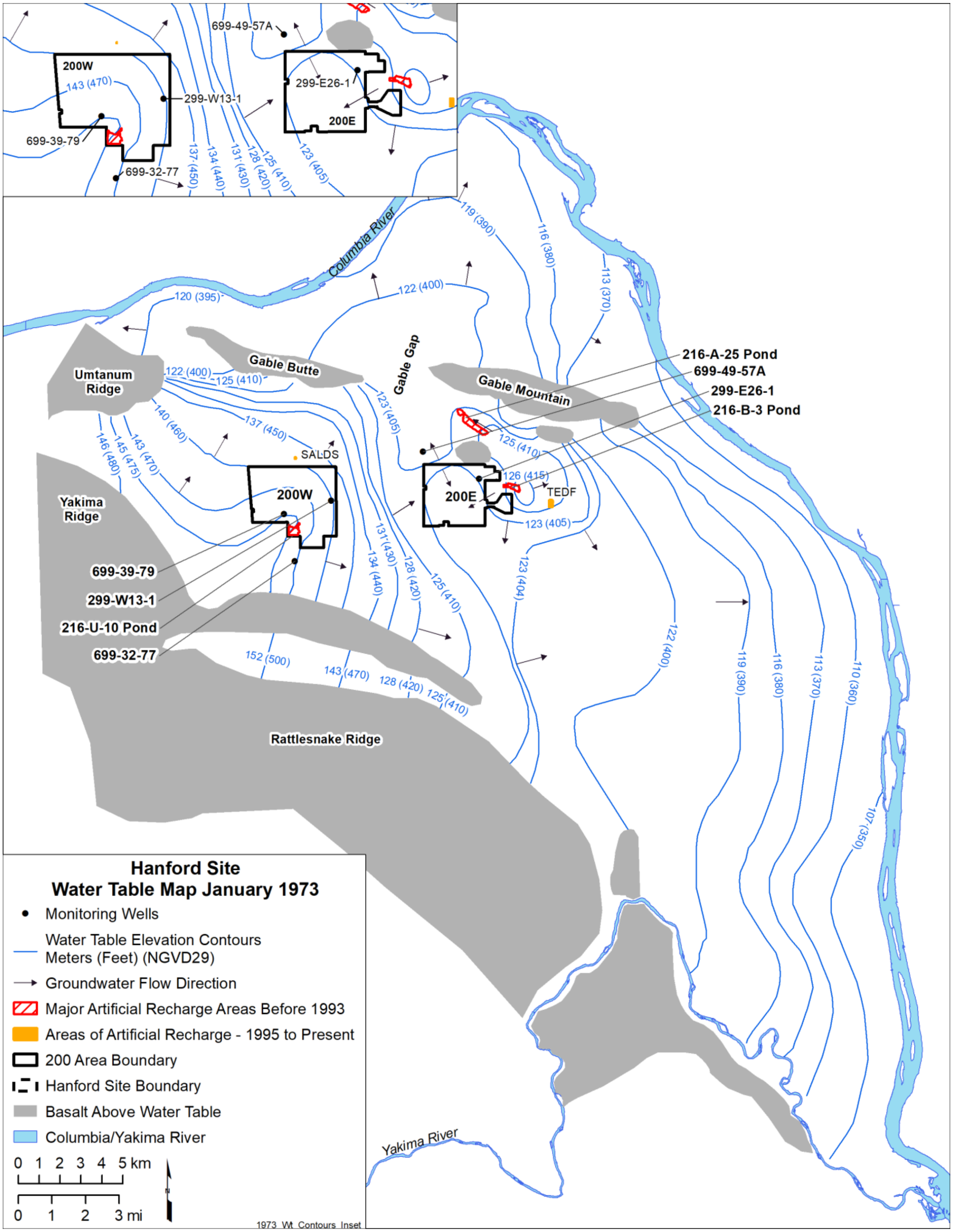
Source: CP-57037, *Model Package Report: Plateau to River Groundwater Model, Version 8.2*, Rev. 1.

Figure 4-7. Effluent Releases at the Hanford Site (1944 to 2016)



Source: Modified from SGW-60338, *Historical Changes in Water Table Elevation and Groundwater Flow Direction at Hanford: 1944 to 2014*.

Figure 4-8. Hanford Site Water Table Map, 1944



Source: Modified from SGW-60338, *Historical Changes in Water Table Elevation and Groundwater Flow Direction at Hanford: 1944 to 2014*.

Figure 4-9. Hanford Site Water Table Map, 1973

Both anthropogenic and natural sources of water must traverse a thick, unsaturated (vadose) zone to reach (and ultimately recharge) the suprabasalt aquifer below. This situation causes the arrival of these discharges at the water table to be delayed with respect to their time of release and to be spread in time. The presence of fine-grained units in the vadose zone caused some of the discharges to form perched zones, further contributing to the delay in reaching the water table and resulting in some lateral migration of water and contamination in the vadose zone.

U Pond (200 West Area) and B Pond (200 East Area) are examples of the effect that wastewater disposal sites had on the Hanford Site water table. Operation of U Pond caused a large groundwater mound to form beneath the 200 West Area (Figures 4-9 and 4-10). The peak water table elevation occurred in 1984, the final year that U Pond operated, at approximately 23 m above the estimated pre-Hanford Site water table, and water levels have been generally declining since.

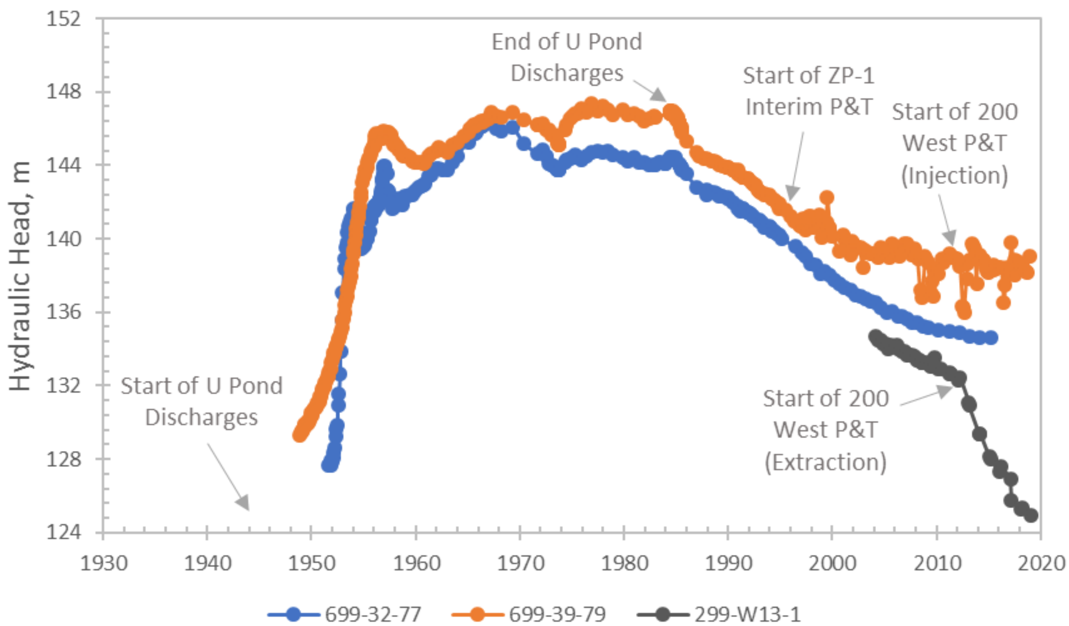


Figure 4-10. Historical Groundwater Levels in the 200 West Area

Wastewater discharges to B Pond substantially affected the water table and the groundwater flow direction in the 200 East Area (Figures 4-9 and 4-11). When B Pond was operating, the addition of water to the aquifer resulted in a flow divide in the central 200 East Area, causing water to flow out of the 200 East Area both to the southeast and to the north through Gable Gap. When B Pond ceased operating in 1997, the water table beneath the 200 East Area declined, and the flow divide shifted to the north. In 2011, the flow direction in the northwestern 200 East Area reversed from northwest to southeast (SGW-54165, *Evaluation of the Unconfined Aquifer Hydraulic Gradient Beneath the 200 East Area, Hanford Site*). The flow divide is now present to the north of the 200 East Area coincident with an anticlinal ridge (Figure 4-12).

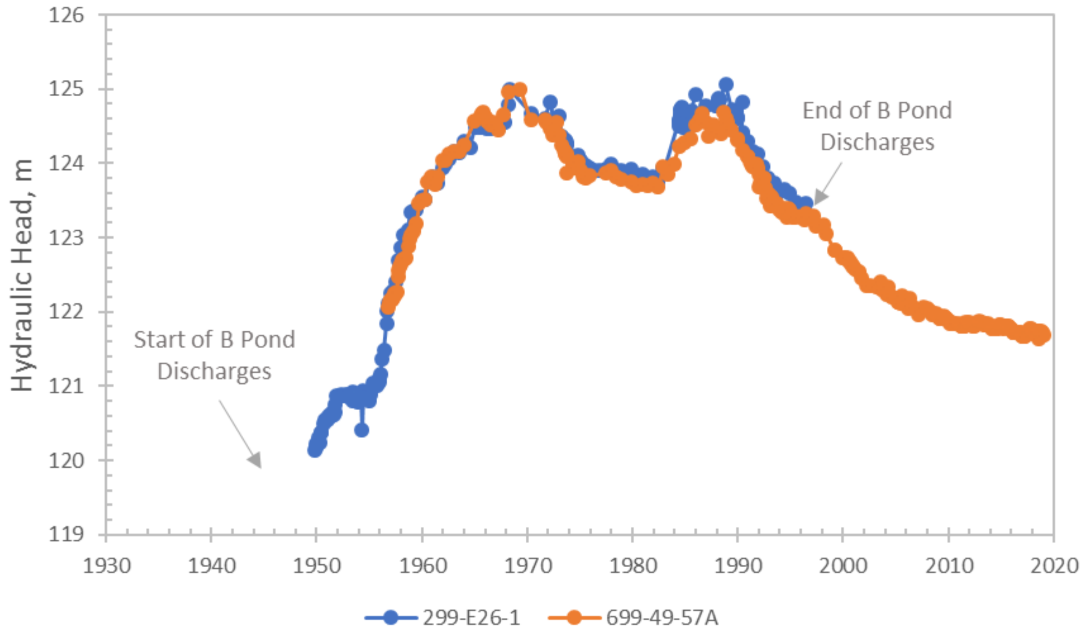
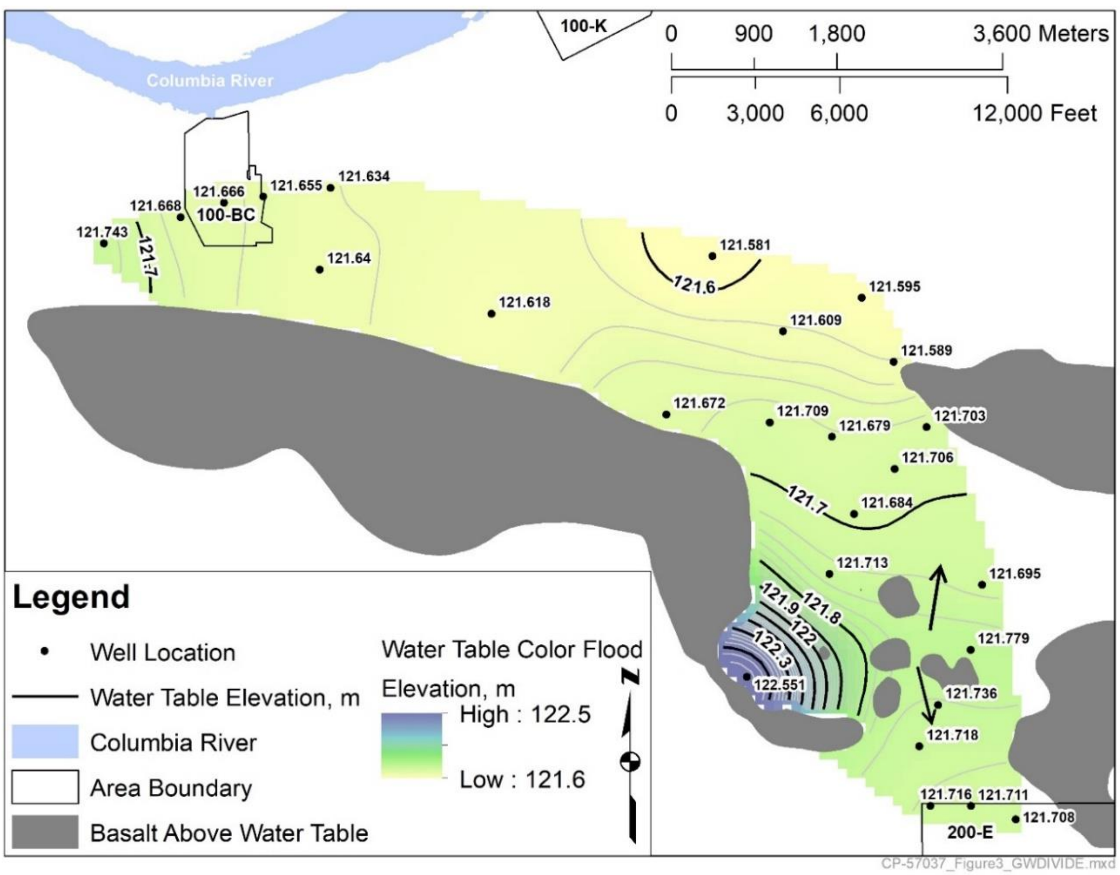


Figure 4-11. Historical Groundwater Levels in the 200 East Area



Source: Modified from CP-57037, *Model Package Report: Plateau to River Groundwater Model, Version 8.2*, Rev. 1.

Figure 4-12. Water Table Map for the Paleochannel North of the 200 East Area, April 2016

As previously noted, the Cold Creek and Dry Creek Valleys west of the Hanford Site are sources of recharge to the suprabasalt aquifer. Irrigation associated with agricultural development in these drainage basins will affect the amount of recharge. Several estimates of recharge from these drainage basins, including calculations and model calibration, have been made, but there is an order of magnitude uncertainty in the results (CP-47631, *Model Package Report: Central Plateau Groundwater Model, Version 8.4.5*). Future agricultural development and changes in irrigation practices will cause variations in recharge, causing the future equilibrium state of the water table to be different from pre-Hanford Site times.

4.1.3.2 200 West Pump and Treat

The CIE saturated zone facet must account for ongoing remedial actions that will impact concentrations and aquifer conditions. Groundwater flow in the 200 West Area has been substantially affected by the 200 West P&T system, which began operating in 2012. Having replaced a smaller 200-ZP-1 interim action P&T system that operated from 1995 to 2012, the 200 West P&T was designed to remediate a carbon tetrachloride plume, although other plumes are also remediated. Water is removed from the aquifer by extraction wells, run through a treatment plant, and returned to the aquifer through injection wells. The system consists of multiple extraction and injection wells with an average total flow rate of approximately 7,600 L/min (2,000 gal/min) (DOE/RL-2017-68, *Calendar Year 2017 Annual Summary Report for Pump-and-Treat Operations in the Hanford Central Plateau Operable Units*). Operation of this system has caused a large cone of depression to form in the northern 200 West Area (Figures 4-5 and 4-10).

4.1.3.3 Columbia River

The Columbia River is the discharge area for the suprabasalt aquifer. Interactions between the river and the aquifer depend on the relationship between river stage and head in the adjacent aquifer, and river stage is affected by runoff and operation of Priest Rapids Dam located 9.1 km (5.7 mi) upstream of the Hanford Site. Further, river stage along the Hanford Site varies in response to changing channel geometry and river bed slope, resulting in a nonuniform gradient profile. During most times of the year, the daily average river stage is lower than the head in the adjacent aquifer, and water from the aquifer discharges into the river. In spring and early summer, increased runoff normally causes a higher daily average river stage, and flow is from the river into the aquifer (bank storage). However, this temporary situation causes a net flow of water from the aquifer to the river during the year (gaining stream).

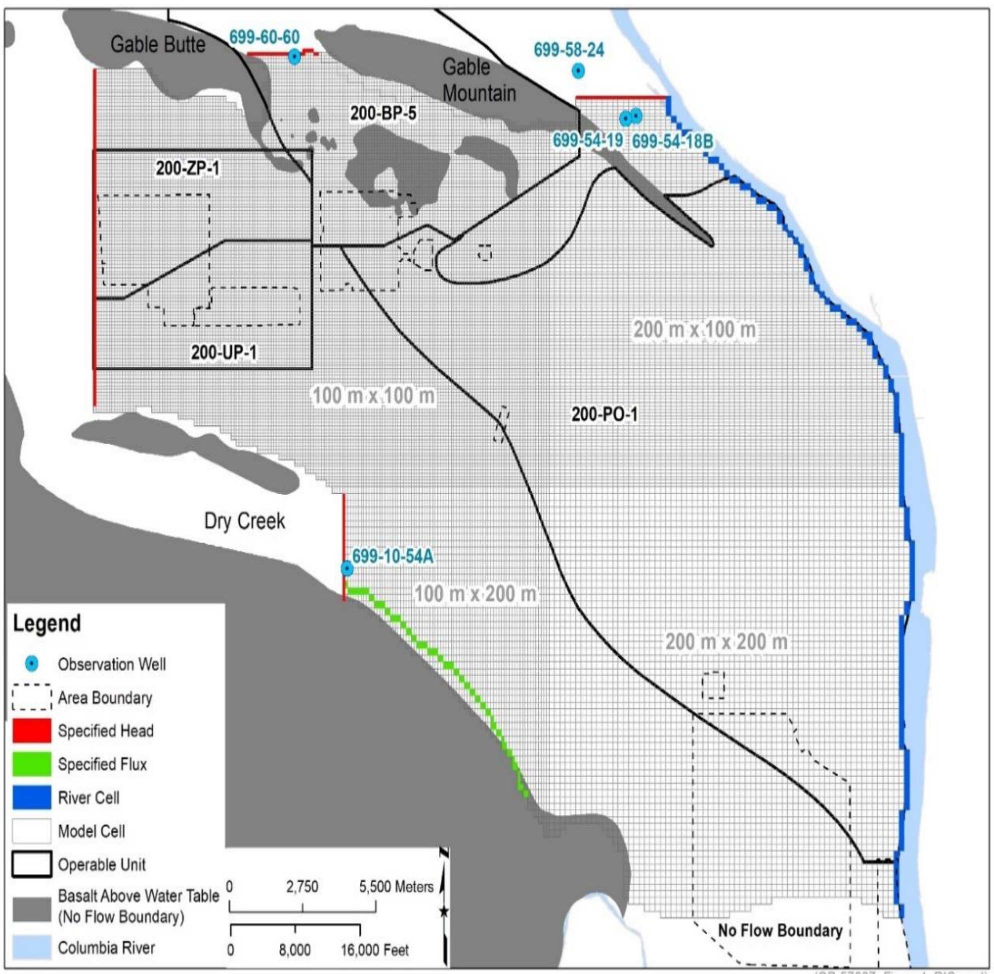
4.1.4 Conceptual Model Uncertainty

Data from groundwater OU investigations, remedy implementation, and long-term monitoring continually become available, and data analysis may lead to revisions of the conceptual model, which is thus continually evolving. For example, there is uncertainty in the interpretation that the top of basalt is generally the base of the suprabasalt aquifer. Perhaps permeable basalt flow top is more widespread than is currently recognized, and the upper portion of the basalt should be interpreted as an HSU. Specifically, permeable basalt flow top was found beneath the Liquid Effluent Retention Facility in the northeastern 200 East Area, where three wells were drilled and screened at least partially in the flow top (SGW-41072). If presence of permeable flow top is widespread, interpretations of the thickness of the suprabasalt aquifer may need to be revised and this may have ramifications in determining aquifer transmissivity. However, if permeable basalt flow top is widespread, this will already be accounted for by the P2R Model in that the calibrated hydraulic conductivity will be higher to account for the higher transmissivity.

There is also uncertainty regarding future groundwater flow through Gable Gap (CP-57037, Rev. 1). The aquifer is thin across the anticlinal ridge north of the 200 East Area, which results in a relatively low transmissivity. As the water table declines, basalt may be exposed above the water table and become a barrier preventing hydraulic communication across the ridge. This situation will continue to be monitored, and the conceptual model will be revised, as needed. As the conceptual model is updated, the CIE saturated zone will also be updated so that the model will continue to represent the current understanding of the Hanford Site hydrogeological environment.

4.2 P2R Model Development

The P2R Model was developed as a tool to simulate groundwater flow and contaminant fate and transport of plumes beneath the Central Plateau downgradient to the Columbia River (CP-57037, Rev. 1). This model was specifically developed to represent the complex geologic and hydrologic environment of the Central Plateau and vicinity, and accounts for heterogeneity in the aquifer system and the operational history of the Hanford Site (i.e., historical effluent discharges, P&T systems, etc.). Figure 4-13 shows the spatial extent of the P2R Model. A description of the P2R Model, including its pedigree, is provided in the following sections. Additional details on model development can be found in CP-57037, Rev. 1.



Source: Modified from CP-57037, *Model Package Report: Plateau to River Groundwater Model, Version 8.2*, Rev. 1.

Figure 4-13. P2R Model Extent and Boundary Conditions

4.2.1 Model Pedigree

A numerical model of a groundwater system consists of two components: software codes that perform the calculations, and the input data that represent the problem being solved. The latter is based on the conceptual model described in Section 4.1. The groundwater flow component of the P2R Model is constructed using the MODFLOW-2000 software (Harbaugh et al., 2000, *MODFLOW-2000, The U.S. Geological Survey Modular Ground-Water Model—User Guide to Modularization Concepts and the Ground-Water Flow Process*). The contaminant fate and transport component is constructed using the MT3DMS software (Zheng and Wang, 1999, *MT3DMS: A Modular Three-Dimensional Multispecies Transport Model for Simulation of Advection, Dispersion, and Chemical Reactions of Contaminants in Groundwater Systems; Documentation and User's Guide*) as follows:

- MODFLOW-2000 is a three-dimensional, finite difference groundwater flow model code developed by the U.S. Geological Survey (USGS) that solves Darcy's law, subject to mass balance constraints.
- MT3DMS is a three-dimensional transport model code that simulates advection, dispersion, and chemical reactions by solving the advection-dispersion equation for solute transport in a porous medium.

Development of the USGS's MODFLOW has been ongoing since its initial release in the early 1980s. In 1990, the U.S. Environmental Protection Agency (EPA) published the first version of the MT3D software (a precursor to MT3DMS) as a companion code to MODFLOW to simulate contaminant fate and transport based on the flow fields output from MODFLOW (Zheng, 1990, *MT3D – A Modular Three-Dimensional Transport Model for Simulation of Advection, Dispersion and Chemical Reaction of Contaminants in Groundwater Systems*), and development of this code has also been ongoing. These codes are publicly available: since their development, they have been widely accepted by the scientific community and have been used in numerous applications worldwide.

The P2R Model was developed to meet the needs of simulating contaminant transport from the Central Plateau in both the near-field and the distal far-field areas toward the Columbia River. Version 7.1[2] of the P2R Model was the original version released in 2015 (CP-57037, *Model Package Report: Plateau to River Groundwater Transport Model, Version 7.1*, Rev. 0). In 2018 , revisions to the P2R Model were completed to incorporate new data and enhancements, including a new grid structure, a longer calibration period, and spatially varying hydraulic properties (CP-57037, Rev. 1). These changes were initiated to address regulatory agency comments regarding the model on the 200-BP-5 OU (DOE/RL-2009-127) and the 200-PO-1 remedial investigation report addendum (DOE/RL-2009-85 ADD1). Version 8.2 of P2R Model will be the initial version used for the CIE saturated zone facet. The model will continue to be revised periodically to incorporate new information on the Hanford Site hydrogeological environment; these future revisions will be used for the saturated zone facet as they become available.

The P2R Model has been successfully used for several applications on the Hanford Site (Table 4-3).

[2] Version numbers for the P2R Model are based on the CHPRC "build" of the USGS MODFLOW software followed the model version. Version 7.1 uses CHPRC build 7 of the MODFLOW code and is the first version of the P2R model. Version 8.2 uses CHPRC build 8 of the MODFLOW code and is the second version of the P2R model.

Table 4-3. Applications of the P2R Model

Model Version	Year	Reference	Description
7.1	2015	ECF-Hanford-13-0031, *Fate and Transport Modeling for Baseline Conditions for Remedial Investigation/Feasibility Studies of the 200-BP-5 and 200-PO-1 Groundwater Operable Units*	Simulated fate and transport of groundwater plumes to support risk screening for the 200-BP-5 and 200-PO-1 groundwater OUs.
	2015	ECF-200BP5-15-0009, *Evaluation of Plume Capture and Hydraulic Performance for B-Complex Vicinity Submodel for 200-BP-5 and 200-PO-1 Operable Units Feasibility Study Evaluation of Remedial Alternatives*	Evaluated drawdown and capture zones for remedy wells in the B Complex area to support the 200-BP-5 groundwater OU feasibility study. The modeling was performed using a local-scale model constructed from the P2R Model by telescopic mesh refinement.
	2016	ECF-200BP5-16-0145, *Particle Tracking and Transport Modeling in Support of Removal Action Memorandum*	Supported evaluations of a non-time-critical removal action at the B Complex area by simulating the extraction of contaminated groundwater using the same local-scale model developed from the P2R Model for ECF-200BP5-15-0009.
	2018	ECF-HANFORD-18-0023, *Evaluation of Contaminant Transport for the 200-BP-5 and 200-PO-1 Operable Units Feasibility Study Evaluation of Remedial Alternatives*	Evaluated alternative P&T remedies for B Complex and C Tank Farm in the 200 East Area, and in Gable Gap, to support the combined 200-BP-5 and 200-PO-1 groundwater operable units feasibility study.
8.2	2019	ECF-200BP5-19-0035, *Simulations of Focused Feasibility Study Remedy at B Complex*	Performed simulations for P&T system design at the B Complex in support of an interim action record of decision using the local-scale model updated to Version 8.2 of the P2R Model.
	2019	ECF-200BP5-19-0036, *Simulations of Focused Feasibility Study Remedy at Waste Management Area C*	Performed simulations for P&T system design for the C Tank Farm in support of an interim action record of decision using a local-scale model developed from the P2R Model.

This table lists notable applications of the Plateau to River Groundwater Model identified by version applied, but not every application of this model is necessarily listed.

4.2.2 Groundwater Flow Model

Model construction is the process of creating model inputs representing the CSM (Section 4.1) within the model domain. This section describes the groundwater flow component of the P2R Model and Section 4.2.3 describes the contaminant fate and transport component of the model. Parameterization of groundwater flow model inputs includes descriptions of the model domain and discretization (Section 4.2.2.1), hydraulic properties (Section 4.2.2.2), and boundary conditions (Section 4.2.2.3), including specified head and flux boundaries, the Columbia River boundary, recharge, and P&T systems. These parameters will be initially set to represent simulations of Hanford's historical period, and some will be calibration parameters (e.g., hydraulic properties and Columbia River interaction) modified within reasonable bounds so that model outputs match historical data (Section 4.3). However, some of these parameters (e.g., boundary conditions, recharge, P&T system flow rates) will need to be modified using best estimates of future conditions to perform predictive simulations that forecast future plume movement and concentrations. This is addressed in Section 4.5.

4.2.2.1 Model Domain and Discretization

The domain of the P2R Model was chosen to include contaminant plume extents associated with the four groundwater OUs in the Central Plateau: 200-BP-5, 200-PO-1, 200-UP-1, and 200-ZP-1 OUs (Figure 4-13). Extending 26.1 km (16.2 mi) north to south and 31.0 km (19.3 mi) east to west, the domain encompasses the 200 East and 200 West Areas and extends east and southeast to the Columbia River, the region in which contaminant plumes from the Central Plateau migrate.

The model domain is discretized laterally and vertically into a finite difference grid. Laterally, the grid is divided into 100 by 100 m (328.1 by 328.1 ft) cells that cover the majority of the Central Plateau, and 100 by 200 m (328.1 by 656.2 ft) cells and 200 by 200 m (656.2 by 656.2 ft) cells that cover the far-field areas (e.g., east and southeast of the Central Plateau toward the Columbia River) of the model domain. The domain is divided vertically into seven layers that represent the thickness of the suprabasalt aquifer. Seven model layers are needed to represent adequately the HSUs present within the model domain (CP-57037, Rev. 1) and are discussed in Section 4.1.2. The thickness of the vertical layers varies to parallel the thickness of the HSUs.

The top elevation of the uppermost basalt below the Hanford Site defines the bottom boundary of the model and is considered a no-flow boundary in most areas. Where the basalt rises above the water table (shown in dark gray in Figure 4-13), the model lateral boundary is also considered a no-flow boundary. As stated in Section 4.1.3, some areas of the uppermost basalt surface consist of permeable flow top breccia able to transmit water (SGW-41072). Where permeable flow top is known to exist, it is simulated in the model as a portion of the saturated thickness of the suprabasalt aquifer.

The entirety of the model domain lies within the boundaries of the HSGF (ECF-HANFORD-13-0029), created to provide a continuous representation of hydrostratigraphic formation thicknesses across the southern portion of the Hanford Site (south of Gable Butte and Gable Mountain) and to integrate the interpretation into a consistent format to estimate geology for Hanford Site projects. Table 4-4 describes the HSUs as they are present in the HSGF and includes one additional HSU to represent the high conductivity paleochannel sediments that extend from Gable Gap southeast through and beyond the 200 East Area. This HSU is not delineated as part of the HSGF because it cannot be uniquely distinguished based on geologic characteristics alone. A subregion of the Hanford formation, CCU, and Ringold unit E HSUs and included in the P2R Model, the high conductivity zone vertical extent was assumed to be in the uppermost part of the aquifer, and its lateral extent was determined using the high concentration portion of the tritium plume as well as the calibration process (the extent of this zone is shown farther below in Figure 4-15 of Section 4.2.2.2). CP-57037, Rev. 1, provides further discussion on the development of the high conductivity HSU.

Figure 4-14 shows a comparison of a cross section through both the HSGF (inset a) and the finite difference grid (inset b) created for the P2R Model. Below the water table (i.e., below the blue line on insets a and b), the P2R Model grid and the HSGF show agreement with respect to the thickness assigned each HSU.

4.2.2.2 Hydraulic Properties

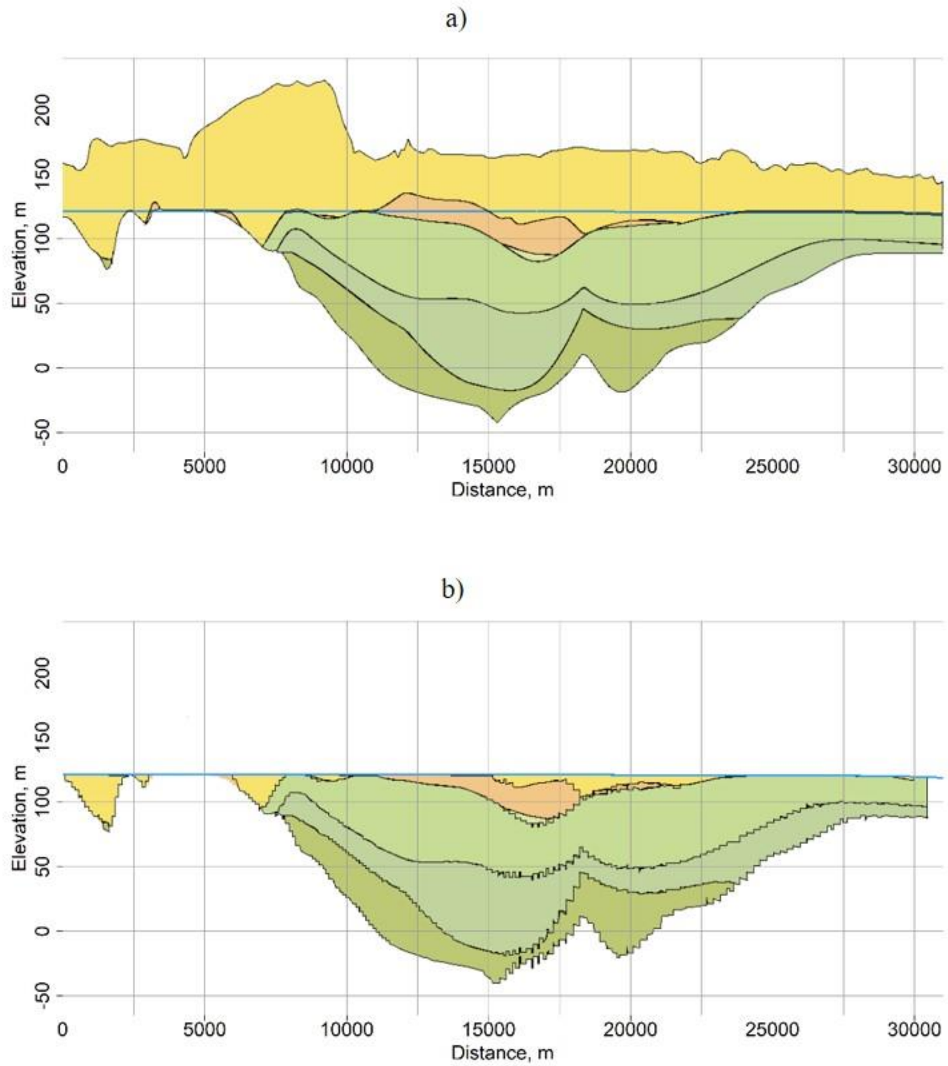
Field data and analyses are used to develop representative model input parameters for the P2R Model. Key input parameters include hydraulic properties and boundary conditions. Boundary conditions include specified head boundaries, the Columbia River boundary, natural and anthropogenic recharge, and injection/extraction wells for pump-and-treat systems. This section summarizes hydraulic property input parameters for the P2R Model.

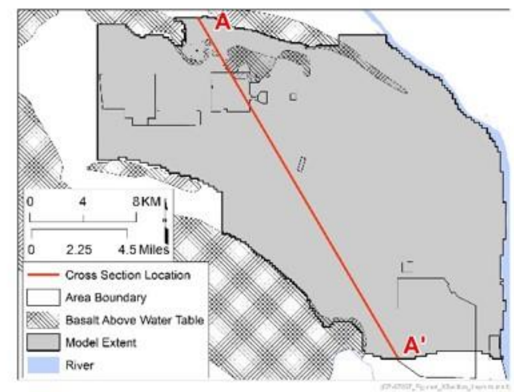
Table 4-4. Description for HSUs Present in the P2R Model

Description	Notes
High conductivity zone	High energy deposit zone within Hanford Site Central Plateau characterized by a relatively flat water table not defined in the Hanford South Geoframework but determined through the model calibration process (CP-57037, Rev. 1)
Hanford formation coarse-grained unit	Dominated by gravel and sand within the aquifer
Cold Creek unit	Dominated by gravelly sand; also called the pre-Missoula gravel
Ringold Formation member of Taylor Flat	Uppermost Ringold Formation unit dominated by sands and silts (BHI-00184)
Ringold Formation member of Wooded Island – unit E	Composed primarily of fluvial gravel that grades upward into interbedded fluvial sand (BHI-00184)
Ringold Formation member of Wooded Island – lower mud unit	Composed of a thick sequence of fluvial overbank, paleosol, and lacustrine silts and clay with minor sand and gravel (PNNL-13858)
Ringold Formation member of Wooded Island – unit A	Composed primarily of fluvial gravel (PNNL-13858)

References: BHI-00184, *Miocene- to Pliocene-Aged Suprabasalt Sediments of the Hanford Site, South-Central Washington*.
CP-57037, *Model Package Report: Plateau to River Groundwater Model, Version 8.2*, Rev. 1.
PNNL-13858, *Revised Hydrogeology for the Suprabasalt Aquifer System, 200-West Area and Vicinity, Hanford Site, Washington*.

The hydraulic properties used as input parameters for the P2R Model are hydraulic conductivity, specific yield, and specific storage, which are entered into the MODFLOW layer property flow package (Harbaugh et al., 2000). Hydraulic conductivity is the constant of proportionality in Darcy's law relating groundwater flow to hydraulic gradient (i.e., the amount of water transmitted in an aquifer per unit cross-sectional area [i.e., specific discharge] under a unit hydraulic gradient). Specific yield and specific storage are parameters that relate water volume changes in the aquifer to changes in hydraulic head, so they maintain water mass balance in the model. Specific yield applies to model layers containing the water table, whereas specific storage applies to layers entirely below the water table. Hydraulic properties were developed using a combination of aquifer testing results and the model calibration process. The values were constrained within the bounds presented in published aquifer test reports.





Note: The high conductivity zone hydrostratigraphic unit (HSU) is composed of portions of the Hanford, Cold Creek, and Ringold unit E HSUs. It is not shown in this figure, but its lateral extent is depicted in Figure 4-15. Basalt bedrock occurs below the lowermost HSU occurring at every point along this cross section.

Source: Modified from CP-57037, *Model Package Report: Plateau to River Groundwater Model, Version 8.2*, Rev. 1.

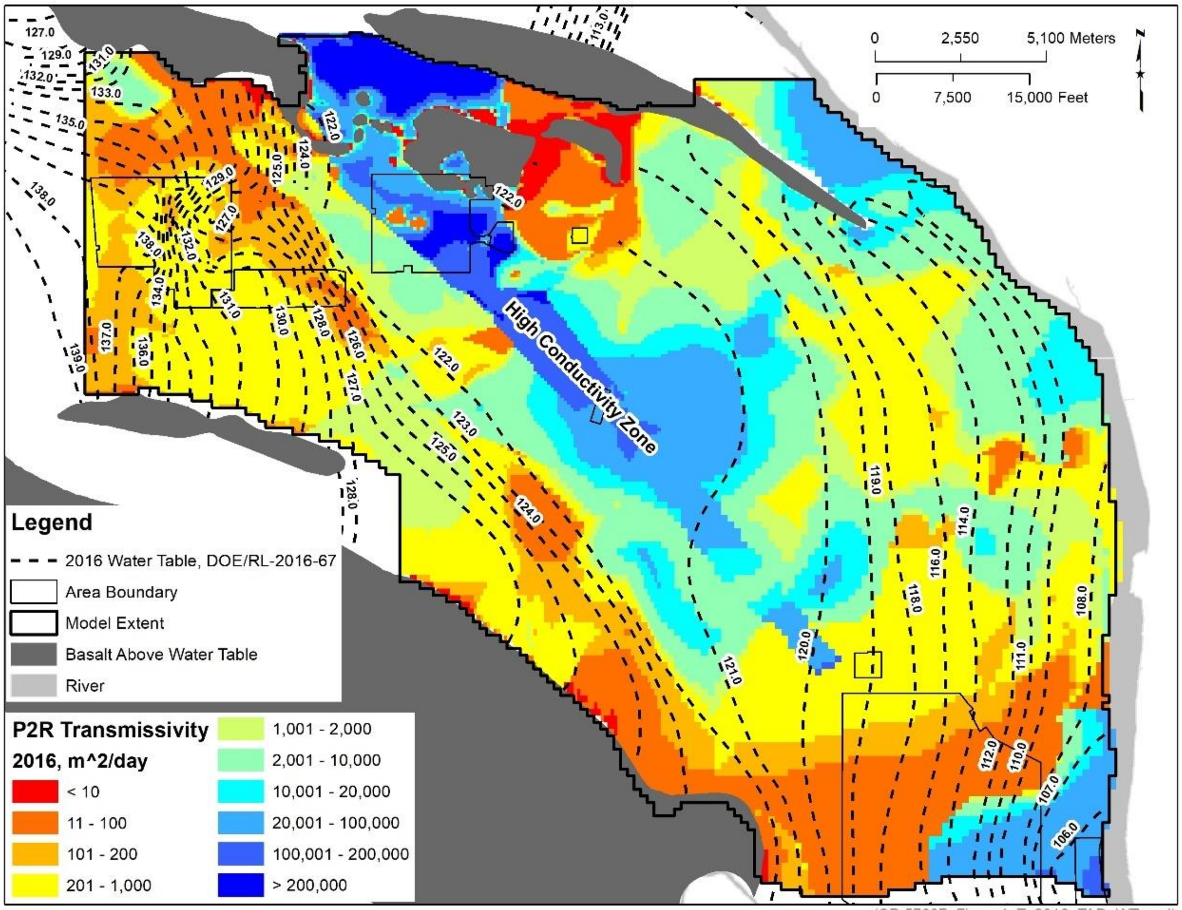
Figure 4-14. Comparison Cross Section View of (a) HSGF HSU Estimates and (b) Initial P2R Model Grid HSU Assignments

Table 4-5 summarizes the hydraulic properties for the HSUs resulting from calibration of the P2R Model (Section 4.3). The calibrated values are within the range of property values determined from aquifer testing (compare with the tables and data in Section 4.1.2.1).

Table 4-5. Calibrated Hydraulic Property Summary for P2R Model Version 8.2

Hydrostratigraphic Unit	Hydraulic Conductivity (m/day)		Specific Yield (-)	Specific Storage (1/m)
	Minimum	Maximum		
High conductivity zone	1,002	21,514	0.25	0.00002846
Hanford formation	0.6	4,959		
Cold Creek unit	1.0	4,959		
Ringold Formation member of Taylor Flat	0.52	120	0.08	
Ringold Formation member of Wooded Island – unit E	0.11	96		
Ringold Formation member of Wooded Island – lower mud unit	0.0026	0.053		
Ringold Formation member of Wooded Island – unit A	0.075	61.5		

Figure 4-15 provides a transmissivity map of the model that generally shows the spatial variation in the hydraulic conductivity field. Transmissivity is a quantitative estimate of the ability of aquifer sediments to transmit water from one location to another: a higher transmissivity indicates that the sediments can transmit water more easily, and a lower number indicates the opposite. Transmissivity in Figure 4-15 was calculated by multiplying the hydraulic conductivity (summarized in Table 4-5) by the simulated saturated thickness based on the hydraulic head field for the calendar year 2016. A major feature of the transmissivity field is the high conductivity HSU (shown in the center of Figure 4-15), which runs from Gable Gap in the north toward the southeast, and is necessary to reproduce reasonably the relatively flat water table observed through the center of the model domain.

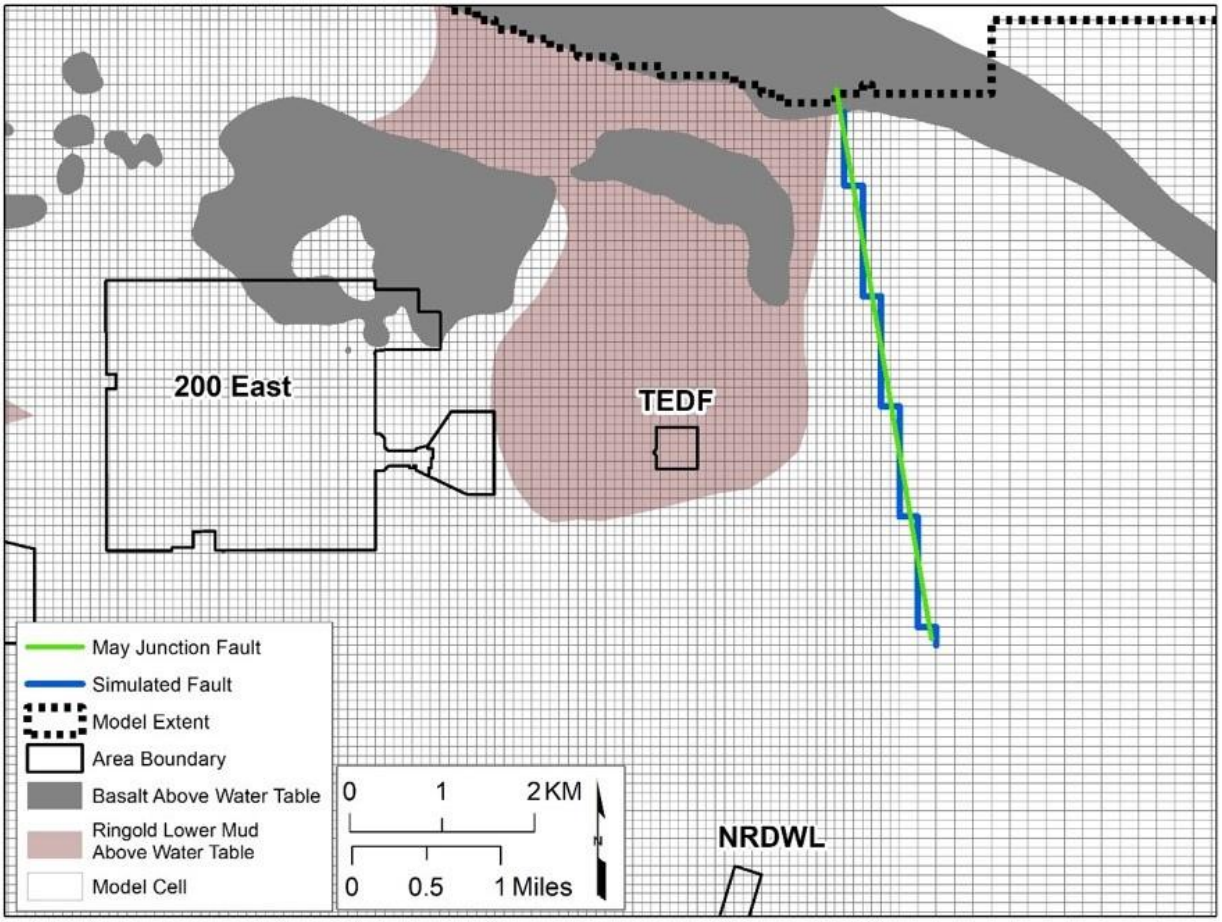


(CP-57037_Figure4_T_2016_TAD_WT.mxd)

Source: Modified from CP-57037, *Model Package Report: Plateau to River Groundwater Model Version 8.2*, Rev. 1.
Reference: DOE/RL-2016-67, *Hanford Site Groundwater Monitoring Report for 2016*.

Figure 4-15. Simulated Transmissivity Field for the P2R Model Version 8.2 (All Model Layers Combined) Based on Simulated Water Table, 2016

The P2R Model accounts for the hydraulic effects of the May Junction fault (Figure 4-16). A horizontal flow barrier was assigned to layers 5 through 7 (lower Ringold unit E, lower mud unit, and Ringold unit A, respectively) along the plane of the fault using the MODFLOW horizontal flow barrier package (Hsieh and Freckleton, 1993, *Documentation of a Computer Program to Simulate Horizontal-Flow Barriers Using the U.S. Geological Survey's Modular Three-Dimensional Finite-Difference Ground-Water Flow Model*). The hydraulic characteristic (i.e., hydraulic conductivity divided by barrier width) assigned to the flow barrier is 0.00692 day^{-1}. This barrier affects Ringold unit A and the lower Ringold unit E (layers 5 through 7 in the model) but not the upper part of the unconfined aquifer.



Source: Modified from CP-57037, *Model Package Report: Plateau to River Groundwater Model, Version 8.2*, Rev. 1.

Figure 4-16. Location of the Horizontal Flow Barrier Cells Used to Simulate the May Junction Fault

4.2.2.3 Boundary Conditions and Pump and Treat Systems

Conditions on the boundaries of a numerical model need to be defined so that the amount of water entering or exiting the model can be determined (external boundaries). Internal boundary conditions such as flow rates for extraction and injection wells (i.e., sources and sinks) must also be defined. The two most common types of boundary conditions are as follows:

1. Specified head or flux– Values of either hydraulic head or water flux at the model boundary are specified as input parameters, and the model calculates the other parameter (head or flux) consistent with the specified values. A no-flow boundary is a type of specified flux boundary where the flux is zero. Extraction and injection well flow rates are a type of specified flux boundary.

2. Head-dependent boundary – The amount of water entering or exiting the model is calculated based on the difference between head at the model boundary and a specified head across the boundary outside the model domain as well as the hydraulic conductivity of the boundary region and distance between the head locations. If the model boundary head is lower than the specified head outside the model, water enters the model domain. If the model boundary head is higher than the specified head, water exits the model domain.

Basalt bedrock underlies the lowermost HSU and as described in Section 4.1.3, it is a barrier to groundwater flow (where permeable flow top is absent); thus, the lower boundary of the P2R Model is a no-flow boundary. Further, basalt is a lateral no-flow boundary where it occurs above the water table (Figure 4-13).

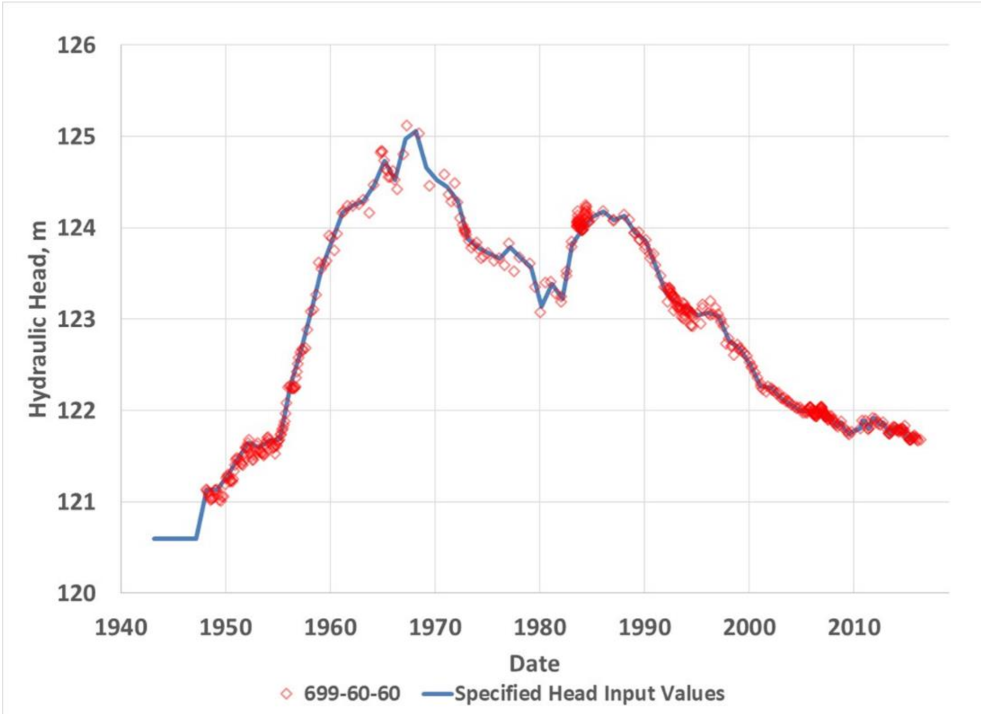
Another type of no-flow condition occurs on the southeast boundary of the P2R Model. This boundary is selected to be far enough south to encompass future migration of contaminants that originate on the Central Plateau but north of the 300 Area because contamination originating there is addressed in other models. This boundary was then aligned with a groundwater flow streamline so that flow is parallel to and does not cross the southern boundary.

The remaining boundaries in the P2R Model are described in the following sections.

Specified Head Boundaries. Four locations (indicated in red in Figure 4-13) at the boundary of the P2R Model occur where basalt is not present above the water table, with water entering or exiting the model by lateral flow from saturated sediments outside the model domain. Specified head boundary conditions were selected in these locations, and the specified head values were determined as follows:

- The western boundary of the model is assigned head values based on measured water levels as well as estimated and projected fluxes from the Cold Creek and Dry Creek Valleys.
- Water-level data from well 699-60-60 (available in the Hanford Environmental Information System [HEIS] database) were used to set the head for the Gable Gap boundary (well locations are shown in Figure 4-13). Figure 4-17 shows the well 699-60-60 water-level measurement data and the specified heads used to define this boundary.
- The model boundary in the mid-southern portion of the P2R Model near Dry Creek Valley is defined by historical head data from well 699-10-54A (Figure 4-18). For time periods prior to the start of data collection at well 699-10-54A (pre-1951), the water table elevation was based on a hydraulic head estimate for 1944 prior to operations at the Hanford Site (BNWL-B-360, *Selected Water Table Contour Maps and Well Hydrographs for the Hanford Reservation, 1944-1973*).
- In the northeastern corner of the model (near the Columbia River), specified heads were developed from a set of wells (699-54-18B, 699-54-19, and 699-58-24). Collectively, data from these three wells provide a historical record of hydraulic head data from 1956 through 2016. Figure 4-19 shows the observed data from each well and the curve representing the simulated values assigned as specified heads at the northeast boundary. The observed hydraulic heads exhibit short-term fluctuations due to changes in Columbia River stage. A low pass filter was used to screen out the high frequency fluctuations, and the results were used to assign the specified head boundary condition. Prior to the availability of historical data, the hydraulic head was estimated from the hindcast maps documented in BNWL-B-360.

Specified heads were entered into the model using the MODFLOW general head boundary package (McDonald and Harbaugh, 1988, “A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model”).



Note: Period prior to 1948 was estimated through calibration.

Figure 4-17. Specified and Observed Head Values at the Gable Gap Boundary of P2R Model Version 8.2 for the Historical Calibration Simulation

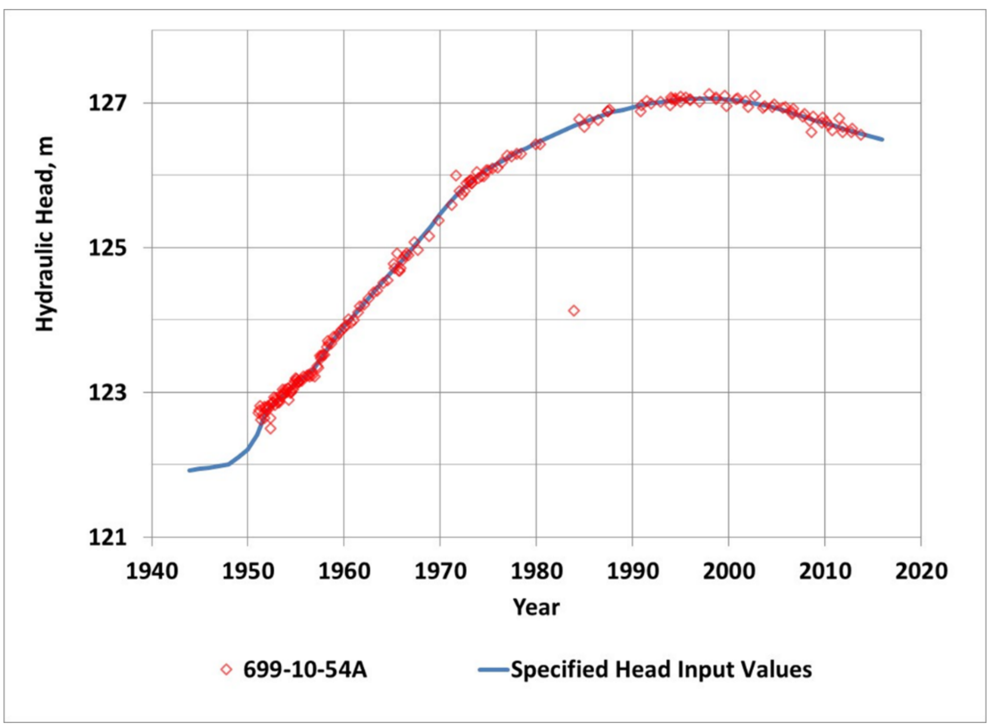
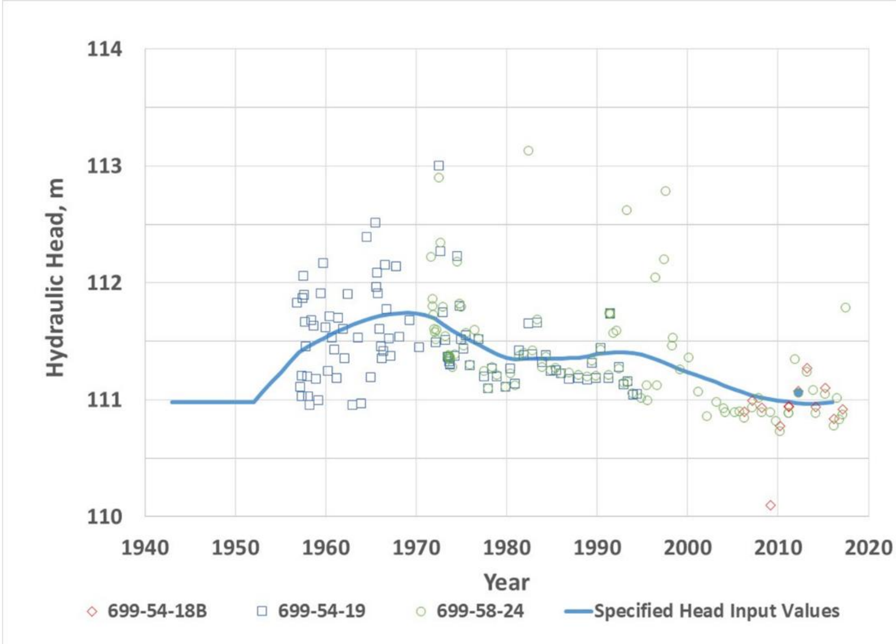


Figure 4-18. Specified and Observed Head Values at the Dry Creek Valley Boundary of P2R Model Version 8.2 for the Historical Calibration Simulation



Note: A low pass filter was used to screen out the high frequency fluctuations due to river stage, and the results were used to assign the specified head boundary condition.

Figure 4-19. Specified and Observed Head Values at the Northeastern Boundary of P2R Model Version 8.2 for the Historical Calibration Simulation

Columbia River Boundary. The Columbia River is a regional discharge area for the suprabasalt aquifer. Using the MODFLOW river package (McDonald and Harbaugh, 1988), the model calculates the water flux across the boundary based on the hydraulic properties of the boundary and the head difference between river stage and hydraulic head on the model boundary (head-dependent boundary). If the boundary heads are higher than river stage, water discharges from the aquifer into the river. If the boundary heads are lower than river stage, water enters the model domain from the river (bank storage). As explained in Section 4.1.3.3, average river stage during the year is lower than the average head in the adjacent aquifer, and the net flow condition is that water from the aquifer discharges into the river.

The P2R Model bases the river stage along the Columbia River on the Modular Aquatic Simulation System 1D (MASS1) river stage model (PNNL-15226, *Hydrodynamic Simulation of the Columbia River, Hanford Reach, 1940-2004*). This model is a one-dimensional flow and water quality model of the Columbia River between Priest Rapids Dam (upstream of the Hanford Site) and McNary Dam (downstream of the Hanford Site). Input data to the model consists of bathymetry and inflows from upstream (Priest Rapids Dam) and tributaries (Yakima and Snake Rivers). The model is calibrated to river stage data collected along the Hanford Reach at river gages located at each reactor area (100B, 100N, 100D, 100H, and 100F) and the 300 Area. Confidence in the MASS1 simulated river stage is sufficient enough that the model was used to assess the effects of potential 100- and 500-year floods on the Hanford Reach (PNNL-26204, *Simulation of Columbia River Floods in the Hanford Reach*).

To set river stage values for the P2R Model, the long-term average river stage at each P2R Model element along the river was determined using the MASS1 model results. To incorporate temporal river stage changes, the average discharge was determined for each year at Priest Rapids Dam, the inflow location of the MASS1 model. The rating curve for the Priest Rapids Dam gage was used to calculate the corresponding average river stage at the gage location based on the average discharge. Then, the difference of this stage value from its long-term average was used to adjust the stage at each P2R Model element along the river by the same amount. This process preserves the representative river gradient calculated by the MASS1 model and simulates the effects of temporal changes in river stage.

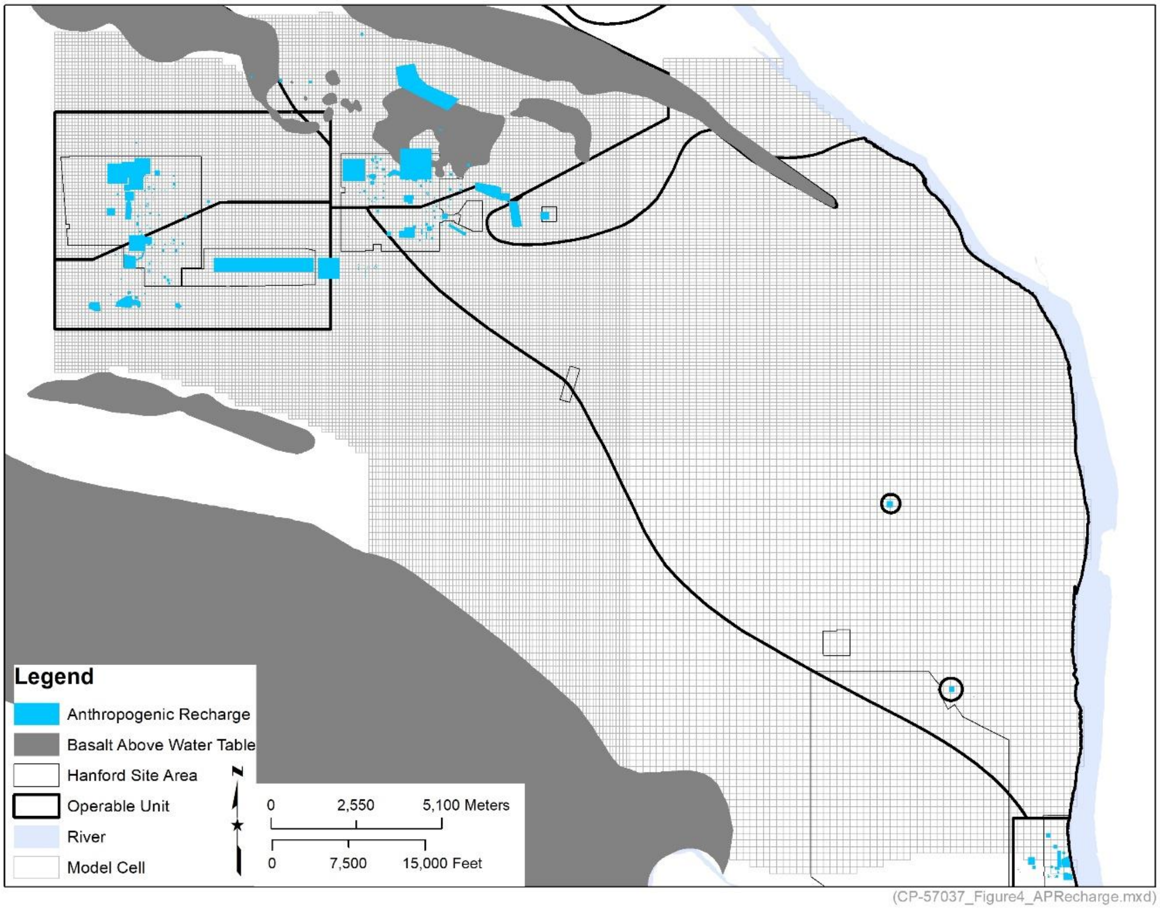
Natural and Anthropogenic Recharge. Recharge within the P2R Model domain is comprised of natural recharge, mountain-front recharge, and anthropogenic recharge. These are specified flux boundaries in that the amount of water entering the model domain is specified as an input parameter using the MODFLOW recharge package (McDonald and Harbaugh, 1988). Natural recharge includes deep percolation of precipitation that is not evaporated/transpired and is not retained in storage in the vadose zone. Mountain-front recharge includes infiltration of snowmelt and runoff from Rattlesnake Mountain. Anthropogenic recharge is derived from wastewater discharges at the Hanford Site. The total recharge is the sum of each of the three components. Additional recharge components of the conceptual model, that is, runoff and irrigation return-flows from Cold Creek and Dry Creek Valleys (Section 4.1.3) are implicit in the specified heads for the western boundary and Dry Creek Valley boundary of the model.

A GIS-based tool will be developed to manage natural recharge (i.e., deep percolation of precipitation) information (Section 3.5.2.2). The tool will allow for spatial and temporal changes in recharge across the site and will consider soil type, vegetation type, and surface condition (e.g., presence of infiltration barriers). It will estimate natural recharge during the Hanford operational period as well as provide forecasts of recharge based on expected future surface conditions of waste sites.

Anthropogenic recharge includes water discharged to the aquifer from waste sites, ponds, sewers, french drains, and documented unplanned releases for the entire Hanford Site operational period. Anthropogenic recharge estimates are provided in EMDT-BC-0002.[3] The data include the magnitudes and locations of operational discharges for the simulated time periods and annual projections into the future. Figure 4-20 shows the discharge locations listed that exist within the P2R Model domain. For large waste sites, the footprint overlaps more than one model cell. In cases where overlap occurs, the total discharge is distributed on an area-weighted basis to all cells that intersect the discharge location footprint.

Historical effluent discharges on the Hanford Site have been well characterized for radiologically contaminated effluent, but other sources of anthropogenic recharge such as non-radiologically contaminated historical discharges, storm water runoff, dust suppression water, pipeline leaks, septic systems, etc. have not been as well characterized. An investigation and development task will be conducted as part of the CIE maintenance program (Chapter 6) to characterize these other recharge sources for potential input into the P2R Model.

[3] EMDT-BC-0002, 2017, *Vadose Zone Attenuated Recharge, Electronic Modeling Data Transmittal – Boundary Condition (Artificial Recharge) – 0002*, Rev. 1, CH2M Hill Plateau Remediation Company, Richland, Washington. This is a data transmittal; a copy is provided in the appendices of CP-57037.



Source: CP-57037, *Model Package Report: Plateau to River Groundwater Model, Version 8.2*, Rev. 1.

Figure 4-20. Model Grid Cell Locations Affected by Anthropogenic Recharge in the P2R Model

Pump and Treat Systems. Groundwater injection and extraction on the Central Plateau is simulated in the P2R Model using the multi-node well package for MODFLOW and the contaminant treatment system package for MT3DMS (Konikow, et al., 2009, *Revised Multi-Node Well (MNW2) Package for MODFLOW Ground-Water Flow Model* and Bedekar, et al., 2016, *MT3D-USGS Version 1: A U.S. Geological Survey Release of MT3DMS Updated with New and Expanded Transport Capabilities for Use with MODFLOW*, respectively). Simulation of injection and extraction allows the model to replicate historical behavior of current P&T system operations. Historical pumping rates are obtained from annual summary reports for the 200-ZP-1 and 200-UP-1 OUs (e.g., DOE/RL-2017-68) as documented in Appendix H of CP-57037, Rev. 1 (EMDT-ST-0004[4]). The physical specifications for the relevant wells are available in the HEIS database (available at: https://ehs.hanford.gov/eda/) and are the same as presented in ECF-200ZP1-16-0076, *Description of Groundwater Calculations and Assessments for the Calendar Year 2015 (CY 2015) 200 Areas Pump and Treat Report*.

4.2.3 Transport Model Parameters

The transport model (MT3DMS) simulates the movement and fate of solutes in the aquifer and calculates their concentrations over time. It uses the same grid as the groundwater flow model (Section 4.2.2.1), and

[4] EMDT-ST-0004, 2014, *Historical Pumping Rates 200 West Area*, Rev. 0, CH2M Hill Plateau Remediation Company, Richland, Washington. This is a data transmittal; a copy is provided in the appendices of CP-57037.

hydraulic heads calculated by the flow model are input to the transport model to allow for groundwater flow direction and velocity to be determined.

The parameters necessary for fate and transport simulations are bulk density, dispersivity, porosity, K_d, and first-order decay rate (Tables 4-6 and 4-7). These parameters are entered into MT3DMS using the basic transport, dispersion, and chemical reaction packages (Zheng and Wang, 1999). Table 4-6 shows the parameters for contaminants anticipated to be included in the initial CIE simulations (Section 2.3).

Table 4-6. Contaminant Transport Parameter Values for the P2R Model Version 8.2

COC	K_d (mL/g)	Half-Life (yr)	Half-Life (day)	Degradation Rate (day^{-1})	Reference: K_d	Reference: Degradation Rate
Tritium	0	12.3	4,500	0.000154	Table 6.9 in PNNL-18564	Appendix F in CP-57037, Rev. 1
Uranium (and U-238)	0.4	4,740,000,000	1,630,000,000,000	0.000000000000425		
Iodine-129	0.1	15,700,000	5,370,000,000	0.000000000121		
Technetium-99	0	211,000	77,100,000	0.00000000899		
Strontium-90	12	28.8	10,500	0.0000660		
Nitrate	0	No decay				ECF-200ZP1-16-0076
Hexavalent chromium Cr(VI)	0					
Cyanide	0				PNNL-19277	Assumed [a]
Trichloroethene	0.025				ECF-200ZP1-16-0076	ECF-200ZP1-16-0076
Carbon tetrachloride	0.011	41.3 (630) [b]	15,100 (230,000) [b]	0.0000459 (0.00000301) [b]	DOE/RL-2009-38	PNNL-13560 (PNNL-22062)

Note: Complete reference citations are provided in Chapter 7.

a. Degradation of cyanide is possible, but there is no site-specific information on degradation rates in Hanford Site groundwater; therefore, the conservative assumption is made that cyanide does not degrade.

b. The half-life and degradation rate, as applicable, for carbon tetrachloride was initially estimated in PNNL-13560 at the values provided, but later work (PNNL-22062) indicated best site-specific values as indicated by the numbers in parentheses. The relationship between half-life and decay rate is: t1/2=ln(2)/decay rate.

COC = contaminant of concern

K_d = distribution coefficient

Table 4-7. Aquifer-Dependent Transport Parameter Values for the P2R Model Version 8.2

Property	Value	Comments
Effective porosity	0.15	Approximate central value (Table D-2 in DOE/RL-2007-28)
Longitudinal dispersivity	3.5–6.2 m	Based on grid cell size according to Schulze-Makuch, 2005
Transverse dispersivity	0.7–1.24 m	20% of longitudinal (consistent with the ratio specified in DOE/RL-2008-56)
Vertical dispersivity	0.0 m	DOE/RL-2008-56
Molecular diffusion constant	0.0 m^2/day	Negligible term

Table 4-7. Aquifer-Dependent Transport Parameter Values for the P2R Model Version 8.2

Property	Value	Comments
Bulk density, Hanford formation, Cold Creek unit	1.93 g/cm^3	PNNL-18564, Table 6.2
Bulk density, Ringold Formation member of Taylor Flat, Ringold Formation member of Wooded Island – unit E, Ringold Formation member of Wooded Island – lower mud unit, Ringold Formation member of Wooded Island – unit A	1.90 g/cm^3	PNNL-18564, Table 6.2

Note: Complete reference citations are provided in Chapter 7.

PR2 = plateau to river (model)

4.3 Model Calibration

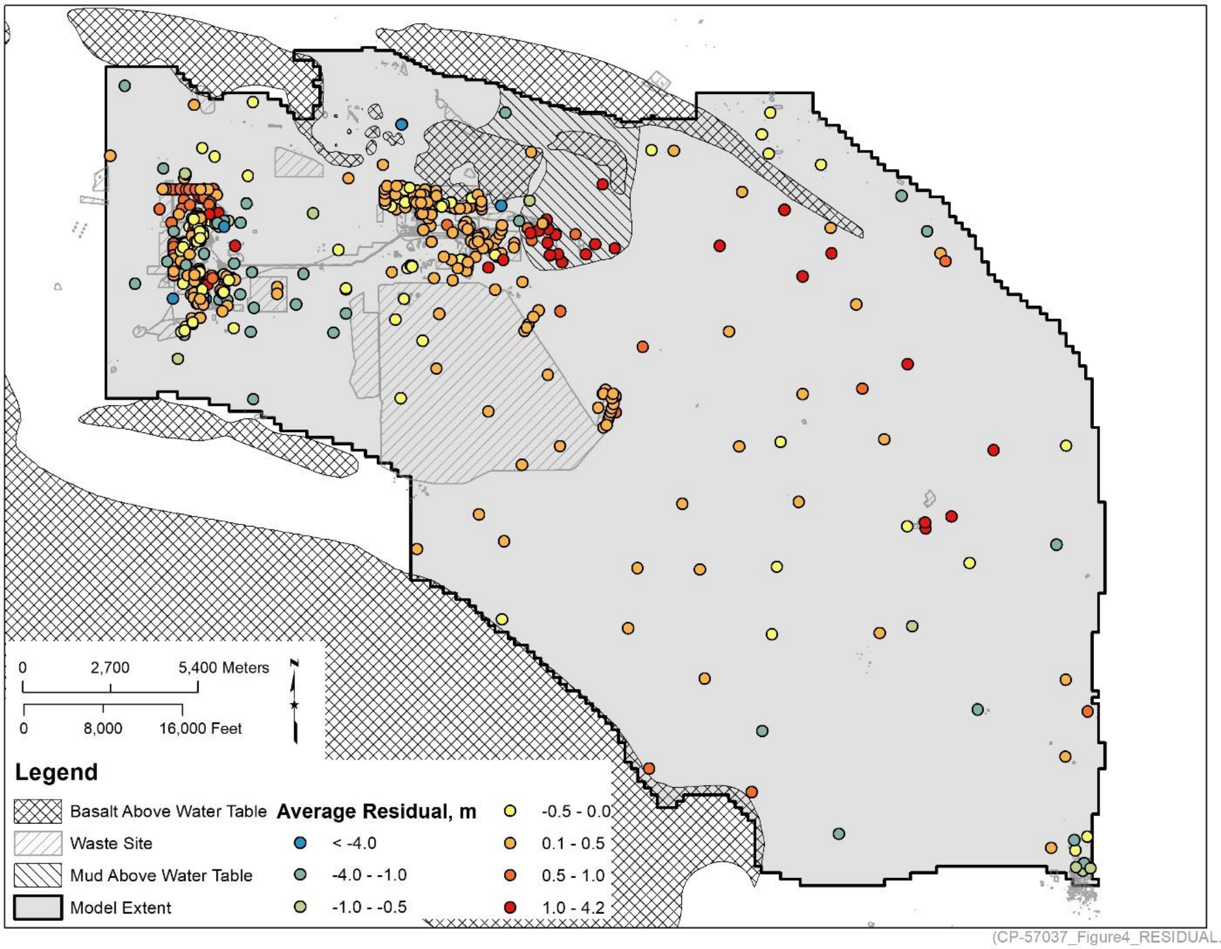
The P2R Model calibration process was performed by comparing simulated results to observed hydraulic head data from 1944 to 2016, hydraulic gradient direction and magnitude calculated from the measured water levels, and estimates of contaminant plume concentration. Model input parameters (hydraulic conductivity, mountain-front recharge, areal extent of anthropogenic recharge for B Pond and Gable Mountain Pond, and Columbia River boundary condition hydraulic properties) were adjusted to reduce the differences between the observations of hydraulic head and the simulated results.

The difference (or sensitivity) in the model results varies by parameter. It was found that recharge from Rattlesnake Mountain was the most sensitive of the calibration parameters due to the large area affected in the model. The next most sensitive was hydraulic conductivity followed by hydraulic properties at the Columbia River boundary. The least sensitive parameter was the areal extent of anthropogenic recharge at B Pond and Gable Mountain Pond. A more complete discussion of sensitivity can be found in CP-57037, Rev. 1.

The goal of the P2R Model calibration process was to produce a model that is a representative of the suprabasalt aquifer within the model domain. The remainder of this section emphasizes key aspects of the conceptual model (Section 4.1) and how they are represented in the numerical model. A detailed summary of the calibration results can be found in CP-57037, Rev. 1.

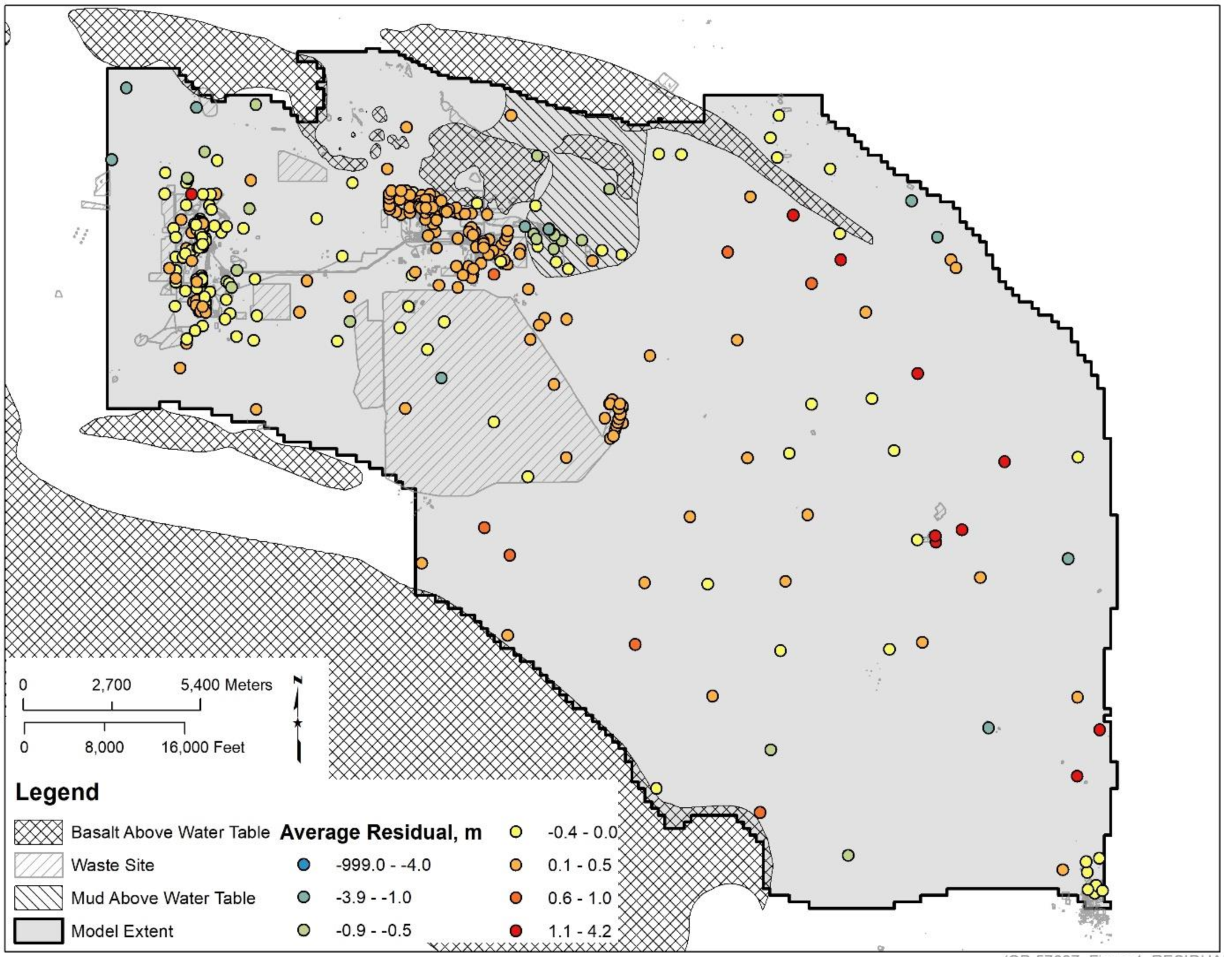
4.3.1 Hydraulic Head

The ability of the P2R Model to reproduce historical head data was quantified by comparing model results to measurements from 479 monitoring wells. Average residuals are examined for this purpose. A residual is the difference between the observed and the simulated hydraulic head at a given well; the average residual is the mean of all residuals at a given well for all observations within a given time period. The average residual can then plotted at each respective well location for all wells to provide a spatial overview of model's goodness of fit within a time period. Average residuals for the period from 1944 to 2016 are shown in Figure 4-21. The residuals are mixed in the 200 West Area where average simulated water levels are higher than the measured values in some areas and lower in others. In the 200 East Area and along the paleochannel to the southeast, simulated water levels tend to be lower than measured values but are generally by less than 0.5 m. Average residuals for 2008 to 2016 (Figure 4-22) show very good agreement between simulated and measured values in the 200 West Area and a slightly low bias for the simulated water levels in the 200 East Area and paleochannel.



Source: CP-57037, *Model Package Report: Plateau to River Groundwater Model, Version 8.2*, Rev. 1.

Figure 4-21. Average Difference Between the Calibrated P2R Model Version 8.2 Water Levels and Measured Water Levels for Years 1944 to 2016

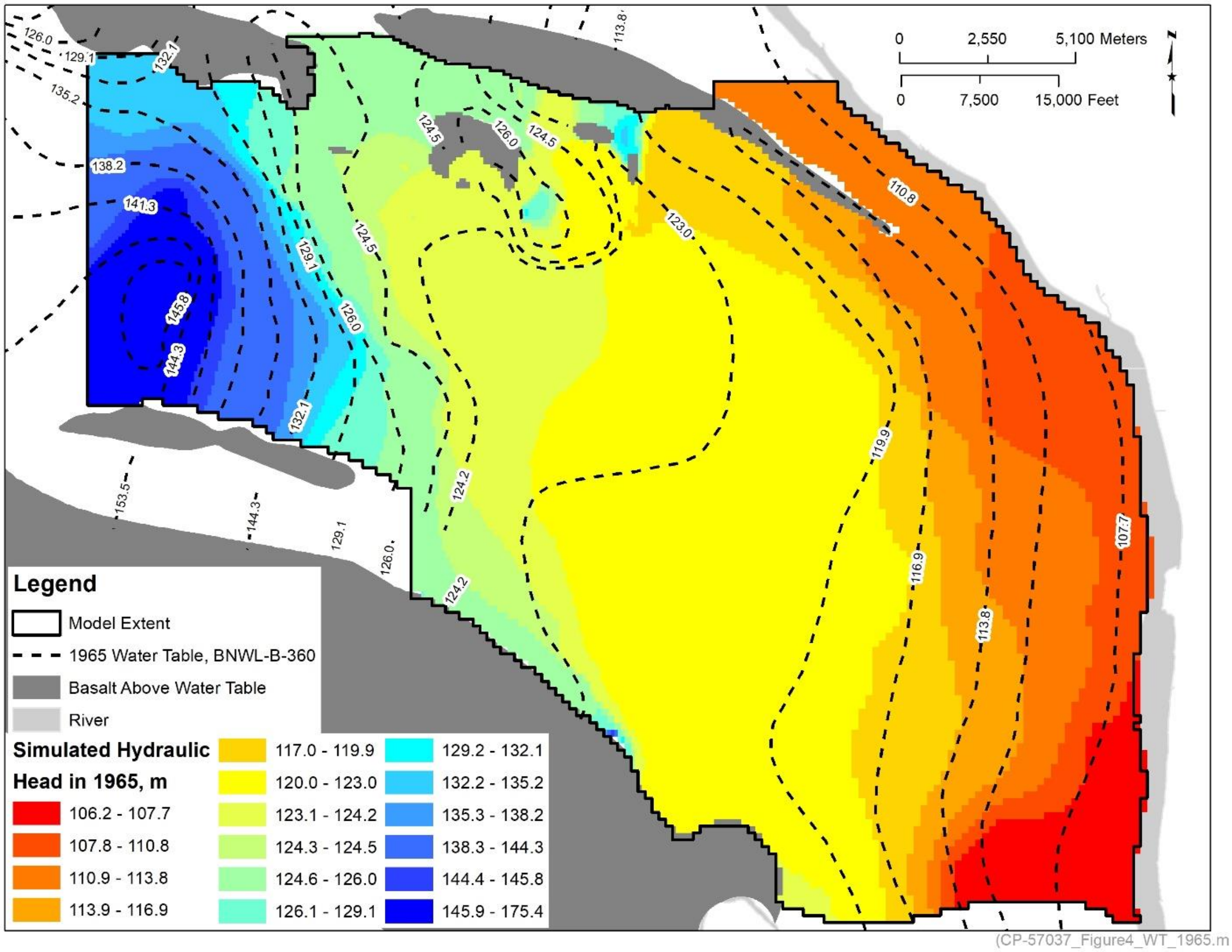


(CP-57037_Figure4_RESIDUAL_

Source: CP-57037, *Model Package Report: Plateau to River Groundwater Model, Version 8.2*, Rev. 1.

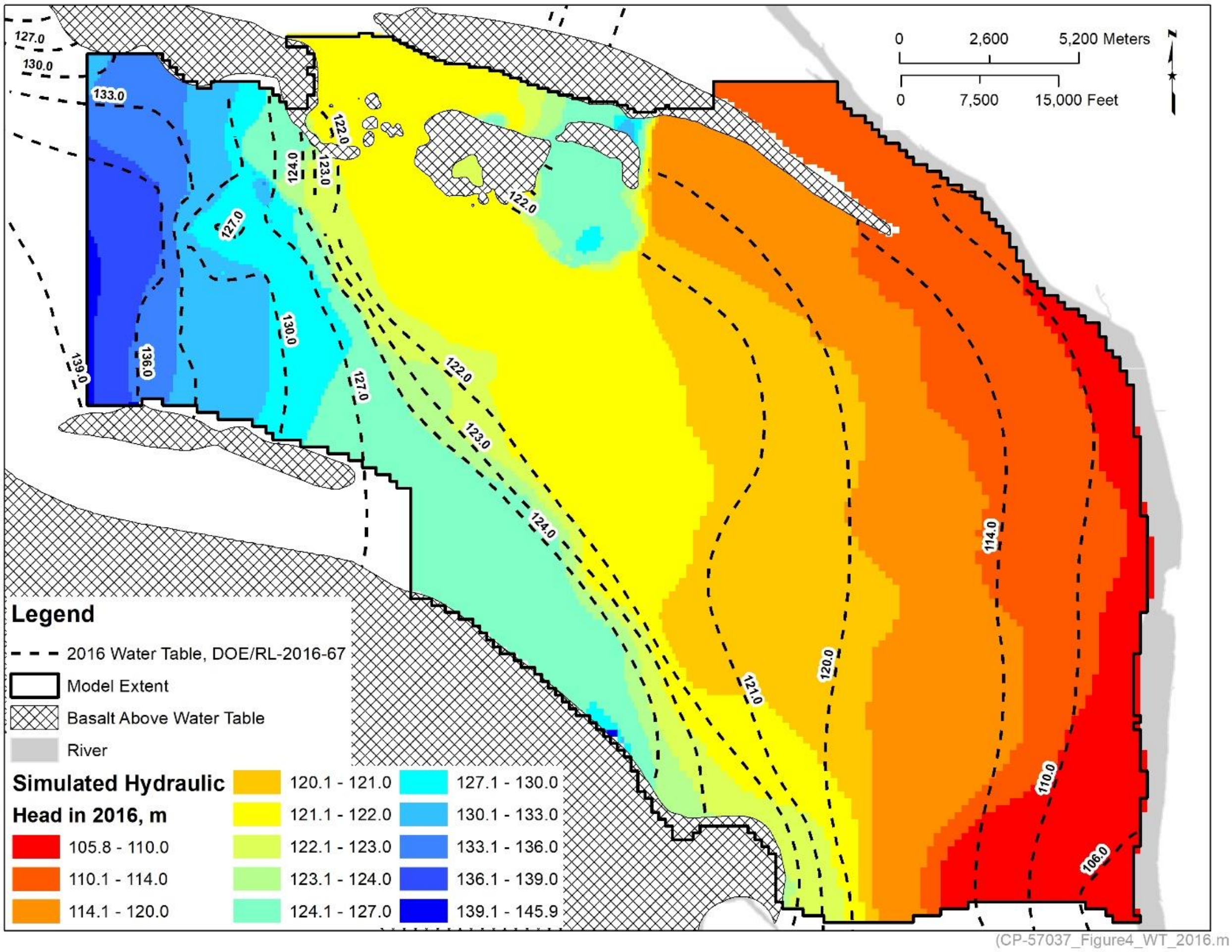
Figure 4-22. Average Difference Between the Calibrated P2R Model Version 8.2 Water Levels and Measured Water Levels for Years 2008 to 2016

To evaluate the model, simulated water table contours were compared to mapped contours for various years. The comparison for 1965 is shown in Figure 4-23. The model simulates the buildup of water table mounds beneath U Pond in the 200 West Area and B Pond near the 200 East Area. Steep hydraulic gradients occur in the west and along the Columbia River to the east and the simulated gradient is lower along the paleochannel, in agreement with the mapped water table. Simulated and mapped water table contours for 2016 are compared in Figure 4-24. The groundwater mounds associated with U Pond and B Pond have dissipated (discharges to U Pond and B Pond ceased after 1984 and 1997, respectively), and the water table has become even more flat in the paleochannel as evidenced by the lack of contours in this region. Drawdown from the 200 West P&T is evident in the deflection of the 130.0 m contours in the 200 West Area.



Source: Modified from CP-57037, *Model Package Report: Plateau to River Groundwater Model, Version 8.2*, Rev. 1.
Reference: BNWL-B-360, *Selected Water Table Contour Maps and Well Hydrographs for the Hanford Reservation, 1944-1973*.

Figure 4-23. Comparison of Simulated and Observed Water Table Contours for 1965



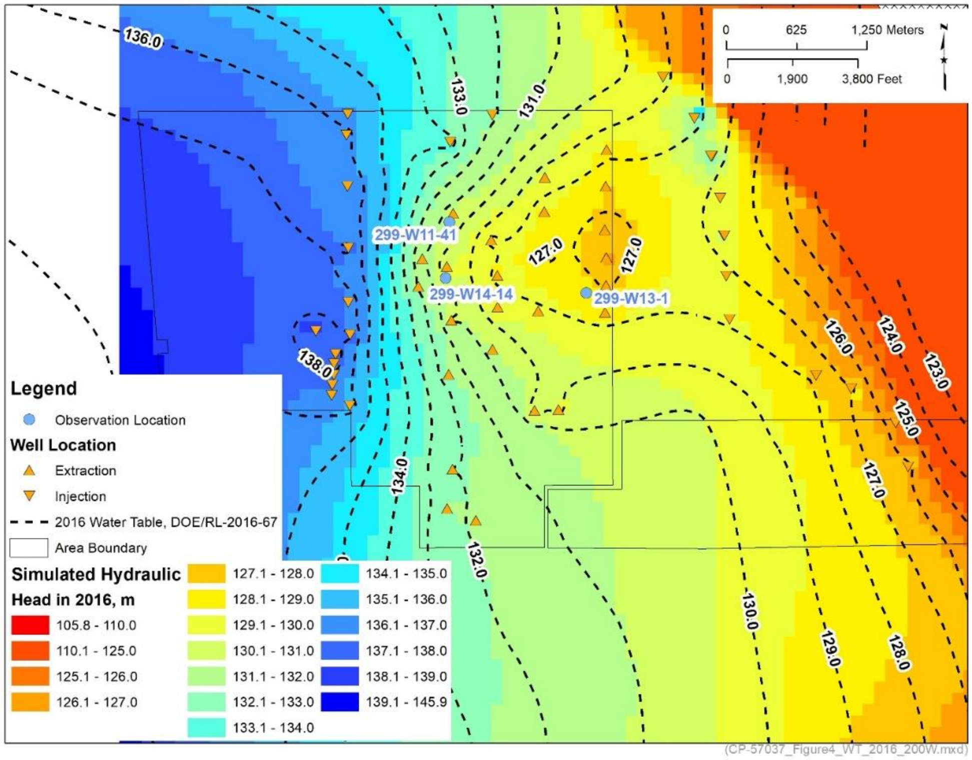
Source: CP-57037, *Model Package Report: Plateau to River Groundwater Model, Version 8.2*, Rev. 1.
Reference: DOE/RL-2016-67, *Hanford Site Groundwater Monitoring Report for 2016*.

Figure 4-24. Comparison of Simulated and Observed Water Table Contours for 2016

4.3.1.1 200 West Pump and Treat

Operation of the 200 West P&T has resulted in substantial drawdown of the water table in the northeastern part of the 200 West Area. The 2016 observed water table in the 200 West P&T vicinity is compared to the water table simulated by the P2R Model in Figure 4-25. The region of maximum drawdown and the overall pattern of flow toward the extraction wells are in good agreement between the mapped and simulated results.

Figure 4-26 shows hydrographs comparing simulated and observed water-level responses in three monitoring wells near the 200 West P&T (well locations are shown in Figure 4-25). The timing and rate of drawdown in the simulated water levels are in good agreement with the field measurements. These comparisons between the simulated and measured water levels demonstrates that the model successfully represents the hydraulic effects of the P&T remedy.



Reference: DOE/RL-2016-67, *Hanford Site Groundwater Monitoring Report for 2016*.

Figure 4-25. Comparison of Simulated and Observed Water Table Contours for 200 West P&T, 2016

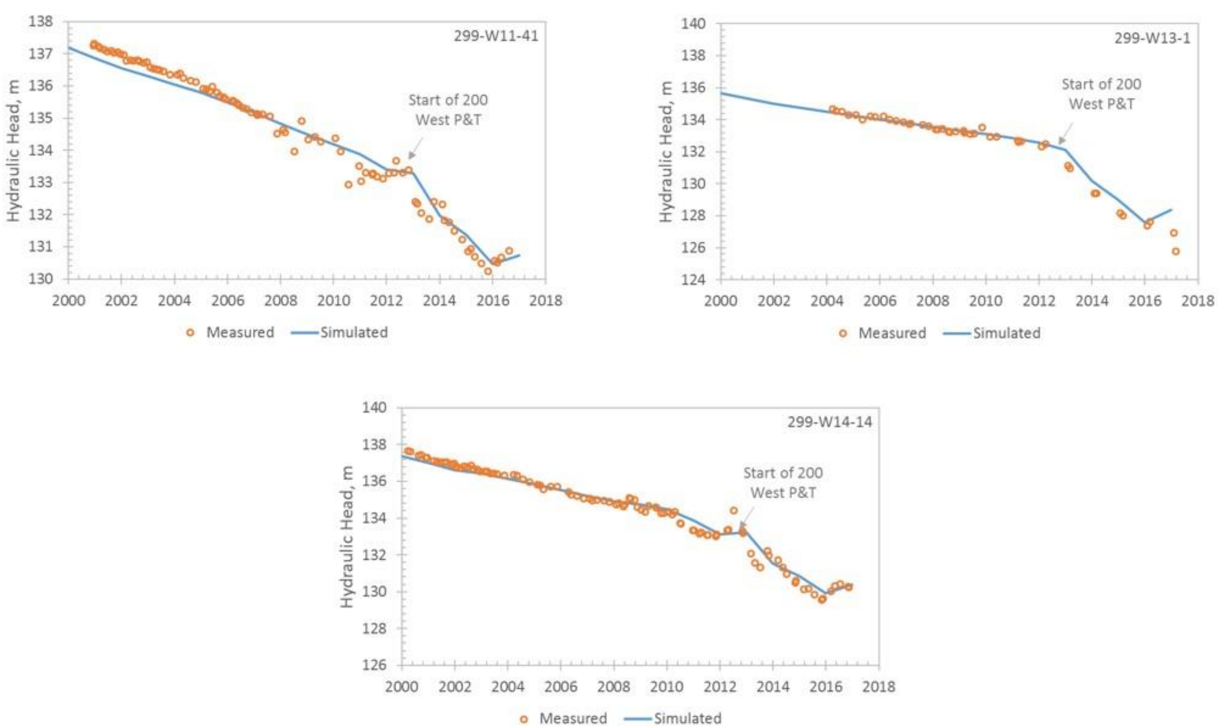


Figure 4-26. Comparison of Simulated and Observed Water Levels in Monitoring Wells Near 200 West P&T

4.3.2 Groundwater Flow Directions

It is possible to achieve an acceptable match between simulated and measured water levels in a model that does not adequately represent groundwater flow conditions. Small differences in water levels can have a significant effect on groundwater flow direction even though hydraulic heads may agree within a reasonable limit. Therefore, groundwater flow directions also are an important metric for evaluating model representativeness. Flow directions were evaluated in the P2R Model by particle tracking, in which particles were released from contaminant sources zones in the 200 East and 200 West Areas and their movement through the aquifer was simulated (flow directions were also evaluated by hydraulic gradient comparisons found in CP-57037, Rev. 1).

Pathlines of particle movement are shown in Figure 4-27 compared with 2017 mapped groundwater plumes. The particles were released at the start of the historical simulation (1943), and there is reasonable agreement between the simulated groundwater flow directions indicated by the pathlines and actual flow directions indicated by the location and orientation of the plumes. Many of the particles from the 200 East Area migrate southeast along the paleochannel and then turn northeast and reach the Columbia River south of the Hanford Townsite in agreement with the path the tritium plume followed to reach the river (Figure 4-6 in Section 4.1.3). Even though this analysis does not account for continuing releases of contaminants to groundwater over time, it generally indicates that flow directions simulated by the P2R Model are representative of field conditions.

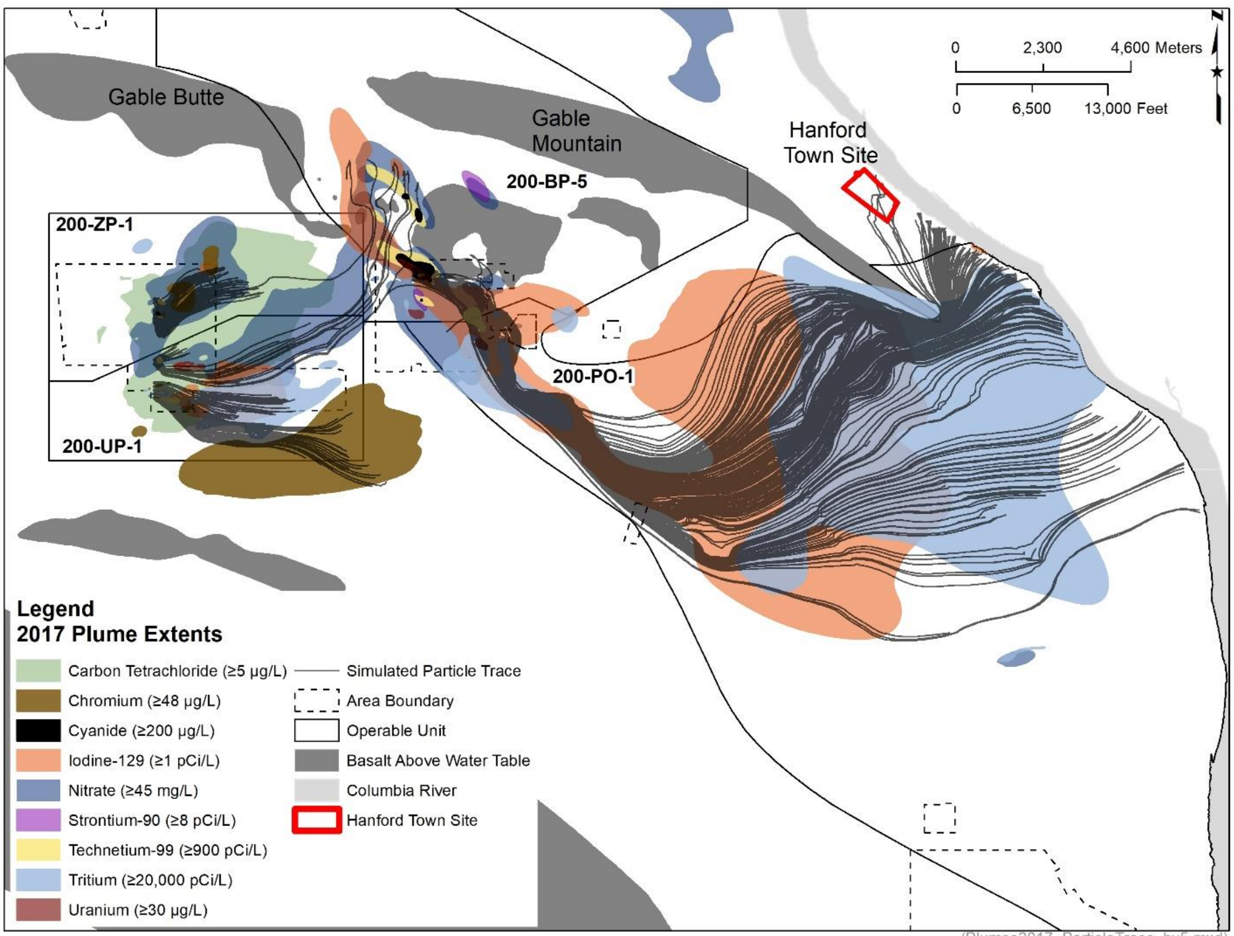


Figure 4-27. Groundwater Flow Directions in the P2R Model Compared to the 2017 Groundwater Plumes

4.3.2.1 200 East Area Flow Divide

When B Pond was operating, the addition of water to the aquifer resulted in a flow divide in the central 200 East Area (Section 4.1.3.1), causing water to flow out of the 200 East Area both to the southeast and to the north through Gable Gap. As effluent release volumes declined and B Pond ceased operating, the water table beneath the 200 East Area was reduced, and the flow divide shifted to the north. In 2011, a reversal of the flow direction in the northwestern 200 East Area from northwest to southeast was documented as the flow divide migrated through this area (SGW-54165).

Figure 4-28 shows the location of the flow divide as simulated in the P2R Model between 1990 and 2016. In 1990, the simulated flow divide was in the southern part of the 200 East Area; in later years, the flow migrates to the north as the water table declines. In 2016, the simulated flow divide coincides with an anticlinal ridge north of the 200 East Area in agreement with observations (compare Figure 4-28 with Figure 4-12).

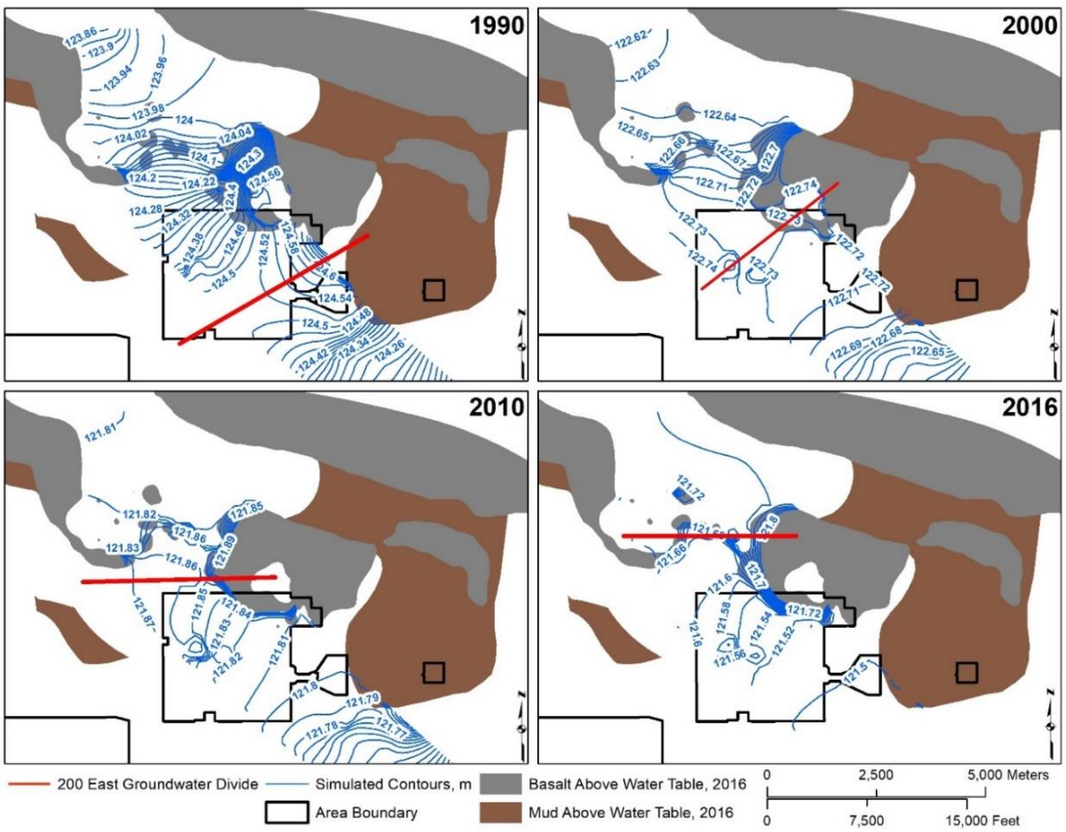


Figure 4-28. Simulated Migration of the 200 East Area Flow Divide in the P2R Model

The particle tracking analysis and the simulated movement of the 200 East Area flow divide provides added confidence that the simulated results from the P2R Model approximate aquifer behavior.

4.4 Predictive Simulation

Although the calibration of the P2R Model focused on simulating historical conditions in the suprabasalt aquifer, the objective of the CIE saturated zone facet is to provide estimates of future contaminant concentrations in the aquifer. The predictive simulations will use the current distribution of plumes (Figure 4-1) as the starting conditions and incorporate estimates of future source contaminant releases to the aquifer provided by the vadose zone facet described in Chapter 3. Predicting future fate and transport of contaminants requires several input parameters and data sets of the P2R Model to be adjusted from the historical calibration presented in Section 4.3. The technical approach for addressing model inputs that require adjustment (which include temporal discretization, boundary conditions and source/sinks, the initial contaminant distribution, and contaminant mass source terms) are presented in Sections 4.5.1 through 4.5.4, respectively.

4.4.1 Temporal Discretization

Like the spatial domain of the P2R Model, time must be discretized as specified in the discretization file for MODFLOW and the basic transport file for MT3DMS. In the P2R Model, time is discretized into specific intervals within which source-term release rates and boundary condition values defined in the model remain constant and can be changed only from one interval to the next. The shorter the time intervals, the better the resolution on the source-term release rates and boundary conditions.

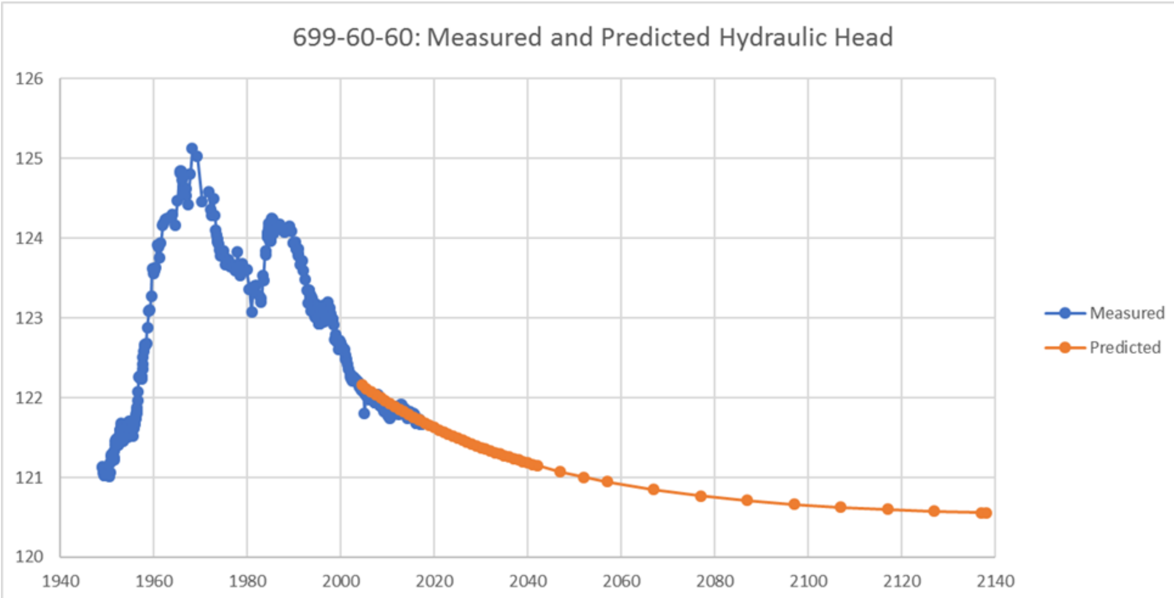
Temporal discretization of the initial CIE runs will be based on the preliminary results of the vadose zone facet. Time intervals will be chosen to represent adequately the source-term breakthrough curves to groundwater, ensuring that the total contaminant flux calculated by the vadose zone facet is preserved from both a total mass and peak mass perspective. In addition, an evaluation of boundary conditions and source/sinks will be performed to identify changes that must be represented in the model.

4.4.2 Boundary Conditions and Pump and Treat Systems

Model parameters representing the specified head boundaries, interaction with the Columbia River, recharge, and extraction and injection rates at pumping wells will need to be adjusted to simulate the predictive timeframe required by the CIE. The approach for developing each of these parameters for predictive simulation is described in the Sections 4.5.2.1 through 4.5.2.4, respectively.

4.4.2.1 Specified Head and Flux Boundaries

During the historical simulation period used for model calibration, specified head boundary conditions at the western boundary, Gable Gap, Dry Creek, and the northeastern boundaries were based on water-level measurements (and estimates of recharge flux from the Cold Creek Valley for the western boundary). During the predictive simulation period in which future transport of the plumes is simulated, future values of the boundary conditions must be predicted and input into the model. Future projections of specified head boundaries will use the process from ECF-Hanford-13-0031, *Fate and Transport Modeling for Baseline Conditions for Remedial Investigation/Feasibility Studies of the 200-BP-5 and 200-PO-1 Groundwater Operable Units*, and ECF-200W-17-0043, *Capture-Zone and Particle-Tracking Analysis for the 200-UP-1/200-ZP-1 Areas Using the 2017 Updated Central Plateau Model*. As an example, the future Gable Gap boundary condition in ECF-200W-17-0043 was determined by estimating the future steady-state water level in well 699-60-60, which was used to define the boundary condition during the historical period. An exponential declining curve was then fitted to the last several years of water-level measurements until the steady-state level was approached asymptotically; Figure 4-29 shows the results. The asymptotic low was selected by hindcasting the early water-level measurements collected from 699-60-60 back to pre-operational times (1944).



Note: Example based on ECF-200W-17-0043, *Capture-Zone and Particle-Tracking Analysis for the 200-UP-1/200-ZP-1 Areas Using the 2017 Updated Central Plateau Model*.

Figure 4-29. Illustration of the Method Used to Determine Future Specified Head Boundaries

4.4.2.2 Columbia River Boundary

The Columbia River boundary is simulated using the MODFLOW river package, which uses a specified river stage value and head in the aquifer to determine the water flux across the boundary. As explained in Section 4.2.2.3, results from the MASS1 model along with measured changes in river discharge are used to set the stage values for each river boundary element in the P2R Model for the historical simulation period. For the predictive simulations, the stage values will be assigned based on the long-term average condition calculated from flow data from 1959 (during Priest Rapids Dam construction) to the present.

4.4.2.3 Natural and Anthropogenic Recharge

Natural recharge from percolation of net precipitation for the predictive model will be handled in the same manner as for the historic model. That is, the new GIS-based tool to manage spatial and temporal variability in natural recharge rates called for in Chapter 3 will be used to specify the time- and space-varying recharge rates over the top boundary of the P2R Model for the predictive simulation period.

Natural recharge rates used for the predictive simulations at waste sites will be modified to reflect projected future surface conditions under alternative baseline dispositions to be evaluated (discussed in Section 3.5.2.2). For example, if a barrier is placed over a waste site, the natural recharge for that portion of the model will be reduced to reflect the change in recharge due to the relative size and temporal lifecycle of the barrier. As noted in Section 3.5.2.2, accounting for spatial and temporal variations in recharge rates across multiple waste sites will be a complex task, so a GIS-based tool will be developed to manage this information.

Anthropogenic recharge for the predictive simulations will be processed in the same manner as the historical simulations in that anthropogenic recharge (projected by EMDT-BC-0002) through calendar year 2400 will be superimposed on the natural recharge field. Anthropogenic recharge values at the Treated Effluent Disposal Facility and the State Approved Land Disposal Site will be updated to reflect recorded discharges and updated projections since the issuance of EMDT-BC-0002.

A study involving other sources of anthropogenic recharge (e.g., storm drainage and sanitary systems not explicitly accounted for in EMDT-BC-0002 (Appendix E of CP-57037, Rev. 1) will be performed to augment the locations and quantities of anthropogenic recharge at the site (Section 3.5.2.2). These estimates will be incorporated into the P2R Model as they become available through the CIE maintenance program discussed in Chapter 6.

4.4.2.4 Pump and Treat Systems

Current and future P&T activities within the P2R Model domain will be simulated as part of the CIE using the MODFLOW multi-node well package. Estimates for future pumping will be developed based on the current configuration and information available in decision documents. Treated water is returned to the aquifer using injection wells, and future flow rates for these will also be developed. DOE/RL-2017-68 and the annual updates to this report will be used to develop the current injection and extraction well configurations for the Central Plateau. The expected duration of remedial alternatives will be based on OU decision documents.

4.4.3 Initial Contaminant Concentrations

The CIE will generate predictions of future contaminant concentrations in the aquifer using current plumes as the starting conditions. The initial plume conditions (input into the MT3DMS basic transport package; Zheng and Wang, 1999) will be based on the most recent published plumes in the Hanford Site annual groundwater reports (e.g., DOE/RL-2017-66) or other reports that document the interpreted groundwater plumes (e.g., ECF-200UP1-17-0238, *Development of the 3D Hexavalent Chromium Groundwater Plume using Leapfrog for Southeast 200-UP-1*). Most of the plumes generated for the annual reports are two-dimensional and represent areal extent and maximum concentrations in the aquifer for each constituent (the exception in the 200 West Area is carbon tetrachloride, which is mapped in three dimensions). These two-dimensional plumes will be evaluated to determine if available depth-discrete sampling data indicates substantial concentration changes with depth. If so, the plumes will be extrapolated to three dimensions using the available depth-discrete sampling data before translating the plumes onto the P2R Model grid. For plumes with no substantial concentration changes with depth, the two-dimensional plumes will be assumed to be fully mixed throughout the aquifer thickness.

The alternative to using current plumes would be to use vadose zone models to simulate the plumes from their inception to present conditions. However, such models would be assessed by their ability to reproduce current observed concentrations in groundwater. Thus, historical modeling of the plumes is not required because the same initial conditions can be achieved by using current interpretations of the groundwater plumes based on sampling results.

4.4.4 Vadose Zone Contaminant Sources

Estimated contaminant mass or activity reaching the saturated zone over time is the key input provided to the saturated zone facet from the vadose zone facet of the CIE (Chapter 3). The vadose zone facet will provide the estimates for mass or activity discharge for dates after the CIE numerical simulation start date (2018 for the initial CIE simulation). Contaminant mass or activity that arrived at the groundwater prior to the CIE simulation start date is represented in the initial condition contaminant plume distribution (discussed in Section 4.5.3). The numerical simulator to be used to implement the vadose zone models will be STOMP (PNNL-12030; see discussion in Chapter 3).

An interface tool is not currently available to enable the MODFLOW/MT3DMS codes used to construct the P2R Model to use the STOMP results directly as model input parameters. Therefore, the ICF facet of the CIE will provide a tool to convert the STOMP results to a format that can be used in P2R Model simulations. The framework tool will convert STOMP results using the hydrocarbon spill source (HSS) package (Zheng, 2010, *MT3DMS v5.3 Supplemental User's Guide, Technical Report*). Although written specifically for application to hydrocarbon spills, the HSS package can also be used for other contaminants, allowing for arbitrary, time-varying mass or activity sources to be input into the MT3DMS code for the P2R Model.

Normally, mass or activity loading of sources to MT3DMS must be specified as average loading rates over each time interval simulated in the model, so resolution of time-varying sources is limited by time discretization in the model (i.e., the number and lengths of the time intervals). With the HSS package, mass or activity loading rates can be specified independent of time discretization, allowing for mass or activity loading rates at an appropriate resolution for each source. The tool for reformatting the STOMP results will convert the STOMP simulation output to create the HSS package for use in the P2R Model.

4.5 Simulation Output

The saturated zone facet of the CIE produces information on contaminant concentration, hydraulic head, and water flux in the suprabasalt aquifer. Output files will be generated for each simulation that record these parameters over time throughout the P2R Model domain. Hydraulic head and groundwater flux will be used to illustrate groundwater conditions, including water table elevations, flow directions, and flow rates, during the predictive period. Predicted contaminant concentrations can be used to create plume maps and trend plots to identify areas of elevated concentrations for any given contaminant or multiple contaminants. Mass or activity within the saturated zone of the aquifer is tracked over time using the MT3DMS software, which records the mass or activity within individual computational cells and amount transferred between computational cells. As part of the code execution, the total mass or activity balance is tabulated, reported as part of standard model output, and includes the calculated fraction of mass or activity that enters any boundary condition, source, or sink (e.g., river boundaries, specified head boundaries, or extraction wells). Charts can be derived from the model output to illustrate how the estimated contribution of mass or activity to the river boundary and the total mass in the aquifer change over time. This information, including contaminant concentration, hydraulic head, and water flux, will be used to inform remedial action decisions for the source and groundwater OUs, thus providing details on cumulative impacts from all the OUs to the decision process.

4.6 Model Updates

The P2R Model is based on current information and will be used in the initial version of the CIE. However, ongoing investigations of source and groundwater OUs and WMAs may reveal additional information that will need to be incorporated in an update of the P2R Model. A process of continual improvement to the CIE saturated zone facet as experience is gained in CIE application is anticipated. Thus, the current configuration of the P2R Model is likely to change because of additional data and evolving application needs.

Two versions of the P2R Model have been released, versions 7.1 and 8.2. In the model package report for version 8.2 (CP-57037, Rev. 1), model enhancement recommendations were made for consideration when planning for future development of the model. The following sections describe planned updates for the P2R Model.

4.6.1 Western Model Boundary

The western edge of the P2R Model is located at the western boundary of the 200 West Area (Figure 4-13) defined by specified heads determined using measured water-level elevations in wells and estimates of the recharge flux from Cold Creek Valley. In the next version of the P2R Model, the boundary will be extended west to where basalt occurs above the water table, and the Cold Creek Valley will be represented as a specified flux boundary. This extension will simplify the boundary condition and allow for recharge from Cold Creek Valley to be a calibration parameter. Similarly, the boundary condition for Dry Creek Valley will be changed from a specified head to a specified flux boundary, and it will also become a calibration parameter.

4.6.2 Columbia River Boundary

The model boundary along the Columbia River will be extended eastward to the deepest part of the river channel. Thus, the saturated sediments below the river will be represented in the model, allowing for a better simulation of aquifer/river interaction. In addition, the MASS1 river stage model was recently updated to support an analysis of flood conditions along the Hanford Reach (PNNL-26204). The update resulted in a more precise simulation of river stage that will be incorporated into the P2R Model.

4.6.3 Recharge

As noted in Section 4.2.2.3, a GIS-based tool will be developed to manage natural recharge (i.e., deep percolation of precipitation) information (Section 3.5.2.2). The tool will allow for spatial and temporal changes in recharge across the site and will consider soil type, vegetation type, and surface condition (e.g., presence of infiltration barriers). This tool will estimate natural recharge during the Hanford Site operational period and provide forecasts of recharge based on expected future surface conditions of waste sites. Estimates of recharge using the tool will be incorporated into the P2R Model. In addition, results of the task that identify other sources of anthropogenic recharge such as storm water runoff, dust suppression water, pipeline leaks, septic systems, etc., will be incorporated into the model.

5 Quality Assurance

This chapter identifies how QA will be addressed in CIE tools development, maintenance, and application. DOE O 414.1D Chg 1, *Quality Assurance*, defines QA as actions that provide confidence that quality is achieved (10 CFR 830.3, "Nuclear Safety Management," "Definitions"). DOE O 414.1D defines a QA program as an overall program or management system that is established to assign responsibilities and authorities, define policies and requirements, and provide for the performance and assessment of work (10 CFR 830.3).

A QA project plan is an integral part of a project lifecycle for performing environmental assessments that use modeling. This process is informed by systematic planning and the development and continued refinement of a CSM. The creation of CSM(s) is a preliminary step that informs the development of a project quality assurance plan (QAP) in the project lifecycle. It identifies important features, events, and processes that must be properly represented in modeling contaminant sources, releases, fate, and transport to the points of potential exposure. The CSM continues to play an important role throughout the project lifecycle (EPA 542-F-11-011, *Environmental Cleanup Best Management Practices: Effective Use of the Project Life Cycle Conceptual Site Model*).

A CIE QAP will be written to augment existing QA plans and procedures that implement U.S. Department of Energy direction and EPA guidance. The CIE QA plan will also manage the complexity of the CIE tools as a multiple-model system and the interfaces within the contractor(s) existing QA plan framework. Section 5.1 summarizes the existing general QA plan, and Section 5.2 discusses the CIE QAP that will be developed to impose additional CIE-specific requirements. Recognizing that a best practice for environmental modeling QA is the use of independent peer review, the CIE tools approach and implementation will be subject to independent peer review, as discussed in Section 5.3.

5.1 Existing General Quality Assurance Plans and Associated Procedures

The prime contractor's QA plans and procedures must fully implement DOE quality requirements for the work identified to be performed for the CIE tools. This also includes flow down of the requirements of ASME NQA-1A-2008, *Quality Assurance Requirements for Nuclear Facility Applications*, and ASME NQA-1A-2009, *Addenda to Quality Assurance Requirements for Nuclear Facility Applications*, Addenda A, which are contractually required.

Work in support of developing and preparing the CIE tools will be performed under a general QA project plan for modeling. This plan is the primary means to manage quality in the development and use of environmental models. It specifies how DOE QA requirements and EPA guidance for quality project planning for modeling are to be implemented for environmental modeling projects. This general plan was expressly written to implement the guidance provided in EPA/240/R-02/007, *Guidance for Quality Assurance Project Plans for Modeling* (EPA QA/G-5M). This guidance was adapted to support quality model development and application as an ongoing service function that supports multiple model development and application efforts. The guidance provides tools for adding necessary information to meet individual project needs.

The CIE tools will be developed, checked, reviewed, and managed in compliance with the general QA project plan for modeling and the associated procedures that implement the following DOE requirements and EPA guidance:

- DOE O 414.1D Chg 1, *Quality Assurance*

- EM-QA-01, *EM Quality Assurance Program*
- EPA/240/R-02/007, *Guidance for Quality Assurance Project Plans for Modeling* (EPA QA/G-5M)
- EPA/240/R-03/003, *Guidance for Geospatial Data Quality Assurance Project Plans* (EPA QA/G-5G)
- EPA/240/B-01/003, *EPA Requirements for Quality Assurance Project Plans* (EPA QA/R-5)
- EPA CIO 2105-P-01-0, *EPA Quality Manual for Environmental Programs*
- EPA/100/K-09/003, *Guidance on the Development, Evaluation, and Application of Environmental Models*

The prime contractor's plans and procedures that implement the above requirements and guidance include the following:

- A general QA project plan for modeling that directs QA for all environmental modeling activities performed by the prime contractor, including requirements for modeler training, model preservation, model documentation, identification of quality objectives, and assessments of modeling activities. This is the source of requirements to develop model package reports used to document the development, calibration, and testing of major environmental models (e.g., the P2R Model discussed in Chapter 4).
- An environmental calculation file preparation and issue procedure to document the application of models to prepare environmental calculations, including requirements for independent checking, senior review, and management review.
- A software controlled-use procedure that implements the requirements of ASME NQA-1A-2008/ASME NQA-1A-2009 requirements imposed by DOE O 414.1D. This includes software lifecycle QA documentation requirements, software testing and acceptance process, and software installation and checkout requirements. For example, software management plans, test plans, requirement tracking, and test reports are in place for codes including:
  - GoldSim® (used to implement the SIM-v2 (CP-59798) inventory model, as discussed in Chapter 2).
  - Leapfrog-Geo® and Kingdom-Geology® (used for creation and maintenance of geoframeworks that integrate geologic data and interpretations into a three-dimensional representation of the subsurface structure that is used to create numerical model grids in the vadose zone and saturated zone facets). Note that the creation and maintenance of geoframeworks, including software use, is performed to the same QA requirements and processes for modeling as numerical modeling of flow and transport.
  - STOMP (used for variably saturated flow and transport modeling, as discussed in Chapter 3).
  - MODFLOW (used for saturated zone flow modeling, as discussed in Chapter 4) and MT3DMS (used for saturated zone transport modeling, as discussed in Chapter 4).

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® Leapfrog-Geo is a registered trademark of ARANZ, Christchurch, New Zealand.
® Kingdom-Geology is a registered trademark of IHS, London, UK.

- The ICF, which will be designed to integrate the other facets of the CIE tools and support automated QC of interfacet data feeds. The ICF will include a number of tools for data translation between facets that will be subject to the ASME NQA-1A-2008 requirements.
- New tools called for creation in this technical approach document will be subject to the same QA/ QC requirements for data input management, software use, and application evaluation as for the other tools noted above. This will include:
  - The GIS-based tool to manage natural recharge rates that vary in space and time to provide boundary conditions for both vadose zone and saturated zone models.
  - The database to be developed to manage disposition baselines and generation of scenarios for alternative future decisions for remediation that can be modeled using the CIE tools.
  - The database to be developed to manage anthropogenic recharge (effluent discharges to ground) over the Central Plateau, including new data and estimation methods to account for previously unaddressed sources.

- A model integration requirement that imposes additional requirements on environmental model calculations to ensure consistency of multiple modeling efforts at the Hanford Site.

5.2 Cumulative Impact Evaluation Quality Assurance Plan

The general requirements and guidance noted above are effective for single-model projects, but the need for additional QA is recognized for the CIE tools due both to its complexity and the use of multiple modeling codes, tools, and interfaces (Figure 5-1). Because the CIE tools will include multiple facets (multiple models) with numerous interfacet information feeds, the opportunity for error to be introduced in the interfaces between facets is recognized. This risk will be addressed by developing and using a CIE QAP. The QA for the CIE tools will need to account for complex transfers of information. For example, the results of the vadose zone facet shown in Figure 5-1 for contaminant release to groundwater represent temporally and spatially variable fluxes of contaminant mass or activity emerging at the bottom boundary of approximately million-node vadose zone models into a large-scale groundwater transport model. These fluxes will be translated across the differing time steps and spatial grids between the dozens of vadose zone models and the larger groundwater model at their interface (the water table) while preserving mass or activity.

Interfacet feeds managed by the ICF will be controlled in a structured database with automated QA tools developed and applied on the interfacet feeds into and out of that database. The ICF will include a simulation identification system to uniquely identify all interfacet feeds and allow traceability to original inputs (specific model runs from individual facets).

The CIE QAP will address three major quality processes:

- **Quality assurance (QA):** An integrated system of management activities involving planning, implementation, documentation, assessment, reporting, and quality improvement to ensure that a process, item, or service is of the type and quality needed and expected by DOE.
- **Quality control (QC):** The overall system of technical activities that measures the attributes and performance of a process, item, or service against defined standards to verify that they meet the requirements established by the DOE; operational techniques and activities that are used to fulfill requirements for quality.

- **Project deliverables and processes acceptance criteria:** Project team members and key stakeholders agree upon the project planning stage on formal project processes and major deliverable acceptance criteria for the CIE tools that will be used to evaluate final deliverable results before the results are formally approved.

The CIE QAP will be consistent with the contractor plans and procedures that implement DOE requirements and EPA guidance cited in this chapter. The QA plan will also impose additional CIE-specific requirements deemed necessary to facilitate delivery of a successful CIE tool set and control its subsequent applications.

The following guiding principles will be used in developing the CIE QA plan:

1. The CIE QA plan will proactively identify and apply existing QA and QC plans and procedures to the development and application of technically defensible CIE tools that represents site CSMs to support Hanford Site decision-making needs.

2. The CIE QA plan will apply lessons learned from a DOE Headquarters audit (DOE, 2006, *Report on the Review of the Hanford Solid Waste Environmental Impact Statement (EIS) Data Quality, Control and Management Issues*) to strengthen the QA/QC of the CIE tool set.

3. The CIE QA plan will be developed to ensure that QA/QC controls address three key areas:

    a. **Software quality and control:** To ensure use of only software that meets DOE requirements for use under a graded approach.

    b. **Data quality and control:** To promote traceable development of model input parameters from traceable and qualified data and consistency with current site CSMs.

    c. **Application quality and control:** To promote traceable calculations using numerical software in which inputs are traceable to data (basis information), code use is traceable to inputs, and outputs are traceable to code use.

The CIE QA plan will include the following content:

- Providing an overview of the plan, its need, and its organization.

- Describing the quality management method, identifying the quality objectives, detailing the project organization, and specifying the roles of key individuals in the CIE QA plan.

- Specifying the processes to provide for QA in terms of data, software, and assessments for the CIE tools and its application.

- Specifying the QC processes, including modeling data change management, model data storage and preservation, model application traceability, model application documentation, and project deliverables QC.

- Identifying the requirements for project audits and quality reviews. This will include management assessments, surveillances, independent assessments, and work site assessments.

The CIE QA plan will be formally issued and maintained as a contractor management plan. It will be periodically reviewed and revised as needed to reflect program and planning changes as the project progresses.

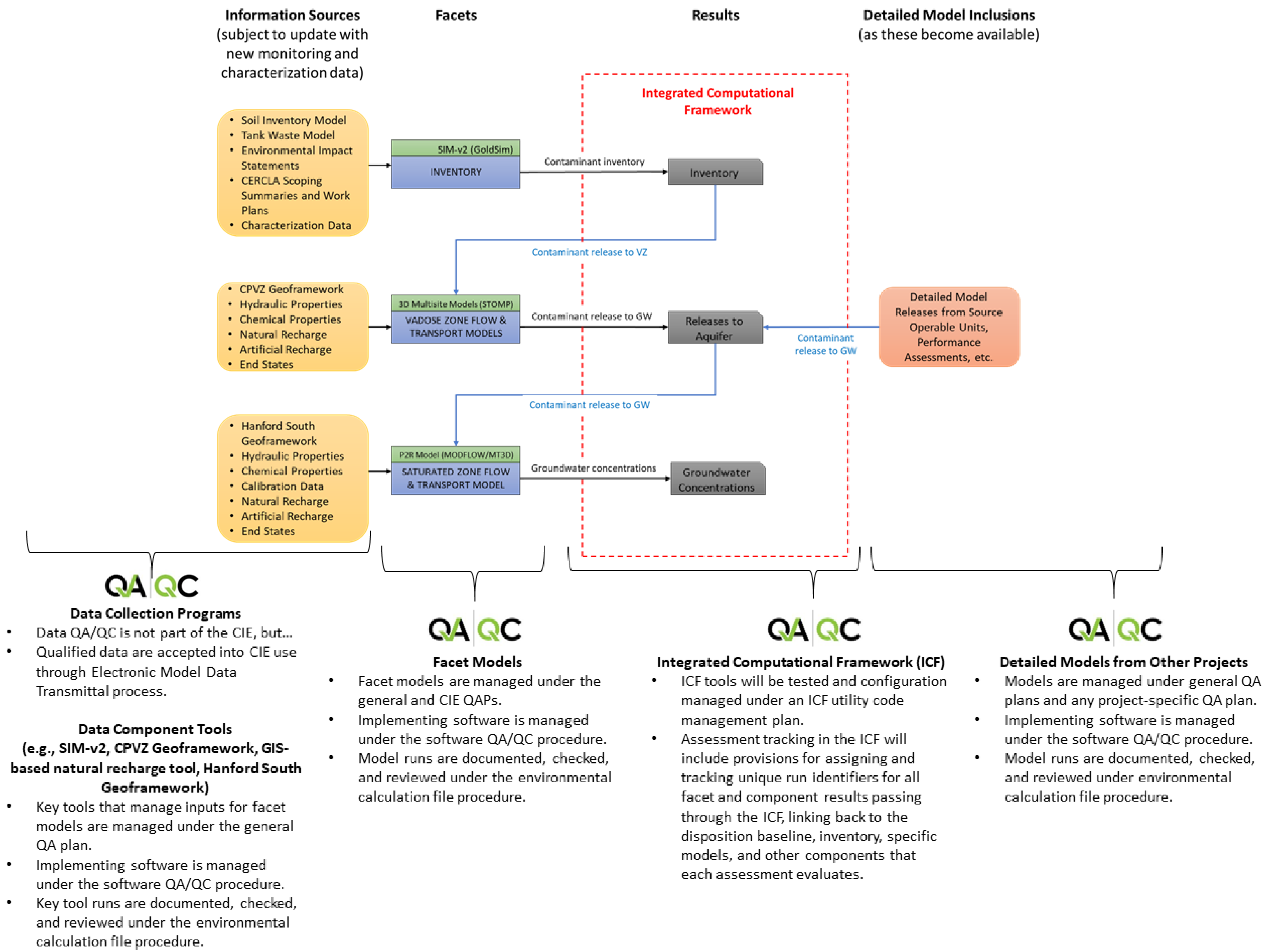

Figure 5-1. Quality Assurance and Quality Control in the CIE Information Flow

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5.3 Independent Peer Review

Independent peer review will be used to provide an additional level of QA during CIE tool development and implementation. This peer review will include review of the CIE technical approach, and initial implementation of the CIE tools.

In accordance with EPA CIO 2105-P-01-0, independent peer review is defined as follows:

> *… a documented critical review of work by qualified individuals (or organizations) who are independent of those who performed the work, but are collectively equivalent in technical expertise. A peer review is conducted to ensure that activities are technically adequate, competently performed, properly documented, and satisfy established technical and quality requirements. The peer review is an in-depth assessment of the assumptions, calculations, extrapolations, alternate interpretations, methodology, acceptance criteria, and conclusions pertaining to specific work and of the documentation that supports them.*

An independent peer review panel will review the CIE technical approach and implementation of the CIE tools. The objective of the panel will be to enhance the following:

- Provide technical defensibility of the CIE approach and implementation
- Support successful implementation on a schedule that meets the Hanford Site decision-making needs

The independent peer panel review will complete their review of the CIE proposed technical approach before issue of the CIE technical approach document (Rev. 0). The peer reviewers will complete their review of the preliminary CIE implementation by the schedule completion of that activity. The review reports will detail the panel's assessment of how the approach and preliminary implementation have adequately considered CIE needs, and the degree to which recommendations from the panel members have been adequately addressed in the approach and implementation.

The expert panel will include personnel who are subject matter experts in scientific and technical disciplines pertinent to the CIE tools. Key disciplines that must be represented in the panel's membership will be identified in the panel charter to cover all of the CIE facets to ensure a comprehensive and balanced review.

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6 Maintenance

This chapter describes how a planned, structured maintenance program will be in place for the CIE to ensure periodic, comprehensive review of new information and recommend CIE software updates. A CIE maintenance program is essential because, as a living tool, the CIE's function is to integrate many sources of data, knowledge, and understanding that will evolve over time. This will include incorporating updates to the OU/WMA CSMs that may be identified as the regulatory decision making continues on the Central Plateau.

The CIE facets are based on best-available information. However, the CSM(s) and data available for each facet will change over time as additional information is gathered and additional analyses are performed. Section 6.1 discusses the scope of the potential changes to be incorporated into the CIE that will require periodic review and potential updates.

A CIE maintenance plan will be developed to establish and direct the maintenance program. The maintenance plan will provide a formal approach to identify, consider, and incorporate updates to the CSM, newly acquired data, additional new information, and advances in computational technologies. Section 6.2 discusses the content of the CIE maintenance plan.

The maintenance plan will be issued in the fiscal year following completion of the initial version of the CIE software. The maintenance plan will address the scope, frequency, and reporting of maintenance activities. Maintenance reports will be prepared annually and will allow planning to prioritize available resources for updates to the CIE, as needed. Section 6.3 discusses the frequency and reporting aspects of the maintenance plan.

The annual maintenance reports will document and evaluate potential updates to the CIE but will not present the results of CIE calculations. The CIE simulation results and interpretations of those results will be reported primarily in individual decision and supporting documents. DOE is also expected to utilize the CIE by means of directed studies for strategic planning purposes, alternatives evaluations, and to evaluate uncertainties.

6.1 Maintenance Plan Content

The maintenance plan content will include the following:

- Providing an overview of the need and purpose of the maintenance plan, the objectives of the CIE maintenance program, and a description of how the plan is organized.
- Specifying the maintenance cycle and reporting deadlines, the format and content of annual maintenance reports, and the process for evaluating the significance of changes identified in those CIE elements tracked by the maintenance program. Section 6.3 discusses the frequency of maintenance activities to be addressed in the maintenance plan in more detail.
- Identification of the scope of items to track and report on in the maintenance program. That is, the maintenance plan will state what components and supporting information must be reviewed to identify and assess potential changes in CSM(s), models, supporting data, software, hardware, etc., that should be considered for inclusion in an update to the CIE tools. Section 6.2 discusses the scope of items to track in more detail.
- Specifying how WMA- and OU-specific models and information are to be tracked and assessed for incorporation into the CIE. Chapter 3, Section 3.7, discusses the inclusion of information from other modeling activities, CSM updates, and characterization data.

- Providing guidance for conducting and reporting on investigation and development activities. For example, Chapter 3 identifies the first two of these needs for investigation and development:
  - The first need identified is to gather information and maintain additional anthropogenic recharge sources not currently quantified for future input into vadose zone models.
  - The second need is to create a GIS-based application to integrate temporally and spatially variable natural recharge rates for inclusion in vadose and groundwater models. Other investigation and development activities may be added to the maintenance plan as new needs are identified.

6.2 Maintenance Program Scope

The scope of the CIE maintenance program covers the major facets and components of the CIE and its supporting software, hardware, models, and data products (Figure 6-1). Facets are the inventory, vadose zone, and saturated zone. The components that support these facets include inputs such as the geoframework models, the disposition baseline, the recharge rates, and other supporting models, tools, and data sources as listed in Figure 6-1.

Maintenance activities will also include system software (e.g., operating system changes), new versions of modeling codes, hardware upgrades, new functionality, diagnosis and repair of errors (as needed), and preventive maintenance. Addressing software and hardware in the maintenance program will increase component maintainability and reliability.

Inputs used in the CIE (e.g., characterization data, groundwater data, and geologic interpretations) provided by other programs will be reviewed as part of the CIE maintenance program for inclusion in CIE updates. For example, the groundwater monitoring programs produce updated plume maps annually. These plumes form the basis for defining the initial plume condition in the saturated zone facet of the CIE. The CIE maintenance program will include review of the updated plumes and assessment to determine when it is appropriate to update the initial condition of the CIE saturated zone facet.

Each facet and component model of the CIE is covered by a model package report that includes a model recommendations chapter; these will be summarized as part of the scope of the CIE maintenance program. The general QA project plan for modeling (described in Section 5.1) establishes the format of the model package report, which includes a chapter on “model recommendations” that is to present recommendations for further refinement, expansion, or improvement to the subject model and benefit that might be derived from each change. The purpose of this element of the model package report will be expanded to identify data needs identified from a model perspective that would serve to improve subject models. The CIE maintenance program scope will include summarizing the current data needs for all current model package reports supporting all CIE facet and component models in a single place in the CIE annual maintenance report.

The scope of maintenance activities is discussed below, organized by CIE facet (6.1.1 for inventory, 6.1.2 for vadose zone, and 6.1.3 for saturated zone), and addresses the associated components.

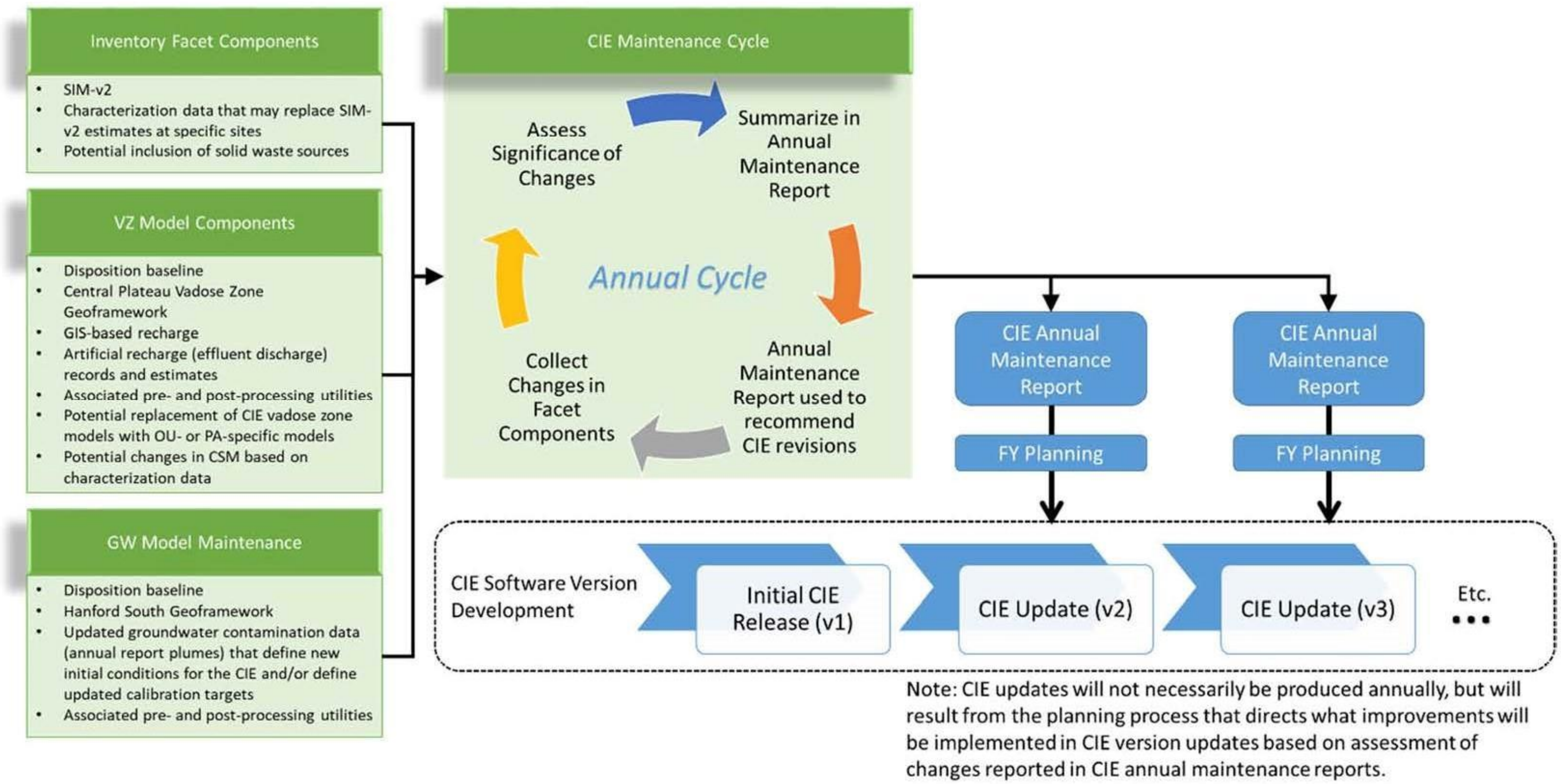

Figure 6-1. Planned CIE Maintenance Cycle

6.2.1 Inventory Facet Maintenance Scope

The inventory model (Chapter 2) and supporting components include:

- SIM-v2 (CP-59798) – This model simulates liquid effluent discharges based on process knowledge and records to estimate inventory released into the soil at specific waste sites.
  - Past leak assessments – These documents estimate volumes and mass or activity of contaminants released in tank and ancillary equipment overfill events, leaks, and other losses; incorporated into SIM-v2 assessments.
- Characterization data – Ongoing characterization work are field data on subsurface contamination levels collected directly.
- Solid Waste Component – As discussed in Chapter 2, solid waste release models will be added as an optional feature that can be run for certain waste sites, including the ability to include additional waste sites that received solid waste forms, and account for waste form degradation rates; many of these waste sites will belong to the 200-SW-2 OU.

The first version of the CIE will focus on liquid source inventories provided by the SIM-v2, and the maintenance program will need to determine if characterization data improves upon the inventory estimates provided in this model. Updates to source information may be identified and would be addressed through new SIM-v2 simulations using updated inputs to incorporate corrections and obtain updated waste site inventory estimates. Another potential future improvement to the SIM-v2 estimates may include reducing uncertainty in estimates at waste sites based on new characterization data that could support refining inventory estimates. Additionally, past leak assessments associated with WMAs are important inputs to the SIM-v2, and these are subject to update. The maintenance program will track and report on updated past leak assessments for incorporation into the SIM-v2 inputs and updated calculations using this model.

Where field characterization data become available that are sufficient to be used to develop three-dimensional initial condition representations of vadose zone contamination for a site, these would be used in preference to SIM-v2 estimates of inventory. Field data on what is present in the subsurface are more reliable than the modeled estimates and will be used in place of SIM-v2 estimates. The assessment of the viability of the field characterization will be done under the maintenance program.

Finally, while the initial CIE runs are planned to include only liquid sources, additional solid sources will be incorporated through the maintenance program in later versions, when needed, to support longer-term CIE evaluations. These solid source inventory updates would be separate from the SIM-v2 because that model only accounts for liquid releases. Later CIE versions will incorporate solid source inventories that may be activated as an option, depending on the timeframe and objectives of specific CIE assessments. Assessments of the influence of solid waste contributions using the CIE will be used to guide the inclusion or exclusion of solid waste sources to suit the objectives of specific CIE assessments.

Inventory data will not be required for sites that are incorporated through site-specific models whose results are directly incorporated into the CIE. Examples include PAs for WMA C, the Environmental Restoration Disposal Facility, and the Integrated Disposal Facility. In cases such as these, detailed model results for vadose zone mass and activity flux to groundwater will be included in place of CIE vadose zone modeling.

6.2.2 Vadose Zone Facet Maintenance Scope

The vadose zone models (Chapter 3) implemented in the STOMP code and supporting components include the following:

- Disposition baseline – The database that includes the collection of past actions, decisions for future actions, and projections of potential end states for to-go decisions that impact models through changes in mass removal and in natural recharges rates; discussed in Section 3.6.2.2.
- GIS-based recharge tool – The new tool proposed that will account for recharge rates that vary by location and over time at multiple locations for use as input to vadose zone and saturated zone flow models. This tool will incorporate information from the disposition baseline and other sources to define the natural recharge on the upper boundary of flow models (need and purpose discussed in Section 3.6.2.2).
- Anthropogenic recharge (effluent discharge) records and estimates – A secondary tool used to assess water balance that records and projections of liquid discharges to soil and their locations resulting from human activity, including process effluent disposal, septic system disposal, dust water suppression, and storm water management, used to input these liquid quantities into the vadose zone flow models; discussed in Section 3.6.2.2.
- CPVZ GFM – The three-dimensional model of the geologic media that comprise the vadose zone used as the basis for discretization and parameterization of the vadose zone flow and transport models; discussed in Section 3.2.
- Associated pre- and post-processing utilities that are used to prepare input files and format results from model simulation results files for presentation and interpretation
- Potential replacement of CIE vadose zone models with OU- or PA-specific models
- Potential changes to the CSM based on characterization data

The initial three-dimensional, multi-site vadose zone models used for the CIE will be constructed as discussed in Chapter 3. It is expected that about two dozen such models will be required to encompass the Central Plateau contamination sources while achieving representative treatment of potential commingling in the vadose zone from nearby sites. These vadose zone models will be documented, checked, and reviewed under the QA plans and procedures discussed in Chapter 5. The models will be configuration controlled, and new versions of each will be developed, documented, checked, and reviewed as the CIE maintenance program identifies the need for updates.

With respect to the vadose zone facet, several key areas of potential, ongoing change (as listed above) will be evaluated through maintenance. The key uncertainty in the CIE evaluations are decision uncertainty, which is reflected by the simulation of alternative waste site dispositions captured in the Disposition Baseline. This database of waste site dispositions will be maintained to incorporate final decisions (typically through Records of Decision under CERCLA, closure actions under *Atomic Energy Act of 1954* authority, and Corrective Action Decisions through RCRA), any interim actions, and all actions performed to date. As the disposition baseline database evolves, updates will be captured through the CIE maintenance program to support new CIE runs as described in Section 3.5.2.2. This database end-state selection is a direct input into the needed GIS-based tool to manage spatial and temporal variability in natural recharge for inclusion in CIE vadose zone models (as described in Section 3.5.2.2). This recharge estimation tool will be version-controlled and maintained, and updates will become available for inclusion in the CIE vadose zone models. Chapter 3 also identifies the need for a CIE program to gather and maintain a broader range of effluent discharges (artificial recharge sources) than those currently available. As this task is performed, a program will be developed that provides updated data sets on effluent discharges (including the continual replacement of estimates with actual values as time progresses). These data will be incorporated into the CIE through the maintenance program.

The CPVZ GFM will provide the three-dimensional structure of all the vadose zone models developed to the technical approach described in Chapter 3. The CPVZ GFM is maintained as a model itself, under the same QA/QC requirements described in Chapter 5. As new versions of the CPVZ GFM are made available through its maintenance program, these new versions will be noted and evaluated for inclusion in the CIE through the CIE maintenance program.

Several utilities and tools will also be required to manage the suite of vadose zone models implemented in STOMP. For example, a program will be needed to translate the CPVZ GFM into the three-dimensional grid zonation of a STOMP file. Such utilities and tools will be subject to improvement and maintenance to incorporate through the maintenance program. These utilities and tools will be tracked in the maintenance program and needs for updating identified.

Finally, as the CP OUs and WMAs go through their regulatory decision-making processes, , they will produce refined, site-specific models and information. These site-specific results will need to be identified through the maintenance report, captured for the CIE, and used to update/replace the CIE models.

6.2.3 Saturated Zone Facet Maintenance Scope

The saturated zone facet is comprised of the P2R Model (Chapter 4) implemented in the MODFLOW and MT3DMS codes for flow and transport, respectively. The supporting components of the P2R Model includes the following:

- Disposition baseline – The database that includes the collection of past actions, decisions for future actions, and projections of potential end states for to-go decisions that impact models through changes in mass removal such as pump-and-treat actions and in natural recharges rates
- HSGF – The three-dimensional model of the geologic media that comprise the saturated zone used as the basis for discretization and parameterization of the P2R Model; discussed in Section 4.2.2.2
- Plume Configuration Changes – Updated groundwater contaminant plume configuration (typically based on annual Hanford Site groundwater report maps, used to define new initial conditions for the CIE as discussed in Section 4.3.3 and/or to define updated calibration targets as discussed in Section 4.2.3
- Associated pre- and post-processing utilities that are used to prepare input files and format results from model simulation results files for presentation and interpretation

The initial version of the CIE will use an updated P2R Model (discussed in Chapter 4). As a maintained model, the P2R Model will be subject to its own maintenance that includes updates to incorporate changes in the information identified above. Updates to the P2R Model inputs (e.g., HSGF, initial plume conditions, parameter values, and calibration data) will be incorporated into the P2R Model grid and aquifer property zonation, as needed. The maintenance plan will identify the models and data sets that support the P2R Model that are to be tracked for changes and assessed in annual maintenance reports.

With respect to the groundwater facet, other sources of information will be reviewed and potentially incorporated through the CIE maintenance program. Examples include changes in mass removal through groundwater OU actions and updates to the GIS-based tool to manage spatial and temporal variability in natural recharge. The technical approach for the groundwater facet (discussed in Chapter 4) also relies on current contaminant plumes for simulations. As part of the maintenance program, new plume interpretations (based on results from the groundwater monitoring program) will be reviewed for inclusion in the CIE. The maintenance program will track the inclusion of new data and reach determinations of when sufficient new information warrants recalibration of the P2R Model. Similar to the vadose zone facet, a number of utilities and tools required to manage the P2R Model and its interface to other facets will also be subject to improvement and maintenance.

6.3 Maintenance Activity Frequency and Reporting

The CIE maintenance plan will identify the activities necessary to provide routine, periodic review of the CIE software through an annual maintenance cycle. The CIE maintenance plan will require that an annual maintenance report be submitted by the end of the second quarter of each fiscal year. This reporting schedule will align maintenance reports to the DOE funding cycle to support prioritizing recommended update activities based on available funding. In the event there are few or no changes to summarize, the annual report will still be prepared to document those few changes for completeness.

The annual maintenance report will document the maintenance activity results and provide an assessment of the value of potential changes. The assessment process will be prescribed in the maintenance plan. The information provided in the annual maintenance report will serve as the basis for planning CIE update activities for the following fiscal year.

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7 References

10 CFR 830.3, "Nuclear Safety Management," "Definitions," *Code of Federal Regulations*. Available at: http://www.gpo.gov/fdsys/pkg/CFR-2010-title10-vol4/xml/CFR-2010-title10-vol4-part830.xml.

ASME NQA-1A-2008, 2008, *Quality Assurance Requirements for Nuclear Facility Applications*, American Society of Mechanical Engineers, New York, New York. Available at: https://www.asme.org/wwwasmeorg/media/ResourceFiles/Shop/Certification%20%26%20Accreditation/NQA-Certification/NQA-Certification_Forms-and-Resources_Requirements-for-ASME-Nuclear-Quality-Assurance.pdf.

ASME NQA-1A-2009, 2009, *Addenda to Quality Assurance Requirements for Nuclear Facility Applications*, Addenda A, American Society of Mechanical Engineers, New York, New York.

Atomic Energy Act of 1954, Pub. L. 83-703, as amended, 42 USC 2011, et seq., 68 Stat. 919. Available at: https://science.energy.gov/~/media/bes/pdf/nureg_0980_v1_no7_june2005.pdf.

BHI-00184, 1995, *Miocene- to Pliocene-Aged Suprabasalt Sediments of the Hanford Site, South-Central Washington*, Rev. 00, Bechtel Hanford, Inc., Richland, Washington. Available at: http://pdw.hanford.gov/arpir/pdf.cfm?accession=0083482H.

BNWL-B-360, 1975, *Selected Water Table Contour Maps and Well Hydrographs for the Hanford Reservation, 1944-1973*, Battelle Pacific Northwest Laboratories, Richland, Washington. Available at: https://www.osti.gov/servlets/purl/4285961.

Comprehensive Environmental Response, Compensation, and Liability Act of 1980, Pub. L. 107-377, as amended, 42 USC 9601, et seq., December 31, 2002. Available at: https://www.csu.edu/cerc/researchreports/documents/CERCLASummary1980.pdf.

CP-47631, 2018, *Model Package Report: Central Plateau Groundwater Model, Version 8.4.5*, Rev. 4, CH2M HILL Plateau Remediation Company, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/pdf.cfm?accession=0066449H.

CP-57037, 2015, *Model Package Report: Plateau to River Groundwater Transport Model, Version 7.1*, Rev. 0. CH2M HILL Plateau Remediation Company, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/pdf.cfm?accession=0080149H.

CP-57037, 2019, *Model Package Report: Plateau to River Groundwater Model, Version 8.2*, Rev. 1, CH2M HILL Plateau Remediation Company, Richland, Washington.

CP-59798, 2018, *Model Package Report: Hanford Soil Inventory Model SIM v.2: Build 1*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington. Available at: https://www.emcbc.doe.gov/SEB/CPCC/Documents/Document%20Library/092718/Other/Model%20Package%20Report%20-%20Hanford%20Soil%20Inventory%20SIM%20v.2,%20Build%201%20-%20(CP-59798,%20Rev.%200).pdf.

CP-60925, 2018, *Model Package Report: Central Plateau Vadose Zone Geoframework Version 1.0,* Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/pdf.cfm?accession=0065500H.

CRC Handbook of Chemistry and Physics, 2018, 99th Edition, J.R. Ramble, ed., CRC Press, Boca Raton, Florida.

DOE O 414.1D Chg 1, 2013, *Quality Assurance*, U.S. Department of Energy, Washington, D.C. Available at: https://www.directives.doe.gov/directives-documents/400-series/0414.1-BOrder-d-admchg1/@@images/file.

DOE, 2006, *Report on the Review of the Hanford Solid Waste Environmental Impact Statement (EIS) Data Quality, Control and Management Issues*, U.S. Department of Energy, Washington, D.C. Available at: https://www.hanford.gov/files.cfm/QA-QC%20Review-Report.pdf.

DOE/EIS-0391, 2012, *Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington (TC & WM EIS)*, U.S. Department of Energy, Office of River Protection, Richland, Washington. Available at: http://energy.gov/nepa/downloads/eis-0391-final-environmental-impact-statement.

DOE/RL-2004-60, 2016, *200-SW-2 Radioactive Landfills Group Operable Unit RCRA Facility Investigation/Corrective Measures Study/Remedial Investigation/Feasibility Study Work Plan*, Rev. 1, U.S. Department of Energy, Richland Operations Office, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/pdf.cfm?accession=0075017H.

DOE/RL-2005-37, 2005, *Status of Hanford Site Risk Assessment Integration, FY2005*, U.S. Department of Energy, Richland Operations Office, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=DA097087.

DOE/RL-2007-28, 2008, *Feasibility Study Report for the 200-ZP-1 Groundwater Operable Unit*, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington. Available at: http://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0808050315. http://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=00098828.

DOE/RL-2008-56, 2012, *200-West Area Pre-Conceptual Design for Final Extraction/Injection Well Network: Modeling Analyses*, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington. Available at: http://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0081011H.

DOE/RL-2009-10, 2013, *Hanford Site Cleanup Completion Framework*, Rev. 1, U.S. Department of Energy, Richland Operations Office, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0076744H.

DOE/RL-2009-38, 2009, *Description of Modeling Analyses in Support of the 200-ZP-1 Remedial Design/Remedial Action Work Plan*, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0095363.

DOE/RL-2009-85, 2012, *Remedial Investigation Report for the 200-PO-1 Groundwater Operable Unit*, Rev. 1, U.S. Department of Energy, Richland Operations Office, Richland, Washington. Available at: http://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0091415.

DOE/RL-2009-85 ADD1, 2018, *Remedial Investigation Report for the 200-PO-1 Groundwater Operable Unit*, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/pdf.cfm?accession=0064654H.

DOE/RL-2009-127, 2018, *Remedial Investigation Report 200-BP-5 Groundwater Operable Unit*, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/pdf.cfm?accession=0064655H.

DOE/RL-2010-49, 2017, *Remedial Investigation/Feasibility Study Work Plan for the 200-WA-1 and 200-BC-1 Operable Unit*, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington. Available at:
https://pdw.hanford.gov/arpir/pdf.cfm?accession=0072177H.
https://pdw.hanford.gov/arpir/pdf.cfm?accession=0072173H.
https://pdw.hanford.gov/arpir/pdf.cfm?accession=0072172H.
https://pdw.hanford.gov/arpir/pdf.cfm?accession=0072171H.
https://pdw.hanford.gov/arpir/pdf.cfm?accession=0072170H.
https://pdw.hanford.gov/arpir/pdf.cfm?accession=0072169H.
https://pdw.hanford.gov/arpir/pdf.cfm?accession=0072168H.
https://pdw.hanford.gov/arpir/pdf.cfm?accession=0072167H.

DOE/RL-2011-50, 2012, *Regulatory Basis and Implementation of a Graded Approach to Evaluation of Groundwater Protection*, Rev. 1, U.S. Department of Energy, Richland Operations Office, Richland, Washington. Available at: http://www.hanford.gov/files.cfm/CAL_Regulatory_Basis_Implementation_Graded_Approach_Groundwater.pdf.

DOE/RL-2011-102, 2016, *Remedial Investigation/Feasibility Study and RCRA Facility Investigation/Corrective Measures Study Work Plan for the 200-DV-1 Operable Unit*, U.S. Department of Energy, Richland Operations Office, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0075538H.

DOE/RL-2014-48, 2016, *Response Action Report for the 200-PW-1 Operable Unit Soil Vapor Extraction Remediation*, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/pdf.cfm?accession=0074963H.

DOE/RL-2015-10, 2015, *Hanford Lifecycle Scope, Schedule and Cost Report*, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/pdf.cfm?accession=0078688H.

DOE/RL-2015-75, 2016, *Aquifer Treatability Test Report for the 200-BP-5 Groundwater Operable Unit*, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington. Available at: http://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0074649H.

DOE/RL-2016-01, 2017, *Hanford Site Fourth CERCLA Five-Year Review Report*, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0071636H.

DOE/RL-2016-67, 2017, *Hanford Site Groundwater Monitoring Report for 2016*, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/pdf.cfm?accession=0068229H.

DOE/RL-2017-65, 2018, *Hanford Site RCRA Groundwater Monitoring Report for 2017*, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/pdf.cfm?accession=0066266H.

DOE/RL-2017-66, *Hanford Site Groundwater Monitoring Report for 2017*, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/pdf.cfm?accession=0064709H.

DOE/RL-2017-67, 2017, *Hanford Site Groundwater Monitoring Report for 2016*, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington. Available at: https://higrv.hanford.gov/Hanford_Reports_2016/Hanford_GW_Report/.

DOE/RL-2017-68, *Calendar Year 2017 Annual Summary Report for Pump-and-Treat Operations in the Hanford Central Plateau Operable Units*, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0064707H.

ECF-200BP5-15-0009, 2017, *Evaluation of Plume Capture and Hydraulic Performance for B-Complex Vicinity Submodel for 200-BP-5 and 200-PO-1 Operable Units Feasibility Study Evaluation of Remedial Alternatives*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0067510H.

ECF-200BP5-16-0145, 2017, *Particle Tracking and Transport Modeling in Support of Removal Action Memorandum*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0066643H.

ECF-200BP5-19-0035, *Simulations of Focused Feasibility Study Remedy at B Complex*, Rev. 0 pending, CH2M HILL Plateau Remediation Company, Richland, Washington.

ECF-200BP5-19-0036, *Simulations of Focused Feasibility Study Remedy at Waste Management Area C*, Rev. 0 pending, CH2M HILL Plateau Remediation Company, Richland, Washington.

ECF-200-UP1-17-0094, 2018, *Fate and Transport Analysis for WMA S-SX Groundwater Plumes in the 200-UP-1 Operable Unit*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington, Available at: https://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0066440H.

ECF-200UP1-17-0238, 2018, *Development of the 3D Hexavalent Chromium Groundwater Plume using Leapfrog for Southeast 200-UP-1*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0065662H.

ECF-200W-17-0029, 2018, *Description of Groundwater Calculations and Assessments for the Calendar Year 2016 (CY 2016) for the 200 Areas Pump and Treat Report*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0065639H.

ECF-200W-17-0030, 2017, *Calculation of Source Terms for the 200 West Pump-and-Treat System Optimization Modeling, FY 2017*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/pdf.cfm?accession=0064963H.

ECF-200W-17-0043 , 2017, *Capture-Zone and Particle-Tracking Analysis for the 200-UP-1/200-ZP-1 Areas Using the 2017 Updated Central Plateau Model*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0064962H.

ECF-200ZP1-16-0076, 2016, *Description of Groundwater Calculations and Assessments for the Calendar Year 2015 (CY 2015) 200 Areas Pump and Treat Report*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington. Available at: http://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0074966H.

ECF-HANFORD-13-0029, 2018, *Development of the Hanford South Geologic Framework Model, Hanford Site, Washington*, Rev. 5, CH2M HILL Plateau Remediation Company, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0064943H.

ECF-Hanford-13-0031, 2015, *Fate and Transport Modeling for Baseline Conditions for Remedial Investigation/Feasibility Studies of the 200-BP-5 and 200-PO-1 Groundwater Operable Units*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0080142H.

ECF-HANFORD-18-0023, 2018, *Evaluation of Contaminant Transport for the 200-BP-5 and 200-PO-1 Operable Units Feasibility Study Evaluation of Remedial Alternatives*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0064587H.

Ecology, EPA, and DOE, 1989a, *Hanford Federal Facility Agreement and Consent Order*, 2 vols., as amended, Washington State Department of Ecology, U.S. Environmental Protection Agency, and U.S. Department of Energy, Olympia, Washington. Available at: http://www.hanford.gov/?page=81.

Ecology, EPA, and DOE, 1989b, *Hanford Federal Facility Agreement and Consent Order Action Plan*, as amended, Washington State Department of Ecology, U.S. Environmental Protection Agency, and U.S. Department of Energy, Olympia, Washington. Available at: http://www.hanford.gov/?page=82.

EM-QA-01, 2012, *EM Quality Assurance Program*, Rev. 1, Office of Environmental Management, U.S. Department of Energy, Washington, D.C. Available at: https://www.energy.gov/sites/prod/files/em/EMQualityAssuranceProgram%28EM-QA-001Revision1%29.pdf.

EPA/100/K-09/003, 2009, *Guidance on the Development, Evaluation, and Application of Environmental Models*, Council for Regulatory Environmental Monitoring, U.S. Environmental Protection Agency, Washington, D.C. Available at: https://www.epa.gov/sites/production/files/2015-04/documents/cred_guidance_0309.pdf.

EPA/240/B-01/003, 2001, *EPA Requirements for Quality Assurance Project Plans*, EPA QA/R-5, Office of Environmental Information, U.S. Environmental Protection Agency, Washington, D.C. Available at: https://www.epa.gov/sites/production/files/2016-06/documents/r5-final_0.pdf.

EPA/240/R-02/007, 2002, *Guidance for Quality Assurance Project Plans for Modeling*, EPA QA/G-5M, Office of Environmental Information, U.S. Environmental Protection Agency, Washington, D.C. Available at: https://www.epa.gov/sites/production/files/2015-06/documents/g5m-final.pdf.

EPA/240/R-03/003, 2003, *Guidance for Geospatial Data Quality Assurance Project Plans*, EPA QA/G-5G, Office of Environmental Information, U.S. Environmental Protection Agency, Washington, D.C. Available at: http://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=20013KUB.PDF.

EPA 402-R-99-001, 1999, *Cancer Risk Coefficients for Environmental Exposure to Radionuclides*, Federal Guidance Report No. 13, Office of Radiation and Indoor Air, U.S. Environmental Protection Agency, Washington, D.C. Available at: https://www.epa.gov/sites/production/files/2015-05/documents/402-r-99-001.pdf.

EPA 542-F-11-011, *Environmental Cleanup Best Management Practices: Effective Use of the Project Life Cycle Conceptual Site Model*, U.S. Environmental Protection Agency, Washington, D.C. Available at: https://www.epa.gov/remedytech/environmental-cleanup-best-management-practices-effective-use-project-life-cycle.

EPA/600/R-17/293, 2017, *Best Practices for Environmental Site Management: A Practical Guide for Applying Environmental Sequence Stratigraphy to Improve Conceptual Site Models*, U.S. Environmental Protection Agency, Washington, D.C. Available at: https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=341373&Lab=NRMRL.

EPA CIO 2105-P-01-0, 2000, *EPA Quality Manual for Environmental Programs*, Office of Environmental Information, U.S. Environmental Protection Agency, Washington, D.C. Available at: https://www.epa.gov/sites/production/files/2013-10/documents/2105p010.pdf.

EPA, Ecology, and DOE, 2008, *Record of Decision Hanford 200 Area 200-ZP-1 Superfund Site, Benton County, Washington*, U.S. Environmental Protection Agency, Washington State Department of Ecology, and U.S. Department of Energy, Olympia, Washington. Available at: https://pdw.hanford.gov/arpir/pdf.cfm?accession=00098825.

EPA, Ecology, and DOE, 2012, *Record of Decision for Interim Remedial Action Hanford 200 Area Superfund Site 200-UP-1 Operable Unit*, U.S. Environmental Protection Agency, Washington State Department of Ecology, and U.S. Department of Energy, Olympia, Washington. Available at: https://pdw.hanford.gov/arpir/pdf.cfm?accession=0091413.

Gee, G.W., M.J. Fayer, M.L. Rockhold, and M.D. Campbell, 1992, "Variations in Recharge at the Hanford Site," *Northwest Sci.* 66(4):237-250.

Green, T.R., J.E. Constantz, and D.L. Freyberg, 1996, "Upscaled Soil-Water Retention Using Van Genuchten's Function," *J. Hydrol. Eng.* 1(3):123-130.

Harbaugh, A.W., E.R. Banta, M.C. Hill, and M.G. McDonald, 2000, *MODFLOW-2000, The U.S. Geological Survey Modular Ground-Water Model—User Guide to Modularization Concepts and the Ground-Water Flow Process*, Open File Report 00-92, U.S. Geological Survey, Denver, Colorado. Available at: http://water.usgs.gov/nrp/gwsoftware/modflow2000/ofr00-92.pdf.

HEIS—Hanford Environmental Information System, Hanford Site database, Richland, Washington. Available at: https://ehs.hanford.gov/eda/.

Hsieh, P.A. and J.R. Freckleton, 1993, *Documentation of a Computer Program to Simulate Horizontal-flow Barriers Using the U.S. Geological Survey's Modular Three-dimensional Finite-difference Ground-water Flow Model*, Open-File Report 92-477, U.S. Geological Survey, Sacramento, California. Available at: https://pubs.usgs.gov/of/1992/0477/report.pdf.

ICRP Publication 107, *Nuclear Decay Data for Dosimetric Calculations*, International Commission on Radiological Protection, New York, New York. Available at: http://www.icrp.org/publication.asp?id=ICRP%20Publication%20107.

Khaleel, Raziuddin, T.-C. J. Yeh, and Zhiming Lu, 2002, "Upscaled flow and transport properties for heterogeneous unsaturated media," *Water Resour. Res.* 38(5):11-1–11-12.

Konikow, L.F., G.Z. Hornberger, K.J. Halford, and R.T. Hanson, 2009, *Revised Multi-Node Well (MNW2) Package for MODFLOW Ground-Water Flow Model*, Techniques and Methods 6A–30, U.S. Geological Survey, Reston, Virginia.

Mayes, M.A., P.M. Jardine, T.L. Mehlhorn, B.N. Bjornstad, J.L. Ladd, and J.M. Zachara, 2003, "Transport of Multiple Tracers in Variably Saturated Humid Region Structured Soils and Semi-Arid Region Laminated Sediments," *J. Hydrol.* 275(3-4):141-161.

McDonald, M.G. and A.W. Harbaugh, 1988, "A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model," *Techniques of Water-Resources Investigations of the United States Geological Survey*, Chapter A1, Book 6, U.S. Geological Survey, Reston, Virginia. Available at: http://pubs.usgs.gov/twri/twri6a1/.

Millington, R.J. and J.P. Quirk, 1961, "Permeability of Porous Solids," *Transactions of the Faraday Society* 57:1200-1207.

Mualem, Yechezkei, 1976, "New Model for Predicting the Hydraulic Conductivity of Unsaturated Porous-Media," *Water Resources Research* 12(3):513-522.

National Environmental Policy Act of 1969, 42 USC 4321, et seq. Available at: https://www.gpo.gov/fdsys/pkg/USCODE-2010-title42/pdf/USCODE-2010-title42-chap55-sec4321.pdf.

NUREG/CR-5965, 1994, *Modeling Field Scale Unsaturated Flow and Transport Processes*, Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, Washington, D.C. Available at: https://www.osti.gov/servlets/purl/10182911.

NUREG/CR-6114, PNL-8842, 1994, *Auxiliary Analyses in Support of Performance Assessment of a Hypothetical Low-Level Waste Facility: Groundwater Flow and Transport Simulation*, Vol. 3, U.S. Nuclear Regulatory Commission, Washington, D.C.

NRC, 2007, *Models in Environmental Regulatory Decision Making*, National Research Council, Washington, D.C. Available at: https://www.nap.edu/catalog/11972/models-in-environmental-regulatory-decision-making.

Oostrom, M., M.J. Truex, M.L Rockhold, and T.C. Johnson, 2017, "Deep Vadose Zone Contaminant Flux Evaluation at the Hanford BY-Cribs Site Using Forward and Imposed Concentration Modeling Approaches," *Environmental Process.* 4(4):771-797.

PNL-10285, 1995, *Estimated Recharge Rates at the Hanford Site*, Pacific Northwest Laboratory, Richland, Washington. Available at: https://www.osti.gov/servlets/purl/10122247.

PNL-10886, 1995, *Development of a Three-Dimensional Ground-Water Model of the Hanford Site Unconfined Aquifer System: FY 1995 Status Report*, Pacific Northwest Laboratory, Richland, Washington. Available at: https://www.osti.gov/servlets/purl/195772.

PNNL-11216, 1997, *STOMP: Subsurface Transport Over Multiple Phases Application Guide*, Pacific Northwest National Laboratory, Richland, Washington. Available at: http://stomp.pnl.gov/documentation/application.pdf.

PNNL-12030, 2000, *Subsurface Transport Over Multiple Phases Version 2.0 Theory Guide*, Pacific Northwest National Laboratory, Richland, Washington. Available at: http://stomp.pnnl.gov/documentation/guides/theory.pdf.

PNNL-12261, 2000, *Revised Hydrogeology for the Suprabasalt Aquifer System, 200-East Area and Vicinity, Hanford Site, Washington*, Pacific Northwest National Laboratory, Richland, Washington. Available at: http://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0906180659.

PNNL-13037, 2004, *Geochemical Data Package for the 2005 Hanford Integrated Disposal Facility Performance Assessment*, Rev. 2, Pacific Northwest National Laboratory, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0911300324.

PNNL-13560, 2001, *Assessment of Carbon Tetrachloride Groundwater Transport in Support of the Hanford Carbon Tetrachloride Innovative Technology Demonstration Program*, Pacific Northwest National Laboratory, Richland, Washington. Available at: http://www.pnl.gov/main/publications/external/technical_reports/PNNL-13560.pdf.

PNNL-13641, 2001, *Uncertainty Analysis Framework – Hanford Site-Wide Groundwater Flow and Transport Model*, Pacific Northwest National Laboratory, Richland, Washington. Available at: http://www.pnl.gov/main/publications/external/technical_reports/pnnl-13641.pdf.

PNNL-13858, 2002, *Revised Hydrogeology for the Suprabasalt Aquifer System, 200-West Area and Vicinity, Hanford Site, Washington*, Pacific Northwest National Laboratory, Richland, Washington. Available at: http://www.pnl.gov/main/publications/external/technical_reports/PNNL-13858.pdf.

PNNL-13895, 2003, *Hanford Contaminant Distribution Coefficient Database and Users Guide*, Rev. 1, Pacific Northwest National Laboratory, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0084439.

PNNL-14027, *An Initial Assessment of Hanford Impact Performed with the System Assessment Capability*, Pacific Northwest National Laboratory, Richland, Washington. Available at: https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-14027/PNNL-14027.pdf.

PNNL-14898, 2004, *Results of Groundwater Modeling for Tritium Tracking at the Hanford Site 200 Area State-Approved Land Disposal Site – 2004*, Pacific Northwest National Laboratory, Richland, Washington. Available at: http://www.pnl.gov/main/publications/external/technical_reports/PNNL-14898.pdf.

PNNL-15226, 2005, *Hydrodynamic Simulation of the Columbia River, Hanford Reach, 1940-2004*, Pacific Northwest National Laboratory, Richland, Washington. Available at: http://www.pnl.gov/main/publications/external/technical_reports/PNNL-15226.pdf.

PNNL-15782, 2006, *STOMP: Subsurface Transport Over Multiple Phases Version 4.0: User's Guide*, Pacific Northwest National Laboratory, Richland, Washington. Available at: http://stomp.pnl.gov/documentation/userguide.pdf.

PNNL-16663, 2007, *Geochemical Processes Data Package for the Vadose Zone in the Single-Shell Tank Waste Management Areas at the Hanford Site*, Pacific Northwest National Laboratory, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0911240118.

PNNL-17154, 2008, *Geochemical Characterization Data Package for the Vadose Zone in the Single-Shell Tank Waste Management Areas at the Hanford Site*, Pacific Northwest National Laboratory, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0911240119.

PNNL-18564, 2009, *Selection and Traceability of Parameters to Support Hanford-Specific RESRAD Analyses: Fiscal Year 2008 Status Report*, Pacific Northwest National Laboratory, Richland, Washington. Available at: http://www.pnl.gov/main/publications/external/technical_reports/PNNL-18564.pdf.

PNNL-18564, 2009, *Selection and Traceability of Parameters to Support Hanford-Specific RESRAD Analyses: Fiscal Year 2008 Status Report*, Pacific Northwest National Laboratory, Richland, Washington. Available at: http://www.pnl.gov/main/publications/external/technical_reports/PNNL-18564.pdf.

PNNL-18732, 2009, *Field Test Report: Preliminary Aquifer Test Characterization Results for Well 299-W15-225: Supporting Phase I of the 200-ZP-1 Groundwater Operable Unit Remedial Design*, Pacific Northwest National Laboratory, Richland, Washington. Availabe at: http://www.pnl.gov/main/publications/external/technical_reports/PNNL-18732.pdf.

PNNL-19277, 2010, *Conceptual Models for Migration of Key Groundwater Contaminants Through the Vadose Zone and Into the Unconfined Aquifer Below the B-Complex*, Pacific Northwest National Laboratory, Richland, Washington. Available at: http://pdw.hanford.gov/arpir/pdf.cfm?accession=0084238.

PNNL-19702, 2010, *Hydrogeologic Model for the Gable Gap Area, Hanford Site*, Pacific Northwest National Laboratory, Richland, Washington. Available at: https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-19702.pdf.

PNNL-22062, 2012, *Abiotic Degradation Rates for Carbon Tetrachloride and Chloroform: Final Report*, RPT-DVZ-AFRI-012, Pacific Northwest National Laboratory, Richland, Washington. Available at: http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-22062.pdf.

PNNL-23711, 2015, *Physical, Hydraulic, and Transport Properties of Sediments and Engineered Materials Associated with Hanford Immobilized Low-Activity Waste*, RPT-IGTP-004, Rev. 0, Pacific Northwest National Laboratory, Richland, Washington. Available at: http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23711.pdf.

PNNL-24731, 2015, *Evaluating Transport and Attenuation of Inorganic Contaminants in the Vadose Zone for Aqueous Waste Disposal Sites*, RPT-DVZ-AFRI-033, Pacific Northwest National Laboratory, Richland, Washington. Available at: https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-24731.pdf.

PNNL-25146, 2016, *Scale-Dependent Solute Dispersion in Variably Saturated Porous Media*, RPT-IGTP-009, Rev. 0, Pacific Northwest National Laboratory, Richland, Washington. Available at: https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-25146.pdf.

PNNL-26204, 2017, *Simulation of Columbia River Floods in the Hanford Reach*, Pacific Northwest National Laboratory, Richland, Washington. Available at: https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-26204.pdf.

Resource Conservation and Recovery Act of 1976, 42 USC 6901, et seq. Available at: https://www.gpo.gov/fdsys/pkg/STATUTE-90/pdf/STATUTE-90-Pg2795.pdf.

RHO-RE-ST-12P, 1984, *An Assessment of Aquifer Intercommunication in the B Pond-Gable Mountain Pond Area of the Hanford Site*, Rockwell Hanford Operations, Richland, Washington. Available at: http://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=D196002251.

RPP-26744, 2005, *Hanford Soil Inventory Model, Rev. 1*, Rev. 0, CH2M HILL Hanford Group, Inc., Richland, Washington. Available at: https://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0081114H.

RPP-ENV-58782, 2016, *Performance Assessment of Waste Management Area C, Hanford Site, Washington*, Rev. 0, Washington River Protection Solutions, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/pdf.cfm?accession=0065503H.

RPP-RPT-59197, 2016, *Analysis of Past Waste Tank Leaks and Losses in the Vicinity of Waste Management Area C, Hanford Site, Washington*, Rev. 1, Washington River Protection Solutions, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/pdf.cfm?accession=0072362H.

RPP-RPT-59344, 2016, *Integrated Disposal Facility Model Package Report: Vadose and Saturated Zone Flow and Transport*, Rev. 0, Washington River Protection Solutions, Richland, Washington.

Russo, D., 1993, "Stochastic Modeling of Macrodispersion for Solute Transport in a Heterogeneous Unsaturated Porous Formation," *Water Resour. Res.* 29(2):383-397.

Schulze-Makuch, D., 2005, "Longitudinal Dispersivity Data and Implication for Scaling Behavior," *Ground Water* 43(3):443-456.

SGW-41072, 2017, *Liquid Effluent Retention Facility Engineering Evaluation and Characterization Report*, Rev. 1, CH2M HILL Plateau Remediation Company, Richland, Washington. Available at: http://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0068831H.

SGW-54165, 2014, *Evaluation of the Unconfined Aquifer Hydraulic Gradient Beneath the 200 East Area, Hanford Site*, Rev. 0. CH2M HILL Plateau Remediation Company, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/pdf.cfm?accession=0085682.

SGW-60338, 2017, *Historical Changes in Water Table Elevation and Groundwater Flow Direction at Hanford: 1944 to 2014*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington. Available at: http://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0072270H.

SGW-62323, 2018, *Central Plateau Groundwater Trace Study Phase I Report*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0064369H.

van Genuchten, M. Th., 1980, "A Closed-Form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils," *Soil Science Society of America Journal* 44(5):892-898. Available at: https://www.ars.usda.gov/ARSUserFiles/20360500/pdf_pubs/P0682.pdf.

WAC 173-340, "Model Toxics Control Act—Cleanup," *Washington Administrative Code*, Olympia, Washington. Available at: http://apps.leg.wa.gov/wac/default.aspx?cite=173-340.

173-340-747, "Deriving Soil Concentrations for Groundwater Protection."

WCH-520, 2013, *Performance Assessment for the Environmental Restoration Disposal Facility, Hanford Site, Washington*, Rev. 1, Washington Closure Hanford, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0083701.

WHC-EP-0645, 1995, *Performance Assessment for the Disposal of Low-Level Waste in the 200 West Area Burial Grounds*, Westinghouse Hanford Company, Richland, Washington. Available at: http://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0075582H.

WHC-IP-0977, 1993, *Estimation of PUREX Equipment and Materials That Are Candidates for Removal and Waste Processing During PUREX Plant Closure*, Westinghouse Hanford Company, Richland, Washington. Not available in Admin Record.

WHC-MR-0227, 1991, *Tank Wastes Discharged Directly to the Soil at the Hanford Site*, Westinghouse Hanford Company, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=D196059556.

WHC-SD-WM-TI-730, 1996, *Performance Assessment for the Disposal of Low-Level Waste in the 200 East Area Burial Grounds*, Rev. 0, Westinghouse Hanford Company, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0071840H.

Williams, A.C., 2012, "Modeling to Support Regulatory Decisionmaking at Hanford" (memorandum to M.S. McCormick, U.S. Department of Energy, Richland Operations Office, and S.L. Samuelson, U.S. Department of Energy, Office of River Protection), U.S. Department of Energy, Washington, D.C., October 9. Not available in Admin Record.

Ye, M., R. Khaleel, and T.-C.J. Yeh, 2005, "Stochastic Analysis of Moisture Plume Dynamics of a Field Injection Experiment," *Water Resour. Res.* 41(3):1-13. Available at: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2004WR003735.

Yeh, T.-C.J., L.W. Gelhar, and A.L. Gutjahr, 1985, "Stochastic Analysis of Unsaturated Flow in Heterogeneous Soils, 2. Statistically Anisotropic Media with Variable α," *Water Resour. Res.* 21(4):457-464.

Yeh, T.-C.J., M. Ye, and R. Khaleel, 2005, "Estimation of Effective Unsaturated Hydraulic Conductivity Tensor Using Spatial Moments of Observed Moisture Plume," *Water Resour. Res.* 41(3):1-12.

Yeh, T.-C.J., R. Khaleel, and K.C. Carroll, 2015, *Flow Through Heterogeneous Geologic Media*, Cambridge University Press, New York, New York.

Zhang, Z.F. and R. Khaleel, 2010, "Simulating Field-Scale Moisture Flow Using a Combined Power-Averaging and Tensorial Connectivity-Tortuosity Approach," *Water Resour. Res.* 46(9):1-14.

Zhang, Z.F., A.L. Ward, and G.W. Gee, 2003, "A Tensorial Connectivity–Tortuosity Concept to Describe the Unsaturated Hydraulic Properties of Anisotropic Soils," *Vadose Zone J.* 2(3):313-321.

Zheng, C., 1990, *MT3D: A Modular Three-Dimensional Transport Model for Simulation of Advection, Dispersion and Chemical Reaction of Contaminants in Groundwater Systems*, S.S. Papadopulos & Associates, Inc., Rockville, Maryland. Available at: https://hydro.geo.ua.edu/mt3d/Mt3d_1990.pdf.

Zheng, C. and P.P. Wang, 1999, *MT3DMS: A Modular Three-Dimensional Multispecies Transport Model for Simulation of Advection, Dispersion, and Chemical Reactions of Contaminants in Groundwater Systems; Documentation and User's Guide*, Contract Report SERDP-99-1, U.S. Army Engineer Research and Development Center, U.S. Army Corps of Engineers, Vicksburg, Mississippi. Available at: Available at: https://apps.dtic.mil/dtic/tr/fulltext/u2/a373474.pdf.

Zheng, C., 2010, *MT3DMS v5.3 Supplemental User's Guide, Technical Report*, Department of Geological Sciences, University of Alabama, Tuscaloosa, Alabama. Available at: http://hydro.geo.ua.edu/mt3d/mt3dms_v5_supplemental.pdf.