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Model Package Report: Plateau to River Groundwater Transport Model

Version 7.1

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

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

ch2m

P.O. Box 1600
Richland, Washington 99352

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T. J. Budge
CH2M HILL Plateau Remediation Company

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P.O. Box 1600
Richland, Washington 99352

APPROVED
By Ashley R Jenkins at 8:13 am, Jul 15, 2015

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Model Package Report

Plateau to River Groundwater Transport Model

Version 7.1

May, 2014

Prepared for:

Technical Integration

Prepared by:

T.J. Budge
CH2M Hill Plateau Remediation Company

Executive Summary

A scale-appropriate groundwater fate and transport model of the unconfined aquifer for evaluation of long-term fate and transport in the 200-PO-1 and 200-BP-5 Groundwater Operable Units (OUs) at the Hanford Site is required to support the Remedial Investigations (RIs) for the U.S. Department of Energy (DOE). Later it is anticipated this model will be revised and updated to meet the needs of the planned Feasibility Study (FS) for these groundwater OUs as well. The model developed for this purpose is designated as the Plateau to River Groundwater Transport Model (P2R Model) and the basis and development of this model are described in this model package report.

Modeling is an iterative process; periodic revisions to the P2R Model will occur to incorporate new data and information. A version number identifies each distinct version in the evolution of the P2R Model to delineate and uniquely identify the configuration state of this model over time. This model package report will be revised for each major version of the P2R Model to document the information incorporated. This revision documents P2R Model Version 7.1.

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Terms

ACM	alternative conceptual model
CERCLA	*Comprehensive Environmental Response, Compensation, and Liability Act of 1982*
CHPRC	CH2M HILL Plateau Remediation Company
CRBG	Columbia River basalt group
DOE	U.S. Department of Energy
DOE-EM	U.S. Department of Energy, Environmental Management
DOE-RL	U.S. Department of Energy, Richland Operations Office
ERDF	Environmental Restoration Disposal Facility
FEPs	features, events, and processes
FS	Feasibility Study
HSGF	Hanford Site Geoframework (Model)
HSGWF	Hanford Site Groundwater Flow (Model)
IDF	Integrated Disposal Facility
LLBG	Low-Level Burial Ground
OU	Operable Unit
PA	Performance Assessment
PNNL	Pacific Northwest National Laboratory
P2R	Plateau to River (groundwater transport model)
RCRA	*Resource Conservation and Recovery Act of 1976*
RI	Remedial Investigation
WMA	Waste Management Area
TC&WM EIS	Tank Closure and Waste Management Environmental Impact Statement
TMR	telescopic mesh refinement

1 Purpose

A scale-appropriate groundwater fate and transport model of the unconfined aquifer for evaluation of long-term fate and transport in the 200-PO-1 and 200-BP-5 Groundwater Operable Units (OUs) at the Hanford Site is required to support the Remedial Investigations (RIs) for the U.S. Department of Energy (DOE). Later it is anticipated this model will be revised and updated to meet the needs of the planned Feasibility Study (FS) for these groundwater OUs as well. The model developed for this purpose is designated as the Plateau to River Groundwater Transport Model (P2R Model) and the basis and development of this model are described in this model package report.

A groundwater flow model was developed for the unconfined aquifer at the U.S. Department of Energy's (DOE) Hanford Site to meet the modeling requirements for the Tank Closure and Waste Management Environmental Impact Statement (TC&WM EIS) (DOE/EIS-0391, *Final Tank Closure and Waste Management Environmental Impact Statement*).

The groundwater flow model developed for the TC&WM EIS was constructed with data and information current through 2006 and later updated with data and information current through 2008. This capability was adopted as "Revision 0" of the newly designated Hanford Site Groundwater Flow Model (HSGWF Model), and work is underway to prepare the first revision to the HSGWF Model to support the following objectives:

- Modify the groundwater flow model to support linkage to the Hanford Site Geologic Framework (HSGF) Model (ECF-Hanford-13-0029) to support efficient, periodic updates of the geologic representation of the geologic structure of the HSGWF Model.
- Initiate periodic updates to incorporate data and other information collected since the TC&WM EIS groundwater flow model was constructed (2008), recalibrate to utilize this information, and provide for future periodic updates to continue to maintain the model with newer data and information.
- Update flow and transport modeling software used to implement the HSGWF Model, as appropriate.

When the HSGWF Model Revision 1 is ready for service, it will support the scale-appropriate transport model described in this model package report. However, the schedule requirements for the 200-BP-5 Remedial Investigation, and 200-PO-1 Remedial Investigation Addendum, require that this scale-appropriate model be developed and placed in service before the HSGWF Model Revision 1 will be ready for service.

Modeling is an iterative process; periodic revisions to the P2R Model will occur to incorporate new data and information. A version number will identify the evolution of the P2R Model to delineate and uniquely identify the configuration state of this model over time. This model package report will revised with each major revision of the P2R Model to document the information incorporated in each revision.

1.1 Need

The 200-PO-1 Groundwater OU RI (DOE/RL-2009-85) utilized the Central Plateau Groundwater (CPGW) Model (CP-47631, *Model Package Report: Central Plateau Groundwater Model Version 3.4*) for groundwater modeling of baseline future conditions within the spatial extent covered by that model's domain (Figure 1-1). This was sufficient for most COPCs evaluated, but the 200-PO-1 Groundwater OU includes two notable mobile COPCs that are dispersed in groundwater well downgradient (east and southeast) of the CPGW Model: tritium and iodine.

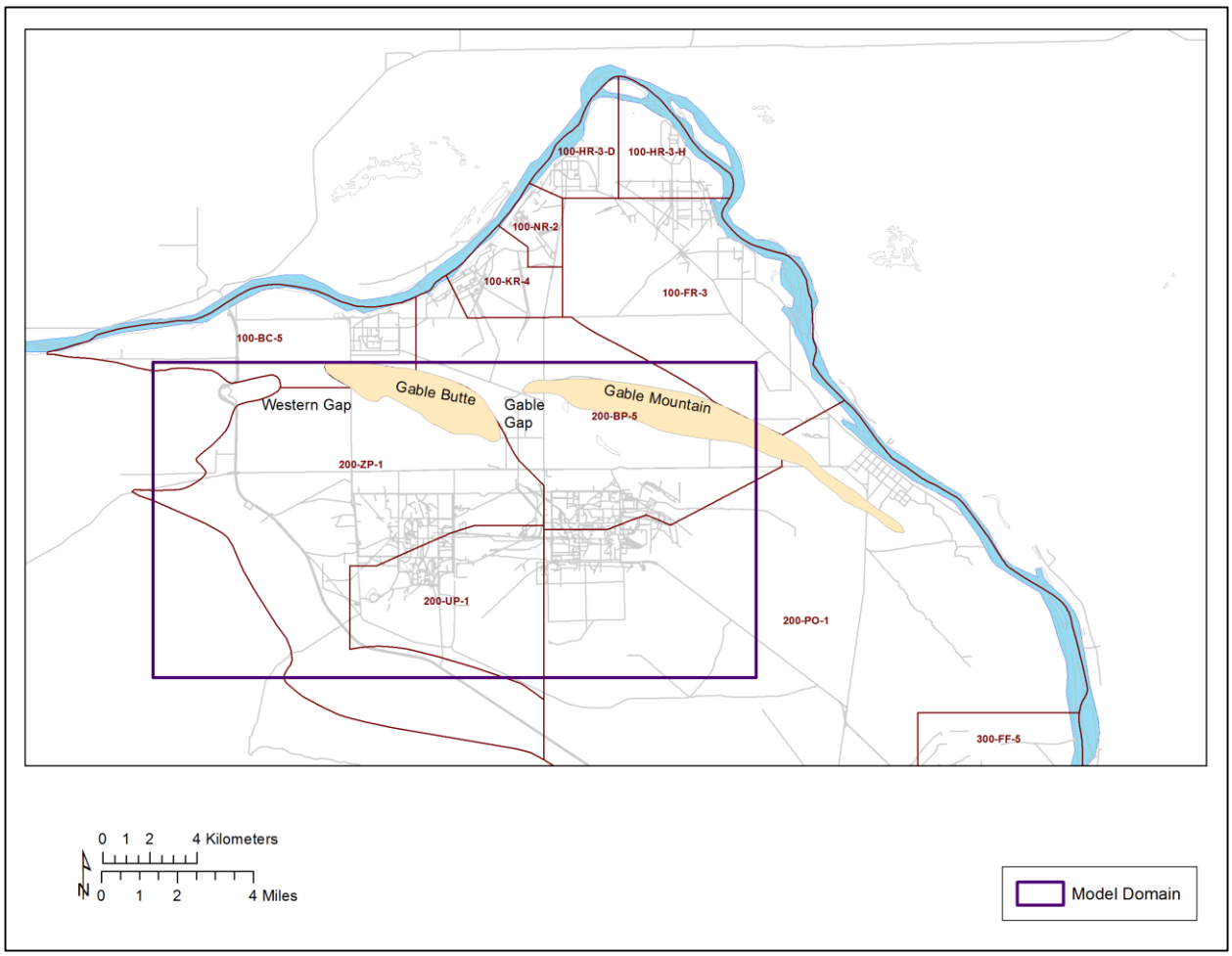


Figure 1-1. Extent of the Central Plateau Groundwater Model Domain

At the time this RI was prepared, restrictions on site-wide modeling were in place at DOE direction while the TC&WM EIS was being prepared. Therefore, to address these relatively mobile COPCs in the distal portions of the 200-PO-1 Groundwater OU, streamtube transport models (ECF-200PO1-09-2007, *200-PO-1 Operable Unit Remedial Investigation Report – Contaminant Fate & Transport Modeling in the Distal Portion of OU*) were developed (Figure 1-2). The adequacy of this modeling approach to meet RI objectives was evaluated in ECF-200PO1- 10-0393, *Evaluating Adequacy of One-Dimensional Transport Calculation in the Saturated Zone of the Far-Field Portion of the 200-PO-1 Operable Unit*.

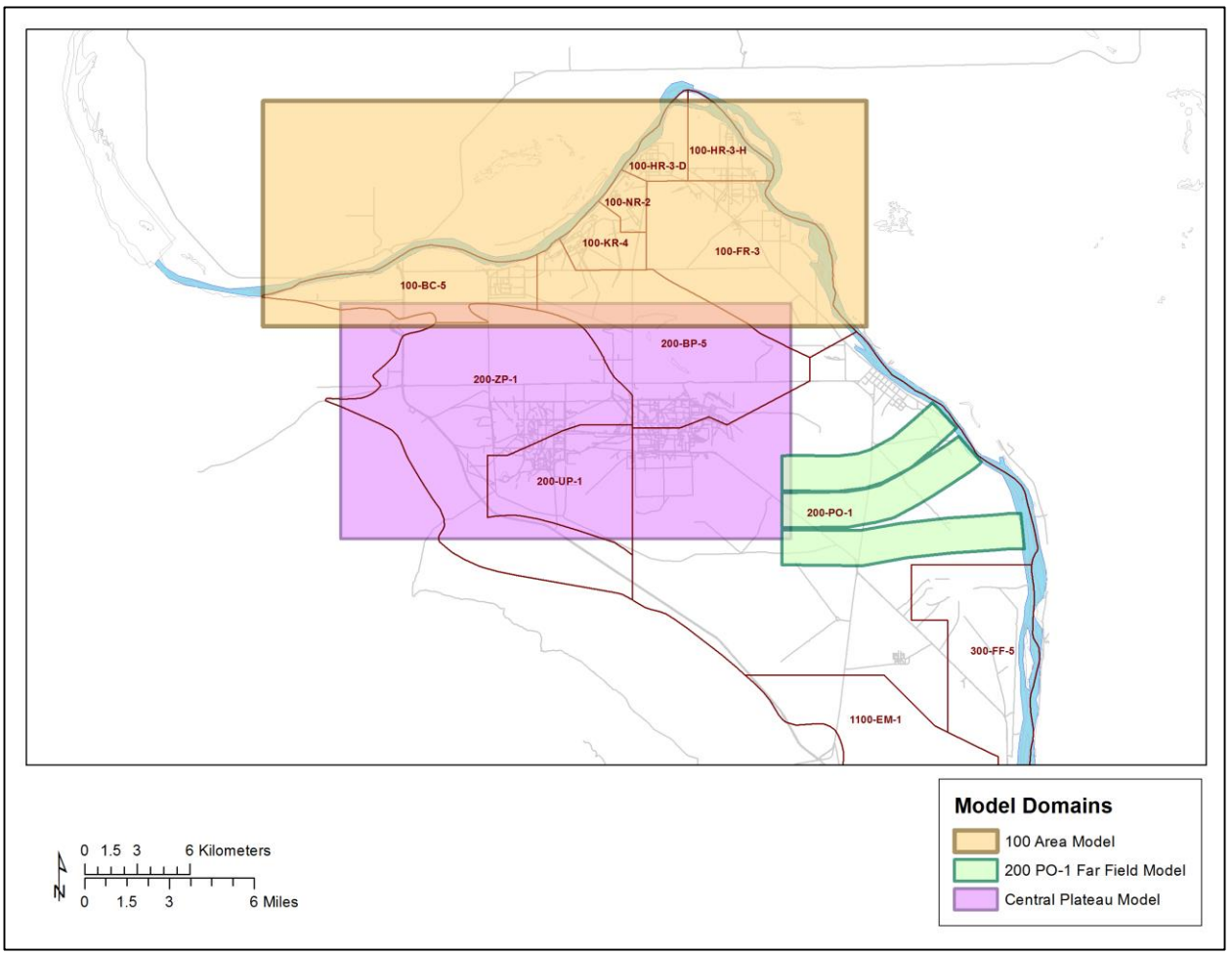


Figure 1-2. Model Domains for the Central Plateau Model and the Streamtube "Far Field" Model Developed for the 200-PO-1 RI to Address Contaminant Migration in the Distal Portion of that OU.

When the 200-PO-1 RI was reviewed by the Washington State Department of Ecology, it was noted that the modeling approach for the distal portion of the OU would be inadequate to the needs of the FS, and it was expected that the entire OU be evaluated in a three-dimensional groundwater model. The model developed and described in this model package report is expressly developed to meet this need.

1.2 Background

A brief overview of the physical setting, site infrastructure, and the process and operational history of the setting for the P2R Model is provided below. A summary of past modeling efforts that addressed approximately the same setting is also provided for context.

1.2.1 Overview of Physical Setting, Site Infrastructure, and Process and Operational History of the Model Setting

Figure 1-3 is a general map of the Hanford Site showing location and principle facilities. The Central Plateau is south of Gable Butte and Gable Mountain, and includes the 200 West and 200 East Areas depicted in the figure. These areas, in an upland area termed the Central Plateau, were the location where chemical separations of nuclear fuel rods that were irradiated in reactors in the 100 Areas along the Columbia River were performed to isolate plutonium for nuclear weapons production. Facilities in the

200 West and 200 East Areas included "canyons" (immense chemical separations plants), waste disposal facilities (large underground tank farms for the most dangerous wastes; as well as ponds, ditches, cribs, and trenches for infiltration of other waste disposal), and other ancillary facilities. The groundwater contamination issues to be addressed by the model described in this report trace to contamination resulting from production activities in these locations.

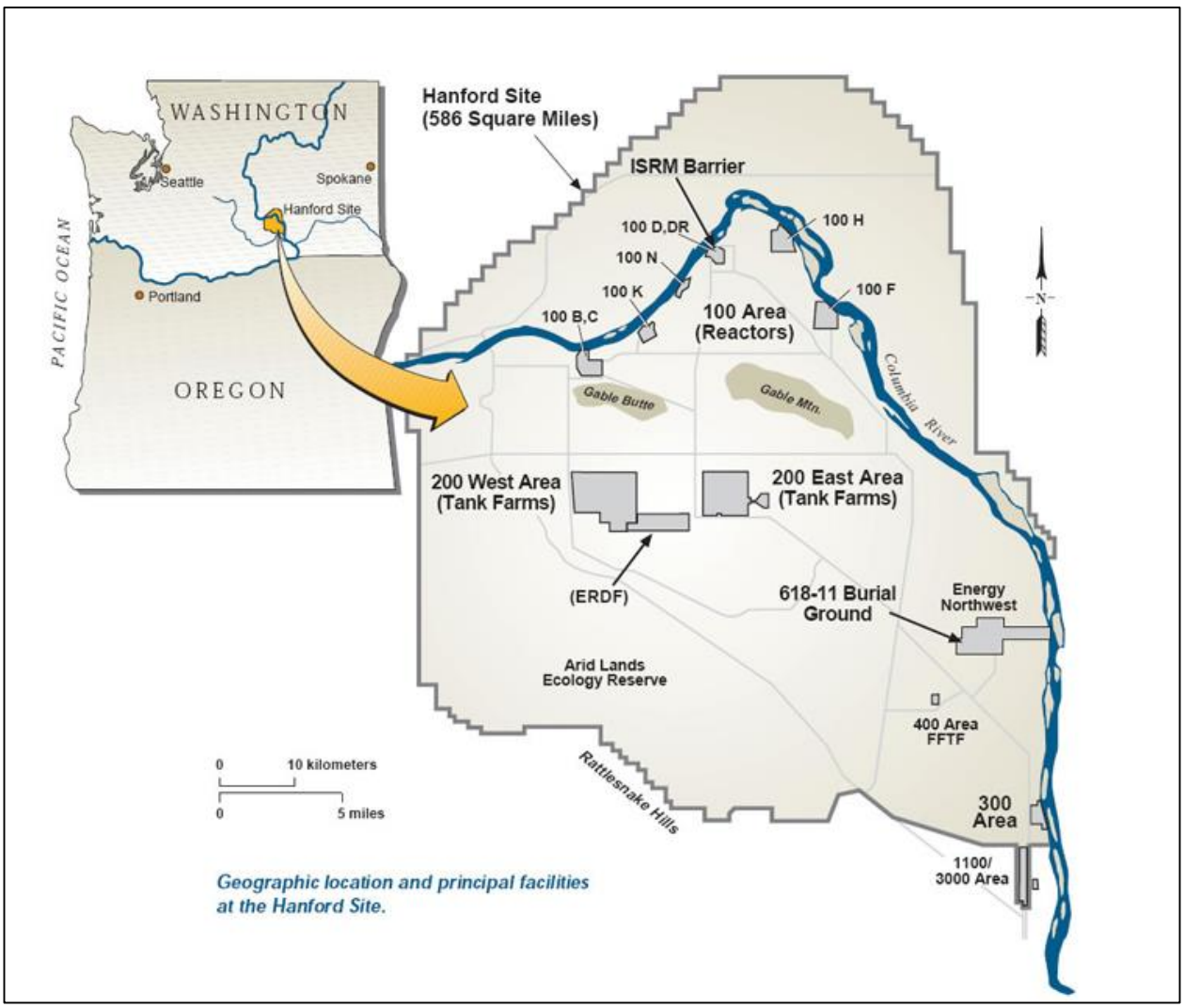


Figure 1-3. Geographic Location and Principal Facilities at the Hanford Site

The principal groundwater resource impacted by contamination from nuclear weapons production activities in the Central Plateau is the uppermost, unconfined aquifer that is primarily comprised of catastrophic flood depositional sequences. A deep vadose zone lies above this unconfined aquifer, typically about 100 meters thick over the area of the Central Plateau. The unconfined aquifer is generally bounded to the north, south, and west by basalt subcrops and outcrops (Figure 1-4). There are two gaps in the basalt subcrops along the northern boundary. In these two regions, the water table is above, or near, the basalt surface. The westernmost region is referred to as the Western Gap and the eastern region is referred to as the Gable Gap. The water table is also above the basalt surface along the eastern boundary and the easternmost part of the southern boundary.

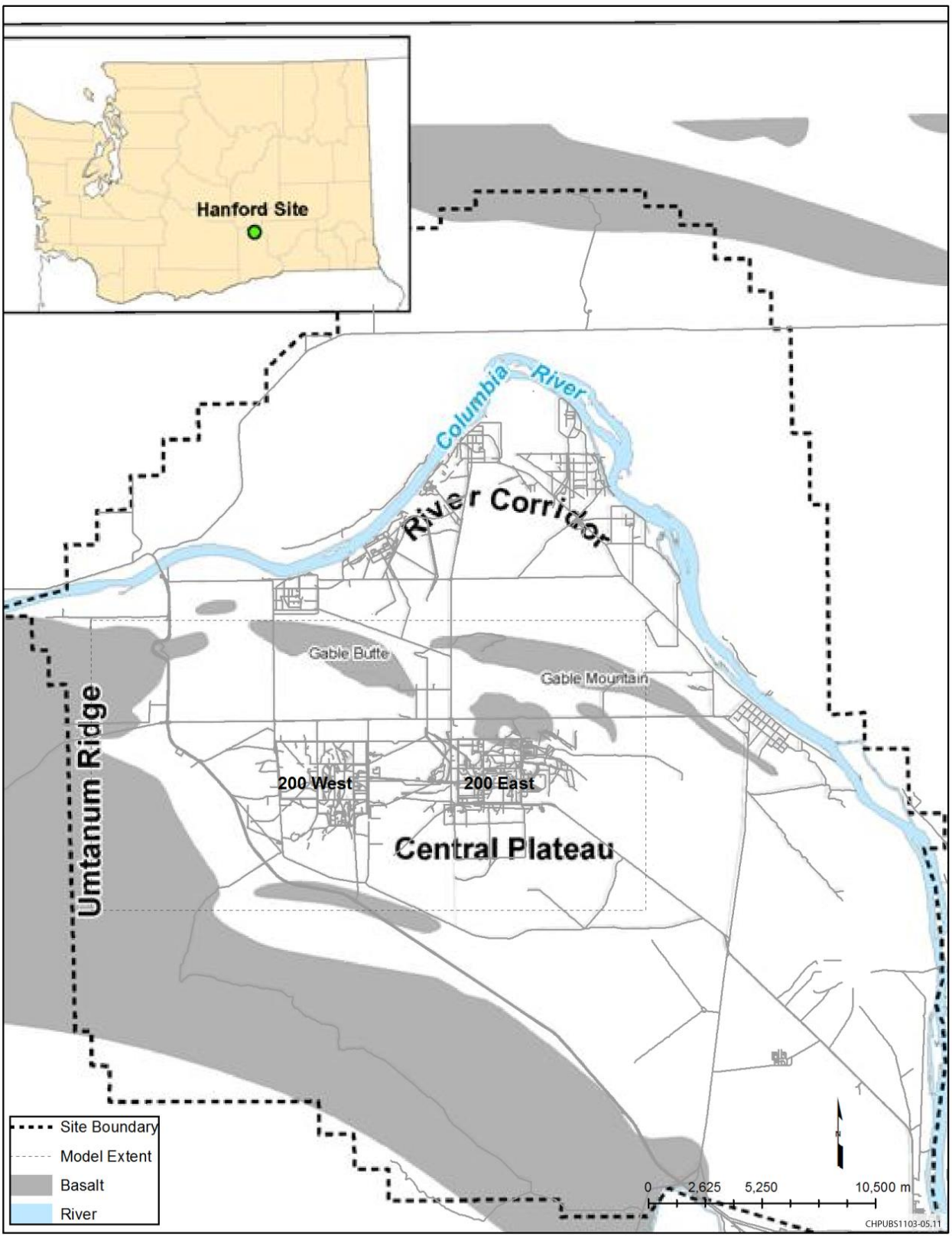


Figure 1-4. Basalt Subcrops and Outcrops

Sources of inflow to the unconfined aquifer include Cold Creek (located in the slot along the western boundary) and Dry Creek (the gap in the basalt subcrops in the southwest corner of the domain).

The bedrock of the domain is composed of basalts that are assumed (at least, in the current version of the model documented in this report) to form an impermeable lower boundary. The top of the model is the land surface; however, geologic variations are usually only represented to the maximum measured water table. The water table was much higher in the Central Plateau during the operational period of the Hanford Site than it is currently due to massive discharges of water associated with operations in that period. These discharges largely ended by the early 1990s, and the unconfined aquifer is presently slowly receding to pre-operational water levels. Hence, the geologic media extent to be addressed must extend vertically to include sediments that are presently above the water table in order to support historical modeling of water flow for model calibration purposes.

1.2.2 Summary of Previous Modeling Efforts

Pacific Northwest National Laboratory (PNNL) developed and improved over a lengthy period a site-wide groundwater flow and transport model implemented in the CFEST software that used the finite-element numerical method (PNL-10886, *Development of a Three-Dimensional Ground-Water 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*; PNNL-14398, *Transient Inverse Calibration of the Site-Wide Groundwater Flow Model (ACM-2): FY 2003 Progress Report*; PNNL-14753, *Groundwater Data Package for Hanford Assessments*). DOE determined in 2006 that a new site-wide modeling capability would be developed to support the Tank Closure and Waste Management (TC&WM) Environmental Impact Statement (EIS). With this decision, further development and applications of the PNNL site-wide model ended. The TC&WM EIS was issued in 2012 (DOE/EIS-0391, *Final Tank Closure and Waste Management Environmental Impact Statement*). The modeling capability was transferred to CH2M HILL Plateau Remediation Company (CHPRC) in 2013 (DOE, 2013, *TC&WM EIS Technology Transfer Document*) and is currently under configuration management and maintenance.

While the TC&WM EIS was in development (2006 to 2008), more limited-scale models developed and applied to meet CERCLA decision-making needs at the Hanford Site:

- A groundwater flow and advective-dispersive transport model was originally developed to perform contaminant fate and transport simulations in support of the 200-ZP-1 Groundwater OU Feasibility Study, Proposed Plan, and Final Record of Decision (ROD) (*Feasibility Study for the 200-ZP-1 Operable Unit* [DOE/RL-2007-28]). This study used analytical and superposition techniques, rather than a numerical model.

- In anticipation of the need for more rigorous analyses of groundwater flow and contaminant transport, this superposition model was replaced during fiscal year (FY) 2008 with a numerical groundwater flow and contaminant transport model. That model was developed to perform calculations supporting the post-ROD remedy design, focusing on the remedial design/remedial action work plan (RD/RAWP) for 200-ZP-1 (*200 West Area Pre-Conceptual Design for Final Extraction/Injection Well Network: Modeling Analyses* [DOE/RL-2008-56]; *Description of Modeling Analyses in Support of the 200-ZP-1 Remedial Design/Remedial Action* [DOE/RL-2009-38]; *200 West Area 200-ZP-1 Pump-and-Treat Remedial Design/Remedial Action Work Plan* [DOE/RL-2008-78, Draft A]). The model developed in support of post-ROD activities at the 200-ZP-1 Groundwater OU was constructed with a geographic extent—or domain—that covers most of the area commonly known as the Hanford Central Plateau, encompassing four groundwater OUs that are located in the Central Plateau area: 200-PO-1, 200-

BP-5, 200-UP-1, and 200-ZP-1. This model was implemented in the MODular groundwater FLOW code (MODFLOW) software to simulate flow, and in Modular 3-Dimensional Multiple Species transport code (MT3DMS) software to simulate contaminant transport. For clarity in this report, the model developed for the 200-ZP-1 Groundwater OU analyses is referred to as the 200-ZP-1 Model.

- During FY 2009, it was decided to accept the general premise (i.e., conceptual basis, computational grid, and discretization) of the 200-ZP-1 Model as a basis for a model to be used throughout the Central Plateau in support of decision making at the encompassed OUs. Because the development of the 200-ZP-1 Model had focused on features, events, and processes (FEPs) associated with the 200-ZP-1 OU, further development of the model was required to make it a suitable tool for use at the other OUs. To distinguish the current version of this model from the precursor 200-ZP-1 Model, this improved model was designated as the Central Plateau Groundwater (CPGW) Model. The CPGW Model replaced the 200-ZP-1 Model in all groundwater simulations for the four groundwater OUs encompassed by the CPGW Model, including any calculations made for the 200-ZP-1 OU. Development of the CPGW Model has progressed through several distinct versions (CP-47631).

- In FY 2009, the need arose to address mobile COPCs in the distal portions of the 200-PO-1 Groundwater OU during preparation of the 200-PO-1 RI. Because an operational site-wide model was not available yet (the TC&WM EIS still being under development), a limited analysis of the distal portion of the 200-PO-1 OU based on using a set of streamtube transport models was employed (ECF-200PO1-09-2007). The adequacy of this modeling approach to meet RI objectives was evaluated in ECF-200PO1- 10-0393. However, as noted above, when the 200-PO-1 RI was reviewed by the Washington State Department of Ecology, it was noted that the modeling approach for the distal portion of the OU would be inadequate to the needs of the FS, and it was expected that the entire OU be evaluated in a three-dimensional groundwater model.

1.3 Document Organization

Model objectives are defined in Section 2. The conceptual basis for the model is described in Section 3. The details of model implementation are presented in Section 4. Sensitivity and uncertainty analyses that were performed to evaluate the model response to variability in key parameters are presented in Section 5. Explicit limitations of the model are identified in Section 6. The method for controlling the model development as a configuration-controlled entity is defined, and version history is provided, in Section 7. Recommendations for future model improvements are listed in Section 8. References are provided in Section 9.

2 Model Objectives

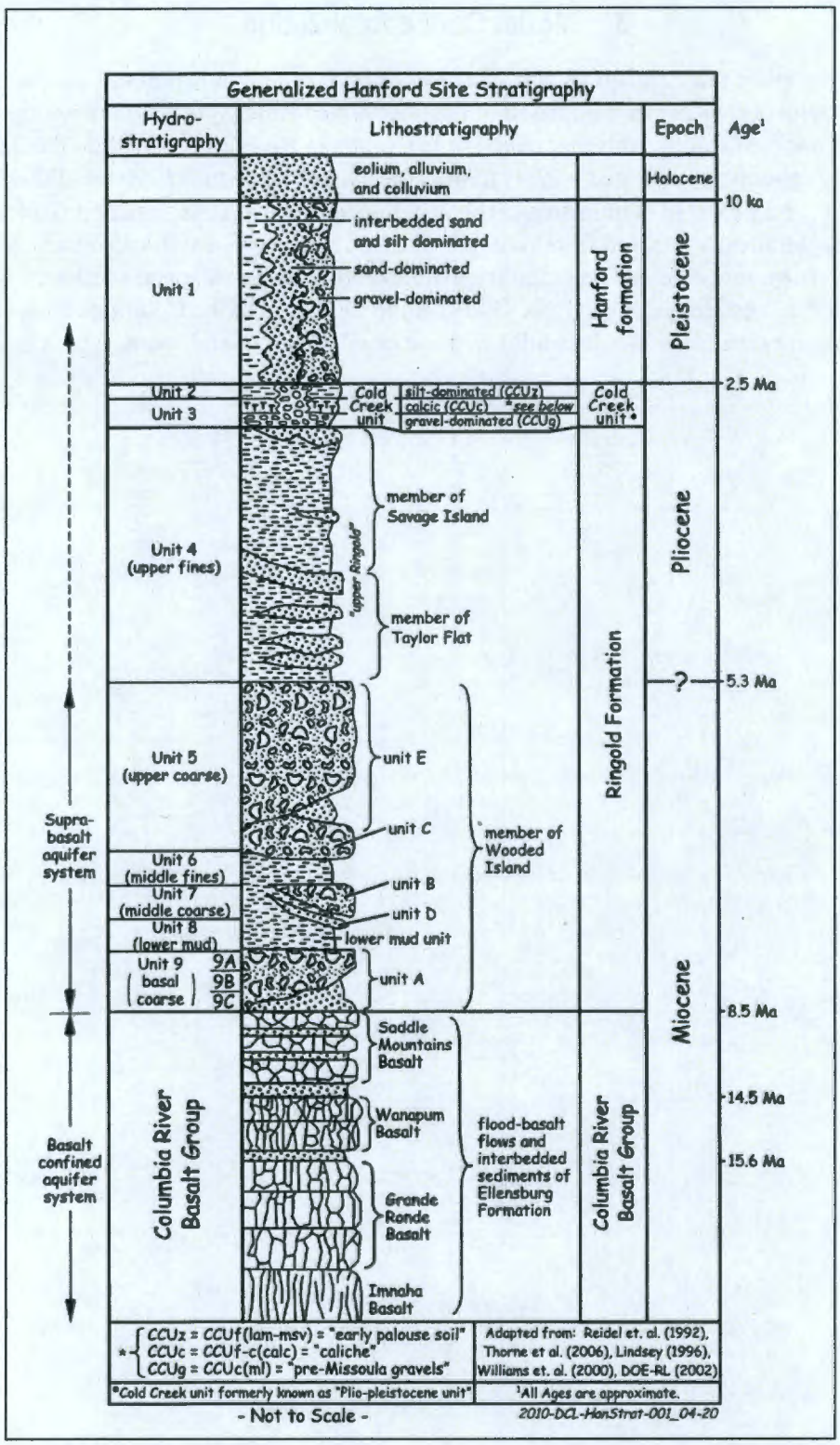
The overall objective of this model is to provide a tool for prediction of groundwater contaminant transport in the unconfined aquifer of the 200-PO-1 and 200-BP-5 groundwater OUs, extending along present and future flow paths as far as the Columbia River. Specific attributes required of this site-wide model include:

- Incorporate updated geology: Incorporate solid geologic framework from the recently completed Hanford Site South Geoframework (HSSGF) Model that includes updated geologic and hydraulic data collected from January 2009 through December 2013. Also, incorporate latest information and interpretation of Gable Gap structure and hydraulic data to improve model predictive power in this key portion of the flow domain.
- Applicable to variable boundary conditions: this model must be robust enough to address variable boundaries, including river stage cycles.
- Computationally efficient: model must provide efficient solutions in reasonable execution times.
- Use qualified software: because of schedule demands for the 200-BP-5 and 200-PO-1 RI documents, this model must be implemented using currently approved site-standard modeling software.

Revision 0 of the HSGW Model provided a tool sufficient for achieving the objectives required for the TC&WM EIS. The work detailed in this report documents the update of HSGW Revision 0 to Revision 1 to develop the model capabilities toward attaining the specific attributes listed.

3 Model Conceptualization

The conceptual model for the P2R Model considers saturated flow and transport of dilute aqueous-phase contaminants through porous media comprised of the unconfined flow system occurs within fluvial, lacustrine, and glaciofluvial sediments that overlay the Columbia River Basalts within the Pasco Basin (Figure 3-1). This uppermost, saturated zone is termed the unconfined aquifer system, although locally confined conditions may exist in certain areas. This local unconfined aquifer system provides a pathway for transport of contaminants released from past, present, and future site activities. Water enters the system through vertical recharge and recharge from upland areas to the west and southwest of the domain, and exits through the Western Gap and Gable Gap north to discharge to the Columbia river (when the water table elevation exceeds the basalt saddles in these gaps), and east and southeast to the Columbia River.



Source: PNNL-14898

Figure 3-1. Generic Stratigraphic Column for the Central Plateau to River Environ

3.1 Geologic Overview

This subsection provides an overview of the geology and hydrogeology of the Central Plateau to Columbia River environ for readers unfamiliar with the hydrogeologic setting. The description presented here is synopsis of the regional geology discussion presented in PNNL-17913, *Hydrogeology of the Hanford Site Central Plateau – A Status Report for the 200 West Area*. More detailed descriptions of the hydrogeology of the Central Plateau can also be found in PNNL-12261, *Revised Hydrogeology for the Suprabasalt Aquifer System, 200-East Area and Vicinity*; PNNL-13858, *Revised Hydrogeology for the Suprabasalt Aquifer System, 200-West Area and Vicinity*; and references therein.

The P2R Model simulates flow in the saturated portion of sedimentary deposits that have formed locally over the Columbia River Basalt Group (CRBG), a series of flood-basalts that formed over a period of 17 to 6 million years ago in north-central and northwest Oregon, eastern Washington, and western Idaho. Regional subsidence and uplift of the Pasco Basin has led to depositional and erosive periods with depositional features also influenced by local deformation of the basalt. Major flooding events, most dramatically of the Missoula floods, caused deep erosion and deposition during the last ice age.

3.1.1 Ringold Formation Units

The oldest depositional sequence is the Ringold Formation deposited between 10.5 and 3.4 million years ago. BHI-00184, *Miocene- to Pliocene-Aged Suprabasalt Sediments of the Hanford Site, South-Central Washington*, divided the Ringold Formation into three informal members: Wooded Island, Taylor Flat, and Savage Island members (Figure 3-1). BHI-00184 subdivided the Wooded Island member into five subunits, A through E. The Ringold Formation that underlies the Central Plateau mostly belongs to the Wooded Island member along with remnants of the of the Taylor Flat member. For the CPGW Model, these units have been grouped into the following:

- Ringold A (also known as unit 9 in PNNL-12261)
- Ringold mud (also referred to as Ringold lower mud) composed of units B, C, and D (units 8, 7, and 6 in PNNL-12261)
- Ringold E composed of subunit E and the Taylor Flat member (units 5 and 4 in PNNL-12261)

Ringold unit A is composed of extensive gravel with interbedded sand. It was deposited in a braided plain of a meandering Columbia River that exited the Pasco Basin through the present Yakima River gap along the southeast end of the Rattlesnake Mountain anticline ("Paleodrainage of the Columbia River on the Columbia Plateau of Washington State - A Summary" [Fecht et al, 1987]). About 6.7 million years ago, the river outlet was captured through the present Wallula Gap. The main river channel was still through the Central Plateau region but the depositional environment became a much lower energy sandy alluvial system with a period of lacustrine and overbank deposits of the Ringold mud.

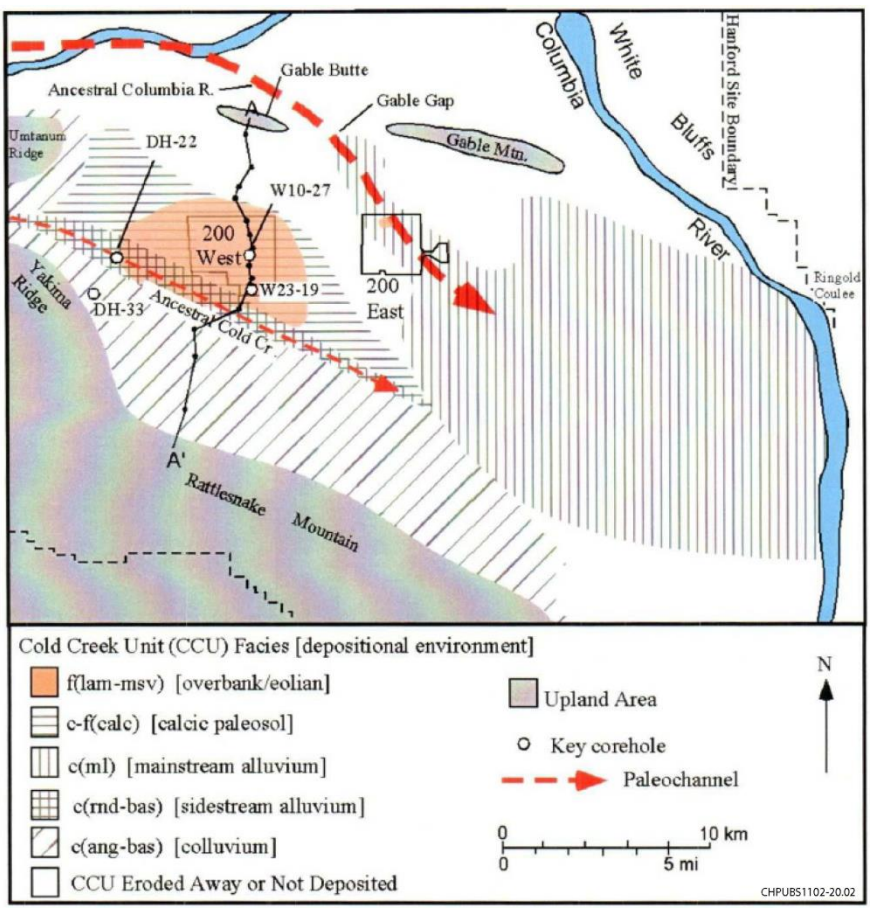
The Ringold mud was subsequently covered by the extensive sequence of mostly alluvial gravels and sand of the Ringold E subunit. Locally, Ringold unit E also contains fine–grained lenses that may have low permeability. About 5 million years ago, the depositional environment produced more than 90 m of sandy Taylor Flat deposits followed by lacustrine deposits of the Savage Island member from 4.8 to 3.4 million years ago.

Regional uplift starting 3.4 million years ago led to extensive erosion removing an estimated 100 m of deposits from the Hanford Site. The Savage Island member has been completely removed from the Central Plateau region and the Taylor Flat member has been removed over much of it. The erosion was

deeper in the eastern portion of the central plateau where the main river channel passed through the gap between Gable Mountain and Gable Butte.

3.1.2 Cold Creek Unit

Following the erosional period was a relatively quiescent period. Alluvial gravel, sand, and silt deposits developed along the main stream channel south of the Gable Gap often referred to as the pre-Missoula gravels (c(ml) in Figure 3-2). Along Cold Creek and Dry Creek, deep drainage channel cuts were filled with alluvium. To the north of the Cold Creek paleochannel (Figure 3-2), overbank deposits form a soil that was calcified by the development of caliche within the soil. Later, less calcified overbank deposits continued to form top of this calcariferous layer. To the south of the Cold Creek paleochannel, coarser grained colluvium from Rattlesnake Mountain accumulated.



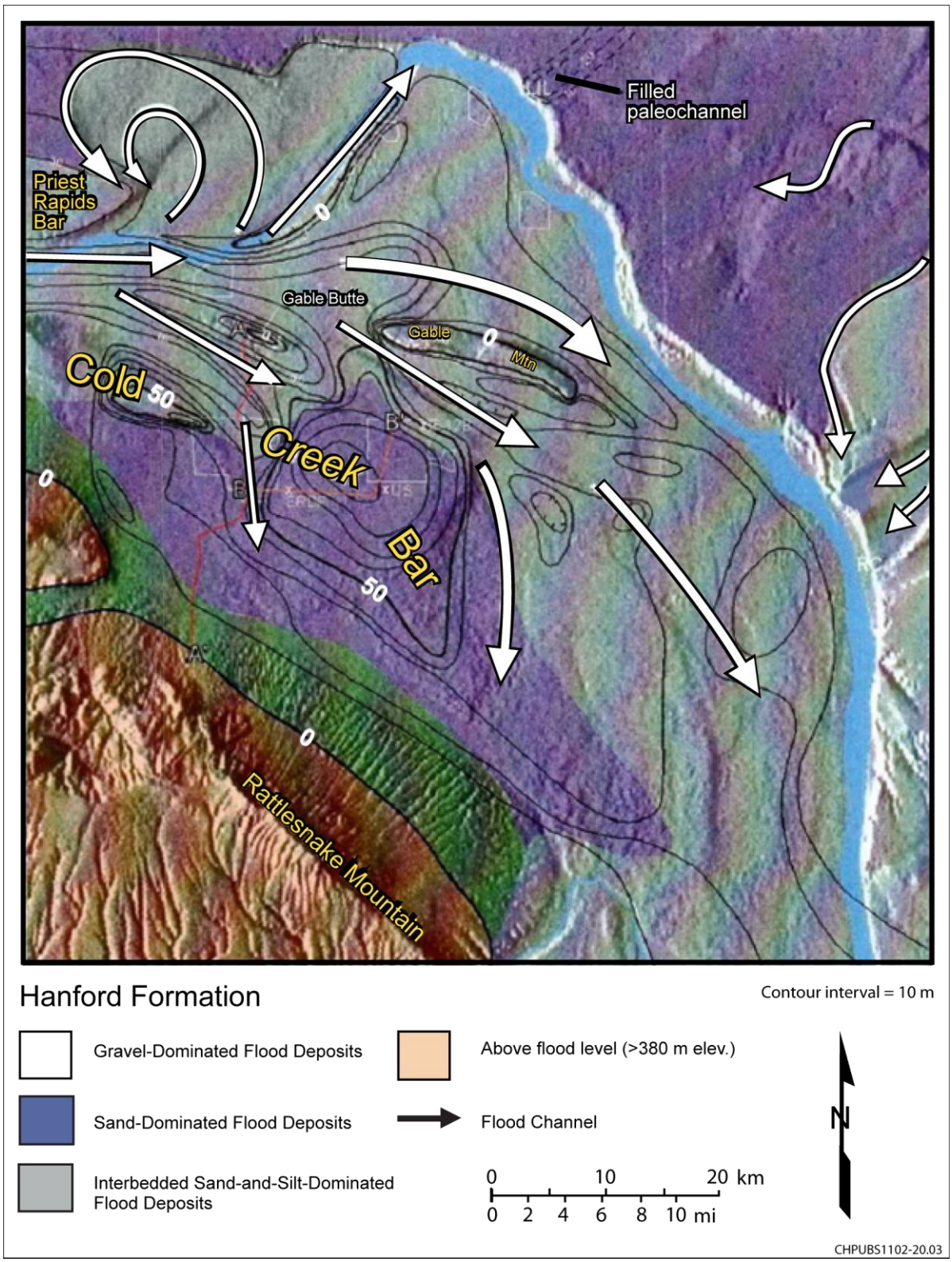
Source: DOE-RL-2002-39

Figure 3-2. Distribution of Cold Creek Facies across the Central Plateau

Only the pre-Missoula (c(ml)) facies of the Cold Creek unit is represented explicitly in the P2R Model. Except for a very small segments of the Cold Creek channel fill, the western portion of the Cold Creek unit lays above the historically high water level. Despite being located within the vadose zone (and thus not explicitly simulated in the P2R Model), the Cold Creek unit had a large influence on aquifer recharge and groundwater dynamics during the operational period of the Hanford Site. Significant perching of water disposed near the surface delayed and laterally offset the arrival of this water at the aquifer. Section 3.2.2 discusses perching.

3.1.3 Hanford formation

The cataclysmic outburst Missoula floods caused repeated large erosional and depositional events, which have significantly shaped the Central Plateau geology that is seen today. Some of these floods may have been the largest ever identified in the history of the world (*The World's Largest Floods, Past and Present – Their Causes and Magnitudes* [O'Conner and Costa, 2004]). The many large floods left a series of overprinted features including scour channels in the basalt, deep erosion of the Cold Creek and Ringold units, highly conductive channel fill deposits extending from the Gable Gap southeast to the Columbia River, and relatively lower energy deposits across the western portion of the Central Plateau. Figure 3-3, from DOE/RL-2002-39, *Standard Stratigraphic Nomenclature for Post-Ringold Formation Sediments within the Central Pasco Basin*, depicts the inferred pathways of these floods and shows the distributions of the major facies groups. The regions of sand-dominated and interbedded sand and silt facies shown in the figure are all above the historic high water level and hence not represented in the P2R Model. As would be expected of deposits formed from multiple erosive/depositional flood events, there are large vertical and horizontal variations within the gravel dominated facies ranging from fine sand to open framework deposits, described as boulders in some drillers logs.



Source: DOE/RL-2002-39

Figure 3-3. Inferred Flood Routes and Associated Hanford Formation Deposit Facies

Aquifer test data have been organized into a database that is accessible using the Hanford Environmental Information System (HEIS). PNNL-14058, *Prototype Database and User's Guide of the Saturated Zone Hydraulic Properties for the Hanford Site*, describes the original database.
A commonly referenced synopsis of hydraulic properties is provided in 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*, presents another data review. These two sources have synthesized interpretations of experimental data. Table 3-1 presents ranges of hydraulic conductivity interpretations.

Table 3-1. Review of Hydrostratigraphic Unit Horizontal Hydraulic Conductivity

	Horizontal Hydraulic Conductivity (m/day)				
	PNL-10886	**PNNL-13641**	**PNNL-14398**	**PNNL-14753**	**CP-47631**
	Hanford Site-wide Groundwater Flow and Transport Model (1995)	Hanford Site-wide Groundwater Flow and Transport Model (2001)	Hanford Site-wide Groundwater Flow and Transport ACM-2 Model	Hanford Site-wide Groundwater Flow and Transport Model (2006)	Central Plateau Groundwater Model v3.4
Unit	Experimental Data	Experimental Data	Calibration Value	Calibration Value	Calibration Value
Hanford	1 – 10,000	10 – >3,500	4,400 – 37,000	6 – 20,000	17,000 (coarse-grained)
Cold Creek			32	1.8 – 5,700	400
Ringold E	0.1 – 200	0.1 – 560	3 – 10	0.24 – 2,562	5
Ringold mud	0.03 - <0.06 (unit 6)	0.002 - 0.03 (unit 6)	0.0002	0.00001 – 101	0.008
Ringold A	0.1 – 200	8	1 – 2.5	0.0005 – 4.2	4.8

Sources:

CP-47631, 2013, *Model Package Report: Central Plateau Groundwater Model Version 3.4*, Rev. 1, CH2M HILL Plateau Remediation Company, Richland, Washington.

PNL-10886, 1995, *Development of a Three-Dimensional Ground-Water Model of the Hanford Site Unconfined Aquifer System: FY 1995 Status Report*, Pacific Northwest National Laboratory, Richland, Washington.

PNNL-13641, 2001, *Uncertainty Analysis Framework – Hanford Site Wide Groundwater Flow and Transport Model,* Pacific Northwest National Laboratory, Richland, Washington.

PNNL-14398, 2003, *Transient Inverse Calibration of the Site-Wide Groundwater Flow Model (ACM-2): FY 2003 Progress Report*, Pacific Northwest National Laboratory, Richland, Washington.

PNNL-14753, 2006, *Groundwater Data Package for Hanford Assessments*, Rev. 1, Pacific Northwest National Laboratory, Richland, Washington.

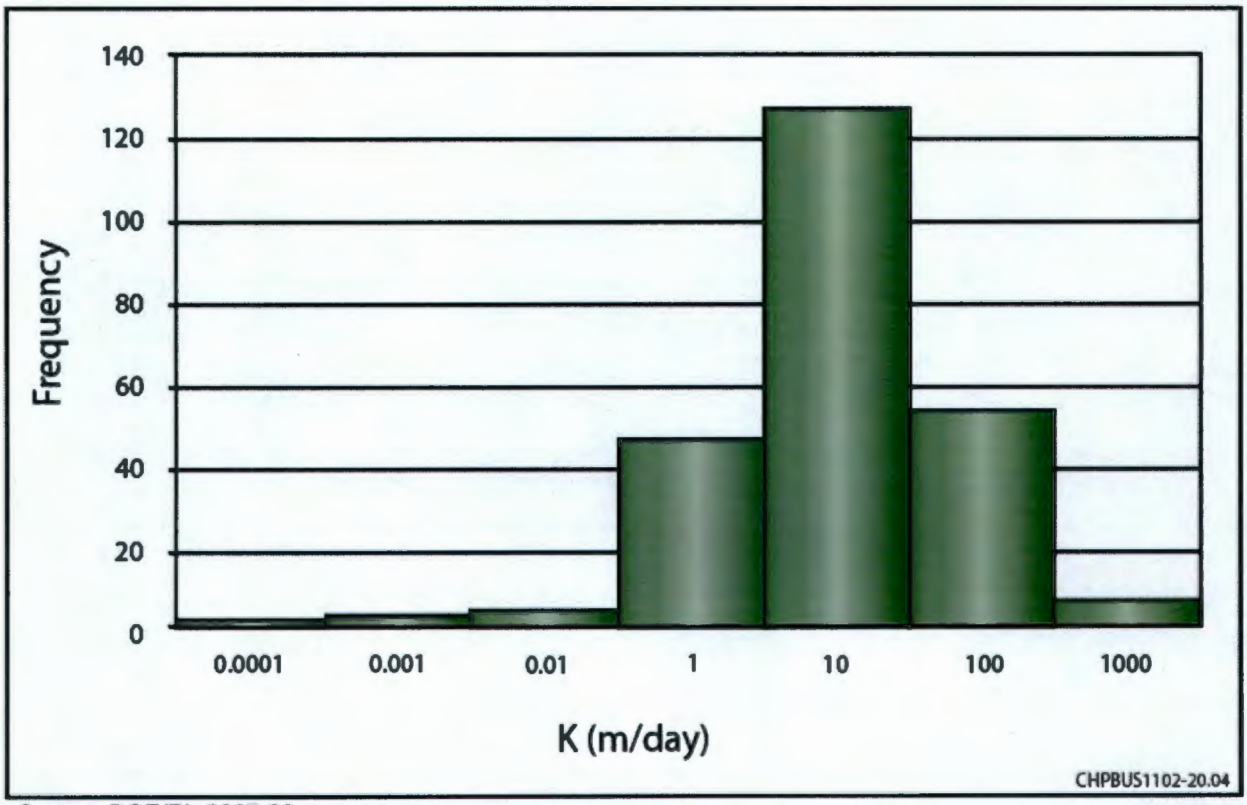
Another source of hydraulic parameter information is past model calibrations. Pacific Northwest National Laboratory (PNNL) developed a series of groundwater flow models. Results from three past model calibrations are included in Table 3-1. These results are taken from PNNL-14398, *Transient Inverse Calibration of the Site-Wide Groundwater Flow Model (ACM-2): FY 2003 Progress Report*, PNNL-14753, *Groundwater Data Package for Hanford Assessments*, and CP-47631.

In both PNL-10886 and PNNL-13641, it is acknowledged that some Hanford formation deposits are essentially too permeable to test and could have hydraulic conductivity as large as 1,000,000 m/day. In PNL-10886, Ringold A, Ringold unit 7, and Ringold E are treated together. The Ringold A value in PNNL-13641 is from a single test. Caution is advised in using the hydraulic values listed in Table 3-1 to evaluate the hydraulic conductivity values used in the P2R Model. Aquifer tests interrogate properties on a scale of meters to hundreds of meters. A single model cell in the P2R Model is 200 by 200 m. Even the largest scale tests of the aquifer are small compared to the scale of HSUs. A total of 256 pumping test results where hydraulic conductivity was estimated were available within the P2R Model domain for constraining estimated hydraulic conductivity. These pumping tests cover 105 of the 12790 model cells or less than 1% of the model domain.

The hydraulic conductivity values from previous calibrations are more closely aligned with values expected for the P2R Model, but here too they are not directly comparable. The models used for PNNL-14398 and PNNL-14753, extended to and beyond the Columbia River, hence covering a larger domain, and also have a more variable distribution of the material properties. For PNNL-14398, the Hanford formation was divided into five zones. The range presented in Table 3-1 represents the two zones that correspond to large fractions of the Hanford formation of the P2R Model. Ringold unit E was also divided into five zones with only two zones coinciding with Ringold unit E of P2R Model. The value for Ringold mud only represents unit 8 of PNNL-14398 and does not include the more permeable unit 7. The range of 1.0 to 2.5 m/day for Ringold unit A was taken from Figure 4.5 of PNNL-14398 using the color scale of the figure as a guide.

For the model described in PNNL-14753, the hydraulic conductivity values for each unit were distributions of parameter values. The creation of the spatial variation for the different units is based on inverse estimates of transmissivity, which were then converted to hydraulic conductivity as described in PNL-10886.As described in PNNL-14753, during the parameter estimation phase of modeling the distribution of hydraulic conductivity was increased or decreased by multiplying the values by a factor that was held constant over the entire model domain. The distribution of conductivity was then modified by a constant factor using parameter estimation

An updated review of Ringold E properties was conducted for the development of the 200-ZP-1 Model (DOE/RL-2007-28). Figure 3-4 presents a distribution of experimentally based hydraulic conductivity estimates. The data summarized in Figure 3-4 contain data from slug tests and sediment sample analysis whereas the data summarized in Table 3-1 are limited to pump test analysis.



Source: DOE/RL-2007-28

Figure 3-4. Hydraulic Conductivity Distribution Ringold E

Vertical anisotropy has been estimated for pumping tests in Ringold E and for at least one test in the Hanford formation. Ringold E values range from 0.01 to 0.1 (PNL-10886) and 0.015 to 0.5 (DOE/RL-2007-28) for post–2000 testing. A Hanford formation estimate is 0.1 (HEIS Hydraulic properties database). Previous calibrations, prior to development of the P2R Model, have found the calibration relatively insensitive to vertical anisotropy. This is largely because of the large horizontal scale of most modeling analyses—and lateral extent of the simulated HSUs—versus the relatively small vertical extent of the modeling analyses, and of the simulated HSUs. In addition, most wells are screened across the water table. There are few instances of multiple zones of measurement with depth. Therefore, anisotropy ratios obtained from (1) large-scale, site-specific pumping tests such as those recently conducted in the 200-ZP-1 OU, and from (2) literature values for equivalent or similar aquifer materials, are considered the most reliable source for this value. A value of 0.1 was assumed for all layers in the prior three-dimensional PNNL models (PNNL-14398 and PNNL-14753).

Specific yield has been estimated from tests of the Hanford formation and Ringold Formation as presented in Table 3-2. Ringold A and E are jointly described in PNL-10886. These models encompass a larger domain than the P2R Model. They had the same water level measurements, over a larger domain, that we have available. They showed limited sensitivity to specific yield. Only the specific yield of the Ringold unit E was modified in the calibration described in PNNL-14753. Specific yield was not estimated for the model described in PNNL-14398.

Table 3-2. Review of Hydrostratigraphic Unit Specific Yield

	Specific Yield (dimensionless)				
	PNL-10886	**PNNL-13641**	**PNNL-14398**	**PNNL-14753**	**CP-47631**
	Hanford Site-wide Groundwater Flow and Transport Model (1995)	Hanford Site-wide Groundwater Flow and Transport Model (2001)	Hanford Site-wide Groundwater Flow and Transport ACM-2 Model	Hanford Site-wide Groundwater Flow and Transport Model (2006)	Central Plateau Groundwater Model (Versions 3.3 & 3.4)
Unit	**Experimental Data**	**Experimental Data**	**Assumed Value**	**Assumed Value**	**Calibration Value**
Hanford	0.1 - 0.3	0.2 - 0.37	0.25	0.1	0.2
Cold Creek			0.1	0.1	0.2
Ringold E	0.05 - 0.2	0.05 - 0.37	0.1	0.11	0.09
Ringold mud				0.1	0.09
Ringold A	0.05 - 0.2	0.15		0.1	0.09

Sources:

CP-47631, 2013, *Model Package Report: Central Plateau Groundwater Model Version 3.4*, Rev. 1, CH2M HILL Plateau Remediation Company, Richland, Washington.

PNL-10886, 1995, *Development of a Three-Dimensional Ground-Water Model of the Hanford Site Unconfined Aquifer System: FY 1995 Status Report*, Pacific Northwest National Laboratory, Richland, Washington.

PNNL 13641, 2001, *Uncertainty Analysis Framework – Hanford Site Wide Groundwater Flow and Transport Model*, Pacific Northwest National Laboratory, Richland, Washington.

PNNL-14398, 2003, *Transient Inverse Calibration of the Site-Wide Groundwater Flow Model (ACM-2): FY 2003 Progress Report*, Pacific Northwest National Laboratory, Richland, Washington.

PNNL-14753, 2006, *Groundwater Data Package for Hanford Assessments*, Rev. 1, Pacific Northwest National Laboratory, Richland, Washington.

3.2 Features, Events, and Processes (FEPs)

This section summarizes the relevant FEPs to be included and excluded from the P2R Model. The list of exclusions is not exhaustive, but is intended to be extensive enough to support the identification of model limitations addressed in Chapter 6.

The most comprehensive application of the FEPs methodology at the Hanford Site to date is presented in BHI-01573, *The Groundwater/Vadose Zone Integration Project: The Application of Feature, Event, and Process Methodology at the Hanford Site*, and discussed in Last et al (2004). The Hanford features, events, and processes (HFEPs) identified in BHI-01573, are identified here as included or excluded. Additional FEPs not listed in the HFEPs that are considered are added to the list. Table 3-3 lists HFEPs identified in BHI-01573. Table 3-3 lists a HFEP number, if identified in BHI-01573, and a name for the FEP. A column labeled included indicates whether the FEP is included in the historic period flow model (flow) described in this report, used for predictive model flow and transport, or has not yet been not

included in either phase (no) either. In the final column labeled "Relevant to P2R Model," "yes" identifies FEPs that are relevant to flow and transport in the P2R Model domain and "no" if they have no relevancy. Many HFEPs that could affect flow in the Central Plateau are listed as not relevant on the assumption of geologic stability for the period to be simulated with this model or because they were rated low or moderate priority in the HFEP evaluation for the groundwater technical element in BHI-01573.

Table 3-3. Hanford Features, Events, and Processes

HFEP Number	Name	Included	Relevant to P2R Model
2.2.07.30	Groundwater flow (in geosphere)	Flow	Yes
3.2.07.35	Groundwater discharge to surface. Groundwater and associated contaminants (either solutes for suspended particulates) may eventually discharge to the Columbia River, to seeps near the river, to springs, or to wells.	Fate and transport	Yes
2.2.07.51	Far-field transport: hydrodynamic dispersion	Fate and transport	Yes
2.2.04.01	Faulting (large scale, in geosphere). Hydraulic influence of May Junction Fault	Flow	Yes
1.4.04.00.04	Future liquid waste disposal	Fate and transport	Yes
1.4.04.00.17	Water resource exploration	No	Yes
1.1.11.00.02	Post closure monitoring	No	Yes
2.3.11.13	Groundwater discharge. The Columbia River is the principal discharge area for the unconfined aquifer system. In this model, the discharge to the Columbia River is not directly modeled because the model domain does not extend to the river, but it is implicitly included with mixed type boundary conditions that represent the discharge to the river.	Fate and transport	Yes
2.3.11.14	Groundwater recharge. Recharge issues related to groundwater flow and contaminant transport within the context of a conceptual model of the natural system on a large scale. Recharge refers to input of water to the groundwater flow system. Recharge of the uppermost unconfined aquifer takes place from infiltration of precipitation, particularly in elevated regions along the western boundary of the Hanford Site, from infiltration of imported water disposed to waste sites, leaked from distribution systems, and applied for irrigation, and from upward leakage from the deeper confined aquifer system. These are all included except for upward leakage from the deeper confined aquifer system, which is excluded from the model at present.	Flow	Yes
	Basalt surface. Section 3.2.4 discusses the assumption that the basalt surface is an impermeable lower boundary.	Flow	Yes
	Groundwater remedial actions (pump-and-treat systems)	Flow and transport	Yes
	Spatial variability. Hydraulic property variation by HSU with differential vertical and horizontal hydraulic conductivity.	Flow	Yes
1.2.02.01.00	Fractures in basalt	No	Yes
1.2.02.02.00	Faulting (movement along existing faults)	No	No

Table 3-3. Hanford Features, Events, and Processes

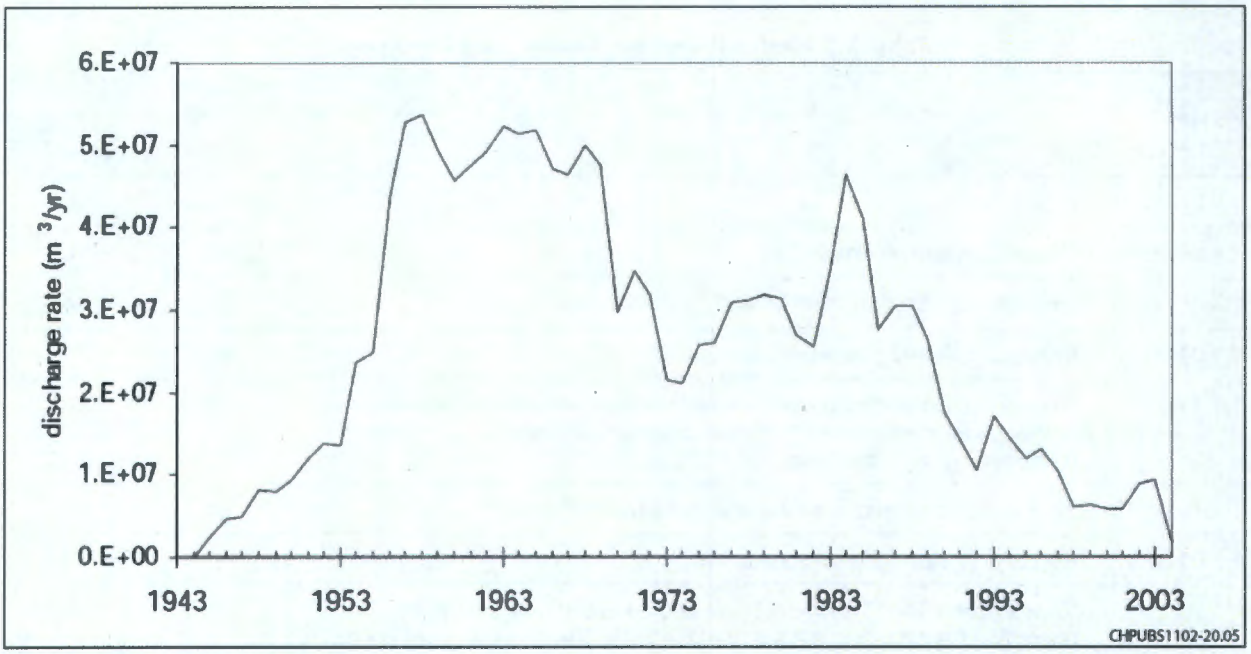
HFEP Number	Name	Included	Relevant to P2R Model
1.2.03.01.00	Seismic activity	No	No
1.2.04.01.00	Magmatic activity affects hydrothermal conditions	No	No
1.2.04.02.00	Magmatic activity affects hydrothermal conditions	No	No
1.4.04.02.00	Abandoned and undetected boreholes	No	No
3.2.07.01.00	Isotopic dilution	No	No
1.2.10.01.00	Hydrological response to seismic activity	No	No
1.2.01.01.01	Folding, uplift, or subsidence lowers facility with respect to the current water table	No	No
1.2.02.01.01	Changes in hydraulic properties of sediments (due to compaction)	No	No
1.2.04.01.01	Volcanism	No	No
1.4.04.02.01	Exploratory borehole creates flow pathway	No	No
1.2.10.01.01	Fault movement pumps fluid from saturated to unsaturated zone (seismic pumping)	No	No
1.2.01.01.02	Tectonic changes to local geothermal flux causes convective flow in saturated zone and elevates water table	No	No
3.2.07.01.02	Natural radionuclides/elements (in host rock disturbed zone)	No	No
1.2.10.01.02	Fault creep causes short term fluctuations of the water table	No	No
1.4.04.02.03	Waste-induced borehole flow (in waste and engineered barrier system)	No	No
1.2.10.01.03	New faulting breaches flow barrier controlling large hydraulic gradient to the north	No	No
1.2.01.01.04	Uplift or subsidence changes drainage at site, increasing infiltration	No	No
1.2.02.02.04	Movements along small-scale faults	No	No
1.2.04.02.04	Igneous activity causes extreme changes in rock geochemical properties	No	No
1.4.04.01.05	Drilling fluid flow	No	No
1.4.04.02.05	Natural borehole fluid flow	No	No
1.2.01.01.06	Effect of plate movements	No	No
1.2.01.01.09	Regional vertical movements	No	No
1.4.04.00.01	Geothermal (drilling associated with exploitation of geothermal sources)	No	No
1.4.04.00.02	Other resources (drilling to explore for other resources)	No	No
1.4.04.00.03	Enhanced oil and gas recovery	No	No
1.4.04.00.05	Hydrocarbon storage	No	No
1.4.04.00.06	Exploratory drilling for hydrocarbons	No	No

Table 3-3. Hanford Features, Events, and Processes

HFEP Number	Name	Included	Relevant to P2R Model
1.4.04.00.07	Blowouts	No	No
1.4.04.00.24	Oil and gas extraction	No	No
1.4.04.00.25	Liquid waste disposal from oil and gas production	No	No
1.4.04.00.26	Enhanced oil and gas production	No	No
1.1.11.00.01	Monitoring. Boreholes used to monitor performance could provide pathways for contaminant transport between different hydrogeological formations.	No	No
1.2.10.01.10	Fault establishes pathway through the saturated zone	No	No
1.2.01.01.12	Regional horizontal movements	No	No
	Vadose zone flow. This model is restricted to the fully saturated unconfined aquifer and, hence, vadose zone flow and transport is not included directly. However, the inclusion of the attenuating impact of the presence of the vadose zone is indirectly incorporated through the use of vadose zone simulated artificial recharge.	No	Yes
	Perching of artificial recharge, discussed in Section 3.2.2.	No	Yes
	Climate change. This model is restricted to recharge conditions that reflect current climate and does not incorporate climate change effects.	No	Yes
	Dam failure. Potential contaminant transport due to flooding of the site caused by upstream dam failure is not considered in the analysis.	No	Yes

3.2.1 FEP Discussion: Anthropogenic Recharge

Wastewater discharges associated with activities at the Hanford Site were significant sources of water to the subsurface during the Hanford Site operational period (1944 through 1988), at times exceeding tens of millions of cubic meters per year (Figure 3-5). Some of the largest sources of process-related water to the subsurface included T-Swamp, U Pond (216-U-10), 216-U-14 Trench, B Pond (216-B-3), 200 Area Treated Effluent Disposal Facility, and Gable Mountain Pond. These large releases exerted significant control on the rates and directions of groundwater flow, as well as contaminant migration and continue to exert some effect as the water table recovers to pre-development conditions. Detailed descriptions of various sources of recharge are provided in several publications, including PNL-6403, *Recharge at the Hanford Site: Status Report*, and PNL-10285, *Estimated Recharge Rates at the Hanford Site*. Both anthropogenic and natural sources of water must traverse a thick, unsaturated (vadose) zone to reach, and ultimately recharge, the unconfined aquifer beneath.



Source: PNNL-14753, Rev. 1

Figure 3-5. Historic Anthropogenic Surface Discharges (1944 to 2005)

Arrival of surface discharges at the water table where they provide recharge to the aquifer is attenuated and delayed by the unsaturated zone. A vadose zone transmission of liquid discharges was simulated for each discharge site as a part of the PNNL's model development (PNNL-14753, Rev. 1, and *Vadose Zone-Attenuated Artificial Recharge for Input to a Ground Water Model [EDTM-BC-0002]*). Figure 3-6 presents the effects of simulated vadose zone attenuation and delay for the sum of all liquid discharge sites at the Hanford Site. The grey line in this figure is the discharge rate to the surface; the green line is the arrival of water flux at the water table. The discharge rates are plotted as m^3/yr over the length year for surface discharges and length of each calculation time step for the water table arrival. The results of these calculations were used to specify artificial recharge for the P2R Model in the historic period with the water table arrival averaged over each year.

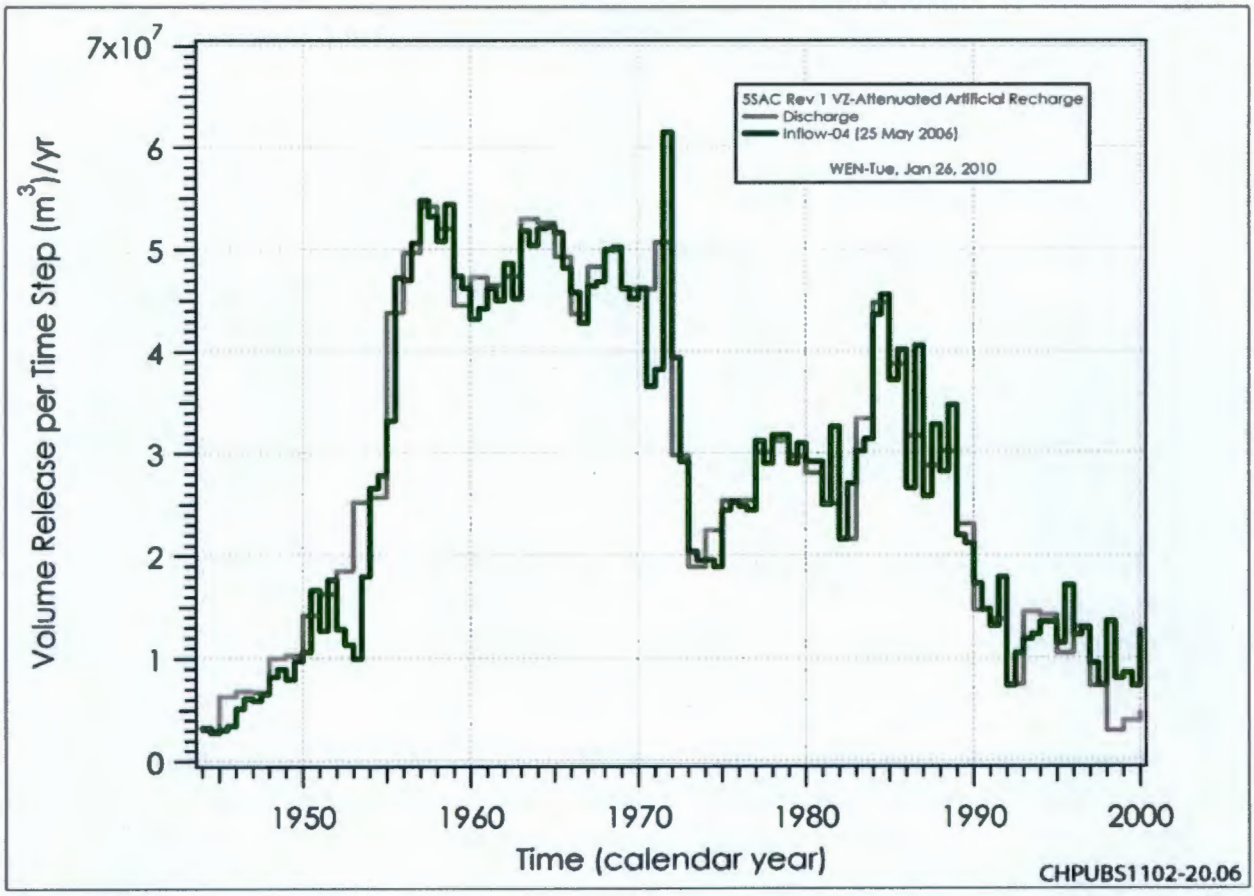


Figure 3-6. Liquid Disposals at Surface and Vadose Zone Simulated Artificial Recharge for the Sum of All Hanford Site Liquid Discharges (1944 to 2000)

3.2.2 FEP Discussion: Perching of Anthropogenic Recharge

There is evidence indicating that perching has occurred influencing flow in the saturated aquifer. Perching is not included in the P2R Model as a simulated process. Instead, the historical water table measurements that were taken when perching may have influenced anthropogenic recharge have not been directly included in the model hydraulic properties calibration. Section 4.4 provides details of how this was accomplished. Locally, the impact can be large. A number of investigations have revealed large perched water bodies in the 200 West Area where well 299-W19-1 is located, summarized here:

1. In 1948, the Office of the Atomic Energy Commission discovered perched conditions in two of the 25 wells drilled during the investigation. In one well (identified today as well 699-45-69A), 1.6 to 3 m of water was found at an elevation of approximately 169 m, which was approximately 43.6 m above the water table. 169 m is very close to the top of the Cold Creek unit in this area (Figure 3-7), but the drillers log does not indicate a change in geologic unit at this elevation. This well is more than 2 km west of T-Swamp, the largest known wastewater discharge location at the time. Perched water was also found in well 699-35-70, located 2 km or more south of T-Swamp. This perched zone was thinner and lower (137 m elevation) than that found in well 699-45-69A. The perched zone is well below the top of Ringold unit E.

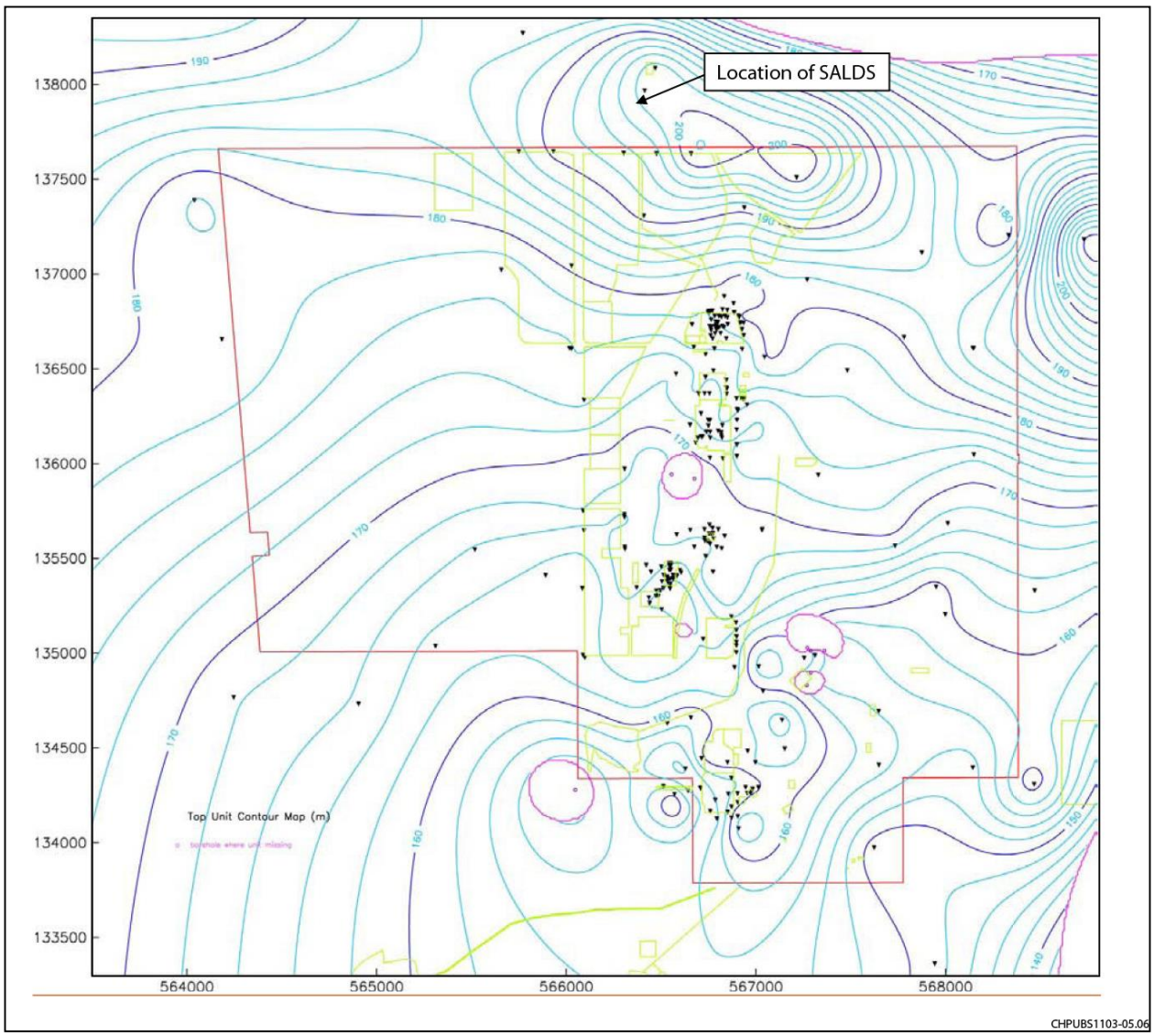
2. Well 699-35-78 was drilled in 1950. The following description is based on the drillers log available on the HEIS. A saturated layer of water at an elevation of 128 m was found. Below an elevation of 127 m, the well was dry again. It was cased and remained dry over a weekend until an elevation of

121.5 m was reached. The well then filled overnight to 128 m. The rapid rise suggests that once the 121.5 m elevation was reached, the well was in hydraulic contact with the same body of water found at 128 m. A 128 m water table elevation is consistent with other wells in the area. It is inferred that near the well, water was perched on a low conductivity lens of Ringold unit E at 128 m, but that away from the well, it was part of the saturated aquifer at nearly the same elevation. Alternately, the lens is saturated but has so little conductivity that only a non-measurable amount of water entered the well over the weekend.

3. A 1994 investigation of perching below the 216-U-14 Ditch identified perched conditions in wells 299-W19-91, 299-W19-92, 299-W19-93, 299-W18-250, 299-W18-251, and 299-W23-27, but not in well 299-W23-22 (*Groundwater Impact Assessment Report for the 216-U-14 Ditch* [WHC-EP-0698-FP]). Perching was considered to be of limited extent beyond the ditch. The top of the perched zone in wells 299-W19-91, 299-W19-92, and 299-W19-93 varied between 190 and 169 m elevation from 1990 through 1994. The perched zone was presumed to extend downward to the top of the Cold Creek unit, which is at an elevation of approximately 165 m at this location.

4. Two dimensional simulations of a perched water table under a generic 200 West Area waste site that incorporated the dip of the Cold Creek unit calculated that 99 percent of the water would exit the down dip side of the simulation rather than directly below the discharge location (*Effects of Varying Recharge on Radionuclide Flux Rates to the Water Table at the Low-Level Solid Waste Burial Site* [WHC-SA-0699-FP]).

5. Mounding evaluations in the unconfined aquifer, in response to discharges at the SALDS facility (Figure 3-7), suggest that the mounding is centered on an area laterally displaced from the SALDS effluent infiltration gallery. This lateral displacement arises from the movement of the discharge water along the Cold Creek unit (*Results of Tritium Tracking and Groundwater Monitoring at the Hanford Site 200 Area State-Approved Land Disposal Site Fiscal Year 2009* [SGW-42604]).



Source: PNNL-17913, Rev. 1

Figure 3-7. Top of Carbonate Facies of Cold Creek Unit

These five investigations suggest that perched water has occurred during the Hanford Site operational period and that these areas of perching may have stored substantial volumes of water. In addition, there may have been lateral migration of water infiltrating through the vadose zone en-route to the water table of the unconfined aquifer. The perching appears to have developed above the calcified Cold Creek unit, and on low conductivity lenses of Ringold unit E.

3.2.3 FEP Discussion: Natural Recharge

Natural recharge includes both percolation of net precipitation to the water table and mountain-front recharge arising from infiltration of snowmelt, agricultural return-flows from irrigation, and run-off from elevated areas. The major sources of mountain-front recharge to the P2R Model are the ephemeral Cold Creek and Dry Creek streams. Rates of net recharge from aerial precipitation were acquired from PNNL-14753, Rev. 1. Recharge associated with stream flows are a significant contributor to groundwater recharge upgradient of the Central Plateau (PNNL-17841, *Compendium of Data for the Hanford Site [Fiscal Years 2004 to 2008] Applicable to Estimation of Recharge Rates*). Since the amount of recharge

that occurs through the Cold Creek and Dry Creek streams is uncertain, they have been included in the model and varied as calibration parameters. The small amounts of recharge from runoff of Gable Mountain, Gable Butte, the basalt subcrop along the southern boundary of the model, and other small slopes toward the model domain have been neglected.

Natural recharge from precipitation at the Hanford Site is highly variable both spatially and temporally, ranging from near-zero to more than 100 mm/yr depending on climate, vegetation, and soil texture ("Variations in Recharge at the Hanford Site" [Gee et al., 1992] and PNL-10285). Vegetative areas and fine-textured soil, like silt loams, tend to have lower recharge rates, while areas with little vegetation and coarse-textured soil, such as dune sands, tend to have higher recharge rates. PNL-10285 developed estimates of natural recharge for 1992 conditions using a systematic procedure. First, distributions of soil and vegetation types were mapped. Then, a recharge rate was assigned to each combination of soil/vegetation type based on data from lysimeters, tracer studies, neutron probe measurements, and computer modeling. The data used for these estimates derive from a number of sources, such as distribution of recharge estimated using the 1992 climate, a 1966 soil map (*Soil Survey Hanford Project in Benton County, Washington* [Hajek, 1966]), and 1979 vegetation/land-use patterns. Estimated recharge rates for 1992 ranged from 2.6 to 127 mm/yr, and the total volume of natural recharge from precipitation over the Hanford Site was estimated to be 2.35×10^4 m^3/d. This value is of the same order of magnitude as the artificial recharge to the 200 Area waste disposal facilities during 1992 and approximately one-sixth of peak discharges to these facilities during the 1960s (PNNL-14753, Rev. 1). The 1992 estimates were used in the calibration of the 2005 model (PNNL-14753, Rev. 1). A constant scale factor adjustment of 1.2 was determined through calibration of the model.

The 1992 estimate from PNL-10285 is used for each year without modification in the P2R Model. Figure 3-8 presents the recharge data taken that is used in the P2R Model (taken from PNNL-14753, Rev. 1). The white lines to the left of the figure are Cold Creek and Dry Creek fluxes and are beyond the color scale of the plot. The small blue area near the Gable Gap is West Lake, a small pond where the water table is above land surface. The B Pond pit just east of the 200 East Area is also a region of large estimated recharge.

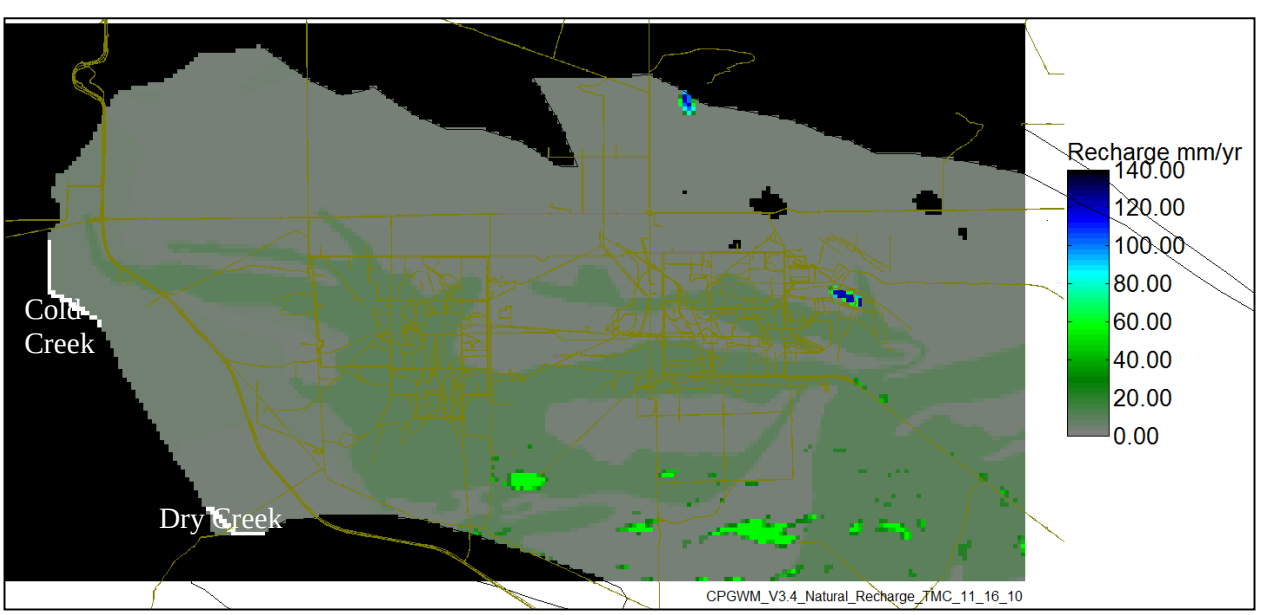


Figure 3-8. Natural Recharge Fluxes Used in the Central Plateau Groundwater Model

Four investigations of ephemeral stream fluxes entering the Central Plateau, as listed in Table 3-4, are reported in BHI-00608, *Hanford Sitewide Groundwater Flow and Transport Model Calibration Report.* Table 3-4 list fluxes for Cold Creek, Dry Creek, and a combination of the two based on these studies. In addition, there are estimates from model calibrations. In three cases, the fluxes were model calibration parameters. In one case, the fluxes were calculated from the calibrated model. These estimates are not entirely consistent. This is in part because the definition of Dry Creek varies. For most studies, Dry Creek refers to the upland area to the west of the P2R Model Dry Creek boundary condition. However, Dry Creek continues to flow east, south of the southern boundary of the P2R Model. Whether the upland flow enters the P2R Model at the location corresponding to the Dry Creek boundary condition or stays south of the model domain is uncertain. In PNNL-11801, *Three-Dimensional Analysis of Future Groundwater Flow Conditions and Contaminant Plume Transport in the Hanford Site Unconfined Aquifer System: FY 1996 and 1997 Status Report*, and PNNL-13447, *Transient Inverse Calibration of Hanford Site-Wide Groundwater Model to Hanford Operational Impact – 1943 to 1996*, most of the Dry Creek flux was assumed to be diverted north in the subsurface to the location corresponding to the P2R Model boundary condition location for Dry Creek. However, in PNNL-14753, Rev. 1, model calibration indicated the entire flow moves east, below the P2R Model boundary, with no northward flow diversion.

Table 3-4. Estimates of Stream Recharge Fluxes

Cold Creek (m^3/day)	Dry Creek (m^3/day)	Combined (m^3/day)	Research	Notes
1,728	1,231	3,305	Newcomb et al (1972)	After 1954
19,872	9,504	29,376	Livesay (1986)	Too Large?
5,184			RHO-ST-42	
		19,872	Bennet (1992)	Post 1969
8,130	15,700	23,830	PNNL-14398	Preliminary estimates
8,812	1,209	10,021	PNL-7144	Model Calibration
10,368	44,068	54,436	BHI-00608	Model Calibration
6,010	1,207	7,217	PNNL-11801	Calculation
5,722	0	6,953	PNNL-14753, Rev.1	Model Calibration Dry Creek too small to estimate

Table 3-4. Estimates of Stream Recharge Fluxes

Cold Creek (m^3/day)	Dry Creek (m^3/day)	Combined (m^3/day)	Research	Notes

Sources:

Bennet, G.B., 1992, "Draft Report – Ground-Water Aspects of the Macroengineering Approach at the Hanford Reservation," (letter to Heather Duncan of A.J. Kerny, Inc.).

BHI-00608, 1997, *Hanford Sitewide Groundwater Flow and Transport Model Calibration Report*, Rev. 0, Bechtel Hanford, Inc., Richland, Washington.

Livesay, D.M., 1986, *The Hydrology of the Upper Wanapum Basalt, Upper Cold Creek Valley, Washington*, M.S. Thesis, Department of Geologic Engineering, Washington State University, Pullman, Washington.

Newcomb, R.C., J.R. Frank, and F.J. Frank, 1972, *Geology and Groundwater Characteristics of the Hanford Formation of the Hanford Reservation of the U.S. Atomic Energy Commission, Washington*, Professional Paper 717, U.S. Geological Survey, Washington, D.C.

PNL-7144, 1990, *An Initial Inverse Calibration of the Ground-Water Flow Model for the Hanford Unconfined Aquifer*, Pacific Northwest Laboratory, Richland, Washington.

PNNL-11801, 1997, *Three Dimensional Analysis of Future Groundwater Flow Conditions and Contaminant Plume Transport in the Hanford Site Unconfined Aquifer System: FY 1996 and 1997 Status Report*, Pacific Northwest National Laboratory, Richland, Washington.

PNNL-14398, 2003, *Transient Inverse Calibration of the Site-Wide Groundwater Flow Model (ACM-2): FY 2003 Progress Report*, Pacific Northwest National Laboratory, Richland, Washington.

PNNL-14753, 2006, *Groundwater Data Package for Hanford Assessments*, Rev. 1, Pacific Northwest National Laboratory, Richland, Washington.

Newcomb et al (1972) estimated fluxes after 1954, when agricultural use of the upland area of the Cold Creek drainage had been prohibited. That injunction was lifted in 1969. Newcomb et al. also estimated a flux of 347 m^3/day from the unconfined aquifer through the "Cold Creek Barrier" (which may be the Cold Creek fault feature). This amount is included in the "Combined" column of Table 3-4.

Livesay's *The Hydrology of the Upper Wanapum Basalt, Upper Cold Creek Valley, Washington* (1986) estimates were developed using a regression analysis of stream flow data from watersheds that had perennial base flow. Livesay (1986) pointed out that the method may overestimate the estimates for Cold Creek and Dry Creek.

Estimates for Cold Creek (*Hydrology of the Separations Area* [RHO-ST-42]) using Darcy's law (Q = WBKi)—assuming a hydraulic conductivity, K, of 12.2 m/day; hydraulic gradient, I, of 0.002; thickness, B, of 61 m; and length, W, of 3,048 m—were 5,184 m^3/day. This estimate is after the resumption of agricultural use in 1969. Bennet,1992, *Draft Report – Ground-Water Aspects of the Macroengineering Approach at the Hanford Reservation*, used a water balance to estimate the combined recharge from Cold Creek and Dry Creek to be 19,872 m^3/day. In summary, these four calculation based estimates have an order of magnitude variation.

PNNL-14398 reports another investigation of Cold Creek (8,130 m^3/day) and Dry Creek (15,700 m^3/day) watersheds using stream flows. The estimates are reported as preliminary as of 2003. A final report detailing this study has not been located at the time of preparation of this report.

Numerical modeling based estimates for Cold Creek vary by less than a factor of two. As indicated in the previous paragraphs, there is disagreement in the numerical studies about if Dry Creek enters the P2R Model domain or not.

3.2.4 FEP Discussion: Basalt Surface Fluxes

The Hanford Site is located within the CRBG province, which comprises hundreds of stacked basalt flows throughout southern/eastern Washington, northeastern Oregon, and western Idaho. Results of studies completed at the Hanford Site specifically, and throughout the CRBG province generally, indicate that the basalt flows can be categorized broadly as a sequence of dense, low-permeability flow interiors. These are separated by more permeable interflow zones, which comprise the base of an overlying flow and the top of the underlying flow, with occasional intermediate clastic sediments. In some locations throughout the CRBG province, these interflow zones are substantial enough to comprise aquifers.

As described earlier, the P2R Model is constructed on the assumption that the basalts form an impermeable base to the unconfined aquifer. However, evidence exists showing the unconfined aquifer overlies and is connected with interflow zones. There may be upward and/or downward flow between the unconfined clastic sediments and the basalt interflow. This process is not included in the current version of the P2R Model. The process was investigated as a part of an alternate conceptual model investigation (*Transient Inverse Calibration of Site-Wide Groundwater Model to Hanford Operational Impacts from 1943 to 1996—Alternative Conceptual Model Considering Interaction with Uppermost Basalt Confined Aquifer* [PNNL-13623], and PNNL-13641). The distributed flux through basalt was estimated using a three-dimensional inverse calibration (PNNL-13623). Implementation of basalt leakage was accomplished by adding:

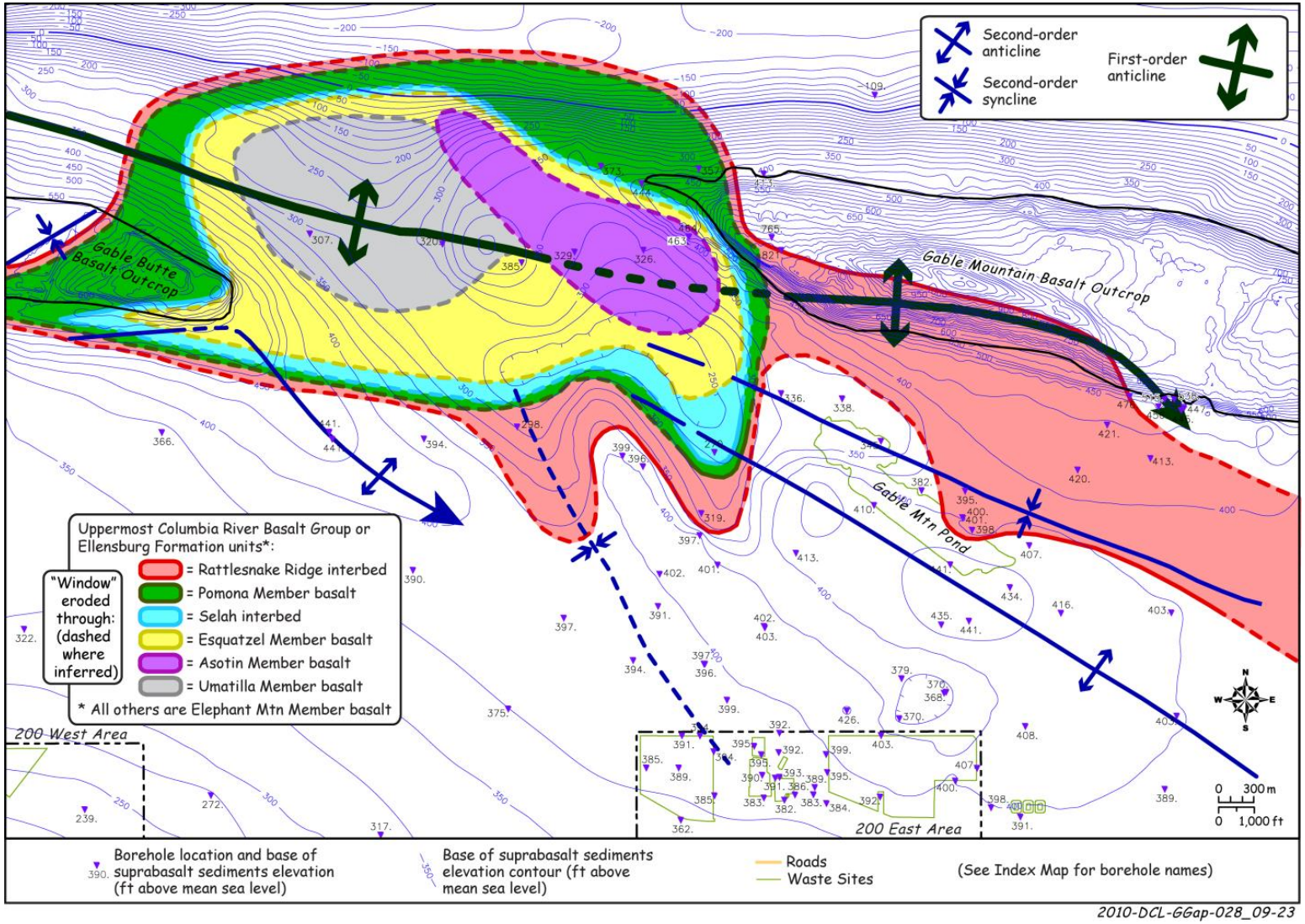
- Head dependent spatially distributed leakage through the basalt confining layer
- Increased leakage at an erosional window near Gable Mountain/Gable Butte
- Increased leakage at a smaller erosional feature near B Pond
- Increased leakage along two fault zones

Figure 3-9 shows the distribution of basalt surfaces for members of the Ellensburg Formation that have been exposed due to erosion of the upper portion of the basalt. The erosion also exposed the Rattlesnake interbed, a permeable sedimentary confined aquifer, below the topmost Elephant Mountain Member that forms the basalt surface below most of the Central Plateau. Basalt flow tops between members can also host permeable aquifers. The model described in PNNL-13623 included the roughly circular central core of the erosional window as a special surface flux feature. Thinning of the Elephant Mountain Member was simulated near B Pond. The larger contact with the Rattlesnake interbed north of B Pond was apparently not recognized at the time.

Figure 3-10 shows the location of four fault zones on the Hanford Site. The simulation described in PNNL-13623 included the two thrust fault zones. These faults are locations of discontinuity in the basalt. Hydraulically, they may be locations of concentrated flux through the basalt-sedimentary aquifer interface. The two normal faults were not expected to be major contributors of flux. The Gable Mountain Fault is outside the domain of the P2R Model.

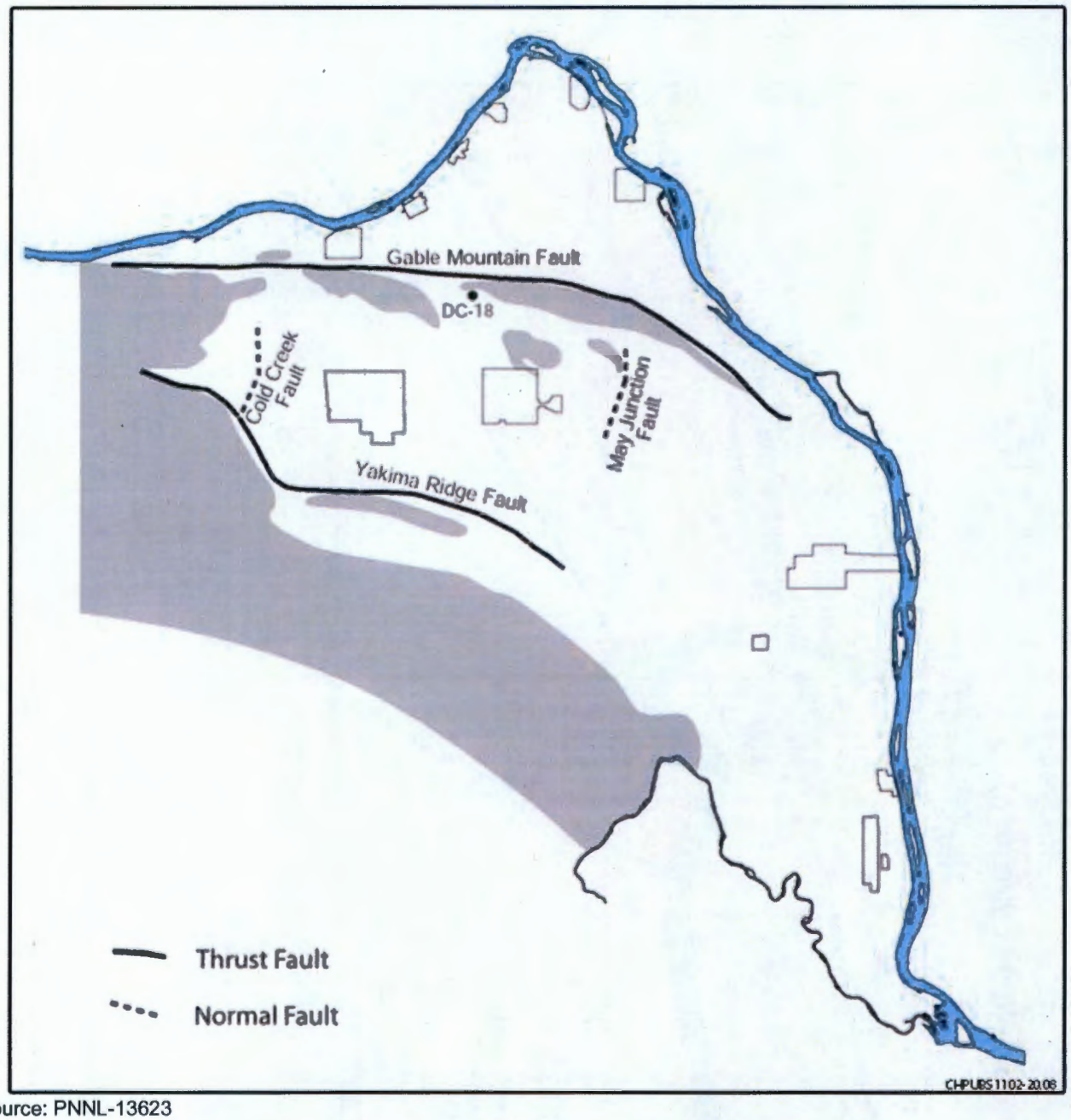
Figure 3-11 presents the estimated distributed flux across the basalt surface and erosional window for 1996. Close inspection reveals much larger fluxes adjacent to the Columbia River. It also reveals both upward and downward flux in the Central Plateau region of the figure. Figure 3-12 presents the estimates for cumulative upward, downward, and net distributed flux as a function of time. Figure 3-13 allows comparisons of the significance of each feature investigated. It reveals that the distributed fluxes dominate the net fluxes. In addition, that the erosional window and Yakima Ridge Fault are relatively minor contributors. Estimated flux of the Gable Mountain Fault is large, but this is outside the P2R Model domain. Within the Central Plateau region, the estimated basalt surface fluxes are small relative to an average 180,000 m^3/day anthropogenic recharge for 1980 (refer to Figure 3-5). Fluxes through the basalt

surfaces were not included in subsequent versions of PNNL's site-wide groundwater model. Because of the thinness of the aquifer, fluxes to and from the basalt surface have a very similar impact on simulated water levels as changes in natural recharge rates. For these later models, it was concluded that neglecting basalt surface flux in these later models was compensated by the increased estimated precipitation recharge of 26,000 m^3/day (found in the calibration described in PNNL-14753, Rev. 1) over cumulative reported recharge determined by PNL-10285 (PNNL-14753, Rev. 1, p. 5.8). Again, most of this additional flux is outside the P2R Model domain.



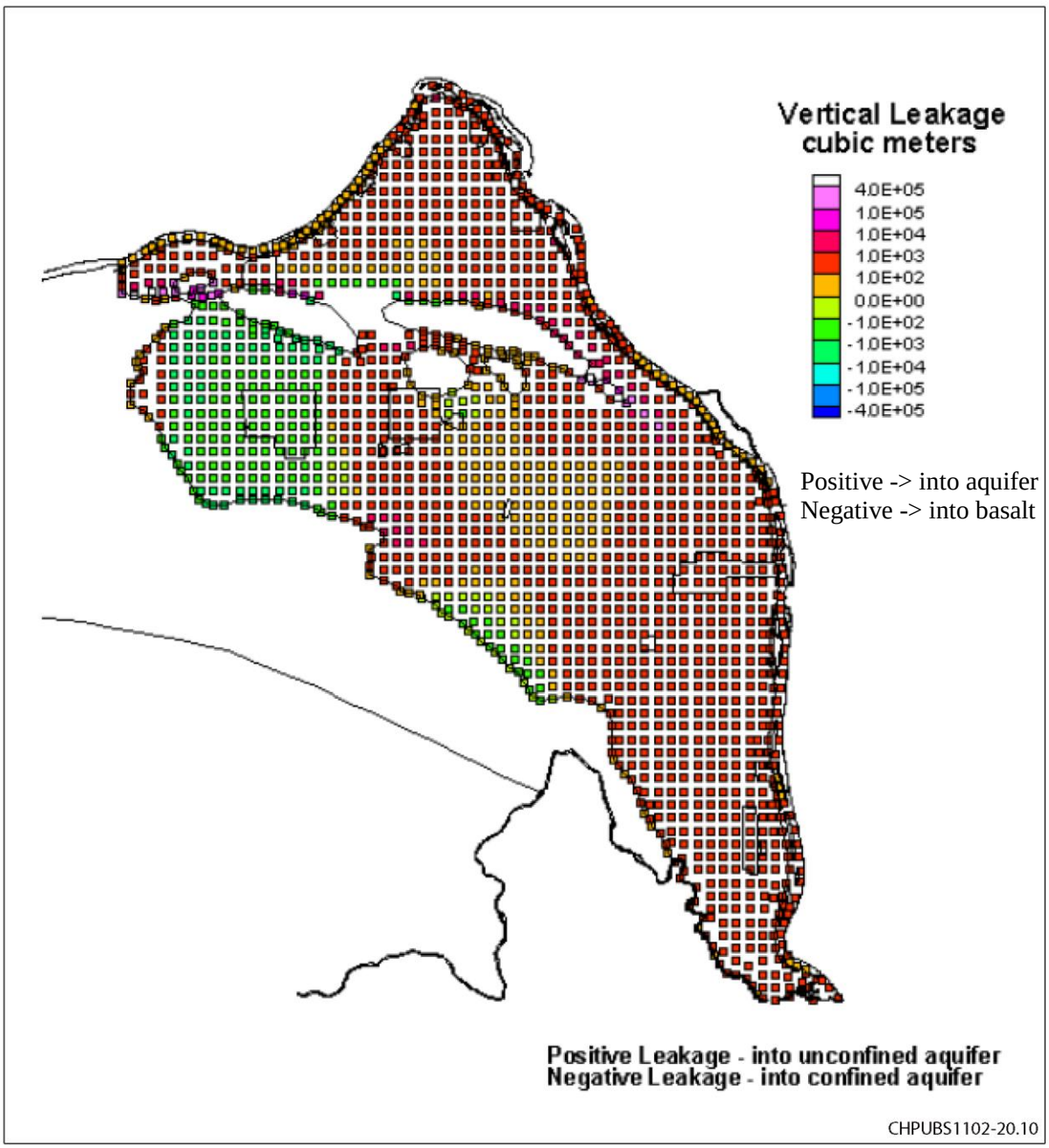
Source: PNNL-19702

Figure 3-9. Map of Upper Confined Basalt Aquifer (Pink) Contact with Unconfined Aquifer of the Central Plateau Groundwater Model



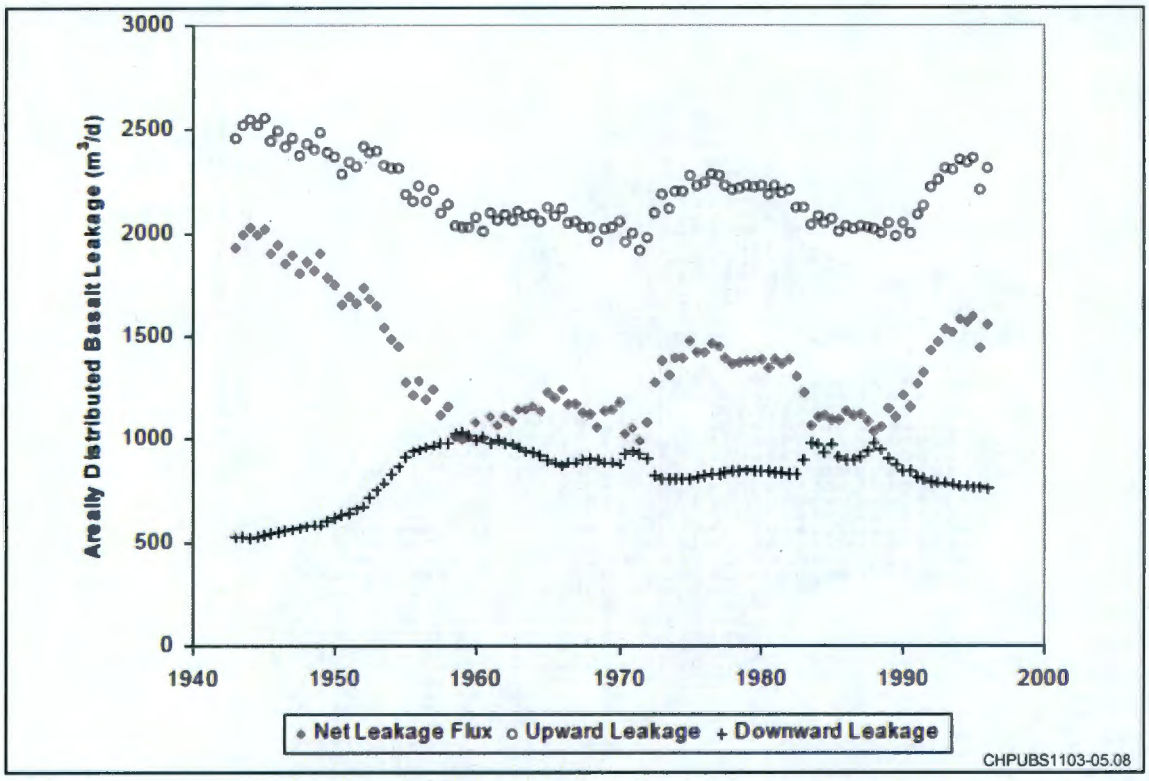
Source: PNNL-13623

Figure 3-10. Location of Thrust and Normal Faults on the Hanford Site



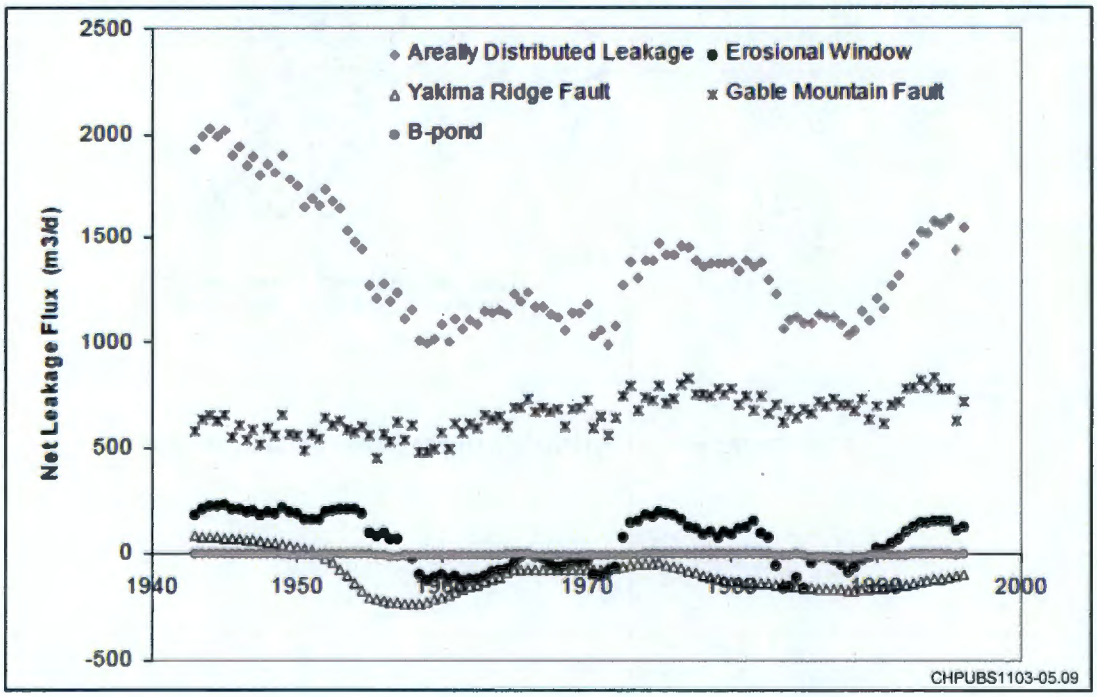
Source: PNNL-13623

Figure 3-11. Estimated Flux (m^3/yr) across Upper Basalt Surface for 1996



Source: PNNL-13623

Figure 3-12. Temporally Varying Estimated Flux across Upper Basalt Surface



Source: PNNL-13623

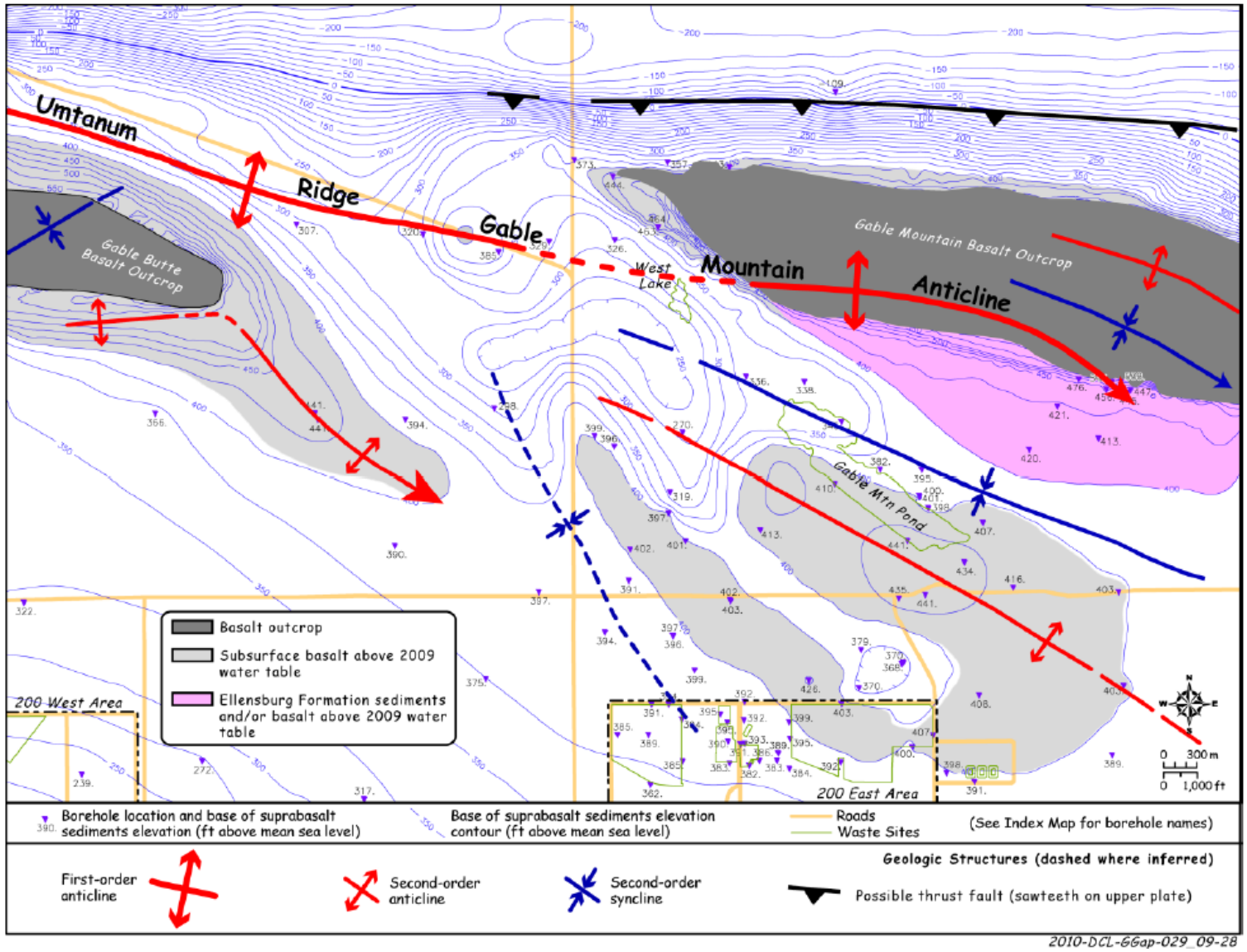
Figure 3-13. Relative Contribution of Each Basalt Leakage Feature to Net Leakage

3.2.5 FEP Discussion: Basalt Ridge Flow Barrier

Figure 3-14 presents a map of basalt above the present water table along with deformational controls of basalt elevation in this region between Gable Gap and 200 East Area. Figure 3-14 suggests the presence of three paleochannel related lows in the basalt surface. Because of a limited number of wells in the area, uncertainty exists on the configuration of the paleochannels and top of basalt. The middle channel crossing the northeast corner of the 200 East Area is thought to be currently above the water table (*Hydrogeologic Model for the Gable Gap Area, Hanford Site* [PNNL-19702]). Water levels have dropped an average rate of about 0.14 m/y in the northern portion of the 200 East Area since the cessation of most surface water disposal (*Data Package for Past and Current Groundwater Flow and Contamination Beneath Single-Shell Tank Waste Management Areas* [PNNL-15837]).

If the water table drops far enough, as seems likely, the ridge of high basalt northeast of the 200 East Area will form a flow barrier between the 200 East Area and the Gable Gap effectively stopping the current flow direction northward from the Central Plateau. The timing of closure will affect contaminant transport. However, there could be channels across the basalt divide that are incised deeper into the basalt than is currently represented in the model, resulting in localized conduits for the preferential flow of groundwater. The Grand Coulee channeled scabland is an example of features that may exist in and south of the Gable Gap. The scabland is about 150 km north of the Hanford Site. Figure 3-15 depicts the Lower Grand Coulee channeled scabland carved out by the Missoula floods. The figure shows multiple meter variations in surface elevation over distances that are small compared to the well spacing used to control the surface of the basalt in the Gable Gap area of the CPGW Model. Being upstream of the Hanford Site, the erosional forces were larger at Grand Coulee, so the scale of erosional features is larger, but similar to what would be expected in 200-BP-5. Figure 3-15 conveys the concept that if the 200-BP-5 basalt is similar to the Grand Coulee scablands, it is impossible estimate basalt surface elevations at the scale of the model cells within a meter from our limited borehole contact information with high confidence.

The basalt saddle to the northwest of the 200 East Area has a minimum elevation of 121.6 m in the model. Historic water level measurements may indicate that this level is too high in the model compared to the actual geography. Figure 3-16 presents water level measurements from 1948 to 1960 for five wells that straddle the basalt ridge saddle. The figure also shows Columbia River discharge measurements over the period. Figure 3-17 shows the locations of these wells. Wells 699-60-60 and 699-55-50A are north of the saddle. The plots indicate that these wells have an annual cycle that lags roughly 4 to 6 months behind the river. Starting in 1950, these wells indicate a steady rise in water level, possibly from discharges at B Pond or possibly due to discharges near the 100-BC Reactors or 100-K Reactor. Well 699-47-60, south of the saddle, indicates a hydraulic connection with the wells north of the saddle below elevation 121.6 m. The well was not installed in time for earlier water level measurements.



Source: PNNL-19702

Figure 3-14. Basalt Deformation and Surface Expression in the Gable Gap and 200 East Area

Source: PNNL-19702

Note: View looking north; blue block arrows show general movement of floodwaters, which scoured and overtopped the crest of the basalt ridge along left side of image.

Figure 3-15. Example of Highly Irregular Topography Eroded by Ice Age Floods, Lower Grand Coulee, Channeled Scabland

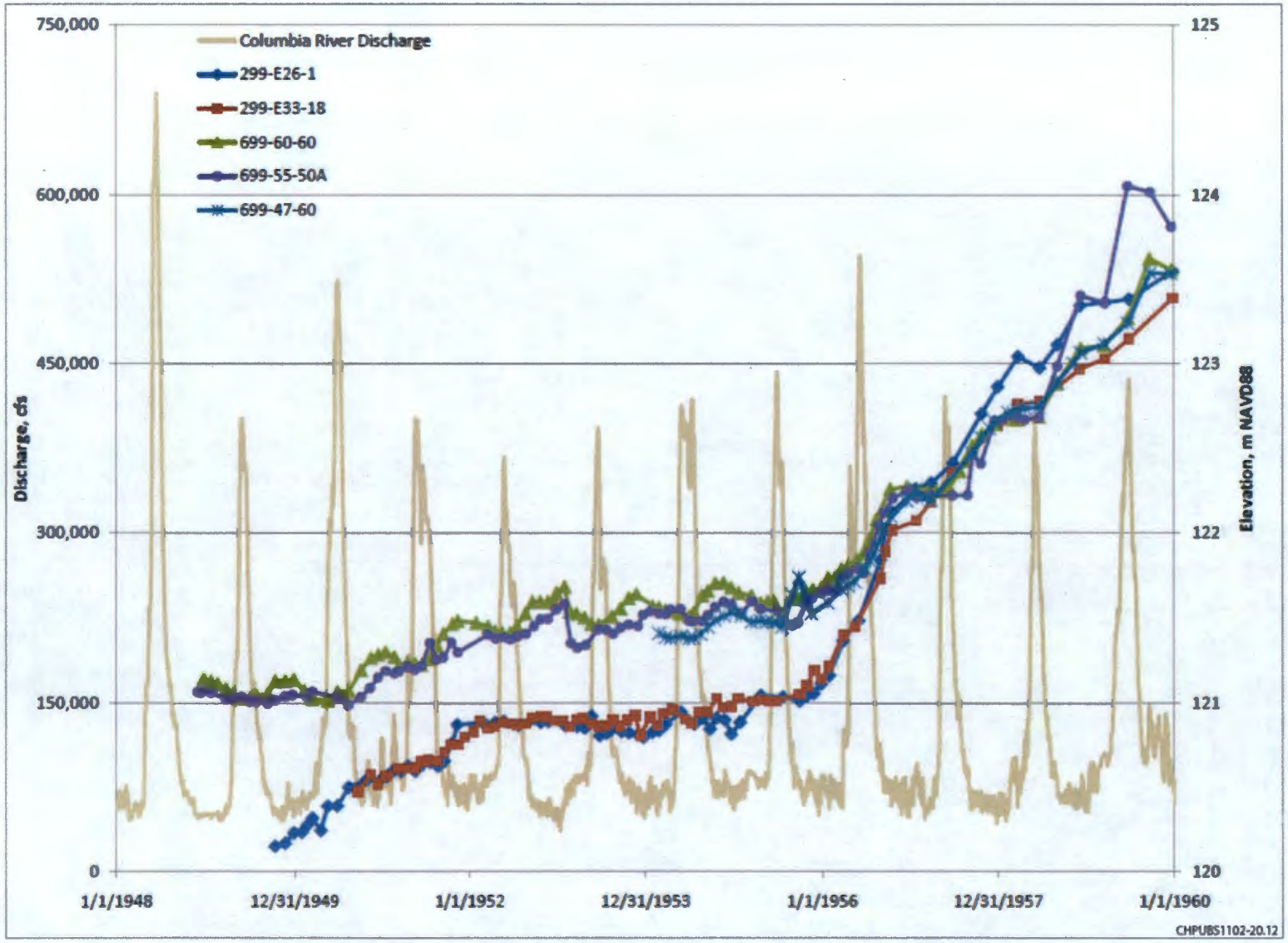


Figure 3-16. Historic Water Level Measurements near the Basalt Ridge Saddle

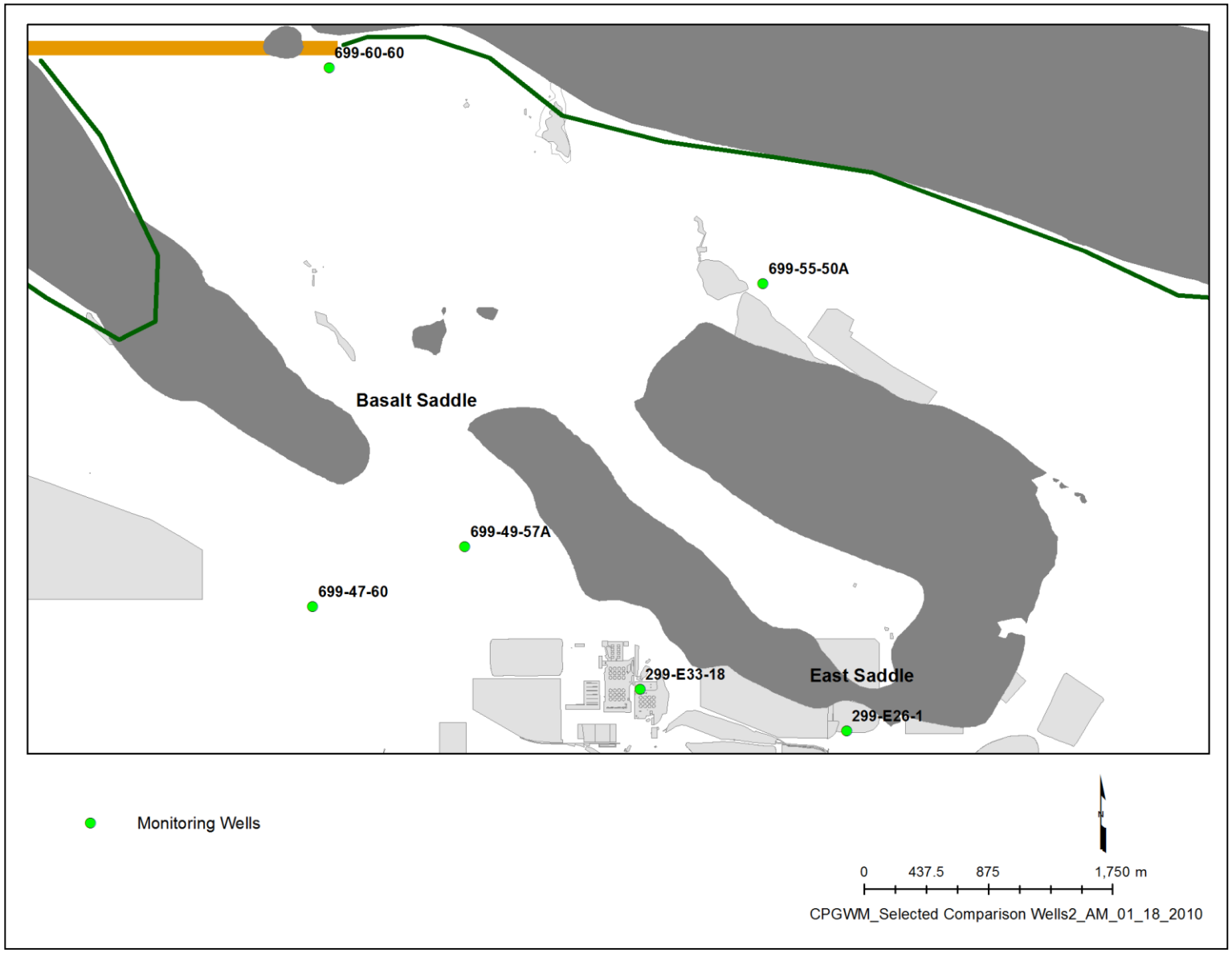


Figure 3-17. Locations of Wells Referred to in Figure 3-16

3.3 Nature and Extent of Contamination

The nature and extent of contamination to be evaluated with the P2R Model is presented in Chapter 4 of the 200-BP-5 and 200-PO-1 RI documents.

4 Model Implementation

This section presents the implementation of the P2R Model. This includes identification of the basis for selection of implementing software, discretization of the model domain for numerical solution, parameterization of the model, and calibration of the model.

4.1 Software

MODFLOW-2000 (CHPRC-00257, Rev 0) was selected for the flow component of the P2R Model to solve the governing equation for transient groundwater flow using the finite difference discretization technique. MT3DMS (CHPRC-00257, Rev 0) was selected to solve the governing equation for advective-diffusive transport for the contaminant transport component of the P2R Model. The basis for selection of these software packages, the quality assurance status of these software packages, and summary additional supporting software utilized are presented in this section.

4.1.1 Flow Component Implementation

MODFLOW-2000 (CHPRC-00257, Rev 0) was selected for the flow component of the P2R Model to solve the governing equation for transient groundwater flow using the finite difference discretization technique for the following reasons:

- MODFLOW is one of the more versatile and widely used software packages for models of this type
- MODFLOW It is freely available and distributed with the source code (nonproprietary software)
- MODFLOW is fully documented and has been verified in applications similar to those at the Hanford Site, as well as for applications at the Hanford Site
- There is wide expertise available for its use
- MODFLOW is capable of directly simulating the principal FEPs that are relevant to the model simulation requirements; for those FEPs that it this software does not directly simulate (e.g., vadose zone flow), those FEPs can be met through links to other codes, such as linking to Subsurface Transport Over Multiple Phases (STOMP) for vadose calculations as described in the FEP section on recharge
- MODFLOW is sanctioned for use for groundwater modeling at the Hanford Site to support decision-making applications under DOE direction (Williams, 2012)
- CHPRC has qualified and manages this software for this intended use under the requirements of DOE O 414.1d, *Quality Assurance*
- A newer software package, MODFLOW-USG (unstructured grid) was evaluated for this application, but while this tool has strong potential for future model development it is not yet supported by a complementary non-proprietary contaminant transport tool

Because this software will be used to implement a model that supports regulatory milestones and decisions, it must be managed as safety software under DOE O 414.1d requirements. CHPRC has qualified this software under procedure PRC-PRO-IRM-309 that implements DOE O 414.1d requirements.

The specific version of MODFLOW-2000 used to implement the P2R Model is identified by the following information:

- Hanford Information System Inventory (HISI) Identification Number: 2517 (Safety Software S3, graded Level C)
- Software Title: MODFLOW-2000 (*MODFLOW-2000, the U.S. Geological Survey Modular Ground water Model - User Guide to Modularization Concepts and the Ground-Water Flow* [Open File Report 00 92])
- Software Version: MODFLOW-2000-MST Version 2.1.18 modified by S.S. Papandopalous and Associates for minimum saturated thickness (MST) and to use the ORTHOMIN Solver—approved for use as CHPRC Build 6 using executable file 'mf2k-mst-chprc06dp.x' (Linux® or Windows® executable file compiled to default double precision for real variables)

The following software quality-assurance documents govern the managed use of this software by CHPRC:

- CHPRC 00257, *MODFLOW and Related Codes Functional Requirements Document*
- CHPRC 00258, *MODFLOW and Related Codes Software Management Plan*
- CHPRC 00259, *MODFLOW and Related Codes Software Test Plan*
- CHPRC 00260, *MODFLOW and Related Codes Acceptance Test Report*
- CHPRC 00261, *MODFLOW and Related Codes Requirements Traceability Matrix*

4.1.2 Contaminant Transport Component Implementation

MT3DMS (CHPRC-00257, Rev 0) was selected to solve the governing equation for advective-diffusive transport for the contaminant transport component of the P2R Model for the following reasons:

- It is one of the more versatile and widely used software packages for models of this type
- It is freely available and distributed with the source code (nonproprietary software)
- It is fully documented and has been verified in applications similar to those at the Hanford Site, and for applications at the Hanford Site
- There is wide expertise available for its use
- It is capable of directly simulating the principal FEPs that are relevant to the model simulation requirements; it is also capable of directly simulating desired principal FEPs for future needs in the Feasibility Study (FS) and Remedial Design steps of the CERCLA process that will follow the current RIs, such as pump-and-treat remedies.
- This software is qualified and managed by CHPRC for the intended use under the requirements of DOE O 414.1d, *Quality Assurance*

Because this software will be used to implement a model that supports regulatory milestones and decisions, it must be managed as safety software under DOE O 414.1d requirements. CHPRC has qualified this software under procedure PRC-PRO-IRM-309 that implements DOE O 414.1d requirements.

The specific version of MT3DMS used to implement the P2R Model is identified by the following information:

- Hanford Information System Inventory (HISI) Identification Number: 2518 (Safety Software S3, graded Level C)
- Software Title: MT3DMS (SERDP-99-1, *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*)
- Software Version: MT3DMS-MST Version 2.1.18 modified by S.S. Papandopalous and Associates for minimum saturated thickness – approved for use as CHPRC Build 6 using executable file 'mt3d-mst-chprc06dp' (Linux® or Windows® executable file compiled to default double precision for real variables)

These software quality-assurance documents govern the managed use of this software by CHPRC:

- CHPRC 00257, *MODFLOW and Related Codes Functional Requirements Document*
- CHPRC 00258, *MODFLOW and Related Codes Software Management Plan*
- CHPRC 00259, *MODFLOW and Related Codes Software Test Plan*
- CHPRC 00260, *MODFLOW and Related Codes Acceptance Test Report*
- CHPRC 00261, *MODFLOW and Related Codes Requirements Traceability Matrix*

4.2 Discretization

This section summarizes the spatial and temporal discretization of the P2R Model.

4.2.1 Spatial Discretization

The objective for spatial discretization of the P2R Model is primarily to support evaluation of fate and transport of contaminant transport plumes that have and/or will migrate beyond the Central Plateau. Evaluation of smaller-scale plumes comprised of low-mobility contaminants will be performed with more-appropriately scaled refined models, such as telescopic mesh refinement (TMR) models based on either the CPGW or P2R Models, where appropriate. Accordingly, the spatial discretization of the P2R Model is selected to provide an appropriate balance between adequate resolution of flow and transport for these larger plumes comprised of more mobile contaminants and acceptable simulation time of available computing platforms. Figure 4-1 shows the areal extent of the numerical model grid. There are a total of 135 rows and 155 columns of computational cells. Each grid block is spaced at 200 m by 200 m. The model origin at the lower left hand corner of the grid is 564000 m and 116000 m easting and northing, respectively in the Washington State Plane South NAD 1983 projection.

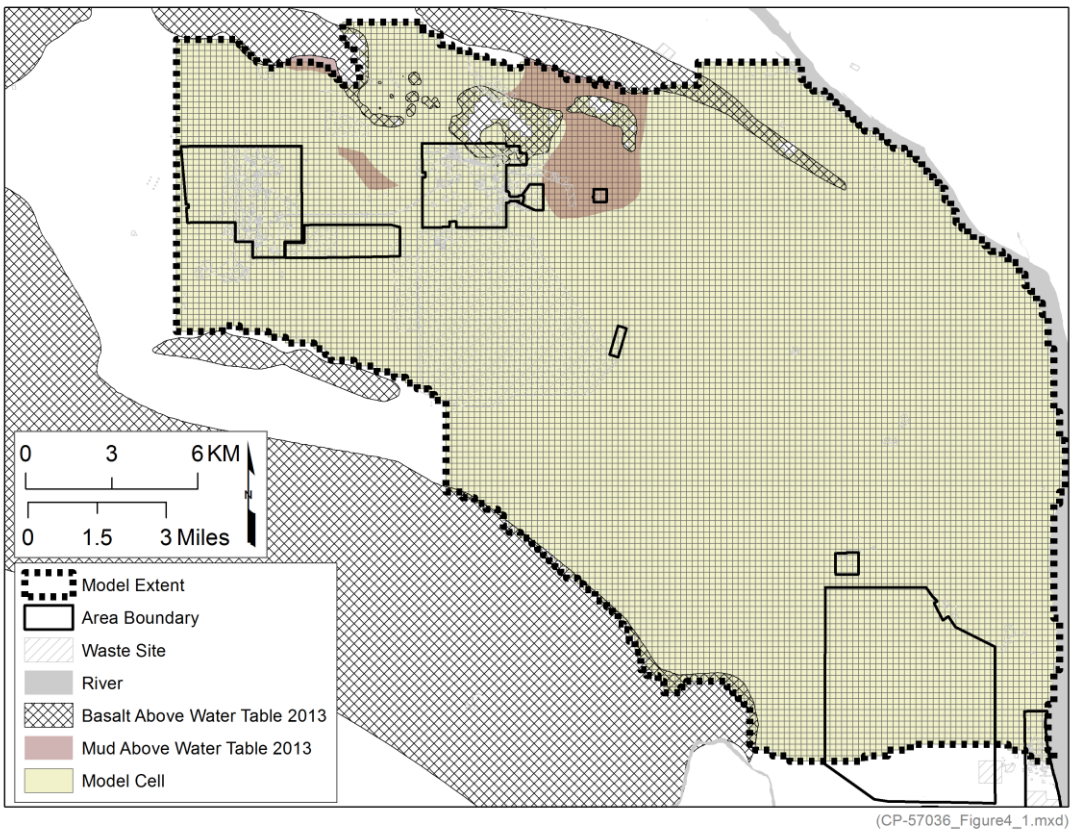
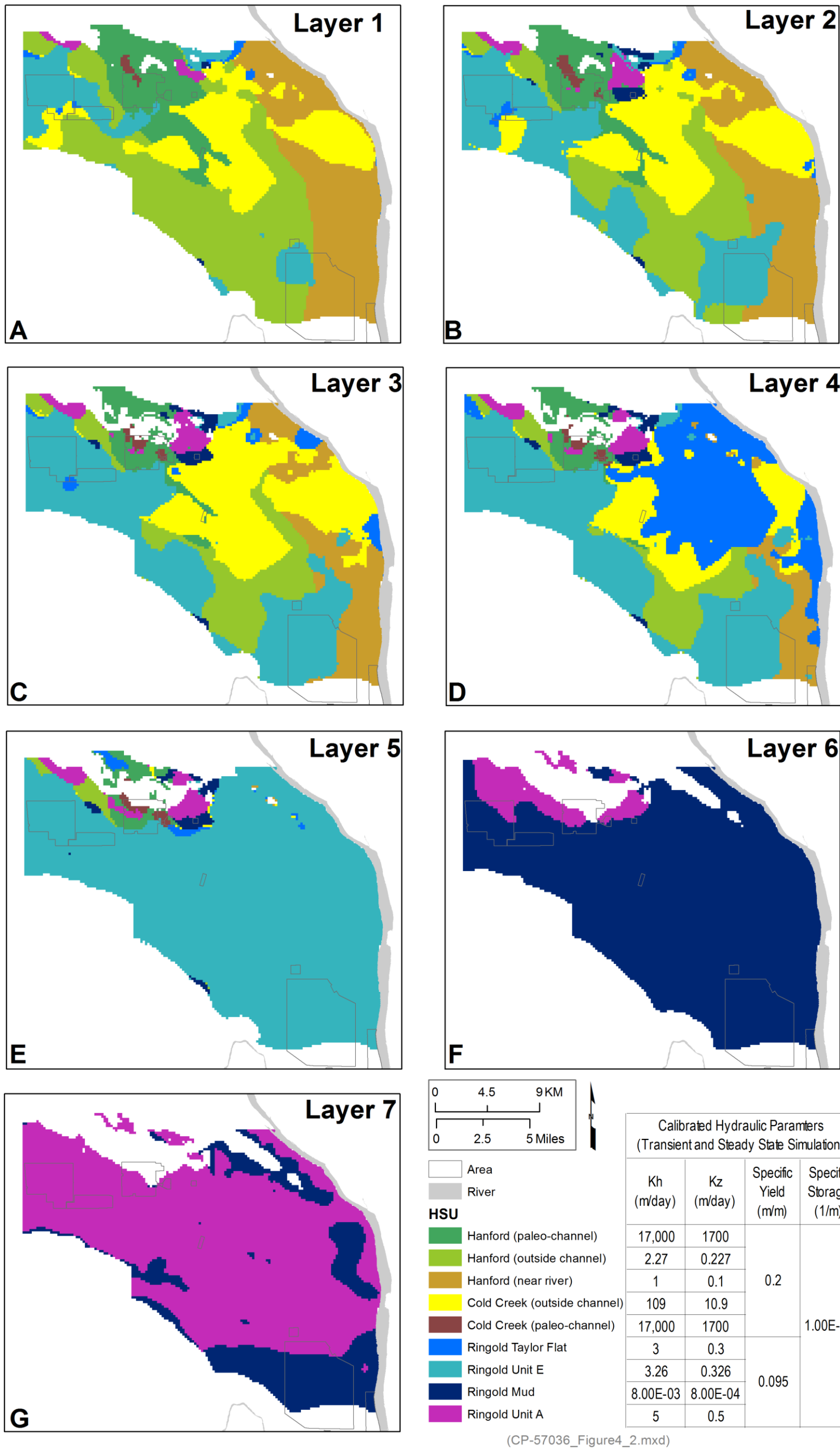


Figure 4-1. Model Extent and Grid for the P2R Model

The geologic representation for the model is derived from the Hanford South Geoframework Model (HSGM) (ECF-Hanford-13-0029, *Geologic Framework Model to Support Fate and Transport Modeling for Remedial Investigation/Feasibility Studies of the 200-BP-5 and 200-PO-1 Groundwater Operable Units*). The HSU definitions presented in ECF-Hanford-13-0029 include the Hanford and Cold Creek formations and the Ringold formation with the Taylor Flat, Unit E, Upper Mud, and Unit A members of that formation. Seven model layers are used to represent the seven HSUs are defined in the HSGM. Assignment of a numerical cell to an HSU is not dependent on model layer. Rather, an algorithm initially developed as part of the CPGW was used to assign model layer bottom and top elevations and assign a HSU to the numerical cells. Figure 4-2 charts a thru g show the HSU definition for each model layer respectively.



Calibrated Hydraulic Paramters (Transient and Steady State Simulation)			
Kh (m/day)	Kz (m/day)	Specific Yield (m/m)	Specific Storage (1/m)
17,000	1700	0.2	1.00E-04
2.27	0.227		
1	0.1		
109	10.9		
17,000	1700		
3	0.3	0.095	
3.26	0.326		
8.00E-03	8.00E-04		
5	0.5		

Figure 4-2. HSU Assignment to Model Layers

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HSU definition of the HGSM only includes one classification for the Hanford formation. This definition of the Hanford formation does not capture the large scale hydraulic features of the groundwater flow within the model domain. Two additional HSU definitions were added to the Hanford formation that are used to assign contrasting hydraulic properties to the model cells. Figure 4-3 shows the how the Hanford HSU is divided into the separate HSUs based on geographic location. The cold creek unit was also split into two HSU definitions to represent contrasting hydraulic properties based on the paleochannel description in Section 3.1.5. The spatial breakdown of the additional HSU added to the Cold Creek formation is shown in Figure 4-4. It roughly follows the pattern Hanford formation but not so far to the south. The decision on how far to extend these zones was ultimately decided during the calibration process as these HSUs were not delineated as part of the geologic framework calculation. However, both the CPGW and the TC & WM EIS models include the region of contrasting hydraulic conductivity representing a paleochannel through the Gable Gap. The apparent change in topography based on surface elevation data was used to create the Hanford (near river) HSU. Figure 4-5 shows the surface elevation data with respect to the Hanford (near river) HSU. The Hanford near river HSU was selected to approximate the drop in elevation towards the eastern boundary in the model.

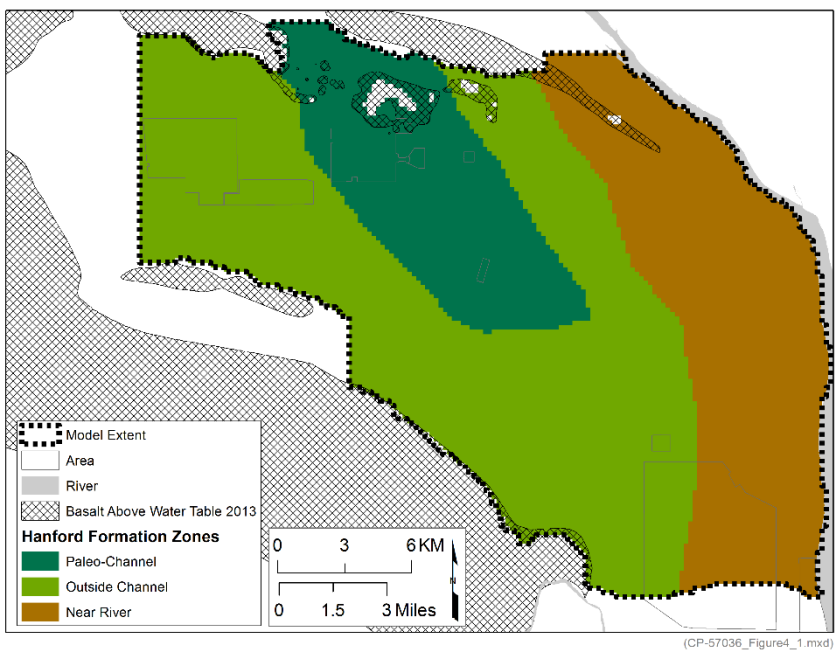

Figure 4-3. The Breakdown of HSU Definitions within the Hanford formation

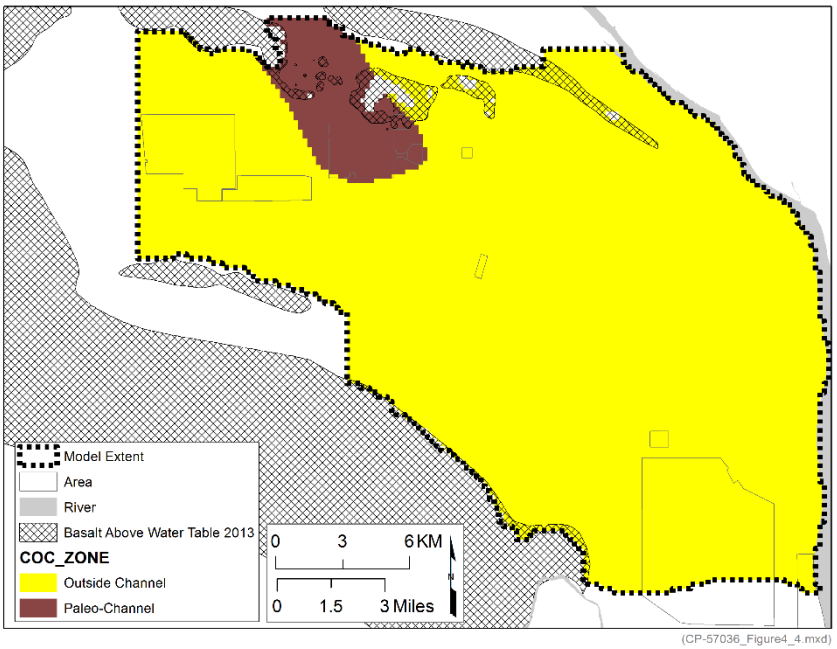

Figure 4-4. Breakdown of HSU Definitions within the Cold Creek formation

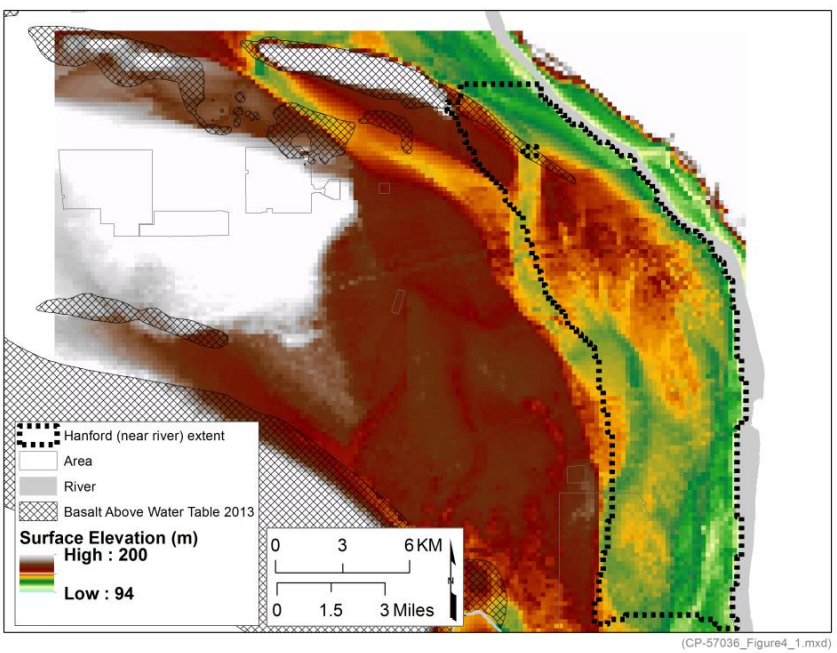

Figure 4-5. Surface Elevations within the Model Domain used to Establish the Hanford Near River HSU at the Eastern Portion of the Model

4.2.2 Temporal Discretization

Two time frames were used to simulate groundwater in the P2R Model. First, a steady state simulation was developed to simulate conditions during March and April of 2012. This simulation was used for the initial calibration of the numerical model. The steady state simulation was developed to target a relatively short duration interval. Therefore, only one stress period representing the March and April 2012 was

simulated. The steady state simulation will be key in the calibration process because the short execution time allows for an increased number of simulations to be completed in a shorter amount of time.

A second time frame was selected for the calibration of the model included a 6 year time period from 1/1/2006 to 1/1/2012. This time period was selected to compare the models response to seasonal changes in the boundary conditions that are used to define the model. This calibration time frame is similar to the time frame used for the calibration of the 100 Area groundwater model (SGW-46279, Rev. 2). The six year simulation was divided into 72 monthly stress periods with an additional steady state stress period at the beginning of the simulation to establish initial head values. Monthly stress periods were selected based on the frequency in pumping data and hydraulic head data (used for calibration and boundary condition definition) available for the majority of wells within the model domain. The boundary conditions for the initial steady state stress period are identical to the boundary conditions of the first transient stress period of the model or, in this case, January 2006.

4.3 Parameterization

This section identifies model parameters, including how values for these parameters are derived and assigned. Several sets of data were collected to aid in assigning input parameters to the model. These include hydraulic head data calibration, boundary conditions, sources and sinks, and hydraulic parameters. These data are detailed in the following sections. The sources of parameter values are specified to provide traceability.

4.3.1 Calibration Data

Calibration data are used to assess the ability of the numerical simulation to represent conditions observed in field. For the P2R Model hydraulic head data were used for this purpose. The following section describes the hydraulic head data used for comparing the simulated results to the observed field conditions.

4.3.1.1 Historic Hydraulic Data

In order to compare simulated results to observed field conditions all available hydraulic head data within the model domain were queried from the HEIS database from the dates 2006 to 2012. The data were filtered to remove data flagged either "R" or "F" based on the "REVIEW_QUALIFIER" field in HEIS. Based on the regional scale of the model (i.e., 200 m x 200 m cell size), local scale heterogeneities are not likely to be represented within the model. Some of these local scale heterogeneities include perching water on mud east of the 200-East area, detailed river interaction along the Columbia River. Because of this, only wells considered to represent the regional scale flow were used in as calibration data. Therefore, only data from wells used in the development of the site wide water table map provided in the annual report were used in the calibration dataset. Figure 4-6 shows the location of these wells with respect to the model domain.

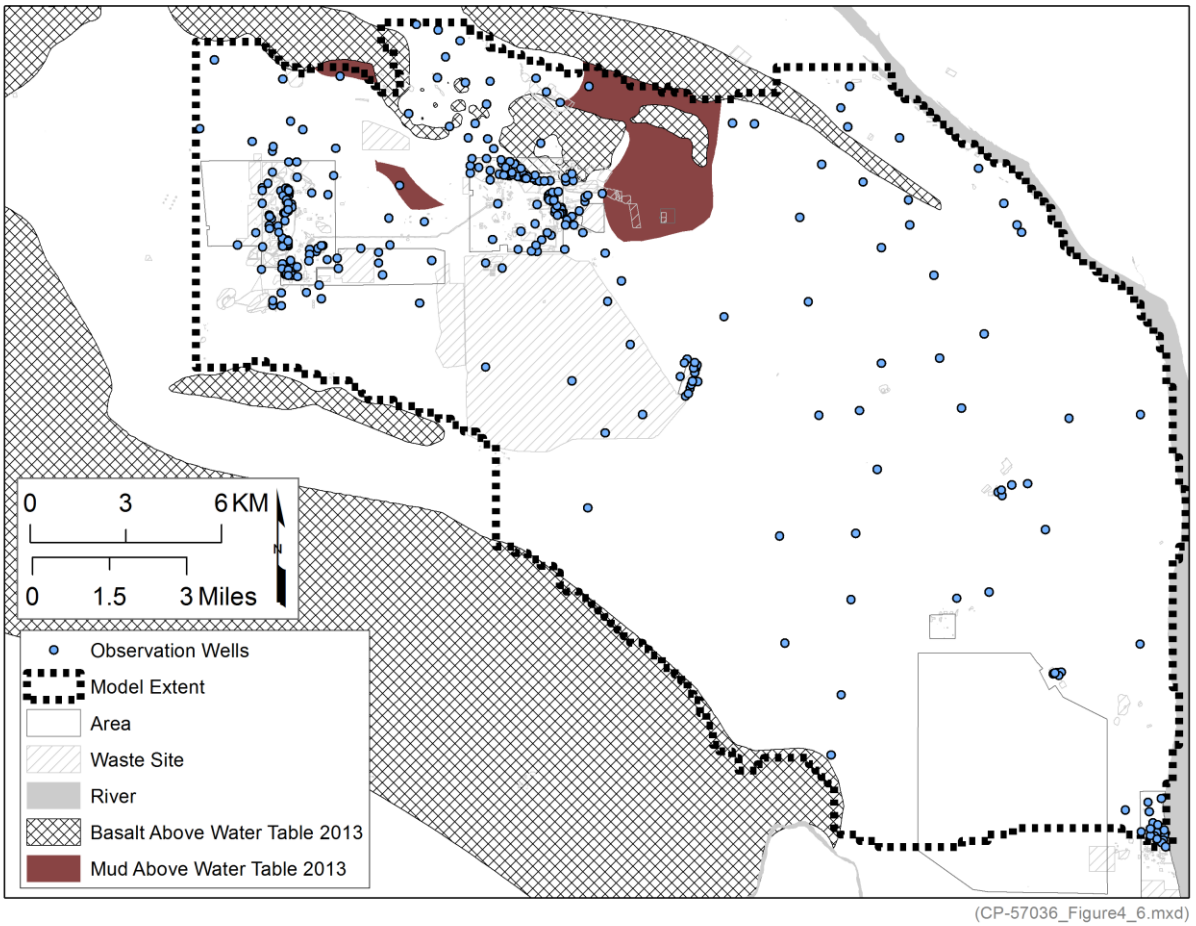

Figure 4-6. Observation Well Locations for the Calibration Data Set used with P2R Model

4.3.2 Boundary Conditions

The boundary conditions for the numerical model represent interactions with the aquifer by water external to the model. These include water infiltrating through the vadose zone that becomes recharge, movement to and from the Columbia River, liquid discharges from waste sites, and extraction and injection at well locations. Figure 4-7 illustrates the locations and types of boundary conditions used to construct the P2R Model. The details of each of these boundary conditions are discussed below.

4.3.2.1 Upper Boundary (Recharge)

The recharge boundary condition represents water that from the top surface of the model infiltrates through the vadose zone until reaching the saturated zone. This water can originate naturally or by anthropogenic sources such as waste site discharge. Each of these types of sources of recharge was included in the model using the MODFLOW Recharge package. This is similar to the approach used by the TC & WM EIS model. The following sections discuss how both natural recharge and anthropogenic recharge were handled in the P2R Model compared with the TC & WM EIS model, respectively.

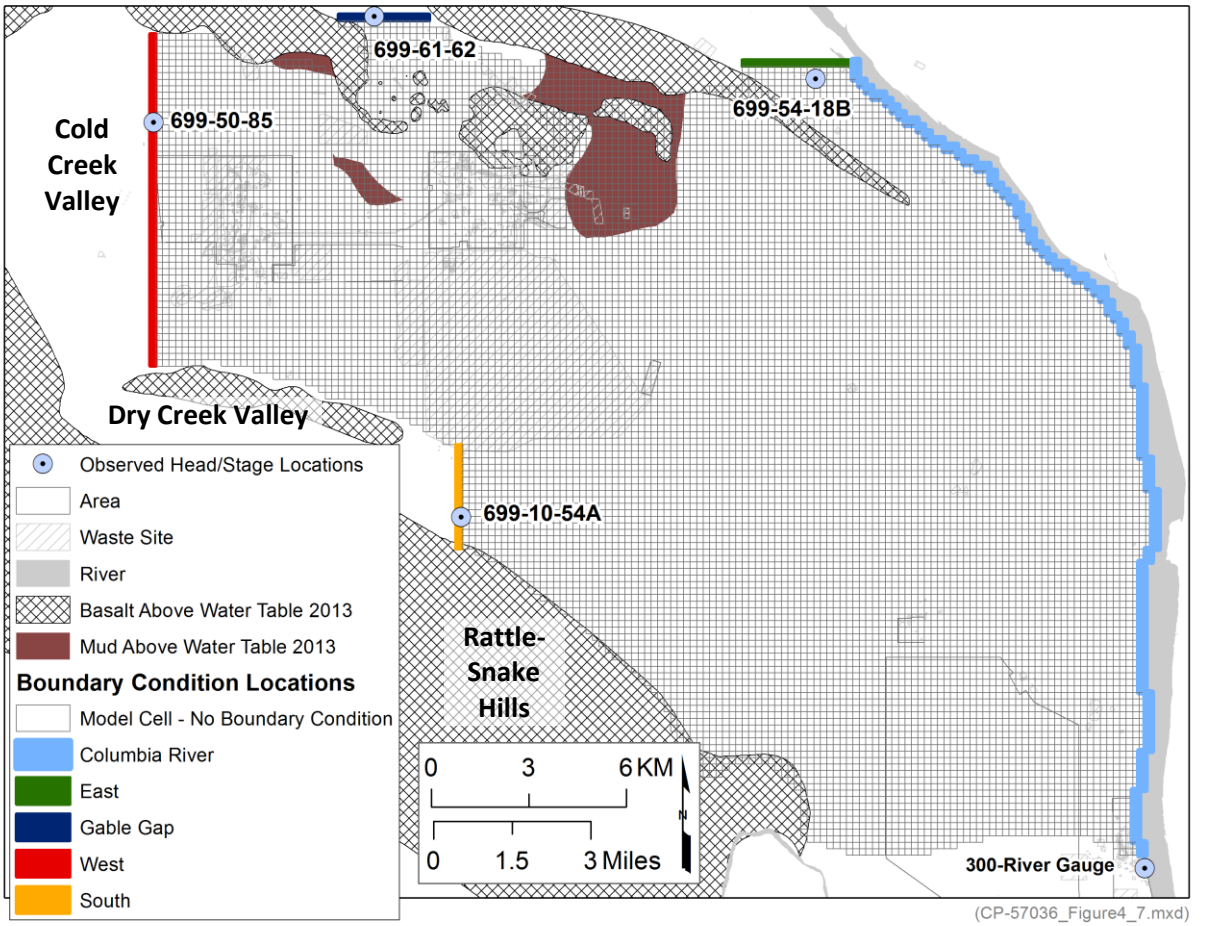

Figure 4-7. Boundary Condition Locations used for the P2R Model

Natural Recharge

The natural component of recharge includes water originating as precipitation and infiltration through the vadose zone that ultimately reaches the saturated zone as recharge. The TC & WM EIS varied recharge spatially based on facility type. Waste sites (e.g., cribs and trenches) and tank farms were assigned a recharge magnitude of 50 and 100 mm/yr respectively. Any other location was assigned a value of 3.5 mm/yr. Each of these values was selected based on values listed in the *Technical Guidance Document* (DOE, 2005). For the P2R Model, the values used in this report were used as the basis for recharge values. In order to account for differences in recharge based on the variability of surface soil (Hajek, 1966) at the Hanford Site, recharge magnitudes were varied spatially based on soil type. This is consistent with the approach taken in previous modeling performed at the Hanford Site (PNNL-14753). Recharge values, shown in Table 4-1, by soil type for the Hanford Site were taken from the *Vadose Zone Hydrogeology Data Package for Hanford* (PNNL-14702) to establish the initial range of recharge value by soil type. The major soil types, Sand, Sandy Loam, Silty Loam, and Dune Sand, in the P2R Model are listed in Table 4-1 along with the simulated recharge value based on the model calibration discussed in Section 4.4. The spatial distribution of these soil types are shown in Figure 4-8.

Table 4-1. Surface Soil Type and Natural Recharge Values

Soil Type	Soil Types for PNNL-14702, Rev. 1	Natural recharge values (mm/yr)		
		Minimum	Maximum	Calibrated (Steady State and Transient)
Silty Loam	Warden Silt Loam	0.04	0.08	0.04
Sandy Loam	Ephrata Sandy Loam, Burbank Loamy Sand,	1.5	52	4.6
Sand	Rupert Sand, Hanford Sand	4	44	12
Dune Sand	Hanford Sand, Graveled Surface	4	100	55

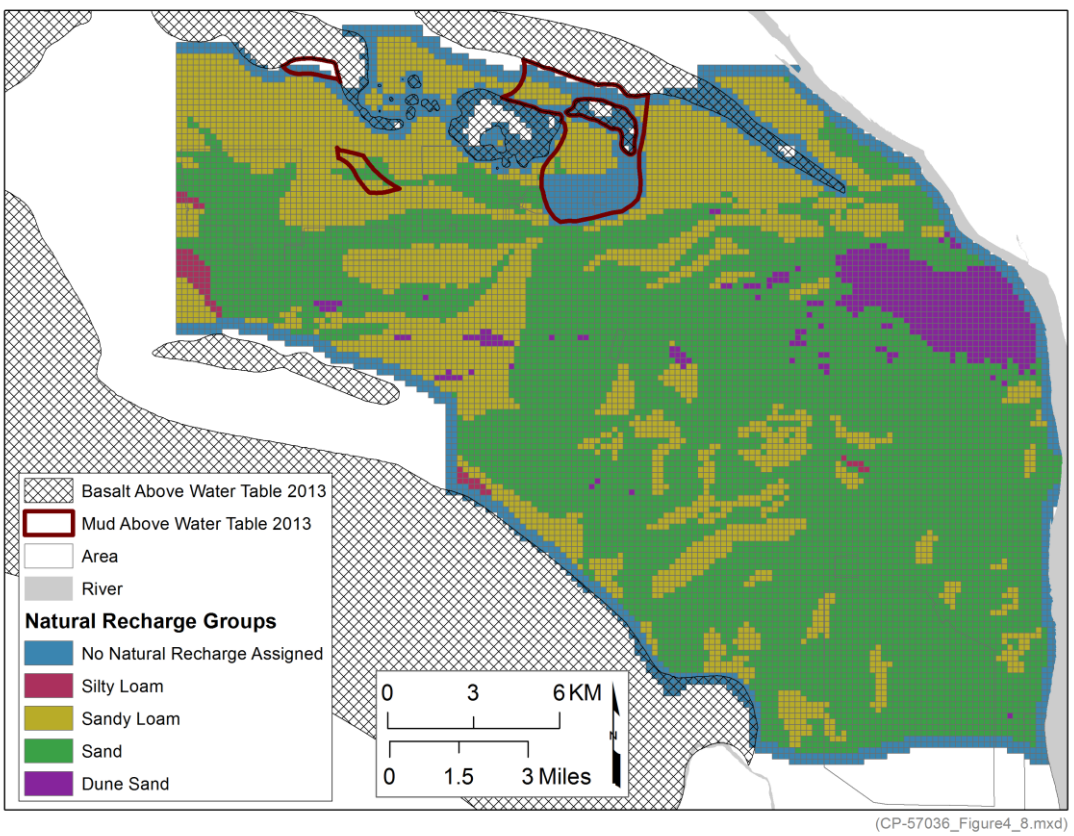

Figure 4-8. Spatial Distribution of Surface Soil Types used to Define Natural Recharge to the Aquifer (based on Hajek, 1966)

Anthropogenic Recharge

Fluxes from surface water discharge due to operations at the Hanford Site are summarized in Electronic Modeling Data Transmittal – Boundary Condition (Artificial Recharge) – 0002 (EMDT-BC-0002, 2009). The data include the magnitudes and locations of operational discharges for the simulated time periods in the model. Locations of discharge include waste sites, ponds, sewer discharge, French drains, and documented unplanned releases for the entire operational period and projections of future discharges.

Figure 4-9 shows the locations of discharges listed in EMDT-BC-0002 and an illustration of how locations that overlap more than one model cell. The total discharge is distributed on an area weighted basis to all cells that intersect the footprint of the discharge location. The anthropogenic flux is added to the natural recharge component in order to establish the final total recharge flux used in the simulations. Discharges included in EMDT-BC-0002 have been attenuated to account for travel through the vadose zone. The changes vary with time according to the values provided in EMDT-BC-0002. The anthropogenic recharge values are not included in any steady state model simulation or stress period.

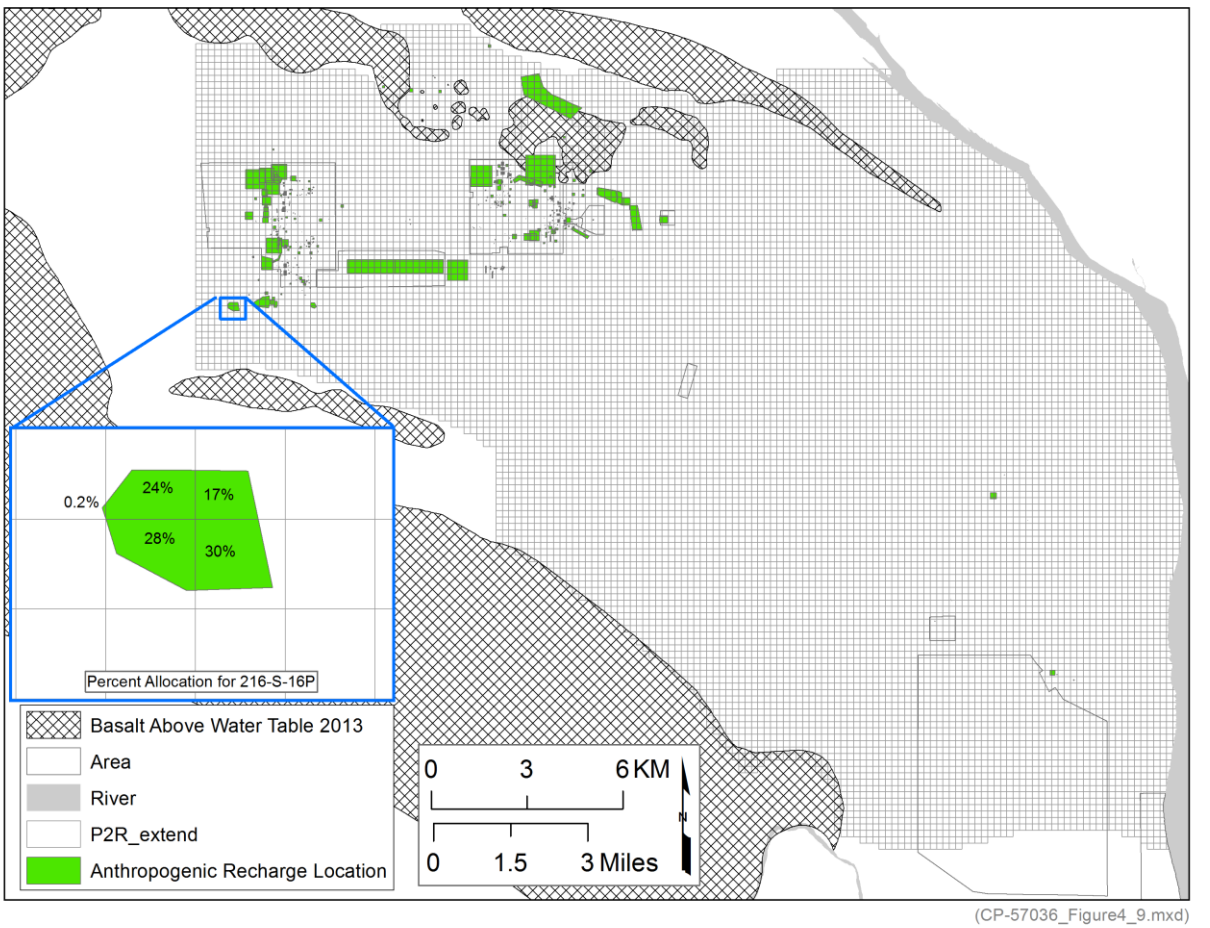

Figure 4-9. Locations of Anthropogenic Recharge in the P2R Model

4.3.2.2 Lower Boundary (Basalt)

The base of the numerical model (bottom of model layer 7) is simulated as a no flow boundary. Section 3.2.4 discussed the possibility of groundwater flux through the basalt as a possible source. However, similarly to the TC & WM EIS model, the basalt surface is considered a no flow boundary.

4.3.2.3 Lateral Boundaries

Figure 4-7 shows the model extent and the various lateral boundary conditions included in the model. The boundaries include specified head boundaries, no flow boundaries, mountain front recharge, and river boundaries representing the Columbia River. Each of these is described in the following sections.

Specified Head Boundaries

There are four separate specified head groups defined in the model. They are labeled, the west, northeast, southwest, and Gable Gap groups. These represent boundaries where groundwater is expected flow across. In each case the location was selected to coincide with a location where groundwater monitoring well was stationed in order to assign a specified head at that position for the calibration simulations. Figure 4-10 shows observed hydraulic head over time at each of these wells and the simulated values used for defining the boundary condition. As required by MODFLOW, only active cells at the BC locations with a bottom elevation less than the specified head value for a given stress period will be assigned a boundary condition in the model input files.

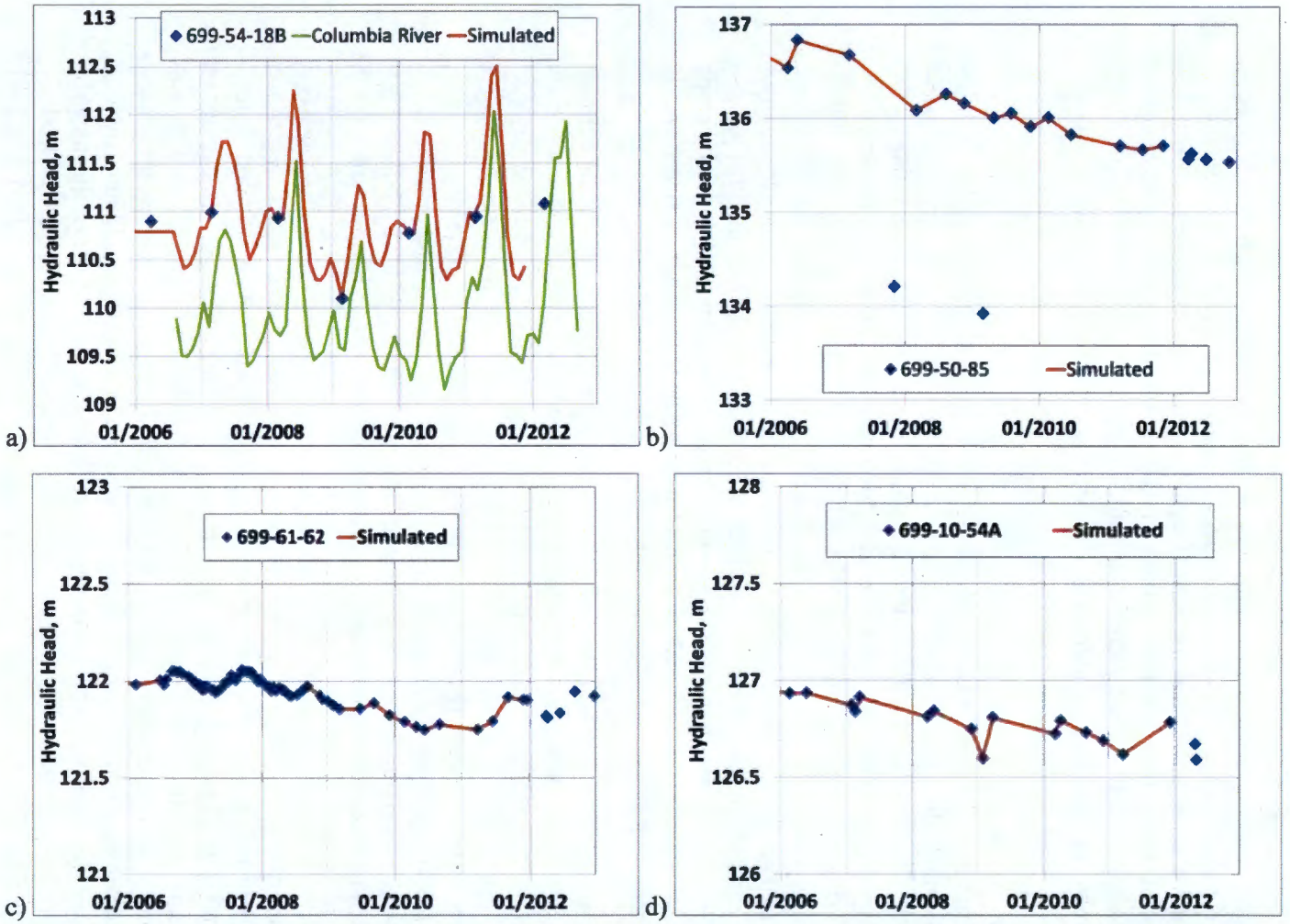

Figure 4-10. Observed Hydraulic Head at Wells used to define the Specified Head Boundary Conditions and the Simulated Time Series for a) the Eastern, b) Western, c) Gable Gap, and d) Southern Boundaries

No-flow (Upland) Boundaries

Where no designation is shown in Figure 4-7 along the lateral boundary is defined the model defaults to a no flow boundary. These represents locations where the basalt outcrops or in the case of the southernmost boundary of the model was modeled to move parallel to the flow of groundwater based on the site-wide contours presented as part of the 2013 Annual Groundwater Monitoring Report. The boundary was selected far enough to the south that any groundwater remedy is sufficient distance away from the boundary to affect the direction of flow at this location. If significant changes to the groundwater magnitude and direction at this location occur in the future, this boundary may need to be reconsidered. Also, based on this boundary selection any remedial option for consideration should not violate the assumption that the option is sufficiently away from the boundary not to affect significantly the direction of groundwater flow.

Mountain-front Inflow Boundaries

Previous modeling efforts simulating site wide flow have included the effects of mountain front inflow boundaries at several locations throughout the site including the Dry Creek and Cold Creek Valleys and the Rattlesnake Hills (PNNL-14753 and DOE/EIS-0391). Figure 4-7 shows the location of these boundary conditions with respect to the P2R Model domain. Mountain front recharge in the previous models was simulated using specified flux and general head boundary conditions for the SGM 2005 and TC & WM EIS models respectively. The model input parameters selected to represent this FEP in each of the models were not based on direct measurement, which introduces a level of uncertainty to the input parameters used for their representation. A calibration process was used to determine the final values in each case. PNNL-14753 acknowledges that mountain front recharge is occurring at all basalt outcrops include those close to Gable Mountain and basalt outcrops. However, the affect was not significant enough to justify their inclusion as a model boundary condition.

For the P2R Model, both the Cold Creek and Dry Creek valleys are largely outside the model domain. The effect of recharge from these locations is represented by specified head boundaries to the west and southwest of the model. In the model construction process recharge included in the model near basalt outcrops was shown to over predict saturated groundwater conditions where it is not observed and over predict hydraulic head at these locations. The coarseness of the model grid and saturated zone only formulation of MODFLOW caused these over predictions. To mitigate the over prediction in these locations no areal recharge was simulated within 300 meters of a basalt outcrop. This includes Rattlesnake hills. Therefore, mountain front recharge was considered but not explicitly simulated in the P2R Model.

Columbia River Boundary

Columbia River stage data were available for the 300-Area gage that is part of the Automated Water Level Network (AWLN) at the Hanford Site. Data were obtained from the Hanford Virtual Library for the period of record available from May 2006 to September 2012. A MODFLOW river package node was assigned to each location at the eastern edge of the model shown in Figure 4-7. River stage elevations at each location were assigned based on applying a gradient established by Thorne et.al. (2006) using hydraulic modeling of the Columbia River to determine the gradient. This method for establishing the river stage was utilized by previous modeling efforts at the site (PNNL-14753 and DOE/EIS-0391). Figure 4-11 shows the period of record river stage from the gage data along with the values used for simulating both the steady state time frame, March/April 2012, and the transient historic time frame, January 2006 to January 2012. Where observed data were not available the average value for that corresponding month was used as the stage. River depth for the simulation matched the value used in the TC & WM EIS model and river conductance was established as part of the model calibration.

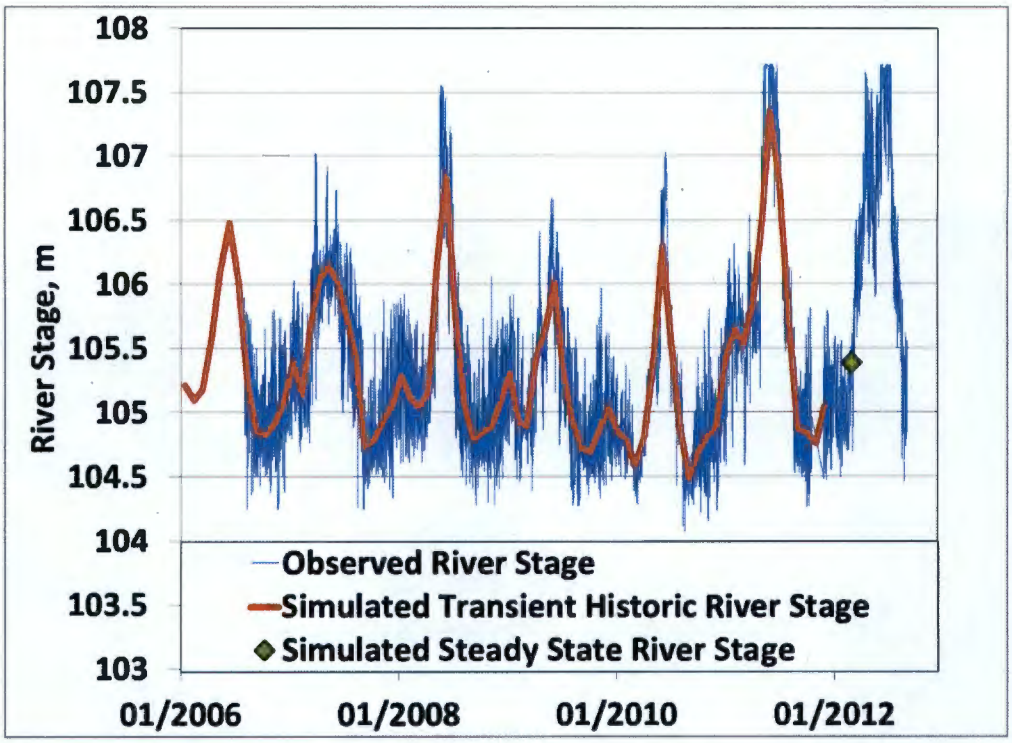

Figure 4-11. Observed Columbia River Stage and Simulated River Stage at the 300 Area River Gage

4.3.3 Pump-and-Treat (Extraction and Injections)

Pump-and-treat remediation systems have been developed at the Hanford Site to aid in the cleanup effort. Within the P2R Model domain several of these systems, associated with 200 West Area, exist within the model domain. Extraction and injection data for these pump-and-treat systems were gathered as part of developing the model. Table 4-2 shows the well names locations and rates for injection and extraction wells within the model domain for the simulated time periods. Data were compiled from various project scientists responsible for project work. Table 4-3 shows the various sources that were used to compile the pumping rates. At this time a database recording the pumping rates for remedial systems is not available and these values represent the most comprehensive list of extraction and injection rates for the wells listed in Table 4-2. Injection and extraction rates were input using the MODFLOW multi-node well package (Konikow et. al., 2009). Figure 4-12 shows the location of pumping wells within the model domain. For the transient historic simulation the monthly values shown in the table were used for each monthly stress period. For the steady state simulation the average pumping rate for the months of March and April 2012 were used for the pumping rate in the simulation.

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Table 4-2. Pumping rates (gpm) for wells within the model domain and active during the simulation time periods.

Well Name	2006	2007	Jan-08	Feb-08	Mar-08	Apr-08	May-08	Jun-08	Jul-08	Aug-08	Sep-08	Oct-08	Nov-08	Dec-08	Jan-09	Feb-09	Mar-09	Apr-09	May-09	Jun-09	Jul-09	Aug-09	Sep-09	Oct-09	Nov-09	Dec-09	Jan-10	Feb-10	Mar-10	Apr-10	May-10	Jun-10	Jul-10	Aug-10	Sep-10	Oct-10	Nov-10	Dec-10	Jan-11	Feb-11	Mar-11	Apr-11	May-11	Jun-11	Jul-11	Aug-11	Sep-11	Oct-11	Nov-11	Dec-11	Mar-12	Apr-12
299-W11-45	0.0	-3.9	-11.6	-10.4	-1.9	0.0	0.0	0.0	-7.6	-2.0	0.0	0.0	0.0	0.0	-7.8	-7.8	-7.8	-7.8	-7.8	-7.8	-7.8	-7.8	-7.8	-7.8	-7.8	-7.8	0.0	-3.4	-10.5	-8.8	-10.0	-11.4	-10.6	-5.9	-0.5	-10.7	-11.1	-11.8	-10.7	-10.7	-9.3	-9.8	-9.9	-9.8	-9.7	-9.5	-7.7	-8.5	-9.2	-8.6	-1.2	0.0
299-W11-46	0.0	-13.0	-37.0	-33.1	-36.4	-37.3	-1.2	-34.2	-35.0	-6.9	0.0	0.0	0.0	0.0	-31.2	-31.2	-31.2	-31.2	-31.2	-31.2	-31.2	-31.2	-31.2	-31.2	-31.2	-31.2	0.0	-11.2	-33.7	-29.5	-13.3	-9.1	-12.4	-17.0	-28.9	-28.7	-22.8	-12.5	-4.7	-27.0	-29.9	-22.6	-28.7	-27.0	-26.5	-25.1	-14.8	-8.5	-10.7	-12.5	-17.4	-18.5
299-W15-1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-10.4	-12.0	-11.2	-12.8	-11.8	-9.9	0.0	0.0	0.0	-4.2	-10.7	-7.6	-10.4	-7.6	-7.5	-6.8	-8.1	-8.7	-8.5	-9.3	-10.5	-3.7	-0.8	-7.0	-11.3	-8.2	-7.9	-8.4	-8.3	-8.8	-10.6	-8.5	-10.4	-9.6	-9.8	-10.0	-10.7	-10.7	-11.1	-9.5	-4.8
299-W15-11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-24.8	-26.7	-28.6	-24.7	-25.7	-20.2	0.0	0.0	0.0	-8.3	-5.2	0.0	0.0	-18.9	-16.0	-18.8	-16.5	-18.1	-17.5	-5.3	-5.2	-5.1	-1.4	-16.8	-14.7	-15.0	-14.5	-13.1	-11.2	-11.3	-11.8	-10.2	-12.0	-12.0	-11.4	-11.7	-11.4	-11.1	-10.7	-10.3	-5.4
299-W15-225	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-3.4	-156.7	-200.9	-18.0	-246.2	-237.7	-250.4	-249.3	-250.1	-248.5	-249.8	-248.2	-214.0	-252.4	-252.3	-241.2	-252.2	-248.4	-252.0	-238.8	-247.0	-241.9
299-W15-29	88.4	74.4	78.4	76.7	86.0	118.3	106.2	0.0	0.0	0.0	0.0	59.0	57.5	64.4	69.2	70.0	49.0	0.7	53.5	3.9	11.6	33.6	21.5	55.5	51.8	39.9	42.5	40.5	39.7	47.7	38.5	91.2	53.5	11.6	92.7	117.0	132.1	133.4	130.2	157.6	148.1	146.3	124.3	144.5	142.1	133.6	137.1	137.1	139.4	132.6	118.4	90.6
299-W15-34	-17.1	-17.0	-17.3	-6.1	-19.2	-19.8	-17.1	0.0	0.0	0.0	0.0	-16.0	-16.2	-19.3	-18.3	-18.8	-15.3	0.0	0.0	0.0	-6.6	-4.2	0.0	0.0	0.0	0.0	0.0	-12.3	-17.4	-15.2	-0.1	0.0	0.0	-1.4	-15.9	-13.9	-14.3	-13.8	-14.2	-14.0	-13.8	-11.4	-9.3	-11.0	-11.1	-10.5	-10.9	-10.8	-10.8	-10.7	-10.4	-6.1
299-W15-35	-45.1	-44.2	-44.0	-43.9	-43.6	-44.3	-37.2	0.0	0.0	0.0	0.0	-37.9	-39.2	-45.2	-43.2	-40.4	-27.7	0.0	0.0	0.0	-18.7	-46.2	-32.3	-45.8	-43.1	-45.6	-45.4	-43.1	-37.3	-36.8	-33.0	-37.4	-4.7	0.0	-1.4	-18.4	-19.8	-19.4	-18.0	-14.3	-16.9	-18.1	-15.3	-17.8	-17.5	-16.8	-17.4	-17.2	-17.8	-17.9	0.0	0.0
299-W15-36	-10.6	-15.5	-17.0	-16.5	-16.2	-16.6	-14.3	0.0	0.0	0.0	0.0	-13.6	-13.6	-16.7	-14.5	-8.1	-7.7	-0.2	-11.9	-0.1	-4.4	-8.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
299-W15-40	-6.5	-5.8	-5.9	-5.2	-5.3	-5.6	-5.2	0.0	0.0	0.0	0.0	-4.8	-4.9	-5.8	-5.6	-5.3	-4.0	0.0	0.0	0.0	-0.5	-6.6	-4.3	-4.3	-5.1	-2.6	-5.6	-5.0	-5.6	-4.2	-4.5	-5.1	-1.5	-0.3	-4.1	-2.2	-2.1	-1.5	-0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
299-W15-43	-46.1	-43.5	-40.0	-38.7	-38.0	-41.0	-35.7	0.0	0.0	0.0	0.0	-33.6	-34.0	-40.9	-38.8	-36.8	-30.0	0.0	0.0	0.0	-11.0	-30.8	-22.4	-31.1	-29.3	-28.3	-26.8	-23.4	-26.3	-25.8	-22.7	-22.6	-5.1	-1.7	-22.9	-22.6	-22.7	-20.3	-17.8	-17.0	-17.2	-16.7	-13.4	-14.8	-13.4	-12.6	-13.0	-12.3	-12.4	-12.4	-12.1	-4.7
299-W15-44	-7.5	-4.9	-5.9	-5.7	-2.4	-4.7	-4.6	0.0	0.0	0.0	0.0	-4.9	-5.5	-5.6	-5.1	-4.8	-4.0	0.0	0.0	0.0	0.0	-1.0	-4.7	-6.4	-5.3	-5.4	-5.3	-0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0													
299-W15-45	-32.4	-28.0	-25.2	-24.4	-24.0	-24.6	-21.1	0.0	0.0	0.0	0.0	-20.5	-20.9	-24.8	-24.3	-24.4	-19.4	0.0	0.0	0.0	-0.7	0.0	0.0	0.0	-20.3	-24.9	-24.8	-23.3	-26.5	-26.3	-20.1	-25.9	-5.5	-2.2	-25.0	-25.0	-23.9	-22.7	-21.0	-20.2	-19.7	-19.2	-16.8	-19.4	-18.7	-12.8	-9.7	-13.3	-14.8	-14.7	-13.7	-8.0
299-W15-46	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-42.9	-43.0	-52.5	-46.9	-51.6	-43.1	-0.5	-50.2	-0.6	-1.9	-21.2	-8.3	-56.0	-54.3	-50.7	-48.8	-47.4	-55.0	-54.5	-47.2	-48.1	-35.1	-4.1	-54.9	-42.8	-40.9	-52.6	-51.8	-49.6	-49.2	-48.2	-42.4	-47.8	-46.1	-44.3	-45.1	-44.4	-44.2	-43.9	-25.8	0.0
299-W15-47	-34.4	-54.9	-54.6	-52.3	-51.6	-51.5	-42.9	0.0	0.0	0.0	0.0	-35.5	-37.8	-41.2	-36.7	-29.2	-22.7	-0.6	-36.6	-0.4	-14.2	-41.8	-30.8	-39.5	-32.6	-37.3	-30.1	-12.9	-18.1	-17.4	-11.1	-14.1	-0.9	0.0	0.0	0.0	-0.1	0.0	-0.3	-18.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
299-W15-6	-2.1	-6.2	-6.1	-5.9	-5.9	-6.2	-5.0	0.0	0.0	0.0	0.0	-4.1	-4.4	-4.7	-5.1	-5.2	-4.3	-0.1	-4.7	-0.1	-1.7	-4.7	-1.6	-4.9	-3.5	-3.2	-4.8	-4.3	-5.2	-4.6	-4.1	-5.2	-2.1	0.0	0.0	0.0	-0.8	-2.7	-3.5	-4.1	-4.3	-3.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
299-W15-7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-11.1	-12.3	-12.5	-12.4	-12.3	-9.6	0.0	0.0	0.0	-4.4	-9.7	-6.7	-9.7	-7.6	-7.3	-6.2	-5.8	-7.8	-7.0	-6.6	-7.3	-1.6	-0.6	-6.9	-6.3	-6.5	-4.5	-4.4	-7.1	-6.2	-5.9	-5.3	-5.6	-5.1	-5.0	-5.2	-5.5	-5.3	-5.0	-2.8	0.0
299-W15-765	-25.1	-18.8	-23.3	-15.0	-14.7	-23.9	-19.9	0.0	0.0	0.0	0.0	-19.8	-20.2	-23.8	-22.5	-21.0	-17.3	0.0	0.0	0.0	-4.4	-12.5	-12.2	-20.2	-18.5	-15.7	-14.5	-12.4	-11.3	0.0	0.0	0.0	0.0	0.0	-12.5	-10.5	-8.9	-7.0	-6.7	-5.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
299-W18-36	87.2	93.6	92.4	69.5	78.1	60.7	63.9	0.0	0.0	0.0	0.0	71.2	68.2	78.8	70.3	63.2	47.9	1.0	55.4	3.5	22.4	28.1	28.6	41.3	52.4	55.8	53.9	45.8	47.7	54.0	41.8	79.0	64.5	10.1	98.0	84.9	82.9	83.4	81.9	94.5	90.2	89.1	76.0	88.7	87.5	82.6	85.2	84.8	86.2	83.4	76.1	63.8
299-W18-37	33.7	64.2	67.0	53.2	53.5	49.4	38.2	21.5	0.0	0.0	0.0	59.3	57.3	65.2	58.1	53.1	44.5	0.0	13.2	2.6	17.9	40.7	28.3	39.0	42.3	47.6	46.3	44.0	48.4	44.9	34.4	63.1	50.7	8.0	77.3	55.9	52.6	54.2	53.2	4.9	0.9	0.9	0.8	0.8	0.8	0.7	0.9	1.0	1.0	1.6	1.1	1.2
299-W18-38	25.4	11.6	0.0	0.3	0.0	6.0	0.0	0.0	0.0	0.0	0.0	37.4	37.2	40.0	33.3	33.2	29.0	0.2	13.5	1.4	12.8	31.0	22.1	37.3	39.3	42.2	42.3	45.0	49.4	45.3	35.3	58.3	50.9	0.1	66.9	69.1	67.4	67.5	66.5	76.6	73.2	72.2	61.3	71.8	70.8	67.0	69.2	68.8	69.7	67.8	61.9	53.1
299-W18-39	0.6	0.8	0.0	8.7	3.2	4.9	0.0	0.0	0.0	0.0	0.0	0.0	54.8	60.0	57.2	59.4	51.4	3.7	17.1	3.7	17.2	43.3	30.8	52.1	60.0	57.1	50.9	48.5	65.0	41.8	35.6	58.0	46.6	0.0	66.3	68.5	67.9	68.0	67.2	76.0	73.2	72.4	61.6	72.5	71.7	68.0	70.2	69.5	70.5	57.3	63.5	55.1
299-W19-36E	0.0	-2.7	-5.6	-4.9	-4.2	-4.2	-4.4	-5.2	-5.5	-3.2	-2.7	-2.7	-2.7	-2.7	-2.6	-2.6	-2.6	-2.6	-2.6	-2.6	-2.6	-2.6	-2.6	-2.6	-2.6	-2.6	0.0	0.0	0.0	0.0	-4.1	-3.8	-3.1	-2.7	0.0	-1.4	-1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
299-W19-43	0.0	-2.5	-4.5	-4.3	-4.2	-2.2	0.0	0.0	-0.6	-2.7	-2.7	-2.7	-2.7	-2.7	-2.6	-2.6	-2.6	-2.6	-2.6	-2.6	-2.6	-2.6	-2.6	-2.6	-2.6	-2.6	0.0	0.0	0.0	0.0	-1.3	-2.6	-0.5	0.0	-0.8	-2.5	-2.4	-2.7	-2.3	-2.3	-2.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 4-3. Data sources used to compile the pumping rates for extraction/injection wells within the model domain.

Color	File modified by SSPA	Original Files	Comment
	Calculated from Cumulative Treated volumes from Annual Reports		
	PumpingPrior2006.xlsx	ZP-1 Recovery Well Rates 1997-2006 (Doughty).xls	Vista. Received by SSPA 11/30/2006
		Zp1_Injection_historic_from_VISTA.xls	
	UP1 Pump Rates_MK.xls	UP1 Pump Rates.xls	From: Kelty, George [mailto:George_Kelty@RL.gov] Sent: Monday, January 26, 2009 2:15 PM To: 'Matt Tonkin' Subject: RE: UP-1 Extraction Rates
	ETF_TOTALIZER_CY2010_011311_2_forDB.xlsx	ETF_TOTALIZER_CY2010_011311_2.xlsx	email from Gene Freeman to Rachel 1/18/2011. File sent by Gene was called "ETF_TOTALIZER_CY2010_011311.xlsx". I added "2_forDB". (The "2" is because this is a revised version of a file he sent the day before).
	ZP-1 History_MK.xlsx	ZP-1 History.xlsx	email from Garry Scheidegger to Rachel 4/4/2011
	ZP2011_2012Combined_MK.xlsx	**ZP1_Totals_Oct Nov & to Dec 27 2011.xlsx**	sent by email from Sally Simmonds to Rachel 2/8/2012
		ZP1_Totals_2012.csv	sent by email from Frederick Biebesheimer to Matt 6/13/2012.
		ZP-1_(Injection_Jan-Sep_2011)_ttbl_Daily_Volume_Report.csv	sent by email from Art Lee to Matt 1/18/2012
		ZP-1_(Extraction_Jan-Sep_2011)_ttbl_Daily_Volume_Report.csv	sent by email from Art Lee to Matt 1/18/2012

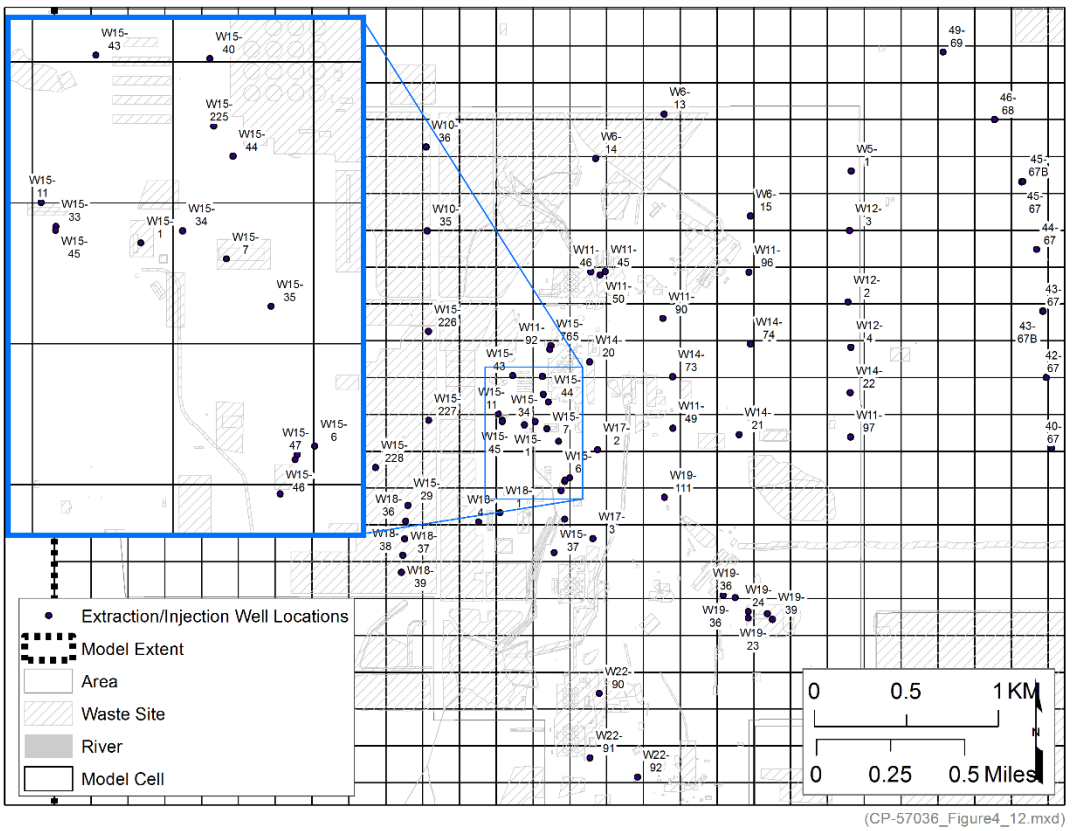


Figure 4-12. Location of Injection and Extraction Wells Included in the P2R Model

4.3.4 Hydraulic Parameters

A PNNL database was developed to provide an accessible repository for saturated media hydraulic properties; it is based on results and supporting data from aquifer tests conducted at the Hanford Site over the past 50 years (PNNL-14753; PNNL-14186). The database includes results from in-situ aquifer tests including pumping tests, slug tests, injection tests, and tracer tests. It does not include hydraulic properties determined from laboratory analysis of discrete samples (e.g., permeameter testing).

The data files that form the database have been developed as a set of Excel®[1] spreadsheets, and because of the nature of the spreadsheets, the database is not included in this report. The database currently resides in INTERA's Richland office.

Selection of hydraulic properties included in the database was based on requirements of the numerical and analytical models. These parameters include the following:

- Transmissivity (*T*)
- Storativity (*S*)
- Aquifer thickness (*b*)
- Hydraulic conductivity (*K*)

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

- Storage coefficient (S_s)
- Specific yield (S_y)
- Vertical anisotropy (K_v/K_h)

The preceding parameters are calculated from measured aquifer response data combined with information on well and aquifer conditions and often based on assumptions about the aquifer flow system. None of these parameters can generally be determined from a single aquifer test analysis. Sometimes, one or more of these parameters must be assumed in order to calculate others. Therefore, each of these fields has a corresponding field to indicate whether the parameter was determined from the analysis, calculated from another parameter, or assumed. Additional fields in the database tables contain information on test analysis methods, well configuration, aquifer conditions, and test conditions. The reliability of hydraulic property estimates from aquifer tests varies widely depending on the appropriateness of applied analysis methods, the amount and duration of applied stress, the well/aquifer configuration, and the quality of data collected. Therefore, a reliability flag field has been created for each of the analysis parameters. This flag will indicate that the reliability of the calculated hydraulic properties is either: R= reliable, Q=questionable or U= unknown. A comment field also exists for each test analysis to document the basis for the reliability flag.

Site-specific data on storage properties are limited; however, some data are available for the Hanford and Ringold units based on field tests conducted in the 200 Areas. According to PNL-10886, *Development of a Three-Dimensional Ground-Water Model of the Hanford Site Unconfined Aquifer System: FY 1995 Status Report,* and PNL-8337, *Summary and Evaluation of Available Hydraulic Property Data for the Hanford Site Unconfined Aquifer System*, specific yield for the Hanford formation is estimated to range from about 0.1 to 0.3 and is expected to be higher for coarse, well-sorted gravel than for poorly sorted mixtures of sand and gravel. From previous work (PNL-10886; PNL-8337), specific yields of the poorly sorted sediments of the Ringold Formation are estimated to range from 0.05 to 0.2.

Table 4-4 shows the parameter ranges selected from the database for use with the P2R Model. They were selected based on analysis results from the database and input from previous modeling results including the TC & WM EIS and the CPGW Model which both have modeling domains that overlap the P2R Model. The table includes the calibrated value used in the final model. The calibration results are discussed in Section 4-5.

Table 4-4. Hydraulic Properties and Ranges used for P2R Model derived from the Hydraulic Properties Database and Previous Modeling Efforts (see Table 3-2 and 3-3)

Property	Units	Hydrostratigraphic Unit	Low	High	Calibrated: Steady State and Transient Simulations
Hydraulic Conductivity	m/day	Hanford, Cold Creek (paleo-channel)	1	37,000	17,000
		Hanford (outside paleo-channel)	0.1	19.7	2.27
		Hanford (near Columbia River)	0.9	62	1
		Cold Creek	1	400	109
		Cold Creek (paleo-channel)	1	37,000	17,000

Table 4-4. Hydraulic Properties and Ranges used for P2R Model derived from the Hydraulic Properties Database and Previous Modeling Efforts (see Table 3-2 and 3-3)

Property	Units	Hydrostratigraphic Unit	Low	High	Calibrated: Steady State and Transient Simulations
		Ringold Taylor Flat*	1	20	3
		Ringold E	0.1	18.6	3.26
		Ringold Upper Mud	2e-4	0.03	8E-03
		Ringold A	1	8	5
Vertical Anisotropy of Hydraulic Conductivity	-/-	All	0.01	0.1	0.1
Specific Yield	m/m	Hanford and Cold Creek	0.1	0.37	0.2
		Ringold	0.05	0.11	0.095
Specific Storage	1/m	All	2.3E-05	1.2E-03	1E-04

*no description for this soil type is within the hydraulic properties database or the previous modeling efforts. Range of values assumed based on pumping test values from other Hanford (outside paleo-channel) and Ringold E values.

4.4 Calibration

Model calibration was completed in an effort to improve the models ability to reproduce observed field conditions. Measured water level data from 2006 through 2012 were used as the qualitative measure of model accuracy. These data were discussed in Section 4.3.1.1. In the calibration process model input parameters were altered in a systematic iterative fashion in order to improve the models fit to the observed data. Both manual and automated calibration to the set of historic water level data using the PEST parameter estimation software (Doherty, 2010) was used to optimize the estimate of the model parameter values. Automated calibration provides valuable information on the response of the model outputs to parameter changes, and can help to identify quickly structural weaknesses in a model. The calibration of the P2R Model is an ongoing process. As new geologic information and other data are incorporated, the calibration must be undertaken again and results in newly calibrated input parameters. This section discusses the results of the calibration process including; 1) the metrics used to assess goodness-of-fit between calibration data and the model, 2) the acceptance criteria for the calibration process, and 3) the results of the calibration process.

4.4.1 Goodness-of-fit metrics

Three goodness-of-fit statistical measures were used to evaluate the comparison of observed and simulated hydraulic head values throughout the model domain. These include; 1) root mean squared error (RMSE), 2) mean absolute error (MAE), and 3) mean error (ME). Equations 1 thru 3 show the formula for calculating each of these measures respectively. In each case, the goal of calibration is to reduce the magnitude of each goodness-of-fit statistic. However, care must be taken to ensure reductions in the goodness-of-fit statistics are not achieved by using input parameter values or producing simulated results that violate the conceptual site model.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \qquad \text{Equation 1}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n} abs(y_i - \hat{y}_i) \qquad \text{Equation 2}$$

$$ME = \frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i) \qquad \text{Equation 3}$$

Where, RMSE = root mean squared error
MAE = mean absolute error
ME = mean error
n = number of measurements
y_i = observed hydraulic head
$\hat{y}_i$ = simulated hydraulic head

Each statistical measure provides a slightly different perspective on the comparison of simulated results. The ME statistic is used to represent the overall bias, high or low, in the model. A positive value signifies the model tends to under predict hydraulic head and a positive value indicates the model. However, when the ME statistic is near zero this may be the result of high and low values that cancel each other out of the calculation. Both the RMSE and the MAE help with this issue by using the squared and absolute residual value, which are always positive, rather than the residual value, which can be positive or negative. The RMSE utilizes the squared residual values to accentuate the effect of values away from the mean residual value. When the residual is large, raising it to the second power will weight that measurement more than those closer to one.

4.4.2 Acceptance Criteria

Several qualitative and quantitative criteria were used to determine whether the model calibration was acceptable for the model. These include: 1) the root mean squared error within 10% of the range of observed hydraulic heads, 2) maintain the mean error below half the value of the RMSE, 3) show a south/southeastern gradient through the 200 East area for the steady state calibration, and 4) keep input parameter values for range of expected values for recharge and hydraulic conductivity based on literature and data used to develop the conceptual site model. The first and second criteria aid in quantitatively showing the match between the observed and simulated head measurements. Criterion number three illustrates the ability of the model to reproduce the dominant flow direction for the predictive simulations. This criterion is only applicable to the steady state model because it is expected that flow direction may change during periods of the transient simulation. Based on the most recent data presented as part of the 2013 Groundwater Monitoring Annual Report, the flow direction for the steady state condition should be to the south through the Gable Gap. Finally, the fourth criterion indicates whether the model fit is in disagreement with the CSM for the model domain. By achieving these criteria the model will be deemed acceptable for use in developing scale appropriate predictive simulations.

4.4.3 Results

Both the calibration of the steady state and historic transient simulations met the acceptance criteria outlined in the previous section. The purpose of this section is to detail simulation and acceptance criteria results for each of these simulations. They are discussed in the following sections.

4.4.3.1 March/April 2012 Steady State Simulation

The objective of the steady state simulation was to reproduce the hydraulic head field presented as part of the *Hanford Site Groundwater Monitoring Report for 2012* (DOE/RL-2013-22). The MODFLOW model boundary conditions were assigned values based on the March/April of 2012 for the simulation. Figure 4-10 shows the simulation results for the steady state simulation including the simulated water table contours and hydraulic head measurement residuals. Head measurement residuals indicate some spatial bias in the model. In the 200 West and far field (east of NRDWL) portion of the model results tend to under predict hydraulic head and in the 200 East most measurements slightly over predict hydraulic head. However, Table 4-5 shows the quantitative goodness-of-fit statistics for the simulation results. The RMSE, MAE, and ME values are 1.0, 0.7, and 0.3 m respectively. The RMSE of 1.0 m is less than 10% of the total range of observed heads at 33 m. Also, the ME of 0.3 is less than half the RMSE. The water table contours in Figure 4-13 indicate the flow direction from the Gable Gap through the 200-BP-5 operable unit is toward the south. Table 4-4 shows the calibrated hydraulic parameters are within the bounds outlined during model construction. Based on these results the acceptance criteria have been met and the model is acceptable for use with predictive simulations.

Table 4-5. Summary of Comparative Statistics for Observed and Simulated Results for the Historical Numerical Groundwater Model

Statistical Measure	Steady State (March/April 2012) (m)	Transient (January 2006 to January 2012)
Root Mean Squared Error	1.0	0.8
Mean Absolute Error	0.7	0.5
Mean Error (Bias)	0.3	0.2

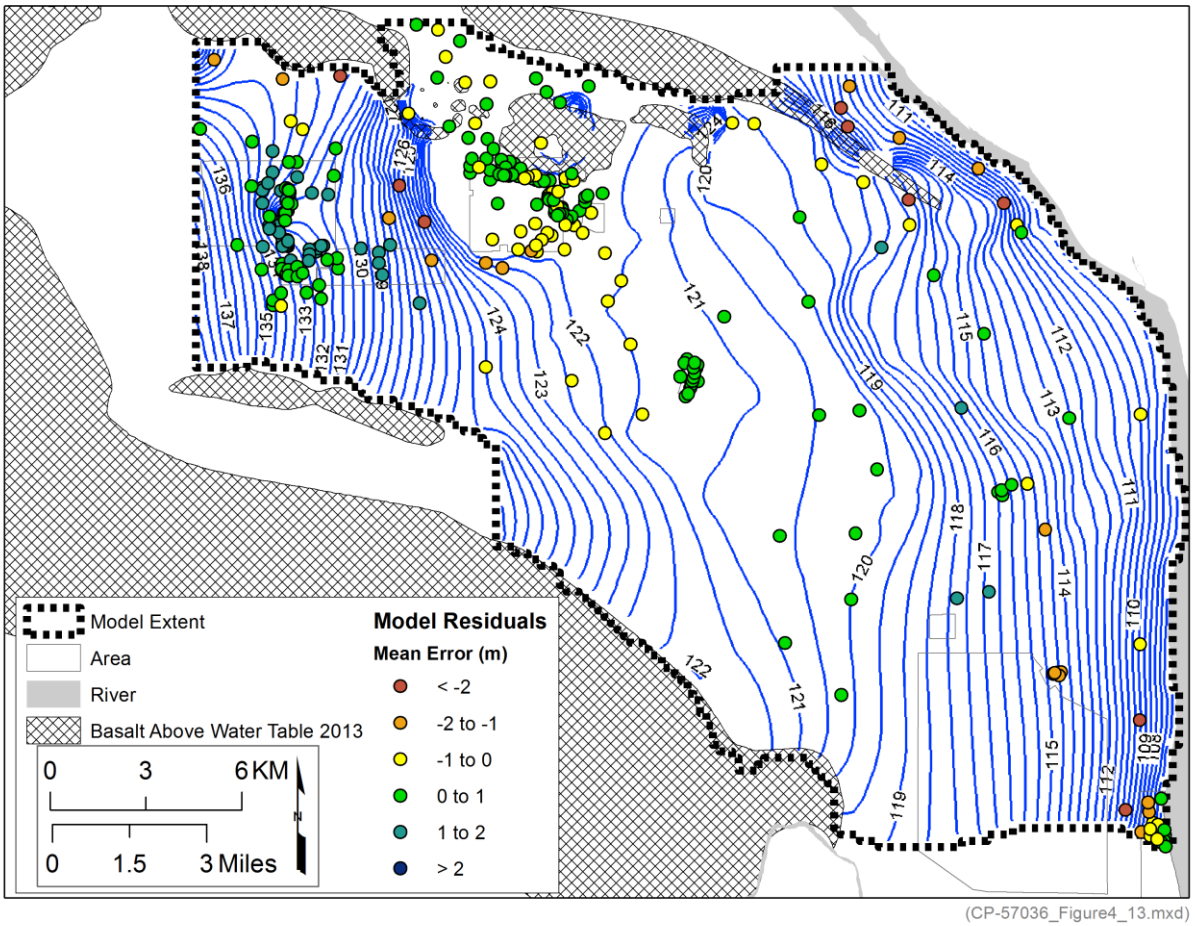
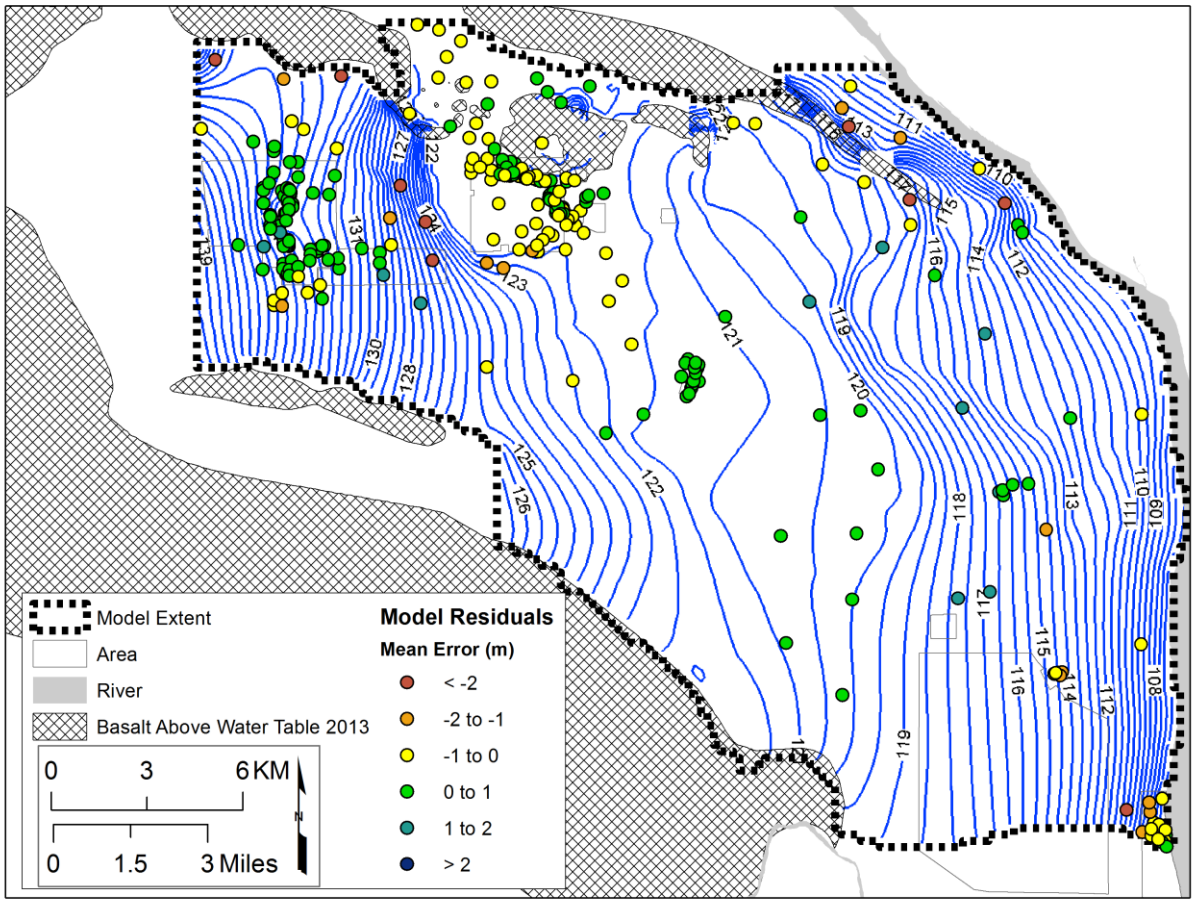


Figure 4-13. Simulation Results for the March/April 2012 Steady State Calibration

4.4.3.2 January 2006 to January 2012 Historic Transient Simulation

The historic transient simulation improved the match between observed and simulated hydraulic head measurements based on the statistical goodness-of-fit criteria. Figure 4-14 shows the measurement residuals and the water table contours for the month of May 2011. Simulated water table contours indicate movement through the Gable Gap to the Columbia River, the eastern boundary of the river. The model produces similar patterns in spatial bias with a reduced magnitude. The RMSE, MAE, and ME were calculated at 0.8, 0.5, and 0.1 m respectively. These statistical measures along with the criterion four satisfy the calibration criteria. The RMSE of 0.8 m is less than 10% of the total range of observed heads at 35 m. Also, the ME of 0.1 is less than half the RMSE.



(CP-57036_Figure4_14.mxd)

Figure 4-14. Simulation Results for the January 2006 to January 2012 Historic Transient Simulation Calibration

5 Model Sensitivity and Uncertainty Analysis

Work on this section is deferred for the present. Sensitivity and uncertainty analyses are schedule for completion under Technical Integration's Hanford Site-wide Modeling activities task.

6 Model Limitations

Limitations of the P2R Model are identified and enumerated in Table 6-1 in terms of model objectives, implementation, and software limitations.

Table 6-1. Plateau to River Groundwater Transport Model Limitations

Limitation ID	Model Aspect	Limitation (Consequence)
Limitation 1	The scale of the P2R Model is appropriate for transport simulations for relatively mobile contaminants with transport times from the 200-East source locations to the Columbia River that are on the order of decades; this is consistent with objectives for this model.	The scale of the P2R Model is not appropriate for refined evaluation of less mobile contaminants that will remain within the Central Plateau for hundreds of years or longer.
Limitation 2	The model grid represents the aquifer with cells of uniform horizontal dimension 200 m by 200 m. This is suitable for making predictions of hydraulic heads, hydraulic gradients, groundwater flow rates, and contaminant mass migration over areas that comprise many model cells.	Predictions of hydraulic heads, hydraulic gradients, groundwater flow rates, and contaminant mass migration at scales less than 200 meters are not reliable (except, perhaps, in areas where uniform hydraulic gradients are present).
Limitation 3	The northern boundary of the P2R Model is set at the Western and Gable Gaps. The P2R Model domain was selected based on current understanding that northward flow in the Gable Gap is ending as water level declines below a basalt saddle elevation and that future northward migration of contaminants from 200-BP-5 OU through Gable Gap will not be significant to the baseline risk assessment.	If the current understanding is incorrect, or if future liquid discharges at the Treated Effluent Disposal Facility (TEDF) and the State Approved Liquid Disposal Site (SALDS) increase in conjunction with tank recovery activities sufficient to reactivate flow through Gable Gap, the P2R Model's current domain will not be adequate to address northward contaminant migration through Gable Gap.
Limitation 4	The model simulates the unconfined aquifer only.	Vadose zone flow and transport are not explicitly accounted for. Continuing sources from the vadose zone may be separately linked to the model as a boundary condition.
Limitation 5	The application of recharge input derived from deep percolation of precipitation at the land surface implicitly represents the effects of vadose zone migration and storage. The rates used represent a best practice combination of empirical data and model simulations of vadose zone migration characteristics at the Hanford Site, to arrive at a fractional rate of meteoric water that constitutes recharge to the unconfined aquifer.	The assignment of natural recharge rates is subject to continued refinement, as more information is made available for such areas through field investigations and measurements. It is also based on persistence of land surface conditions that control recharge (vegetative cover and surface soil type); accordingly, model predictive power is limited if these factors are significantly altered in the future over significant portions of the model domain.

Table 6-1. Plateau to River Groundwater Transport Model Limitations

Limitation ID	Model Aspect	Limitation (Consequence)
Limitation 6	Attenuation of facility discharges to the ground surface, cribs, trenches, shallow wells, ponds, ditches, and other infiltration areas is indirectly accounted for using STOMP simulations of the discharge sites following the methodology of EMDT-BC-0002 (2009). The predicted attenuation (delay of recharge arrival and reduction in peak volume) of discharge to the surface at the water table is included as data input for the CPGW Model. This methodology does provide a dramatic improvement compared to ignoring the presence of the considerable vadose zone when incorporating artificial discharges	The approach for accounting for vadose zone attenuation of artificial recharge has the following limitations: • The vadose zone for each liquid discharge site is simulated as a quasi-two-dimensional cross section model using local hydraulic stratigraphy, scaling the horizontal dimension to achieve unit gradient conditions in the lowest conductivity layer during the highest artificial discharge period. Further, some calibration was applied for certain sites where more detailed three-dimensional modeling studies were available. • This approach achieves rapid simulation times and a generally representative treatment of vadose zone attenuation of liquid discharges, but is not entirely adequate where perching of water on fine-grained layers and subsequent lateral redistribution of moisture in the vadose zone occurs. • Perching is believed to have been a significant vadose zone process in the 200 West Area (200-ZP-1 and 200-UP-1 Groundwater OUs) and is suspected to be the reason for the inability of the calibration to date to match measured water levels in these locales.
Limitation 7	It is assumed that the large discharges to the surface that occurred in the historic period will not occur in the future.	Therefore, perching is not considered a significant process in predictive simulations of future flow and transport
Limitation 8	Fluid flow through the basalt bedrock is assumed negligible, and as a result, is not explicitly simulated.	If there are sources and/or sinks of water associated with the basalt bedrock, then the model is limited with respect to the exclusion of this FEPs item.
Limitation 9	There remain considerable areas with limited well control in the Central Plateau	The assignment of HSUs is subject to continued refinement, as more information is made available for such areas.
Limitation 10		

7 Model Configuration Management

The model described in this model package report is uniquely designated as the "Plateau to River Groundwater Transport Model" and in abbreviation form as the "P2R Model".

Version control for this model will conform to the following version numbering convention:

- P2R Model Version #.#.# (or #.#.#.#)
    - The first version index will match the CHPRC-approved build number of MODFLOW and Related Codes in which the model is implemented.
    - The second version index will denote sequential versions of the model grid (the use of "grid" here refers to both the grid structure and parameter values).
    - The third version index will denote the boundary condition version used.
    - The optional fourth index is reserved to denote 'variant' versions. A variant version here is defined as a unique model configuration in which key hydraulic or structural parameters have been changed for specific purposes without recalibration of the model.

For example, P2R Model Version 6.1.1 would refer to the Plateau-to-River Groundwater Transport Model, implemented in MODFLOW-2000-MST CHPRC Build 6 using grid version 1 and boundary condition version 1. Similarly, P2R Model Version 7.2.1.1 would refer to (as an example) the Plateau to River Groundwater Transport Model, implemented in MODFLOW-2000-MST CHPRC Build 7 using grid version 2, boundary condition set 1, and a variant treatment of (for example) the structure of the basalt top in the Gable Gap area.

Note that individual simulations (or applications) are separately configuration controlled following the guidance provided in Appendix G of CHPRC-00189. Simple changes in model stresses (e.g., pump-and-treat system injection and extraction rates) do not constitute a variant because these will not impact model calibration; these are properly the subject of an ECF and model files for those will be archived in the EMMA application bin by ECF number.

As required by Appendix G of CHPRC-00189, all inputs and outputs for the development of this model will be committed to EMMA to maintain and preserve this configuration-managed basis of this model. Basis information (that information collected to form the basis for model input parameterization; e.g., historical pump-and-treat rates) is also stored in the EMMA for traceability purposes.

The software used to implement this model, CHPRC Build 7 of MODFLOW-2000, is configuration managed as discussed in Section 4.1. Configuration-managed software is obtained from the Hanford Site MKS Integrity™ configuration management system as required by CHPRC-00258.

7.1 Version History

All prior versions, and the current version, are described in this section.

7.1.1 P2R Model Version 7.1

The first released version of the P2R Model is Version 7.1, documented in CP-57037 Rev. 0.

8 Model Enhancement Recommendations

Development of model enhancement recommendations will be made following evaluation of the initial application of the P2R Model for the 200-BP-5 and 200-PO-1 OU RI work.

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