PNNL-14702, Rev. 1

Pacific Northwest National Laboratory
Operated by Battelle for the U.S. Department of Energy

Vadose Zone Hydrogeology Data Package for Hanford Assessments

G. V. Last
E. J. Freeman
K. J. Cantrell
M. J. Fayer
G. W. Gee
W. E. Nichols
B. N. Bjornstad
D. G. Horton

June 2006

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information,
P.O. Box 62, Oak Ridge, TN 37831-0062;
ph: (865) 576-8401
fax: (865) 576-5728
email: reports@adonis.osti.gov

Available to the public from the National Technical Information Service,
U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161
ph: (800) 553-6847
fax: (703) 605-6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

This document was printed on recycled paper.

PNNL-14702, Rev. 1

Vadose Zone Hydrogeology
Data Package for Hanford Assessments

G. V. Last
E. J. Freeman
K. J. Cantrell
M. J. Fayer
G. W. Gee
W. E. Nichols
B. N. Bjornstad
D. G. Horton

June 2006

Prepared for
the U.S. Department of Energy
under Contract DE-AC05-76RL01830

Pacific Northwest National Laboratory
Richland, Washington 99352

Preface

This data package was originally prepared to support a 2004 composite analysis (CA) of low-level waste disposal at the Hanford Site. The *Technical Scope and Approach for the 2004 Composite Analysis of Low-Level Waste Disposal at the Hanford Site* (Kincaid et al. 2004) identified the requirements for that analysis and served as the basis for the data collection effort documented in this data package. Completion of the 2004 CA was later deferred, and the *2004 Annual Status Report for the Composite Analysis of Low-Level Waste Disposal in the Central Plateau at the Hanford Site* (DOE 2005) indicated that a comprehensive update to the CA was in preparation and would be submitted in 2006.

However, the U.S. Department of Energy (DOE) has recently decided to further defer the CA update and will use the cumulative assessment currently under preparation for the environmental impact statement (EIS) being prepared for tank closure and other site decisions as the updated CA. Submittal of the draft EIS is currently planned for FY 2008.

Acknowledgments

The authors would like to acknowledge Thomas W. Fogwell and the Groundwater Remediation Project managed by Fluor Hanford, Inc. for supporting this work. We would like to thank Raziuddin Khaleel (Fluor Federal Services), and Charles T. Kincaid, Christopher J. Murray, Stephen P. Reidel, R. Jeffery Serne, and Robert W. Bryce for their technical reviews. The authors would also like to thank Anderson L. Ward for his technical support throughout the completion of this work, and Christopher A. Newbill for preparation of the site location map. We would also like to thank Launa F. Morasch for her technical editorial support, Kathy R. Neiderhiser, Shannon B. Neely, and the rest of the Publication Design team for their support in producing this document.

Executive Summary

This data package documents the technical basis for selecting physical and geochemical parameters and input values that will be used in vadose zone modeling for Hanford assessments. This work was originally conducted as part of the Characterization of Systems Task of the Groundwater Remediation Project managed by Fluor Hanford, Inc., Richland, Washington, and revised as part of the Characterization of Systems Project managed by the Pacific Northwest National Laboratory (PNNL) for the U.S. Department of Energy, Richland Operations Office (DOE-RL).

This data package describes the geologic framework, the physical, hydrologic, and contaminant transport properties of the geologic materials, and deep drainage (i.e., recharge) estimates, and builds on the general framework developed for the initial assessment conducted using the System Assessment Capability (SAC) (Bryce et al. 2002). The general approach for this work was to update and provide incremental improvements over the previous SAC data package completed in 2001. As with the previous SAC data package, much of the data and interpreted information were extracted from existing documents and databases. Every attempt was made to provide traceability to the original source(s) of the data or interpretations.

Kincaid et al. (2004) identified 1,052 waste sites from the Waste Information Data System (WIDS) sites and several existing and future storage sites for inclusion in Hanford assessments, with analyses to be conducted on a site-by-site basis whenever inventory and release data permit.[1] The complexity of these assessments, together with the lack of detailed characterization data for some of the fine-scale fate and transport processes necessitates simplification of site features, release events, and contaminant fate and transport processes to those factors considered most dominant. The dominant factors affecting modeling of transport of contaminants through the vadose zone include: (1) waste inventory and release estimates, (2) estimates of deep drainage (recharge), (3) the hydrogeologic profiles and properties of the vadose zone affecting aqueous phase advection and dispersion, and (4) estimates of geochemical reactions (e.g., sorption and precipitation) affecting the retardation of contaminants. The last three of these data types are addressed by this data package. The first one, waste inventory and release estimates, is addressed in the inventory and release model data packages.

Many large scale Hanford assessments will generally use a one-dimensional vadose zone model for computational efficiency (although the SAC framework is not inherently limited to a one-dimensional representation), configured to account for lateral spreading, and in selected cases, conditioned against multi-dimensional model results (Kincaid et al. 2004). In this report, and that of Kincaid et al. (2004), waste sites are grouped into a number of geographic areas assumed to have similar hydrogeologic structure and properties. Hydrogeologic units were identified and their thickness specified for each of these hydrogeologic provinces. To account for uncertainty in the model parameters, a stochastic distribution was developed for each process model parameter for each hydrogeologic unit.

[1] Originally 974 of 2,730 Waste Information Data System (WIDS) sites were identified for inclusion in a large-scale Hanford assessment. Further work identified 48 more waste sites bringing the total to 1,022. Subsequent reviews identified an additional 30 sites that have been included, many of which account for offsite transfers of waste and nuclear material. This brings the total to 1,052.

The vadose zone hydrostratigraphic profiles and hydrogeochemical property distributions for Hanford assessments are represented by 30 generalized one-dimensional vertical columns representing 17 general geographic areas and 13 site-specific locations. Each hydrostratigraphic profile (template) is configured with the hydraulic and geochemical parameters necessary to simulate the flow and transport through the vadose zone using the Subsurface Transport Over Multiple Phases (STOMP) code (White and Oostrom 2000). As many as five variations of a single hydrostratigraphic template are incorporated for some geographic areas in order to more accurately represent the depth of waste release, the thickness of the vadose zone beneath the point of release, and variations in contaminant distribution coefficients (K_d values) associated with different waste chemistry designations. Each template represents the vadose zone using a few major hydrostratigraphic units that are treated as horizontal layers with constant thicknesses, and that are homogeneous and isotropic. Hydraulic and geochemical parameters for each hydrostratigraphic unit are represented by stochastic distributions to facilitate sensitivity and uncertainty analyses.

This data package is a compilation of the data available to support Hanford assessments. As site characterization is completed at waste sites, and as investigations into contaminant behavior are completed, the uncertainty in this information will be reduced and, as a result, the uncertainty in future assessments will be reduced.

Contents

Figures

Tables

1.0 Introduction

In fiscal year (FY) 2003, the U.S. Department of Energy's Richland Operations Office (DOE-RL) initiated activities, including the development of data packages, to support Hanford assessments. This report describes the data compiled in FY 2003 and updated in FY 2005 to support vadose zone modeling for Hanford assessments. This work was originally conducted as part of the Characterization of Systems Task of the Groundwater Remediation Project (formerly the Groundwater Protection Program) managed by Fluor Hanford, Inc., Richland, Washington (Last et al. 2004b). It was revised in FY 2005 to incorporate updated approaches and parameter estimates as part of the Characterization of Systems Project managed by the Pacific Northwest National Laboratory (PNNL), for DOE-RL.

1.1 Purpose

The purpose of this data package is to summarize the conceptual understanding of flow and transport through the vadose zone (i.e., the conceptual model), describe how this model will be simplified for numerical simulation in support of Hanford assessments (i.e., implementation model), and finally to provide the input parameters needed for these vadose zone simulations.

1.2 Scope and Approach

The scope of this data package covers the geologic framework, the physical, hydrologic, and contaminant transport properties of the geologic materials in the vadose zone, and estimates of deep drainage (i.e., recharge). This data package builds on the general framework developed for the initial assessment conducted using the System Assessment Capability (SAC) as presented in:

- Preliminary System Assessment Capability Concepts for Architecture, Platform, and Data Management - Appendix C, Vadose Zone Conceptual Model (http://www.hanford.gov/cp/gpp/modeling/sacarchive/App%20C.pdf)

- Draft 2001 SAC Data Package, *Appendix C - Vadose Zone Data for Initial Assessment Performed with System Assessment Capability* (Revision 0) (http://www.hanford.gov/cp/gpp/modeling/sacarchive/dp_vadose.pdf).

- *Vadose Zone Hydrogeology Data Package for the 2004 Composite Analysis* (PNNL-14702, Rev. 0) (Last et al. 2004b)

The general approach for this work was to update and provide incremental improvements over the previous 2004 data package. As with the previous SAC data packages, much of the data and interpreted information were extracted from existing documents and databases. Every attempt was made to provide traceability to the original source(s) of the data or interpretations.

2.0 Background

The vadose zone is the hydrogeologic region that extends from the soil surface to the water table (DOE 1998). At the Hanford Site, the vadose zone ranges in thickness from less than 1 m along the river in the 100 and 300 Areas to more than 100 m on the Central Plateau in the center of the Hanford Site. At discrete locations, the vadose zone contains waste inventories from past waste disposal practices (e.g., direct liquid waste disposal to the ground via engineered facilities) and from unplanned releases (e.g., spills and tank leaks).

The geologic framework of the vadose zone is very complex, with a high degree of heterogeneity and anisotropy in its physical, hydrologic, and geochemical properties. This complex hydrogeochemical framework, together with waste water and meteoric water fluxes, lead to a highly complex three-dimensional movement of moisture and contaminants through the vadose zone. Wilson et al. (1995) describe flow within the vadose zone as dynamic and characterized by periods of unsaturated flow at varying degrees of partial saturation that is punctuated by episodes of preferential, saturated flow in response to hydrologic events or releases of liquids.

This section summarizes our conceptual understanding of flow and transport through the vadose zone and the technical basis and approach for modeling the vadose zone for large scale Hanford assessments. Conceptual models are evolving hypotheses that identify the important features, events, and processes controlling fluid flow and contaminant transport at a specific field site, within the context of a specific problem. Looney and Falta (2000) further describe a conceptual model as answering the question "How do we believe the system actually operates?" The conceptual model is one of the key initial elements in the overall modeling process. Once the site-specific problem has been defined and the important features, events, and processes conceptualized, quantitative descriptions can be prepared and implemented. Field and laboratory data are used to provide the input data, as well as to calibrate and independently test the predictive capabilities of the model. Of particular interest to this data package are the subsurface geologic, hydraulic, and geochemical parameters and the deep drainage estimates that control flow and transport through the vadose zone.

2.1 Conceptual Model of the Hanford Site Vadose Zone

Conceptual models of the vadose zone at the Hanford Site have been developed from information on the geology, geophysics, geochemistry, and hydrologic regime as well as the distribution and movement of waste in the subsurface. Most of the information has been obtained through borehole drilling, sediment sampling and analysis, and geophysical logging. This provides a considerable amount of information about the lithology and stratigraphy, but a more limited amount of hydrologic and geochemical information. These investigations into the vadose zone have traditionally been at or near the waste disposal sites; however, a few areas that represent background conditions or that provide representative test sites have also been studied. The integrated knowledge from these previous studies and ongoing work provides a conceptual understanding of the geologic, hydraulic, and geochemical controls on contaminant movement and distribution within the vadose zone of the Hanford Site (DOE 1999). Figure 2.1 illustrates some of these controls. However, there are still many outstanding technical issues, some of which require additional study and some of which may never be completely resolved.

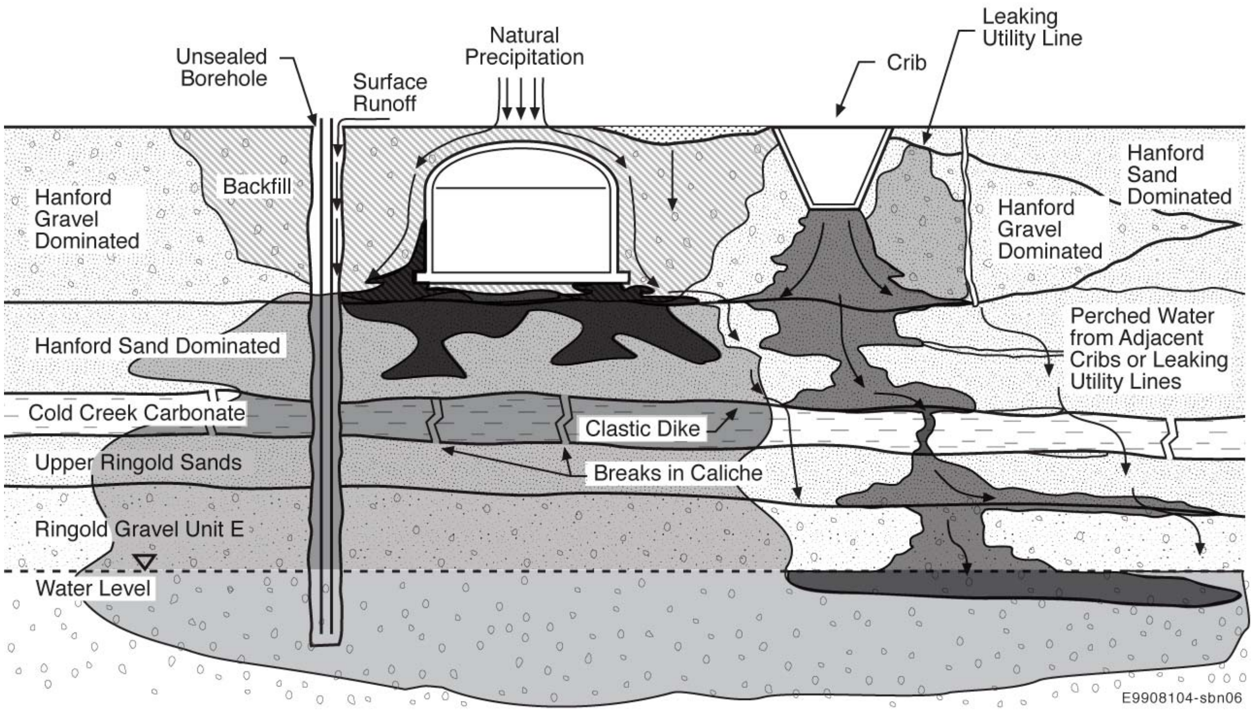

Figure 2.1. General Vadose Zone Conceptual Model Concepts after Caggiano (1996) and Johnson and Chou (1998)

The *Preliminary System Assessment Capability Concepts for Architecture, Platform and Data Management, Appendix C*[2] describes the conceptual models of vadose zone flow and transport and the preferred approach (and the rationale behind it) used for representing vadose zone transport in the initial assessments conducted using SAC. A common process to define the modeling requirements for a particular assessment is to break the conceptual model down into potentially relevant factors (i.e., features, events, and processes [FEPs]) and to logically screen and select the factors that should be included in the assessment (Last et al. 2004a). The process of identifying, classifying, and screening these factors is often called FEP analysis (NEA 2000) or FEP analysis methodology (Bailey and Billington 1998).

Kincaid's *Candidate Sets Report*[3] and Soler et al. (2001) provide comprehensive compilations of the (1) features (the structure and transport properties of the various pathways); (2) events (e.g., recharge, source releases, etc.); and (3) processes (the fate and transport processes/mechanisms, including driving forces) considered potentially relevant to contaminant flow and transport within the vadose zone beneath the Hanford Site. Last et al. (2001) developed a process relationship diagram as a tool to illustrate the interrelations between factors and to facilitate analysis/screening of the dominant versus subordinate

---

[2] *Groundwater/Vadose Zone Integration Project Preliminary System Assessment Capability Concepts for Architecture, Platform, and Data Management*. September 30, 1999. http://www.hanford.gov/cp/gpp/modeling/sacarchive/9-30rpt.pdf

[3] Kincaid CT et al. June 25 1999. *Candidate Sets Report*. http://www.hanford.gov/cp/gpp/modeling/sacarchive/candsets.pdf

factors of a given conceptual model. Figure 2.2 illustrates the main features and processes potentially effecting flow and transport within the vadose zone.

The following sections (modified from Preliminary System Assessment Capability Concepts for Architecture, Platform, and Data Management - Appendix C, Vadose Zone Conceptual Model)[4] describe these important features, events, and processes, and identifies those factors that are considered most dominant and have been selected as study sets for numerical representation (modeling) in large scale Hanford assessments.

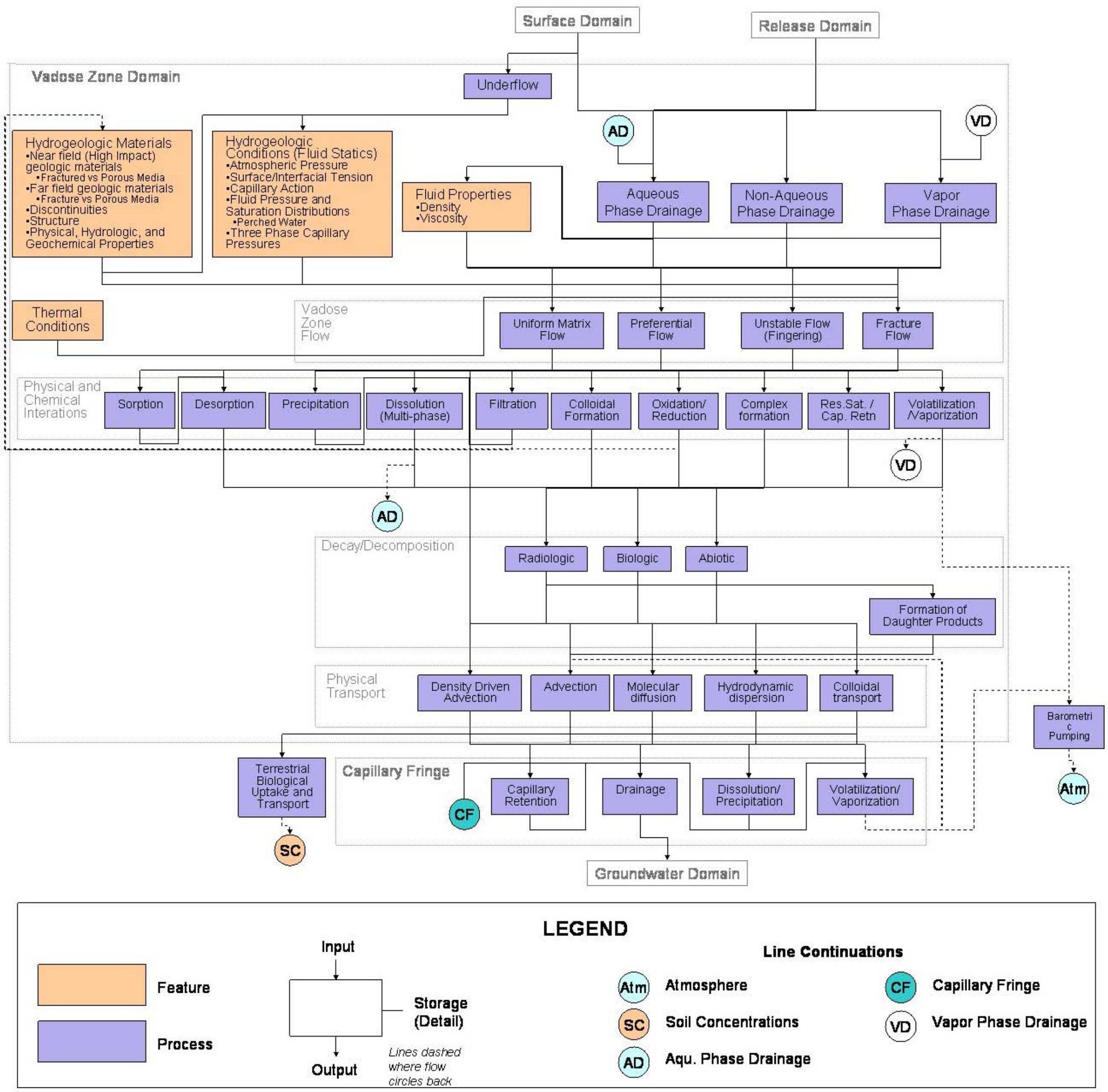

Figure 2.2. Process Relationship Diagram of Vadose Zone Flow and Transport

---

[4] *Preliminary System Assessment Capability Concepts for Architecture, Platform, and Data Management - Appendix C, Vadose Zone Conceptual Model* (http://www.hanford.gov/cp/gpp/modeling/sacarchive/App%20C.pdf)

2.1.1 Features

The primary features relevant to the vadose zone flow and transport include the hydrogeologic materials (and their physical, hydraulic, and geochemical properties); subsurface conditions (e.g., fluid statics and thermal conditions); and fluid properties. Other features relevant to the vadose zone conceptual model, such as climate and weather statistics, terrestrial ecology, and projected land use are not specifically discussed here. Instead, the reader is referred to Neitzel et al. (2005). Some aspects of the climate and weather phenomena are discussed later as they relate to precipitation, run-off, and infiltration (i.e., deep drainage) events.

There is a significant amount of hydrogeologic data available for the Hanford Site, primarily from borehole drilling in the vicinity of waste disposal operations. Interpretation of the geologic data are presented in numerous reports, including Tallman et al. (1979); DOE (1988, 1993a, 1994, 2002); Delaney et al. (1991); Connelly et al. (1992a and b); Lindsey (1992, 1995); Lindsey et al. (1992a, b); Lindsey and Jager (1993); Hartman and Peterson (1992); Peterson et al. (1996); Thorne et al. (1993, 1994); Hartman (2000); Williams et al. (2000); Williams et al. (2002); Reidel (2004); and Reidel et al. (2006).

The thickness of the vadose zone varies from less than 1 m along the river in the 100 and 300 Areas to more than 100 m beneath the Central Plateau. The vadose zone lies mostly within cataclysmic flood deposits of the Hanford formation, but in places such as the 200 West Area and portions of the 100 Areas it extends into the underlying Cold Creek unit, and/or the upper portions of the Ringold Formation. The physical structure and properties of the geologic framework and its principal transport pathways is complex, with a high degree of heterogeneity and anisotropy. To capture some of the site-wide variability in these features, this discussion is broken into three general physiographic areas (the 100, 200, and 300 Areas). While other areas, such as areas representative of background conditions and areas that have the potential to become contaminated in the future, are also important to the general vadose zone technical element, they are not specifically discussed here.

2.1.1.1 100 Areas

The average thickness of the vadose zone in the reactor areas ranges from 6 m (100-F Area) to over 30 m (100-B/C Area) with each reactor area being slightly different. During operations, groundwater mounding reduced the thickness of the vadose zone by 6 to 9 m directly under the retention basins or other liquid-waste disposal facilities.

Hydrogeologic Materials. The hydrogeologic framework of the vadose zone is complex; however, locally within the 100 Areas, it can be divided into two primary hydrostratigraphic units: (1) the gravel-dominated facies association of the Hanford formation and (2) the conglomeratic member of Wooded Island, Unit E, of the Ringold Formation (DOE 2002; Peterson et al. 1996; Hartman and Lindsey 1993; Lindberg 1993a, b; Lindsey and Jaeger 1993). The Ringold Formation makes up the lower portion of the vadose zone at the 100-K, 100-N, and the 100-D Areas. It is only partially present in the 100-B/C Area and absent in the 100-H and 100-F Areas. The Hanford formation extends from the surface to just above the water table when the Ringold Formation is present. The Hanford formation extends beneath the water table and makes up the unconfined aquifer in the 100-H and 100-F Areas.

The Ringold Formation Unit E is a fluvially deposited pebble-to-cobble gravel with a sandy matrix. It is characterized by complex interstratified beds and lenses of sand and gravel with low to moderate degrees of cementation.

The gravel-dominated facies of the Hanford formation is generally composed of uncemented, clast-supported pebble, cobble, and boulder gravel with a poorly sorted silty sandy matrix and minor sand and silt interbeds or stringers. It occasionally exhibits an open framework texture with little or no matrix. The clast size decreases in the lower portion of the Hanford formation. The Hanford formation is generally less cemented and more poorly sorted than the Ringold Formation and typically contains a higher percentage of angular basaltic detritus.

Although clastic dikes have been observed in the vadose zone beneath the 100 Areas (Fecht et al. 1999), this occurrence is fairly uncommon. Their limited distribution and lack of vertical continuity may render them insignificant as preferential pathways.

The contact between Ringold Unit E and the Hanford formation is important because the saturated hydraulic conductivity for the gravel-dominated sequence of the Hanford formation is one to two orders of magnitude higher than the more compacted and locally cemented Ringold Unit E. Since hydraulic conductivity varies with the formation, different groundwater level responses may occur where channels now filled with the Hanford formation have been scoured into the Ringold Unit E. These buried channels could become preferential pathways for contaminated groundwater during high river stages.

Hydraulic Properties and Conditions. The physical properties of the vadose zone in the 100 Areas are not well characterized. Peterson et al. (1996) reported saturated hydraulic conductivity, moisture content, specific gravity, and bulk density for samples taken from the single-pass reactor areas. No scaling of hydraulic conductivity based on particle-size distribution was done for that report. Khaleel and Relyea (1997) published moisture retention data for the 100-D, 100-F, and 100-H Areas. In the 100-N Area, Connelly et al. (1991) collected 10 surface samples for moisture retention data and DOE (1996a) collected four samples each from boreholes 199-N-108A and 199-N-109A. The measured physical properties for these samples vary widely, reflecting the heterogeneity of the vadose zone. These data are recorded in the catalog of vadose zone flow parameters for the Hanford Site (Freeman et al. 2002).

The large volume of liquid discharges during operations created water table mounds 6 to 9 m above the nominal water table under the retention basins and other liquid disposal facilities. The volumetric moisture content found in sediment under the 100-N Area liquid waste disposal facilities (DOE 1996a) appears to be high for the given sediment type and natural recharge rate. This suggests these soils are still draining.

Geochemical Properties and Conditions. Results from the geochemical characterization studies in the 100 Areas show a contaminant zoning (chromatographic) effect in the vadose zone. For radionuclides and inorganic contaminants that are not adsorbed (i.e., tritium, nitrate), the large releases of water to the vadose zone at the retention basin and liquid waste disposal facilities quickly pushed these contaminants through the vadose zone, into the unconfined aquifer, and subsequently out to the Columbia River. Crews and Tillson (1969), using iodine-131 isotopic analysis, estimated the travel time to the Columbia River from the 1301-N (116-N-1) liquid waste disposal facility to be approximately 10 days during active disposal (a distance of some 225 m).

Contaminants that show moderate adsorption such as strontium-90 show differential distribution (i.e., chromatographic zoning) within the vadose zone. Serne and LeGore (1996) examined characterization data from 12 boreholes within the 100-N Area and found that strontium-90 in the vadose zone is bound to sediment directly underneath the liquid waste disposal facilities in a relatively thin layer at depths that correspond to the elevated water table formed during operations. Serne and LeGore (1996) also reported the average bulk distribution coefficient (K_d) for strontium-90 to be 15 mL/g for these sediments. Contaminants with strong adsorption such as cobalt-60, cesium-137, and plutonium-239/240 remained within 1 m of the bottom of the disposal facility. Contaminated sediment that is now part of the vadose zone should be considered a source term for further downward migration to the water table.

Further complicating the release of contaminants from the vadose zone in the 100 Areas is the seasonal and diurnal fluctuations of the Columbia River. A high river stage can cause the water table to rise into sediment that contains higher concentrations of contaminants. Additionally, the chemistry changes caused by the constant re-wetting of the soil due to diurnal fluctuations could affect the release of contaminants from the vadose zone (Petersen and Connelly 2001).

2.1.1.2 200 Areas

The 200 East and 200 West Areas are located on the Central Plateau of the Hanford Site. The vadose zone beneath the 200 Areas ranges in thickness from about 50 m in the western portion of the 200 West Area (beneath the former U Pond) to 104 m in the southern part of the 200 East Area. The stratigraphy of the vadose zone varies significantly across the up to 100-m-thick Cold Creek flood bar that makes up the Central Plateau. A generalized geologic cross section showing the general stratigraphy through the 200 Areas is shown in Figure 2.3.

Hydrostratigraphy. The geology and hydrology of the 200 Areas have been extensively studied because they contain major sources of groundwater contamination (Hartman 2000). The major stratigraphic units making up the vadose zone include (1) Ice Age flood deposits of the Pleistocene-Age Hanford formation, (2) alluvial, eolian, and pedogenic deposits of the Pliocene/Pleistocene-Age Cold Creek unit, and (3) the fluvial, overbank, and lacustrine deposits of the Miocene/Pliocene-Age Ringold Formation.

200 West Area. The vadose zone beneath the 200 West Area ranges from 50 to 80 m thick and can be subdivided into six principal hydrostratigraphic units (Lindsey et al. 1992a; Connelly et al. 1992a; Thorne et al. 1993; Williams et al. 2002; DOE 2002). These units include two facies associations of the Hanford formation (gravel-dominated and sand-dominated), two lithofacies of the Cold Creek unit (the fine-grained, laminated to massive facies, and the coarse to fine-grained carbonate-cemented facies) and two members of the Ringold Formation (Taylor Flat and Wooded Island, Unit E). Not all of these units are present everywhere within the 200 West Area, and as in any depositional system, the thickness, distribution, and continuity of these units vary significantly from site to site.

Clastic dikes (Figure 2.4) occur as near-vertical sediment-filled structures that cut across bedding planes. Clastic dikes have been observed to form multisided polygonal cells (up to 150 m across) enclosing the host sediment. Individual polygonal cells are bounded by other polygons to form polygonal-patterned ground (Fecht et al. 1999) that resembles giant mudcracks or a honeycomb pattern in plan view. Vertically oriented clay skins within clastic dikes can form a local impediment to lateral flow.

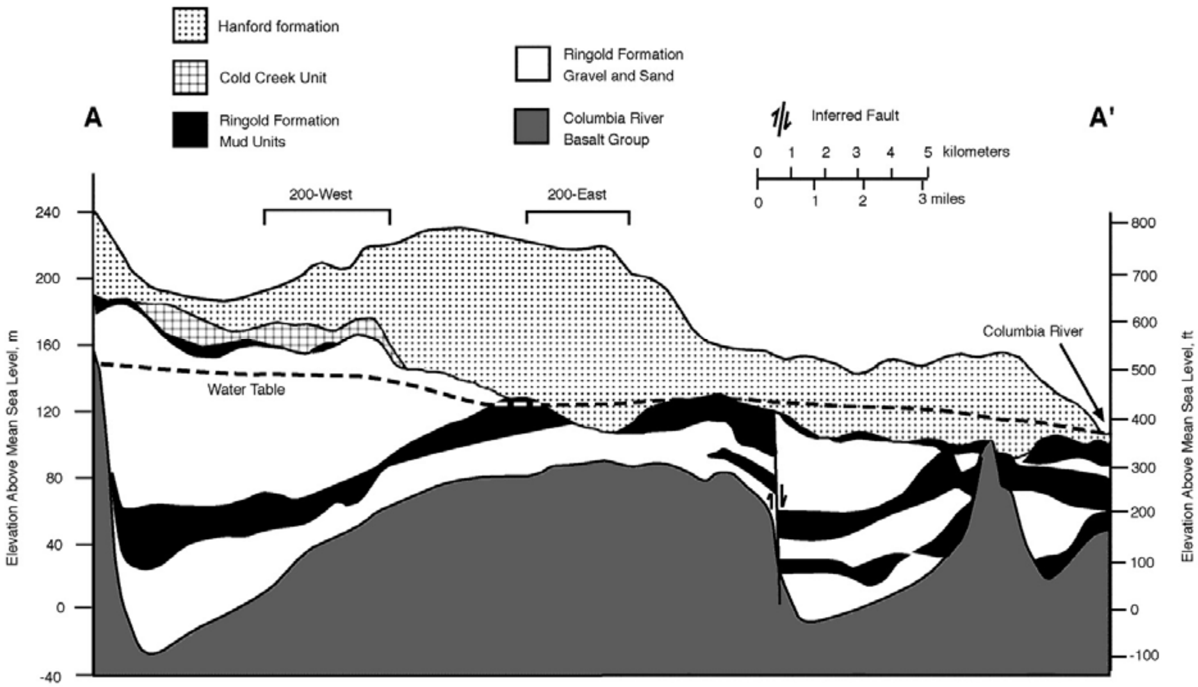

Figure 2.3. Generalized West-to-East Geologic Cross Section Through the Hanford Site (after Hartman 2000)

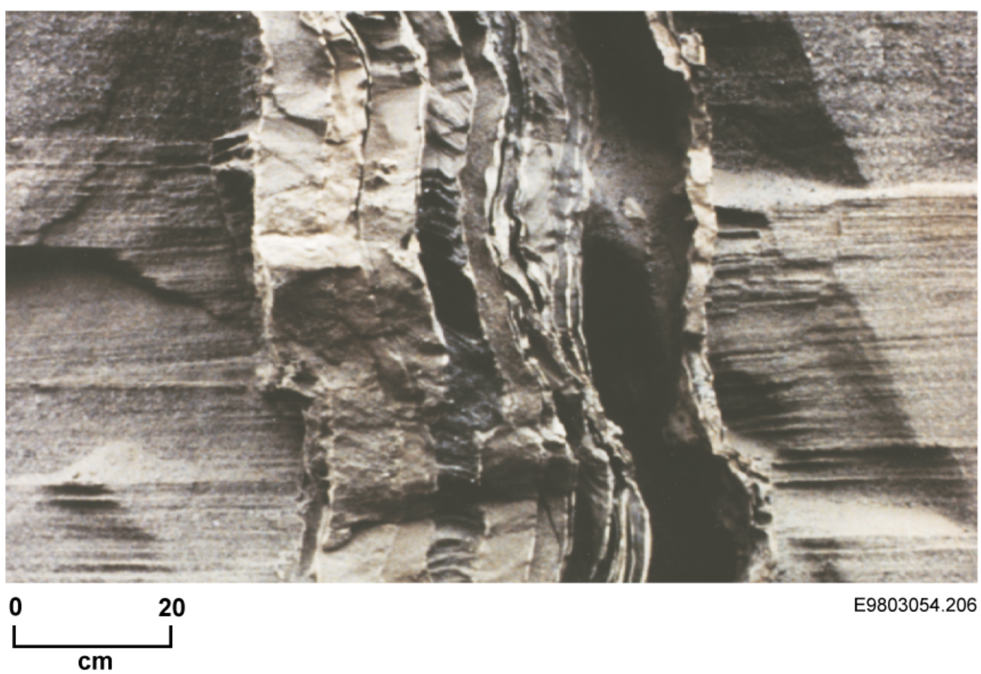

Figure 2.4. Photograph of a Typical Clastic Dike as Found at the U.S. Ecology Site in Central Hanford (after Fecht et al. 1999)

Clastic dikes are most common in the Hanford formation, but have been noted within the Cold Creek unit and/or Ringold Formation as well. Elsewhere, clastic dikes have also been observed in the Columbia River Basalt Group.

Perhaps the most significant features in the 200 West Area affecting vadose-zone transport are the fine-grained siliciclastic and carbonate-cemented facies of the Cold Creek unit, previously referred to as the Plio-Pleistocene unit, (Rohay et al. 1994; DOE 2002), which represent an ancient buried calcic paleosol sequence (Slate 1996, 2000). Because of the cemented nature of the Cold Creek unit, it is often considered impervious; however, it is also structurally brittle and may contain abundant fractures that have developed during or since soil development. The degree of cementation varies considerably within the Cold Creek unit so that contaminants could breach the unit through discontinuities. The Cold Creek unit contains abundant weathering products (e.g., oxides and carbonates) and may chemically react on contact with transported wastes. Immediately overlying the carbonate-cemented facies of the Cold Creek unit is the fine-grained, laminated to massive facies (formerly referred to as the 'early Palouse soil'), which has a relatively high moisture-retention capacity with a corresponding low permeability that tends to retard the downward movement of moisture and contaminants.

200 East Area. The vadose zone beneath the 200 East Area can be subdivided into six principal hydrostratigraphic units, including three units with in the Hanford formation, a fluvial gravel facies of the Cold Creek unit (equivalent to the Pre-Missoula Gravels of Webster and Crosby 1982 and Delaney et al. 1991), and two units belonging to the Ringold Formation (Lindsey et al. 1992b; Connelly et al. 1992b; Thorne et al. 1993; Williams et al. 2000; DOE 2002). The Hanford formation units include (1) an upper gravel-dominated facies, (2) a sand-dominated facies, and (3) a lower gravel-dominated facies. Over most of the 200 East Area, the Hanford sand-dominated facies lies between the upper and lower gravel-dominated facies (Lindsey et al. 1992b; Connelly et al. 1992b; DOE 2002). Based on borehole samples, the upper and lower gravel-dominated facies appear to have similar physical and chemical properties. The Ringold Formation in the 200 East Area is, for the most part, eroded away in the northern half of the 200 East Area. Here, the Hanford formation lies directly on top of basalt bedrock. With the dropping water table, basalt crops out above the water table and, thus, is unsaturated beneath the north-eastern portion of the 200 East Area. Just south of the 200 East Area, the top of the unconfined aquifer lies within the Ringold Formation. Because the physical and chemical characteristics of the Ringold Formation, Member of Wooded Island, Unit A and Unit E gravels are similar, and because only a small portion of the vadose zone lies within Unit A, these units can be combined into a single hydrostratigraphic unit.

Clastic dikes have also been observed in the Hanford formation beneath the 200 East Area. The vertically oriented clay skins within clastic dikes may locally form an impediment to lateral flow. This could then cause ponding (perching) of the water and eventual breakthrough to underlying strata.

Sublinear channel-cut scour and fill features occur within the Hanford formation and may act as preferential pathways in the horizontal direction. Other types of heterogeneity are associated with stratigraphic pinch out or offlapping/onlapping of facies.

Both the Ringold and the Hanford formations contain thin fine-grained stringers that can result in lateral spreading of moisture and may slow the vertical movement of contaminants within the vadose zone. Low-permeability layers, where they exist, are often solitary, relatively thick (meters or more), continuous layers within the Ringold Formation. Low-permeability layers within the Hanford formation, on the other hand, occur more frequently, are thin (0.5 m or less) and laterally discontinuous. Low-permeability layers within the sand-dominated facies of the Hanford formation are generally thicker and more continuous than those in the gravel-dominated facies. Some paleosols and facies changes (i.e., the contact between fine grained and coarser grained facies) may be fairly continuous over the range of 100 m or so, with some lateral spreading of crib effluent noted on that same scale.

Hydraulic and Transport Properties. Accurate predictions of flow and transport in the vadose zone require a detailed characterization of the hydrologic properties and their variability, as well as estimates of transport parameters such as dispersivity. In particular, data that are essential for quantifying the water storage and flow properties of unsaturated soil include the soil moisture characteristics (i.e., soil moisture content versus pressure head, and unsaturated hydraulic conductivity versus pressure head relations) for sediment in various geologic units.

Data on particle-size distribution, moisture retention, and saturated hydraulic conductivity (K_s) have been cataloged for over 284 samples from throughout the Hanford Site, including 12 locations in the 200 East and West Areas (Khaleel and Freeman 1995; Khaleel et al. 1995; Khaleel and Relyea 1997; Freeman et al. 2001, 2002; Freeman and Last 2003; and Khaleel and Heller 2003). Laboratory analyses of the hydraulic properties of samples collected at Hanford have been performed at a number of different laboratories using techniques similar to those described by Klute (1986).

Macrodispersivity estimates for non-reactive species have been estimated using the Gelhar and Axness (1983) equation where the longitudinal macrodispersivity depends on the mean pressure head. Khaleel (1999) estimated a longitudinal macrodispersivity of about 1 m for the sand-dominated facies of the Hanford formation in the 200 East Area. The transverse dispersivities have been estimated as one-tenth of the longitudinal values (Gelhar et al. 1992).

Ward et al.[5] obtained dispersivity estimates via field measurements at a location close to the immobilized low-activity waste site, using potassium chloride (KCl) as a tracer. Analysis of the data provided dispersivities from 1.3 to 7.8 cm for travel distances ranging from 25 to 125 cm. Dispersivity increased with depth to about 0.75 m, after which it essentially became constant. These estimates are for the Hanford formation, but the transport distance within the vadose zone is of very limited extent. Nevertheless, results based on the limited data are consistent with the concept of a scale-dependent dispersivity. Thus, although no data exist on large-scale dispersivities for the vadose zone, it is expected that they will be larger (as is suggested by the longitudinal dispersivity estimate of 1 m) than those based on the small-scale tracer experiment of Ward et al.[5]

Based on a survey of literature, Gelhar (1993) examined the longitudinal vadose zone dispersivities as a function of the scale of the experiment, and found an increase of dispersivity with an increase in scale.

Geochemical Properties. The Hanford formation sediment consists of glaciofluvial materials deposited by cataclysmic Ice Age floods. The mineralogy of this sediment is highly variable, depending on grain size. Gravel-dominated sediment tends to have a high abundance of lithic fragments (mostly basaltic, with some plutonic, metamorphic, and detrital caliche fragments) (DOE 2002). Finer grained

[5] Ward AL, RE Clayton, and JS Ritter. 31 December 1998. "Hanford Low-Activity Tank Waste Performance Assessment Activity: Determination of In Situ Hydraulic Parameters of the Upper Hanford Formation." In Letter to Dr. Fredrick M Mann (CH2M HILL Hanford, Inc., Richland, Washington) from AL Ward (Pacific Northwest National Laboratory, Richland, Washington), dated 31 March, 1999.

facies have proportionally less lithic fragments and more quartz, feldspar, and mica grains. Microprobe analysis of the sand and finer-grained fraction indicates dominance by quartz (18 to 67.1% by weight), plagioclase (5.1 to 41.5%) and microcline (1.8 to 30.1%) (Tallman et al. 1979; Serne et al. 1993; Xie et al. 2003). Other common minerals include amphiboles up to 36.6%, pyroxenes up to 27.5%, Mica (Biotite/Illite) up to 13.1%, and calcite up to 6.5% by weight. Smectite clays represent a few weight percent of the bulk sand fraction (3.3 to 5% [Serne et al. 1993]) and generally dominate the clay fraction (Tallman et al. 1979). Reidel (2004) reported chlorite concentrations generally <3 wt.% except for one sample that had 8 wt.% chlorite.

Hanford formation sediment is typified as having low organic carbon content, generally <0.1% by weight (Serne et al. 1993), and low-to-moderate cation exchange capacity (2.6 to 7.8 milliequivalents per 100 g, Serne et al. 1993). The sediment has a slightly basic pH when wetted (Serne et al. 1993 found the pH of saturation extract ranging from 7.66 to 8.17). Small amounts of detrital calcium carbonate (calcite) are common and can act as a weak buffer.

Much less mineralogy data are available for the Cold Creek unit. Tallman et al. (1979) found that the sediments they referred to as Early 'Palouse' Soil are fairly similar in mineralogy to those of the Hanford formation (25.3 to 29.4% quartz, 15.1 to 18.2% plagioclase, 15 to 17.8% microcline, 7.9 to 10% amphiboles, 1.3 to 12.5% micas), but generally contain more calcite (8 to 8.8%), and lack pyroxenes. Bjornstad (1990) found similar results for these fine-grained sediments, but found that drill cuttings of the carbonate-rich facies (referred to as the Plio-Pleistocene unit) consisted predominantly of calcium carbonate and/or sedimentary rock fragments, with lesser amounts of quartz and feldspars.

Thin beds of caliche along with variable amounts of ferric oxide exist in the 200 West Area in the Cold Creek unit just above the Ringold Formation.

Bjornstad (1990) and Xie et al. (2003) found significant mineralogical differences in electron microprobe and petrographic results between the Hanford and Ringold Formations. The Ringold Formation sediment is generally higher in quartz but lower in plagioclase and pyroxene. Deeper within the Ringold Formation, calcic/ferric oxide cements are often present. This cementation can significantly decrease the permeability of coarse-grained Ringold sediment.

Empirical K_d data for Hanford formation and Ringold Formation sediments are fairly abundant for dilute waste solutions and groundwater (Cantrell et al. 2002, 2003a). Fewer K_d data are available for the Cold Creek unit sediments, or for high ionic strength waste solutions with slightly acidic to slightly basic pH values. A relatively small amount of K_d data exists for the combined high ionic-strength/highly-basic tank liquors for many common radionuclides. These distribution coefficient (K_d) data have been well tabulated by Cantrell et al. (2003a); Kincaid et al. (1998); Serne and Wood (1990); Kaplan and Serne (1995); Kaplan et al. (1996, 1998); and Krupka et al. (2004). In most instances, adsorption appears to be the controlling geochemical process, but neutralization of acid waste by the alkaline sediment and neutralization of basic tank waste can cause precipitation of some contaminant species within the sediment pores. Outside the zone of pH neutralization, adsorption is considered to be the dominant contaminant retardation process in the vadose zone.

The geochemical processes that affect contaminant migration and mineral alteration within the vadose zone sediment for both the 200 East and the 200 West Areas are quite similar. Some difference may occur, because the fine-grained sediment and caliche zones above the Ringold are less prevalent in the 200 East Area.

2.1.1.3 300 Area

The vadose zone beneath the 300 Area ranges in thickness from about 15 m to less than 1 m along the Columbia River.

Hydrostratigraphy. The geology of the vadose zone consists almost entirely of the Pleistocene Hanford formation with a thin veneer of Holocene eolian sand. Thin portions of the Ringold Formation may also extend above the water table in portions of the site. Schalla et al. (1988) described the eolian sand deposits as ranging from 0 to nearly 4.6 m thick. Where missing, these deposits are thought to have been removed by construction activities and often replaced by or covered with construction gravel. The geologic contact with the underlying Hanford formation is quite distinct.

Schalla et al. (1988) described the Hanford formation in this area as poorly sorted sandy gravel with some silt and local sand stringers. The upper portion contains pebble to boulder gravel that becomes finer with depth. The gravel fraction is mainly basaltic in nature, with some quartz-rich and metamorphic clasts. Rip up clasts of semi-consolidated fine-grained Ringold Formation materials up to a meter or more in diameter are also present.[6] The thickness of the Hanford formation varies from 6.4 to 24.7 m.

Gaylord and Poeter (1991) describe the Hanford formation beneath the 300 Area as consisting predominantly of three lithofacies: gravelly sand, sandy granule to pebble-size gravel, and sandy cobble to boulder-size gravel. The finer grained sand facies, comprising only a minor percentage of the 300 Area Hanford formation deposits, are concentrated in the southern part of the area, interwoven with the coarse-grained gravel dominated deposits.

In order to define the spatial distribution of hydrologic properties (particularly in the unconfined aquifer) Gaylord and Poeter (1991) divided the 300 Area sediment into four hydrofacies. These hydrofacies were based on grain size and sorting, and recognized the importance of the fine-grained component to hydraulic behavior.

The hydrostratigraphy of vadose sediment in the 300 Area can be broken into five different units: (1) backfill (or surface cover); (2) eolian sands (if present at the waste site); (3) sand-dominated Hanford sediment; (4) gravel-dominated Hanford sediment; and (5) gravel-dominated Ringold sediment (if present above the water table). Although these sediments are primarily coarse, some silt stringers and fine-grained rip up clasts (some over 1 m in diameter) are present, particularly in the Hanford formation.[6] The location and extent of these stringers is uncertain. Bjornstad described the Hanford formation in the 300 Area is relatively heterogeneous and anisotropic.[6]

Hydraulic Properties and Conditions. Schalla et al. (1988) presented the results of physical (e.g., field moisture content, water retention, particle-size analysis) and bulk geochemical analyses of selected samples. The field water content ranged from <2 to nearly 5% by weight.

---

[6] Bjornstad, BN. 2004. *Sampling and Hydrogeology of the Vadose Zone Beneath the 300 Area Process Ponds*. PNNL-14834 (Unpublished). Pacific Northwest National Laboratory, Richland, Washington.

Geochemical Properties and Conditions. Gaylord and Poeter (1991) provided whole rock geochemical (via x-ray fluorescence) and rare earth/trace element (inductively coupled plasma/mass spectroscopy [ICP/MS]) analyses for the Hanford and Ringold Formations. These data are similar to those for Central Plateau sediment (Xie et al. 2003). Existing sorption data are somewhat limited for the 300 Area (Cantrell et al. 2003b; Brown et al. 2005); therefore, sorption parameters are generally derived from the waste chemistry and existing sorption values from other Hanford Site sediments (similar to the selection process used in the Hanford composite analysis [Kincaid et al. 1998]). Without site-specific geochemical data, values for the geochemical properties (i.e., K_d values) have to be estimated from the sediment type (e.g., grain-size data and the presence of secondary mineralization) and waste type. The mineralogy and contaminant adsorption properties of the Hanford formation sediment in the 300 Area appear to be quite similar to those in the 200 Areas, thus, the available K_d data base (Cantrell et al. 2003b) should be adequate for large scale Hanford assessments that includes the 300 Area.

2.1.2 Events

Various events considered for inclusion in the conceptual model include those that are naturally occurring (e.g., meteoric recharge), those that are manmade (e.g., intentional or unintentional contaminant and water releases), those that occur slowly over a long period of time, and those that represent extreme or unusual occurrences (e.g., 500 year storms, volcanism). A brief synopsis of some of the important types of events that should be considered is presented in the following sections.

2.1.2.1 Recharge Events

The long-term natural driving force for flow and transport through the vadose zone is precipitation that has infiltrated below the zone of evaporation and below the influence of plant roots. Such water eventually flows to the water table, carrying with it any dissolved species. Gee et al. (1992) presented evidence from multiple experiments showing that measurable diffuse natural recharge occurs across the lower elevations of the Hanford Site, with rates ranging from near zero in undisturbed shrub-steppe plant communities to more than 100 mm per year beneath the unvegetated graveled surfaces of tank farms.

The arid climate of the Hanford Site, with cool wet winters and dry hot summers, dictates that recharge potential is greatest in winter (Gee et al. 1992). During winter months, precipitation is greatest and evaporation potential is lowest; therefore, precipitation has the greatest chance to infiltrate into the sediments. This type of recharge can occur as either diffuse or focused recharge. The contribution of each event is site- and event-dependent. Winter water runoff from the higher elevations over frozen ground, while infrequent, can be extensive (e.g., Pearce et al. 1969). Cushing and Vaughan (1988) indicate runoff from higher elevations has a 3.8-year return period. Extensive water runoff does not appear prevalent between Highway 240 and the Columbia River, based on the absence of geomorphic features such as erosion rills and gullies. Undisturbed (natural) sites in the 100 and 200 Areas, typically have gentle terrain and coarse soils that foster diffuse recharge. In contrast, at disturbed waste sites, localized ponding can give rise to focused flow. Observations confirm that local runoff does occur at waste sites when there is a heavy rain or quick snowmelt and where the ground is frozen or compacted as a result of normal waste operations (e.g., Jones 1989; Ward et al. 1997, 2005).

2.1.2.2 Source/Release Events

A second source of water that transports contaminants originates from industrial activities. Historically, millions of gallons of contaminated water were disposed to subsurface infiltration structures and surface ditches and ponds. Most waste water disposal ceased by the mid-1990s. Currently, two facilities are permitted to discharge to the vadose zone: the State-Approved Liquid Disposal (SALD) Facility and the Treated Effluent Disposal Facility (TEDF). Discharges from these facilities are closely monitored and regulated. Numerous discharges of water, collectively called miscellaneous streams, are also permitted but do not need to be monitored unless they exceed certain discharge rates and annual amounts (DOE 1998). These streams include hydrotesting, maintenance, construction, cooling water and steam condensate, sanitary wastes, and storm water control. Other possible sources of additional recharge water are roads, road shoulders, parking lots, power and fire lines, and all structures that do not have precipitation controls. These also fall under the miscellaneous streams permit.

Source events include accidental or intentional discharges of fluids, gases, and contaminants to the environment. Unintentional releases include spills, tank leaks, and distribution pipe leaks. The quantity, quality, duration, and phases of waste or fluid released are generally unknown. Other potential source events include remediation activities that involve the injection of liquid, chemicals, gases, and heat.

2.1.2.3 Discharge/Exit Events

Discharge or withdrawal events include all actions to remove fluids, gases, and contaminants from the environment. These events must be characterized for quantity, quality, duration, and phases of waste or fluid removed. These events include remediation activities such as groundwater pumping, vapor extraction, and heat removal (e.g., cryogenic barriers).

2.1.2.4 Climate Events

Abundant data indicate the Pacific Northwest is warming and that since the beginning of the 20th century, average precipitation has increased 30–40% in eastern Washington.[7] Scientists generally expect average temperatures in the Pacific Northwest to continue to rise, with temperatures increasing by approximately 1.5°C by 2030 and 3°C by 2050. However, predictions regarding change in precipitation are very uncertain.

A change to a drier and/or warmer climate could result in a sparser plant community, a change in the mix of plant and animal species, increased wind erosion and deposition (e.g., re-activated sand dunes), and changes in natural recharge. The stress of this change could allow non-native plant and animal species to supplant native species.

2.1.2.5 Volcanism

Continental flood basalt volcanism and volcanism associated with the Cascade Range have repeatedly affected the Hanford Site during the past 16 million years. However, the recurrence of flood basalt volcanism that produced the Columbia River Basalt Group is not considered a credible volcanic event

[7] Scientific Consensus Statement on the Likely Impacts of Climate Change on the Pacific Northwest. Product of the Impacts of Climate Change on the Pacific Northwest scientific meeting, June 2004. Institute for Natural Resources, Oregon State University, Corvallis, Oregon. (http://inr.oregonstate.edu/reports_atmosphere, html)

(DOE 1988). Volcanism associated with the Cascade Range does have the potential to deposit a few inches of ash on the Hanford Site. Such deposition could potentially reduce evaporation and plant activity for a few years that could increase the natural recharge rate. Probabilistic volcanic hazard studies have been completed by the U.S. Geological Survey (DOE 1988; Scott et al. 1995).

2.1.2.6 Seismicity

Earthquakes and other related events, such as fault rupture, landslides, or differential settlement could potentially affect the integrity of surface or subsurface structures, thus impacting recharge and vadose zone transport. Potential seismic sources determined to be major contributors to the seismic hazard in and around the Hanford Site include: fault sources related to the Yakima Folds, shallow basalt sources that account for observed seismicity not associated with the Yakima Folds, crystalline basement source region, and Cascadia Subduction Zone earthquakes (Reidel et al. 2006). Geomatrix (1996) completed a probabilistic seismic hazard analysis for the Hanford Site.

2.1.2.7 Flooding Events

Natural flooding of the Columbia River is predicted to affect low-lying areas along the river, but not the 200 Areas. Failure of the upriver dams has the potential to affect the entire Hanford Site. The probable maximum flood in the Cold Creek drainage basin could affect the southwestern portion of the 200 West Area (Skaggs and Walter 1981). Under this scenario, water from the flood would reach the Yakima River.

2.1.2.8 Human Disturbance Events

Human activities are capable of degrading surface covers over waste sites and exposing the waste to increased recharge and more direct contract with the biosphere.

2.1.3 Processes

The primary processes governing flow and transport through the vadose zone are complex and interrelated. These processes depend on the physical and chemical nature of the geologic materials that make up the vadose zone (described above) as well as the types, amounts, and compositions of the fluids that occupy the pore spaces (Looney and Falta 2000, p. 13). At a first order level, one can discuss these processes in terms of the mechanisms, rates, and routes by which contaminants move (or are moved) through the vadose zone to the water table (i.e., fluid flow, physical transport, and the capillary fringe) and the fate of the contaminants (i.e., physical and chemical interactions, decay and decomposition).

2.1.3.1 Transport Mechanisms

Gas, aqueous and non-aqueous phase liquids flow in response to phase pressure and gravitational forces. The phases interact with one another in such a way that the flow of each fluid is coupled with flow of the other fluids (Looney and Falta 2000). Chemicals move through the vadose zone by a variety of mechanisms, including advection with the bulk flow of the fluid phases, diffusion and dispersion within the fluid phases, and mass transfer between the phases. Many compounds interact physically or chemically with the solid phase matrix of the vadose zone.

For the majority of contaminants, movement through the vadose zone is contingent on being dissolved within flowing water (i.e., aqueous phase drainage). The flow of water through the unsaturated soils depends on complex interactions between rate of water infiltration, moisture content of the soil, textural heterogeneity, and soil hydraulic properties. Infiltrating water provides the primary driving force for downward migration of contaminants. Perched water zones and lateral spreading may develop when vadose water accumulates on top of low-permeability soil lenses, highly cemented horizons, or along contrasting lithofacies boundaries (e.g., contacts between fine-grained horizons and underlying coarse-grained horizons). Unsaturated hydraulic conductivities may vary by several orders of magnitude depending on the water content of the soils.

Some contaminants (as well as water) are volatile and move in the gas phase. The bulk of this movement is diffusional, but convective flow can occur near the soil surface and near open boreholes in response to barometric changes. Remediation activities (e.g., vapor extraction, thermal treatment) can also affect local convective gas flow.

The geothermal gradient has a small but steady impact on the movement of water upward through the vadose zone. Enfield et al. (1973) used field measurements of temperature and matric (matrix) potential at a site about 1 km to the south of the 200 East Area to calculate an upward water flux of 0.04 mm/year.

2.1.3.2 Transport Rates

Fluids such as water move through the vadose zone at rates determined by the hydraulic, thermal, and vapor gradients and the relevant properties of the sediment. For many applications, common assumptions include a static air phase, isothermal conditions, and no density effects. With these assumptions, flow rates are calculated using Richards' equation with gravity and capillary potential gradients. When these assumptions are not appropriate (e.g., organic liquids, vapor flow, hot saline tank waste), more sophisticated equations are used to calculate rates.

The rate of diffuse recharge at a particular location is influenced by four main factors: climate, soil, vegetation, and topography. Other factors can significantly impact recharge by affecting one or more of the main factors. These other factors include soil development, animal activity, fire, water and wind erosion and deposition, plant community changes, surface flow from other areas, disturbance, and human structures (e.g., roads, buildings). The rate of recharge at each waste site will depend on the design of the surface cover. Plants and animals live within the upper 1 to 2 m of soil, and some plant roots can reach depths of 3 m. Surface covers can be designed to protect against such intrusion by including biobarriers, which are layers that resist biotic intrusion. For thinner cover designs, the biobarrier may be closer to the surface and more susceptible to degradation. Intrusion of surface covers by plants and animals can create macropores that could become conduits for surface water to flow into the soil much deeper than expected. Inadvertent intrusion by humans can result in surface depressions that could become areas of focused recharge when surface runoff occurs.

Some of the liquids disposed or leaked to the vadose zone had properties that differed significantly from the properties of pure water, and their rates and routes of movement through the vadose zone may differ as well. The specific gravity of waste leaked from single-shell tanks ranged from 1.1 to 1.65, which could enhance the transport of contaminants. Increased density has been demonstrated to elongate contaminant plumes vertically and reduce lateral spreading caused by stratigraphic variations in hydraulic properties (Ward et al. 1997). The properties of these fluids will change as contaminants are diluted, sorbed, or the fluid evaporates into the sediment air space.

Organic fluids were also disposed at Hanford. The movement of these fluids through the vadose zone and groundwater aquifer is complicated by multiphase flow of the organic non-aqueous phase liquid, the dissolved phase in water, and the vapor phase in the vadose zone air space. The movement of organic fluids can be enhanced if their density is much higher than the density of water. That is the case for the primary organic fluid contaminant at Hanford - the dense non-aqueous phase liquid, carbon tetrachloride. Between 1955 and 1973, roughly 577 to 922 metric tons of carbon tetrachloride was disposed to three subsurface infiltration facilities at the Hanford Site (Rohay et al. 1994). The current groundwater plume containing concentrations above 0.5 mg/L covers an area of about 11 km^2 (Hartman et al. 2005). Soil-vapor extraction and pump-and-treat technologies are being used to prevent further movement of the plume and reduce contaminant mass, and have been effective in reducing the area of highest concentrations. However, efficiencies of the vapor extraction activities have decreased, and carbon tetrachloride concentrations above the remedial action goal have been detected north of the Plutonium Finishing Plant, as well as deeper in the aquifer beneath the eastern portion of the 200 West Area. The behavior of carbon tetrachloride in the subsurface and in the vadose zone is poorly understood and requires additional characterization and assessment to determine the dominant processes governing its fate and transport.

The rate of gas movement in the vadose zone is affected by the magnitude of any temperature gradients. The vadose zone across the entire Hanford Site experiences temperature changes due to diurnal and seasonal temperature changes at the soil surface. The magnitude of the temperature changes diminishes with depth; at 10 m, the seasonal change appears to be less than 1°C. Near-surface temperatures appear to have a minimal effect on recharge rates if the rates exceed 10 mm/year, but they could be important when rates are less. In addition to the near-surface temperature changes, a steady upward geothermal gradient exists that drives gas (and water vapor) upward. The elevated temperatures of the leaked waste from the single-shell tanks and previous operational discharges may have induced local movement of both liquids and vapor.

The formation of colloids and occurrence of colloid-facilitated transport of contaminants were identified by the Expert Panel as a potentially important processes affecting vadose zone transport (DOE 1997). At waste sites that received large-volume discharges or highly concentrated waste from leaking tanks, conditions may have existed for both colloid formation and colloid-facilitated transport. However, data are insufficient to adequately characterize the potential for colloidal transport. Zhuang et al. (2004) found that several interacting mechanisms might be involved simultaneously during colloid transport, but that their importance depends on the chemical and physical properties of the colloids and transport media as well as the environmental conditions. Current understanding of colloid-soil interactions and the ability to predict transport of colloids in natural subsurface media are limited. However, for most waste sites at Hanford, the low water contents and relatively simple geochemistry are not conducive to colloid formation or colloid-facilitated transport.

2.1.3.3 Transport Pathways

The predominant direction for contaminant movement in the vadose zone is downward, due to gravity. Variations in the hydraulic properties and the presence of impeding features such as bedding interfaces, caliche layers and disposal facilities can locally alter and redirect the movement laterally.

Relatively simple stratigraphic layering can give rise to complex water content distributions and enhanced lateral spreading that impedes vertical migration of contaminants.

Various preferential pathways such as discordant clastic dikes and fractures are capable of concentrating or contributing to phenomena such as fingering and funnel flow. Preferential flow has been documented along poorly sealed well casings at the Hanford Site (Baker et al. 1988) and transport along clastic dikes may be potentially important (DOE 1997). Murray et al. (2003) suggest that clastic dikes might serve as a conduit for more rapid movement of mobile contaminants to the water table, but only under a restricted set of recharge (or leak) conditions. The relatively high content of reactive minerals, especially clay, within the dikes, suggests that movement of reactive contaminants may be restricted within the dikes, even if the dikes provide a fast path for downward movement of water.

Because of the nature of some waste, local routes of contaminant movement will vary. The Vadose Zone Expert Panel (DOE 1997) stated that the likely mode of transport for leaked or disposed tank waste in the Hanford geology is along preferential, vertical, and possibly tortuous pathways. They identified possible preferential flow caused by:

- Hot (177°C) caustic tank waste leaking into the vadose zone, flashing to steam, fracturing the matrix, and enlarging pores
- Hot (177°C) caustic tank waste leaking into the vadose zone with a self-healing nature, creating geothermal convection systems that could move contaminants upward with the hot alkaline slurry reacting with Hanford sediment
- Dissolution of siliceous sediment by the hot and alkaline tank waste, which may increase porosity in some places (by dissolution) and lower porosity in others (by precipitation)

2.1.3.4 Contaminant Behavior

The fate of contaminants in the vadose zone depends on geochemical conditions, the speciation of the contaminant, residence time, and microbial activity.

Sediment has the capacity to sorb most contaminants from solution. The amount of sorption is a function of many factors, including mineral surface area and type, contaminant type (speciation) and concentration, overall solution concentration, pH, Eh, and reaction rates for the controlling adsorption or precipitation, dissolution, and hydrolysis reactions.

Some contaminants do not sorb at all (i.e., soluble anions such as nitrate, chromate, and protectonate) and are moved along with the bulk solution. The movement of contaminants through the vadose zone is affected by their sorption in the far-field and sometimes by complex dissolution/precipitation reactions between waste liquids of extreme pH and the slightly alkaline sediment in the near field. Sorption delays downward movement of the contaminant and allows degradation processes to occur (e.g., radioactive decay) and, for some, irreversible incorporation into the sediment. Sorption can be described using a simple linear relationship (i.e., a distribution coefficient or K_d) that is determined empirically. Values of K_d have been measured for a wide range of contaminants and waste types at the Hanford Site (Kincaid et al. 1998). The K_d approach is applicable for conditions at Hanford where the contaminant concentrations are low and the chemistry is relatively constant. However, conditions near some waste sources are so variable due to the strong influence of the waste that the K_d approach may not be applicable. This is the case for hot, highly concentrated tank wastes in contact with Hanford sediment. The general consensus is that the presence of this type of waste will likely decrease the sorption of contaminants (e.g., cesium-137). The net effect will be an increase in contaminant mobility until conditions in the sediment pore water (e.g., lower concentrations via waste dilution) become more appropriate for the K_d approach. The complex reactions between the sediment and the highly acidic and (more importantly for Hanford) highly basic wastes are currently under study. Each specific Hanford assessment will have to determine if more complex chemical reaction processes should be considered to increase the accuracy of transport models for key contaminants.

Contaminants that exist in the gas phase (e.g., radon, carbon-14, carbon tetrachloride) are subject to atmospheric venting and remediation activities such as vapor extraction. Carbon-14 as carbon dioxide also reacts strongly with alkaline earth cations to form insoluble carbonates at neutral to basic pH values. Further it reacts with industrial cement, a common constituent of waste form containers and structures used in many solid waste burial grounds, to form carbonate precipitates (Krupka and Serne 1996; Serne et al. 1992).

Contaminants near the soil surface are subject to animal and plant uptake. Plants and animals live within the upper 1 to 2 m of soil, and some plant roots reach depths of 3 m or more. Waste present within this zone is subject to ecological uptake and dispersal above ground.

Contaminants that are consumed by microbes are subject to degradation into other compounds that may or may not be considered contaminants. This degradation process depends on the presence of a microbial population that is capable of degrading a given contaminant and on the availability of any additional nutrients that may be required for the microbes to be effective.

Sometimes the water is consumed, rather than the waste. Waste forms, such as the immobilized low-activity waste, undergo a corrosion process that consumes water. In a dry disposal, this consumption process will create a water vapor gradient that draws vapor toward the waste form.

2.2 Uncertainty and Unresolved Technical Issues

Unresolved technical issues and sources of uncertainty affect the ability to predict the behavior of contaminants in the vadose zone. These include property representation, scale effects, spatial and temporal resolution of data, preferential flow, funneled flow, colloid transport, density effects, and thermal effects. Many of these issues are not specifically addressed in this data package but may be addressed in future revisions after resolution of key issues by the science and technology program.

Discussions of outstanding issues are generally focused on performance/risk assessment under future conditions and future releases. However, there are also site characterization and laboratory study needs related to interpreting observations from past tank leaks, spills, and nearby intentional discharges. Interpretation of site characterization data is important to estimate existing inventories for use as initial conditions, and also to demonstrate the validity of our understanding and the predictive ability of the models used for flow and transport of contaminants. Interpreting the mass and distribution of contaminants is difficult because much of the history and character of the leaks, spills, and water losses is difficult to characterize. The resulting uncertainties will hamper the ability of models to predict observed distributions of contaminants in the vadose zone, even if the distributions are well known.

2.2.1 Property Representation/Parameterization

The physical, chemical, and hydraulic properties of the various solids, liquids, and gases in the subsurface are typically represented within numerical simulators using mathematical functions. The form of these functions, and their resulting suite of parameters, change with increased process knowledge and characterization information. Good examples are the water retention and hydraulic conductivity properties of the sediments. The parameters for these functions are determined by fitting them directly to data or by inferring them from physical properties. Many functions have been proposed to represent hydraulic properties. One of the most commonly used hydraulic models is the van Genuchten-Mualem model (Kosugi et al. 2002). A standard practice is to fit the van Genuchten retention model to retention data and the saturated conductivity value and use the resulting parameters with the Mualem conductivity model to predict unsaturated conductivity values. In this standard approach, the "*m*" parameter is fixed equal to 1-1/*n* and the pore interaction term is fixed at 0.5. This approach has been shown to work for a number of soils, but it is not universally applicable and, for many soils, it becomes increasingly less applicable as the soil dries out (e.g., Stephens 1992; Khaleel et al. 1995). Predictions of dry-end conductivity can be improved by including one or more measured values of unsaturated conductivity in the fitting process and excluding the saturated conductivity value. Improvements can also be obtained by treating the '*m'* parameter as independent and fitting both '*m'* and the pore interaction term. The drawback to increasing the number of fitting parameters is the possibility of obtaining a non-unique set of parameter values during the fitting process. Some soils have unique structural features such as fractures and macropores that make them less amenable to characterization using a single function like the van Genuchten function. For such cases, Durner (1992) and others propose multiple functions, either linked or combined. The resulting fits to the data are better, but the number of parameters is so large that these techniques are not often used. To date, nearly all analyses at Hanford have used a single van Genuchten-Mualem function to represent hydraulic properties. Many analyses have used the standard approach of fitting to retention and saturated conductivity data, but a portion have included an unsaturated conductivity value in the fitting process (Khaleel et al. 1995). As more knowledge is gained and the original data evaluated more fully, the parameter values can be revised and uncertainty in the conductivity predictions can be reduced.

2.2.2 Effects of Scale

One of the greatest challenges facing Hanford assessments is adequately understanding the effects of spatial and temporal scale related to the processes, observations, modeling, and purpose of the assessment. Little is known about how vadose zone processes interact at various spatial and temporal scales, which processes are dominant, and how these interactions can be related to and interpreted from existing field and/or laboratory observations. It is also difficult to determine what must be measured and modeled to assess both risk, and the validity of the models to assess the risk, within useful uncertainty bounds.

In past assessments, the hydrogeologic units were generally assumed to be homogeneous and isotropic in character. In reality, these units display complex sedimentary structures at various scales. The effects of these complex structures are known to enhance lateral spreading and impede downward migration. However, the assignment of physical properties (e.g., effective permeability, porosity, moisture retention characteristics, anisotropy, dispersivity) to properly account for these effects in larger modeled units is still the subject of debate and uncertainty. The effects of small-scale structures on large scale flow and transport parameters needs to be assessed, in order to understand the degree of uncertainty, make appropriate choices for bounding calculations and determine the effects of simplification on assessment predictions.

Scaling and volume averaging tools are needed that can help determine effective values of parameters from small scale (often disturbed) borehole samples in conjunction with soft information on the fine-scale structure of these sediments. Data are lacking for much of the vadose zone where subsurface contamination is present so scale-up and volume averaging will be required. The justification for upscaling and averaging methods will need to be evaluated either deterministically or by a probabilistic assessment that clearly reflects the uncertainties involved in the analysis.

2.2.3 Spatial and Temporal Resolution of Site Data

Our understanding of the nature and extent of various hydrogeologic units beneath a given waste site is primarily based on borehole samples. The resolution of these interpretations are generally about 1.5 m vertically and tens of meters or more horizontally, with the minimum discernable thickness of fine-grained units at about 15 cm. The internal structure of sedimentary units sampled during drilling is often disrupted or lost due to the drilling and sampling process. Vertical borehole data alone cannot provide the quality and quantity of data needed for accurate analysis of vadose zone transport, and much of our knowledge on the internal structure and heterogeneities of these units comes from extrapolation of qualitative examination of 'representative' outcrops. At the Hanford Site, only a few limited geostatistical studies have quantitatively described the internal structure and heterogeneities in outcrop and core samples. Thus, in many cases there is a lack of site specific data to support the development of detailed three dimensional geologic models for a given waste site.

2.2.4 Preferential Flow

Preferential flow (which may reduce the cross-sectional area of flow and bypass much of the unsaturated medium) has received increased emphasis recently. There has been some concern that preferential flow may be important for contaminant transport associated with tank-farm releases and/or other lower-volume discharges where mobile constituents remain in the vadose zone. It is important to differentiate between structurally controlled flow (e.g., funnel flow) and unstable flow. Structurally controlled flow occurs when the structure of the porous medium or the presence of a buried structure (e.g., tank) routes the water along a 'preferential path.' Unstable flow or wetting-front instability occurs during infiltration when an instability develops at the fluid-fluid interface (e.g., water-air, dense nonaqueous phase liquid-water). While there has been increased interest in preferential flow, Scanlon et al. (1997) suggest that piston-like flow (predominantly uniform flow through the unsaturated matrix) is the dominant flow mechanism at arid sites with unconsolidated sediments.

2.2.4.1 Structure Controlled Flow

Preferential flow is greatest when the preferred flow path consists of a series of connected large pore spaces. Because flux is proportional to the fourth power of the pore radius, large pores transmit very large quantities of fluid, but only when the pores are filled. Thus, water saturation determines the effectiveness of preferred pathways to conduct water: when water contents are at or near saturation, large pore pathways can conduct relatively higher quantities of water than the surrounding smaller pore materials. When water contents are low (dry vadose zone), preferred pathways with large pores do not conduct water because they cannot fill with water.

Whenever there are variations in sediment properties, the potential exists for water flow to be affected and perhaps funneled into preferential pathways. The capillary barrier effect is a good example. The arrangement of fine textured material over coarse-textured material delays the downward migration of water and allows it to be evaporated and transpired back into the atmosphere. The net effect is that deep drainage is reduced. Such textural breaks are used for surface covers, but they also occur naturally throughout the vadose zone. When such 'capillary breaks' are sloped, the water retained above the break can move laterally. This feature has been used to improve the performance of waste disposal facilities in the vadose zone (Frind et al. 1977). Scanlon et al. (1997) indicated that while funneled flow has not been found in arid settings, lateral flow in geologically layered materials may resemble funnel flow, where inclined beds and capillary barriers result in lateral flow.

Clastic dikes and unsealed boreholes may potentially act as preferential (macropore) flow paths for saturated flow by providing large connected pore spaces. These discordant features are of particular interest because they cut across the normally horizontally layered sedimentary sequences. The actual influence of clastic dikes on flow is somewhat uncertain: although some portions of clastic dikes have large connected pore spaces, other portions have fine-grained clay skins that may actually limit high rates of lateral flow (Murray et al. 2002). Wood et al. (1995, 1996) and Jacobs (1999) suggested that both clastic dikes and unsealed boreholes are insufficiently large and continuous to be significant to the overall contaminant mass transport through the vadose zone. A recent field study of clastic dikes suggested that dikes are not important preferential flow and transport pathways when the drainage flux was less than 100 mm/year (Murray et al. 2003). Thus, these potential pathways are not considered dominant enough to be incorporated into large scale assessments.

2.2.4.2 Unstable Flow

Unstable flow fingering may develop when a saturated fine-grained textured soil overlies a coarse-grained soil. Water accumulates in and over the fine-grained unit until the thickness of the perched water provides sufficient driving force to allow the water to 'drip' into the large pore spaces of the underlying coarse-grained sediment. This situation results in fingers with inner cores that are saturated surrounded by an unsaturated layer. However, fingers that are clearly caused only by the instability of a wetting front have been primarily observed in the laboratory. Experiments by Yao and Hendrix (1996) found that at low infiltration rates, wetting fronts stabilize and capillarity dominates over gravity; there is no mechanism to cause instability, and no fingers form. They also found an increase in the number, and decrease in the size, of fingers as the infiltration rate increased. Similar studies are needed to understand finger formation and its scale when the fluid properties differ from those of water at ambient temperatures (e.g., high density fluids, hot liquids). The unstable flow or fingering observed in laboratory experiments may be an artifact of the uniform, horizontal, and homogeneous layers (e.g., glass beads) used in the experiments, and the phenomena may not occur in natural layered geologic media. Scanlon et al. (1997) also suggest that unstable flow should be negligible in porous media in many arid regions because of the dominance of capillary and adsorptive forces over gravity forces in these areas.

2.2.4.3 Temporal Effects

In dry environments, deep vadose zone flow (i.e., recharge to the aquifer) can be dominated by the extreme transient events (e.g., snowmelt and run-on events) if they result in saturated or nearly saturated conditions in regions with fast preferential pathways. Proper assessment of deep recharge and effects related to enhanced transport down borehole annular space or any near surface preferential pathways and/or man-made structures must be addressed at a higher resolution both spatially and temporally. Interactions of spatial and temporal variations (particularly the extreme events) with sediment heterogeneity and interfaces (particularly sloping interfaces with breaks or holes) to change pathways and rates, needs more investigation. The interactions of geologic complexity with the spatial and temporal complexity of adjacent, interacting sources (e.g., water line leaks, fire hydrant flushing, adjacent cribs) have also not been adequately addressed.

2.2.4.4 Funneled Flow Coupled with Colloid Transport

The Tank Waste Remediation System (TWRS) Expert Panel (DOE 1997) hypothesized that structure controlled flow coupled with colloid transport was the most likely mechanism to move large quantities of contaminants that normally have limited mobility (such as cesium-137). This combination of processes needs more investigation. Research is currently underway to investigate the impact of colloids on contaminant transport in Hanford sediment (e.g., Zhuang et al. 2003, 2004; Cherrey et al. 2003).

2.2.5 Temperature and Density Effects

Other important issues raised by the TWRS Expert Panel include interaction between hot (177ºC) caustic waste from tank leaks and the geohydrologic system through time and the effects on fluid movement and contaminant transport processes. Many of the heat effects related to the high temperatures of the tanks, elevated temperatures surrounding the tanks, and self-heating nature of the leaked waste have yet to be investigated and resolved.

The high heat load of the single-shell tanks coupled with vapor transfer could potentially set up a system whereby soluble briny waste, leaked from the tank, could migrate toward the heat source (e.g., center of the bottom of the tank). Pruess et al. (2002) found that for temperatures in excess of the boiling point, the dominant mechanism for flow, heat transfer, and solute transport is a vapor-liquid counter flow 'heat pipe' process. The possibility of a heat pipe being created needs to be further investigated, as does the nature and scale of the effect. In addition, the possibility of high heat lowering infiltration rates needs to be investigated.

Density effects have been investigated to a limited degree (e.g., Ward et al. 1997). These studies did not fully investigate the interactions of density with temperature, unstable flow effects, structurally controlled preferential flow (e.g., clastic dikes), colloidal transport, and/or waste-soil chemical and physical effects to determine inter-relationships and importance among the processes.

2.2.6 Geochemical Processes

Geochemical processes in the vadose zone are not well quantified. Field studies are currently in progress on representative contaminated sites to improve the conceptual models for waste interactions, and on contaminant transport processes; directed laboratory research is underway to clarify details of the chemical processes. The goal of these studies is to evaluate the key short- and long-term processes controlling the key risk driving contaminants. Processes to be quantified include adsorption, mineral precipitation and dissolution, bio-mineralization, matrix diffusion, pore plugging, and colloid formation and transport.

Another activity in which geochemists contribute is through development of a credible reactive transport model. At the present time, large scale assessments will likely rely on the K_d construct to describe all contaminant retardation reactions/processes. More sophisticated descriptions of contaminant/ sediment interactions may be required for some future assessments.

Field studies to characterize the near-field geochemical environments at representative inactive liquid waste disposal sites and past leaks at single-shell tanks focus on 'extreme-pH' chemical environments, including acidic process liquids and highly alkaline tank liquors. The latter were high temperature fluids, and both sometimes contained organic complexing agents. Our knowledge base is most sparse for the extreme-pH wastes that are far from chemical equilibrium with the sediments. Interactions of highly reactive solutions with sediments can be accompanied by significant mineral dissolution and precipitation. Such large changes in mass between phases can significantly change pore structure and hydraulics (permeability) of vadose zone sediments. Formation and sequestration of colloids may also be most active in this dynamic zone. This highly interactive near-field zone merits detailed study to improve current modeling approaches that rely on the simplistic K_d construct. More detailed discussions of the planned field characterization and focused laboratory studies can be found in DOE (1998, 2000a) and individual project work plans such the Office of River Protection's (ORP's) *Phase I RCRA Facility Investigation/Corrective Measures Study Work Plan for Single-Shell Tank Waste Management Areas* (DOE/RL 2000b) and the *Immobilized Low-Activity Waste Multi-Year Statement of Work* (LMHC 1999).

2.3 Technical Basis and Approach for Vadose Zone Modeling

Kincaid et al. (2004) describe the basis and technical approach for a large-scale Hanford assessment, to be conducted using SAC (Kincaid et al. 2000; Bryce et al. 2002; Eslinger et al. 2002 a, b). SAC consists of a set of modules (models and data) that allow the collective impact of all the waste that will remain at the Hanford Site to be estimated. These modules include: Inventory, Release, Air Transport, Vadose Zone Transport, Groundwater Transport, Soil, River, Riparian Zone, and Risk/Impact Modules. These modules have been organized to simulate the transport and fate of contaminants through the environment. In general, inventory feeds to release, which feeds to the atmospheric, vadose zone, groundwater, and Columbia River pathways. The atmosphere, groundwater, Columbia River and riparian zone modules provide media-specific concentration estimates used in the risk and impact assessment.

Kincaid et al. (2004) identified 1,052 waste sites from the 2,730 Waste Information Data System (WIDS) sites and several existing and future storage sites for inclusion in a large-scale Hanford assessment.[8] They indicated that analysis of liquid discharge and unplanned release sites would be conducted on a site-by-site basis whenever inventory and release data permit, since the superposition of liquid discharge to a single soil column results in non-representative contaminant migration and release from the vadose zone. Solid waste burial grounds would be simulated at the burial ground scale; for example, individual burial trenches would be aggregated for a single burial ground. The inventory of solid waste disposal will be increased over time until all burial grounds are closed. Vadose zone flow and transport simulations for the assessment would be based on the following: 1) hydrogeologic profiles and properties for selected areas, 2) estimates of deep drainage rates that drive contaminant migration, 3) estimates of geochemical reactions between contaminants and the soil and sediment of the vadose zone profile, and

[8] Originally 974 of 2,730 Waste Information Data System (WIDS) sites were identified for inclusion in the large scale Hanford assessment. Further work identified 48 more waste sites bringing the total to 1,022. Subsequent reviews identified an additional 30 sites that have been included, many of which account for offsite transfers of waste and nuclear material. This brings the total to 1,052.

4) waste inventory and release projections. The first three of these data types are the focus of this data package. The fourth, waste inventory and release projections, is the subject of other data packages.

The behavior of contaminants in the vadose zone is complex and subject to many unresolved issues and levels of uncertainty. The options for numerically simulating this behavior can be equally as complex. Table 2.1 attempts to summarize some of the important features and processes that can be incorporated into the simulations, depending on the complexity of the model. On a large scale, and for the purposes of simulating the release of mobile contaminants from the vadose zone to the groundwater, the vadose zone can be simulated in a fairly simple manner to account for the most dominant features, events, and processes, as highlighted in Table 2.1.

Table 2.1. Options for a Large-Scale Hanford Assessment (after the Preliminary Concepts Document)[a]

Model Type	Dimensions and Hydrogeology	Transport Processes	Scale and Temporal Factors	Degradation and Decay Processes
Simple	• 1-D • 4-6 Horizontal Layers • Homogeneous, Isotropic	• Aqueous Phase Transport • Linear Sorption Isotherm (K_d)	• Step-Wise Steady State • One Site per Area per Waste Type	• Radioactive Decay • Biological Pseudo-Decay
Semi-Complex	• 2-D • Up to 10 Sloping Layers • Homogeneous, Isotropic	• Density and Temperature Effects • Linear Sorption Isotherms (K_d values) • Peak Arrivals	• Long Term Climate Changes • Sites on Finer Grid	• Radioactive Decay • Biological Decay
Complex	• 2 and 3-D • Numerous Complexly Formed Layers • Heterogeneous and Anisotropic • Preferential Flowpaths • Chemically Enhanced Permeability	• Multiphase Transport • Colloidal Transport • Barometric Effects • Reactive Transport • Wind and Water Erosion	• Episodic, Seasonal Variations • Long Term Climate Changes • Scale on Site-Specific Basis • Near and Long Term	• Radioactive Decay • Biological Decay • Inorganic Decay (Oxidative/ Reductive)

(a) *Groundwater/Vadose Zone Integration Project Preliminary System Assessment Capability Concepts for Architecture, Platform, and Data Management*. September 30, 1999. http://www.hanford.gov/cp/gpp/modeling/sacarchive/9-30rpt.pdf
(b) Shaded area identifies the model type options selected for a large-scale Hanford Assessment.

2.3.1 Features

The physical architecture (e.g., geology, hydrologic properties, geochemical properties) of the vadose zone and its principal transport pathways varies by location. Because the geometry and configuration of hydrostratigraphic facies and heterogeneities are not well defined, the effects of these features will be captured via sensitivity or uncertainty analyses, within the context of larger hydrostratigraphic units. The omission of small-scale stratifications and variations in texture will likely lead to an underestimation of lateral spreading.

The limited quantity of site-specific data requires that values for the hydraulic properties be estimated from existing hydraulic property values provided by Freeman et al. (2002) and Freeman and Last (2003).

For a large-scale assessments, the relations between moisture content, pressure head, and unsaturated hydraulic conductivity are assumed to be nonhysteretic and representable using the van Genuchten (1980) and Mualem (1976) functions.

Predictions of unsaturated conductivity can be markedly improved by simultaneously fitting van Genuchten parameters to retention and unsaturated conductivity data (Kosugi et al. 2002). A subset of the Hanford samples were analyzed for unsaturated hydraulic conductivity. Because unsaturated conductivity data were unavailable for a majority of samples, the parameter database contains only those parameters determined from retention data, to provide an internally consistent set of parameters. Setting up the database in this manner allowed the generation of statistical distributions that support a Monte Carlo approach for assessments. For future assessments, methods are being developed to incorporate and benefit from actual unsaturated conductivity data. Just as important, methods will also be developed to scale lab-derived parameters to field-scale as well as methods to use field-derived parameters.

Again, with very limited site-specific geochemical data, values for the geochemical properties (i.e., K_d values) must be estimated from the sediment type (e.g., textural data and the presence of secondary mineralization) and waste type, based on data from existing laboratory measurements (Cantrell et al. 2003a). For most circumstances, the linear sorption model approach is adequate for modeling transport, especially for the far-field and low impact sites, where geochemical conditions remain fairly constant and contaminant loading is low (Cantrell et al. 2003b). However, where large changes in chemical conditions occur within a small spatial zone (e.g., where highly concentrated, alkaline or acidic wastes have been discharged), a more sophisticated approach to surface adsorption modeling may be warranted. A simplified way to account for changes in mobility is to use a multitude of different K_d values to represent the sorptive capacity of the soil as waste becomes more diluted or buffered by meteoric recharge and waste-sediment interactions (Kincaid et al. 1998 and Bryce et al. 2002).

2.3.2 Events

Events that could be considered in the implementation model for a large-scale Hanford assessment include those that are: naturally occurring (e.g., meteoric recharge), manmade (intentional or unintentional contaminant and water releases), long-term normally occurring, and those that represent extreme or unusual occurrences (e.g., 500 year storms, volcanism). Of primary importance to the composite analysis are the source release events that discharged large volumes of waste water to the vadose zone, and the deep drainage (recharge) of meteoric water. Climate change and disruptive events such as volcanism, earthquakes, flooding, or human disturbance are currently outside the scope of large-scale Hanford assessments (Kincaid et al. 2004).

2.3.3 Processes

For the majority of contaminants, movement through the vadose zone is contingent on dissolution in flowing water. The primary long term source of flowing water is precipitation that has infiltrated below the zone of evaporation and below the influence of plant roots. Such water eventually flows to the water table, carrying dissolved species. Other transport mechanisms, including gaseous transport, temperature gradients, and colloidal transport, are not considered significant to large-scale Hanford assessments.

The rate of recharge (deep drainage) at a particular location is influenced by climate, soil, vegetation, topography, springs and streams, animal activity, fire, water and wind erosion and deposition, plant community changes, disturbance, and human structures (e.g., roads, buildings). For most applications, flow rates through the vadose zone can be calculated using Richards' equation with gravity and capillary potential gradients providing the dominant forces.

Zhuang et al. (2004) found that Hanford data are insufficient to adequately characterize the potential for colloidal transport. Although the formation of colloids and occurrence of colloid-facilitated transport of contaminants may be a potentially important process for the vadose zone (DOE 1997), the low water content and relatively simple geochemistry at most Hanford waste sites are not considered conducive to colloid formation or colloid-facilitated transport.

Preferential pathways such as clastic dikes and fractures are capable of concentrating or contributing to phenomena such as fingering and funnel flow. Local routes of contaminant movement will vary by waste type. The Vadose Zone Expert Panel (DOE 1997) concluded that a likely mode of transport for leaked or disposed tank waste in the Hanford geology is along preferential, vertical, and possibly tortuous pathways. However, detailed analyses of tank farm plumes and vadose zone transport field studies suggest that these mechanisms are not significant contributors to groundwater contamination under normal recharge environments (i.e., fluxes <100 mm/year) (Knepp 2002; CH2M HILL Hanford Group 2002; Murray et al. 2003). Scanlon et al. (1997) suggest that the dominant flow mechanism in unsaturated unconsolidated fluvial sediments at arid sites is predominantly 'piston-like' flow.

The fate of contaminants in the vadose zone depends on geochemical conditions, the speciation of the contaminant, residence time, and microbial activity. Sediment has the capacity to sorb most contaminants from solution. The amount of sorption is a function of many factors, and some contaminants do not sorb at all. Sorption can be described using a simple linear relationship (i.e., a distribution coefficient or K_d) that is determined empirically. The K_d approach is applicable for most analyses at Hanford where contaminant concentrations are low and the chemistry is relatively constant. In environments where wastes are highly concentrated, contaminant mobility may be strongly influenced by the chemical components of the wastes, resulting in decreased sorption of normally sorbed contaminants (e.g., cesium-137). However, as the wastes migrate through the subsurface, contaminant concentrations in the sediments decrease until they eventually reach the range appropriate for the K_d approach.

Contaminants that can, under certain conditions, exist in the gas phase (e.g., radon, carbon-14, carbon tetrachloride, iodine-129) are subject to atmospheric venting and vapor extraction. Carbon-14 as carbon dioxide also reacts strongly with alkaline earth cations to form insoluble carbonates at neutral to basic pH values, and can also react with industrial cement (Krupka and Serne 1996; Serne et al. 1992). Contaminants near the soil surface are subject to animal and plant uptake and dispersal within the aboveground environment. Contaminants can also be consumed by microbes, degrading into other compounds that may or may not be considered contaminants. In some cases water, rather than waste, is consumed. For example, immobilized low-activity waste undergoes a corrosion process that consumes water and will create a water vapor gradient that draws vapor toward the waste form.

2.4 Implementation

The scale and complexity of an assessment that can cover the entire Hanford Site together with the existing limitations on characterization data and fate and transport processes, necessitates simplification of the site features, events, and processes to permit timely results. Thus, the simplified model approach shown in Table 2.1 was selected for large-scale Hanford assessments.

Implementation of this modeling approach is schematically illustrated in Figure 2.5. The primary transport mechanism to be simulated is aqueous phase transport represented by 'piston-like' flow through porous media of the vadose zone, with radiological decay simulated using first order decay models.

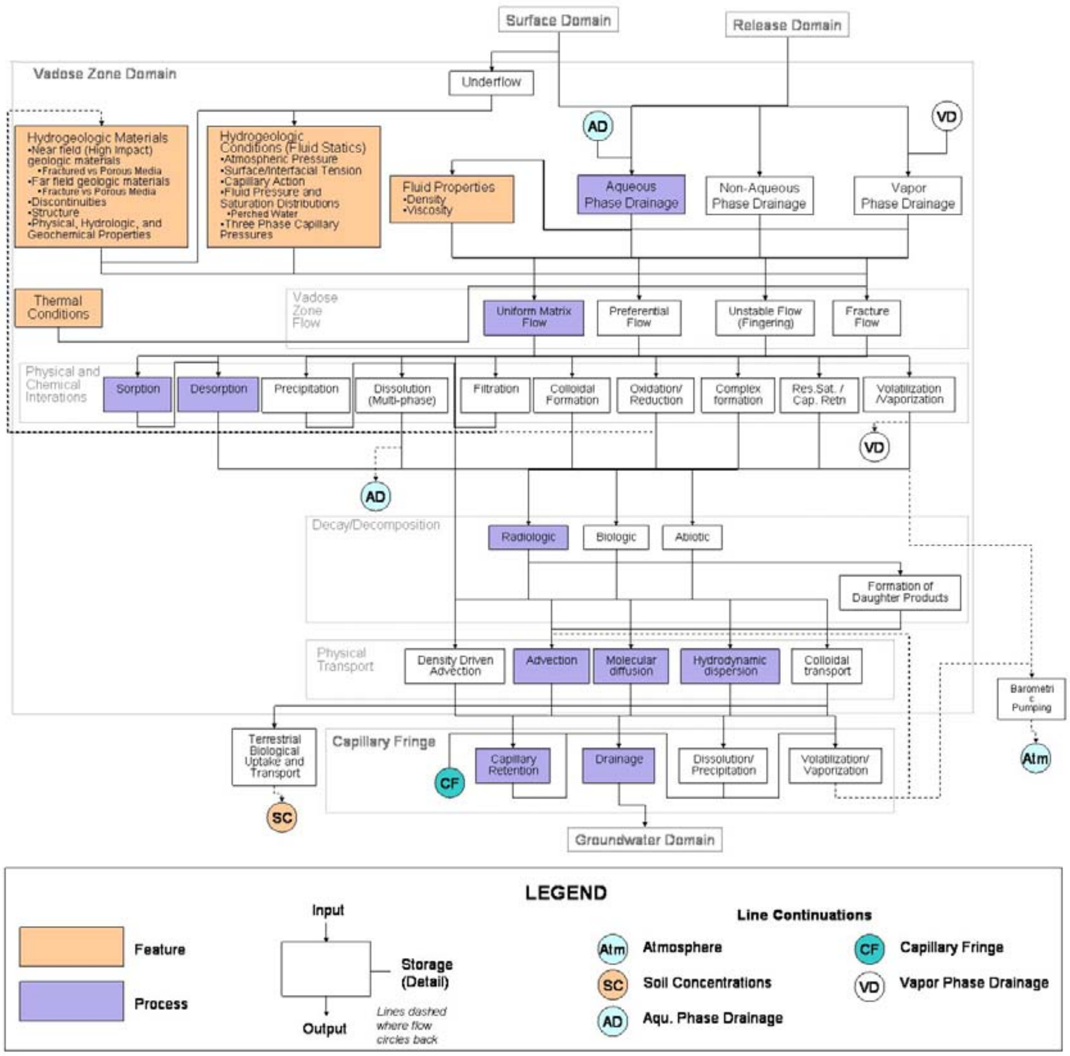

Figure 2.5. Schematic of Vadose Zone Implementation Model for Large-Scale Hanford Assessments

2.4.1 Hydrogeologic Profiles

Large-scale Hanford assessments will, in general, use a one-dimensional vadose zone model, with some subordinate analyses to explore the use of multidimensional models that explicitly account for structural features within the Hanford Site, and/or to condition the one-dimensional model results (Kincaid et al. 2004). To account for large scale variability in the hydrostratigraphy across the Hanford Site, the preparation of hydrogeologic profiles and hydraulic and transport property datasets for each site have been grouped into a number of geographic areas assumed to have similar hydrogeologic structure and properties. Hydrogeologic units are identified and their thickness ranges specified for each of these hydrogeologic provinces. To account for finer scale variability and uncertainty in the model parameters, probability distribution functions for the parameters were developed by hydrogeologic unit.

Kincaid et al. (2000) selected the Subsurface Transport Over Multiple Phases (STOMP) computer code (White and Oostrom 2000) as the code of choice for the Vadose Zone Flow and Transport Module for SAC. Properties to be represented in the model include unsaturated hydraulic conductivity, porosity, water retention parameters, dispersivity, and diffusion coefficient. Data to support the vadose zone profile and property models have been assembled by geographic area. Kincaid et al. (2004) also indicated that care should be taken to develop and apply correlated model parameters (where such correlations have been derived), to appropriately model properties (for example, parameters of the van Genuchten and Mualem models - van Genuchten 1980) of unsaturated hydraulics and water retention. Although Carsel and Parrish (1988) have reported cross-correlations between a number of these parameters, recent examination of the Hanford Site data have not found any statistically significant correlations.[9]

2.4.2 Deep Drainage Rates

Deep drainage (recharge) rates are critical to Hanford assessments, as they affect both the release of waste from the disposal zone and the transport of waste to the water table. Deep drainage rates are a function of the climate, soil, topography, and vegetation. Kincaid et al. (2004) indicated that estimates of deep drainage for a large-scale Hanford assessment will be based on the assumption of a continuation of current climate as defined by Hanford Site weather records (Hoitink et al. 2005). Hanford weather data have been collected regularly since 1946 at the Hanford Meteorological Station (HMS), located between the 200 East and 200 West Areas.

For a large-scale Hanford assessment, a set of deep drainage rates have been assigned for four specific intervals of time. The first interval, the *pre-Hanford* period, is the natural environment that existed prior to the start of Hanford activities. The undisturbed soil profiles and the shrub-steppe plant community determine the rates during this interval.

The second interval is the *operations* period, during which much of the land surface at waste sites was disturbed (e.g., trenches excavated; cribs constructed; waste disposed and buried) and maintained free of vegetation. In most cases it has been assumed that at the beginning of the operations period, as the waste sites were being constructed, that the existing topsoil at a given site was excavated and stockpiled separately from the underlying sediments. Following construction of the waste site, the stockpiled topsoil was then used as the final surface materials. Thus, the soil type during the operations period is the same as that used for pre-Hanford conditions, except that is has been disturbed (no longer retains the structured soil profile) and is maintained free of vegetation.

The third time interval for simulation is the *remediation* period, during which sites will be covered with a protective surface barrier, remediated by retrieval and/or treatment, or left intact. For sites receiving a surface barrier, the remediation period begins with construction of the barrier and lasts throughout the period of institutional control and through out the design life of the barrier. For sites being remediated by retrieval, the remediation period follows removal of the contamination (and inventory) to a prescribed depth, its placement in the Environmental Remediation Disposal Facility, and placement of backfill over the excavated waste site. For sites being treated in place, the remediation period follows treatment of the contaminants so that they are altered or destroyed and the site restored. For both retrieval and treatment activities, the remediation period includes a period of institutional control during which a

---

[9] Freeman EJ and ML Rockhold. 2003. *Estimation of Site-Specific Probability Distribution Functions for Soil Hydraulic Parameters using Bayesian Updating*. Letter Report, Pacific Northwest National Laboratory, Richland, Washington.

shrub-steppe plant community is re-established. In both cases, the vadose zone simulations will continue to predict the migration and fate of residual contamination in the vadose zone below the cleanup depth.

The fourth and final interval is the *post-Hanford* period. This time period represents the longest time interval simulated, and during which long-term changes can occur. This time period begins after the Hanford Site is no longer under active institutional control and the design life of the site's surface barrier has been exceeded. During the post-Hanford period, over an interval of time equivalent to the design life of the barrier, the deep drainage rate is changed in stages until it reaches the rate associated with an equivalent natural soil and native shrub-steppe plant community.

2.4.3 Geochemical Reactions

Kincaid et al. (2004) indicated that for large-scale Hanford assessments, interaction of contaminants with vadose zone sediment will be approximated using the linear sorption isotherm model. The mobility of contamination is highly dependent on its speciation and surrounding environment. It is assumed that upon introduction to the vadose zone environment, waste mobility is dominated by waste characteristics. After being in contact with vadose zone sediment and soil water for some distance, it is assumed that the waste undergoes a change in its mobility based on reaction buffering lag of the contaminant solution with the vadose zone hydrogeologic units. Finally, it is assumed once contaminants have migrated a short distance in the Hanford Site unconfined aquifer, another mobility state would be defined by the highly buffered, neutralized, and diluted contaminant. Distribution coefficients have been defined for each contaminant in several zones; for example, upper (near field) vadose zone, lower (far field) vadose zone, and unconfined aquifer. Where indicated, K_d dependency on waste chemistry and hydrogeologic units have been included. Available empirical K_d data have been assembled to generate probability distribution functions for a suite of waste chemistry types. These broad ranges in K_d for a given waste chemistry are used to represent the variability in waste speciation and surrounding environmental conditions.

2.4.4 Interaction with the Inventory, Release, and Groundwater Modules

The inventory and release modules of SAC provide input to the vadose zone module. In addition to curie or kilogram amounts of waste and waste volume, the inventory module provides data on the location and dimensions of each storage or disposal facility. The release module, in concert with the inventory module, provides the contaminant flux to the vadose zone. Large-volume contaminant releases to sites where the vadose zone is thin, such as the cooling water discharges to retention basins in the 100 Areas, are routed directly to the Columbia River, bypassing the vadose zone.

For areas with a thicker vadose zone, the vadose zone module provides estimates of the mass flux of contaminant entering the unconfined aquifer as a function of time. The estimates address releases from all operational areas for the radionuclide and chemical contaminants selected for the large-scale assessment. Released flux to the aquifer is provided for individual waste sites (for example, liquid discharge sites), and/or aggregations of waste sites where applicable (for example, the combination of trenches that comprise solid waste burial grounds). The vadose zone releases to the aquifer are aggregated to groundwater model nodes in order to introduce contaminants into the aquifer model. The vadose zone module provides estimates of mass flux of contaminants from the vadose zone to groundwater for the period of analysis.

3.0 Data Compilation

Kincaid et al. (2004) selected a simplified model approach for simulating vadose zone flow and transport for a large-scale Hanford assessment (see Table 2.1). In this approach, flow and transport are treated as either one-dimensional processes or as a one-dimensional approximation of two-dimensional processes. Vadose zone simulations will use the STOMP computer code (White and Oostrom 2000). Input parameters include (1) hydrostratigraphy; (2) physical and hydraulic properties (e.g., unsaturated hydraulic conductivity, porosity, water retention parameters, dispersivity, diffusion coefficients); (3) contaminant distribution coefficients; and (4) estimates of deep drainage rates. These parameters have been derived from existing geologic, soil physics, and geochemical databases. To facilitate sensitivity and uncertainty analyses, probability distribution functions were developed for each of the primary transport parameters.

3.1 Hydrostratigraphy

The vadose zone stratigraphic profiles and hydrogeochemical property distributions for large-scale Hanford assessments are represented by 30 generalized one-dimensional vertical columns. These 30 stratigraphic profiles represent 17 general geographic areas and 13 site-specific locations. Each hydrostratigraphic profile (template) was configured with the hydraulic and geochemical parameters necessary for STOMP to simulate the flow and transport through the vadose zone. As many as five variations of a single hydrostratigraphic template were necessary to more accurately represent the depth of waste releases and thickness of the vadose zone beneath the point of injection. Additional variations of the hydrostratigraphic templates accommodate variations in K_d values associated with different waste chemistry designations. Two additional template designations were added to facilitate special handling of those sites that discharged waste effluents directly to the river or those that represent pumping wells. Thus, a series of 72 templates were ultimately identified for application in the 17 geographic areas shown in Figure 3.1. These templates consist of the one-dimensional stratigraphy, hydrologic properties, and geochemical properties as well as the waste site type (e.g., crib, tank, etc.) and waste chemistry designation. A more complete discussion regarding the development of the templates is provided in Section 3.2 and in Last et al. 2006.

The preferred approach for modeling contaminant transport through the vadose zone uses these templates to represent the vadose zone beneath each waste site within a given geographic area. The actual simulation of each waste site assigned to a given template is implemented at that site's centroid coordinates.

Each template consists of three to eight major hydrostratigraphic units that are assumed to be horizontally layered with constant thicknesses, homogeneous, and isotropic (Figure 3.2). Hydrologic and geochemical parameters for each hydrostratigraphic unit are represented by stochastic distributions to facilitate sensitivity and uncertainty analyses. Once each site was assigned to a geographic area and representative stratigraphic template, site-specific parameters such as the site location (centroid), and recharge rates (based on surface cover changes) were added. Each site was then assigned a unique alphanumeric identifier (refer to Last et al. 2006).

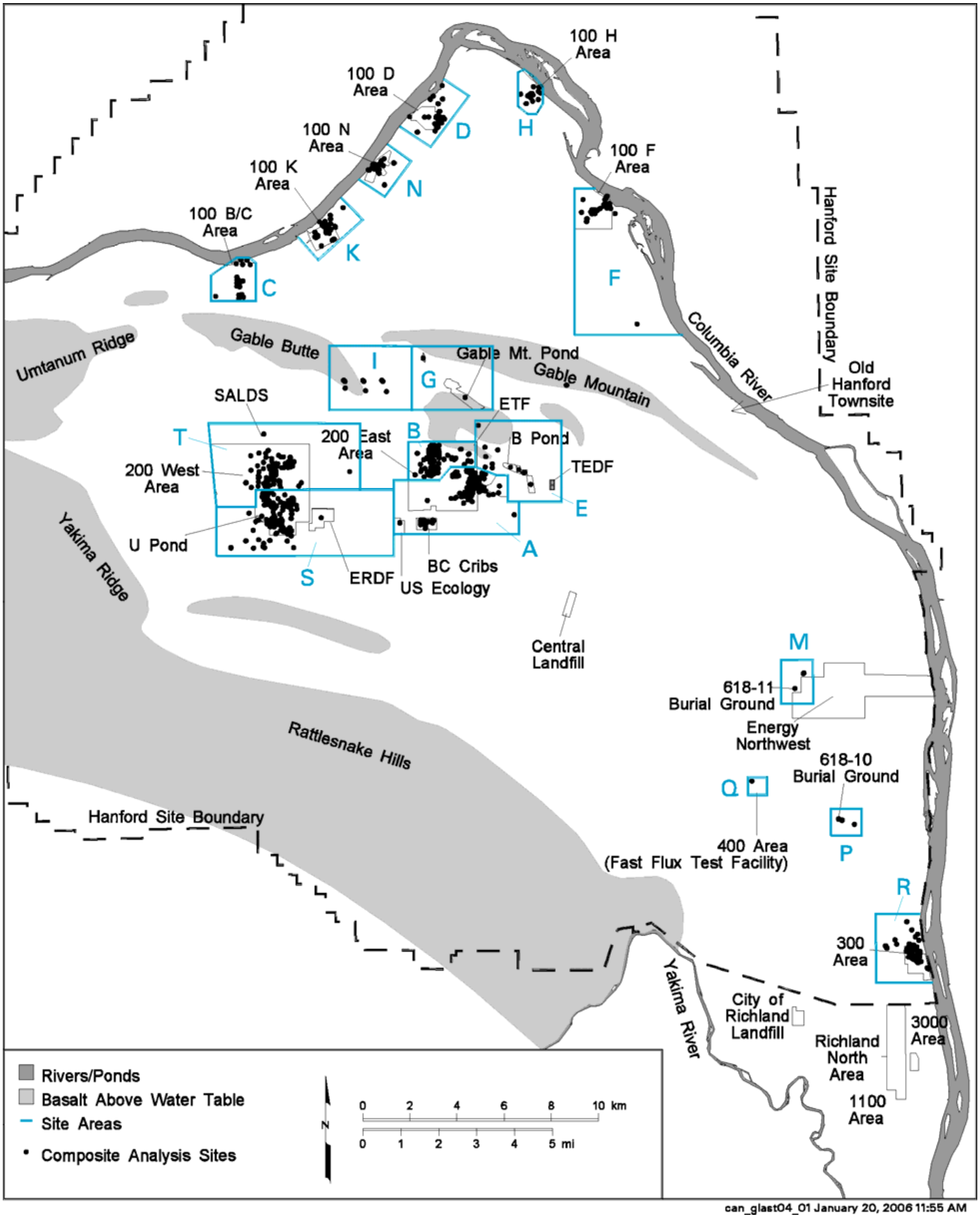

Figure 3.1. Location of Geographic Areas Represented by Similar Hydrostratigraphic Columns

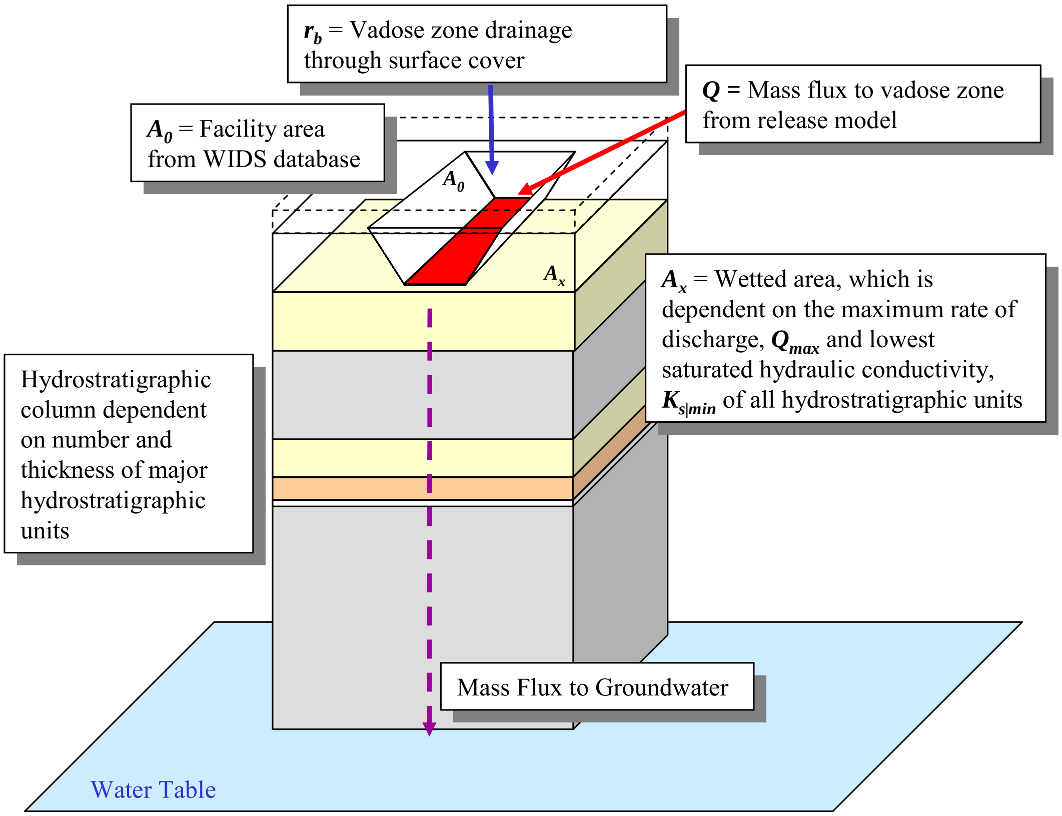

Figure 3.2. Schematic of One-Dimensional Vadose Zone Simulation

3.2 Hydrostratigraphic Templates

Seventy-two hydrostratigraphic templates were defined on the basis of (1) the types of waste sites, (2) the general hydrostratigraphy for 17 selected geographic areas (Figure 3.1), and (3) the chemical characteristics of the waste streams. To accommodate the large number of hydrostratigraphic templates, an alphanumeric code was developed to identify each unique hydrostratigraphic template. This code generally consists of a three-digit number that reflects the waste site type, a letter designating the geographic area, and a number designating the waste chemistry group for assigning K_d values. Thirteen site-specific hydrostratigraphic templates were created by adding additional alphanumeric characters to the geographic area designation.

3.2.1 Waste Site Type (reflecting the depth of waste injection)

Nearly all waste sites selected for simulation in a large-scale Hanford assessment have a Waste Information Data System (WIDS) site code. This code generally includes a three-digit number, with the first digit identifying the operational area where the facility is located, and the second and third digits identifying the type of facility. For example, the site code 116 indicates that the facility is in the 100 Area and that it is a liquid disposal facility (i.e., crib, pond, ditch); the site code 241 indicates that it is in the 200 Area and that it is an underground high-level waste tank. For the purposes of defining the base templates, six main categories of waste sites were distinguished: (1) surface facilities such as ponds, ditches, retention basins, buildings, unplanned releases; (2) near surface facilities such as cribs, specific retention trenches, French drains, burial grounds; (3) underground storage tanks; (4) reverse (injection) wells; (5) very deep reverse (injection) wells, and (6) river outfalls. Each of these site types (except the river outfalls) release waste to the vadose zone at increasingly deeper depths, making the hydrostratigraphic column shorter, and moving the location of high impact versus intermediate impact K_d zones deeper in the soil profile. The waste site designation scheme for implementation in the base template nomenclature is shown in Table 3.1.

Table 3.1. Waste Site Type Designations Used in the Hydrostratigraphic Template Codes

Site Type Code[(a)]	Relative Depth of Waste Release	Representative WIDS Site Types
100, 200, 300, 400	Ground Surface (generally less that 3 m deep).	Surface and/or near surface facilities (e.g., process sewers, reactor buildings,[(b)] laboratory buildings, storage, stacks, ponds, ditches, valve pits, process unit/plants,[(b)] unplanned releases except tank leaks).
116, 216, 316, 616	Shallow Subsurface (generally 3-15 m below ground surface)	Shallow liquid and/or dry waste disposal facilities (e.g., cribs, burial grounds, retention basins, trenches, French drains, storage tunnels, drain/tile fields, pipelines, sewers).
241	Intermediate Subsurface (generally 9 to 17 m below ground surface)	High level waste tanks, settling tanks, diversion boxes, catch tanks, tank leak unplanned releases.
166, 266	Deep Subsurface (generally greater than 18 m below ground surface)	Deep injection sites (e.g., reverse [injection] wells)
276	Very Deep Subsurface (generally near or into the water table)	Very deep injection sites (e.g., very deep reverse [injection] wells)
River[(c)]	River Level	River outfalls and associated pipelines
Pump[(d)]	Not Applicable	Water supply wells

(a) First digit represents the area: 1 = 100 Area, 2 = 200 Area, 3 = 300 Area, 4 = 400 Area, 6 = 600 Area. Second and third digits indicate the general facility type and relative release depth.
(b) Some reactors and process unit/plants (such as canyon buildings) have basements and/or fairly deep foundations, however for the ease of simulation, all above ground structures are treated the same.
(c) River outfall discharged waste directly to the river, thus there is no vadose zone flow and transport component for these sites.
(d) Water supply wells withdraw water from the aquifer, thus there is no waste released, and no vadose zone flow and transport component for these sites.
WIDS = Waste Information Data System.

3.2.2 Geographic and Site-Specific Areas Designations

Seventeen geographic areas (Figure 3.1) were identified that could each be represented by a single generalized hydrostratigraphic column. Each of the six 100 Areas were designated as separate geographic areas because each area is geographically distinct and has distinct hydrogeologic characteristics. The 200 Areas were divided into six geographic areas based on differences in hydrogeologic characteristics. The 200 West and 200 East Areas were each divided into two geographic areas. Additional geographic areas were designated for the 200 North, Gable Mountain Pond, and the B Pond areas. A single geographic area was designated to encompass waste sites in the 300 Area. Finally, three additional geographic areas were defined for isolated sites in the 400 and 600 Areas. Table 3.2 presents the letter designations and brief descriptions of each geographic area. Thirteen site-specific designations were created by adding additional alphanumeric characters to two of the geographic area designations (Table 3.3).

Table 3.2. Geographic Area Designations Used in the Hydrostratigraphic Template Codes

Designation	Geographic Area Description
A	Southern 200 East Area - encompassing the PUREX (A plant), hot semi-works (C-Plant), associated facilities (including PUREX tunnels), BC cribs, US Ecology, and the A, AN, AP, AW, AX, AY, AZ, C Tank Farms
B	Northwestern 200 East Area - encompassing the B-plant, associated waste disposal facilities, and the B, BX, BY Tank Farms
C	100-B/C Area
D	100-D/DR Area
E	East of 200 East – B Pond
F	100-F Area
G	Gable Mountain Pond Areas
H	100-H Area
I	200 North
K	100-KE/KW Area
M	600 Area near Energy Northwest and the 618-11 burial ground
N	100-N Area
P	600 Area southwest of the 400 area near the 618-10 burial ground
Q	400 Area
R	300 Area (and a few isolated facilities in and near the 400 Area)
S	Southern 200 West Area - encompassing the REDOX (S-Plant), U-plant, Z-plant associated facilities, ERDF, and the S, SX, SY, U Tank Farms
T	Northern 200 West Area - encompassing T Plant , associated facilities, and the T, TX, TY Tank Farms

3.2.3 Waste Chemistry Groupings (for assigning K_d ranges)

Six waste chemistry types were defined by Kincaid et al. (1998) for use in the Composite Analysis. These waste chemistry types describe chemically distinct waste streams that impact the sorption of contaminants. These same waste chemistry designations were adapted for use in the initial assessment conducted using SAC to assign K_d values to the vadose zone base templates (Bryce et al. 2002). However, based on waste stream chemistry and potential impact on the fate and transport of contaminants of concern, the original six waste stream categories used in these assessments were reduced to four.[10] Two additional waste stream categories were then later added to better represent waste releases from the Integrated Disposal Facility (Krupka et al. 2004).

[10] Cantrell KJ, RJ Serne, and GV Last, Pacific Northwest National Laboratory, Richland, Washington. A white paper, *Waste Stream Descriptions, Impact Zones and Associated K_d Estimates Including Rational for Selections*, dated May 16, 2003.

Table 3.3. Site-Specific Area Designations Used in the Hydrostratigraphic Template Codes

Designation	Site-Specific Area Description
A_BC_W	Southern 200 East Area – representing the western portion of the BC cribs area
A_BC_E	Southern 200 East Area – representing the eastern portion of the BC cribs area
A_BCT_N	Southern 200 East Area – representing the northern portion of the BC trench area
A_BCT_S	Southern 200 East Area – representing the southern portion of the BC trench area
A_BCT_W	Southern 200 East Area – representing the western portion of the BC trench area
A_C	Southern 200 East Area – representing the 241-C Tank Farm
A_ILAW_C	Southern 200 East Area – representing the central portion of the ILAW site
S_ERDF_E	Southern 200 West Area – representing the eastern half of ERDF
S_ERDF_W	Southern 200 West Area – representing the western half of ERDF
S_U	Southern 200 West Area – representing the 241-U Tank Farm
S_U_N	Southern 200 West Area – representing the northern portion of the 216-U-1&2 crib area
S_U_S	Southern 200 West Area – representing the southern portion of the 216-U-1&2 crib area
S_Z9	Southern 200 West Area – representing the 216-Z-9 trench area

K_d values used in the 1998 Composite Analysis were initially tabulated for six source term categories (Kincaid et al. 1998, Table E.2) and three impact zone categories (Kincaid et al. 1998, Table E.3). In addition to the three impact zone categories (High Impact, Intermediate Impact and Groundwater), another K_d category (Intermediate Impact Zone – Gravel) was included in the SAC initial assessment to represent very coarse lithologies composed of ≥90% by weight gravel. K_d measurements are generally material are applicable. For materials that contain significant amounts of gravel, K_d values will be much lower than those determined with <2 mm-size material because surface area and corresponding conducted on material that is <2 mm in size. The first three impact zone categories mentioned assume that the material is sand size or smaller, and that K_d values measured using <2 mm-size quantity of adsorption sites is much lower. For the Intermediate Impact Zone – Gravel category it is necessary to make a correction to K_d values due to the high gravel content. For the Intermediate Impact Zone – Gravel case, it was assumed that the material is 90% gravel with the corresponding correction factor of 0.31 for relatively high K_d contaminants (cesium, strontium, and plutonium) and 0.1 for low K_d contaminants (see Kaplan and Serne 2000, Appendix A). In future Hanford assessments, stratigraphic correlations will be used to estimate gravel contents of sediment to make gravel corrections to the K_d values rather than using an assumed gravel content of 90% for gravel rich sediment.

As indicated above, the original six waste stream designations defined by Kincaid et al. (1998) were reduced to four. The original six waste stream designations were:

1. High Organic/Very Acidic
2. High Organic/Near Neutral
3. High Salt/Very Basic
4. Chelates/High Salt
5. Low Organic/Low Salt/Acidic
6. Low Organic/Low Salt/Near Neutral

These were simplified to the following four:

1. Very Acidic (simplified from 1 above)
2. High Salt/Very Basic (same as 3 above)
3. Chelates/High Salt (same as 4 above)
4. Low Salt/Near Neutral (same 6 above with incorporation of 2 and 5)

The reasons for these simplifications follow. The high organic designation can be eliminated because waste streams that were termed high organic generally refer to waste streams containing significant concentrations of tributyl phosphate, hexone, kerosene, lard oil, and/or carbon tetrachloride. These organics compounds do not complex metals and radionuclides under normal aqueous environmental conditions and as a result will not enhance their transport through chemical mechanisms. However, it is possible that if these materials were to occur as a free organic phase, they could significantly affect transport through multiphase flow and alteration of the hydrologic properties of the sediments.

Tributyl phosphate is a weak complexant and after any dilution is not capable of significantly mobilizing metals and radionuclides. These organic compounds, if disposed in large quantities and high concentration, could potentially affect radionuclide and metal migration by creating a reducing zone; however, no field evidence for such an occurrence has been found. As a result of this simplification, the High Organic/Very Acidic waste stream was re-designated as the Very Acidic waste stream and the High Organic/Near Neutral waste stream was combined with the Low Salt/Near Neutral waste stream. The Low Organic/Low Salt/Acidic waste stream was combined with the Low Salt/Near Neutral waste stream because mildly acidic waste streams will generally be neutralized relatively quickly near the disposal location by calcite that occurs naturally in most Hanford sediment. Slower reactions with alumino-silicate minerals could also account for some acid neutralization.

In addition to the four waste streams discussed above, two additional waste stream categories were added to better represent waste releases from the Integrated Disposal Facility (Krupka et al. 2004). These two waste stream categories are:

5. Integrated Disposal Facility (IDF) vitrified waste (new)
6. IDF cementitous waste (new)

To better describe the selection of the K_d values for each waste stream designation, semi-quantitative values (chemical concentrations) were defined for each waste stream category. This provides a less ambiguous and more technically defensible approach for the assignment of K_d values. These compositions are shown in Table 3.4. The compositions are meant to represent major components that are generic for each waste stream category and not an actual measured waste stream. Only major components that are expected to have a significant influence on adsorption are included. In the case of the Very Acidic waste stream, the composition is based largely on professional judgment. No actual acid concentration data could be located for this waste stream. The composition of the High Salt/Very Basic waste stream provided in Table 3.4 is meant to represent a generic composite composition of Hanford fuel processing waste that has leaked from single-shell tanks or been intentionally discharged to specific retention cribs. Because a large number of leaking single-shell tanks occur in the single-shell waste management areas (S-SX, B-BX-BY, T and TX-TY, and U), estimated compositions available for SX Tanks and Tank T-106 (Agnew et al. 1996) were used to guide the selected compositions. Similar to the High Salt/Very Basic waste stream, the composition selected to represent the Chelates/High Salt waste stream is a generic composite composition and does not represent any single or specific waste stream. The concentration of ethylenediaminetetraacetic acid (EDTA) is based on measured concentrations of chelating agents in actual tank waste (Campbell et al. 1998a, 1998b).

Table 3.4. Waste Stream Designation and Assumed Compositions for Determination of K_d Values

Waste Stream	Composition
Very Acidic	1.0 M HNO_3
High Salt/Very Basic	2 M NaOH, 4 M $NaNO_3$, 2 M $NaNO_2$
Chelates/High Salt	1.0 M $NaNO_3$, 0.05 M EDTA, pH 12
Low Salt/Near Neutral	Same as Hanford Groundwater
IDF vitrified waste	High pH, high ionic strength
IDF cementitious waste	High pH, medium ionic strength
IDF = Integrated Disposal Facility	

The two IDF waste streams are problematic in terms of assigning representative compositions. IDF waste form leach rates are functions of waste form composition and system variables (Bacon and McGrail 2005). Important system variables include temperature, pH and composition of the fluid contacting the waste forms. The temperature of the IDF disposal system is assumed to be known and constant. Both pH and the composition of the fluid contacting the glass are variables affected by flow rate, reactions with other engineered materials, gas-water equilibria, secondary phase precipitation, alkali ion exchange, and glass dissolution. As a result, the IDF waste form leach rates will be highly dynamic, being a function of both time, position in the disposal system, and other variables that are not yet known. Because of these factors, a specific composition to these waste streams are not provided in Table 3.4, instead only a generic composition is provided (Krupka et al. 2004).

Intermediate impact zone compositions are assumed to be 10% of the concentrations of the high impact zone (Table 3.4), except in the case of the Very Acidic waste stream where it is assumed that all the acid is neutralized in the High Impact zone. The un-impacted zone is assumed to have the composition of typical Hanford groundwater. Several typical compositions of Hanford groundwater (uncontaminated) are tabulated in (Cantrell et al. 2002). In general, Hanford groundwater is calcium bicarbonate dominated water with a pH that typically ranges from approximately 7.5 to 8.5. Other prominent major ions are sodium, chloride, sulfate, and magnesium. Typically, total ion composition is between 4 and 10 meq/L. Table 3.5 presents the waste chemistry designations used in the hydrostratigraphic templates.

Table 3.5. Waste Chemistry Designations Used in the Base Template Codes

Waste Chemistry Designation	Waste Stream Description
1	Very Acidic
2	High Salt/Very Basic
3	Chelates/High Salt
4	Low Salt/Near Neutral
5	IDF Vitrified Waste
6	IDF Cementitious Waste
IDF = Integrated Disposal Facility.	

3.2.4 Hydrostratigraphic Template Designations

A total of 72 hydrostratigraphic templates have been identified based on various combinations of geographic areas, site types, and waste chemistry types. Table 3.6 provides a description of the general hydrostratigraphic templates established for each geographic area. Table 3.7 describes the site-specific templates set up for a number of key facilities within two of these general geographic areas.

Table 3.6. General Hydrostratigraphic Templates for Each Geographic Area

Template Designation	Geographic Area		Waste Site Types		Waste Chemistry Designation[d]
	Area	Designation[a]	Description	Designation[b]	
100C-4	100 B/C	C	Surface Facilities	100	4
116C-4			Near Surface Facilities	116	4
100D-4	100 D	D	Surface Facilities	100	4
116D-4			Near Surface Facilities	116	4
100F-4	100 F	F	Surface Facilities	100	4
116F-4			Near Surface Facilities	116	4
100H-4	100 H	H	Surface Facilities	100	4
116H-4			Near Surface Facilities	116	4
100K-4	100 K	K	Surface Facilities	100	4
116K-4			Near Surface Facilities	116	4
166K-4			Reverse (Injection) Wells	166	4
100N-4	100 N	N	Surface Facilities	100	4
116N-4			Near Surface Facilities	116	4
200G-4	Gable Mtn.	G	Surface Facilities	200	4
200I-4	200N	I	Surface Facilities	200	4
200E-4	E 200 E (B-Pond)	E	Surface Facilities	200	4
216E-4			Near Surface Facilities	216	4
200B-2	N 200 E (B-Plant)	B	Surface Facilities	200	2
200B-4					4
216B-2			Near Surface Facilities	216	2
216B-3					3
216B-4					4
241B-2			Tanks	241	2
266B-4			Reverse (Injection) Wells	266	4
267B-2				267[c]	2
200A-2	S 200 E (PUREX, BC Cribs)	A	Surface Facilities	200	2
200A-4					4
216A-2			Near Surface Facilities	216	2
216A-4					4
241A-2			Tanks	241	2
241A-3					3
266A-4			Reverse (Injection) Wells	266	4
200S-2	S 200 W (Redox, U-Plant, Z-Plant)	S	Surface Facilities	200	2
200S-4					4

Table 3.6. (contd)

Template Designation	Geographic Area		Waste Site Types		Waste Chemistry Designation[(d)]
216S-1	S 200 W (Redox, U-Plant, Z-Plant)	S	Near Surface Facilities	216	1
216S-2					2
216S-4					4
241S-2			Tanks	241	2
241S-3					3
241S-4					4
266S-4			Reverse (Injection) Wells	266	4
200T-2	N 200 W (T Plant)	T	Surface Facilities	200	2
200T-4					4
216T-2			Near Surface Facilities	216	2
216T-3					3
216T-4					4
241T-2			Tanks	241	2
266T-2			Reverse (Injection) Wells	266	2
266T-4					4
300R-4	300 Area (North Richland	R	Surface Facilities	300	4
316R-4			Near Surface Facilities	316	4
400Q-4	400	Q	Surface Facilities	400	4
616M-4	600	M	Near Surface Facilities	616	4
616P-4	600	P	Near Surface Facilities	616	4
Pump	-	-	Water Supply Wells	Pump	-
River	-	-	River outfalls	River	-

(a) Assigned letter designation for geographic area.
(b) Assigned number designation for waste site type: First number designates traditional Hanford Site area (i.e., 100, 200, 300, 400, 600 Areas); last two numbers designate waste site type (00 = surface facilities, 16 = near surface facilities, 41 = tanks, 66/67 = reverse wells).
(c) Two designations are used for reverse (injection) wells that have very different depths within a single geographic area. The “67” designation distinguishes the very deep reverse (injection) wells from those at a more intermediate depth (66).
(d) Assigned number designation for waste chemistry type (see Table 3.5).

Table 3.7. Site-Specific Templates Established for a Few Key Facilities

Template Designation	Site-Specific Area		Waste Site Types		Waste Chemistry Designation[c]
	Area	Designation[a]	Description	Designation[b]	
216A_BC_W-3	S 200 E, BC Cribs, Western Portion	A_BC_W	Near Surface Facilities	216	3
216A_BC_E-3	S 200 E, BC Cribs, Eastern Portion	A_BC_E	Near Surface Facilities	216	3
216A_BCT_N-3	S 200 E, BC Trenches, Northern Portion	A_BT_N	Near Surface Facilities	216	3
216A_BCT_N-4					4
216A_BCT_S-3	S 200 E, BC Trenches, Southern Portion	A_BT_S	Near Surface Facilities	216	3
216A_BCT_W-3	S 200 E, BC Trenches, Western Portion	A_BT_W	Near Surface Facilities	216	3
216A_ILAW_C-5	S 200 E, ILAW Site, Central Portion	A_ILAW_C	Near Surface Facilities	216	5
216A_ILAW_C-6					6
216S_ERDF_E-4	S 200 W, ERDF, eastern half	S_ERDF_E	Near Surface Facilities	216	4
216S_ERDF_W-4	S 200 W, ERDF, western half	S_ERDF_W	Near Surface Facilities	216	4
216S_U_N-4	S 200 W, 216-U-1&2 Area, Northern Portion	S_U_N	Near Surface Facilities	216	4
216S_U_S-4	S 200 W, 216-U-1&2 Area, Northern Portion	S_U_S	Near Surface Facilities	216	4
216S_Z9-1	S 200 W, 216-U-1&2 Area, Northern Portion	S_Z9	Near Surface Facilities	216	1
241A_C-2	S 200 E, 241-C Tank Farm	A_C	Tanks	241	2
241A_C-3					3
241S_U-2	S 200 W, 241-U Tank Farm	S_U	Tanks	241	2

(a) Assigned letter designation for geographic area.
(b) Assigned number designation for waste site type: First number designates traditional Hanford Site area (i.e., 100, 200, 300, 400, 600 Areas); last two numbers designate waste site type (00 = surface facilities, 16 = near surface facilities, 41 = tanks, 66/67 = reverse [injection] wells).
(c) Assigned number designation for waste chemistry type (see Table 3.5).

4.0 Input Parameters

This section describes the input data sets assembled for use in vadose zone modeling for large-scale Hanford Assessments. These data sets are managed under a data configuration and communication management plan.[11] A readiness review was conducted prior to placing each data set under configuration management. Any subsequent changes were managed and documented via a data change request (DCR). Each revised data set is uniquely identified with a descriptive name, the date the data set was revised, and the corresponding DCR number. For example:

Sorption_2005-09-15_DCR-0014.xls

identifies the K_d input files that were accepted into configuration control on September 15, 2005 under DCR number 0014; the file extension identifies this as a Microsoft Excel spreadsheet. Table 4.1 summarizes the pertinent input data sets and the location of their representation in this or other companion documents.

Table 4.1. Summary of Vadose Zone Input Parameter Data Sets Under Configuration Management

Description	File Name	File Type	Location
Hydrostratigraphy. These files provide the hydrostratigraphic column for each geographic area, including the layer thickness, and their hydraulic and geochemical property designations.	vadose_2006-01-31_DCR-0038	Folder containing 26 Excel spreadsheets (templates), plus a change log.	Appendix A
Hydraulic properties important to vadose zone simulations	Hydraulic_Properties_2006-03-07_DCR-0045.xls	Excel workbook.	Appendix B
Contaminant distribution coefficients	Sorption_2005-12-20_DCR-0030.xls	Excel work book	Table 4.11
Hydrostratigraphic template definition and other geographic and operational site parameters used to specify the location, dimensions, recharge rates, remedial actions, etc.	GOSPL_2006-04-14_DCR-0047.xls	Excel workbook; worksheet 'Full SAC Rev1 List'	See GOSPL Data Package (Last et al. 2006)
Recharge rates	GOSPL_2006-04-14_DCR-0047.xls	Excel workbook; worksheet 'Infiltration Class'	Tables 4.19 through 4.20
Pond evaporation estimates	Evaporation_2005-07-20_DCR-0008.xls	Excel workbook; worksheet 'time-evaporate'	Table 4.21

4.1 Hydrostratigraphy

The geology of the vadose zone forms the framework through which contaminants move. The physical structure of the vadose zone, along with its hydraulic and geochemical properties, controls the

[11] Nichols, WE, PW Eslinger, and GV Last. February 3, 2006. *Hanford Remediation Assessment Project Data Configuration and Communication Management Plan, Rev. 1.1.* Pacific Northwest National Laboratory, Richland, Washington.

migration and distribution of contaminants. Of particular interest are the interrelations between the coarse- and fine-grained sediments within the vadose zone, and the types and degree of contrast in their physical and geochemical properties.

As described by Kincaid et al. (2004), the large scale and complexity of an assessment for the entire Hanford Site necessitates the use of a simplified modeling approach. In this approach, industrial waste sites were grouped into one of 17 geographic areas that were identified as having unique hydrostratigraphic properties. The vadose zone beneath each geographic area is represented as a single one-dimensional hydrostratigraphic column (Figure 3.2). The hydrostratigraphic information that describes a geographic area has been assembled into a common template for all waste sites within that area. These templates were assembled from existing information including:

- Published interpretive depths to the top and bottom surfaces of hydrogeologic units (as taken from tabulated geologic contact data or interpolated from structure contour maps, cross sections, log plots, or other graphical representations).
- Unpublished raw data (e.g., driller's logs, geologists' logs, and geophysical logs).
- Surface elevations (to convert hydrogeologic unit depths to elevations), interpolated from topographical maps (e.g., Hanford Quadrangle 15 Minute Series).
- Elevation of the 1944 water table (to define the bottom of the vadose zone prior to waste disposal), interpolated from historic water table maps (e.g., Kipp and Mudd 1974)

In general, the main hydrostratigraphic units, contact depths, and thicknesses were taken from available published tables, maps, and cross-sections. The estimated average strata thicknesses were used to assemble the generalized columns extending from the ground surface to the 1944 water table. However, because the sum of the average thicknesses did not always equal the distance from the ground surface to the water table, small adjustments were made to normalize the average strata thicknesses to equal the total thickness of the vadose zone. Table 4.2 lists the references used to assign hydrogeologic units to each of the hydrostratigraphic templates.

Since lithofacies identification and geologic nomenclature has varied over time and by published sources, some translation was necessary to relate the major geologic units to a common classification. Table 4.3 describes the generalized hydrostratigraphic nomenclature used in this study based on that defined by DOE (2002), and Lindsey (1996). Appendix A provides the hydrostratigraphic column for each geographic area, including the layer thicknesses and their hydraulic and geochemical property designations.

In the simplified modeling approach selected for large-scale Hanford assessments, the number and thicknesses of the hydrostratigraphic units within each template remain fixed. However, it must be recognized that there is uncertainty associated with these hydrostratigraphic representations. The primary source of information for these interpretations is borehole data. Uncertainties in the borehole data are related to the drilling and sampling techniques, the logging of the borehole, elevation control, and interpretation of the stratigraphy. Subtle differences between some stratigraphic units make identification of the stratigraphic contacts difficult (Reidel et al. 2006). In addition, there is spatial uncertainty due to variations in thickness and presence/absence of the stratigraphic units across the geographic areas represented in each template.

Table 4.2. Sources of Hydrogeologic Data for the Seventeen Geographic Areas to be Analyzed

Geographic Area	Designation	References
100 B/C	C	Lindberg 1993a; Lindsey 1992; Peterson et al. 1996
100 D	D	Lindsey and Jaeger 1993; DOE 1993b; Lindsey 1992; Peterson et al. 1996
100 F	F	Raidl 1994; Lindsey 1992; Peterson et al. 1996
100 H	H	Lindsey and Jaeger 1993; Liikala et al. 1988; Vermuel et al. 1995; DOE 1993b; Peterson et al. 1996
100 K	K	Lindsey 1992; Lindberg 1995; Peterson et al. 1996
100 N	N	Hartman and Lindsey 1993
Gable Mountain Pond Area	G	Lindsey et al. 1992b; DOE 1993c; DOE 1993d; Wurstner et al. 1995
200 N	I	Lindsey et al. 1992b; DOE 1993c; DOE 1993d; Wurstner et al. 1995
E 200 E (B-Pond)	E	Barnett et al. 2000; Cearlock et al. 2000; Lindsey et al. 1992b; Wurstner et al. 1995
N 200 E (B-Plant)	B	Lindsey et al. 1992b; Price and Fecht 1976a, b, c; Tallman et al. 1979; Wurstner et al. 1995; Wood et al. 2000, Kephart et al. 2005; Reidel et al. 2006
S 200 E (PUREX, BC cribs, BC Trenches, ILAW)	A A_BC_E A_BC_W A_BCT_N A_BCT_S A_BCT_W A-C A_ILAW_C	Lindsey et al. 1992b; Reidel and Horton 1999; Valenta et al. 2000; Reidel et al. 2001; Reidel and Ho 2002; Tallman et al. 1979; Wurstner et al. 1995; Wood et al. 2003; Kephart et al. 2005; Reidel et al. 2006.
S 200 W (Redox, U-Plant, Z-Plant)	S S_U S_U_N S_U_S S_Z9 S_ERDF_E S_ERDF_W	Johnson and Chou 1988; Lindsey et al. 1992a; Price and Fecht 1976d; Slate 2000; Tallman et al. 1979; Wurstner et al. 1995; Rohay et al. 1994; Connelly et al. 1992a; Last et al. 1989; Last and Rohay 1993; Swanson et al. 1999; Weekes et al. 1996; Wood and Jones 2003; Kephart et al. 2005; Reidel et al. 2006; Well logs for 299-W19-14, -15, and -16; and borehole data from wells 299-W15-8, -9, -83, -84, -86, -95, -101, and -207.
N 200 W (T-Plant)	T	Lindsey et al. 1992a; Slate 2000; Tallman et al. 1979; Wurstner et al. 1995; Wood et al. 2001, Kephart et al. 2005; Reidel et al. 2006,
300 Area (North Richland)	R	Gaylord and Poeter 1991; Lindberg and Bond 1979; Schalla et al. 1988; Swanson et al. 1992
400 Area	Q	HEDL 1975; Meier Associates Log Book Project V-749; Well logs from 499-S1-8J, and 499-S1-7B.
600 Area (618-10 Area)	P	Well Logs from 699-S6-E4A
600 Area (618-11 Area, Energy Northwest)	M	Well Logs from 699-13-3A

Table 4.3. Hydrostratigraphic Units Used in this Study (after DOE 2002 and Lindsey 1996)

Formation/Unit	Facies/Subunit	Code	Description
Holocene	Backfill	HDb	Poorly sorted gravel, sand, and silt derived from the Hanford formation and/or Holocene deposits
	Medium-grained, Cross-Bedded, Well Sorted	HDs	Medium-grained dune sand, moderate to well sorted, and cross laminated to cross-bedded.
Hanford formation	Interbedded Sand- to Silt-dominated	HISSD	Rhythmite sequences of slackwater deposits. Graded beds of horizontal or climbing ripple laminated sand, to fine sand, to silt (laminated to massively bedded).
	Sand-Dominated, Silty Sand	HSD(f)	Silt to fine sand, massively bedded to horizontally laminated or cross laminated.
	Sand-Dominated, Fine Sand	HSD-Sm	Fine to coarse sand, massively bedded, with or without silt.
	Sand-Dominated, Coarse Sand	HSD-Sh(c)	Medium to coarse sand with minor amounts of pebbly sand, exhibiting horizontal to low-angle cross stratification.
	Sand-Dominated, Gravelly Sand	HSD(c)	Medium to coarse sand to pebbly sand (with up to 30 wt% very fine pebble to cobble), with high angle planar-tabular cross stratification to trough cross-stratification
	Gravel-Dominated	HGD	Silty sandy pebble to boulder gravel (with 30-60 wt% gravel), massive to cross stratified.
	Gravel-Dominated, Coarse	HGD(c)	Pebble to boulder gravel (with greater than 60 wt% gravel), to silty sandy gravel, massive to cross stratified.
Cold Creek unit	Fine-Grained, Laminated to Massive	CCUf(lam-msv)	Fine sand, silt, and/or clay, buff, pale to dark brown, well sorted to very well sorted, micaceous, and having high natural-gamma activity
	Coarse to Fine-Grained, Carbonate Cemented	CCUf-c(calc)	Calcium-carbonate cemented clay, silt, sand, and/or gravel, white to light gray, very poor to moderately sorted, with a massive to platy structure and bioturbated with root casts (rhyzoliths).
Ringold Formation	Fluvial Sand (Member of Taylor Flat)	Rtf	Interstratified sand and silt deposits
	Fluvial Gravel (Member of Wooded Island, subunit E)	Rwi(e)	Moderate to strongly cemented well rounded gravel and sand deposits, and interstratified finer-grained deposits.

4.2 Hydraulic Properties

Hydraulic property data for the vadose zone simulations were derived from the laboratory measurements of 284 soil samples (both repacked and splitspoon samples) taken from the 100 and 200 Areas (Appendix B). These data were selected from a catalog of vadose zone hydraulic properties (Freeman et al. 2002) and a subsequent prototype database (Freeman and Last 2003). Because the hydraulic property data are limited in the spatial location of samples and the soil types represented, individual stochastic data sets were developed to represent ten different soil classes. These ten classes build on the six soil classes originally identified by Khaleel and Freeman (1995) and are based on texture (i.e., particle size), International Society of Soil Science (ISSS) classification, and moisture retention curve characteristics. Four additional soil classes were incorporated to separate out the Cold Creek unit (formerly referred to as the Plio-Pleistocene unit) sediment, add additional detail for the Hanford formation sand-dominated sediment, and add a new class for very coarse gravel. The resulting 10 soil hydraulic property classes and their associated hydraulic property distributions were later correlated to the hydrostratigraphic units used in the 17 geographic area templates. Table 4.4 describes the hydraulic-property soil classes assembled for a large-scale Hanford assessment.

Table 4.4. Description of Hydraulic-Property Soil Classes

Formation	Soil Class	Code	Description	Hydrostratigraphic Unit Code(s)
Holocene Deposits	Backfill	Bf	Sand and gravel mixed with finer fraction. Same as the SSG soil category identified by Khaleel and Freeman (1995)	HDb
Hanford formation	Silty Sand	Hss	Sand mixed with finer fraction, containing >50% fine sands, silt, and clay, with >15% silt and clay. Derived from the SS soil category identified by Khaleel and Freeman (1995)	HISSD/HSD(f)
	Fine Sand	Hfs	Sand, containing 35-70% fine sand, silt, and clay, with <15% silt and clay. Derived from the S soil category identified by Khaleel and Freeman (1995)	HSD-Sm
	Coarse Sand	Hcs	Sand, containing >60% coarse sand. Derived from the S soil category identified by Khaleel and Freeman (1995)	HSD-Sh(c)
	Gravelly Sand	Hgs	Gravelly sand. Same as the GS soil category identified by Khaleel and Freeman (1995)	HSD(c)
	Sandy Gravel	Hg	Sandy gravel for which gravel content is approximately <60%. Same as the SG1 soil category identified by Khaleel and Freeman (1995)	HGD
	Gravel	Hrg	Very high gravel content soils (>60% gravel) from the 100 areas (along the river).	HGD(c)
Cold Creek unit (formerly referred to as the Plio-Pliestocene unit)	Silt Dominated	PPlz	Derived from the SS soil category identified by Khaleel and Freeman (1995) but correlated to Cold Creek unit silt. Includes additional samples from borehole B8814.	CCUf(lam-msv)
	Caliche	PPlc	Derived from the SS soil category identified by Khaleel and Freeman (1995) but correlated to the Cold Creek unit carbonate.	CCUf-c(calc)
Ringold Formation	Gravel Dominated	Rg	Sandy gravel for which gravel content is approximately >60%. Same as the SG2 soil category identified by Khaleel and Freeman (1995).	Rwi(e)

The statistical distributions of van Genuchten model (van Genuchten 1980) parameters (α, n, θ_R, θ_s, S_r), saturated hydraulic conductivity (K_s), and bulk density data were developed from laboratory data described in a catalog of vadose zone hydraulic properties by Freeman et al. (2001, 2002), and a subsequent prototype database (Freeman and Last 2003). Ideally, all parameters in this database should be based on gravel-corrected data derived using the same gravel-correction procedure. Some of the parameters are known to have been based on gravel-corrected data derived using the Gardner method (e.g., Khaleel and Relyea 1997), but it is not clear that all samples were treated in a consistent manner.

Gravel percentages are included in Tables 4.5 to 4.9 to indicate which soil classes might be affected. Future revisions of this database should address any disparity that might exist among samples. Values for residual saturation (S_r) are statistically derived from the sample population where the raw residual water content (θ_R) for an individual sample was divided by the raw saturated content (θ_S) for that sample. Effective porosity is assumed to be equal to the saturated water content (θ_s).

Table 4.5. Statistical Mean Values for Site-Wide Samples

Site Wide									
Soil Class	Count	α (1/cm)	n	θ_R (cm^3/cm^3)	θ_s (cm^3/cm^3)	K_s (cm/sec)	S_r	% gravel	Bulk Density (g/cm^3)
Bf	6	0.019	1.400	0.030	0.262	5.98E-04	0.103	33.5	1.94
Hss	38	0.008	1.915	0.072	0.445	8.58E-05	0.162	0.2	1.61
Hfs	36	0.027	2.168.	0.032	0.379	3.74E-04	0.086	0.6	1.60
Hcs	81	0.061	2.031	0.027	0.349	2.27E-03	0.080	2.6	1.67
Hgs	16	0.014	2.120	0.033	0.238	6.65E-04	0.140	25.8	1.94
Hg	28	0.017	1.725	0.022	0.167	3.30E-04	0.134	51.4	1.93
Hrg	40	0.007	1.831	0.020	0.102	1.46E-03	0.200	67.6	1.97
PPlz	9	0.005	2.249	0.040	0.419	5.57E-05	0.097	0.4	1.68
PPlc	14	0.011	1.740	0.054	0.281	8.45E-04	0.185	16.7	1.72
Rg	18	0.008	1.660	0.026	0.177	4.13E-04	0.135	46.1	1.90

Table 4.6. Statistical Mean Values for BC-Crib Samples

BC Cribs									
Soil Class	Count	α (1/cm)	n	θ_R (cm^3/cm^3)	θ_s (cm^3/cm^3)	K_s (cm/sec)	S_r	% gravel	Bulk Density (g/cm^3)
Bf	6	0.019	1.400	0.030	0.262	5.98E-04	0.103	32.5	1.94
Hfs_BC	18	0.201	2.507	0.033	0.380	2.25E-03	0.089	0.4	1.65
Hcs_BC	46	0.072	2.047	0.026	0.357	5.32E-03	0.074	2.7	1.67

Table 4.7. Statistical Mean Values for U1 and U2 Samples

U1 and U2									
Soil Class	Count	α (1/cm)	n	θ_R (cm^3/cm^3)	θ_s (cm^3/cm^3)	K_s (cm/sec)	S_r	% gravel	Bulk Density (g/cm^3)
Bf	6	0.019	1.400	0.030	0.262	5.98E-04	0.103	32.5	1.94
Hss_U	6	0.007	2.347	0.066	0.437	2.49E-05	0.147	0.0	1.58
Hfs_U	4	0.013	2.451	0.042	0.347	1.71E-05	0.122	0.0	1.72
Hg_U	3	0.011	1.845	0.029	0.150	2.88E-04	0.204	57.1	2.09
PPlz_U	5	0.004	2.285	0.047	0.398	7.27E-06	0.117	0.1	1.71
Rg_U	7	0.014	1.675	0.047	0.315	7.83E-05	0.138	16.5	1.82

Table 4.8. Statistical Mean Values for 200-ZP-1 Samples

200-ZP-1									
Soil Class	Count	α (1/cm)	n	θ_R (cm^3/cm^3)	θ_s (cm^3/cm^3)	K_s (cm/sec)	S_r	% gravel	Bulk Density (g/cm^3)
Bf	6	0.0191	1.400	0.030	0.262	5.98E-04	0.103	32.5	1.94
Hss_Z	5	0.003	1.840	0.047	0.351	6.55E-06	0.133	0.0	1.80
Hfs_Z	4	0.008	1.903	0.042	0.366	7.88E-05	0.113	0.8	1.68
Hcs_Z	5	0.067	1.692	0.021	0.292	1.49E-03	0.069	0.0	1.56
Hg_Z	8	0.016	1.703	0.022	0.155	3.65E-03	0.133	53.4	1.79
PPlz_Z	4	0.007	2.203	0.033	0.448	7.11E-04	0.073	1.0	1.58
PPlc_Z	13	0.011	1.750	0.056	0.286	1.03E-03	0.190	15.07	1.68

Table 4.9. Statistical Mean Values for 200 West Area Samples

200W									
Soil Class	Count	α (1/cm)	n	θ_R (cm^3/cm^3)	θ_s (cm^3/cm^3)	K_s (cm/sec)	S_r	% gravel	Bulk Density (g/cm^3)
Bf	6	0.032	1.4	0.03	0.262	1.50E-02	0.102	32.5	1.94
Hss_2W	11	4.53E-03	2.116	0.057	0.398	1.91E-05	0.141	0.00	1.67
Hfs_2W	8	1.02E-02	2.177	0.042	0.356	3.67E-05	0.118	0.38	1.70
Hcs_2W	7	4.15E-02	1.759	0.026	0.318	1.09E-03	0.077	2.14	1.65
Hgs_2W	2	7.90E-03	2.223	0.030	0.273	2.35E-04	0.133	24.00	1.81
Hg_2W	12	1.65E-02	1.745	0.027	0.154	1.48E-03	0.172	54.36	1.89
PPlz	9	5.57E-03	2.101	0.034	0.420	5.57E-05	0.080	0.44	1.68
PPlc	16	1.08E-02	1.727	0.072	0.306	5.00E-04	0.214	16.73	1.71
Rg_2W	8	1.32E-02	1.753	0.126	0.297	1.06E-04	0.334	22.18	1.84

The high, low, mean, and standard deviation values were calculated for each soil hydraulic property class. However, most of these soil classes do not have enough data points to qualify as a statistically significant distribution (Warrick et al. 1986). The residual water content (θ_r), saturated water content (θ_s), bulk density (ρ_b), gravel content, and fitting parameter n are assumed as normal Gaussian distributions based, in part on the report of Khaleel and Freeman (1995). The saturated hydraulic conductivity (K_s) and the fitting parameter α, are treated as lognormal distributions, in accordance with Domenico and Schwartz (1990) and Carsel and Parrish (1988), respectively. In addition to the normal distribution statistics, the statistics for the log-normal parameters are also included and truncation values are calculated for all parameters. Although Carsel and Parrish (1988) have reported cross-correlations between a number of these parameters, recent examination of the Hanford Site data have not found any statistically significant correlations.[12]

In addition to statistical tables for the full suite of samples, subsets of samples were also assembled near specific areas of interest; specifically, 200 West Area, BC cribs and trenches, 200-UP-1 (216-U-1

[12] Freeman EJ and ML Rockhold. 2003. *Estimation of Site-Specific Probability Distribution Functions for Soil Hydraulic Parameters using Bayesian Updating*. Letter Report, Pacific Northwest National Laboratory, Richland, Washington.

and -2 cribs), and the 200-ZP-1 (216-Z-9 trench). The site-specific data for the 216-U-1 and -2 cribs were derived from the S-SX Tank Farm, 216-U-1 and -2 crib, and Environmental Restoration Disposal Facility samples. The 216-Z-9 site-specific data consists of samples from the T, TX-TY Waste Management Area, the 216-ZP-1 area, the 218-W-5 burial grounds, and project C-018-H. A composite table of all 200 West Area samples was created to provide a greater sample population that is unique to the unsaturated hydraulic properties of sediments found beneath the 200 West Area. The site-specific data for the BC cribs and trenches are derived from the closest sites to that facility, the immobilized low-activity waste (ILAW) site, the Sisson and Lu Injection test site, and the U.S. Ecology site. A disadvantage to including only those sample sets close to the site of interest is that the population size is greatly diminished, resulting in cases where the statistical distribution may not adequately represent the actual formation properties.

Methods to increase the sample size (e.g., use an inverse distance weighting)[13] or otherwise incorporate information from large data sets (e.g., Bayesian Updating),[13] and yet still account for site-specific information are being examined. However, for the purposes of this data package, the site-specific parameter distributions are based on equally weighted parameter values from samples nearest the site of interest. Tables 4.5 to 4.9 present mean hydraulic property estimates for the Hanford site-wide data set as well as the site-specific data sets.

4.2.1 Site-Wide Hydraulic Property Distributions

The site-wide sample distribution (Table 4.5) uses all the data in each of the soil classes to calculate the statistical mean van Genuchten parameters that were then used to generate the hydraulic properties curves shown in Figures 4.1, 4.2, and 4.3. Figure 4.1 shows that the Hanford formation silty sand (Hss) and the Cold Creek unit silt (PPlz) attain the highest saturated water content, while the Hanford formation coarse gravels (Hrg) and Hanford formation sandy gravels (Hg) have the lowest water content. Table 4.5 illustrates that the finer textured sediments typically have greater saturated water content, lower saturated hydraulic conductivity and lower bulk density. In contrast, the coarser sediments typically have lower saturated water contents, higher saturated hydraulic conductivity, and higher bulk densities. The properties in Table 4.5 and Figure 4.1 represent matrix characteristics and do not account for preferential flow through cracks and fractures (Freeman et al. 2002; Freeman and Last 2003).

Uncertainties arise from the following: drilling and sampling methods used to collect the samples (e.g., core barrel, splits poon), how the samples are handled in the lab (e.g., repacked), subjectivity in assigning the samples to various geologic formations and facies (i.e., soil classes), systematic or measurement errors associated with the laboratory analyses, and scaling issues when using small sample data to represent larger field scale processes.

The saturated hydraulic conductivity is highest for the Hanford coarse gravel (Hrg) and lowest for the silty Cold Creek unit (PPlz) and Hanford formation silty sand (Hss). The hydraulic conductivity as a function of pressure head (Figure 4.2) does not drop off rapidly as would be expected for some of the coarse textured sediment (e.g., Hrg). This may indicate a higher fraction of fines than accounted for in those samples.

[13] Freeman EJ. May 14, 2003. *Revised SAC Statistical Properties Tables of Vadose Hydraulic Propertie*s. Letter Report, Pacific Northwest National Laboratory, Richland, Washington.

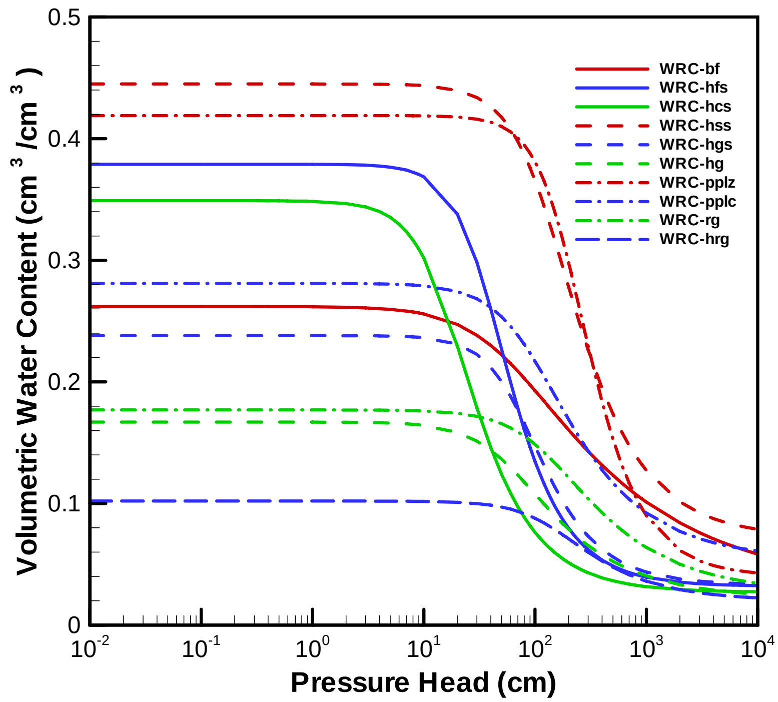

Figure 4.1. Statistically Derived Water Retention Functions Calculated from the van Genuchten Parameters for Each Soil Class in the Site-Wide Distribution (see Table 4.5) (Note that pressure head is negative.)

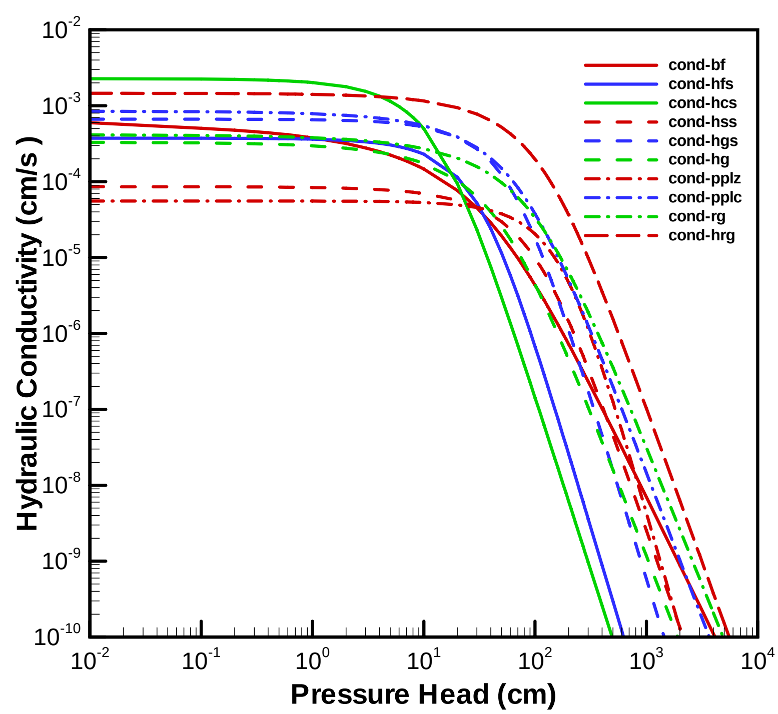

Figure 4.2. Soil Class Specific Hydraulic Conductivity Curves for the Site-Wide Distribution Derived from the Saturated Hydraulic Conductivity (K_s) Values Listed in Table 4.5 Using the Mualem Equation (Note that pressure head is negative.)

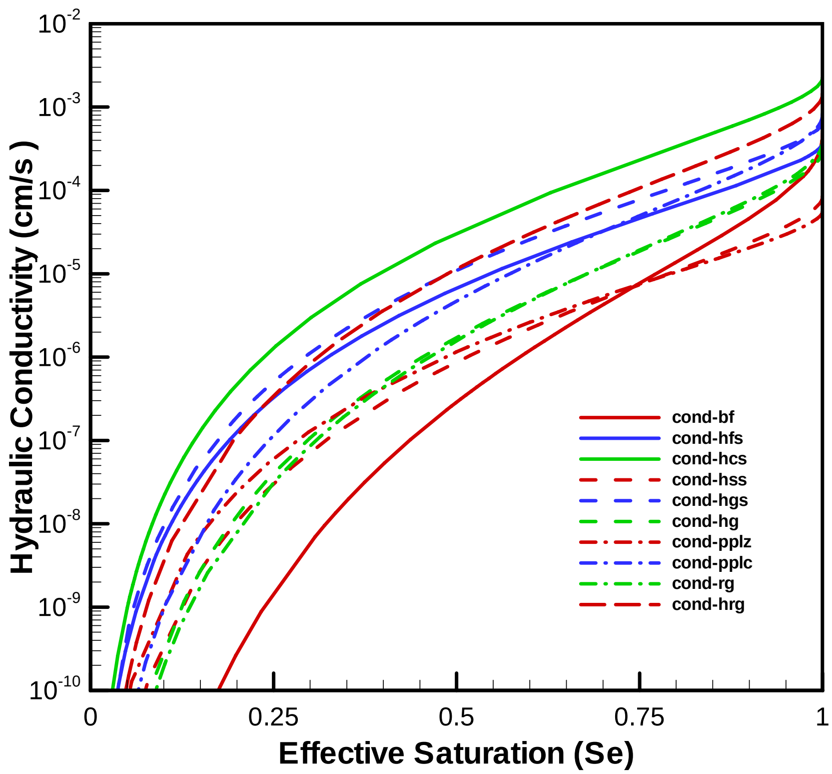

Figure 4.3. Soil Class Specific Hydraulic Conductivity Curves Versus Effective Saturation for the Site-Wide Distribution

4.2.2 Site-Specific Hydraulic Property Distributions

When evaluating the hydraulic properties at a particular location it is valuable to only use those data that are most representative of the hydraulic properties at that site. Three sites were selected for generation of site-specific hydraulic properties data sets: (1) the BC cribs and trenches, (2) the 216-U-1 and -2 crib area, and (3) the 216-Z-9 trench area. A fourth set of hydraulic property data was generated for all 200 West Area samples. Tables 4.6 to 4.9 list the mean hydraulic property data derived for each of these specific areas. Appendix B provides the hydraulic property distributions for the each site-wide and site-specific soil class.

4.2.3 Application to Vadose Zone Simulations

Each vadose zone hydrostratigraphic template represents a one-dimensional soil column made up of several hydrostratigraphic units. Each hydrostratigraphic unit occupies a number of model nodes depending on the thickness of the hydrostratigraphic unit. The hydraulic properties for each hydrostratigraphic unit are determined by stochastically sampling the probability distribution function for each parameter, for a given simulation (realization). All model nodes within a single hydrogeologic unit are assigned the same hydraulic properties for a single realization.

4.2.3.1 Conditioning of One-Dimensional Flow Simulations Against Detailed Site-Specific Assessments

Several studies were conducted to examine multiple hydrostratigraphic models and two-dimensional vadose zone simulations of selected waste sites where previous one-dimensional simulations failed to provide reasonable results. One of the main areas of interest was the BC cribs and trenches. Here multiple hydrostratigraphic profiles (templates) were developed to generate reasonable two-dimensional representations of the vadose zone. Multiple two-dimensional flow simulations were conducted to provide the basis with which to estimate the wetted column area needed as input for one-dimensional flow and transport simulations (Appendix C). Additional work was aimed at trying to incorporate the up-scaling techniques developed through the Science and Technology Project (Zhang et al. 2002) to improve hydraulic property estimates for the BC crib and trench area.

Another main area of interest was the 216-U-1 and -2 cribs. Here, the approach taken was to model this site as two separate sites to account for the multiple release mechanisms. Field data indicate this location experienced a fast path release (perhaps due to flow through a borehole annulus or similar mechanism) that allowed a significant quantity of contamination to effectively bypass the vadose zone and travel directly to the unconfined aquifer. Because the mechanism for this fast path is not characterized, the 216-U-1 and -2 site was modeled with an empirical two-site arrangement wherein a duplicate site, "216-U-1 and -2-Fast" was defined that uses a special hydrostratigraphic template that immediately releases any waste it receives directly to groundwater. No waste is routed to this "fast" site by the inventory model. However, a 'remedial action' is declared in the overall SAC model input set that declares that a fraction of the waste in the vadose zone in the year of the suspected fast path event (1988) is to be 'remediated' from 216-U-1 and -2 site and sent to the 216-U-1 and -2-Fast site (which effectively sends it immediately to the unconfined aquifer). The fraction transferred to the aquifer using this mechanism was determined by dividing the estimated contaminant mass in the aquifer after the fast path event (as determined by history matching data prepared by Murray et al. [2004]) by the total mass in the vadose zone at 216-U-1 and -2 in 1988 (as modeled in an initial median-inputs simulation of the 216-U-1 and -2 site). Thus, the model is effectively forced to deliver the field-observed mass of contaminant directly from the vadose zone to groundwater in a single event in 1988.

Several other sites (e.g., IDF [formerly the Immobilized Low-Level Activity Waste facility] and the tank farms) were the subject of more detailed site-specific performance assessments. Thus, efforts were made to incorporate the results of these performance assessments more directly into large-scale Hanford assessments so that the central tendency of the results mimics the deterministic results from these site-specific assessments. None of these more detailed site-specific performance assessments are stochastic, so the results are used directly in SAC median-inputs runs in place of the embedded STOMP one-dimensional model results. The results are also used to calibrate the STOMP one-dimensional model at these sites so that the stochastic simulations will better mimic the expected behavior of the site-specific assessments where they run stochastically with the SAC data. This is done by comparing the release rates of the median-inputs STOMP model in SAC for these sites to the more-detailed site-specific modeling results for a range of vadose zone wetted area scaling factors, and choosing the factor that results in the best agreement for use in later stochastic simulations. This is similar to the approach used for the BC cribs and trenches in which the one-dimensional model used in SAC was calibrated against idealized two-dimensional models.

4.2.4 Transport Parameters

The two key parameters that govern transport of non-sorbed contaminants in the subsurface are the dispersion coefficient and the species-specific water-content-dependent diffusion coefficient. Dispersion is the mixing and spreading of contaminants that is caused by variations in water velocity. The dispersion process is represented by the dispersion coefficient, which relates the dispersive solute flux to the solute concentration gradient. The dispersion coefficient is the product of dispersivity (λ) and pore water velocity. At the scale of soil core or laboratory column, the dispersivity reflects the variation in water velocity within pores and around grains and is sometimes called microdispersivity. In field settings, interbedding and interfingering of materials with different conductivities creates additional variations in water velocity that lead to higher dispersivities. These field-based values are typically referred to as macrodispersivities; it is these values that are needed for Hanford assessments.

The value of dispersivity depends on the direction of water flow. Longitudinal dispersivity addresses dispersion that occurs in the direction of flow. Transverse dispersivity addresses dispersion that occurs orthogonal to the direction of flow. Longitudinal dispersivity is typically larger than transverse dispersivity and both are scale dependent (Khaleel et al. 2002). Field measurements of dispersivity (i.e., macrodispersivity) are extremely rare and small-scale laboratory measurements have only marginal utility in estimating field values (Meyer et al. 2004). Estimates of longitudinal macrodispersivity for large-scale Hanford assessments were primarily taken from Ho et al. (1999) and are presented with the hydraulic property data in Appendix B. In the absence of data, longitudinal macrodispersivity values are often based on simple guidelines related to the size of the computational elements in numerical simulation codes. These simple guidelines (based on the work by Gelhar et al. 1985), generally assume that the vertically oriented longitudinal macrodispersivity is 0.01 times thickness (length) of the computational element.

Dispersion during transport of contaminants can potentially be enhanced when the contaminants react with either the sediments or the fluid or gas constituents. Although not entirely understood (e.g., Khaleel and Heller 2003), enhanced macrodispersion has been estimated at specific sites at Hanford. For example, the modeling data package for the S-SX FIR (Khaleel et al. 2001) suggested that dispersion of cesium was enhanced by 10 to 15% for all but the Cold Creek (a.k.a Plio-Pleistocene) unit, for which the enhancement factor was roughly a factor of 2. Enhanced macrodispersion is not addressed in the current version of the Hanford assessment tool but will be considered for future versions.

The diffusion coefficient is the proportionality factor in Fick's Law that relates the diffusive transport flux to the gradient in solute concentration (Meyer et al. 2004). According to Meyer et al. (2004), the diffusion process results in mass transport from regions of high solute concentration to regions of lower concentration and occurs as a result of the random thermal motion (Brownian motion) of molecules and atoms. The diffusion process will be represented in large-scale Hanford assessments.

In the subsurface environment, porous medium and the water content affect the diffusion process. Thus, the effective diffusion coefficient $D_{\ell e}^{C}$ is computed using a conventional approach (White and Oostrom 2000):

$$D_{\ell e}^{C} = \tau_{\ell} s_{\ell} n_{D} D_{\ell}^{C}$$

where: τ_{ℓ} = the liquid phase tortuosity
s_{ℓ} = the liquid phase saturation
n_D = the diffusive porosity
D_{ℓ}^{C} = the aqueous-phase molecular diffusion coefficient at 20°C

The liquid phase tortuosity τ_{ℓ} is computed from the methods of Millington and Quirk (1959) based on theoretical pore-size distribution models for partially and fully saturated two-phase systems (White and Oostrom 2000):

$$\tau_{\ell} = (n_D)^{10/3} (s_{\ell})^{4/3}$$

The liquid phase saturation s_{ℓ} is computed from van Genuchten constitutive relations (van Genuchten 1980) that estimates aqueous-phase saturation as a function of liquid phase pressure, a state variable of the governing equations solved by the STOMP simulator. The diffusive porosity is an input parameter provided for each soil type by this data package; for Hanford assessments conducted using SAC Rev. 1, diffusive porosity is assumed equal to total porosity, n_T ,(which is represented by the saturated water content, θ_s, as provided in Appendix B and described earlier in this section). The aqueous-phase molecular diffusion coefficient at 20°C is 1.05 x 10^{-5} cm^2/s.

4.3 Contaminant Distribution Coefficients

Geochemical properties were assigned to each hydrogeologic unit, in a manner similar to that in the 1998 Composite Analysis (Kincaid et al. 1998). The waste characteristics were assumed to dominate the near-field mobility of the contaminants in the vadose zone. After being in contact with vadose zone sediments and soil water for some distance, the waste undergoes a change in its mobility based on buffering of the contaminant solution by the vadose zone sediments. Thus, distribution coefficients were defined separately for each contaminant in the upper vadose zone (near-field or high impact zone) and in the lower vadose zone (far-field or intermediate impact zone) (Kincaid et al. 1998).

Distribution coefficient zones were defined as either high impact or intermediate impact depending on the nature of the contamination fluid. Zones in which the organic concentration, pH, or salt concentration in the fluids may have affected the K_d values were designated high-impact. Zones in which the acidic or basic nature of the wastes was estimated to have been neutralized by the natural soil were designated intermediate impact. Kincaid et al. (1998) estimated the depths of this transition zone by examining the peak location of beta/gamma contamination (as presented by Fecht et al. 1977) for the 200 Area cribs receiving very acid or high-salt/very basic waste. In general, these transition depths ranged from 10 to 40 m. Given the limited data available on which to base further interpretations on the depths of transition, and the desire to simplify the numerical simulations, a slightly different approach is used here. Generally, the hydrogeologic unit into which waste streams were introduced was designated as high-impact regardless of waste stream characteristics. If those hydrogeologic units were thin (e.g., <3 m), then the hydrogeologic unit immediately below was also designated high-impact. All other hydrogeologic units lower in the profile were designated intermediate impact. This approach enables us to keep the numerical simulations relatively simple by using the existing number of hydrogeologic units (i.e., we did not have to add new layers to make the K_d change within a single hydrogeologic unit). At the same time, the depths of change, corresponding to the thickness of the hydrogeologic units, are still on the same scale (tens of meters) as those used by Kincaid et al. (1998). Appendix A provides the detailed hydrogeologic columns and locations of the various K_d zones, for each base template.

As described in Section 3.2.3, several K_d classes were defined for mapping distribution coefficients to high or intermediate impact zones and chemical waste type. These K_d classes were labeled using a two or three digit alpha-numeric code. The first digit represents the waste chemistry type (numbers 1 through 6) (see Table 3.5). The second digit represents the impact zone (i.e., H for high impact [i.e., near field vadose zone], I for intermediate impact [i.e., far field vadose zone], or G for the zone not impacted [i.e., very far field vadose] and groundwater). For K_d values in the intermediate impact zone, a third digit was added to identify those K_d classes adjusted for the gravel-dominated hydrostratigraphic units. Since significant gravel content decreases K_d values (Kaplan and Serne 2000), each K_d class in the intermediate impact zone was subdivided into gravel rich and gravel poor zones. K_d classes with a third digit of '1' pertain to gravel poor (i.e., sand-dominated) strata and K_d classes ending in a '2' pertain to gravel rich (i.e., gravel dominated) strata (See Section 3.2.3).

Kincaid et al. (2004) identified sixteen radionuclides as contaminants of concern to be addressed in a large-scale Hanford assessment, see Table 4.10. However, two of these radionuclides, radium-226 and protactinium-231 are to be simulated as progeny of uranium-234 and uranium-238, and will not be directly incorporated into the flow and transport simulations for large-scale Hanford assessments. Thus, K_d estimates were not developed for those contaminants. For all other contaminants of interest, a best estimate K_d value and range (minimum and maximum) were developed for each K_d class. A brief discussion for each contaminant is presented below. Probability distribution functions for these K_d values were generated according to the following set of rules and derived from the minimum, maximum, and best estimate K_d values.

Case #1: Where the minimum estimate, best estimate, and maximum estimate were all greater than zero, a lognormal distribution was assumed. The best estimate was assigned to the median value. The minimum estimate was assigned to the lower 1% tail of the distribution, and the maximum estimate was not used in defining the distribution.

Case #2: Where the minimum estimate was zero, but the best estimate and maximum estimate were greater than zero. A lognormal distribution was used, with the best estimate assigned to the median value, the lower 1% tail of the distribution assigned to the value 0.001, and the maximum estimate used to define a probability truncation limit for the upper tail of the distribution (if less than 0.99 probability, otherwise truncation was set to 0.99).

Case #3: Where the minimum and best estimates were zero, but the maximum estimate was greater than zero. A composite distribution was used. The value zero was assigned a 50% probability. The other portion of the distribution was assigned a triangular distribution where the minimum and mode were both zero and the maximum was assigned to the upper tail estimate.

Case #4: Where the best estimate is 'unsuitable' or not provided, a uniform distribution is assumed between the minimum and maximum values.

Table 4.10. List of Contaminants of Concern to be Included in large-scale Hanford assessments (Kincaid et al. 2004)

Contaminants of Concern	
Tritium	Carbon-14
Chlorine-36	Selenium-79
Strontium-90	Technetium-99
Iodine-129	Cesium-137
Europium-152[(a)]	*Radium-226*[(b)]
Protactinium-231[(c)]	Uranium-233
Uranium-234[(d)]	Uranium-235[(e)]
Uranium-238[(d)]	Neptunium-237

(a) Europium-152 will be simulated using median values in a deterministic simulation. Because of its relatively short decay half-life, the simulation will extend at most two or three hundred years beyond Hanford Site closure.
(b) Radium-226 will be simulated as progeny of uranium-234 and uranium-238. It will be further evaluated in Hanford assessments because the chemical separation for uranium may have placed radium-226 in Hanford waste at levels not in secular equilibrium with the uranium in the waste.
(c) Protactinium-231 will be simulated as progeny of uranium-238. It will be further evaluated in Hanford assessments because the chemical separation for uranium may have placed protactinium-231 in Hanford waste at levels not in secular equilibrium with the uranium in the waste.
(d) Uranium-238 and uranium-234 will be summed and shown as uranium-238 to represent both in this simulation. It is assumed that these two uranium isotopes are always in secular equilibrium.
(e) Uranium-235 is modeled separately to properly generate protactinium-231 through radioactive decay and progeny ingrowth.

In those cases where a lognormal distribution was assumed, the lognormal distributions were truncated at the 1% and 99% levels, thereby preventing the generation of values that could fall below the minimum estimate.

Table 4.11 provides the current compilation of distribution coefficients for each waste stream category and impact zone (derived from the Contaminant Distribution Coefficient Database and Users Guide by Cantrell et al. 2002, 2003a). The hydrostratigraphic templates provided in Appendix A identify the K_d classes assigned to each hydrostratigraphic unit for each geographic and site-specific area. As with the hydraulic parameters, all model nodes within a single hydrogeologic unit are assigned the same K_d values for a given realization.

4.3.1 Tritium

The best estimates for K_d values of tritium are zero, and the ranges were selected to be zero for all source and impact zone categories. It is assumed that tritium atoms are incorporated into water molecules and, as a result, no adsorption or other significant geochemical interactions are expected.

4.3.2 Carbon-14

Under typical Hanford conditions, it is assumed that carbon-14 will occur predominately as the bicarbonate ion ($H^{14}CO_3^-$), though at high pH bicarbonate will deprotonate to carbonate ($^{14}CO_3^{2-}$) and at low pH will protonate to form $^{14}CO_2(aq)$. In general, adsorption of any anion (through surface complexation) onto Hanford sediment in the alkaline pH range is expected to be negligible because the pH point

Table 4.11. Contaminant Distribution Coefficient Estimates by Waste Chemistry Type

Waste Chemistry/Source Category 1: Very Acidic									
	High Impact (1H)			Intermediate Impact – Sand (1I1)			Intermediate Impact – Gravel (1I2)		
	Kd Estimate (mL/g)			Kd Estimate (mL/g)			Kd Estimate (mL/g)		
Analyte	Best	Min	Max	Best	Min	Max	Best	Min	Max
Non-Adsorbing Radionuclides									
H3	0	0	0	0	0	0	0	0	0
Tc99	0	0	0.1	0	0	0.1	0	0	0.01
Cl36	0	0	0	0	0	0	0	0	0
Moderately Adsorbing									
I129	4	0	15	0.2	0	2	0.02	0	0.2
U238	0.2	0	4	0.8	0.2	4	0.08	0.02	0.4
Se79	5	3	10	5	3	10	0.5	0.3	1
Np237	0	0	2	10	2	30	1	0.2	3
C14	0	0	0	0	0	100	0	0	100
Highly Adsorbing									
Sr90	10	5	15	22	10	50	6.8	3.1	15.5
Cs137	1000	200	10000	2000	200	10000	620	62	3100
Pu239	0.4	0.1	1	600	200	2000	186	62	620
Eu152	20	1	100	200	10	1000	62	3.1	310

Waste Chemistry/Source Category 2: Very High Salt/Very Basic									
	High Impact (2H)			Intermediate Impact - Sand (2I1)			Intermediate Impact – Gravel (2I2)		
	Kd Estimate (mL/g)			Kd Estimate (mL/g)			Kd Estimate (mL/g)		
Analyte	Best	Min	Max	Best	Min	Max	Best	Min	Max
Non-Adsorbing Radionuclides									
H3	0	0	0	0	0	0	0	0	0
Tc99	0	0	0.1	0	0	0.1	0	0	0.01
Cl36	0	0	0	0	0	0	0	0	0
Moderately Adsorbing									
I129	0.02	0	0.2	0.1	0	0.2	0.01	0	0.02
U238	0.8	0.2	4	0.8	0.2	4	0.08	0.02	0.4
Se79	0	0	0.1	0	0	1	0	0	0.1
Np237	200	100	500	200	100	500	200	100	500
C14	100	0	100	7	0	100	7	0	100
Highly Adsorbing									
Sr90	22	10	50	22	10	50	6.8	3.1	15.5
Cs137	10	0	500	100	10	1000	31	3.1	310
Pu239	200	70	600	600	200	2000	190	62	620
Eu152	200	10	1000	200	10	1000	62	3.1	310

Table 4.11. (contd)

Waste Chemistry/Source Category 3: Chelates/High Salts									
	High Impact (3H)			Intermediate Impact – Sand (3I1)			Intermediate Impact – Gravel (3I2)		
	Kd Estimate (mL/g)			Kd Estimate (mL/g)			Kd Estimate (mL/g)		
Analyte	Best	Min	Max	Best	Min	Max	Best	Min	Max
Highly Mobile Elements									
H3	0	0	0	0	0	0	0	0	0
Tc99	0	0	0.1	0	0	0.1	0	0	0.01
Cl36	0	0	0	0	0	0	0	0	0
Somewhat Mobile Elements									
I129	0.2	0	2	0.2	0	2	0.02	0	0.2
U238	0.2	0	4	0.8	0.2	4	0.08	0.02	0.4
Se79	0	0	0.1	0	0	1	0	0	0.1
Np237	2	1	15	5	2	30	0.5	0.2	3
C14	0	0	100	0	0	100	0	0	100
Moderately Immobile Elements									
Sr90	1	0.2	20	10	5	20	3.1	1.6	6.2
Cs137	10	0	500	100	10	1000	31	3.1	310
Pu239	10	1	100	600	200	2000	190	62	620
Eu152	20	1	100	200	10	1000	62	3.1	310

Waste Chemistry/Source Category 4: Low Organic/Low Salt/Near Neutral												
	High Impact (4H)			Intermediate Impact – Sand (4I1)			Intermediate Impact – Gravel (4I2)			Groundwater (4G)		
	Kd Estimate (mL/g)			Kd Estimate (mL/g)			Kd Estimate (mL/g)			Kd Estimate (mL/g)		
Analyte	Best	Min	Max	Best	Min	Max	Best	Min	Max	Best	Min	Max
Highly Mobile Elements												
H3	0	0	0	0	0	0	0	0	0	0	0	0
Tc99	0	0	0.1	0	0	0.1	0	0	0.01	0	0	0.1
Cl36	0	0	0	0	0	0	0	0	0	0	0	0
Somewhat Mobile Elements												
I129	0.2	0	2	0.2	0	2	0.02	0	0.2	0.2	0	2
U238	0.8	0.2	4	0.8	0.2	4	0.08	0.02	0.4	0.8	0.2	4
Se79	5	3	10	5	3	10	0.5	0.3	1	5	3	10
Np237	10	2	30	10	2	30	1	0.2	3	10	2	30
C14	0	0	100	0	0	100	0	0	10	0	0	100
Moderately Immobile Elements												
Sr90	22	10	50	22	10	50	7	3	16	22	10	50
Cs137	2000	200	10000	2000	200	10000	620	62	3100	2000	200	10000
Pu239	600	200	2000	600	200	2000	190	62	620	600	200	2000
Eu152	200	10	1000	200	10	1000	62	3.1	310	200	10	1000

Table 4.11. (contd)

Waste Chemistry/Source Category 5: IDF Vitrified Waste									
Analyte	High Impact (5H)			Intermediate Impact - Sand (5I1)			Intermediate Impact - Gravel (5I2)		
	Kd Estimate (mL/g)			Kd Estimate (mL/g)			Kd Estimate (mL/g)		
	Best	Min	Max	Best	Min	Max	Best	Min	Max
Non-adsorbing Radionuclides									
H3	0	0	0.1	0	0	0.1	0	0	0.01
Tc99	0	0	0.1	0	0	0.1	0	0	0.01
Cl36	0	0	0.1	0	0	0.1	0	0	0.01
Moderately Adsorbing									
I129	0.1	0.04	0.16	0.1	0	0.2	0	0	0.02
U238	0.2	0	800	0.2	0	500	0.2	0.02	5
Se79	1	0	3	2	0	10	0.04	0.02	1
Np237	0.2	0.1	4	0.8	0.2	5	0.08	0.04	0.5
C14	0	0	0	20	5	50	2	0.5	5
Highly Adsorbing									
Sr90	15	4	70	10	0.2	50	1	0.02	5
Cs137	1.5	1	25	80	40	2000	8	4	200
Pu239	10	5	100	200	80	1000	20	8	100
Eu152	5	2	10	350	100	1500	35	10	150

Waste Chemistry/Source Category 6: IDF Cementitious Waste									
Analyte	High Impact (6H)			Intermediate Impact - Sand (6I1)			Intermediate Impact - Gravel (6I2)		
	Kd Estimate (mL/g)			Kd Estimate (mL/g)			Kd Estimate (mL/g)		
	Best	Min	Max	Best	Min	Max	Best	Min	Max
Non-Adsorbing Radionuclides									
H3	0	0	0.1	0	0	0.1	0	0	0.01
Tc99	0	0	0.1	0	0	0.6	0	0	0.06
Cl36	0	0	0.1	0	0	0.1	0	0	0.01
Moderately Adsorbing									
I129	2	1	5	0.25	0	15	0.02	0	1.5
U238	100	70	250	1	0.1	4	1	0.01	7
Se79	1	0	300	7	3	15	0.7	0.3	1.5
Np237	200	140	500	15	2	25	1.5	0.2	2.5
C14	0	0	0	5	0.5	1000	0.5	0.05	100
Highly Adsorbing									
Sr90	10	7	25	14	5	200	1.4	0.5	20
Cs137	30	20	50	2000	500	4000	200	50	400
Pu239	500	100	1000	150	50	2000	15	5	200
Eu152	500	400	1000	300	60	1300	30	6	130

of zero charge (pzc) or pH_{pzc} for most minerals is below the typical pH of Hanford groundwater. For example, the pH_{pzc} for montmorillonite and feldspar is approximately 3 (Stumm and Morgan 1996). The pH_{pzc} for calcite (at $p_{CO2} = 10^{-3.5}$ atm) is approximately 8.2 and goes down to 6.5 at p_{CO2} = 1 atm. This indicates that Hanford sediments will be dominated by negatively charged sites in the alkaline pH range; conditions which are not conducive to adsorption of anions. This is clearly demonstrated with CrO_4^{2-} (Cantrell et al. 2002).

Although surface adsorption of $H^{14}CO_3^-$ or $^{14}CO_3^{2-}$ is not likely to be significant under Hanford conditions, two other processes could potentially remove these species from solution. These two mechanisms are isotopic exchange and precipitation. Calcite is common within Hanford sediment (often as caliche or mineral grain coatings) and is the most readily available carbonate phase for solid surface exchange with $^{14}CO_3^{2-}$. Like ion exchange, isotopic exchange can be written as a chemical reaction (Garnier 1985):

$$^{12}C_s + {}^{14}C_m = {}^{14}C_s + {}^{12}C_m \qquad (4.1)$$

where C_s and C_m refer to the carbon content in the stationary and mobile phases, respectively. The equilibrium constant can be defined as:

$$K(^{14}C/^{12}C) = [(^{14}C/^{12}C)_s/(^{14}C/^{12}C)_m] \qquad (4.2)$$

This equilibrium constant is a pure thermodynamic constant. At a given temperature, it leads to a selectivity that is based only on the mass difference. Application of this concept to selection of a K_d value for ^{14}C is problematic. Previous laboratory work using columns of a natural carbonate sand (aragonite and calcite) has demonstrated that the exchange process occurs at the first mono-molecular layer (Garnier 1985); however, the adsorption process was found to be complicated by kinetic and other factors. Kinetic factors that affected the results included flow rate and sediment aging. Adsorption of other ions such as HPO_4^- was also found to significantly reduce uptake of $H^{14}CO_3^-$ by the carbonate surfaces.

In addition to isotopic exchange, the migration of $H^{14}CO_3^-$ or $^{14}CO_3^{2-}$ could potentially be retarded through precipitation of sodium/calcium carbonates during exposure to high pH, high salt concentrations in high level waste within tanks, or released from leaking tanks or disposed in trenches. Because of the high pH conditions within the tanks, any CO_2 within the system will be in the form of CO_3^{2-}. As a result of the extremely high sodium concentrations within the tanks, most of the CO_3^{2-} will precipitate as Na_2CO_3. Initially the $^{14}CO_3^{2-}$ within the tanks is likely to be at trace concentrations and could be below the solubility limit; however, as CO_2 from the atmosphere enters the system from openings in the tank, Na_2CO_3 will precipitate, removing $^{14}CO_3^{2-}$ in the process. If a tank leak were to occur, this process would continue within the vadose zone as CO_2 from the atmosphere diffuses through the vadose zone into the tank leak impact zone.

Because of the complex processes that impact the mobility of ^{14}C, a simple linear adsorption model will not adequately describe its transport from a tank leak and through groundwater. As a result of these uncertainties with regard to $H^{14}CO_3^-$ or $^{14}CO_3^{2-}$ retardation within Hanford sediments, a large range in K_d values has been selected. The best estimate was taken to be zero and the minimum and maximum were taken to be zero and 100 ml/g, respectively.

4.3.3 Chlorine-36 (as chloride)

Chloride K_d value measurements are not available for Hanford sediment. This species is not expected to form complexes in Hanford groundwater, nor is it expected to undergo significant adsorption. Chloride is generally considered to exhibit conservative behavior. Measurements of chloride adsorption on clay, sandstone and granite indicated no adsorption (Stenhouse 1995). In acidic soil rich in kaolinite, and iron and aluminum hydrous oxides, some chloride adsorption can occur (Higgo 1988); however, Hanford sediment does not have these characteristics. As a result the minimum, maximum, and best value for the chloride K_d value is taken to be 0.0 ml/g.

4.3.4 Selenium-79 (as selenate)

A fair number of *Se(VI)* K_d values have been determined using natural Hanford sediment (Cantrell et al. 2002). These results indicate that at trace concentrations, adsorption of *Se(VI)* is low to moderate with K_d values ranging from 3 to 10 mL/g. At higher *Se(VI)* concentrations, the K_d values are lower (0 to 3 mL/g). Acidic conditions typically increase adsorption for anions such as selenate, but this cannot be confirmed for Hanford sediments with the available data. Basic conditions significantly reduce adsorption.

4.3.5 Strontium-90

The best estimate K_d value for strontium selected for most Hanford impact zones and source categories is 22 ml/g with a range of 10 to 50. In acidic high impact zones the best estimate is reduced to 10 ml/g with a range of 5 to 15. For the chelates/high salts waste category, the best estimate for the high impact zone is 1 ml/g with a range of 0.2 to 20 and for the intermediate impact zone the best estimate is 10 ml/g with a range of 5 to 20. It is expected that future work will incorporate ongoing multi-component ion exchange data to provide a more scientifically defensible approach for estimating K_d values for strontium-90.

4.3.6 Technetium-99 (as pertechnetate)

The best estimates for the K_d values of pertechnetate are zero. The ranges were taken to be from zero to 0.1 ml/g for all waste and impact zone categories (except gravel corrected). When comparing this range to values tabulated in Cantrell et al. (2002), the range may appear to be somewhat narrow; however, in most cases when higher K_d values were measured, the K_d values were not significantly greater than the standard deviation. As a result of this and the fact that it is known that pertechnetate is a very weak adsorbate, this narrow range for the K_d values was selected. It should be noted that in environments where reducing agents are present, significantly higher immobilization of pertechnetate could potentially occur that is not represented by this range of K_d values.

4.3.7 Iodine-129 (as iodide)

The best estimate value selected for the iodide K_d appropriate for most Hanford impact zones and waste categories is 0.2 ml/g with a range of 0 to 2. For acidic high impact zones, the best estimate value selected is 4 with a range of 0 to 15. Because pH effects resulting from acidic discharges were assumed to impact only the high impact zone categories, intermediate impact zones K_d values are assumed to be the same as for groundwater. High pH and high salt appear to reduce K_d values. This would result from increasing negative charges on sediment surfaces at high pH and increased competition with other anions at high salt concentrations. As a result, for high pH and high salt in the high impact zone a range of K_d values of 0 to 0.2 was selected with a best estimate of 0.02 ml/g. For the intermediate impact zone, the best estimate is 0.1 ml/g.

4.3.8 Cesium-137

For cesium, the best estimate K_d value selected for most Hanford impact zones and waste categories is 2,000 ml/g with a range of 200 to 10,000. For acidic source categories and high impact zones, the best estimate is reduced somewhat to 1,000 ml/g. For the high impact zones of the very high salt/very basic and chelates/high salts source categories, the best estimate is 10 ml/g with a range of 0 to 500; for the intermediate impact zone the best estimate is 100 ml/g with a range of 10 to 1,000. It is expected that future work will incorporate available multi-component ion exchange data to provide a more scientifically defensible approach for estimating K_d values for cesium-137.

4.3.9 Europium-152

K_d value data are not available for adsorption of Eu^{3+} on Hanford sediments; however, the chemistry of Eu^{3+} is very similar to Am^{3+} (Cantrell 1988; Allard 1982), so K_d data available for Am^{3+} adsorption onto Hanford sediments has been used as an analog for Eu^{3+} (Cantrell et al. 2002). Review of these data suggests a best estimate of 200 ml/g with a range of between 10 and 1,000.

4.3.10 Uranium

The best estimate K_d value for uranium selected for most Hanford impact zones and source categories is 0.8 ml/g, with a range of 0.2 to 4. For high impact zones with sources that are acidic or contain chelates, the best estimate value is reduced to 0.2 ml/g and with a range of 0 to 4. Although the K_d value for very basic conditions is taken to be the same across each impact zone, no reliable data are available at high pH (one measurement is available at pH 11, but precipitation of the uranium is believed to have occurred in this case).

4.3.11 Neptunium-237

Np(V) K_d values for Hanford sediment compiled in Cantrell et al. (2002) indicate *Np(V)* adsorption is generally moderate, with K_d values in the general range of 2 to 30 ml/g. Lower values can result at contact times of 1 day or less, and high calcium or chelate concentrations in solution. High solution pH values can result in very high K_d values; however, this may actually be due to precipitation. These results indicate that *Np(V)* migration from a tank leak should be minimal except when the tank wastes contain chelates. Moderate migration of *Np(V)* could occur in the vadose zone and groundwater under natural Hanford conditions. Because precipitation is the most likely removal mechanism for *Np(V)* retardation at high pH, the same range of high K_d values was used for the High Impact, Intermediate Impact and the Intermediate Impact – Gravel Zones of the Very High Salt/Very Basic waste category.

4.4 Hydrostratigraphic Templates

Of the more than 2,730 waste sites at Hanford and several storage sites, a subset of 1,052 sites has been selected for inclusion in a large-scale Hanford assessment. A unique alphanumeric identification tag (i.e., the site code as given in the Hanford WIDS system), was used to identify each waste site for vadose zone simulation. For example, the 241-T-106 tank was identified by its WIDS site code “241-T-106.” Initially each site was assigned to a hydrostratigraphic template based on its location within one of the 17 geographic areas, its site type (surface, near surface, tank, or injection well), and its waste chemistry designation. Other waste site-specific information (location, facility dimensions, and surface cover) was assigned to define the site-specific parameters needed to perform the vadose zone simulations (refer to Last et al. 2006, PNNL-14725, Rev. 1).

4.4.1 Assignment of Waste Chemistry Types

As described in Section 3.2.3, a waste chemistry designation was assigned to each facility to be simulated in the large-scale Hanford assessments. This assignment was based on the original waste chemistry designations used in the 1998 Composite Analysis (Kincaid et al. 1998) and translating these six waste chemistry categories to the six categories used in this study (see Section 3.2.3). In assigning waste chemistry designation to facilities not included in the 1998 Composite Analysis, the following approach was taken:

- Burial grounds, process sewers, ponds, retention basins, buildings, cooling water, stacks, steam condensate, and sand filters were assigned a 'low salt, near neutral' waste type (waste type 4).
- All 241 facilities (e.g., high-level waste tanks) were assigned to either a 'high salt, very basic' waste type (waste type 2) or were designated as containing 'chelates and high salt' (waste type 3) (Kincaid et al. 1998). This simplifying assumption to group essentially all tank waste into just two waste types on which to assign K_d values does have obvious limitations.
- Liquid waste facilities that lacked a waste type designation by Kincaid et al. (1998), were assigned a waste type based on waste descriptions by Maxfield (1979) and/or the various Source Aggregate Area Management Study Reports (e.g., DOE 1992; DOE 1993a, c, d, e).
- The WIDS was consulted for all remaining facilities. If the WIDS indicated a waste type description or source for the effluent discharged to a facility, the facility was assigned the comparable waste type based on professional judgment. In a few instances, WIDS provided no information and a waste type 4 was assigned.
- Unplanned releases associated with a facility were assigned the waste type given to the facility.
- Unplanned releases of solids (e.g., animal waste, contaminated equipment, particulates), and atmospheric releases were assigned waste type 4.
- Unplanned releases with insufficient information were assigned waste type 4.
- Petroleum spills are obviously high organic but they do not fit the idea of waste type 3. Therefore, petroleum spills were assigned waste type 4.

The waste chemistry designations for all facilities represented in Hanford assessments are provided in a master spreadsheet of site-specific parameters and model designations (the General Operational Site Parameters List [GOSPL], see Last et al. 2006).

4.4.2 Facility Location, Dimensions, and Wetted Area

The facility location is used to assign geohydrologic properties and specify where waste that is leaving the vadose zone enters the groundwater model. The locations of most waste facilities were obtained from the WIDS. If a facility location was not in WIDS at the time data was being gathered, the location was estimated using other available resources such as the *Hanford Site Waste Management Units Report* (DOE 2003), the *Hanford Site Atlas* (BHI 1998) and Maxfield (1979). Facility locations were assumed to be the centroid of the facility (in state-plane coordinates). Long linear facilities (such as ditches) generally do not have center coordinates listed in WIDS, so their coordinates were estimated based on visual inspection of the *Hanford Site Atlas* and/or other site maps.

The facility surface area (also called the facility footprint) was used to estimate the waste release area (e.g., the bottom area of a crib) and the dimensions of the surface barrier (if any). Facility surface areas of many sites were obtained from the WIDS. If the WIDS did not contain the facility surface area, the area was estimated using the facility length and width or the facility diameter. If no data were found to estimate facility area, a default value was assigned. The default values are combinations of three '9s' for easy recognition as default values. Table 4.12 lists the default values used for various site types.

Table 4.12. Default Surface Areas

Facility (site) Type	Default Area (m^2)
Unplanned Release, French Drain	0.999
Storage Tank, Trench	9.99
Radioactive Process Sewer, Crib	99.9
Burial Ground	999

The wetted column area (in essence, the wetted vadose zone area) represents the maximum areal extent of the waste as it migrates to the water table. For at least some sites, the facility area in WIDS represents the fenced boundary rather than the actual waste release area, which can be significantly smaller. It is also possible that the waste at some sites could spread laterally and extend beyond the facility boundaries. Until the waste-zone area of each individual waste site is determined, we will continue to assume, as was done for the 1998 CA (Kincaid et al. 1998), that the waste zone area equals the facility area. The result of this assumption is that, whenever the waste zone area is significantly smaller than the wetted column area, the source term will be dispersed over the larger wetted column and migrate downward more slowly. Conversely, when the waste zone area is larger than the wetted column, the source term will be dispersed over the smaller wetted column area and migrate downward more quickly.

In certain simulation cases, the volume of liquid disposed per facility area exceeds the capacity of the vadose zone to transmit it. Either the vadose zone sediments have very low conductivity values or the facility area is inordinately small (e.g., reverse [injection] wells listed as having a facility area equivalent to the borehole diameter). In the field, this situation would result in significant lateral spreading beyond the facility footprint. The impact of lateral spreading will be represented in large-scale Hanford assessments using the K_s-dependent approach. In this approach, the wetted vadose zone area $A_x(m^2)$ is related to the facility footprint by the scaling factor λ (dimensionless), as follows:

$$A_x = \lambda A_0 = \left[\frac{|Q_{max}|}{K_{s/min} A_0}\right] A_0;\ \lambda \geq 1 \tag{4.3}$$

where Q_{max} = the maximum artificial liquid discharge rate (m^3/s)
$K_{s|min}$ = the minimum hydraulic conductivity (m/s) of all layers for the given site and realization
A_0 = the facility area (m^2) from the WIDS database

The major assumptions underlying Equation 4.3 are that the vadose zone layer with the lowest K_s controls flow, a unit gradient is always present across the controlling layer, and flow is steady. The scaling factor, λ, is constrained by the SAC Environmental Settings Definition keyword file to be equal to or greater than 1.0 so that the effective area is not less than the facility footprint area, unless specified for a specific site. For example, λ is usually permitted to be less than 1.0 for the underground storage tanks, for which the actual wetted area from leaks is commonly less than the facility footprint. For most sites with little or no artificial discharges, λ usually resolves to 1.0 (no scaling) and hence the assigned WIDS area is used. For large-volume discharge sites, λ values greater than 1.0 are common.

4.5 Recharge Estimates

This section provides recharge (deep drainage) estimates for use in Hanford assessments. The recharge estimates were derived from a suite of available field data and computer simulation results (Fayer and Walters 1995; Murphy et al. 1996; Prych 1998; Fayer et al. 1999; Wittreich et al. 2003; Fayer and Szecsody 2004; Gee et al. 2005; Ward et al. 2005; Fayer and Gee 2006). The estimates do not account for overland flow from roadways or roofs, water line leaks, or any other manmade additions of water, the impacts wrought by future climate change or land use alterations, variations within soil types, or dune-sand deposition. The estimates were developed for fairly large geographic areas and may not represent the local recharge rates at specific locations. Estimates of manmade additions of water (i.e., liquid discharges) are provided by the Inventory Data Package for Hanford Assessments (Kincaid et al. 2006). However, at surface disposal sites such as ponds, ditches, and retention basins, evapotranspiration can reduce the volume that actually infiltrates into the subsurface and recharges the unconfined aquifer. Estimates of the evapotranspiration rates are discussed in Section 4.6.

The following sections provide recharge estimates for natural and disturbed soils and for surface barriers for each of four time periods: pre-operations, operations, post-remediation, and final state. The conditions during these periods include natural soil and shrub-steppe plant communities, disturbances that alter the surface soil and vegetation, emplacement of surface barriers, and long-term changes that occur as the waste sites stabilize and return to natural conditions. These sections also describe the probability distributions of the recharge estimates. These distributions support Monte Carlo analyses to represent the expected range of recharge rates. This section describes a method to examine the impact of surface barrier side slopes and the terrain surrounding surface barriers, both of which could significantly affect waste release and vadose zone transport. Finally, this section summarizes the recharge estimates for all conditions.

4.5.1 Natural and Disturbed Soil

Prior to the establishment of the Hanford Site in 1943, the mostly undisturbed soil and shrub-steppe plant communities generally resulted in very low recharge rates throughout the interior portions of the Hanford Site. Some portions of the Hanford Site along the Columbia River were farmed under irrigation and thus may have experienced increased recharge rates. However, the low rates throughout most of the Hanford Site led to very dry vadose zone conditions that characterize the pre-Hanford period beneath most waste sites. During the subsequent operations period, the soil and vegetation at most waste sites were disturbed, which increased recharge rates; similar conditions will exist during the remediation period. In addition to the recharge that occurs directly in a waste site, recharge in the immediate vicinity of the site could affect transport of contaminants to the groundwater.

Examination of the Hanford soil map produced by Hajek (1966) revealed four natural soil types prevalent in and around the waste areas: Rupert sand (R_p), Burbank loamy sand (B_a), Ephrata sandy loam (E_1), and Ephrata stony loam (E_b). Fayer and Szecsody (2004) suggested that the soil in the southeast quadrant of the 200 East Area in the vicinity of the Integrated Disposal Facility (IDF) should be treated as a separate soil type because of extensive subsurface layers. Therefore, for this data package, a soil type in that area was labeled as Rupert sand IDF (R_{pi}). The State Environmental Policy Act environmental impact statement (SEPA-EIS) for the US Ecology Site (DOH 2004) used an infiltration/recharge rate different from those of other soils in the area, so yet another soil typed was defined and labeled as Rupert sand US Ecology (R_{pu}). All six soils are assumed to be nominally 0.5 to 1 m thick (at most) and easily disrupted during construction activities. Experience shows that the dominant soil condition following construction is the underlying sediment, i.e., the Hanford sands. The only other soil type that might occur in the waste areas is a silt loam (Wa). Such soil does not currently exist in these areas. However, surface barriers constructed using 1-2 m of silt loam as the topsoil will eventually age and resemble a silt loam soil. Recharge estimates were assigned to the five undisturbed soil types and two sediment types for the following four plant community conditions:

1. *Shrub-Steppe Plant Community*. This condition is a mature plant community consisting of shrubs and bunchgrasses and associated fauna and flora. Table 4.13 lists the recharge estimates for the five soil types that dominate the areas to be evaluated in large-scale Hanford assessments. It is assumed that these soils, when undisturbed, support a shrub-steppe plant community.

Table 4.13. Estimated Recharge Rates for Predominant Soil Types and Sediment with a Shrub-Steppe Plant Community

Soil Type	Recharge Rate Estimate (mm/yr)	Description
Ephrata stony loam (E_b)	1.5	No data; used estimate for E_l, which is a similar soil
Ephrata sandy loam (E_l)	1.5	Avg. of two estimates (1.2; 1.8) from deep (>10 m) chloride data collected from the two boreholes B17 and B18 (Prych 1998)
Burbank loamy sand (B_a)	3.0	Avg. of three estimates (0.66, 2.8, 5.5) from deep (>10 m) chloride data collected from the three boreholes B10, B12, and B20 (Prych 1998)
Rupert Sand (R_p)	4.0	Estimated from chloride data collected from a borehole near the Wye Barricade (Murphy et al. 1996). Murphy et al. described the site as a stabilized dune area with low shrub cover.
Rupert Sand (R_{pi}) near the IDF in 200 East	0.9	Avg. of seven estimates from deep (5 to 30 m) chloride data collected from the boreholes around the IDF site (Fayer and Szecsody 2004)
Rupert Sand (R_{pu}) near the US Ecology site	5.0	Taken from the SEPA EIS (DOH 2004)
Hanford-formation sand (Hs)	4.0	No data; used estimate for Rupert sand outside the 200 East Area
Warden silt loam (Wa)	0.04 *(0.11)** *(1.0)***	Average of four estimates (0.013; 0.008; 0.024; 0.11) from chloride data collected in silt loam soil (Prych 1998). **Value is the highest of these four estimates, and may be used in sensitivity tests*[(a)] ***Value used in reference case analyses to represent the final state of ET surface barriers after design life*[(a)]

(a) DOE. October 21, 2005. *Technical Guidance Document for Composite Analysis of Low-Level Waste Disposal at the Hanford Site*. DOE/RL-2005-66, U.S. Department of Energy, Richland, Washington (unsigned).

2. *No Plants*. This condition describes the case in which vegetation was removed and plants were prevented from re-establishing (e.g., weed control). This condition can be applied to the analysis of fire effects, although the duration without plants will be short (<1 year). Table 4.14 shows the recharge estimates for the case without vegetation.

Table 4.14. Estimated Recharge Rates for Disturbed Soil Types Without Vegetation

Soil Type	Recharge Rate Estimate (mm/yr)	Description
Ephrata stony loam (E_b)	17	Simulation estimate for period 1958 to 1992 (Fayer and Walters 1995)
Ephrata sandy loam (E_l)	17	Simulation estimate for period 1958 to 1992 (Fayer and Walters 1995)
Burbank loamy sand (B_a)	52 *(53)**	Simulation estimate for the period 1957 to 2003 (Fayer and Szecsody 2004). ** Estimate in parenthesis is based on a simulation estimate for period 1957 to 1997 (Fayer et al. 1999). This value is used in reference case analyses DOE/RL-2005-66).*
Rupert Sand (R_p)	44	Simulation estimate for period 1957 to 1997 (Fayer et al. 1999)
Rupert Sand near the IDF (R_{pi})	44	Assumed to be the same as Rupert Sand above.
Rupert Sand near US Ecology (R_{pu})	30	Taken from the SEPA EIS (DOH 2004)
Hanford-formation sand (H_s)	63 *(55)**	22-yr (1982-1993, 1995-2004) lysimeter record for Hanford sand in the 300 Area (Gee et al. 2005) ** 8-yr (July 1984 to June 1993) lysimeter record for Hanford sand (Fayer and Walters 1995). Used in reference case analyses DOE/RL-2005-66)*
Graveled surface (G)	92 *(100)**	Value is based on the average rate derived from two lysimeter records for gravel surfaces (Fayer and Szecsody 2004). Lysimeters C1 and D1 showed 48% and 58% of precipitation received became deep drainage. Scaling the drainage rate to the long-term precipitation rate of 173 mm/yr (1946-2004; Hoitink et al. 2005) yielded an average estimate of 92 mm/yr. * *Value in parenthesis to be used for reference case analyses*[a]

(a) DOE. October 21, 2005. *Technical Guidance Document for Composite Analysis of Low-Level Waste Disposal at the Hanford Site*. DOE/RL-2005-66, U.S. Department of Energy, Richland, Washington (unsigned).

3. *Shallow-Rooted Plants*. This condition describes the case in which the existing shrub-steppe vegetation is destroyed (e.g., by fire or Hanford operations) and the plants that re-vegetate the site are strictly shallow-rooted (e.g., cheatgrass). Very few recharge data are available for native soils and backfilled sediments with shallow rooted grasses such as cheatgrass (Fayer and Walters 1995). For the purposes of this analysis, it was estimated that a cheatgrass cover will reduce the recharge rates listed in Table 4.14 by 50% relative to the rates that would occur in the absence of any vegetation. For example, Ephrata stony loam with cheatgrass will have an expected mean annual recharge of 8.5 mm/year compared to 17 mm/year when there is no vegetation.

4. *Young Shrub-Steppe Plant Community*. This condition describes the case in which a young shrub-steppe plant community is developing in an area that had previously been disturbed by an event such as a fire. It was estimated that recharge in such areas will be double the rates estimated for mature shrub-steppe conditions (Table 4.13).

Table 4.15 shows the estimated recharge rates for various surface conditions for the 17 geographic areas, along with a brief description of each setting and major soil type that was identified using the Hajek (1966) soil map. If a significant secondary soil type is present, that soil type and its estimated recharge rate are shown in parentheses. Note that only those values to be used in the analyses are presented. The alternate values shown in parentheses in Table 4.14 are not included. Note also that a recharge estimate of 1 mm/year was assumed for those sites that discharged directly to the river, and an estimate of 0.1 mm/year was assumed for those sites covered by asphalt, concrete, or building.

Table 4.15. Estimated Recharge Rates by Soil Type/Sediment and Vegetation Condition in Each Hanford Area. Significant secondary soil types and their associated recharge estimates are shown in parentheses.

Area Label	Brief Description	Major (Secondary)[a] Soil Type(s) and Sediments	Estimated Recharge Rate (mm/yr)[b]			
			No Vegetation	Cheatgrass	Young Shrub-Steppe	Shrub-Steppe
C	Reactor along river	E_b (B_a)	17 (52)	8.5 (26.5)	3.0 (6.0)	1.5 (3.0)
K	Reactor along river	E_b (E_l)	17 (17)	8.5 (8.5)	3.0 (3.0)	1.5 (1.5)
N	Reactor along river	E_b	17	8.5	3.0	1.5
D	Reactor along river	E_l	17	8.5	3.0	1.5
H	Reactor along river	B_a	52	26	6.0	3.0
F	Reactor along river	R_p (E_l)	44 (17)	22 (8.5)	8.0 (3.0)	4.0 (1.5)
R	300 Area	R_p (E_l)	44 (17)	22 (8.5)	8.0 (3.0)	4.0 (1.5)
Q	400 Area	R_p (B_a)	44 (52)	22 (26)	8.0 (3.0)	4.0 (3.0)
P	618-10 Area	R_p (B_a)	44 (52)	22 (26)	8.0 (3.0)	4.0 (3.0)
M	618-11 Area	R_p (B_a)	44 (52)	22 (26)	8.0 (3.0)	4.0 (3.0)
G	Gable Mtn. Pond Area	E_l (B_a)	17 (52)	8.5 (26)	3.0 (6.0)	1.5 (3.0)
I	200N Area	E_l (B_a)	17 (52)	8.5 (26)	3.0 (6.0)	1.5 (3.0)
T	Northern 200W Area	R_p (B_a)	44 (52)	22 (26)	8.0 (3.0)	4.0 (3.0)
S	Southern 200W Area and ERDF	R_p	44	22	8.0	4.0
A	Southern 200E Area	R_p (B_a, R_{pi}, R_{pu})	44 (52, 44, 30)	22 (26, 22, na)	8.0 (6.0, 1.8, na)	4.0 (3.0, 0.9, na)
B	Northwestern 200E Area	E_l	17	8.5	3.0	1.5
E	Eastern 200E Area	B_a (R_p)	52 (44)	26 (22)	6.0 (1.8)	3.0 (0.9)
--	All Areas with soils disturbed by excavations	Hanford sand	63	31.5	8.0	4.0
--	All Areas with an Evapotranspiration (ET) surface barrier after design life	Warden silt loam (Wa)	na	na	0.08	0.04
--	All Areas with gravel surface and no plants	gravel	92	46	na	na

B_a = Burbank loamy sand
E_b = Ephrata stony loam
E_l = Ephrata sandy loam
R_p = Rupert sand
R_{pi} = Rupert sand in the IDF in the 200 East Area.
R_{pu} = Rupert sand at the US Ecology Site, southwest of the 200 East Area.
na = not applicable
(a) Only the major soil types were used to represent each aggregate area.
(b) Alternate/reference case values shown in Table 4.14 are not provided here.
(c) Value to be used in reference case analyses (DOE. October 21, 2005. *Technical Guidance Document for Composite Analysis of Low-Level Waste Disposal at the Hanford Site*. DOE/RL-2005-66, U.S. Department of Energy, Richland, Washington [unsigned]).

4.5.2 Surface Barriers

The *Hanford Site Disposition Baseline (HSDB)* as described in the *Inventory Data Package for Hanford Assessments* (Kincaid et al. 2006) represents the most credible end-state of the Hanford Site based on information made available by DOE and its contractors. It is a combination of remedial actions based on interim and final records of decision or proposed by DOE but not yet interim or finally approved by regulatory agencies. The HSDB provides the schedule and type of engineered surface barriers to be applied to each site for a large-scale Hanford assessment.

This section describes the recharge rates to be used for surface barriers during the institutional control period, their design life, and after their design life. A key assumption of these large-scale Hanford assessments is that deep drainage beneath barrier side slopes and the surrounding terrain does not appreciably affect contaminant release and transport. This assumption is consistent with the Composite Analysis (Kincaid et al. 1998) as well as with recent and ongoing assessments. Since this assumption has not been tested, estimates of side slope drainage are provided here for possible use in sensitivity tests.

4.5.2.1 Barrier Tops

DOE conducted a focused feasibility study of engineered surface barriers and identified four designs that met Hanford needs (DOE 1996b). Table 4.15 lists the four designs and the expected design life of each. For large-scale Hanford assessments, two evapotranspiration (ET) surface barriers will be evaluated for sites that require protection: the Hanford barrier and barriers equivalent to the modified RCRA C barrier. Recharge rates for the top portion of the surface barriers were estimated from field studies of surface barrier systems at Hanford and are shown in Table 4.16. Fayer and Szecsody (2004) and Fayer and Gee (2006) described lysimeter tests and numerical modeling that showed recharge rates beneath silt loam soils with capillary breaks were much lower than 0.1 mm/year and in many cases were effectively zero (to the limits of measurement technology). Ward et al. (2005) reported drainage rates for four 322-m^2 plots in a field-scale prototype barrier having 2 m of silt loam soil above a capillary break. They reported drainage rates ranging from 0.00003 to 0.02 mm/year during a 10-year period that included two of the wettest years on record and irrigation (for stress testing) on two of the plots during the first three years when vegetation was just starting to get established. Even without the capillary break, silt loam soils appear to be effective at limiting drainage. For example, recharge estimates for natural silt loam soils at Hanford show rates average about 0.04 mm/year (Prych 1998). To some, such low rates do not seem possible despite the evidence. Rather than expend the additional effort necessary to support using very low rates, researchers elected to specify a barrier recharge rate of 0.1 mm/year.

4.5.2.2 Barrier Side Slopes and Surrounding Terrain

This discussion of recharge through barrier side slopes and surrounding terrain is provided only for completeness and to provide the basis for possible use in sensitivity analyses. Barrier side slopes and/or the surrounding terrain are likely to have recharge rates that are higher than rates through the surface barrier. Once the water from those areas enters the vadose zone, it can move laterally beneath the "shadow" of the surface barrier and effectively increase the transport of contaminants to groundwater. Recharge rates in the surrounding soils are provided in Table 4.15. Estimates of recharge rates beneath potential barrier side slopes are needed. A large number of surface barriers is being considered for use at Hanford and some may be above-grade structures that require stabilizing side slopes. Two side slope designs are currently being tested at the Prototype Surface Barrier (Ward et al. 2005). One design, called

'Gravel,' is a sandy gravel/gravelly sand mix emplaced at a 10 horizontal (H):1 vertical (V) slope. The second design, called 'Basalt, ' is open-work basalt riprap emplaced at a 2H:1V slope. Neither design incorporates any plant-promoting features. Since being constructed in November 1994, some plants have established on the sandy gravel side slope (the quantity is less than the barrier top) and none has established on the basalt side slope. Drainage data have been collected since November 1994. During that period, records show that Hanford received higher-than-normal precipitation (Hoitink et al. 2005). Therefore, the side-slope drainage data were scaled to the long-term precipitation average (173 mm/year for the period from 1946 to 2004; Hoitink et al. 2005) to yield long-term estimates of side slope recharge rates. Table 4.17 shows the scaled recharge estimates for the two side slope materials.

Table 4.16. Barrier Design Life and Estimated Recharge Rates for Barrier Tops

FFS Design (DOE 1996b)	Design Life (yr)	Recharge Rate (mm/yr)[b]	Source
Hanford Barrier	1,000	0.1[a]	Based on lysimeter data and simulation results (Ward et al. 2005; Fayer and Gee 2006)
Modified RCRA C (or equivalent ET barrier)	500	0.1[a]	Based on lysimeter data and simulation results (Fayer and Szecsody 2004; Fayer and Gee 2006)
Standard RCRA C (not explicitly evaluated in Hanford assessments)	30	0.1[a]	No data; recommendation is based on presence of Geomembrane and 0.69-m thick clay admix layer
Modified RCRA D (not explicitly evaluated in Hanford assessments)	100	0.1[a]	Based on simulation results using parameters from Fayer et al. (1999)
Geosynthetic Cap used at the US Ecology Site	500	0.5	Taken from the SEPA-EIS (DOH 2004)

(a) The value of 0.1 mm/yr was chosen to represent the performance of ET barriers utilizing silt loam because the rate is more easily defended that the expected value, which is much lower that 0.1 mm/yr.
(b) Note that the value to be used in reference case analyses is 0.5 mm/yr (DOE. October 21, 2005. *Technical Guidance Document for Composite Analysis of Low-Level Waste Disposal at the Hanford Site.* DOE/RL-2005-66, U.S. Department of Energy, Richland, Washington [unsigned]).

Table 4.17. Initial Side Slope Recharge Rates for Hanford Site Climate Conditions

Side Slope Type	Slope	Initial Recharge Rate (mm/yr)	Source
Gravel (mix of sand and gravel)	10H:1V	33	Based on ten years of drainage data from the prototype surface barrier (Ward et al. 2005) scaled to average (1946–2004) precipitation of 173 mm/yr.
Basalt (open-work riprap)	2H:1V	26	Based on ten years of drainage data from the prototype surface barrier (Ward et al. 2005) scaled to average (1946–2004) precipitation of 173 mm/yr.

The initial recharge rates shown in Table 4.17 are not expected to persist forever. During the 100 years of institutional control, the plant community and soil on the side slopes is expected to slowly develop and mature to the point where recharge rates beneath the side slopes resemble Burbank loamy sand and a shrub-steppe plant community. Therefore, the side-slope recharge rates should be represented in a time-dependent fashion during the period of institutional control.

4.5.2.3 Surface Barriers After Their Design Life

No guidance is available for specifying barrier performance after their design life. In the CA (Kincaid et al. 1998), barrier performance after the design life was simply assumed to end, after which recharge rates were set equal to those of the original soil type at each location. However, there is no basis for assuming the surface barrier will disappear or evolve to resemble the local soil. Instead, the barrier will continue to experience soil and ecological processes that will alter the nature of the barrier and affect its performance.

Processes that could affect barrier performance after the design life include erosion, deposition, biotic intrusion, fire, drought, plant succession, subsidence, human intrusion, and climate change. Of these, the two key natural processes are erosion of the silt loam layer and deposition of dune sand on the barrier. Fayer et al. (1999) examined both processes; their results suggested that neither process would significantly alter barrier performance. Thus, after the barrier design life, the barrier would continue to function as designed. Eventually, the barrier top would most likely resemble a Warden silt loam and the side slope would most likely resemble the Ephrata stony loam.

For large-scale Hanford assessments, barrier performance after the design life will be described for what is envisioned to be the final state of the barrier and for a transition period between the design life and the final state. For example, the final state of a silt-loam-based modified RCRA C barrier is expected to be equivalent to the silt loam soils found at the Hanford Site. The transition period will be equivalent in duration to the design life, which in this case would be 500 years. During the transition period, barrier performance would be progressively changed from the rate during the design life to the rate appropriate to the final state (e.g., Warden silt loam). For simplicity and ease of implementation, the changes during this transition period will be represented by five equal stepwise changes in the recharge rates.

4.5.3 Probability Distribution Functions

After reviewing the possible probability distributions, we chose a three-point triangular distribution to represent recharge at all sites. In this distribution, the low value is equal to the mean recharge rate minus the standard deviation and the high value is equal to twice the mean value. The number of recharge estimates is too small to calculate adequate statistics, so recharge standard deviations were estimated using statistics from winter precipitation, which is considered to be the primary source of recharge water. Data from HMS precipitation records (Hoitink et al. 2005) were used to obtain the mean and standard deviation of the extended-winter (November through March) precipitation for the period from November 1946 to March 2004. The HMS record yielded a mean value of 101 mm/year and standard deviation of 40 mm/year, or roughly 40% of the mean value. Because the available recharge data were limited, we estimated the standard deviation for each surface as equal to half the mean recharge rate. This choice is slightly conservative, based on the statistic for the extended winter precipitation. For sites with very high recharge rates, the triangular distribution results in unreasonably high upper limits. We reasoned that, because winter precipitation was the primary source of recharge, recharge would seldom, if ever, exceed winter precipitation. Therefore, all recharge rate distributions were truncated to the mean extended winter precipitation rate of 101 mm/year. As more data are collected for various surface conditions, the actual standard deviations in recharge can be substituted.

4.5.4 Integrated Drainage Calculations

A key assumption of large-scale Hanford assessments is that vadose zone waste is only affected by the recharge that occurs beneath the surface barrier tops. The implication of this assumption is that recharge occurring beneath the barrier side slopes (if present) or in the areas immediately surrounding the surface barrier will not affect the mobilization of waste beneath the surface barrier nor the transport of the waste contaminants to the water table. To test the assumption, a method was developed to integrate the drainage rates from the barrier top and side slopes and surrounding terrain into a single composite rate that could be used for sensitivity analyses in the Hanford assessments.

For Hanford assessments, each waste site is characterized by two drainage estimates defined as follows:

Release Model Drainage. This drainage rate directly affects the behavior of the release model. The assumption is that the waste form is directly beneath the intact and functional part of the surface barrier and affected only by recharge through the barrier top. Any recharge through the barrier side slopes or in the areas surrounding the barrier is assumed to have no impact on the waste form.

Vadose Zone Model Drainage. This drainage rate directly impacts the transport of contaminants released by the waste form through the vadose zone and to the water table. In large-scale Hanford assessments, the vadose zone drainage rate is equivalent to the barrier top drainage rate. However, for sensitivity tests of this assumption, the vadose zone drainage rate could be assigned a value that is a composite of recharge through the barrier and recharge through a portion of the barrier side slopes and surrounding terrain.

The impact of higher drainage rates around a surface barrier is a function of individual site characteristics such as barrier geometry and dimensions, distance to the water table, geology, physical-hydraulic-chemical properties, and contaminant depth and characteristics. Given the diversity of site characteristics and the one-dimensional conceptual model used in large-scale Hanford assessments, the sensitivity could be demonstrated without having to represent the unique features of every site. For this purpose, the recharge rates could be integrated by weighting the recharge contributions from the barrier and the contributing portion of the side slope and surrounding terrain based on their respective areas referenced to the total area.

Some of the recharge beneath the side slope can flow beneath the barrier and affect contaminant transport. The quantity of side slope recharge that affects contaminant transport beneath the barrier depends highly on the site-specific conditions noted above. In lieu of site-specific multidimensional data, the sensitivity to side slope recharge can be demonstrated with a one-dimensional analysis by assuming that recharge beneath half the side slope area contributes to contaminant transport. The resulting integrated vadose zone drainage rate (r_b) can be computed as follows:

$$r_b = \left(r_{bt} A_{bt} + r_{bs} 0.5 A_{bs}\right) / A_b \qquad (4.4)$$

where r_{bt} = drainage rate of the barrier top

r_{bs} = drainage rate of the barrier side slope

A_{bt} = area of the barrier top

A_{bs} = area of the barrier side slope

A_b = total area of the barrier and contributing side slope; sum of A_{bt} and $0.5*A_{bs}$

The following example illustrates how the integrated recharge rate from a modified RCRA C barrier with side slopes might affect the overall vadose zone drainage rate.

Modified RCRA C Barrier

- shape = square, 316 m on a side, yielding area A_{bt} = 10 ha
- height = 5 m above the surrounding terrain
- surface barrier drainage rate r_{bt} = 0.1 mm/year

Gravel Side Slope

- slope = 5H:1V
- slope length = 25 m
- contributing area, 0.5 * A_{bs} = 1.71 ha (equal to one-half of the side slope area)
- drainage rate r_{bs} = 3.0 mm/year (assumed mature shrub-steppe plant community)

Using Equation 4.4 and the values provided above, the integrated vadose zone drainage rate is

$$r_b = [0.1 \text{ x } 10 + 3.0 \text{ x } 1.71]/11.7 = 0.52 \text{ mm/year}$$

This calculation reveals that the integrated drainage rate for the 10-ha waste site is 5 times larger than the barrier top drainage rate. In other words, large side slopes have the potential to seriously reduce the performance of the surface barrier. Similar calculations for waste site areas of 1 and 20 ha (2.5 and 50 acres) yield integrated vadose zone drainage rates of 1.22 and 0.41 mm/year, respectively. These values demonstrate that smaller barriers are far more affected by side slope recharge than are larger barriers.

4.5.5 Recharge Classes

To facilitate the assignment of recharge rates for individual waste sites, three sets of recharge classes were developed: (1) rates for baseline soil conditions with shrub-steppe plant community; (2) rates for disturbed conditions with various degrees of vegetation (e.g., native soils or backfilled soils; with various types of vegetation or without; asphalt, concrete, or gravel covers); and (3) rates for surface barrier components. Each recharge class was identified with a unique code based on either the primary native soil and vegetation type or the type and size of the surface barrier. Tables 4.18 through 4.21 provide the estimated recharge rates for each class.

4.6 Pond Evaporation Estimates

Large volumes of liquid waste disposed to surface and subsurface infiltration facilities created significant groundwater mounds in the unconfined aquifer during site operations. Evaporation and evapotranspiration from surface water bodies can significantly reduce the volumes of waste water that ultimately infiltrate into the soils and recharge the aquifer. Thus, to improve estimates of deep drainage and recharge from the major anthropogenic sources, evaporation from surface ponds has been estimated. These estimates assume maximum possible evaporation by selecting atmospheric properties that promote evaporation. The parameters used for each month include (1) the highest temperature, (2) the lowest pressure, (3) the lowest relative humidity, (4) the highest wind speed, and (5) the highest net solar radiation.

Table 4.18. Estimated Recharge Rates for Baseline Soil Conditions

Recharge Class Code	Description	Best Estimate (mm/yr)	Estimated Standard Deviation (mm/yr)	Minimum (mm/yr)	Maximum (mm/yr)
E_b-s	Ephrata stony loam (E_b) - with shrub-steppe (*s*) plant community	1.5	0.75	0.75	3.0
E_l-s	Ephrata sandy loam (E_l) - with shrub-steppe (*s*) plant community	1.5	0.75	0.75	3.0
B_a-s	Burbank loamy sand (B_a) - with shrub-steppe (*s*) plant community	3.0	1.5	1.5	6.0
R_p-s	Rupert sand (R_p) - with shrub-steppe (*s*) plant community	4.0	2.0	2.0	8.0
R_{pi}-s	Rupert sand (R_p) near the IDF ($_i$) - with shrub-steppe (*s*) plant community	0.9	0.45	0.45	1.8
R_{pu}-s	Rupert sand (R_p) near US Ecology ($_u$)- with shrub-steppe (*s*) plant community	5.0 *(5)*[(a)]	2.5 *NA*[(a)]	2.5 *NA*[(a)]	10.0 *NA*[(a)]
W_a-s	Warden silt loam (W_a) – with shrub-steppe (*s*) plant community	0.04 *(0.11)** *(1.0)***	0.02 *(0.06)** *(0.5)***	0.02 *(0.06)** *(0.5)***	0.08 *(0.22)** *(2.0)***
River	Columbia River outfall locations	1	*NA*	*NA*	*NA*

(a) Value used in reference case analyses.
*Values are based on the highest (rather than the average) of four values estimated from chloride data. These values maybe used in sensitivity analyses (DOE. October 21, 2005. *Technical Guidance Document for Composite Analysis of Low-Level Waste Disposal at the Hanford Site.* DOE/RL-2005-66, U.S. Department of Energy, Richland, Washington [unsigned]).
**Value used in reference case analyses to represent the final state of ET surface barriers after design life (DOE/RL-2005-66.
NA = Not applicable.

Evaporation from open water surfaces (i.e., ponds) was calculated, using a combined aerodynamic and energy balance, Penman equation. Calculations were performed in a spreadsheet to produce average maximum monthly estimates over a one-year interval spanning January to December (Table 4.21). Data input to the equations are derived from meteorological measurements collected at the HMS. These include: the mean of the maximum monthly temperature (°F), the average maximum monthly wind speed (mph), the mean of the lowest monthly relative humidity (%), the mean of the maximum monthly solar radiation (average daily totals in Langley's), and the mean of the lowest monthly atmospheric pressure (ins. of Hg). The input data was based on monthly averages spanning 1945 through 1980, where summary statistics had already been generated and were readily available (e.g., Stone et al. 1983). Summary statistics that include meteorological data collected after 1980 have not been published. The expectation is that they would be similar to the statistics based on the 1945-1980 data. Before any calculations could be performed, the HMS data were converted to consistent units of °C for temperature, W/m^2 for solar radiation, kPa for atmospheric pressure, and m/s for wind speed.

The first step in the process is to calculate evaporation by the energy balance method. The equation for evaporation due to radiant energy is

$$E_r = \frac{R_n}{l_v \rho_w}$$

where R_n = the net radiation flux
l_v = the latent heat of vaporization
ρ_w = the density of water (977 kg/m^3).

Table 4.19. Estimated Recharge Rates for Disturbed Conditions and Sensitivity Tests

Recharge Class Code	Description	Best Estimate (mm/yr)	Estimated Standard Deviation (mm/yr)	Minimum (mm/yr)	Maximum (mm/yr)[a]
E_b-ds	Ephrata stony loam (E_b), disturbed (*d*) - with young shrub-steppe (*s*) vegetation	3.0 *(4.0)*[b]	1.5 *(2.0)*[b]	1.5 *(2.0)*[b]	6.0 *(8.0)*[b]
E_b-dg	Ephrata stony loam (E_b), disturbed (*d*) - with cheatgrass (*g*) vegetation	8.5 *(9)*[b]	4.25 *(4.5)*[b]	4.25 *(4.53)*[b]	17 *(18)*[b]
E_b -dn	Ephrata stony loam (E_b), disturbed (*d*) - with no (*n*) vegetation	17	8.5	8.5	34
E_l-ds	Ephrata sandy loam (E_l), disturbed (*d*) - with young shrub-steppe (*s*) vegetation	3.0 *(4.0)*[b]	1.5 *(2.0)*[b]	1.5 *(2.0)*[b]	6.0 *(8.0)*[b]
E_l-dg	Ephrata sandy loam (E_l), disturbed (*d*) - with cheatgrass (*g*) vegetation	8.5 *(9)*[b]	4.25 *(4.5)*[b]	4.25 *(4.5)*[b]	17 *(18)*[b]
E_l-dn	Ephrata sandy loam (E_l), disturbed (*d*) - with no (*n*) vegetation	17	8.5	8.5	34
B_a-ds	Burbank loamy sand (B_a), disturbed (*d*) - with young shrub-steppe (*s*) plant community	6.0 *(4.0)*[b]	3.0 *(2.0)*[b]	3.0 *(2.0)*[b]	12 *(8.0)*[b]
B_a-dg	Burbank loamy sand (B_a), disturbed (*d*) - with cheatgrass (*g*) plant community	26	13.0	13.0	52
B_a-dn	Burbank loamy sand (B_a), disturbed (*d*) - with no (*n*) vegetation	52 *(53)*[b]	26 *(26.5)*[b]	26 *(26.5)*[b]	101 *(106)*[b]
R_{pi}-ds	Rupert sand (R_p) near the IDF ($_i$), disturbed (*d*) - with young shrub-steppe (*s*) plant community	1.8 *(4.0)*[b]	0.9 *(2.0)*[b]	0.9 *(2.0)*[b]	3.6 *(8.0)*[b]
R_{pi}-dg	Rupert sand (R_p) near the IDF ($_i$), disturbed (*d*) - with cheatgrass (*g*) plant community	22	11	11	44
R_{pi}-dn	Rupert sand (R_p) near the IDF ($_i$), disturbed (*d*) - with no (*n*) vegetation	44	22	22	88
R_{pu}-dn	Rupert sand (R_p) near US Ecology ($_u$), disturbed (*d*) - with no (*n*) vegetation	30 *(30)*[b]	15 *NA*[b]	15 *NA*[b]	60 *NA*[b]
R_p-ds	Rupert sand (R_p) , disturbed (*d*) - with young shrub-steppe (*s*) plant community	8.0 *(4.0)*[b]	4.0 *(2.0)*[b]	4.0 *(2.0)*[b]	16.0 *(8.0)*[b]
R_p-dg	Rupert sand (R_p), disturbed (*d*) - with cheatgrass (*g*) plant community	22	11	11	44
R_p-dn	Rupert sand (R_p), disturbed (*d*) - with no (*n*) vegetation	44	22	22	88
H_s-dn	Hanford Sand (H_s), disturbed (*d*) - with no (*n*) vegetation	63 *(55)*[b]	31.5 *(27.5)*[b]	31.5 *(27.5)*[b]	101 *(107.5)*[b]
G-dn	Gravel surface (*G*), disturbed - with no (*n*) vegetation	92 *(100)*[b]	46 *NA*[b]	46 *NA*[b]	101 *NA*[b]
ABC	Soil Surface covered by Asphalt, Building, or Concrete	0.1	0.05	0.05	0.2

(a) Note: the maximum recharge was truncated at the mean extended winter precipitation value of 101 mm/yr.
(b) Value to be used in reference case analyses (DOE. October 21, 2005. *Technical Guidance Document for Composite Analysis of Low-Level Waste Disposal at the Hanford Site*. DOE/RL-2005-66, U.S. Department of Energy, Richland, Washington [unsigned]).
NA = Not applicable.

Table 4.20. Estimated Recharge Rates for Surface Barrier Components

Recharge Class Code	Description	Best Estimate (mm/yr)	Estimated Standard Deviation (mm/yr)	Minimum (mm/yr)	Maximum (mm/yr)
RCRA C (or equivalent ET barrier)	Modified RCRA C (or equivalent) – barrier top during design life	0.1 *(0.5)*[(a)]	0.05 *(0.25)*[(a)]	0.05 *(0.25)*[(a)]	0.20 *(1.0)*[(a)]
GS-Cap	Geosynthetic Cap used at the US Ecology Site	0.5 *(0.5)*[(a)]	0.25 *NA*[(a)]	0.25 *NA*[(a)]	1.0 *NA*[(a)]
Hanford	Hanford Barrier- barrier top during design life	0.1 *(0.5)*[(a)]	0.05 *(0.25)*[(a)]	0.05 *(0.25)*[(a)]	0.20 *(1.0)*[(a)]
W_a-s	Warden Silt Loam (W_a) - with shrub-steppe (*s*) plant community (Could be used to represent state of barrier top after design life)	0.04 *(1)*[(a)]	0.02 *(0.5)*[(a)]	0.02 *(0.5)*[(a)]	0.08 *(2)*[(a)]
G_r-s	Gravel side slope – with shrub-steppe (*s*) plant community (assumed final state of a sandy gravel side slope)	3.0	1.5	1.5	6.0
G_r-n	Gravel side slope – no vegetation (*n*) (data source had sparse vegetation on the surface)	33	16.5	16.5	66

(a) Value to be used in reference case analyses (DOE. October 21, 2005. *Technical Guidance Document for Composite Analysis of Low-Level Waste Disposal at the Hanford Site*. DOE/RL-2005-66, U.S. Department of Energy, Richland, Washington [unsigned]).
NA = Not applicable.

The radiation flux is solar radiation derived from the 1945 to 1980 HMS data set and the latent heat of vaporization is derived from the measured temperature (T) using the equation

$$l_v = 2.5E + 6 - 2370 \times T(°C)$$

and has units of J/kg.

After the energy evaporation term is calculated, the aerodynamic evaporation component is calculated using the equation

$$E_a = B(e_s - e_a)$$

Where B is the vapor transfer coefficient, which is derived from the equation

$$B = \frac{0.622 k^2 \rho_a u_2}{p \rho_w \left[\ln\left({z_2}/{z_0} \right)^2 \right]}$$

Table 4.21. Average Maximum Monthly and Yearly Total Evaporation (m^3) from Hanford Surface Ponds

Month	216-B-3	216-B-3A	216-B-3B	216-B-3C	216-A-25	216-T-4	216-T-4-2	216-S-16	216-S-11	216-S-19	216-S-10	216-U-10
Jan	14,881.09	3,720.23	3,720.23	15,253.14	31,941.67	9,223.16	560.77	11,532.82	854.03	1,302.10	1,860.11	11,160.87
Feb	21,125.85	5,281.40	5,281.40	21,654.02	45,345.79	13,093.61	796.10	16,372.49	1,212.42	1,848.52	2,640.70	15,844.45
March	36,644.92	9,161.12	9,161.12	37,561.08	78,656.85	22,712.18	1,380.91	28,399.74	2,103.06	3,206.44	4,580.56	27,483.81
April	51,527.04	12,881.60	12,881.60	52,815.27	110,600.71	31,935.98	1,941.73	39,933.35	2,957.15	4,508.62	6,440.80	38,645.44
May	66,307.80	16,576.75	16,576.75	67,965.56	142,327.01	41,096.96	2,498.72	51,388.40	3,805.43	5,801.94	8,288.37	49,731.06
June	72,537.22	18,134.08	18,134.08	74,350.72	155,698.21	44,957.89	2,733.47	56,216.19	4,162.93	6,347.02	9,067.04	54,403.14
July	80,518.76	20,129.44	20,129.44	82,531.80	172,830.25	49,904.78	3,034.24	62,401.86	4,621.00	7,045.40	10,064.72	60,389.32
Aug	70,992.55	17,747.92	17,747.92	72,767.43	152,382.63	44,000.52	2,675.26	55,019.07	4,074.28	6,211.86	8,873.96	53,244.63
Sept	51,207.68	12,801.76	12,801.76	52,487.92	109,915.22	31,738.04	1,929.69	39,685.84	2,938.82	4,480.68	6,400.88	38,405.92
Oct	34,116.53	8,529.03	8,529.03	34,969.47	73,229.75	21,145.11	1,285.63	26,440.24	1,957.96	2,985.20	4,264.51	25,587.50
Nov	15,157.78	3,789.40	3,789.40	15,536.74	32,535.57	9,394.65	571.20	11,747.25	869.91	1,326.31	1,894.70	11,368.38
Dec	10,079.90	2,519.94	2,519.94	10,331.91	21,636.10	6,247.43	379.85	7,811.90	578.49	881.99	1,259.97	7,559.96
Yearly	5.25E+05	1.31E+05	1.31E+05	5.38E+05	1.13E+06	3.25E+05	1.98E+04	4.07E+05	3.01E+04	4.59E+04	6.56E+04	3.94E+05

where k is von Karmans constant (0.4), ρ_a is the air density (1.19 kg/m^3 @ 25°C), u_2 is the wind speed, p is atmospheric pressure, z_2 is the height above the water where measurements were taken (chosen as 1 m), and z_0 is the roughness height of water (0.03 cm). The saturation vapor pressure, e_s, is calculated by

$$e_s = 611\exp\left(\frac{17.27T}{237.3+T}\right)$$

and the actual vapor pressure, e_a, is calculated from

$$e_a = RHe_s$$

Where RH is the relative humidity, derived from the 1945 to 1980 HMS data set.

Now that the energy balance and aerodynamic components are calculated, a weighted estimate of evaporation is derived from the two calculated evaporation rates. The equation used to calculate the final evaporation is

$$E = \frac{\Delta}{\Delta+\gamma}E_r + \frac{\gamma}{\Delta+\gamma}E_a$$

where Δ is the gradient of the saturated vapor pressure curve at air temperature and γ is the psychometric constant. The equations for Δ and γ are,

$$\Delta = \frac{4098e_s}{(237.3+T)^2}$$

and

$$\gamma = \frac{C_p k_h p}{0.622 l_v k_w}$$

where k_h/k_w are the heat and vapor diffusivities, the ratio of which is 1, C_p is the specific heat of air (1005 J/kg), and *p* is the atmospheric pressure in kilopascals.

After the daily evaporation rate is calculated, the net, total monthly evaporation is calculated by multiplying the daily evaporation rate by the number of days in the month and the surface area of the pond (as taken from the Waste Information Data System). The total yearly evaporation from each pond is simply, the sum of the monthly evaporation for each pond (Table 4.22). Average maximum monthly and yearly evaporation from Hanford ponds are listed in Table 4.21.

Evaporation estimates are applied in the SAC model as a sink term in the STOMP model. Because the evaporation estimate can occasionally exceed the actual liquid disposal at a site, a pre-conditioner utility is used in SAC to truncate the evaporation sink term so that it cannot exceed the liquid discharge rate in any period.

Table 4.22. Hanford Pond Identification, Surface Area, and Operational Life Taken from the Waste Information Data System

Description	Site Name	Area (m^2)	Start Year	End Year
B-pond main lobe	216-B-3	161,874	1945	1994
B-pond A lobe	216-B-3A	40,468	1983	1995
B-pond B lobe	216-B-3B	40,468	1983	1995
B-pond C lobe	216-B-3C	165,921	1985	1997
Gable Mtn pond	216-A-25	347,456	1957	1987
T-pond	216-T-4	100,328	1944	1972
T-pond	216-T-4-2	6,100	1972	1995
S pond	216-S-16	125,452	1957	1975
S pond	216-S-11	9,290	1954	1965
S pond	216-S-10	20,234	1952	1984
S pond	216-S-19	14,164	1952	1984
U pond	216-U-10	121,406	1944	1985

5.0 Conclusions and Recommendations

Kincaid et al. (2004) identified 1,052 waste sites from the 2,730 Waste Information Data System (WIDS) sites and several existing and future storage sites for inclusion in a large-scale Hanford assessment.[14] Large-scale assessments will include one-dimensional stochastic simulations of flow and transport through the vadose zone. Data and interpreted information needed to define the input parameters for the vadose zone simulations have been extracted from existing documents and databases.

This report describes the assumptions and rationale for vadose zone modeling in large-scale assessments conducted using SAC. This includes (1) defining the hydrostratigraphy, hydraulic properties, and distribution coefficients for each site to be simulated; and (2) defining the recharge estimates for each site. To simplify the preparation of input files for the large number of sites, and to improve the computational efficiencies, the Hanford Site was subdivided into 17 geographically similar areas that could each be represented by a single generalized hydrostratigraphic column. The hydrostratigraphic columns for each of the 17 geographic areas were further modified to account for differences in the depth of waste releases, and differences in solid/liquid distribution coefficients (K_d values) affected by different waste chemistries. This resulted in 72 base templates, each with their own unique hydrogeologic stratigraphy, hydraulic parameter distributions, and K_d distributions. Flow and transport parameters are to be stochastically sampled for each hydrogeologic unit for each realization. Thus, each model node within a given hydrogeologic unit has the same set of parameters for a given realization.

Recharge estimates are provided for four different conditions: pre-Hanford, operations, post-remediation, and post-Hanford. The conditions during these periods include natural soil with shrub-steppe plant communities, disturbed soil with or without various types of vegetation, surface barriers, and the final surface conditions as surface barriers exceed their design life and the waste sites stabilize and return to natural conditions. Probability distributions have been provided for each of these recharge estimates, to facilitate Monte Carlo analysis in estimating the uncertainty in transport rates given the expected range of recharge rates.

There are many issues and sources of uncertainty that can affect the ability to predict the behavior of contaminants in the vadose zone. These include scale effects, spatial resolution of data, preferential flow, funneled flow, colloid transport, density effects, and thermal effects. Fogwell et al. (2003) has identified a number of data gaps related to key technical issues and parameter uncertainties. This includes a number of site characterization and laboratory study needs related to interpreting observations from past tank leaks, spills, and deliberate discharges. Adequate site characterization is important to reduce uncertainties in existing inventory estimates, initial conditions, and also to demonstrate the validity of our understanding and the predictive ability of the models used for flow and transport. Estimating inventories and contaminant distributions is difficult because much of the history and character of the leaks, spills, and water losses is difficult to characterize with a reasonable level of uncertainty. This level of uncertainty will always hamper the ability of models to predict observed distributions of contaminants in the vadose zone, even if those contaminant distributions are well known.

---

[14] Originally 974 of 2,730 Waste Information Data System (WIDS) sites were identified for inclusion in a large scale Hanford assessment. Further work identified 48 more waste sites bringing the total to 1,022. Subsequent reviews identified an additional 30 sites that have been included, many of which account for offsite transfers of waste and nuclear material. This brings the total to 1,052.

Recommendations to reduce uncertainty and improve the site-wide data sets presented in this document include the following:

- Increase the number of hydrostratigraphic profiles to better represent the site-specific conditions beneath the waste sites. Efforts are underway to refine the Hanford Site geologic model to provide detail on the distribution of facies associations within the vadose zone and to enable sampling of this model to generate the site-specific hydrostratigraphic profiles. Detailed facies-based, site-specific, two or three dimensional representations should also be developed for those sites found to be high risk drivers with correspondingly high uncertainty.

- Improve our quantitative representation (i.e., through geostatistics) of the geologic structure and heterogeneities associated with the various hydrogeologic facies.

- Improve defensibility and traceability of assigning physical, hydrologic, and geochemical properties to the hydrostratigraphic units. Efforts are underway to develop facies- and location-specific pedotransfer functions to improve our understanding and quantification between geologic facies and hydraulic and geochemical property distributions.

- Continue to improve the hydraulic property database and to develop scaling relationships. These data include measured values of unsaturated conductivity, parameter estimates from resulting outflow experiments, and data and parameters resulting from field-scale tests.

- Continue to improve our ability to quantify of the impacts of gravel on hydraulic and sorption behavior of the various hydrogeologic facies, in a systematic and defensible manner.

- Improve the physical and hydraulic property distribution estimates. This would entail addition of unsaturated hydraulic conductivity data to improve curve fitting at the dry-end, improving the number of sample analyses we have for each of the hydraulic property classes, improving these data via pedotransfer functions tied to particle-size data, using Bayesian updating to improve site-specific property distributions, and incorporating concepts for scaling up sample analytical data to the field and model cell scale.

- Improve contaminant distribution coefficient estimates by correcting for gravel content based on particle-size data of the geologic facies and addressing scale-up issues from sample derived K_d values to field and model cell scales.

- Improve our recharge estimates, particularly for coarse surface soil and side slope material.

- Improve our technical basis and modeling parameters to investigate the effect of side-slope design on deep infiltration rates.

- Improve the technical basis and modeling parameters for barrier performance after the design life.

- Improve estimates of pond/surface water evaporation based on the median monthly averages using the complete record of meteorological data, rather than the maximum monthly averages for a more limited date range.

6.0 References

Agnew SF, J Boyer, RA Corbin, TB Duran, JR Fitzpatrick, KA Jurgensen, TP Ortiz, and BL Young. 1996. *Hanford Tank Chemical and Radionuclide Inventories: HDW Model Rev. 3*. LA-UR-96-858, Los Alamos National Laboratory, Los Alamos, New Mexico.

Allard B. 1982. *Actinides in Perspective.* NM Edenlstein (ed.), pp. 553-580, Pergamon Press, Oxford.

Bacon DH and BP McGrail. 2005. Waste Form Release Calculation for the 2005 Integrated Disposal Facility Performance Assessment. PNNL-15198, Pacific Northwest National Laboratory, Richland, Washington.

Bailey LEF and DE Billington. 1998. *Overview of the FEP Analysis Approach to Model Development*. NIREX Science Report S/98/009, United Kingdom Nirex Limited, Oxfordshire, United Kingdom.

Baker SM, RF Lorang, RP Elmore, AJ Rossi, and MD Freshley. 1988. *U1/U2 Uranium Plume Characterization, Remedial Action Review and Recommendation for Future Action*. WHC-EP-0133, Westinghouse Hanford Company, Richland, Washington.

Barnett DB, RM Smith, and CJ Chou. 2000. *Groundwater Monitoring Plan for the Hanford Site 216-B-3 Pond RCRA Facility.* PNNL-13367, Pacific Northwest National Laboratory, Richland, Washington.

BHI. 1998. *Hanford Site Atlas.* BHI-01119, Rev. 2, Bechtel Hanford Inc., Richland, Washington.

Bjornstad BN. 1990. *Geohydrology of the 218-W-5 Burial Ground, 200-West Area, Hanford Site.* PNL-7336, Pacific Northwest Laboratory, Richland, Washington.

Brown CF, RJ Serne, KM Krupka, EM Pierce, and MJ Lindberg. 2005. "Uranium Contamination at the 300 Area of the Hanford Site" In *Third International Conference of Remediation of Contaminated Sediments*. Battelle Press, Columbus, Ohio.

Bryce RW, CT Kincaid, PW Eslinger, and LF Morasch (eds.). 2002. *An Initial Assessment of Hanford Impact Performed with the System Assessment Capability*. PNNL-14027, Pacific Northwest National Laboratory, Richland, Washington.

Caggiano JA. 1996. *Assessment Groundwater Monitoring Plan for Single-Shell Tank Waste Management Area S-SX.* WHC-SD-EN-AP-191, Westinghouse Hanford Company, Richland, Washington.

Campbell JA, SA Clauss, KE Grant, V Hoopes, GM Mong, R Steele, D Bellofatto, and A Sharma. 1998a. *Organic Analysis Progress Report FY1997.* PNNL-11738, Pacific Northwest National Laboratory, Richland, Washington.

Campbell JA, AK Sharma, SA Clauss, GM Mong, and D Bellofatto. 1998b. *Organic Speciation of AX-102, BX-104, C-104, C-201, and C-202 Tank Wastes*. PNNL-11955, Pacific Northwest National Laboratory, Richland, Washington.

Cantrell KJ, RJ Serne, and GV Last. 2002. Hanford Contaminant Distribution Coefficient Database and Users Guide. PNNL-13895, Pacific Northwest National Laboratory, Richland, Washington.

Cantrell KJ, RJ Serne, and GV Last. 2003a. *Hanford Contaminant Distribution Coefficient Database and Users Guide*. PNNL-13895, Rev. 1, Pacific Northwest National Laboratory, Richland, Washington.

Cantrell KJ, RJ Serne, and GV Last. 2003b. *Applicability of the Linear Sorption Isotherm Model to Represent Contaminant Transport Processes in Site-Wide Performance Assessments – A White Paper*. CP-17089, Fluor Hanford, Inc., Richland, Washington.

Cantrell KJ. 1988. "Actinide(III) Carbonate Complexation." *Polyhedron* 7(7):573-574.

Carsel RF and RS Parrish. 1988. "Developing Joint Probability Distributions of Soil Water Retention Characteristics." *Water Resour. Res*. 24(5):755-769.

Cearlock CS, KM Singleton, ME Todd, and DB Barnett. 2000. *200-CW-1 Operable Unit Borehole/Test Pit Summary Report.* BHI-01367, Bechtel Hanford, Inc., Richland Washington.

CH2M HILL Hanford Group, Inc. 2002. *Field Investigation Report for Waste Management Area S-SX; Volume 1, Main Text and Appendices A – C, Volume 2, Appendices D – I.* RPP-7884, Rev. 0, CH2M HILL Hanford Group, Inc., Richland, Washington.

Chamness, M. A., and J. K. Merz. 2003. *Hanford Wells.* PNL-8800. Pacific Northwest National Laboratory, Richland, Washington.

Cherrey KD, M Flury, and JB Harsh. 2003. "Nitrate and Colloid Transport through Coarse Hanford Sediments under Steady-State, Variably-Saturated Flow." *Water Resour. Re*s. 39, 1165, doi:10.1029/2002WR001944.

*Comprehensive Environmental Response, Compensation, and Liability Act (*CERCLA). 1980. Public Law 96-150, as amended, 94 Stat. 2767, 42 USC 9601 et seq.

Connelly MP, JD Davis, and PD Rittman. 1991. *Numerical Simulation of Strontium-90 Transport from the 100-N Area Liquid Waste Disposal Facility*. WHC-SD-ER-TA-001, Rev. 0, Westinghouse Hanford Company, Richland, Washington.

Connelly MP, BH Ford, and JV Borghese. 1992a. *Hydrogeologic Model for the 200 West Area Groundwater Aggregate Area*. WHC-SD-EN-TI-014, Westinghouse Hanford Company, Richland, Washington.

Connelly MP, JV Borghese, CD Delaney, BH Ford, JW Lindberg, and SJ Trent. 1992b. *Hydrogeologic Model for the 200 East Groundwater Aggregate Area.* WHC-SD-EN-TI-019, Westinghouse Hanford Company, Richland, Washington.

Crews WS and DD Tillson. 1969. *Analysis of Travel Time of I-131 from the 1301-N Crib to the Columbia River During July 1969*. BNWL-CC-2326, Pacific Northwest Laboratory, Richland, Washington.

Cushing CE and BE Vaughan. 1988. "Springs and Streams' in Shrub-Steppe Balance and Change in a Semi-Arid Terrestrial Ecosystem." WH Rickard et al. (ed.), *Developments in Agricultural and Managed-Forest Ecology 20*, Elsevier Science Publishers, New York.

Delaney CD, KA Lindsey, and SP Reidel. 1991. *Geology and Hydrology of the Hanford Site: A Standardized Text for Use in Westinghouse Hanford Company Documents and Reports.* WHC-SD-ER-TI-003, Westinghouse Hanford Company, Richland, Washington.

DOE. 1987. *Final Environmental Impact Statement, Disposal of Hanford Defense High-Level, Transuranic and Tank Wastes, Hanford Site, Richland, Washington.* DOE/EIS-0113, Volumes 1-5. U. S. Department of Energy, Washington, D.C.

DOE. 1988. *Consultation Draft Site Characterization Plan. Reference Repository Location, Hanford Site, Washington.* DOE/RW-0164, U.S. Department of Energy, Richland Operations Office, Richland, Washington.

DOE. 1992. *Z-Plant Source Aggregate Area Management Study.* DOE/RL-91-58, U.S. Department of Energy, Richland Operations Office, Richland, Washington.

DOE. 1993a. *200 East Groundwater Aggregate Area Management Study Report*. DOE/RL-92-19, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington.

DOE. 1993b. *Limited Field Investigation Report for the 100-HR-3 Operable Unit.* DOE/RL-93-34, U.S. Department of Energy, Richland Operations Office, Richland, Washington.

DOE. 1993c. *B Plant Source Aggregate Area Management Study Report.* DOE/RL-92-05, U.S. Department of Energy, Richland Operations, Richland, Washington.

DOE. 1993d. *200 North Aggregate Area Source AAMS Report.* DOE/RL-92-17, U.S. Department of Energy, Richland Operations, Richland, Washington.

DOE. 1993e. *PUREX Source Aggregate Area Management Study Report.* DOE/RL-92-04, U.S. Department of Energy, Richland Operations, Richland, Washington.

DOE. 1994. *Remedial Investigation and Feasibility Study Report for the Environmental Restoration Disposal Facility*. DOE/RL-93-99, Rev. 1, U.S. Department of Energy, Richland Operations Offices, Richland, Washington.

DOE. 1996a. *1301-N and 1325-N Liquid Waste Disposal Facilities Limited Field Investigation Report.* DOE/RL-96-11, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington.

DOE. 1996b. *Focused Feasibility Study of Engineered Barriers for Waste Management Units in the 200 Areas.* DOE/RL-93-33, Rev. 0, U.S. Department of Energy, Richland, Washington.

DOE. 1997. *TWRS Vadose Zone Contamination Issue, Expert Panel Status Report.* DOE/RL-97-49, Rev. 0, U.S. Department of Energy, Richland, Washington.

DOE. 1998. *Groundwater/Vadose Zone Integration Project Specification.* DOE/RL-98-48, Draft C, U.S. Department of Energy, Richland Operations Office, Richland, Washington.

DOE. 1999. *Groundwater/Vadose Zone Integration Project Background Information and State of Knowledge*. DOE/RL-98-48, Vol. II, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington.

DOE. 2000a. *Groundwater/Vadose Zone Integration Project Science and Technology Summary Description*. DOE/RL-98-48, Vol. III, Rev. 1, U.S. Department of Energy, Richland Operations Office, Richland, Washington.

DOE. 2000b. *Phase I RCRA Facility Investigation/Corrective Measures Study Work Plan for Single-Shell Tank Waste Management Areas*. DOE/RL-99-36, Rev. 1, U.S. Department of Energy, Richland Operations Office, Richland, Washington.

DOE. 2002. *Standardized Stratigraphic Nomenclature for Post-Ringold-Formation Sediments within the Central Pasco Basin*. DOE/RL-2002-39, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington.

DOE. 2003. *Hanford Site Waste Management Units Report*. DOE/RL-88-30, Rev. 12, U.S. Department of Energy, Richland Operations Office, Richland, Washington.

DOE. 2005. *2004 Annual Status Report for the Composite Analysis of Low-Level Disposal in the Central Plateau at the Hanford Site*. DOE/RL-2005-58. U.S. Department of Energy, Richland Operations Office, Richland, Washington.

DOE M 435.1-1. 1999. *Radioactive Waste Management Manual.* U.S. Department of Energy, Washington, D.C. Available on the Internet at http://www.directives.doe.gov/pdfs/doe/doetext/neword/435/m4351-1c1.html

DOE Order 435.1. 1999. *Radioactive Waste Management.* U.S. Department of Energy, Washington, D.C. Available on the Internet at http://www.hanford.gov/wastemgt/doe/psg/pdf/doeo435.1.pdf

DOH (Washington State Department of Health and Washington State Department of Ecology). 2004. *Final Environmental Impact Statement: Commercial Low-Level Radioactive Waste Disposal Site, Richland, Washington.* DOH Publication 320-031. Washington State Department of Health, Olympia, Washington.

Domenico PA and FW Schwartz. 1990. *Physical and Chemical Hydrogeology.* Wiley and Sons, New York, New York.

Durner W. 1992. "Predicting the Unsaturated Hydraulic Conductivity using Multi-Porosity Water Retention Curves." *Proceedings of the International Workshop on Indirect Methods for Estimating the Hydraulic Properties of Unsaturated Soils*, Riverside, California, October 11-13, 1989, MTh van Genuchten, FJ Leij, and LJ Lund (eds.), University of California, Riverside, California, p. 185-202.

Enfield CG, JJC Hsieh, and AW Warrick. 1973. "Evaluation of Water Flux above a Deep Water Table Using Thermocouple Psychrometers" in *Soil Sci. Soc. Amer. Proc*. 37:968-970.

Eslinger PW, DW Engel, LH Gerhardstein, CA Lo Presti, WE Nichols, and DL Strenge. 2002a. "User Instructions for the Systems Assessment Capability, Rev. 0," in *Computer Codes, Volume 1: Inventory, Release, and Transport Modules*. PNNL-13932, Volume 1, Pacific Northwest National Laboratory, Richland, Washington.

Eslinger PW, C Arimescu, DW Engel, BA Kanyid, and TB Miley. 2002b. "User Instructions for the Systems Assessment Capability, Rev. 0," in *Computer Codes, Volume 2: Impacts Modules*. PNNL-13932, Volume 2, Pacific Northwest National Laboratory, Richland, Washington.

Fayer MJ and TB Walters. 1995. *Estimated Recharge Rates at the Hanford Site.* PNL-10285, Pacific Northwest Laboratory, Richland, Washington.

Fayer MJ, EM Murphy, JL Downs, FO Khan, CW Lindenmeier, and BN Bjornstad. 1999. *Recharge Data Package for the Immobilized Low-Activity Waste 2001 Performance Assessment.* PNNL-13033, Pacific Northwest National Laboratory, Richland, Washington.

Fayer MJ, and JE Szecsody. 2004. *Recharge Data Package for the 2005 Integrated Disposal Facility Performance Assessment*. PNNL-14744, Pacific Northwest National Laboratory, Richland, Washington.

Fayer MJ and GW Gee. 2006. "Multiple-Year Water Balance of Soil Covers in a Semiarid Setting" *J. Environ. Qual.* 35:366–377.

Fecht KR, GV Last, and KR Price. 1977. *Evaluation of Scintillation Probe Profiles from 200 Area Crib Monitoring Wells, Volumes II and III.* ARH-ST-156, Atlantic Richfield Hanford Company, Richland, Washington.

Fecht KR and DC Weekes. 1996. *Geologic Field Investigation of the Sedimentary Sequence at the Environmental Restoration Disposal Facility.* BHI-00230, Bechtel Hanford, Inc., Richland, Washington.

Fecht KR, KA Lindsey, DG Horton, GV Last, and SP Reidel. 1999. *An Atlas of Clastic Injection Dikes of the Pasco Basin and Vicinity*. BHI-01103, Rev. 0, Bechtel Hanford, Inc., Richland, Washington.

Fogwell TW, GV Last, AL Bunn, KJ Cantrell, FM Coony, JL Downs, MJ Fayer, EJ Freeman, GW Gee, DG Horton, CT Kincaid, CJ Murray, BA Napier, GW Patton, VV Rawhalf, RG Riley, and PD Thorne. 2003. *Characterization of Systems Task Fiscal Year 2003 Status Report*. WMP-18045, Fluor Hanford, Inc., Richland, Washington.

Freeman EJ and GV Last. 2003. *Vadose Zone Hydraulic Property Letter Reports*. WMP-17524, Rev. 0, Fluor Hanford, Richland, Washington.

Freeman EJ, R Khaleel, and PR Heller. 2001. *A Catalog of Vadose Zone Hydraulic Properties for the Hanford Site*. PNNL-13672, Pacific Northwest National Laboratory, Richland, Washington.

Freeman EJ, R Khaleel, and PR Heller. 2002. *A Catalog of Vadose Zone Hydraulic Properties for the Hanford Site*. PNNL-13672, Rev. 1, Pacific Northwest National Laboratory, Richland, Washington.

Frind EO, RW Gillham, and J Pickens. 1977. "Application of Unsaturated Flow Properties in the Design of Geologic Environments for Radioactive Waste Storage Facilities" in *Finite Elements in Water Resources*, pp. 3.144-3.163. WG Gray, GF Pinder, and CA Brebbia (eds.), Pantech, London.

Garnier JM. 1985. "Retardation of Dissolved Radiocarbon through a Carbonated Matrix." *Geochim. Cosmochim. Acta* 49:683-693.

Gaylord DR and EP Poeter. 1991. *Geology and Hydrology of the 300 Area and Vicinity, Hanford Site, South Central Washington.* WHC-EP-0500, Westinghouse Hanford Company, Richland, Washington.

Gee GW and D Hillel. 1988. "Groundwater Recharge in Arid Regions: Review and Critique of Estimation Methods" in *Journal of Hydrological Processes* 2:255-266.

Gee GW, MJ Fayer, ML Rockhold, and MD Campbell. 1992. "Variations in Recharge at the Hanford Site" in *Northwest Science* 66:237-250.

Gee GW, JM Keller, and AL Ward. 2005. "Measurement and Prediction of Deep Drainage from Bare Sediments at a Semiarid Site ." Vadose Zone Journal 4(1):32-40

Gelhar LW. 1993. *Stochastic Subsurface Hydrology*. Prentice Hall, New York.

Gelhar LW and CL Axness. 1983. "Three-Dimensional Analysis of Macrodispersion in a Stratified Aquifer" in *Water Resources Research* 19:161-180.

Gelhar LW, C Welty, and KR Rehfeldt. 1992. "A Critical Review of Data on Field-Scale Dispersion in Aquifers," in *Water Resources Research* 28:1955-1974.

Gelhar LW, A Mantoglou, C Welty, and KR Rehfeldt. 1985. A Review of Field-Scale Physical Solute Transport Processes in Saturated and Unsaturated Porous Media. EPRI Report EA-4190, Research Project 2485-5, Electrical Power Research Institute, Palo Alto, California.

Geomatrix. 1996. *Probabilistic Seismic Hazard Analysis for DOE Hanford Site, Washington.* WHC-SD-W236SA-TI-002, Rev. 1. Westinghouse Hanford Company, Richland, Washington.

Hajek BF. 1966. *Soil Survey Hanford Project in Benton County, Washington.* BNWL-243, Pacific Northwest Laboratory, Richland, Washington.

Hartman MJ (ed.). 2000. *Hanford Site Groundwater Monitoring: Setting, Sources, and Methods.* PNNL-13080, Pacific Northwest National Laboratory, Richland, Washington.

Hartman MJ and KA Lindsey. 1993. *Hydrogeology of the 100-N Area, Hanford Site, Washington.* WHC-SD-EN-EV-027, Westinghouse Hanford Company, Richland, Washington.

Hartman MJ and RE Peterson. 1992. *Hydrologic Information Summary for the Northern Portion of the Hanford Site*. WHC-SD-EN-TI-023, Westinghouse Hanford Company, Richland, Washington.

Hartman MJ and P Dresel. 1998. *Hanford Site Groundwater Monitoring for Fiscal Year 1997.* PNNL-11793. Pacific Northwest National Laboratory , Richland, Washington.

Hartman MJ. 1999. *Hanford Site Groundwater Monitoring for Fiscal Year 1998.* PNNL-12086. Pacific Northwest National Laboratory, Richland, Washington.

Hartman MJ, LF Morasch, and WD Webber, eds. 2005. Hanford Site Groundwater Monitoring for Fiscal Year 2004. PNNL-15070. Pacific Northwest National Laboratory, Richland, Washington.

HEDL (Hanford Engineering Development Laboratory). 1975. *Site Investigation Report for the Fast Flux Test Facility, Richland, Washington.* BCL-1701, prepared by Hanford Engineering Development Laboratory, Westinghouse Hanford Company, Richland, Washington, for the United States Atomic Energy Commission.

Higgo JJW. 1988. *Review of Sorption Data Applicable to the Geologic Environment of Interest for Deep Disposal of ILW and LLW in the UK.* NSS/R-162, British Geological Survey, Keyworth, Nottingham, UK.

Ho CK, RG Baca, SH Conrad, GA Smith, L Shyr, and TA Wheeler. 1999. *Stochastic Parameter Development for PORFLOW Simulations of the Hanford AX Tank Farm*. SAND98-2880, Sandia National Laboratories, Albuquerque, New Mexico.

Hoitink DJ, JV Ramsdell, Jr, KW Burk, and WJ Shaw. 2005. *Hanford Site Climatological Summary 2004 with Historical Data*. PNNL-15160, Pacific Northwest National Laboratory, Richland, WA.

Jacobs Engineering Group, Inc. 1999. *Retrieval Performance Evaluation Methodology for the AX Tank Farm*. DOE/RL-98-72, prepared by Jacobs Engineering Group Inc. for U.S. Department of Energy, Richland Operations Office, Richland, Washington.

Johnson VG and CJ Chou. 1998. *Results of Phase I Groundwater Quality Assessment for Single-Shell Tank Waste Management Areas S-SX at the Hanford Site.* PNNL-11810, Pacific Northwest National Laboratory, Richland, Washington.

Jones TL. 1989. *Simulating the Water Balance of an Arid Site*. PNL-SA-17633, Pacific Northwest Laboratory, Richland, Washington.

Kaplan DI and RJ Serne. 1995. *Distribution Coefficient Values Describing Iodine, Neptunium, Selenium, Technetium, and Uranium Sorption to Hanford Sediments*. PNL-10379, SUP. 1, Pacific Northwest Laboratory, Richland, Washington.

Kaplan DI and RJ Serne. 2000. *Geochemical Data Package for the Hanford Immobilized Low-Activity Tank Waste Performance Assessment (ILAW PA*). PNNL-13037, Rev. 1, Pacific Northwest National Laboratory, Richland, Washington.

Kaplan DI, KE Parker, and JC Ritter. 1998. *Effects of Aging a Hanford Sediment and Quartz Sand with Sodium Hydroxide on Radionuclide Sorption Coefficients and Sediment Physical and Hydrological Properties: Final Report for Subtask 2a*. PNNL-11965, Pacific Northwest National Laboratory, Richland, Washington.

Kaplan DI, RJ Serne, AT Owen, JA Conca, TW Wietsma, and TL Gervais. 1996. *Radionuclide Adsorption Distribution Coefficients Measured in Hanford Sediments for the Low Level Waste Performance Assessment Project*. PNNL-11385, Pacific Northwest National Laboratory, Richland, Washington.

Kephart JL, GV Last, and SK Wurstner. 2005. "Enhancement of Stratigraphic Representations for Site Specific Tank Locations within the 200 West and 200 East Areas for the Hanford Site." *Journal of Undergraduate Research*, Volume V, 2005. Office of Science, U.S. Department of Energy, Washington, D.C.

Khaleel R. 1999. *Far-Field Hydrology Data Package for Immobilized Low-Activity Tank Waste Performance Assessment.* HNF-4769, Rev. 1, Fluor Daniel Northwest, Inc., Richland, Washington.

Khaleel R and EJ Freeman. 1995. *Variability and Scaling of Hydraulic Properties for 200 Area Soils, Hanford Site.* WHC-EP-0883, Westinghouse Hanford Company, Richland, Washington.

Khaleel R and PR Heller. 2003. "On the Hydraulic Properties of Coarse-Textured Sediments at Intermediate Water Contents." *Water Resour. Res.* 39(9):1233.

Khaleel R and JF Relyea. 1997. "Correcting Laboratory-Measured Moisture Retention Data for Gravel" in *Water Resources Research* 33(8):1875-1878.

Khaleel R, JF Relyea, and JL Conca. 1995. "Evaluation of van Genuchten-Mualem Relationships to Estimate Unsaturated Hydraulic Conductivity at Low Water Contents." *Water Resources Research* 31(11):2659-2668.

Khaleel R, T-CJ Yeh, and Z Lu. 2002. "Upscaled Flow and Transport Properties for Heterogeneous Unsaturated Media." *Water Resources Research* 38(5).

Khaleel R, TE Jones, AJ Knepp, FM Mann, DA Myers, PM Rogers, RJ Serne, and MI Wood. 2001. *Modeling Data Package for S-SX Field Investigation Report (FIR)*. RPP-6296, Rev. 0, CH2M HILL Hanford Group, Inc., Richland, Washington.

Kincaid CT, PW Eslinger, RL Aaberg, TB Miley, IC Nelson, DL Strenge, and JC Evans. 2006. *Inventory Data Package for Hanford Assessments*. PNNL -15829, Rev. 0. Pacific Northwest National Laboratory, Richland, Washington.

Kincaid CT, RW Bryce, and JW Buck. 2004. *Technical Scope and Approach for the 2004 Composite Analysis of Low-Level Waste Disposal at the Hanford Site*. PNNL-14372, Pacific Northwest National Laboratory, Richland, Washington.

Kincaid CT, PW Eslinger, WE Nichols, AL Bunn, RW Bryce, TB Miley, MC Richmond, SF Snyder, and RL Aaberg. 2000. *Groundwater/Vadose Zone Integration Project, System Assessment Capability (Revision 0), Assessment Description, Requirements, Software Design, and Test Plan.* BHI-01365, Draft A, Bechtel Hanford, Inc., Richland, Washington.

Kincaid CT, MP Bergeron, CR Cole, MD Freshley, NL Hassig, VG Johnson, DI Kaplan, RJ Serne, GP Streile, DL Strenge, PD Thorne, LW Vail, GA Whyatt, and SK Wurstner. 1998. *Composite Analysis for Low-Level Waste Disposal in the 200 Area Plateau of the Hanford Site.* PNNL-11800, Pacific Northwest National Laboratory, Richland, Washington.

Kipp KL and RD Mudd. 1974. *Selected Water Table Contour Maps and Well Hydrographs for the Hanford Reservation, 1944-1973.* BNWL-B-360, Pacific Northwest Laboratory, Richland, Washington.

Klute A. 1986. *Methods of Soil Analysis, Part 1*. 2nd ed., American Society of Agronomy, Madison, Wisconsin.

Knepp AJ. 2002. *Field Investigation Report for Waste Management Area B-BX-BY; Volume 1, Main Text and Appendices A - C, Volume 2, Appendices D - I.* RPP-10098, Rev. 0. CH2M HILL Hanford Group, Inc., Richland, Washington.

Kosugi K, JW Hopmans, and JH Dane. 2002. "3.3.4 Parameteric Models" in *Methods of Soil Analysis" Part 4 – Physical Methods*. Soil Science Society of America, Madison, Wisconsin, p. 739-757.

Krupka KM and RJ Serne. 1996. *Performance Assessment of Low-Level Radioactive Waste Disposal Facilities: Effects on Radionuclide Concentrations by Cement/Ground-Water Interactions*. NUREG/CR-6377, U.S. Nuclear, Regulatory Commission, Washington, D.C.

Krupka KM, RJ Serne, and DI Kaplan. 2004. Geochemical Data Package for the 2005 Hanford Integrated Disposal Facility Performance Assessment. PNNL-13037, Rev. 2. Pacific Northwest National Laboratory, Richland, Washington.

Last GV and VJ Rohay. 1993. *Refined Conceptual Model for the Volatile Organic Compounds-Arid Integrated Demonstration and 200 West Area Carbon Tetrachloride Expedited Response Action.* PNL-8597, Pacific Northwest Laboratory, Richland, Washington.

Last GV, BN Bjornstad, MP Bergeron, DW Wallace, DR Newcomer, JA Schramke, MA Chamness, CS Cline, SP Airhart, and JS Wilbur. 1989. *Hydrogeology of the 200 Areas Low-Level Burial Grounds – An Interim Report*. PNL-6820, Vol. 1 and 2, Pacific Northwest Laboratory, Richland, Washington.

Last GV, VJ Rohay, FJ Schelling, and L Soler. 2001. *Use of Process Relationship Diagrams in Development of Conceptual Models*. PNNL-SA-34515, Pacific Northwest National Laboratory, Richland, Washington.

Last GV, VJ Rohay, FJ Schelling, AL Bunn, MA Delamare, RL Dirkes, RD Hildebrand, JG Morse, BA Napier, RG Riley, L Soler, PD Thorne. 2004a. "A Comprehensive and Systematic Approach to Developing and Documenting Conceptual Models of Contaminant Release and Migration at the Hanford Site." *Journal of Stochastic Environmental Research and Risk Assessment* 18(2):190-116.

Last GV, EJ Freeman, KJ Cantrell, MJ Fayer, GW Gee, WE Nichols, BN Bjornstad, and DG Horton. 2004b. *Vadose Zone Hydrogeology Data Package for the 2004 Composite Analysis*. PNNL-14702, Rev. 0. Pacific Northwest National Laboratory, Richland, Washington.

Last GV, WE Nichols, and CT Kincaid. 2006. *Geographic and Operational Site Parameters List (GOSPL) for Hanford Assessments*. PNNL-14725, Rev. 1, Pacific Northwest National Laboratory, Richland, Washington.

Liikala TL, RL Aaberg, NJ Aimo, DJ Bates, TJ Gilmore, EJ Jensen, GV Last, PL Oberlander, KB Olsen, KR Oster, LR Roome, JC Simpson, SS Teel, and EJ Westergard. 1988. *Geohydrologic Characterization of the Area Surrounding the 183-H Solar Evaporation Basin.* PNL-6728, Pacific Northwest Laboratory, Richland, Washington.

Lindberg JW and FW Bond. 1979. *Geohydrology and Ground-Water Quality Beneath the 300 Area, Hanford Site, Washington.* PNL-2949, Pacific Northwest Laboratory, Richland, Washington.

Lindberg JW. 1993a. *Geology of the 100-B/C Area, Hanford Site, South-Central Washington.* WHC-SD-EN-TI-133, Westinghouse Hanford Company, Richland, Washington.

Lindberg JW. 1993b. *Geology of the 100-K Area, Hanford Site, South-Central Washington.* WHC-SD-EN-TI-155, Westinghouse Hanford Company, Richland, Washington.

Lindberg JW. 1995. *Hydrogeology of the 100-K Area, Hanford Site, South-Central Washington.* WHC-SD-EN-TI-294, Westinghouse Hanford Company, Richland, Washington.

Lindsey KA. 1991. *Revised Stratigraphy for the Ringold Formation, Hanford Site, South-Central Washington.* WHC-SD-EN-EE-004. Westinghouse Hanford Company, Richland, Washington.

Lindsey KA. 1992. *Geology of the Northern Part of the Hanford Site: An Outline of Data Sources and Geologic Setting of the 100 Areas.* WHC-SD-EN-TI-011, Westinghouse Hanford Company, Richland, Washington.

Lindsey KA. 1995. *Miocene- to Pliocene-Aged Suprabasalt Sediments of the Hanford Site, South-Central Washington.* BHI-00184, Rev. 00, Bechtel Hanford, Inc., Richland, Washington.

Lindsey KA. 1996. *Miocene to Pliocene Ringold Formation and Associated Deposits of the Ancestral Columbia River System, South-Central Washington and North Central Oregon.* Open File Report 96-8, Washington State Department of Natural Resources, Olympia, Washington.

Lindsey KA and GK Jaeger. 1993. *Geologic Setting of the 100-HR-3 Operable Unit, Hanford Site, South-Central Washington.* WHC-SD-EN-TI-132, Westinghouse Hanford Company, Richland, Washington.

Lindsey KA and DR Gaylord. 1999. "Lithofacies and Sedimentology of the Miocene-Pliocene Ringold Formation, South-Central Washington." In *Northwest Science.* Vol. 64, No. 3, pp. 165-180, May 1990.

Lindsey KA, MP Connelly, and BN Bjornstad. 1992a. *Geologic Setting of the 200 West Area: An Update.* WHC-SD-EN-TI-008, Westinghouse Hanford Company, Richland, Washington.

Lindsey KA, BN Bjornstad, JW Lindberg, and KM Hoffmann. 1992b. *Geologic Setting of the 200 East Area: An Update.* WHC-SD-EN-TI-012, Rev. 0, Westinghouse Hanford Company, Richland, Washington.

LMHC. 1999. *Statements of Work for FY 2000 to FY 2005 for the Hanford Low-Activity Tank Waste Performance Assessment Program*. HNF-SD-WM-PAP-062, Rev. 4, Lockheed Martin Hanford Company, Richland, Washington.

Looney BB and RW Falta (eds.). 2000. *Vadose Zone, Science and Technology Solutions*. Two Volumes, Battelle Press, Columbus, Ohio.

Maxfield HL. 1979. *Handbook - 200 Areas Waste Sites.* RHO-CD-673, Volumes I, II, and III. Rockwell Hanford Operations, Richland, Washington.

Meyer PD, KP Saripalli, and VL Freedman. 2004. *Near-Field Hydrology Data Package for the Integrated Disposal Facility 2005 Performance Assessment*. PNNL-14700, Pacific Northwest National Laboratory, Richland, Washington.

Millington RJ and JP Quirk. 1959. "Permeability of Poros Media." *Nature* 183:387-388.

Mualem Y. 1976. "A New Model for Predicting the Hydraulic Conductivity of Unsaturated Porous Media" in *Water Resources Research* 12:513.

Murphy EM, TR Ginn, and JL Phillips. 1996. "Geochemical Estimates of Paleorecharge in the Pasco Basin: Evaluation of the Chloride Mass-Balance Technique." *Water Resources Research* 32(9):2853-2868.

Murray CJ, AL Ward, and JL Wilson. 2003. *Influence of Clastic Dikes on Vertical Migration of Contaminants in the Vadose Zone at Hanford*. PNNL-14224, Pacific Northwest National Laboratory, Richland, Washington.

Murray CJ, Y Chien, and PD Thorne. 2004. *A Geostatistical Analysis of Historical Field Data on Tritium, Technetium-99, Iodine-129, and Uranium*. PNNL-14618, Rev. 0, Pacific Northwest National Laboratory, Richland, Washington.

Murray CJ, DG Horton, AL Ward, and GW Gee. 2002. "Hydrogeologic Influence of Clastic Dikes on Vadose Zone Transport," Section 7.3.3 pp. 7.26-7.27, in *Hanford Site Environmental Report for Calendar Year 2001*. PNNL-13910, Pacific Northwest National Laboratory, Richland, Washington.

NEA (Nuclear Energy Agency). 2000. *Features, Events and Processes (FEPs) for Geologic Disposal of Radioactive Waste, An International Database*. Organization For Economic Co-Operation and Development (OECD) Publications, France.

Neitzel DA, AL Bunn, SD Cannon, JP Duncan, RA Fowler, BG Fritz, DW Harvey, PL Hendrickson, DJ Hoitink, DG Horton, GV Last, TM Poston, EL Prendergast-Kennedy, SP Reidel, AC Rohay, MJ Scott, and PD Thorne. 2005. *Hanford Site National Environmental Policy Act (NEPA) Characterization, Revision 17*. PNNL-6415, Rev. 17, Pacific Northwest National Laboratory, Richland, Washington.

Oostrom. M, ML Rockhold, PD Thorne, GV Last, and MJ Truex. 2004. *Three-Dimensional Modeling of DNAPL in the Subsurface of the 216-Z-9 Trench at the Hanford Site.* PNNL-14895. Pacific Northwest National Laboratory, Richland, Washington.

Pearce GG, RE Brown, and TP O'Farrell. 1969. *The Arid Lands Ecology Reserve at Pacific Northwest Laboratory, Richland, Washington*. BNWL-SA-2574, Pacific Northwest Laboratory, Richland, Washington.

Peterson RE, RF Raidl, and CW Denslow. 1996. *Conceptual Site Models for Groundwater Contamination at the 100-BC-5, 100-KR-4, 100-HR-3, and 100-FR-3 Operable Units.* BHI-00917, Bechtel Hanford Company, Richland, Washington.

Peterson RE and MP Connelly. 2001. *Zone of Interaction Between Hanford Site Groundwater and Adjacent Columbia River*. PNNL-13674, Pacific Northwest National Laboratory, Richland, Washington.

Price WH and KR Fecht. 1976a. *Geology of the 241-U Tank Farm.* ARH-LD-138, Informal Report, Atlantic Richfield Hanford Company, Richland, Washington.

Price WH and KR Fecht. 1976b. *Geology of the 241-B Tank Farm.* ARH-LD-129, Atlantic Richfield Hanford Company, Richland, Washington.

Price WH and KR Fecht. 1976c. *Geology of the 241-BX Tank Farm.* ARH-LD-130, Atlantic Richfield Hanford Company, Richland, Washington.

Price WH and KR Fecht. 1976d. *Geology of the 241-BY Tank Farm.* ARH-LD-131, Atlantic Richfield Hanford Company, Richland, Washington.

Pruess K., S Yabusaki, C Steefel, and P Lichtner. 2002. Fluid Flow, Heat Transfer, and Solute Transport at Nuclear Waste Storage Tanks in the Hanford Vadose Zone. *Vadose Zone Journal,* 1:68-88. Soil Science Society of America, Madison, Wisconsin.

Prych EA. 1998. *Using Chloride and Chlorine-36 as Soil-Water Tracers to Estimate Deep Percolation at Selected Locations on the U.S. Department of Energy Hanford Site, Washington*. Water-Supply Paper 2481, U.S. Geological Survey, Tacoma, Washington.

Raidl RF. 1994. *Geology of the 100-FR-3 Operable Unit, Hanford Site, South-Central Washington*. WHC-SD-EN-TI-221, Westinghouse Hanford Company, Richland, Washington.

Reidel SP. 2004. *Geologic Data Package for 2005 Integrated Disposal Facility Waste Performance Assessment.* PNNL-14586. Pacific Northwest National Laboratory, Richland, Washington.

Reidel SP and AM Ho. 2002. *Geologic and Wireline Summaries from Fiscal Year 2002 ILAW Boreholes*. PNNL-14029, Pacific Northwest National Laboratory, Richland, Washington.

Reidel SP and DG Horton. 1999. *Geologic Data Package for 2001 Immobilized Low-Activity Waste Performance Assessment.* PNNL-12257, Rev. 1, Pacific Northwest National Laboratory, Richland, Washington.

Reidel SP, DG Horton, and MM Valenta. 2001. *Geologic and Wireline Borehole Summary from the Second ILAW Borehole (299-E24-21)*. PNNL-13652, Pacific Northwest National Laboratory, Richland, Washington.

Reidel SP, DG Horton, Y Chien, DB Barnett, and K Singleton. 2006. *Geology, Hydrogeology, Geochemistry, and Mineralogy Data Package for the Single-Shell Tank Waste Management Areas at the Hanford Site.* RPP-23748, Rev. 0. CH2M HILL Hanford Group, Inc. Richland, Washington.

Riley RG and C LoPresti. 2004. R*elease Model Data Package for the 2004 Composite Analysis*. PNNL-14760, Rev. 0, Pacific Northwest National Laboratory, Richland, Washington.

Rohay VJ, KJ Swett, and GV Last. 1994. *1994 Conceptual Model of the Carbon Tetrachloride Contamination in the 200 West Area at the Hanford Site.* WHC-SD-EN-TI-248, Westinghouse Hanford Company, Richland, Washington.

Scanlon BR, SW Tyler, and PJ Wierenga. November 1997. "Hydrologic Issues in Arid, Unsaturated Systems and Implications for Contaminant Transport" in *Reviews of Geophysics*, 35, 4, pages 461-490. American Geophysical Union.

Schalla R, RW Wallace, RL Aaberg, SP Airhart, DJ Bastes, JVM Carlile, CS Cline, DI Dennison, MD Freshley, PR Heller, EJ Jensen, KB Olsen, RG Parkhurst, JT Rieger, and EJ Westergard. 1988. *Interim Characterization Report for the 300 Area Process Trenches.* PNL-6716, Pacific Northwest Laboratory, Richland, Washington.

Scott, WE, R. Iverson, M Vallance, W James, and W Hildreth. 1995. *Volcano Hazards in the Mount Adams Region, Washington.* Open-File Report 95-492. U.S. Geological Survey, Washington, D.C.

Serne RJ and MI Wood. 1990. *Hanford Waste-Form Release and Sediment Interaction: A Status Report with Rationale and Recommendations for Additional Studies*. PNL-7297, Pacific Northwest Laboratory, Richland, Washington.

Serne RJ and VL LeGore. 1996. *Strontium-90 Adsorption-Desorption Properties and Sediment Characterization at the 100-N Area.* PNNL-10899, Pacific Northwest National Laboratory, Richland, Washington.

Serne RJ, JL Conca, VL LeGore, KJ Cantrell, CW Lindenmeier, JA Campbell, JE Amonette, and MI Wood. 1993. *Solid-Waste Leach Characteristics and Contaminant-Sediment Interactions, Volume 1: Batch Leach and Adsorption Tests and Sediment Characterization.* PNL-8889, Vol. 1, Pacific Northwest Laboratory, Richland, Washington.

Serne RJ, RO Lokken, and LJ Criscenti. 1992. "Characterization of Grouted LLW to Support Performance Assessment" in *Waste Management* 12:271-287.

Skaggs RL and WH Walters. 1981. *Flood Risk Analysis of Cold Creek Near the Hanford Site*. RHO-BWI-C-120, Rockwell Hanford Operations, Richland, Washington.

Slate JL. 1996. "Buried Carbonate Paleosols Developed in Plio-Pleistocene Deposits of the Pasco Basin, South-Central Washington" in *Quaternary International* 34-36:191-196.

Slate JL. 2000. *Nature and Variability of the Plio-Pleistocene Unit in the 200 West Area of the Hanford Site.* BHI-01203, Bechtel Hanford, Inc., Richland, Washington.

Soler L, GV Last, BA Napier, VJ Rohay, and FJ Schelling. 2001. T*he Application of Features, Events, and Process Methodology at the Hanford Site*. BHI-01573, Rev. 0, Bechtel Hanford, Inc., Richland, Washington.

Stenhouse MJ. 1995. *Sorption Databases for Crystalline, Marl and Bentonite for Performance Assessment*. NTB 93-06, Nagra, Wettingen, Switzerland.

Stephens DB. 1992. "A Comparison of Calculated and Measured Unsaturated Hydraulic Conductivity of Two Uniform Soils in New Mexico." *Proceedings of the International Workshop on Indirect Methods for Estimating the Hydraulic Properties of Unsaturated Soils*, Riverside, California, October 11-13, 1989, MTh van Genuchten, FJ Leij, and LJ Lund (eds.), University of California, Riverside, California, p. 249-261.

Stone, WA, JM Thorp, OP Gifford and DJ Hoitink. 1983. *Climatological Summary for the Hanford Area.* PNL-4622. Pacific Northwest National Laboratory, Richland, Washington.

Stumm W and JJ Morgan. 1996. "Aquatic Chemistry," *Chemical Equilibria and Rates* in *Natural Waters*, 3rd ed., John Wiley and Sons, Inc., New York.

Swanson LC, GG Kelty, KA Lindsey, KR Simpson, RK Price, and SD Consort. 1992. *Phase I Hydrogeologic Summary of the 300-FF-5 Operable Unit, 300 Area.* WHC-SD-EN-TI-052, Rev. 0, Westinghouse Hanford Company, Richland, Washington.

Swanson LD, VJ Rohay, and JM Faurote. 1999. *Hydrogeologic Conceptual Model for the Carbon Tetrachloride and Uranium/Technetium Plumes in the 200 West Area: 1994 through 1999 Update*. BHI-01311, Bechtel Hanford, Inc., Richland, Washington.

Tallman AM, KR Fecht, MC Marratt, and GV Last. 1979. *Geology of the Separation Areas, Hanford Site, South-Central Washington.* RHO-ST-23, Rockwell Hanford Operations, Richland, Washington.

Thorne PD, MA Chamness, FA Spane, Jr., VR Vermeul, and WD Webber. 1993. *Three-Dimensional Conceptual Model for the Hanford Site Unconfined Aquifer System, FY93 Status Report*. PNL-8971, Pacific Northwest Laboratory, Richland, Washington.

Thorne PD, MA Chamness, VR Vermeul, QC MacDonald, and SE Schubert. 1994. *Three-Dimensional Conceptual Model for the Hanford Site Unconfined Aquifer System, FY 1994 Status Report*. PNL-10195, Pacific Northwest Laboratory, Richland, Washington.

Valenta MM, MB Martin, JR Moreno, RM Ferri, DG Horton, and SP Reidel. 2000. *Particle Size Distribution Data From Existing Boreholes at the Immobilized Low-Activity Waste Site*. PNNL-13328, Pacific Northwest National Laboratory, Richland, Washington.

van Genuchten MTh. 1980. "A Closed-Form Solution for Predicting the Conductivity of Unsaturated Soils." *Soil Sci. Soc. Am. J.* 44:892-898.

Vermeul VR, SS Teel, JE Amonette, CR Cole, JS Fruchter, YA Gorby, FA Spane, JE Szecsody, MD Williams, and SB Yabusaki. 1995. *Geologic, Geochemical, Microbiologic, and Hydrologic Characterization at the In Situ Redox Manipulation Test Site.* PNL-10633, Pacific Northwest Laboratory, Richland, Washington.

Ward AL, GW Gee, and MD White. 1997. *A Comprehensive Analysis of Contaminant Transport in the Vadose Zone Beneath Tank SX-109*. PNNL-11463, Pacific Northwest National Laboratory, Richland, Washington.

Ward AL, JK Linville, JM Keller, GH Seedahmed. 2005. *200-BP-1 Prototype Hanford Barrier Annual Monitoring Report for Fiscal Year 2004.* PNNL-14960. Pacific Northwest National Laboratory, Richland, Washington

Warrick A, DE Myers, and D Nelson. 1986. "Geostatistical Methods Applied to Soil Science, in Methods of Soil Analysis," Part I, *Soil Science Society Amer*. 53-82.

Webster GD and JW Crosby. 1982. "Appendix 2R - Stratigraphic Investigation of the Skagit/Hanford Nuclear Project" In *Skagit/Hanford Nuclear Project, Preliminary Safety Analysis Report.* Volume 5. Pudget Power, Pudget Sound Power and Light Company, Bellevue, Washington.

Weekes, DC, BH Ford, and GK Jaeger. 1996. *Preoperational Baseline and Site Characterization Report for the Environmental Restoration Disposal Facility*. BHI-00270, Rev. 1. Bechtel Hanford, Inc., Richland, Washington.

White MD and M Oostrom. 2000. *STOMP Subsurface Transport Over Multiple Phases Version 2.0 Theory Guide*. PNNL-12030, Pacific Northwest National Laboratory, Richland, Washington.

Williams BA, BN Bjornstad, R Schalla, and WD Webber. 2000. *Revised Hydrogeology for the Suprabasalt Aquifer System, 200-East Area and Vicinity, Hanford Site, Washington.* PNNL-12261, Pacific Northwest National Laboratory, Richland, Washington.

Williams BA, BN Bjornstad, R Schalla, and WD Webber. 2002. *Revised Hydrogeology for the Suprabasalt Aquifer System, 200-West Area and Vicinity, Hanford Site, Washington.* PNNL-13858, Pacific Northwest National Laboratory, Richland, Washington.

Wilson LG, LG Everett, and SJ Cullen. 1995. *Handbook of Vadose Zone Characterization and Monitoring*. CRC Press, Inc., Lewis Publishers, Raton, Florida.

Wittreich CD, JK Linville, GW Gee, and AL Ward. 2003. *200-OP-1 Prototype Hanford Barrier Annual Monitoring Report for Fiscal Year 2002*. CP-14873, Rev. 0, Fluor Hanford, Inc., Richland, Washington.

Wood MI, R Khaleel, PD Rittman, AH Lu, SH Finfrock, RJ Serne, KJ Cantrell, and TH DeLorenzo. 1995. *Performance Assessment for the Disposal of Low-Level Waste in the 200-West Area Burial Grounds*. WHC-D-0645, Westinghouse Hanford Company, Richland, Washington.

Wood MI, R Khaleel, PD Rittman, SH Finfrock, TH DeLorenzo, and DY Gorbrick. 1996. *Performance Assessment for the Disposal of Low-Level Waste in the 200-East Area Burial Grounds.* WHC-SD-WM-TI-730, Westinghouse Hanford Company, Richland, Washington.

Wood MI, R Schalla, BN Bjornstad, and SM Narbutovskih. 2000. *Subsurface Conditions Description of the B-BX-BY Waste Management Area.* HNF-5507, Rev. 0, CH2M HILL Hanford Group, Inc., Richland, Washington.

Wood MI, TE Jones, BN Bjornstad, and F. N. Hodges. 2001. *Subsurface Conditions Description of the T and TX-TY Waste Management Areas.* HNF-7123, Rev. 0. CH2M Hill Hanford Group, Inc., Richland, Washington.

Wood MI, TE Jones, BN Bjornstad, D. G. Horton, SM Narbutovskih, and R Schalla. 2003. *Subsurface Conditions Description of the C and A-AX Waste Management Areas*. RPP-14430, Rev. 0. CH2M Hill Hanford Group, Inc., Richland, Washington.

Wood MI, and TE Jones. 2003. *Subsurface Conditions Description of the U Waste Management Areas*. RPP-15808, Rev. 0. CH2M Hill Hanford Group, Inc., Richland, Washington.

Wurstner SK, PD Thorne, MA Chamness, MD Freshly, and MD Williams. 1995. *Development of a Three-Dimensional Ground-Water Model of the Hanford Site Unconfined Aquifer System: FY 1995 Status Report.* PNL-10886, Pacific Northwest Laboratory, Richland, Washington.

Xie Y, CJ Murray, GV Last, and R Mackley. 2003. *Mineralogical and Bulk-Rock Geochemical Signatures of Ringold and Hanford Formation Sediments*. PNNL-14202, Pacific Northwest National Laboratory, Richland, Washington.

Yao T-M and JMH Hendricks. 1996. "Stability of Wetting Forests in Dry Homogeneous Soils Under Low Infiltration Ratios." *Soil Science Society of America Journal*, 60, 20-28, Madison, Wisconsin: Soil Science Society of America TIC 286692.

Zhang ZF, AL Ward, and GW Gee. 2002. *Estimating Field-Scale Hydraulic Parameters Using a Combination of Parameter Scaling and Inverse Methods*. PNNL-14109, Pacific Northwest National Laboratory, Richland, Washington.

Zhang ZF, AL Ward, and GW Gee. 2003. "Estimating Soil Hydraulic Parameters of a Field Drainage Experiment Using Inverse Techniques." *Vadose Zone J.* 2:201-211.

Zhuang J, M Flury, and Y Jin. 2003. "Colloid-Facilitated Cs Transport through Water-Saturated Hanford Sediment and Ottawa Sand." *Environ. Sci. Technol*. 37:4905-4911.

Zhuang J, Y Jin, and M Flury. 2004. "Comparison of Hanford Colloids and Kaolinite Transport in Porous Media" *Vadose Zone Journal* 3:395-402. Soil Science Society of America, Madison, Wisconsin.

Appendix A

Hydrostratigraphic Templates

VZ Base Templates A

South 200 East Area (A Plant, C Plant, U. S. Ecology) Stratigraphic Columns

Notes/Assumptions:

1) Topography ranges from 735 ft MSL in southwest corner of 200 East Area to 645 ft MSL in the 241-C area (USGS Gable Butte 7.5 min. Quadrangle Map). Will assume an average elevation of 690 ft MSL.
2) The pre-Hanford Water Table (January 1944) is estimated to range from an elevation of 116 m (380 ft) in the eastern part of 200 East to 119 m (390 ft) in the western part (Kipp and Mudd 1974). Will assume an average water table elevation of 117 m (385 ft) MSL.
3) A thin blanket of eolian sand and silt covers the surface of the site where not disturbed. However, this material was generally removed during excavation and construction of the waste disposal sites and then incorporated into backfill materials.
4) The depth of the sites and thus, the backfull over these sites range from 0 ft for ponds and unplanned releases, to an average of about 15 ft for cribs and burial grounds, and about 50 ft for tanks. Injection well 216-C-2 is screened from 15-40 ft. Well 299-E24-11 is 60 ft deep (Hanford Wells). Assume average depth of 50 ft for deep injection/reverse wells.

Template 200A-x for surface disposal sites (e.g., Ponds)

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**	200A-2 K_d Class		200A-4 K_d Class
		0	690	Surface	NA	NA	NA	NA			
15	15	15	675	Eolian	Sand and Silt	S	Hss	HI	2H		4H
15	15	30	660	Hanford Gravel	Slightly Silty pebbly very coarse to coarse sand	SG1	Hg	II	2I2		4I2
200	203	233	457	South 200 East Sand	Slightly silty medium to coarse sand to coarse to fine sand	S	Hfs	II	2I1		4I1
62	62	295	395	Hanford Gravel	Pebbly very coarse to coarse sand to medium to fine pebble	SG1	Hg	II	2I2		4I2
10	10	305	385	Ringold Unit E	Silty sandy medium to fine pebble to sandy very coarse to fine pebble	SG2	Rg	II	2I2		4I2
		305	385	Water Table	NA	NA	NA	NA	NA		NA

Template 216A-x for shallow disposal sites (e.g., Cribs, Burial Grounds)

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**	216A-2 K_d Class	216A-3 K_d Class	216A-4 K_d Class
		0	690	Surface	NA	NA	NA	NA	NA	NA	NA
15	15	15	675	Backfill	Backfill	B	B	HI	2H	3H	4H
15	15	30	660	Hanford Gravel	Slightly Silty pebbly very coarse to coarse sand	SG1	Hg	HI	2H	3H	4H
200	203	233	457	South 200 East Sand	Slightly silty medium to coarse sand to coarse to fine sand	S	Hfs	II	2I1	3I1	4I1
62	62	295	395	Hanford Gravel	Pebbly very coarse to coarse sand to medium to fine pebble	SG1	Hg	II	2I2	3I2	4I2
10	10	305	385	Ringold Unit E	Silty sandy medium to fine pebble to sandy very coarse to fine pebble	SG2	Rg	II	2I2	3I2	4I2
		305	385	Water Table	NA	NA	NA	NA	NA	NA	NA

Template 241A-x for tanks (modified after Reidel et al. 2006)

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**	241A-2 K_d Class	241A-3 K_d Class	
		0	690	Surface	NA	NA	NA	NA	NA	NA	
50	50	50	640	Backfill	Dominated by gravel consisting of poorly to moderately sand with some sand evolved from coarse grained Hanford formation	B	B	HI	2H	3H	
81.5	82	132	558	(Gravel dominated facies association) H1-b?	Upper gravel dominated unit, gravelly sand	SG1	Hg	HI	2H	3H	
162.3	162	294	396	(Sand dominated facies association) H2?	Upper sand dominated unit, slightly silty	S	Hfs	HI	2H	3H	
5	5	299	391	Hanford Gravel	Pebbly very coarse to coarse sand to medium to fine pebble	SG1	Hg	II	2I2	3I2	
2.6	3	302	388	Cold Creek Upper Sub-unit/Plio-Pleistocene Silt Unit	Locally thick layer of silt overling the gravelly sediments of lower subunit	SS	PPlz	II	2I1	3I1	
2.5	3	305	385	Cold Creek Lower Sub-unit	Silty sandy medium to fine pebble to sandy very coarse to fine pebble	SG2	Rg	II	2I2	3I2	
		305	385	Water Table	NA	NA	NA	NA	2I2	3I2	
									NA	NA	

Template 266A-x for deep injection sites (e.g., reverse wells 216-C-2)

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**			266A-4 K_d Class
		0	690	Surface	NA	NA	NA	NA			NA
15	15	15	675	Eolian	Sand and silt	S	Hfs	II			4I1
15	35	50	640	Hanford Gravel	Slightly Silty pebbly very coarse to coarse sand	SG1	Hg	HI			4H
200	183	233	457	South 200 East Sand	Slightly silty medium to coarse sand to coarse to fine sand	S	Hfs	HI			4H
62	62	295	395	Hanford Gravel	Pebbly very coarse to coarse sand to medium to fine pebble	SG1	Hg	II			4I2
10	10	305	385	Ringold Unit E	Silty sandy medium to fine pebble to sandy very coarse to fine pebble	SG2	Rg	II			4I2
		305	385	Water Table	NA	NA	NA	NA			NA

* After Khaleel and Freeman (1995), per white paper by Khaleel (September 2000).

** HI=high impact, II=Intermediate Impact (After Kincaid et al. 1998).

BLUE = Injection/release point.

(a) Note: Injection well 216-C-2 is screened from 15-40 ft. Well 299-E24-11 is 60 ft deep (Hanford Wells). Assume average depth of 50 ft.

VZ Base Templates - A_BC Cribs
BC-Cribs (216-B-14 through -19), South 200 East Area Stratigraphic Columns

Notes/Assumptions:

1) Well head elevations range between 747 and 748 ft (HWIS). Well heads are typically about 3 ft about ground surface. However, the site was also interim stabilized in 1981 by covering with a minium of 2 ft (0.61 m) of clean soil and revegetated (WIDS). Therefore will assume an average elevation of 742 ft.
2) The pre-Hanford Water Table (January 1944) is estimated to have been at an elevation of 387 ft (118 m) MSL (based on Kipp and Mudd 1974).
3) The site depth to the crib bottom is reported to be 13 ft (4 m) based on Maxfield (1979). Thus, the backfill is assumed to be 13 ft deep.

Template 216A_BC_E-X for the Eastern corner of the BC crib area based on 299-E13-1 (N 134404.512, E 573655.723). **216A_BC_E-3**

Estimated Thickness (ft)***	Adjusted Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	Kd Zone**		Kd Class
		0	742	Surface	NA	NA	NA	NA		NA
13	13	13	729	Backfill	Backfill	B	B	HI		3H
9	9	22	720	Hanford Sand - horizontally bedded coarse sand (Sh[c])	Pebbly very coarse to medium sand to coarse to medium sand	S	Hcs_BC	HI		3H
221	221	243	499	Handford Sand - horizontally bedded fine sand (Sh[f])	Coarse to fine sand to slightly silty coarse to fine sand	S	Hfs_BC	II		3I1
83	112	355	387	Ringold Unit E	Silty sandy coarse to fine pebble to slightly silty pebbly very coarse to medium sand	SG2	Rg	II		3I2
		355	387	Water Table	NA	NA	NA	NA		NA

Template 216A_BC_W-X for the Western corner of the BC crib area based on 299-E13-6 (N 134341.797, E 573564.077). **216A_BC_W-3**

Estimated Thickness (ft)***	Adjusted Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type			Kd Class
		0	742	Surface	NA	NA	NA	NA		NA
13	13	13	729	Backfill	Backfill	B	B	HI		3H
10	10	23	719	Hanford Sand - horizontally bedded coarse sand (Sh[c])	Pebbly very coarse to medium sand to coarse to medium sand	S	Hcs_BC	HI		3H
215	215	238	504	Handford Sand - horizontally bedded fine sand (Sh[f])	Coarse to fine sand to slightly silty coarse to fine sand	S	Hfs_BC	II		3I1
98	117	355	387	Ringold Unit E	Silty sandy coarse to fine pebble to slightly silty pebbly very coarse to medium sand	SG2	Rg	II		3I2
		355	387	Water Table	NA	NA	NA	NA		NA

* After Khaleel and Freeman (1995), per white paper by Khaleel (September 2000).
** HI=high impact, II=Intermediate Impact (after Kincaid et al. 1998).
BLUE = Injection/release point.

VZ Base Templates - A_BC Trenches

BC-Trenches (216-B-20 through -31, -52 through -54, and -58), South 200 East Area Stratigraphic Columns

Notes/Assumptions:

1) Topography ranges from 228.5 m (750 ft) MSL near the 216-B-58 trench to 225 m (738) ft MSL south of the 216-B-28 trench (as taken from the Hanford Site Atlas). Note however, that the site was interim stabilized in 1981 by covering with a minium of 2 ft (0.61 m) of clean soil and revegetated (WIDS). Ground surface elevations based on top of casing elevations in Hanford Wells (Chamness and Merz 1993).
2) The pre-Hanford Water Table (January 1944) is estimated to have been at an elevation of 387 ft (118 m) MSL (based on Kipp and Mudd 1974).
3) The site depth to the trench bottom is reported to be 8 to 10 ft-min. (2.4-3 m) based on Maxfield (1979). Thus, the backfill is assumed to be 10 ft deep.

Template 216A_BCT_W-X for the Western corner of the BC crib area based on 299-E13-6 (N 134341.797, E 573564.077).

Estimated Thickness (ft)***	Adjusted Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		216A_BCT_W-3 K_d Class	
		0	742	Surface	NA	NA	NA	NA		NA	
13	13	13	729	Backfill	Backfill	B	B	HI		3H	
10	10	23	719	Hanford Sand - horizontally bedded coarse sand (Sh[c])	Pebbly very coarse to medium sand to coarse to medium sand	S	Hcs_BC	HI		3H	
215	215	238	504	Hanford Sand - horizontally bedded fine sand (Sh[f])	Coarse to fine sand to slightly silty coarse to fine sand	S	Hfs_BC	II		3I1	
98	117	355	387	Ringold Unit E	Silty sandy coarse to fine pebble to slightly silty pebbly very coarse to medium sand	SG2	Rg	II		3I2	
		355	387	Water Table	NA	NA	NA	NA		NA	

Template 216A_BCT_N-X for the northwestern corner of the BC trench area based on 299-E13-14 (N 134474.132, E 573087.497).

Estimated Thickness (ft)***	Adjusted Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		216A_BCT_N-3 K_d Class	216A_BCT_N-4 K_d Class
		0	745	Surface	NA	NA	NA	NA		NA	NA
10	10	10	735	Backfill	Backfill	B	B	HI		3H	4H
17	17	27	718	Hanford Sand - horizontally bedded coarse sand (Sh[c])	Pebbly very coarse to medium sand to coarse to medium sand	S	Hcs_BC	HI		3H	4H
188	188	215	530	Hanford Sand - horizontally bedded fine sand (Sh[f])	Coarse to fine sand to slightly silty coarse to fine sand	S	Hfs_BC	II		3I1	4I1
58	58	273	472	Hanford Sand - horizontally bedded coarse sand (Sh[c])	Slightly pebbly very coarse to medium sandy coarse to fine pebble	S	Hcs_BC	II		3I1	4I1
22	22	295	450	Hanford Sand - horizontally bedded fine sand (Sh[f])	Coarse to fine sand to slightly silty coarse to fine sand	S	Hfs_BC	II		3I1	4I1
43	63	358	387	Ringold Unit E	Silty sandy coarse to fine pebble to slightly silty pebbly very coarse to medium sand	SG2	Rg	II		4I2	4I2
		358	387	Water Table	NA	NA	NA	NA		NA	NA

Template 216A_BCT_S-X for the southwestern portion of the BC trench area based on 299-E13-12 (N 134146.593, E 573188.669).

Estimated Thickness (ft)***	Adjusted Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		216A_BCT_S-3 K_d Class	216A_BCT_S-4 K_d Class
		0	731	Surface	NA	NA	NA	NA		NA	NA
10	10	10	721	Backfill	Backfill	B	B	HI		3H	4H
187	187	197	534	Hanford Sand - horizontally bedded fine sand (Sh[f])	Coarse to fine sand to slightly silty coarse to fine sand	S	Hfs_BC	HI		3H	4H
87	87	284	447	Hanford Sand - horizontally bedded coarse sand (Sh[c])	Slightly pebbly very coarse to medium sandy coarse to fine pebble	S	Hcs_BC	II		3I1	4I1
5	5	289	442	Hanford Sand - horizontally bedded fine sand (Sh[f])	Coarse to fine sand to slightly silty coarse to fine sand	S	Hfs_BC	II		3I1	4I1
35	55	344	387	Ringold Unit E	Silty sandy coarse to fine pebble to slightly silty pebbly very coarse to medium sand	SG2	Rg	II		3I2	4I2
		344	387	Water Table	NA	NA	NA	NA		NA	NA

Alternate Template 216A_BCT_A-X for the BC cribs and trenches and US Ecology areas based on Borehole C4191.

Estimated Thickness (ft)***	Adjusted Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		216A_BCT_A-3 K_d Class	216A_BCT_A-4 K_d Class
		0	731	Surface	NA	NA	NA	NA		NA	NA
10	10	10	721	Backfill	Sand, silt, and gravel	B	B	HI		3H	4H
75	75	85	646	Hanford Sand - horizontally bedded fine sand (Sh[f])	Coarse to very fine sand to silty fine to very fine sand and some silt lenses	S	Hfs_BC	HI		3H	4H
10	10	95	636	Hanford Sand - Laminated Silt to Fine Sand (Fl)	Compact, dense silt to sandy silt	SS	Hss	II		3I1	4I1
55	55	150	581	Hanford Sand - horizontally bedded fine sand (Sh[f])	Very coarse to very fine sand with some silt lenses	S	Hfs_BC	II		3I1	4I1
70	70	220	511	Hanford Sand - Laminated Silt to Fine Sand (Fl)	Sandy silt to silt with some silty to slightly silty coarse to medium sand lenses	SS	Hss	II		3I1	4I1
65	65	285	446	Hanford Sand - horizontally bedded coarse sand (Sh[c])	Slightly silty gravelly very coarse to medium sand to silty fine to very fine sand	S	Hcs_BC	II		3I1	4I1
<60	59	344	387	Ringold Unit E	Silty sandy coarse to fine pebble to slightly silty pebbly very coarse to medium sand	SG2	Rg	II		3I2	4I2
		344	387	Water Table	NA	NA	NA	NA		NA	NA

* After Khaleel and Freeman (1995), per white paper by Khaleel (September 2000).

** HI=high impact, II=Intermediate Impact (after Kincaid et al. 1998).

BLUE = Injection/release point.

VZ Base Templates A_C Tanks
South 200 East Area (C Tank Farm) Stratigraphic Columns

Notes/Assumptions:

1) Topography is about 645 ft MSL in the 241-C area (USGS Gable Butte 7.5 min. Quadrangle Map).
   Will assume an average elevation of 645 ft MSL.
2) The pre-Hanford Water Table (January 1944) is estimated to range from an elevation of 116 m (380 ft) in the eastern part of 200 East to 119 m (390 ft) in the western part (Kipp and Mudd 1974).
   Will assume an average water-table elevation of 116 m (380 ft) MSL.
3) A thin blanket of eolian sand and silt covers the surface of the site where not disturbed. However, this material was generally removed during excavation and construction of the waste disposal sites and then incorporated into backfill materials.
4) The depth of the sites and, thus, the backfull over these sites range up to about 16.4 m (54 ft) for tanks. Will assume an average thickness of backfill to be 50 ft.

Template 241A_C-3 for tanks. Modified from Joe Kephart, after the SST geologic data package by SP Reidel.										**241A_C-2**	**241A_C-3**
Average Thickness (ft)	**Adjusted Average Thickness (ft)**	**Depth (ft)**	**Elevation (ft)**	**Geologic Unit**	**Description**	**Hydraulic Property Type ***	**SAC Soil Type**	**K_d Zone****		**K_d Class**	**K_d Class**
		0	645	Surface	NA	NA	NA	NA		NA	NA
50	50	50	595	Backfill	Dominated by gravel consisting of poorly to moderately sand with some sand evolved from coarse grained Hanford formation	B	B	HI		2H	3H
34	29	79	566	(Gravel dominated facies association) H1-b?	Upper gravel dominated unit, gravelly sand	SG1	Hg	HI		2H	3H
152	128	207	438	(Sand dominated facies association) H2?	Upper sand dominated unit, slightly silty	S	Hfs	HI		2H	3H
34	29	236	409	Hanford Gravel	Pebbly very coarse to coarse snad to medium to fine pebble	SG1	Hg	I2		2I2	3I2
17.7	15	251	394	Cold Creek Upper Sub-unit/Plio-Pleistocene Silt Unit	Locally thick layer of silt overlying the gravelly sediments of lower subunit	SS	PPlz	II		2I1	3I1
17	14	265	380	Cold Creek Lower Sub-unit	Silty sandy medium to fine pebble to sandy very coarse to fine pebble	SS	PPlc	II		2I1	3I1
		265	380	Water Table	NA	NA	NA	NA		2I2	3I2

* After Khaleel and Freeman (1995), per white paper by Khaleel (September 2000).
** HI=high impact, II=Intermediate Impact (after Kincaid et al. 1998).
BLUE = Injection/release point.

VZ Base Templates - A_ILAW
South 200 East Area (ILAW) Stratigraphic Columns

Notes/Assumptions:

1) Thicknesses, elevation, and water table are averages from wells 299-W17-21, 299-E17-23, and 199-E17-25 for the south template, averages from wells 299-E17 22, 299-E24-7, and 299-W4-21 for the central template, and taken from well 299-E24-21 for the north template.
2) A thin blanket of eolian sand and silt covers the surface of the site where not disturbed. This is ignored because ILAW activities will remove this unit prior to excavation.
3) All data from Reidel et al. (1998, 2001), Reidel and Ho (2002), and Reidel (2004).

Template 216A_ILAW_S-X for the southern portion of the ILAW sitebased on 299-E17-21 (N 134893, E 574107)

										200A_ILAW_S-5	200A_ILAW_S-6
Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		K_d Class	K_d Class
		0	736	Surface	NA	NA	NA	NA		NA	NA
50	**50**	**50**	**686**	**Backfill**	**Sand and gravel**	**B**	**B**	**HI**		**5H**	**6H**
187	187	237	499	Hanford formation, sand-dominated	Sand (S2)	S	Hfs	HI		5H	6H
11	11	248	488	Hanford formation, gravel-dominated	Gravelly sand to sandy gravel (G3)	SG1	Hg	II		5I2	6I2
11	11	259	477	Hanford formation, sand-dominated	Sand (S3)	S	Hfs	II		5I1	6I1
75	75	334	402	Hanford formation, gravel-dominated	Gravel to sandy gravel (G4)	SG2	Hrg	II		5I2	6I2
		334	402	Water Table	NA	NA	NA	NA		NA	NA

Template 216A-ILAW_C-X for the central portion of the ILAW site based pm 299-E24-7 (N 135560, E 574407).

										200A_ILAW_C-5	200A_ILAW_C-6
Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	Hydraulic Property Type *	K_d Zone**		K_d Class	K_d Class
		0	718	Surface	NA	NA	NA	NA		NA	NA
50	**50**	**50**	**686**	**Backfill**	**Sand and Gravel**	**B**	**B**	**HI**		**5H**	**6H**
164	164	214	522	Hanford formation, sand dominated	Sand (S2)	S	Hfs	HI		5H	6H
20	20	234	502	Hanford formation, gravel dominated	Gravelly sand to sandy gravel (G3)	SG1	Hg	II		5I2	6I2
33	33	267	469	Hanford formation, sand dominated	Sand (S3)	S	Hfs	II		5I1	6I1
51	51	318	418	Hanford formation, gravel dominated	Gravel to sandy gravel (G4)	SG2	Hrg	II		5I2	6I2
		318	400	Water Table	NA	NA	NA	NA		NA	NA

Template 216A-ILAW_N-X, for the northern portion of the ILAW Site based on 299-E24-21 (N 135698, E 574636)

										200A_ILAW_N-5	200A_ILAW_N-6
Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	Hydraulic Property Type *	K_d Zone**		K_d Class	K_d Class
		0	714	Surface	NA	NA	NA	NA		NA	NA
50	**50**	**50**	**686**	**Backfill**	**Sand and Gravel**	**B**	**B**	**HI**		**5H**	**6H**
168	168	218	518	Hanford formation, sand dominated	Sand (S2)	S	Hfs	HI		5H	6H
14	14	232	504	Hanford formation, gravel dominated	Gravelly sand to sandy gravel (G3)	SG1	Hg	II		5I2	6I2
38	38	270	466	Hanford formation, sand dominated	Sand (S3)	S	Hfs	II		5I1	6I1
48	48	318	418	Hanford formation, gravel dominated	Gravel to sandy gravel (G4)	SG2	Hrg	II		5I2	6I2
		318	396	Water Table	NA	NA	NA	NA		NA	NA

* After Khaleel and Freeman (1995), per white paper by Khaleel (September 2000).

** HI=high impact, II=Intermediate Impact (after Kincaid et al. 1998).

BLUE = Injection/release point.

VZ Base Templates B

North 200 East Area (B Plant facilities and burial grounds) Stratigraphic Columns

Notes/Assumptions:

1) Topography ranges from 700 ft MSL east of B Plant to 590 ft MSL in the northeast corner of 200 East Area (USGS Gable Butte 7.5 min. Quadrangle Map).
Will assume an average elevation of 645 ft MSL.
2) The pre-Hanford Water Table (January 1944) is estimated to range from an elevation of 116 m (380 ft) in the eastern part of 200 East to 119 m (390 ft) in the western part (Kipp and Mudd 1974).
Will assume an average water-table elevation of 117 m (385 ft) MSL.
3) A thin blanket of eolian sand and silt covers the surface of the site where not disturbed.
However, this material was generally removed during excavation and construction of the waste disposal sites and then incorporated into backfill materials.
The depth of the sites and thus, the backfill over these sites range from 0 m for ponds and unplanned releases, to an average of about 4.5 m (15 ft) for cribs and burial grounds, and up to 16.4 m (54 ft) for tanks.
4) Five reverse wells are located in this area ranging in depth from 15-92 m. Assume average depth of 50 m (164 ft), with an average perforated interval of 11.5 m (38 ft).

Template 200B-X for surface disposal sites (e.g., Buildings, Ponds, Ditches, Unplanned Releases)

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		200B-2 K_d Class	200B-3 K_d Class	200B-4 K_d Class
		0	645	Surface	NA	NA	NA	NA		NA	NA	NA
2	2	2	643	Eolian	Sand and silt	S	Hss	HI		2H	3H	4H
60	64	66	579	Hanford Gravel	Silty sandy medium to fine pebble to slightly silty pebbly very coarse to coarse sand	SG1	Hg	HI		2H	3H	4H
173	183	249	396	North 200 East Hanford Sand	Coarse to medium sand to slightly pebbly slightly silty coarse to medium sand	S	Hcs	II		2I1	3I1	4I1
10	11	260	385	Undifferenciated Hanford/Plio-Pleistocene	Pebbly very coarse to coarse sand to sandy medium to fine pebble	SG1	Hg	II		2I2	3I2	4I2
		260	385	Water Table	NA	NA	NA	NA		NA	NA	NA

Template 216B-X for shallow disposal sites (e.g., Cribs, Burial Grounds)

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		216B-2 K_d Class	216B-3 K_d Class	216B-4 K_d Class
		0	645	Surface	NA	NA	NA	NA		NA	NA	NA
15	*15*	*15*	*630*	*Backfill*	*Backfill*	B	B	HI		2H	3H	4H
47	51	*66*	*579*	Hanford Gravel	Silty sandy medium to fine pebble to slightly silty pebbly very coarse to coarse sand	SG1	Hg	HI		2H	3H	4H
173	183	249	*396*	North 200 East Hanford Sand	Coarse to medium sand to slightly pebbly slighly silty coarse to medium sand	S	Hcs	II		2I1	3I1	4I1
10	11	260	*385*	Undifferenciated Hanford/Plio-Pleistocene	Pebbly very coarse to coarse sand to sandy medium to fine pebble	SG1	Hg	II		2I2	3I2	4I2
		260	*385*	Water Table	NA	NA	NA	NA		NA	NA	NA

Template 241B-X for tanks (based on Reidel et al. 2006).

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		241B-2 K_d Class		
		0	645	Surface	NA	NA	NA	NA		NA		
50	50	50	595	Backfill	Dominated by gravel consisiting of poorly to moderately sand with some sand evolved from coarse grained Hanford formation	B	B	HI		2H		
35	35	85	564	(Gravel dominated facies association) H1.b?	Upper gravel dominated unit, gravelly sand	SG1	Hg	HI		2H		
105	105	190	455	(Sand dominated facies association) H2?	Upper sand dominated unit, slightly silty	S	Hfs	HI		2H		
35	35	225	420	Hanford Gravel	Pebbly very coarse to coarse sand to sandy medium to fine pebble	SG1	Hg	II		2I2		
11.7	12	237	408	Cold Creek Upper Sub-unit/Plio-Pleistocene Silt Unit	Locally thick layer of silt overlying the gravelly sediments of lower subunit	SS	PPlz	II		2I1		
23.3	23	260	385	Cold Creek Lower Sub-unit	Silty sandy medium to fine pebble to sandy very coarse to fine pebble	SG2	PPlc	II		2I1		
		260	385	Water Table	NA	NA	NA	NA		NA		

Template 266B-X for deep injection sites (e.g., reverse wells - except 216-B-4 (a)).

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**				266B-4 K_d Class
		0	645	Surface	NA	NA	NA	NA				NA
2	2	2	643	Eolian	Sand and silt	S	Hss	NA				4I1
60	64	66	579	Hanford Gravel	Silty sandy medium to fine pebble to slightly silty pebbly very coarse to coarse sand	SG1	Hg	NA				4I2
20	19	85	560	North 200 East Hanford Sand	Coarse to medium sand to slightly pebbly slightly silty coarse to medium sand	S	Hfs	NA				4I1
25	25	110	535	North 200 East Hanford Sand	Coarse to medium sand to slightly pebbly slightly silty coarse to medium sand	S	Hcs	HI				4H
140	139	249	396	North 200 East Hanford Sand	Coarse to medium sand to slightly pebbly slightly silty coarse to medium sand	S	Hcs	HI				4H
10	11	260	385	Undifferenciated Hanford/Plio-Pleistocene	Pebbly very coarse to coarse sand to sandy medium to fine pebble	SG1	Hg	II				4I2
		260	385	Water Table	NA	NA	NA	*NA*				NA

Template 267B-X for very deep injection sites (i.e., the 216-B-5 reverse well (a))

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		267B-2 K_d Class		
		0	645	Surface	NA	NA	NA	NA		NA		
2	2	2	643	Eolian	Sand and silt	S	Hss	NA		2I1		
60	64	66	579	Hanford Gravel	Silty sandy medium to fine pebble to slightly silty pebbly very coarse to coarse sand	SG1	Hg	NA		2I2		
	183	249	396	North 200 East Hanford Sand	Coarse to medium sand to slightly pebbly slightly silty coarse to medium sand	S	Hfs	NA		2I1		
10	3	252	393	Undifferenciated Hanford/Plio-Pleistocene	Pebbly very coarse to coarse sand to sandy medium to fine pebble	S	Hcs	HI		2H		
10	8	260	385			SG1	Hg	HI		2H		
		260	385	Water Table	NA	NA	NA	NA		NA		

* After Khaleel and Freeman (1995).
** HI=high impact, II=Intermediate Impact (after Kincaid et al. 1989).
BLUE = Injection/release point.
(a) Injection well 216-B-4 is 108' deep; 216-B-5 is perfed 252-302'; 216-B-6 is perfed 73-75'.

VZ Base Templates C
100-B/C Stratigraphic Columns

Notes/Assumptions:

1) Elevation ranges from 500 ft AMSL in the south to about 400 ft AMSL to the north along the rivers edge (USGS Vernita Bridge and Riverland 7.5 min. Quad Maps).
   Average elevation near retention basins is ~440 ft and increases to the south (up to 460 ft) away from the river.
2) The water table ranges from an elevation of 122 m (400.3 ft) to 123 m (403.5 ft) (Hartman and Dresel 1998).
   Assume an average water-table elevation of 122.5 m (402 ft) AMSL.
3) A thin (≤ 1m) blanket of eolian or fluvial sand or silt may cover the surface of the site where not disturbed.

Template 100C-X - For surface disposal sites (i.e., reactors) — **100C-4**

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		K_d Class
		0	460	Surface	NA	NA	NA	HI		4H
	30	30	430	Hanford fm gravel	Silty sandy pebble to boulder gravel with lenses of gravelly medium to coarse sand. (DOE 1993)	SG1	Hg	HI		4H
	28	58	402	Hanford fm gravel	Silty sandy pebble to boulder gravel with lenses of gravelly medium to coarse sand. (DOE 1993)	SG1	Hg	II		4I2
		58	402	Water Table	NA	NA	NA	NA		NA

Template 116C-X - For shallow disposal sites (i.e., cribs, trenches, burial grounds, sand filter) — **116C-4**

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		K_d Class
		0	460	Surface	NA	NA	NA	NA		NA
	15	15	445	Backfill		B	B	HI		4H
	30	45	415	Hanford fm gravel	Silty sandy pebble to boulder gravel with lenses of gravelly medium to coarse sand. (DOE 1993)	SG1	Hg	HI		4H
	13	58	402	Hanford fm gravel	Silty sandy pebble to boulder gravel with lenses of gravelly medium to coarse sand. (DOE	SG1	Hg	II		4I2
		58	402	Water Table	NA	NA	NA	NA		NA

* After Khaleel and Freeman (1995), per white paper by Khaleel (September 2000).
** HI=high impact, II=Intermediate Impact (after Kincaid et al. 1989).
Blue = injection/release point.

VZ Base Templates D
100-D/DR Stratigraphic Columns

Notes/Assumptions:

1) Surface elevation ranges from 470 ft MSL along the southern boundary to about 390 ft MSL to the northwest along rivers edge (USGS Coyote Rapids 7.5 min. Quad Map).
   Will assume an average elevation of 460 ft MSL.
2) Water table ranges from an elevation of 116.5 m (382 ft) along the eastern boundary to 119 m (390.5 ft) to the northwest (DOE 1993; Hartman and Dresel 1998).
   Will assume an average water table elevation of 118 m (387 ft) MSL.
3) A thin (≤1m) blanket of eolian or fluvial sand or silt may cover the surface of the site where not disturbed.

Template 100D-X - For surface disposal sites (i.e., reactors) — **100D-4**

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		K_d Class
		0	460	Surface	NA	NA	NA	NA		NA
	30	30	430	Hanford fm gravel	Sandy gravel and gravelly sand, with local sandy and silty interbeds (Peterson et al. 1996)	SG1	Hg	HI		4H
	23	53	407	Hanford fm gravel	Sandy gravel and gravelly sand, with local sandy and silty interbeds (Peterson et al. 1996)	SG1	Hg	II		4I2
	20	73	387	Ringold Unit E	Silty sandy gravel	SG2	Rg	II		4I2
		73	387	Water Table		NA	NA	NA		NA

Template 116D-X - For shallow disposal sites (i.e., cribs, trenches, burial grounds, sand filter) — **116D-4**

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		K_d Class
		0	460	Surface	NA	NA	NA	NA		NA
	15	15	445	Backfill		B	B	HI		4H
	30	45	415	Hanford fm gravel	Sandy gravel and gravelly sand, with local sandy and silty interbeds (Peterson et al. 1996)	SG1	Hg	HI		4H
	8	53	407	Hanford fm gravel	Sandy gravel and gravelly sand, with local sandy and silty interbeds (Peterson et al. 1996)	SG1	Hg	II		4I2
	20	73	387	Ringold Unit E	Silty sandy gravel	SG2	Rg	II		4I2
		73	387	Water Table		NA	NA	NA		NA

* After Khaleel and Freeman (1995), per white paper by Khaleel (September 2000).
** HI=high impact, II=Intermediate Impact (after Kincaid et al. 1998).
BLUE = injection/release point.

VZ Base Templates E

East 200 East Area (B-Pond) Stratigraphic Columns

Notes/Assumptions:

1) Topography ranges from 460 to 650 ft (137 to 198 m) MSL (USGS Gable Butte 7.5 min. Quadrangle Map).
   Will assume an average elevation of 169 m (555 ft) MSL.
2) The pre-Hanford Water Table (January 1944) is estimated to range from an elevation of 113 m (370 ft) to 116 m (380 ft) MSL (Kipp and Mudd 1974).
   Will assume an average water-table elevation of 115 m (375 ft) MSL.
3) A thin blanket of eolian sand and silt covers the surface of the site where not disturbed.
   However, this material was generally removed during excavation and construction of the waste disposal sites and then incorporated into backfill materials.
4) The depth of the sites and, thus, the backfull over these sites range from 0 m for ponds and unplanned releases, to an average of about 4.5 m (15 ft) for cribs and burial grounds.

Template 200E-X for surface disposal sites (e.g., Ponds) — **200E-4**

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		K_d Class
		0	555	Surface	NA	NA	NA	HI		4H
3	3	3	552	Eolian	Sand and silt	S	Hss	HI		4H
12	11	14	541	Hanford Gravel	Silty sandy gravel to sandy gravel to gravelly sand	SG1	Hg	HI		4H
62	58	72	483	Hanford sand	Slightly pebbly, slightly silty coarse to medium sand to coarse to fine sand	S	Hcs	II		4I1
85	79	151	404	Hanford gravel	Sandy gravel to silty sandy gravel	SG1	Hg	II		4I2
30	29	180	375	Ringold Lower Mud	silt, sandy silt	SS	PPlz	II		4I1
		180	375	Water Table	NA	NA	NA	NA		NA

Template 216E-X for shallow disposal sites (i.e., cribs, trenches, burial grounds, sand filter, septic systems) — **216E-4**

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		K_d Class
		0	555	Surface	NA	NA	NA	NA		NA
15	15	15	540	Backfill		B	B	HI		4H
62	57	72	483	Hanford sand	Slightly pebbly, slightly silty coarse to medium sand to coarse to fine sand	S	Hcs	HI		4H
85	79	151	404	Hanford gravel	Sandy gravel to silty sandy gravel	SG1	Hg	II		4I2
30	29	180	375	Ringold Lower Mud	silt, sandy silt	SS	PPlz	II		4I1
		180	375	Water Table	NA	NA	NA	NA		NA

* After Khaleel and Freeman (1995), per white paper by Khaleel (September 2000).

** HI=high impact, II=Intermediate Impact (after Kincaid et al. 1998).

BLUE = Injection/release point.

VZ Base Templates F
100-F Stratigraphic Columns

Notes/Assumptions:

1) Surface elevation ranges from 420 ft MSL within the north-central 100-F Area to about 380 ft MSL to the northeast along rivers edge (USGS Locke Island 7.5 min. Quad Map).
   Will assume an average elevation of 410 ft MSL.
2) Water table ranges from an elevation of 113.5 m (372 ft) in the southeast to 115 m (377 ft) to the north (Hartman and Dresel 1998).
   Will assume an average water-table elevation of 114 m (374 ft) MSL.
3) A thin (≤1m) blanket of eolian or fluvial sand or silt may cover the surface of the site where not disturbed.

Template 100F-X for surface disposal sites (i.e., reactors) — **100F-4**

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		K_d Class
		0	410	**Surface**	**NA**	**NA**	**NA**	**NA**		**NA**
	30	30	380	Hanford Gravel	Sandy gravel to silty sandy gravel (Peterson et al. 1996). Gravel-dominated with subordinate sand-dominated facies (Raidl 1994).	SG1	Hg	HI		4H
	6	36	374	Hanford Gravel	Sandy gravel to silty sandy gravel (Peterson et al. 1996). Gravel-dominated with subordinate sand-dominated facies (Raidl 1994).	SG1	Hg	II		4I2
		36	374	Water Table	NA	NA	NA	NA		NA

Template 116F-X for shallow disposal sites (e.g., cribs, trenches, burial grounds, sand filter) — **116F-4**

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		K_d Class
		0	410	Surface	NA	NA	NA	NA		NA
	15	15	395	Backfill	NA	B	B	HI		4H
	21	36	374	Hanford fm gravel	Sandy gravel to silty sandy gravel (Peterson et al. 1996). Gravel-dominated with subordinate sand-dominated facies (Raidl 1994).	SG1	Hg	HI		4H
		36	374	Water Table	NA	NA	NA	NA		NA

* After Khaleel and Freeman (1995), per white paper by Khaleel (September 2000).
** HI=high impact, II=Intermediate Impact (after Kincaid et al. 1998).
BLUE = Injection/release point.

VZ Base Templates G
Gable Mountain Pond (Aggregate Area G) Stratigraphic Columns

Notes/Assumptions:

1) Topography ranges from 435 ft MSL at Gable Mountain Pond to 410 ft MSL at West Lake (Gable Butte Quadrangle, 7.5 Minute Series, 1986).
   Will assume an average elevation of 430 ft MSL.
2) The pre-Hanford water table (January 1944) is estimated at elevation of 119 m (390 ft) (Kipp and Mudd 1974).
   Will assume an average water-table elevation of 119 m (390 ft) MSL.
3) Stratigraphy interpreted from as-built drawings of wells 699-53-50, -54-49, -56-53, - 59-55, and 51-46. Undifferentiate Hanford formation materials range from a thickness of 12 to over 149 ft. Laying directly on basalt.
   Will assume an average thickness of the Hanford formation of 48 ft.
4) The depth of the sites and, thus, the backfull over these sites range from 0 m for ponds and unplanned releases to an average of about 4.5 m (15 ft) for cribs and burial grounds.

Template 200G-X for surface disposal sites (e.g., Ponds, trenches, buildings) — **200G-4**

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		K_d Class
		0	430	Surface	NA	NA	NA	NA		NA
48	40	40	390	Undifferenciated Hanford formation	coarse sand to gravel, cobbles, and boulders (up to 95% cobble and boulders)	SG1	Hg	HI		4H
		40	390	Water Table	NA	NA	NA	NA		NA

Template 216G-X for shallow disposal sites (e.g., Cribs) — **216G-4**

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		K_d Class
		0	430	Surface	NA	NA	NA	NA		NA
15	15	15	415	Backfill	Backfill	B	B	HI		4H
33	25	40	390	Undifferenciated Hanford formation	Coarse gravel and sand to silty sandy gravel	SG1	Hg	HI		4H
		40	390	Water Table	NA	NA	NA	NA		NA

* After Khaleel and Freeman (1995), per white paper by Khaleel (September 2000).
** HI=high impact, II=Intermediate Impact (after Kincaid et al. 1998).
BLUE = Injection/release point.

VZ Base Templates H

100-H Stratigraphic Columns

Notes/Assumptions:

1) Surface elevation ranges from 425 ft MSL in the center of the 100-H Area to about 380 ft MSL along rivers edge to the northeast (USDOE, Hanford Site Topography - Locke Island, Bechtel Job #22192; USGS Locke Island 7.5 min. Quad Map). Will assume an average elevation of 415 ft MSL.
2) Water table ranges from an elevation of 116 m (380 ft) to the south to 117 m (384 ft) to the northeast (Hartman and Dresel 1998). Will assume an average water-table elevation of 116.5 m (382 ft) MSL.
3) A thin (≤1m) blanket of eolian or fluvial sand or silt may cover the surface of the site where not disturbed.

Template 100H-X for surface disposal sites (i.e., retention basins) — **100H-4**

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		K_d Class
		0	415	**Surface**	**NA**	**NA**	**NA**	**NA**		**NA**
	30	30	385	Hanford fm gravel	Sandy gravel with subordinate gravelly sand (Peterson et al. 1996)	SG1	Hg	HI		4H
	3	33	382			SG1	Hg	II		4I2
		33	382	Water Table	NA	NA	NA	NA		NA

Template 116H-X for shallow disposal sites (e.g., cribs, trenches, burial grounds) — **116H-4**

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		K_d Class
		0	415	Surface	NA	NA	NA	NA		NA
	15	15	400	Backfill		B	B	HI		4H
	18	33	382	Hanford fm gravel	Sandy gravel with subordinate gravelly sand (Peterson et al. 1996)	SG1	Hg	HI		4H
		33	382	Water Table	NA	NA	NA	NA		NA

* After Khaleel and Freeman (1995), per white paper by Khaleel (September 2000).

** HI=high impact, II=Intermediate Impact (after Kincaid et al. 1998).

BLUE = Injection/release point.

VZ Base Templates I
200 North Area Stratigraphic Columns

Notes/Assumptions:

1) Topography ranges from 580 ft MSL near 216-N-3 in the NW portion of this geographic area to 540 ft MSL beneath the old 216-N-6 Pond in the SE portion of the area (Gable Butte Quadrangle, 7.5 Minute Series, 1986). Will assume an average elevation of 565 ft MSL.
2) The pre-Hanford water table (January 1944) is estimated at an elevation of 395 ft (Kipp and Mudd 1974). Will assume an average water-table elevation of 395 ft MSL.
3) Stratigraphy based on as-built drawings of 699-55-60A,B, and -51-63 (see HWIS). A thin blanket of top soil (eolian sand and silt) covers the surface of the site where not disturbed. However, this material was generally removed during excavation and construction of the waste disposal sites and then incorporated into backfill materials.
4) The depth of the sites and, thus, the backfull over these sites range from 0 m for ponds and unplanned releases to an average of about 4.5 m (15 ft) for cribs and burial grounds.

Template 200I-X for surface disposal sites (e.g., Ponds, trenches, buildings) — **200I-4**

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		K_d Class
		0	565	Surface	NA	NA	NA	NA		NA
3	3	3	562	Eolian	Sand and silt	S	Hss	HI		4H
122	167	170	395	Undifferenciated Hanford formation	Gravel and sand to boulders	SG1	Hg	HI		4H
		170	395	Water Table	NA	NA	NA	NA		NA

Template 216I-X for shallow disposal sites (e.g., Cribs) — **216I-4**

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		K_d Class
		0	565	Surface	NA	NA	NA	NA		NA
15	15	15	550	Backfill	Backfill	B	B	HI		4H
110	155	170	395	Undifferenciated Hanford formation	Gravel and sand to boulders	SG1	Hg	HI		4H
		170	395	Water Table	NA	NA	NA	NA		NA

* After Khaleel and Freeman (1995), per white paper by Khaleel (September 2000).

** HI=high impact, II=Intermediate Impact (after Kincaid et al. 1998).

BLUE = Injection/release point.

VZ Base Templates K
100-K Stratigraphic Columns

Notes/Assumptions:

1) Surface elevation ranges from 515 ft MSL in adjacent waste sites south of K Area to about 390 ft MSL to the northwest along rivers edge (USGS Coyote Rapids 7.5 min. Quad Map).
   Will assume an average elevation of 480 ft MSL, except injection wells which have projected surface elevation of 465 ft MSL.
2) Water table ranges from an elevation of 121 m (397 ft) to the northeast to 121.5 m (399 ft) to the south (Hartman and Dresel 1998).
   Will assume an average water-table elevation of 121.5 m (399 ft) MSL.
3) A thin (<1 m) layer of eolian or fluvial sand or silt may cover the surface of the site where not disturbed (Lindberg 1995).
4) Two injection wells (116-KE-3 and 116-KE-2) extend 10 ft into water table, and approximately 10 ft of the perforated casings extend above the water table (i.e., open to the vadose zone) within Ringold Unit E.

Template 100K-X for surface disposal sites (i.e., ponds and reactors) — **100K-4**

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		K_d Class
		0	480	Surface	NA	NA	NA	NA		NA
	30	30	450	Hanford fm gravel	Sandy gravel to silty sandy gravel intercalated with gravelly sand to sand (Lindberg 1995; Peterson et al. 1996)	SG1	Hg	HI		4H
	15	45	435	Hanford fm gravel	Sandy gravel to silty sandy gravel intercalated with gravelly sand to sand (Lindberg 1995; Peterson et al. 1996)	SG1	Hg	II		4I2
	36	81	399	Ringold Unit E	Fluvial sandy gravel to silty sandy gravel (Lindberg 1995)	SG2	Rg	II		4I2
		81	399	Water Table	NA	NA	NA	NA		NA

Template 116K-X for shallow disposal sites (e.g. cribs, trenches, burial grounds) — **116K-4**

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		K_d Class
		0	480	Surface	NA	NA	NA	NA		NA
	15	15	465	Backfill	Loose sandy gravel to silty sandy gravel	B	B	HI		4H
	30	45	435	Hanford fm gravel	Sandy gravel to silty sandy gravel intercalated with gravelly sand to sand (Lindberg 1995; Peterson et al. 1996)	SG1	Hg	HI		4H
	36	81	399	Ringold Unit E	Fluvial sandy gravel to silty sandy gravel (Lindberg 1995)	SG2	Rg	II		4I2
		81	399	Water Table	NA	NA	NA	NA		NA

Template 166K-X for deep disposal sites (e.g. reverse wells) — **166K-4**

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		K_d Class
		0	465	Surface	NA	NA	NA	NA		NA
	20	20	445	Backfill	Loose sandy gravel to silty sandy gravel	B	B	II		4I2
	20	40	425	Hanford fm gravel	Sandy gravel to silty sandy gravel intercalated with gravelly sand to sand (Lindberg 1995; Peterson et al. 1996)	SG1	Hg	II		4I2
	16	56	409	Ringold Unit E	Fluvial sandy gravel to silty sandy gravel (Lindberg 1995)	SG2	Rg	II		4I2
	10	66	399	Ringold Unit E	Fluvial sandy gravel to silty sandy gravel (Lindberg 1995)	SG2	Rg	HI		4H
		66	399	Water Table	NA	NA	NA	NA		NA

* After Khaleel and Freeman (1995), per white paper by Khaleel (September 2000).
** HI=high impact, II=Intermediate Impact (after Kincaid et al. 1998).
BLUE = Injection/release point.

VZ Base Templates M

South Central 600 Area (e.g. 618-11) Stratigraphic Columns

Notes/Assumptions:

1) Assume an average elevation of 450 ft (137.2 m) MSL (USGS Topo - Richland, Washington, 15 min. Quad. 1951).
2) Assume an average water-table elevation of 365 ft (111.3 m) MSL (Kipp and Mudd 1974).
3) Lithofacies taken from well logs (699-13-3A) found in the Hanford Well Log Library, Sigma V Building.

Template 600M-X for surface disposal sites (e.g., Trenches, ponds, unplanned releases) — **600M-4**

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	Kd Zone**		Kd Class
		0	450	Surface	NA	NA	NA	NA		NA
	6	6	444	Hanford Hfs	Silty Silty Sand	S	Hcs	HI		4H
	12	18	432	Hanford Hg	Sandy Gravel	SG1	Hg	HI		4H
	22	40	410	Hanford Hgs	Gravelly Sand	GS	Hgs	II		4I1
	10	50	400	Hanford Hg	Gravel	SG1	Hg	II		4I2
	35	85	365	Ringold Rg	Gravelly Sand (Ringold Formation)	SG2	Rg	II		4I2
		85	365	Water Table	NA	NA	NA	NA		NA

Template 616M-X for shallow disposal (e.g., cribs, burial grounds) — **616M-4**

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	Kd Zone**		Kd Class
		0	450	Surface	NA	NA	NA	NA		NA
	15	15	435	Backfill		B	B	HI		4H
	3	18	432	Hanford Hg	Sandy Gravel	SG1	Hg	HI		4H
	22	40	410	Hanford Hgs	Gravelly Sand	GS	Hgs	HI		4H
	10	50	400	Hanford Hg	Gravel	SG1	Hg	II		4I2
	35	85	365	Ringold Rg	Gravelly Sand (Ringold Formation)	SG2	Rg	II		4I2
		85	365	Water Table	NA	NA	NA	NA		NA

* After Khaleel and Freeman (1995), per white paper by Khaleel (September 2000).

** HI=high impact, II=Intermediate Impact (after Kincaid et al. 1998).

BLUE = Injection/release point.

VZ Base Templates N
100-N Stratigraphic Columns

Notes/Assumptions:

1) Surface elevation ranges from 460 ft MSL in the center of the 100-N Area to about 390 ft MSL along the rivers edge to the northwest (USGS Coyote Rapids 7.5 min. Quad Map).
   Will assume an average elevation of 455 ft MSL.
2) Water table ranges from an elevation of 119 m (390 ft) to the east to 120.5 m (395 ft) to the west (Hartman and Dresel 1998).
   Will assume an average water-table elevation of 119.5 m (392 ft) MSL.
3) A thin (≤1m) blanket of eolian or fluvial sand or silt may cover the surface of the site where not disturbed.

Template 100N-X for surface disposal sites (i.e., ponds and reactor) — **100N-4**

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		K_d Class
		0	455	Surface	NA	NA	NA	NA		NA
	30	30	425	Hanford fm gravel	Glaciofluvial sandy pebble to boulder gravel (Hartman and Lindsey 1993)	SG1	Hg	HI		4H
	10	40	415	Hanford fm gravel	Glaciofluvial sandy pebble to boulder gravel (Hartman and Lindsey 1993)	SG1	Hg	II		4I2
	23	63	392	Ringold Unit E	Fluvial, sandy pebble to cobble gravel (Hartman and Lindsey 1993)	SG2	Rg	II		4I2
		63	392	Water Table	NA	NA	NA	NA		NA

Template 116N-X for shallow disposal sites (e.g., cribs and trenches) — **116N-4**

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	Hydraulic Property Type *	K_d Zone**		K_d Class
		0	455	Surface	NA	NA	NA	NA		NA
	15	15	440	Backfill		B	B	HI		4H
	25	40	415	Hanford fm gravel	Glaciofluvial sandy pebble to boulder gravel (Hartman and Lindsey 1993)	SG1	Hg	HI		4H
	23	63	392	Ringold Unit E	Fluvial, sandy pebble to cobble gravel (Hartman and Lindsey 1993)	SG2	Rg	II		4I2
		63	392	Water Table	NA	NA	NA	NA		NA

* After Khaleel and Freeman (1995), per white paper by Khaleel (September 2000).
** HI=high impact, II=Intermediate Impact (after Kincaid et al. 1998).
BLUE = Injection/release point.

VZ Base Templates P
Southern 600 Area (e.g. 316-4, 618-10) Stratigraphic Columns

Notes/Assumptions:

1) Assume an average elevation of 440 ft (134.1 m) MSL (USGS Topo - Richland, Washington, 15 min. Quad. 1951).
2) Assume an average water-table elevation of 358 ft (109.1 m) MSL (based on well S6-4D in Kipp and Mudd 1974).
3) Lithofacies taken from well logs (699-S6-E4A and D) found in the Hanford Well Log Library in the Sigma V Building.

Template 600P-X for surface disposal sites (e.g., Trenches, ponds, unplanned releases) — **600P-4**

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**	K_d Class
		0	440	Surface	NA	NA	NA	NA	NA
	35	35	405	Hanford Hcs	Grey to Black Basaltic Sand	S	Hcs	HI	4H
	45	80	360	Hanford Hg	Gravel with sand and small amount of clay	SG1	Hg	II	4I2
	2	82	358	Ringold Unit E	Cemented gravel and pure gravel, drills hard, all colors	SG2	Rg	II	4I2
		82	358	Water Table	NA	NA	NA	NA	NA

Template 616P-X for shallow disposal (e.g., cribs, burial grounds) — **616P-4**

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**	K_d Class
		0	440	Surface	NA	NA	NA	NA	NA
	15	15	425	Backfill		B	B	HI	4H
	20	35	405	Hanford Hcs	Grey to Black Basaltic Sand	S	Hcs	HI	4H
	45	80	360	Hanford Hg	Gravel with sand and small amount of clay	SG1	Hg	II	4I2
	2	82	358	Ringold Unit E	Cemented gravel and pure gravel, drills hard, all colors	SG2	Rg	II	4I2
		82	358	Water Table	NA	NA	NA	NA	NA

* After Khaleel and Freeman (1995), per white paper by Khaleel (September 2000).
** HI=high impact, II=Intermediate Impact (after Kincaid et al. 1998).
BLUE = Injection/release point.

VZ Base Templates Q
400 Area (FFTF) Stratigraphic Columns

Notes/Assumptions:

1) Assume an average elevation of 540 ft (164.6 m) MSL (USGS Topo - Richland, Washington, 15 min. Quad. 1951).
2) Assume an average water-table elevation of 370 ft (112.8 m) MSL (based on well 2-3 in Kipp and Mudd 1974).
3) Lithofacies taken from Summary Report, FFTF Well No. 4 (499-S1-8J) in Project Inspection Log Book Project V-749, Meier Associates, Inc., Kennewick, Washington, and well logs for 499-S1-7B from the Hanford Well Log Library in the Sigma V Building.

Template 400Q-X for surface disposal sites (e.g., Trenches, ponds, unplanned releases) — **400Q-4**

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		K_d Class
		0	540	Surface	NA	NA	NA	NA		NA
	54	54	486	Hanford Hfs	Fine sand to silty medium sand, with occational lenses of coarse sand.	S	Hfs	HI		4H
	70	124	416	Hanford Hss	Silty fine to medium sand.	S	Hss	II		4I1
	33	157	383	Hanford Hcs	Interbedded gravelly sand, and silty sand, and silty gravel.	S	Hcs	II		4I1
	13	170	370	Ringold Unit E	Silty gravels with interbedded gravelly sands	SG2	Rg	II		4I2
		170	370	Water Table	NA	NA	NA	NA		NA

Template 416Q-X for shallow disposal (e.g., cribs, burial grounds) — **416Q-4**

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		K_d Class
		0	540	Surface	NA	NA	NA	NA		NA
	15	15	525	Backfill		B	B	HI		4H
	39	54	486	Hanford Hfs	Fine sand to silty medium sand, with occational lenses of coarse sand.	S	Hfs	HI		4H
	70	124	416	Hanford Hss	Silty fine to medium sand.	S	Hss	II		4I1
	33	157	383	Hanford Hcs	Interbedded gravelly sand, and silty sand, and silty gravel.	S	Hcs	II		4I1
	13	170	370	Ringold Unit E	Silty gravels with interbedded gravelly sands	SG2	Rg	II		4I2
		170	370	Water Table	NA	NA	NA	NA		NA

* After Khaleel and Freeman (1995), per white paper by Khaleel (September 2000).

** HI=high impact, II=Intermediate Impact (after Kincaid et al. 1998).

BLUE = Injection/release point.

VZ Base Templates R
300 Area Stratigraphic Columns

Notes/Assumptions:

1) Assume an average elevation of 380 ft (115.8 m) MSL (Schalla et al. 1988).
2) Assume an average water-table elevation of 347 ft (106 m) MSL (Hartman et al. 2000).
   Water levels fluctuate daily, weekly, and seasonally up to a meter depending on postion relative to the river.
   Water levels have been increasing recently due to irrigation west of 300 Area.
3) Lithofacies are based on Lindsey (1991) and Gaylord Lindsey (1990). Lithofacies are highly varible in thickness and extent because of the fluvial nature of depostion.

Template 300R-X for surface disposal sites (e.g., Trenches, ponds, unplanned releases) — **300R-4**

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		K_d Class
		0	380	Surface	NA	NA	NA	NA		NA
2	2	2	378	Eolian	Sand and silt (absent for trenches and ponds)	S	Hss	HI		4H
37	31	33	347	Hanford Hg	Gravel (Cobble/boulder to gravel/pebble lithofacies after Lindsey [1989, 1991] and Gaylord Lindsey [1990]).	SG1	Hg	HI		4H
		33	347	Water Table	NA	NA	NA	NA		NA

Template 316R-X for surface disposal sites (e.g., Trenches, ponds, unplanned releases) — **316R-4**

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		K_d Class
		0	380	Surface	NA	NA	NA	NA		NA
15	15	15	365	Backfill		B	B	HI		4H
37	18	33	347	Hanford Hg	Gravel (Cobble/boulder to gravel/pebble lithofacies after Lindsey [1989, 1991] and Gaylord Lindsey [1990]).	SG1	Hg	HI		4H
		33	347	Water Table	NA	NA	NA	NA		NA

* After Khaleel and Freeman (1995), per white paper by Khaleel (September 2000).

** HI=high impact, II=Intermediate Impact (after Kincaid et al. 1998).

BLUE = Injection/release point.

VZ Base Templates - S_ERDF_E

Template for east half of ERDF and US Ecology

Notes/Assumptions:

1) Template applies only to east half of ERDF and the US Ecology Site. The west half of ERDF includes the Plio-Pleistocene and upper Ringold units, which are missing under the east half of ERDF.
2) Based on 1:24,000-scale USGS topographic maps, topography ranges from 720 ft AMSL along southeastern margin of ERDF to 750 ft AMSL along northeastern boundary.
Will assume an average elevation of 735 ft AMSL.
3) Pre-Hanford water-table elevation is ~390 ft AMSL at east end of ERDF, based on Kipp and Mudd (1974).
Will assume an average water-table elevation of 390 ft AMSL.
4) Depth of the ERDF excavation is ~60 ft bgs based on measured sections at west end reported in Fecht and Weekes (1996).
5) Depths to strata beneath ERDF are based on cross sections presented in Weekes et al. (1996).
6) Assumes bottom of excavation is not level, but an even 60 ft depth that parallels the land surface.

Template 216S_ERDF_E-X.

Estimated Thickness (ft)	Adjusted Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		216S_ERDF_E-4 K_d Class
		0	735	Surface	NA	NA	NA	NA		NA
60	60	60	675	Backfill	Backfill	B	B	HI		4H
220	220	280	455	Hanford Sand	Slightly silty coarse to very fine sand	S	Hfs_BC	HI		4H
65	65	345	390	Ringold Unit E	Silty Sandy Medium to fine pebble to sandy very coarse to fine pebble (semi-indurated)	SG2	Rg	II		4I2
		345	390	Water Table	NA	NA	NA	NA		NA

* After Khaleel and Freeman (1995), per white paper by Khaleel (September 2000).
** HI=high impact, II=Intermediate Impact (after Kincaid et al. 1998).
BLUE = Injection/release point.

VZ Base Templates S - ERDF
South 200 West Area - ERDF_W Stratigraphic Columns

Notes/Assumptions:

1) Template applies only to west half of ERDF. East half of ERDF is missing Plio-Pleistocene and upper Ringold units.
2) Based on 1:24,000-scale USGS topographic maps, topography ranges from 675 ft AMSL at southwest corner of ERDF to 750 ft AMSL along northern boundary. Average elevation at west end is ~720 ft AMSL.
   Will assume an average elevation of 720 ft AMSL.
3) Pre-Hanford water-table elevation at west end of ERDF is ~400 ft AMSL based on Kipp and Mudd (1974).
   Will assume an average water-table elevation of 400 ft AMSL.
4) Depth of the ERDF excavation is ~60 ft bgs based on measured sections at west end reported in Fecht and Weekes (1996).
5) Depths to strata beneath ERDF are based on cross sections presented in Weekes et al. (1996).

Template 216S_ERDF_W-X for the western portion of the ERDF Site — **216S_ERDF_W-4**

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		K_d Class
		0	720	Surface	NA	NA	NA	NA		NA
60	60	**60**	**660**	Backfill	Backfill	B	B	HI		4H
180	180	240	480	Hanford Sand	Slightly silty coarse to very fine sand	S	Hfs_2W	HI		4H
10	10	250	470	Old Hanford/Cold Creek Silt ("Early Palouse")	Silty fine to very fine sand	SS	PPlz	II		4I1
15	15	265	455	Cold Creek Carbonate	Pebbly silty coarse to very fine sand to silty medium to very fine sand	SS	PPlc	II		4I1
15	15	280	440	Upper Ringold Unit	Felsic fine to medium sand with minor silt	S	PPlz	II		4I1
40	40	320	400	Ringold (Unit E)	Silty Sandy Medium to fine pebble to sandy very coarse to fine pebble (semi-indurated)	SG2	Rg_2W	II		4I2
		320	400	Water Table	NA	NA	NA	NA		NA

* After Khaleel and Freeman (1995), per white paper by Khaleel (September 2000).
** HI=high impact, II=Intermediate Impact (after Kincaid et al. 1998).
BLUE = Injection/release point.

VZ Base Templates S

South 200 West Area (S, U [except U-1&2], Z Areas [except 216-Z-9]) Stratigraphic Columns

Notes/Assumptions:

1) Topography ranges from 730 ft MSL east of ERDF to 625 ft MSL southwest of the S-16 Pond (USGS Gable Butte and Riverland 7.5 min. Quad Maps).
   Will assume an average elevation of 680 ft MSL.
2) The pre-Hanford water table (January 1944) is estimated to range from an elevation of 122 m (400 ft) east of 200 W Area to 127 m (417 ft) west of the S-16 Pond (DOE 1987, page 4.21).
   Will assume an average water-table elevation of 124 m (407 ft) MSL.
3) A thin blanket of eolian sand and silt covers the surface of the site where not disturbed. However, this material was generally removed during excavation and construction of the waste disposal sites and then incorporated into backfill materials.
4) The depth of the sites and, thus, the backfull over these sites range from 0 m for ponds and unplanned releases to an average of about 4.5 to 5.7 m (~15 ft) for cribs and burial grounds and 13.7 to 16.4 m (~50 ft) for tanks.
5) The two reverse wells in this area range in depth from 23-46 m (75-150 ft).

Template 200S-X for surface disposal sites (e.g., Ponds)

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**	200S-1 K_d Class	200S-2 K_d Class	200S-3 K_d Class	200S-4 K_d Class
		0	680	Surface	NA	NA	NA	NA	NA	NA	NA	NA
2.5	5	5	675	Eolian	Sand and silt	S	Hss	HI	1H	2H	3H	4H
60	65	70	610	Hanford Gravel	Pebbly very coarse to medium sand to silty sandy medium to fine pebble	SG1	Hg_2W	HI	1H	2H	3H	4H
30	30	100	580	Hanford Sand	Slightly silty coarse to very fine sand	S	Hfs_2W	II	1I1	2I1	3I1	4I1
30	30	130	550	Hanford Silty Sand	Slightly silty medium to very fine sand to silty medium to very fine sand	S	Hss_2W	II	1I1	2I1	3I1	4I1
15	20	150	530	Old Hanford/Cold Creek silt ("Early Palouse")	Silty fine to very fine sand	SS	PPlz	II	1I1	2I1	3I1	4I1
20	20	170	510	Cold Creek Carbonate	Pebbly silty coarse to very fine sand to silty medium to very fine sand	SS	PPlc	II	1I1	2I1	3I1	4I1
	103	273	407	Ringold (Unit E)	Silty Sandy Medium to fine pebble to sandy very coarse to fine pebble (semi-indurated)	SG2	Rg_2W	II	1I2	2I2	3I2	4I2
		273	407	Water Table	NA	NA	NA	NA		NA	NA	NA

Template 216S-X for shallow disposal sites (e.g., Cribs, Burial Grounds)

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**	216S-1 K_d Class	216S-2 K_d Class	216S-3 K_d Class	216S-4 K_d Class
		0	680	Surface	NA	NA	NA	NA	NA	NA	NA	NA
15	15	15	665	Backfill	Backfill	B	B	HI	1H	2H	3H	4H
50	55	70	610	Hanford Gravel	Pebbly very coarse to medium sand to silty sandy medium to fine pebble	SG1	Hg_2W	HI	1H	2H	3H	4H
30	30	100	580	Hanford Sand	Slightly silty coarse to very fine sand	S	Hfs_2W	II	1I1	2I1	3I1	4I1
30	30	130	550	Hanford Silty Sand	Slightly silty medium to very fine sand to silty medium to very fine sand	S	Hss_2W	II	1I1	2I1	3I1	4I1
15	20	150	530	Old Hanford/Cold Creek silt ("Early Palouse")	Silty fine to very fine sand	SS	PPlz	II	1I1	2I1	3I1	4I1
20	20	170	510	Cold Creek Carbonate	Pebbly silty coarse to very fine sand to silty medium to very fine sand	SS	PPlc	II	1I1	2I1	3I1	4I1
	103	273	407	Ringold (Unit E)	Silty Sandy Medium to fine pebble to sandy very coarse to fine pebble (semi-indurated)	SG2	Rg_2W	II	1I2	2I2	3I2	4I2
		273	407	Water Table	NA	NA	NA	NA	NA	NA	NA	NA

Template 217S-x for shallow disposal sites (e.g., Cribs, Tilefields) receiving NAPL CCl4

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**	217S-1 K_d Class
		0	680	Surface	NA	NA	NA	NA	NA
15	15	15	665	Backfill	Backfill	B	B	HI	1H
50	55	70	610	Hanford Gravel	Pebbly very coarse to medium sand to silty sandy medium to fine pebble	SG1	Hg_2W	HI	1H
30	30	100	580	Hanford Sand	Slightly silty coarse to very fine sand	S	Hfs_2W	II	1I1
30	30	130	550	Hanford Silty Sand	Slightly silty medium to very fine sand to silty medium to very fine sand	S	Hss_2W	II	1I1
15	20	150	530	Old Hanford/Cold Creek silt ("Early Palouse")	Silty fine to very fine sand	SS	PPlz	*II*	1I1
20	20	170	510	Cold Creek Carbonate	Pebbly silty coarse to very fine sand to silty medium to very fine sand	SS	PPlc	*II*	1I1
	103	273	407	Ringold (Unit E)	Silty Sandy Medium to fine pebble to sandy very coarse to fine pebble (semi-indurated)	SG2	Rg_2W	*II*	1I2
		273	407	Water Table	NA	NA	NA	NA	NA

VZ Base Templates S

South 200 West Area (S, U [except U-1&2], Z Areas [except 216-Z-9]) Stratigraphic Columns

Template 241S-X for intermediate depth disposal sites (e.g., high-level waste tanks) (modified after Reidel et al. 2006)

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**			241S-2 K_d Class	241S-3 K_d Class	241S-4 K_d Class
		0	680	Surface	NA	NA	NA	NA			NA	NA	NA
50	50	50	630	Backfill	Medium sands and silt with poorly sorted gravel evolved from Hanford formation	B	B	HI			2H	3H	4H
28.7	29	79	580	H1-b	Upper gravel dominated unit, gravelly sand	SG1	Hg_2W	HI			2H	3H	4H
25.1	25	104	576	H1-a	Upper sand dominated unit, slightly silty	S	Hfs_2W	HI			2H	3H	4H
13.1	13	117	563	H1	Slightly silty coarse to very fine sand	S	Hfs_2W	II			2I1	3I1	4I1
58.2	58	175	505	H2	Slightly silty medium to very fine sand to silty medium to very fine sand	S	Hss_2W	II			2I1	3I1	4I1
33	33	208	472	Old Hanford/Cold Creek silt ("Early Palouse")	Silty fine to very fine sand	SS	PPlz	II			2I1	3I1	4I1
7.4	7	215	465	Cold Creek Carbonate	Pebbly silty coarse to very fine sand to silty medium to very fine sand	SS	PPlc	II			2I1	3I1	4I1
9.2	9	224	456	Taylor flat member, Upper Ringold	Interstratified, well-bedded fine to coarse sand to silt	SS	PPlz	II			2I1	3I1	4I1
92.8	49	273	407	Ringold (Unit E)	Silty Sandy Medium to fine pebble to sandy very coarse to fine pebble (semi-indurated)	SG2	Rg_2W	II			2I2	3I2	4I2
		273	407	Water Table	NA	NA	NA				NA	NA	NA

Template 266S-X for deep injection sites (e.g., reverse wells [e.g., 216-Z-10 (a)])

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**					266S-4 K_d Class
		0	680	Surface	NA	NA	NA	NA					NA
2.5	5	5	675	Eolian	Sand and silt	Hs	Hss	II					4I1
60	65	70	610	Hanford Gravel	Pebbly very coarse to medium sand to silty sandy medium to fine pebble	Hg	Hg_2W	II					4I2
30	30	100	580	Hanford Sand	Slightly silty coarse to very fine sand	S	Hfs_2W	II					4I1
30	30	130	550	Hanford Silty Sand	Slightly silty medium to very fine sand to silty medium to very fine sand	S	Hss_2W	II					4I1
15	20	150	530	Old Hanford/Cold Creek silt ("Early Palouse")	Silty fine to very fine sand	PP	PPlz	HI					4H
20	20	170	510	Cold Creek Carbonate	Pebbly silty coarse to very fine sand to silty medium to very fine sand	PP	PPlc	HI					4H
	103	273	407	Ringold (Unit E)	Silty Sandy Medium to fine pebble to sandy very coarse to fine pebble (semi-indurated)	Rg	Rg_2W	II					4I2
		273	407	Water Table	NA	NA	NA	NA					NA

* After Khaleel and Freeman (1995), per white paper by Khaleel (September 2000).

** HI=high impact, II=Intermediate Impact (after Kincaid et al. 1998).

BLUE = Injection/release point.

(a) Note: Injection well 216-Z-10 is screened from 118-150 ft. Well 216-U-4 is screened from 50-75 ft.

VZ Base Templates - U Cribs
U Cribs (216-U-1, -2 and -16)

Notes/Assumptions:

1) Surface elevation ranges from 211.0 m (692.3 ft) near 216-U-16 to 212.5 m (697.2 ft) MSL near the 216-U-1 and -2 Cribs as taken from the Hanford Site Atlas (BHI 1998).
2) Ground surface and water-table elevations from the HYDRODAT database managed by the Pacific Northwest National Laboratory.
3) The pre-Hanford water table (January 1944) is estimated to have been at an elevation of 405 MSL (based on Kipp and Mudd 1974).
4) The site depth to bottom of the 216-U-1 and -2 Cribs is reported to be 24 ft/min (7.3 m) based on Maxfield (1979). No bottom is reported for the 216-U-16 Crib. Thus, the backfill is assumed to be 24 ft deep for all three cribs.

Template 216S_U_N-x for the area N-NE of the 216-U-1&2 Cribs, based on well 299-W19-16 (N 135029.21, E 567270.68) located 24 m (80 ft) north of 216-U-1 Crib. **216S_U_N-4**

Estimated Thickness (ft)***	Adjusted Thickness (ft)	Bottom Depth (ft)	Bottom Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		K_d Class
		0	695.157	Surface	NA	NA	NA	NA		NA
24	24	24	671	Backfill	Backfill	B	B	HI		4H
67	67	91	604	Hanford H1	Interbedded layers of fine to coarse sand and sandy gravel	S	Hcs_2W	HI		4H
55	55	146	549	Hanford H2	Interbedded layers of silty to fine, medium, and coarse sand	S	Hfs_U	II		4I1
19	19	165	530	CCU-upper	Silt and fine sand	SS	PPlz_U	II		4I1
2	2	167	528	CCU-lower	Calcium-carbonate cemented sand, silt and clay (caliche)	SS	PPlc	II		4I1
83	83	250	445	Ringold Unit E	Sandy gravel	SG2	Rg_U	II		4I2
		250.59	444.57	Water Table	NA	NA	NA	NA		NA

Template 216S_U_S-x for the southern portion of the 216-U-1& 2 crib area, based on well 299-W19-14 (N 134831.14, E 567267.99), located 9 m (30 ft) from SE edge of 216-U-16 Crib. **216S_U_S-4**

Estimated Thickness (ft)***	Adjusted Thickness (ft)	Bottom Depth (ft)	Bottom Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		K_d Class
		0	693.44	Surface	NA	NA	NA	NA		NA
24	24	24	669	Backfill	Backfill	B	B	4H		4H
86	86	110	583	Hanford H1	Interbedded layers of fine to coarse sand and sandy gravel	S	Hcs_2W	4H		4H
42	42	152	541	Hanford H2	Interbedded layers of silty to fine, medium, and coarse sand	S	Hfs_U	4I1		4I1
14	14	166	527	CCU-upper	Silt and fine sand	SS	PPlz_U	4I1		4I1
4	4	170	523	CCU-lower	Calcium-carbonate cemented sand, silt and clay (caliche)	SS	PPlc	4I1		4I1
78	78	248	445	Ringold Unit E	Sandy gravel	SG2	Rg_U	4I2		4I2
		248.02	445.42	Water Table	NA	NA	NA	NA		NA

* After Khaleel and Freeman (1995), per white paper by Khaleel (September 2000).
** HI=high impact, II=Intermediate Impact (after Kincaid et al. 1998).
BLUE = Injection/release point.

VZ Base Templates S_U tanks

South 200 West Area (U-Tanks) Stratigraphic Columns

Notes/Assumptions:

1) Surface elevation is roughly 665 ft based on well 299-W18-132.
   Will assume an average elevation of 665 ft MSL.
2) The pre-Hanford water table (January 1944) is estimated to be about 407 ft (Kipp and Mudd 1974).
   Will assume an average water-table elevation of 124 m (407 ft) MSL.
3) A thin blanket of eolian sand and silt covers the surface of the site where not disturbed. However, this material was generally removed during excavation and construction of the waste disposal sites and then incorporated into backfill materials.
4) The depth of the sites and, thus, the backfull over these sites range from about 13.7 to 16.4 m (~50 ft) for tanks.

Template 241S_U-x for intermediate depth disposal sites (e.g., high-level waste tanks). Modified after Reidel et al. (2006).										241S_U-2	241S_U-3	241S_U-4
Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		K_d Class	K_d Class	K_d Class
		0	665	Surface	NA	NA	NA	NA		NA	NA	NA
50	50	50	615	Backfill	Medium sands and silt with poorly sorted gravel evolved from Hanford formation	B	B	HI		2H	3H	4H
26-36	26	76	589	H1	Slightly silty coarse to very fine sand	S	Hfs_2W	HI		2H	3H	4H
89	89	165	500	H2	Slightly silty medium to very fine sand to silty medium to very fine sand	S	Hss_2W	HI		2H	3H	4H
32	32	197	468	Cold Creek Upper: Old Hanford/Plio-Pleistocene ("Early Palouse")	Silty fine to very fine sand	SS	PPlz	II		2I1	3I1	4I1
8	8	205	460	Cold Creek Lower: Plio-Pleistocene Caliche	Pebbly silty coarse to very fine sand to silty medium to very fine sand	SS	PPlc	II		2I1	3I1	4I1
102	53	258	407	Ringold (Unit E)	Silty Sandy Medium to fine pebble to sandy very coarse to fine pebble (semi-indurated)	SG2	Rg_2W	II		2I2	3I2	4I2
		258	407	Water Table	NA	NA	NA			NA	NA	NA

* After Khaleel and Freeman (1995), per white paper by Khaleel (September 2000).
** HI=high impact, II=Intermediate Impact (after Kincaid et al. 1998).
BLUE = Injection/release point.

VZ Base Templates - S_Z9
216-Z-9 Trench Stratigraphic Columns

Notes/Assumptions:

1) Land surface elevations range from 201.1 m (660 ft) near well 299-W15-39 to 209.4 m (687 ft) near well 299-W15-18.
   Will assume an average elevation of 205.2 m (673 ft) MSL.
2) The pre-Hanford water table (January 1944) is estimated to range from an elevation of 122 m (400 ft) east of 200 W Area to 127 m (417 ft) west of the S-16 Pond (DOE 1987, page 4.21).
   Will assume a minimum water-table elevation of 124 m (407 ft) MSL.
3) Lithofacies data taken from 9 wells near Z-9 (Wells 299-W15-5, -8, -9, -83, -84, -86, -95, -101, -217).
4) A thin blanket of eolian sand and silt covers the surface of the site where not disturbed. However, this material was generally removed during excavation and construction of the waste disposal sites and then incorporated into backfill materials.
5) The depth of the 216-Z-9 Trench is about 6.1 m (20 ft). Note that it has a concrete cover. A building also partially overlies the site.

Template 216S_Z9-X for the 216-Z-9 Trench — **216S_Z9-1**

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	VZ Hydraulic Property Type *	SAC Soil Type	K_d Zone**		K_d Class
		0	673	Surface	Concrete	NA	NA	NA		NA
15.5	20	20	653	Backfill	Gravelly Medium Sand	B	B	HI		1H
29.2	24	44	629	Hanford Gravel (H1)	Sandy Gravel	SG1	Hg_Z	HI		1H
39.2	39	83	590	Hanford Sand (H2)	Coarse to Medium Sand	S	Hfs_Z	II		1I1
23.4	23	106	567	Hanford Interbedded sand and mud (H4)	Slightly Muddy Medium to Fine Sand to Sandy Mud	S	Hss_Z	II		1I1
8.7	9	115	558	CCU Silt	Sandy Mud	SS	PPlz_Z	II		1I1
4.0	4	119	554	CCU Carbonate	Calcareous Gravelly, Muddy, Sand	SS	PPlc_Z	II		1I1
146.1	147	266	407	Ringold (Unit E)	Semi-indurated Muddy Sandy Gravel	SG2	Rg_2W	II		1I2
127.0	163	429	244	Ringold (Unit E) - Saturated	Semi-indurated Muddy Sandy Gravel	NA	NA	GW		NA
54.0	54	483	190	Ringold Lower Mud	Muddy Medium to Fine Sand	NA	NA	GW		NA
45.0	45	528	145	Ringold Unit A	Sandy Gravel	NA	NA	GW		NA
				Elephant Mountain Basalt	Basalt	NA	NA	NA		NA

* After Khaleel and Freeman (1995), per white paper by Khaleel (September 2000).
** HI=high impact, II=Intermediate Impact (after Kincaid et al. 1998).

BLUE = Injection/release point.
LT. BLUE = Saturated Zone.

VZ Base Templates T
North 200 West Area (T Areas) Stratigraphic Columns

Notes/Assumptions:

1) Topography ranges from 790 ft MSL in the NW corner of the 218-W-5 burial ground to about 665 ft MSL east of the TX Tank Farm (USGS Gable Butte and Riverland 7.5 min. Quad Maps).
Will assume an average elevation of 690 ft MSL.
2) The pre-Hanford water table (January 1944) is estimated to range from an elevation of 122 m (400 ft) east of 200 W to 127 m (417 ft) on the west side of the 218-W-5 Burial Ground (Kipp and Mudd 1974; DOE 1987, page 4.21).
Will assume an average water-table elevation of 124 m (407 ft) MSL.
3) A thin blanket of eolian sand and silt covers the surface of the site where not disturbed. However, this material was generally removed during excavation and construction of the waste disposal sites and then incorporated into backfill materials.
4) The depth of the sites and, thus, the backfill over these sites range from 0 m for ponds and most unplanned releases to an average of about 5 m (17 ft) for cribs and burial grounds and up to 15 m (48 ft) for tanks.
5) Two reverse wells in this area range in depth from 22-62 m (75-206 ft). Will assume an average depth of 180 ft.

Template 200T-X for surface disposal sites (e.g., Ponds)

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		200T-2 K_d Class		200T-4 K_d Class
		0	690	Surface	NA	NA	NA	NA		NA		NA
2.5	2	2	688	Eolian	Sand and silt	S	Hss	HI		2H		4H
90	90	92	598	Hanford Gravel	Silty sandy medium to fine pebble to slightly silty pebbly very coarse to coarse sand.	SG1	Hg_2W	HI		2H		4H
35	35	127	563	Hanford Gravelly Sand	Pebbly very coarse to medium sand to slightly silty very coarse to medium sand	GS	Hgs_2W	II		2I1		4I1
10	10	137	553	Old Hanford/Cold Creek Silt ("Early Palouse")	Silty fine to very fine sand to slightly silty fine to very fine sand	SS	PPlz	II		2I1		4I1
18	18	155	535	Cold Creek Carbonate	Pebbly silty coarse to fine sand to silty medium to very fine sand with caliche	SS	PPlc	II		2I1		4I1
25	25	180	510	Upper Ringold	silty fine to very fine sand to silty medium to very fine sand (semi-indurated)	S	PPlz	II		2I1		4I1
	103	283	407	Ringold Unit E	Silty Sandy Medium to fine pebble to sandy very coarse to fine pebble (semi-indurated)	SG2	Rg_2W	II		2I2		4I2
		283	407	Water Table	NA	NA	NA	NA		NA		NA

Template 216T-X for shallow disposal sites (e.g., Cribs, Burial Grounds)

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		216T-2 K_d Class	216T-3 K_d Class	216T-4 K_d Class
		0	690	Surface	NA	NA	NA	NA		NA	NA	NA
17	17	17	673	Backfill		B	B	HI		2H	3H	4H
90	75	92	598	Hanford Gravel	Silty sandy medium to fine pebble to slightly silty pebbly very coarse to coarse sand.	SG1	Hg_2W	HI		2H	3H	4H
35	35	127	563	Hanford Gravelly Sand	Pebbly very coarse to medium sand to slightly silty very coarse to medium sand	GS	Hgs_2W	II		2I1	3I1	4I1
10	10	137	553	Old Hanford/Cold Creek Silt ("Early Palouse")	Silty fine to very fine sand to slightly silty fine to very fine sand	SS	PPlz	II		2I1	3I1	4I1
18	18	155	535	Cold Creek Carbonate	Pebbly silty coarse to fine sand to silty medium to very fine sand with caliche	SS	PPlc	II		2I1	3I1	4I1
25	25	180	510	Upper Ringold	silty fine to very fine sand to silty medium to very fine sand (semi-indurated)	S	PPlz	II		2I1	3I1	4I1
	103	283	407	Ringold Unit E	Silty Sandy Medium to fine pebble to sandy very coarse to fine pebble (semi-indurated)	SG2	Rg_2W	II		2I2	3I2	4I2
		283	407	Water Table	NA	NA	NA	NA		NA	NA	NA

VZ Base Templates T
North 200 West Area (T Areas) Stratigraphic Columns

Template 241T-X for tanks (Modified after Reidel et al. 2006)

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		241T-2 K_d Class		
		0	690	Surface	NA	NA	NA	NA		NA		
48	48	48	642	Backfill	Medium sands and silt with poorly sorted gravel evolved from Hanford formation	B	B	HI		2H		
35.4	35	83	607	H1	Slightly silty coarse to very fine sand	S	Hfs_2W	HI		2H		
43.4	43	126	564	H2	Slightly silty medium to very fine sand to silty medium to very fine sand	S	Hss_2W	HI		2H		
13.11	13	139	551	Cold Creek Upper	Silty fine to very fine sand	SS	PPlz	II		2I1		
14.8	15	154	536	Cold Creek Lower	Pebbly silty coarse to fine sand to silty medium to very fine sand with caliche	SS	PPlc	II		2I1		
35.6	36	190	500	Upper Ringold	Sand and silt deposits	SS	PPlz	II		2I1		
91.8	93	283	407	Ringold Unit E	Silty Sandy Medium to fine pebble to sandy very coarse to fine pebble (semi-indurated)	SG2	Rg_2W	II		2I2		
		283	407	Water Table	NA	NA	NA	NA		NA		

Template 266T-X for deep injection sites (e.g., reverse wells [e.g., 216-T-2 & -3 (a)])

Average Thickness (ft)	Adjusted Average Thickness (ft)	Depth (ft)	Elevation (ft)	Geologic Unit	Description	Hydraulic Property Type *	SAC Soil Type	K_d Zone**		266T-2 K_d Class		266T-4 K_d Class
		0	690	Surface	NA	NA	NA	NA		NA		NA
2.5	2	2	688	Eolian	Sand and silt	S	Hss	II		2I1		4I1
90	90	92	598	Hanford Gravel	Silty sandy medium to fine pebble to slightly silty pebbly very coarse to coarse sand.	SG1	Hg_2W	II		2I2		4I2
35	35	127	563	Hanford Gravelly Sand	Pebbly very coarse to medium sand to slightly silty very coarse to medium sand	GS	Hgs_2W	II		2I1		4I1
10	10	137	553	Old Hanford/Cold Creek Silt ("Early Palouse")	Silty fine to very fine sand to slightly silty fine to very fine sand	SS	PPlz	II		2I1		4I1
18	18	155	535	Cold Creek Carbonate	Pebbly silty coarse to fine sand to silty medium to very fine sand with caliche	SS	PPlc	II		2I1		4I1
25	25	180	510	Upper Ringold	silty fine to very fine sand to silty medium to very fine sand (semi-indurated)	S	PPlz	HI		2H		4H
	103	283	407	Ringold Unit E	Silty Sandy Medium to fine pebble to sandy very coarse to fine pebble (semi-indurated)	SG2	Rg_2W	HI		2H		4H
		283	407	Water Table	NA	NA	NA	NA		NA		NA

* After Khaleel and Freeman (1995), per white paper by Khaleel (September 2000).
** HI=high impact, II=Intermediate Impact (after Kincaid et al. 1998).
BLUE = Injection/release point.
(a) Note: Injection well 216-T-2 is 75 ft deep. Well 216-T-3 is reported as 206 ft. Screened interval is unknown -- will assume 25 ft screened interval.

References

BHI. 1998. *Hanford Site Atlas*. BHI-01119, Rev. 2, Bechtel Hanford Inc., Richland, Washington.

Chamness MA and JK Merz. 2003. *Hanford Wells.* PNL-8800, Pacific Northwest National Laboratory, Richland, Washington.

DOE. 1987. *Final Environmental Impact Statement, Disposal of Hanford Defense High-Level, Transuranic and Tank Wastes, Hanford Site, Richland, Washington.* DOE/EIS-0113, Volumes 1-5, U.S. Department of Energy, Washington, D.C.

DOE. 1993. *Limited Field Investigation Report for the 100-HR-3 Operable Unit*. DOE/RL-93-34, U.S. Department of Energy, Richland, Washington.

Fecht KR and DC Weekes. 1996. *Geologic Field Investigation of the Sedimentary Sequence at the Environmental Restoration Disposal Facility.* BHI-00230, Bechtel Hanford, Inc., Richland, Washington.

Hartman MJ. 1999. *Hanford Site Groundwater Monitoring for Fiscal Year 1998.* PNNL-12086, Pacific Northwest National Laboratory, Richland, Washington.

Hartman MJ and P Dresel. 1998. *Hanford Site Groundwater Monitoring for Fiscal Year 1997.* PNNL-11793, Pacific Northwest National Laboratory , Richland, Washington.

Hartman MJ and KA Lindsey. 1993. *Hydrogeology of the 100-N Area, Hanford Site, Washington*. WHC-SD-EN-EV-027, Westinghouse Hanford Company, Richland, Washington.

Hartman MJ, LF Morasch, and WD Webber (eds). 2000. *Hanford Site Groundwater Monitoring for Fiscal Year 1999*. PNNL-13116, Pacific Northwest National Laboratory, Richland, Washington.

Khaleel R and EJ Freeman. 1995. *Variability and Scaling of Hydraulic Properties for 200 Area Soils, Hanford Site*. WHC-EP-0883, Westinghouse Hanford Company, Richland, Washington.

Kincaid CT, MP Bergeron, CR Cole, MD Freshley, NL Hassig, VG Johnson, DI Kaplan, RJ Serne, GP Streile, DL Strenge, PD Thorne, LW Vail, GA Whyatt, and SK Wurstner. 1998. *Composite Analysis for Low-Level Waste Disposal in the 200 Area Plateau of the Hanford Site*. PNNL-11800, Pacific Northwest National Laboratory, Richland, Washington.

Kipp KL and RD Mudd. 1974. *Selected Water Table Contour Maps and Well Hydrographs for the Hanford Reservation, 1944-1973*. BNWL-B-360, Pacific Northwest Laboratory, Richland, Washington.

Lindberg JW. 1995. *Hydrogeology of the 100-K Area, Hanford Site, South-Central Washington*. WHC-SD-EN-TI-294, Westinghouse Hanford Company, Richland, Washington.

Lindsey KA and DR Gaylord. 1990. "Lithofacies and Sedimentology of the Miocene-Pliocene Ringold Formation, Hanford Site, South-Central Washington." *Northwest Sci*. 4:165-180.

Lindsey KA. 1991. *Revised Stratigraphy for the Ringold Formation, Hanford Site, South-Central Washington.* WHC-SD-EN-EE-004, Westinghouse Hanford Company, Richland, Washington.

Maxfield HL. 1979. *Handbook - 200 Areas Waste Sites*. RHO-CD-673, Volumes I, II, and III, Rockwell Hanford Operations, Richland, Washington.

Peterson RE, RF Raidl, and CW Denslow. 1996. *Conceptual Site Models for Groundwater Contamination at the 100-BC-5, 100-KR-4, 100-HR-3, and 100-FR-3 Operable Units*. BHI-00917, Bechtel Hanford Company, Richland, Washington.

Raidl RF. 1994. *Geology of the 100-FR-3 Operable Unit, Hanford Site, South-Central Washington*. WHC-SD-EN-TI-221, Westinghouse Hanford Company, Richland, Washington.

Reidel SP. 2004. *Geologic Data Package for 2005 Integrated Disposal Facility Waste Performance Assessment.* PNNL-14586, Pacific Northwest National Laboratory, Richland, Washington.

Reidel SP and AM Ho. 2002. *Geologic and Wireline Summaries from Fiscal Year 2002 ILAW Boreholes*. PNNL-14029, Pacific Northwest National Laboratory, Richland, Washington.

Reidel SP, DG Horton, and MM Valenta. 2001. *Geologic and Wireline Borehole Summary from the Second ILAW Borehole (299-E24-21)*. PNNL-13652, Pacific Northwest National Laboratory, Richland, Washington.

Reidel, SP, KD Reynolds, and DG Horton. 1998. *Immobilized Low-Activity Waste Site Borehole 299-E17-21*. PNNL-11957, Pacific Northwest National Laboratory, Richland, Washington.

Reidel SP, DG Horton, Y Chien, DB Barnett, and K Singleton. 2006. *Geology, Hydrogeology, Geochemistry, and Mineralogy Data Package for the Single-Shell Tank Waste Management Areas at the Hanford Site.* RPP-23748, Rev. 0, CH2M HILL Hanford Group, Inc., Richland, Washington.

Schalla R, RW Wallace, RL Aaberg, SP Airhart, DJ Bastes, JVM Carlile, CS Cline, DI Dennison, MD Freshley, PR Heller, EJ Jensen, KB Olsen, RG Parkhurst, JT Rieger, and EJ Westergard. 1988. *Interim Characterization Report for the 300 Area Process Trenches*. PNL-6716, Pacific Northwest Laboratory, Richland, Washington.

Weekes, DC, BH Ford, and GK Jaeger. 1996. *Preoperational Baseline and Site Characterization Report for the Environmental Restoration Disposal Facility*. BHI-00270, Rev. 1, Bechtel Hanford, Inc., Richland, Washington.

Appendix B

Hydraulic Property Distributions

Appendix B

Hydraulic Property Distributions

Table B.1. Approximation for the Distribution Function for Soil Type "B" (backfill) Based on Khaleel and Freeman (1995) Soil Category SSG (sand and gravel mixed with finer fraction)

B	Number of Samples	Raw				Transform †	Transformed (normal distribution)				Observed Data Range Truncation Limits	
Parameter		Low	High	Mean	Standard Deviation		Upper Limit	Lower Limit	Mean	Standard Deviation	Lower	Upper
q_S	6	0.187	0.375	0.262	0.072	NO					0.151	0.942
q_R	6	0.000	0.064	0.030	0.029	NO					0.146	0.879
s_r	6	0.000	0.213	0.103	0.098	NO					0.146	0.869
a (1/cm)	6	0.003	0.103	0.019	0.036	LN	-2.276	-5.843	-3.957	1.166	0.053	0.925
n	6	1.256	1.629	1.400	0.131	NO					0.134	0.960
K_s (cm/s)	6	2.76E-05	6.80E-02	5.98E-04	2.73E-02	LN	-2.688	-10.498	-7.421	3.359	0.180	0.921
Longitudinal Dispersivity[1] (m)	NA	0.0270	0.178	0.09	NA	UN	-	-	-	-		
% Gravel												
Bulk Density (g/cm^3)	NA	-	-	1.94	-	CO	-	-	-	-		

†NO = Normal (no transformation required); LN = Lognormal; LR = Log ratio; SN = Hyperbolic arcsine; UN = Uniform; CO = Constant; BE = Beta.

[1] Taken from Ho et al. (1999).

Table B.2. Approximation for the Distribution Function for Soil Type "Hss" (Hanford silty fine sand) Modified from Khaleel and Freeman (1995) Soil Category SS (sand mixed with finer fraction)

Hss	Number of Samples	Raw				Transform †	Transformed (normal distribution)				Observed Data Range Truncation Limits	
Parameter		Low	High	Mean	Standard Deviation		Upper Limit	Lower Limit	Mean	Standard Deviation	Lower	Upper
q_S	38	0.321	0.587	0.445	0.060	NO					0.019	0.991
q_R	38	0.019	0.181	0.072	0.033	NO					0.053	1.000
s_r	38	0.047	0.339	0.159	0.059	NO					0.030	0.999
a (1/cm)	38	0.001	0.387	0.008	0.076	LN	-0.949	-7.131	-4.866	1.212	0.031	0.999
n	38	1.262	3.265	1.915	0.461	NO					0.078	0.998
K_s (cm/s)	30	3.20E-07	8.88E-04	8.58E-05	2.66E-04	LN	-7.027	-14.955	-9.363	1.885	0.002	0.892
Longitudinal Dispersivity[1] (m)	NA	0.0279	0.0341	0.031	NA	UN	-	-	-	-		
% Gravel	38	0	2	0.18	0.51							
Bulk Density (g/cm^3)	35	1.28	2.13	1.61	0.17	NO	-	-	-	-		

†NO = Normal (no transformation required); LN = Lognormal; LR = Log ratio; SN = Hyperbolic arcsine; UN = Uniform; CO = Constant; BE = Beta.

[1] Taken from Ho et al. (1999).

Table B.3. Approximation for the Distribution Function for Soil Type "Hss_2W" (Hanford silty fine sand - 200 West Area) Modified from Khaleel and Freeman (1995) Soil Category SS (sand mixed with finer fraction)

Hss_2W	Number of Samples	Raw				Transform †	Transformed (normal distribution)				Observed Data Range Truncation Limits	
Parameter		Low	High	Mean	Standard Deviation		Upper Limit	Lower Limit	Mean	Standard Deviation	Lower	Upper
q_S	11	0.321	0.566	0.398	0.076	NO					0.155	0.987
q_R	11	0.019	0.102	0.057	0.027	NO					0.077	0.952
s_r	11	0.054	0.211	0.141	0.052	NO					0.046	0.914
a (1/cm)	11	0.001	0.017	0.005	0.004	LN	-4.080	-7.131	-5.397	0.804	0.015	0.949
n	11	1.527	3.265	2.116	0.528	NO					0.132	0.985
K_s (cm/s)	5	4.90E-06	1.27E-04	1.91E-05	5.10E-05	LN	-8.971	-12.226	-10.865	1.312	0.150	0.926
Longitudinal Dispersivity[1] (m)	NA	0.0279	0.0341	0.031	NA	UN	-	-	-	-		
% Gravel	11	0.000	0.000	0.000	0.000							
Bulk Density (g/cm^3)	10	1.400	1.900	1.668	0.167	NO	-	-	-	-		

†NO = Normal (no transformation required); LN = Lognormal; LR = Log ratio; SN = Hyperbolic arcsine; UN = Uniform; CO = Constant; BE = Beta.
[1] Taken from Ho et al. (1999).

Table B.4. Approximation for the Distribution function for soil type "Hss_U" (Hanford silty fine sand - 200-UP-1) Modified from Khaleel and Freeman (1995) Soil Category SS (sand mixed with finer fraction)

Hss_U	Number of Samples	Raw				Transform †	Transformed (normal distribution)				Observed Data Range Truncation Limits	
Parameter		Low	High	Mean	Standard Deviation		Upper Limit	Lower Limit	Mean	Standard Deviation	Lower	Upper
q_S	6	0.353	0.566	0.437	0.078	NO					0.140	0.952
q_R	6	0.019	0.102	0.066	0.033	NO					0.074	0.866
s_r	6	0.054	0.211	0.147	0.064	NO					0.071	0.841
a (1/cm)	6	0.003	0.017	0.007	0.005	LN	-4.080	-5.843	-4.994	0.596	0.077	0.937
n	6	1.527	3.265	2.347	0.597	NO					0.085	0.938
K_s (cm/s)	2	4.90E-06	1.27E-04	2.49E-05	8.63E-05	LN	-8.971	-12.226	-10.599	2.302	0.240	0.760
Longitudinal Dispersivity[1] (m)	NA	0.0279	0.0341	0.031	NA	UN	-	-	-	-		
% Gravel	6	0	0	0	0							
Bulk Density (g/cm^3)	6	1.4	1.72	1.58	0.13	NO	-	-	-	-		

†NO = Normal (no transformation required); LN = Lognormal; LR = Log ratio; SN = Hyperbolic arcsine; UN = Uniform; CO = Constant; BE = Beta.
[1] Taken from Ho et al. (1999).

Table B.5. Approximation for the Distribution Function for Soil Type "Hss_Z" (Hanford silty fine sand - 200-ZP-1) Modified from Khaleel and Freeman (1995) Soil Category SS (sand mixed with finer fraction)

Hss_Z	Number	Raw					Transformed (normal distribution)				Observed Data Range Truncation Limits	
Parameter	of Samples	Low	High	Mean	Standard Deviation	Transform †	Upper Limit	Lower Limit	Mean	Standard Deviation	Lower	Upper
q_S	5	0.321	0.413	0.351	0.040	NO					0.229	0.941
q_R	5	0.030	0.060	0.047	0.015	NO					0.136	0.799
s_r	5	0.093	0.178	0.133	0.038	NO					0.150	0.886
a (1/cm)	5	0.001	0.006	0.003	0.002	LN	-5.051	-7.131	-5.880	0.797	0.058	0.851
n	5	1.638	2.259	1.840	0.274	NO					0.230	0.937
K_s (cm/s)	1	6.55E-06	6.55E-06	6.55E-06	0.00E+00	CO						
Longitudinal Dispersivity[1] (m)	NA	0.0279	0.0341	0.031	NA	UN	-	-	-	-		
% Gravel	5	0	0	0	0							
Bulk Density (g/cm^3)	4	1.61	1.9	1.8	0.130	NO	-	-	-	-		
Particle Density (g/cm^3)						NO						

†NO = Normal (no transformation required); LN = Lognormal; LR = Log ratio; SN = Hyperbolic arcsine; UN = Uniform; CO = Constant; BE = Beta.
[1] Taken from Ho et al. (1999).

Table B.6. Approximation for the Distribution Function for Soil Type "Hfs" (Hanford fine sand) Modified from Khaleel and Freeman (1995) Soil Category S (sand)

Hfs	Number	Raw					Transformed (normal distribution)				Observed Data Range Truncation Limits	
Parameter	of Samples	Low	High	Mean	Standard Deviation	Transform †	Upper Limit	Lower Limit	Mean	Standard Deviation	Lower	Upper
q_S	36	0.266	0.482	0.379	0.053	NO					0.016	0.974
q_R	36	0.000	0.080	0.032	0.018	NO					0.037	0.996
s_r	36	0.000	0.184	0.086	0.047	NO					0.035	0.980
a (1/cm)	36	0.004	0.742	0.027	0.141	LN	-0.299	-5.613	-3.596	1.298	0.060	0.994
n	36	1.193	4.914	2.168	0.882	NO					0.134	0.999
K_s (cm/s)	36	6.72E-08	4.42E-02	3.74E-04	8.23E-03	LN	-3.119	-16.516	-7.891	2.657	0.001	0.964
Longitudinal Dispersivity[1] (m)	NA	0.183	0.223	0.203	NA	UN	-	-	-	-		
% Gravel	40	0	10	0.57	1.63							
Bulk Density (g/cm^3)	26	1.33	2.16	1.60	0.17	NO	-	-	-	-		

†NO = Normal (no transformation required); LN = Lognormal; LR = Log ratio; SN = Hyperbolic arcsine; UN = Uniform; CO = Constant; BE = Beta.
[1] Taken from Ho et al. (1999).

Table B.7. Approximation for the Distribution Function for soil type "Hfs_BC" (Hanford fine sand - BC cribs and trenches) Modified from Khaleel and Freeman (1995) Soil Category S (sand)

Hfs_BC	Number	Raw					Transformed (normal distribution)				Observed Data Range Truncation Limits	
Parameter	of Samples	Low	High	Mean	Standard Deviation	Transform †	Upper Limit	Lower Limit	Mean	Standard Deviation	Lower	Upper
q_S	18	0.323	0.444	0.380	0.040	NO					0.081	0.945
q_R	18	0.016	0.061	0.033	0.011	NO					0.065	0.992
s_r	18	0.045	0.184	0.089	0.035	NO					0.102	0.997
a (1/cm)	18	0.005	0.201	0.021	0.045	LN	-1.604	-5.279	-3.874	0.889	0.057	0.995
n	18	1.542	4.914	2.507	1.036	NO					0.176	0.990
K_s (cm/s)	18	1.40E-04	4.42E-02	2.25E-03	1.09E-02	LN	-3.119	-8.874	-6.097	1.563	0.038	0.972
Longitudinal Dispersivity[1] (m)	NA	0.183	0.223	0.203	NA	UN	-	-	-	-		
% Gravel	18	0	2	0.38	0.57							
Bulk Density (g/cm^3)	8	1.52	1.79	1.65	0.10	NO	-	-	-	-		

†NO = Normal (no transformation required); LN = Lognormal; LR = Log ratio; SN = Hyperbolic arcsine; UN = Uniform; CO = Constant; BE = Beta.
[1] Taken from Ho et al. (1999).

Table B.8. Approximation for the Distribution Function for soil type "Hfs_2W" (Hanford fine sand- 200 West Area) Modified from Khaleel and Freeman (1995) Soil Category S (sand)

Hfs_2W	Number	Raw					Transformed (normal distribution)				Observed Data Range Truncation Limits	
Parameter	of Samples	Low	High	Mean	Standard Deviation	Transform †	Upper Limit	Lower Limit	Mean	Standard Deviation	Lower	Upper
q_S	8	0.325	0.433	0.356	0.035	NO					0.188	0.986
q_R	8	0.027	0.058	0.042	0.014	NO					0.143	0.869
s_r	8	0.074	0.167	0.118	0.040	NO					0.142	0.889
a (1/cm)	8	0.004	0.026	0.010	0.008	LN	-3.646	-5.613	-4.584	0.704	0.072	0.909
n	8	1.574	3.294	2.177	0.546	NO					0.135	0.980
K_s (cm/s)	8	6.72E-08	4.62E-04	3.67E-05	1.76E-04	LN	-7.680	-16.516	-10.212	2.808	0.012	0.816
Longitudinal Dispersivity[1] (m)	NA	0.183	0.223	0.203	NA	UN	-	-	-	-		
% Gravel	8	0	2	0.38	0.74							
Bulk Density (g/cm^3)	7	1.58	1.82	1.70	0.10	NO	-	-	-	-		
Particle Density (g/cm^3)						NO						

†NO = Normal (no transformation required); LN = Lognormal; LR = Log ratio; SN = Hyperbolic arcsine; UN = Uniform; CO = Constant; BE = Beta.
[1] Taken from Ho et al. (1999)

Table B.9. Approximation for the Distribution Function for Soil Type "Hfs_U" (Hanford fine sand - 200-UP-1) Modified from Khaleel and Freeman (1995) Soil Category S (sand)

Hfs_U	Number	Raw					Transformed (normal distribution)				Observed Data Range Truncation Limits	
Parameter	of Samples	Low	High	Mean	Standard Deviation	Transform †	Upper Limit	Lower Limit	Mean	Standard Deviation	Lower	Upper
q_S	4	0.325	0.374	0.347	0.021	NO					0.150	0.902
q_R	4	0.028	0.057	0.042	0.015	NO					0.173	0.837
s_r	4	0.074	0.163	0.122	0.047	NO					0.153	0.809
a (1/cm)	4	0.004	0.026	0.013	0.010	LN	-3.646	-5.613	-4.380	0.888	0.082	0.796
n	4	1.673	3.294	2.451	0.663	NO					0.120	0.898
K_s (cm/s)	4	6.72E-08	4.62E-04	1.71E-05	2.15E-04	LN	-7.680	-16.516	-10.975	3.841	0.075	0.805
Longitudinal Dispersivity[1] (m)	NA	0.183	0.223	0.203	NA	UN	-	-	-	-		
% Gravel	4	0	0	0	0							
Bulk Density (g/cm^3)	4	1.58	1.82	1.72	0.12	NO	-	-	-	-		

†NO = Normal (no transformation required); LN = Lognormal; LR = Log ratio; SN = Hyperbolic arcsine; UN = Uniform; CO = Constant; BE = Beta.

[1] Taken from Ho et al. (1999).

Table B.10. Approximation for the Distribution Function for Soil Type "Hfs_Z" (Hanford fine sand - 200-ZP-1) Modified from Khaleel and Freeman (1995) Soil Category S (sand)

Hfs_Z	Number	Raw					Transformed (normal distribution)				Observed Data Range Truncation Limits	
Parameter	of Samples	Low	High	Mean	Standard Deviation	Transform †	Upper Limit	Lower Limit	Mean	Standard Deviation	Lower	Upper
q_S	4	0.326	0.433	0.366	0.047	NO					0.199	0.925
q_R	4	0.027	0.058	0.042	0.015	NO					0.169	0.850
s_r	4	0.082	0.167	0.113	0.040	NO					0.218	0.911
a (1/cm)	4	0.004	0.013	0.008	0.004	LN	-4.358	-5.521	-4.788	0.508	0.074	0.802
n	4	1.574	2.086	1.903	0.238	NO					0.083	0.779
K_s (cm/s)	4	1.38E-05	3.70E-04	7.88E-05	1.61E-04	LN	-7.902	-11.191	-9.449	1.446	0.114	0.858
Longitudinal Dispersivity[1] (m)	NA	0.183	0.223	0.203	NA	UN	-	-	-	-		
% Gravel	4	0	2	0.75	0.96	NO						
Bulk Density (g/cm^3)	4	1.59	1.76	1.68	0.09	NO	-	-	-	-		

†NO = Normal (no transformation required); LN = Lognormal; LR = Log ratio; SN = Hyperbolic arcsine; UN = Uniform; CO = Constant; BE = Beta.

[1] Taken from Ho et al. (1999).

Table B.11. Approximation for the Distribution Function for Soil Type "Hcs" (Hanford coarse sand) Modified from Khaleel and Freeman (1995) Soil Category S (sand)

Hcs		Raw					Transformed (normal distribution)				Observed Data Range Truncation Limits	
Parameter	Number of Samples	Low	High	Mean	Standard Deviation	Transform †	Upper Limit	Lower Limit	Mean	Standard Deviation	Lower	Upper
q_S	81	0.197	0.519	0.349	0.070	NO					0.015	0.992
q_R	81	0.000	0.103	0.027	0.017	NO					0.056	1.000
s_r	81	0.000	0.246	0.080	0.047	NO					0.044	1.000
a (1/cm)	81	0.006	0.861	0.061	0.133	LN	-0.149	-5.116	-2.797	0.996	0.010	0.996
n	81	1.266	5.000	2.031	0.687	NO					0.133	1.000
K_s (cm/s)	80	2.100E-05	5.800E-02	2.270E-03	1.200E-02	LN	-2.847	-10.771	-6.088	1.721	0.003	0.970
Longitudinal Dispersivity[1] (m)	NA	0.183	0.223	0.203	NA	UN	-	-	-	-		
% Gravel	82	0.00	31.90	2.55	4.56							
Bulk Density (g/cm^3)	68	1.51	2.02	1.67	0.10	NO	-	-	-	-		

†NO = Normal (no transformation required); LN = Lognormal; LR = Log ratio; SN = Hyperbolic arcsine; UN = Uniform; CO = Constant; BE = Beta.

[1] Taken from Ho et al. (1999).

Table B.12. Approximation for the Distribution Function for Soil Type "Hcs_BC" (Hanford coarse sand - BC crib and trench area) Modified from Khaleel and Freeman (1995) Soil Category S (sand)

Hcs_BC		Raw					Transformed (normal distribution)				Observed Data Range Truncation Limits	
Parameter	Number of Samples	Low	High	Mean	Standard Deviation	Transform †	Upper Limit	Lower Limit	Mean	Standard Deviation	Lower	Upper
q_S	46	0.245	0.453	0.357	0.052	NO					0.016	0.968
q_R	46	0.000	0.045	0.026	0.011	NO					0.007	0.964
s_r	46	0.000	0.129	0.074	0.031	NO					0.009	0.964
a (1/cm)	46	0.013	0.861	0.072	0.146	LN	-0.149	-4.343	-2.632	0.800	0.016	0.999
n	46	1.337	4.170	2.047	0.581	NO					0.111	1.000
K_s (cm/s)	46	5.16E-04	4.93E-02	5.32E-03	1.18E-02	LN	-3.010	-7.569	-5.235	1.173	0.023	0.971
Longitudinal Dispersivity[1] (m)	NA	0.183	0.223	0.203	NA	UN	-	-	-	-		
% Gravel	46	0	31.9	2.68	5.34							
Bulk Density (g/cm^3)	37	1.51	1.92	1.67	0.10	NO	-	-	-	-		

†NO = Normal (no transformation required); LN = Lognormal; LR = Log ratio; SN = Hyperbolic arcsine; UN = Uniform; CO = Constant; BE = Beta.

[1] Taken from Ho et al. (1999).

Table B.13. Approximation for the Distribution Function for Soil Type "Hcs_2W" (Hanford coarse sand - 200 West Area) Modified from Khaleel and Freeman (1995) Soil Category S (sand)

Hcs_2W	Number	Raw					Transformed (normal distribution)				Observed Data Range Truncation Limits	
Parameter	of Samples	Low	High	Mean	Standard Deviation	Transform †	Upper Limit	Lower Limit	Mean	Standard Deviation	Lower	Upper
q_S	7	0.208	0.416	0.317	0.083	NO					0.095	0.885
q_R	7	0.000	0.111	0.035	0.035	NO					0.163	0.984
s_r	7	0.000	0.266	0.099	0.082	NO					0.114	0.980
a (1/cm)	7	0.004	0.131	0.038	0.043	LN	-2.034	-5.624	-3.275	1.178	0.023	0.854
n	7	1.311	3.059	1.945	0.576	NO					0.135	0.973
K_s (cm/s)	7	1.80E-04	5.80E-02	1.09E-03	2.16E-02	LN	-2.847	-8.623	-6.822	2.002	0.184	0.976
Longitudinal Dispersivity[1] (m)	NA	0.183	0.223	0.203	NA	UN	-	-	-	-		
% Gravel	7	0.000	15.000	2.143	5.669							
Bulk Density (g/cm^3)	5	1.490	1.860	1.650	0.143	NO	-	-	-	-		

†NO = Normal (no transformation required); LN = Lognormal; LR = Log ratio; SN = Hyperbolic arcsine; UN = Uniform; CO = Constant; BE = Beta.

[1] Taken from Ho et al. (1999).

Table B.14. Approximation for the Distribution Function for Soil Type "Hcs_Z" (Hanford coarse sand - 200-ZP-1) Modified from Khaleel and Freeman (1995) Soil Category S (sand)

Hcs_Z	Number	Raw					Transformed (normal distribution)				Observed Data Range Truncation Limits	
Parameter	of Samples	Low	High	Mean	Standard Deviation	Transform †	Upper Limit	Lower Limit	Mean	Standard Deviation	Lower	Upper
q_S	5	0.208	0.392	0.292	0.083	NO					0.157	0.886
q_R	5	0.000	0.040	0.021	0.014	NO					0.065	0.903
s_r	5	0.000	0.110	0.069	0.043	NO					0.054	0.824
a (1/cm)	5	0.041	0.131	0.067	0.037	LN	-2.034	-3.199	-2.710	0.496	0.162	0.914
n	5	1.311	2.067	1.692	0.319	NO					0.116	0.880
K_s (cm/s)	5	1.80E-04	5.80E-02	1.49E-03	2.55E-02	LN	-2.847	-8.623	-6.512	2.361	0.186	0.940
Longitudinal Dispersivity[1] (m)	NA	0.183	0.223	0.203	NA	UN	-	-	-	-		
% Gravel	5	0	0	0	0							
Bulk Density (g/cm^3)	3	1.49	1.65	1.56	0.08	NO	-	-	-	-		

†NO = Normal (no transformation required); LN = Lognormal; LR = Log ratio; SN = Hyperbolic arcsine; UN = Uniform; CO = Constant; BE = Beta.

[1] Taken from Ho et al. (1999).

Table B.15. Approximation for the Distribution Function for Soil Type "Hgs" (Hanford gravelly sand) Based on Khaleel and Freeman (1995) Soil Category GS

Hgs	Number of Samples	Raw				Transform †	Transformed (normal distribution)				Observed Data Range Truncation Limits	
Parameter		Low	High	Mean	Standard Deviation		Upper Limit	Lower Limit	Mean	Standard Deviation	Lower	Upper
q_S	16	0.180	0.337	0.238	0.054	NO	-	-	-	-	0.143	0.966
q_R	16	0.010	0.074	0.033	0.019	NO	-	-	-	-	0.107	0.986
s_r	16	0.030	0.244	0.140	0.066	NO					0.047	0.942
a (1/cm)	16	0.004	0.090	0.014	0.023	LN	-2.411	-5.655	-4.250	1.032	0.087	0.963
n	16	1.529	4.148	2.120	0.703	NO					0.200	0.998
K_s (cm/s)	16	2.60E-05	9.00E-02	6.65E-04	2.22E-02	LR	-2.408	-10.557	-7.315	2.290		
Longitudinal Dispersivity[1] (m)	NA	0.0468	0.134	0.088	NA	UN	-	-	-	-		
% Gravel	17	10	40.00	25.78	9.65	NO						
Bulk Density (g/cm^3)	14	1.73	2.16	1.94	0.15	NO	-	-	-	-		

†NO = Normal (no transformation required); LN = Lognormal; LR = Log ratio; SN = Hyperbolic arcsine; UN = Uniform; CO = Constant; BE = Beta.

[1] Taken from Ho et al. (1999).

Table B.16. Approximation for the Distribution Function for Soil Type "Hgs_2W" (Hanford gravelly sand - 200 West Area) Based on Khaleel and Freeman (1995) Soil Category GS

Hgs_2W	Number of Samples	Raw				Transform †	Transformed (normal distribution)				Observed Data Range Truncation Limits	
Parameter		Low	High	Mean	Standard Deviation		Upper Limit	Lower Limit	Mean	Standard Deviation	Lower	Upper
q_S	2	0.208	0.337	0.273	0.091	NO	-	-	-	-	0.240	0.760
q_R	2	0.010	0.049	0.030	0.028	NO	-	-	-	-	0.240	0.760
s_r	2	0.030	0.237	0.133	0.147	NO					0.240	0.760
a (1/cm)	2	0.004	0.016	0.008	0.008	LN	-4.160	-5.521	-4.841	0.962	0.240	0.760
n	2	2.023	2.423	2.223	0.283	NO				-	0.240	0.760
K_s (cm/s)	2	5.43E-05	1.02E-03	2.35E-04	6.83E-04	LR	-6.888	-9.821	-8.354	2.074		
Longitudinal Dispersivity[1] (m)	NA	0.0468	0.134	0.088	NA	UN	-	-	-	-		
% Gravel	2	17.00	31.00	24.00	9.90	NO						
Bulk Density (g/cm^3)	2	1.73	1.89	1.81	0.11	NO	-	-	-	-		

†NO = Normal (no transformation required); LN = Lognormal; LR = Log ratio; SN = Hyperbolic arcsine; UN = Uniform; CO = Constant; BE = Beta.

[1] Taken from Ho et al. (1999).

Table B.17. Approximation for the Distribution Function for Soil Type "Hsg" (Hanford sandy gravel) Based on Khaleel and Freeman (1995) Soil Category SG1 (sandy gravel with gravel fraction < 60%) (formerly called "Hg" Hanford gravel)

Hg	Number of Samples	Raw				Transform †	Transformed (normal distribution)				Observed Data Range Truncation Limits	
Parameter		Low	High	Mean	Standard Deviation		Upper Limit	Lower Limit	Mean	Standard Deviation	Lower	Upper
q_S	28	0.072	0.307	0.167	0.048	NO	-	-	-	-	0.023	0.998
q_R	28	0.000	0.054	0.022	0.012	NO	-	-	-	-	0.033	0.996
s_r	28	0.000	0.275	0.134	0.071	NO					0.030	0.976
a (1/cm)	28	0.002	0.919	0.017	0.193	LN	-0.084	-6.075	-4.072	1.487	0.089	0.996
n	28	1.347	2.947	1.725	0.367	NO					0.151	1.000
K_s (cm/s)	27	1.90E-07	3.70E-02	3.30E-04	8.88E-03	LN	-3.297	-15.476	-8.016	3.265	0.011	0.926
Longitudinal Dispersivity[1] (m)	NA	0.027	0.178	0.09	NA	UN	-	-	-	-		
% Gravel	29	22	80	51.42	12.81	NO						
Bulk Density (g/cm^3)	25	1.6	2.3	1.93	0.21	NO	-	-	-	-		

†NO = Normal (no transformation required); LN = Lognormal; LR = Log ratio; SN = Hyperbolic arcsine; UN = Uniform; CO = Constant; BE = Beta.

[1] Taken from Ho et al. (1999). Same as SSG.

Table B.18. Approximation for the Distribution Function for Soil Type "Hsg_2W" (Hanford sandy gravel -200 West Area) Based on Khaleel and Freeman (1995) Soil Category SG1 (sandy gravel with gravel fraction < 60%) (formerly called "Hg" Hanford gravel - 200 West Area)

Hg_2W	Number of Samples	Raw				Transform †	Transformed (normal distribution)				Observed Data Range Truncation Limits	
Parameter		Low	High	Mean	Standard Deviation		Upper Limit	Lower Limit	Mean	Standard Deviation	Lower	Upper
q_S	11	0.072	0.217	0.154	0.042	NO	-	-	-	-	0.026	0.932
q_R	11	0.000	0.045	0.024	0.013	NO	-	-	-	-	0.037	0.941
s_r	11	0.000	0.243	0.152	0.086	NO					0.038	0.854
a (1/cm)	11	0.002	0.276	0.014	0.080	LN	-1.288	-6.075	-4.234	1.301	0.079	0.988
n	11	1.347	2.269	1.742	0.339	NO					0.122	0.940
K_s (cm/s)	11	3.30E-06	3.70E-02	1.40E-03	1.26E-02	LN	-3.297	-12.622	-6.569	2.960	0.020	0.866
Longitudinal Dispersivity[1] (m)	NA	0.027	0.178	0.09	NA	UN	-	-	-	-		
% Gravel	12	39.000	80.000	54.358	12.380	NO						
Bulk Density (g/cm^3)	9	1.630	2.300	1.891	0.225	NO	-	-	-	-		

†NO = Normal (no transformation required); LN = Lognormal; LR = Log ratio; SN = Hyperbolic arcsine; UN = Uniform; CO = Constant; BE = Beta.

[1] Taken from Ho et al. (1999). Same as SSG.

Table B.19. Approximation for the Distribution Function for Soil Type "Hsg_U" (Hanford sandy gravel - 200-UP-1) Based on Khaleel and Freeman (1995) Soil Category SG1 (sandy gravel with gravel fraction < 60%) (formerly called "Hg" Hanford gravel - 200-UP-1)

Hg_U	Number	Raw					Transformed (normal distribution)				Observed Data Range Truncation Limits	
Parameter	of Samples	Low	High	Mean	Standard Deviation	Transform †	Upper Limit	Lower Limit	Mean	Standard Deviation	Lower	Upper
q_S	3	0.124	0.194	0.150	0.039	NO	-	-	-	-	0.249	0.875
q_R	3	0.028	0.030	0.029	0.001	NO	-	-	-	-	0.136	0.805
s_r	3	0.144	0.239	0.204	0.052	NO					0.125	0.746
a (1/cm)	3	0.006	0.033	0.011	0.015	LN	-3.417	-5.083	-4.473	0.918	0.253	0.875
n	3	1.660	2.205	1.845	0.312	NO					0.277	0.876
K_s (cm/s)	3	3.300E-06	5.590E-03	2.884E-04	2.924E-03	LN	-5.187	-12.622	-8.151	3.940	0.128	0.774
Longitudinal Dispersivity[1] (m)	NA	0.027	0.178	0.09	NA	UN	-	-	-	-		
% Gravel	3	43.3	65	57.10	11.99	NO						
Bulk Density (g/cm^3)	3	1.8	2.3	2.09	0.26	NO	-	-	-	-		

†NO = Normal (no transformation required); LN = Lognormal; LR = Log ratio; SN = Hyperbolic arcsine; UN = Uniform; CO = Constant; BE = Beta.
[1] Taken from Ho et al. (1999). Same as SSG.

Table B.20. Approximation for the Distribution Function for Soil Type "Hsg_Z" (Hanford sandy gravel - 200-ZP-1) Based on Khaleel and Freeman (1995) Soil Category SG1 (sandy gravel with gravel fraction < 60%) (formerly called "Hg" Hanford gravel - 200-ZP-1)

Hg_Z	Number	Raw					Transformed (normal distribution)				Observed Data Range Truncation Limits	
Parameter	of Samples	Low	High	Mean	Standard Deviation	Transform †	Upper Limit	Lower Limit	Mean	Standard Deviation	Lower	Upper
q_S	8	0.072	0.217	0.155	0.046	NO	-	-	-	-	0.035	0.910
q_R	8	0.000	0.045	0.022	0.016	NO	-	-	-	-	0.078	0.931
s_r	8	0.000	0.243	0.133	0.090	NO					0.070	0.888
a (1/cm)	8	0.002	0.276	0.016	0.093	LN	-1.288	-6.075	-4.145	1.464	0.094	0.974
n	8	1.347	2.269	1.703	0.361	NO					0.162	0.942
K_s (cm/s)	7	2.83E-05	3.70E-02	3.65E-03	1.42E-02	LN	-3.297	-10.473	-5.613	2.546	0.028	0.819
Longitudinal Dispersivity[1] (m)	NA	0.027	0.178	0.09	NA	UN	-	-	-	-		
% Gravel	9	39	80	53.44	13.08	NO						
Bulk Density (g/cm^3)	6	1.63	1.92	1.79	0.13	NO	-	-	-	-		

†NO = Normal (no transformation required); LN = Lognormal; LR = Log ratio; SN = Hyperbolic arcsine; UN = Uniform; CO = Constant; BE = Beta.
[1] Taken from Ho et al. (1999). Same as SSG

Table B.21. Approximation for the Distribution Function for Soil Type "Hcg" (Hanford coarse gravel) Based on Khaleel and Freeman (1995) Soil Category SG2 (sandy gravel with gravel fraction >60%) (formerly called "Hrg" Hanford river gravel)

Hrg	Number of Samples	Raw				Transform †	Transformed (normal distribution)				Observed Data Range Truncation Limits	
Parameter		Low	High	Mean	Standard Deviation		Upper Limit	Lower Limit	Mean	Standard Deviation	Lower	Upper
q_S	40	0.051	0.191	0.102	0.031	NO					0.048	0.998
q_R	40	0.007	0.036	0.020	0.007	NO					0.045	0.987
s_r	40	0.082	0.359	0.197	0.066	NO					0.042	0.993
a (1/cm)	40	0.002	0.048	0.007	0.010	LN	-3.047	-6.119	-4.907	0.763	0.056	0.993
n	40	1.449	2.315	1.831	0.197	NO					0.026	0.993
K_s (cm/s)	40	3.70E-05	3.90E-01	1.46E-03	6.26E-02	LN	-0.942	-10.205	-6.532	2.062	0.037	0.997
Longitudinal Dispersivity[1] (m)	NA	0.027	0.178	0.09	NA	UN	-	-	-	-		
% Gravel	40	50	85	67.63	8.83	NO						
Bulk Density (g/cm^3)	40	1.56	2.42	1.97	0.16	NO	-	-	-	-		

†NO = Normal (no transformation required); LN = Lognormal; LR = Log ratio; SN = Hyperbolic arcsine; UN = Uniform; CO = Constant; BE = Beta.
[1] Taken from Ho et al. (1999). Same as SSG.

Table B.22. Approximation for the Distribution Function for Soil Type "CCUz" (Cold Creek unit-silt - formerly called "PPlz" [Plio-Pleistocene-silt]) Modified from Khaleel and Freeman (1995) Soil Category SS (sand mixed with finer fraction)

PPlz	Number of Samples	Raw				Transform †	Transformed (normal distribution)				Observed Data Range Truncation Limits	
Parameter		Low	High	Mean	Standard Deviation		Upper Limit	Lower Limit	Mean	Standard Deviation	Lower	Upper
q_S	9	0.288	0.533	0.419	0.091	NO					0.075	0.895
q_R	9	0.010	0.087	0.040	0.023	NO					0.096	0.979
s_r	9	0.020	0.169	0.097	0.046	NO					0.047	0.941
a (1/cm)	9	0.001	0.014	0.005	0.004	LN	-4.269	-6.522	-5.298	0.645	0.029	0.945
n	9	1.522	2.815	2.249	0.440	NO					0.049	0.901
K_s (cm/s)	9	4.12E-07	1.36E-01	5.57E-05	4.53E-02	LN	-1.995	-14.702	-9.795	3.805	0.099	0.980
Longitudinal Dispersivity[1] (m)	NA	0.0279	0.0341	0.031	NA	UN	-	-	-	-		
% Gravel	9	0	4	0.44	1.33							
Bulk Density (g/cm^3)	9	1.55	1.8	1.68	0.08	NO	-	-	-	-		

†NO = Normal (no transformation required); LN = Lognormal; LR = Log ratio; SN = Hyperbolic arcsine; UN = Uniform; CO = Constant; BE = Beta.
[1] Taken from Ho et al. (1999).

Table B.23. Approximation for the Distribution Function for Soil Type "CCUz_U" (Cold Creek unit-sit l 200-UP-1, formerly called "PPlz_U" [Plio-Pleistocene-silt - 200-UP-1]) Modified from Khaleel and Freeman (1995) Soil Category SS (sand mixed with finer fraction)

PPlz_U	Number of Samples	Raw				Transform †	Transformed (normal distribution)				Observed Data Range Truncation Limits	
Parameter		Low	High	Mean	Standard Deviation		Upper Limit	Lower Limit	Mean	Standard Deviation	Lower	Upper
q_S	5	0.288	0.514	0.395	0.101	NO					0.145	0.881
q_R	5	0.025	0.087	0.047	0.024	NO					0.180	0.952
s_r	5	0.075	0.169	0.117	0.041	NO					0.153	0.898
a (1/cm)	5	0.001	0.014	0.004	0.005	LN	-4.269	-6.522	-5.521	0.816	0.110	0.938
n	5	1.522	2.743	2.285	0.470	NO					0.052	0.835
K_s (cm/s)	5	4.12E-07	6.74E-04	7.27E-06	3.00E-04	LN	-7.302	-14.702	-11.831	2.818	0.154	0.946
Longitudinal Dispersivity[1] (m)	NA	0.0279	0.0341	0.031	NA	UN	-	-	-	-		
% Gravel	5	0	0.4	0.08	0.18							
Bulk Density (g/cm^3)	5	1.55	1.8	1.71	0.10	NO	-	-	-	-		

†NO = Normal (no transformation required); LN = Lognormal; LR = Log ratio; SN = Hyperbolic arcsine; UN = Uniform; CO = Constant; BE = Beta.

[1] Taken from Ho et al. (1999).

Table B.24. Approximation for the Distribution Function for Soil Type "CCUz-Z (Cold Creek unit-silt - 200-ZP-1, formerly called "PPlz_Z" [Plio-Pleistocene-silt - 200-ZP-1]) Modified from Khaleel and Freeman (1995) Soil Category SS (sand mixed with finer fraction)

PPlz_Z	Number of Samples	Raw				Transform †	Transformed (normal distribution)				Observed Data Range Truncation Limits	
Parameter		Low	High	Mean	Standard Deviation		Upper Limit	Lower Limit	Mean	Standard Deviation	Lower	Upper
q_S	4	0.373	0.533	0.448	0.081	NO					0.177	0.855
q_R	4	0.010	0.060	0.033	0.022	NO					0.155	0.893
s_r	4	0.020	0.113	0.073	0.044	NO					0.114	0.821
a (1/cm)	4	0.005	0.010	0.007	0.002	LN	-4.605	-5.279	-5.007	0.295	0.179	0.913
n	4	1.702	2.815	2.203	0.465	NO					0.141	0.906
K_s (cm/s)	4	6.70E-05	1.36E-01	7.11E-04	6.79E-02	LN	-1.995	-9.611	-7.249	3.532	0.252	0.932
Longitudinal Dispersivity[1] (m)	NA	0.0279	0.0341	0.031	NA	UN	-	-	-	-		
% Gravel	4	0	4	1	2							
Bulk Density (g/cm^3)	3	1.49	1.66	1.58	0.09	NO	-	-	-	-		

†NO = Normal (no transformation required); LN = Lognormal; LR = Log ratio; SN = Hyperbolic arcsine; UN = Uniform; CO = Constant; BE = Beta.

[1] Taken from Ho et al. (1999).

Table B.25. Approximation for the Distribution Function for Soil Type "CCUc" (Cold Creek unit-carbonate, formerly called "PPlc" [Plio-Pleistocene-carbonate]) Modified from Khaleel and Freeman (1995) Soil Category SS (sand mixed with finer fraction)

PPlc	Number	Raw					Transformed (normal distribution)				Observed Data Range Truncation Limits	
Parameter	of Samples	Low	High	Mean	Standard Deviation	Transform †	Upper Limit	Lower Limit	Mean	Standard Deviation	Lower	Upper
q_S	14	0.193	0.422	0.281	0.073	NO					0.116	0.973
q_R	14	0.019	0.110	0.054	0.027	NO					0.096	0.979
s_r	14	0.097	0.275	0.185	0.059	NO					0.069	0.935
a (1/cm)	14	0.003	0.073	0.011	0.018	LN	-2.620	-5.843	-4.495	0.897	0.066	0.982
n	14	1.262	2.537	1.740	0.354	NO					0.088	0.988
K_s (cm/s)	14	5.80E-06	6.80E-02	8.45E-04	1.82E-02	LN	-2.688	-12.058	-7.077	2.778	0.036	0.943
Longitudinal Dispersivity[1] (m)	NA	0.0279	0.0341	0.031	NA	UN	-	-	-	-		
% Gravel	15	0	59	16.73	19.21	NO						
Bulk Density (g/cm^3)	14	1.48	2.13	1.72	0.18	NO	-	-	-	-		

†NO = Normal (no transformation required); LN = Lognormal; LR = Log ratio; SN = Hyperbolic arcsine; UN = Uniform; CO = Constant; BE = Beta.

[1] Taken from Ho et al. (1999).

Table B.26. Approximation for the Distribution Function for Soil Type "CCUc-Z" (Cold Creek unit-carbonate - 200-ZP-1, formerlly called "PPlc_Z" [Plio-Pleistocene-carbonate - 200-ZP-1]) Modified from Khaleel and Freeman (1995) Soil Category SS (sand mixed with finer fraction)

PPlc_Z	Number	Raw					Transformed (normal distribution)				Observed Data Range Truncation Limits	
Parameter	of Samples	Low	High	Mean	Standard Deviation	Transform †	Upper Limit	Lower Limit	Mean	Standard Deviation	Lower	Upper
q_S	13	0.193	0.422	0.286	0.074	NO					0.107	0.967
q_R	13	0.019	0.110	0.056	0.027	NO					0.081	0.976
s_r	13	0.097	0.275	0.190	0.058	NO					0.055	0.927
a (1/cm)	13	0.003	0.073	0.011	0.019	LN	-2.620	-5.843	-4.484	0.933	0.073	0.977
n	13	1.262	2.537	1.750	0.366	NO					0.091	0.984
K_s (cm/s)	13	5.80E-06	6.80E-02	1.03E-03	1.88E-02	LN	-2.688	-12.058	-6.878	2.786	0.031	0.934
Longitudinal Dispersivity[1] (m)	NA	0.0279	0.0341	0.031	NA	UN	-	-	-	-		
% Gravel	14	0.00	59.00	15.07	18.79	NO						
Bulk Density (g/cm^3)	12	1.48	1.94	1.68	0.16	NO	-	-	-	-		

†NO = Normal (no transformation required); LN = Lognormal; LR = Log ratio; SN = Hyperbolic arcsine; UN = Uniform; CO = Constant; BE = Beta.

[1] Taken from Ho et al. (1999).

Table B.27. Approximation for the Distribution Function for Soil Type "Rg" (Ringold sandy gravel) Based on Khaleel and Freeman (1995) Soil Category SG2 (sandy gravel with gravel fraction >60%)

Rg	Number	Raw					Transformed (normal distribution)				Observed Data Range Truncation Limits	
Parameter	of Samples	Low	High	Mean	Standard Deviation	Transform †	Upper Limit	Lower Limit	Mean	Standard Deviation	Lower	Upper
q_S	18	0.056	0.433	0.177	0.137	NO					0.188	0.969
q_R	18	0.000	0.150	0.026	0.033	NO					0.215	1.000
s_r	18	0.000	0.375	0.135	0.089	NO					0.065	0.996
a (1/cm)	18	0.003	0.059	0.008	0.014	LN	-2.827	-5.952	-4.853	0.878	0.105	0.989
n	18	1.421	1.914	1.660	0.162	NO					0.070	0.942
K_s (cm/s)	18	6.20E-06	1.30E-01	4.13E-04	3.04E-02	LN	-2.040	-11.991	-7.791	2.572	0.051	0.987
Longitudinal Dispersivity[1] (m)	NA	0.027	0.178	0.09	NA	UN	-	-	-	-		
% Gravel	18	0	82	46.08	30.71	NO						
Bulk Density (g/cm^3)	18	1.63	2.17	1.90	0.15	NO	-	-	-	-		

†NO = Normal (no transformation required); LN = Lognormal; LR = Log ratio; SN = Hyperbolic arcsine; UN = Uniform; CO = Constant; BE = Beta.
[1] Taken from Ho et al. (1999). Same as SSG.

Table B.28. Approximation for the Distribution Function for Soil Type "Rg_2W" (Ringold sandy gravel - 200 West Area) Based on Khaleel and Freeman (1995) Soil Category SG2 (sandy gravel with gravel fraction >60%)

Rg_2W	Number	Raw					Transformed (normal distribution)				Observed Data Range Truncation Limits	
Parameter	of Samples	Low	High	Mean	Standard Deviation	Transform †	Upper Limit	Lower Limit	Mean	Standard Deviation	Lower	Upper
q_S	8	0.083	0.437	0.294	0.129	NO					0.051	0.866
q_R	8	0.000	0.144	0.041	0.046	NO					0.186	0.987
s_r	8	0.000	0.330	0.120	0.097	NO					0.108	0.985
a (1/cm)	8	0.004	0.059	0.014	0.018	LN	-2.827	-5.547	-4.269	0.807	0.057	0.963
n	8	1.421	1.914	1.671	0.172	NO					0.073	0.921
K_s (cm/s)	8	7.80E-06	8.70E-03	1.06E-04	3.02E-03	LN	-4.744	-11.761	-9.155	2.564	0.155	0.957
Longitudinal Dispersivity[1] (m)	NA	0.027	0.178	0.09	NA	UN	-	-	-	-		
% Gravel	8	0	70	22.175	28.788	NO						
Bulk Density (g/cm^3)	8	1.630	2.118	1.838	0.167	NO	-	-	-	-		

†NO = Normal (no transformation required); LN = Lognormal; LR = Log ratio; SN = Hyperbolic arcsine; UN = Uniform; CO = Constant; BE = Beta.
[1] Taken from Ho et al. (1999). Same as SSG.

Table B.29. Approximation for the Distribution Function for Soil Type "Rg_U" (Ringold sandy gravel - 200-UP-1) Based on Khaleel and Freeman (1995) Soil Category SG2 (sandy gravel with gravel fraction >60%)

Rg_U	Number of Samples	Raw				Transform †	Transformed (normal distribution)				Observed Data Range Truncation Limits	
Parameter		Low	High	Mean	Standard Deviation		Upper Limit	Lower Limit	Mean	Standard Deviation	Lower	Upper
q_S	7	0.083	0.437	0.315	0.123	NO					0.029	0.839
q_R	7	0.009	0.144	0.047	0.046	NO					0.205	0.983
s_r	7	0.060	0.330	0.138	0.091	NO					0.195	0.983
a (1/cm)	7	0.004	0.059	0.014	0.019	LN	-2.827	-5.547	-4.269	0.870	0.071	0.951
n	7	1.421	1.914	1.675	0.186	NO					0.086	0.901
K_s (cm/s)	6	8.90E-06	1.75E-03	7.83E-05	6.87E-04	LN	-6.348	-11.629	-9.455	1.961	0.134	0.943
Longitudinal Dispersivity[1] (m)	NA	0.027	0.178	0.09	NA	UN	-	-	-	-		
% Gravel	7	0	70.00	16.49	25.78	NO						
Bulk Density (g/cm^3)	7	1.63	2.12	1.82	0.17	NO	-	-	-	-		

†NO = Normal (no transformation required); LN = Lognormal; LR = Log ratio; SN = Hyperbolic arcsine; UN = Uniform; CO = Constant; BE = Beta.

[1] Taken from Ho et al. (1999). Same as SSG.

References

Ho CK, RG Baca, SH Conrad, GA Smith, L Shyr, and TA Wheeler. 1999. *Stochastic Parameter Development for PORFLOW Simulations of the Hanford AX Tank Farm*. SAND98-2880, Sandia National Laboratories, Albuquerque, New Mexico.

Khaleel R and EJ Freeman. 1995. *Variability and Scaling of Hydraulic Properties for 200 Area Soils, Hanford Site*. WHC-EP-0883, Westinghouse Hanford Company, Richland, Washington.

Appendix C

Resolution of Discrepancies in the System Assessment Capability Vadose Zone Model for the BC Cribs and Trenches

Appendix C

Resolution of Discrepancies in the System Assessment Capability Vadose Zone Model for the BC Cribs and Trenches

W. E. Nichols

The System Assessment Capability (SAC) Initial Assessment (Bryce et al. 2002) exhibited large, early releases of technetium-99. In all cases, the releases from the vadose zone to groundwater were nearly instant, following disposal to ground by only a year or two. To date, no groundwater monitoring data show evidence of any technetium-99 plume from the area of these sites consistent with such large releases.

Because of the large predicted impact of technetium-99 from the BC cribs and trenches and inconsistency between predictions and groundwater monitoring data, resolution of the vadose zone model at these sites is required.

C.1 Approach

The SAC vadose zone modeling uses a one-dimensional approach for computational speed. It is recognized that the multidimensional aspects of the vadose zone are highly important, but multidimensional modeling of the hundreds of waste disposal sites addressed in the SAC in a stochastic framework is computationally untenable. For vadose zone sites with liquid discharges, this is compensated by applying a K_s-dependent wetted area adjustment, wherein the area of the vadose zone area represented in the one-dimensional model is scaled so that a unit gradient is attained in the layer with the lowest saturated hydraulic conductivity for the period with the highest liquid discharge rate.

However, for the BC trenches, the K_s-depended wetted area adjustment method does not yield an area larger than the site area, so the SAC model defaults to using the Waste Information Data System (WIDS) area. This is equivalent to declaring there is no lateral movement of liquid associated with the liquid discharges at these sites.

Lateral spreading undoubtedly still occurs for the short-duration (less than one year) discharges that occurred at the BC trenches, and two-dimensional modeling of each crib and trench for median input values can be used to quantify the extent of lateral spreading. Lateral spreading of fluid will tend to delay arrival of technetium-99 at the aquifer. If enough delay occurs, then the disposal inventory could still be consistent with the groundwater monitoring data that does not indicate a substantial technetium-99 plume in the vicinity of the BC cribs and trenches before calendar year 2000.

C.2 Multidimensional Modeling of BC Trenches

The BC trenches and their respective areas and discharge volumes are listed in Table C.1. The BC trenches are long relative to their width and were, therefore, idealized as a two-dimensional feature symmetric about the length axis of the trench. An idealized two-dimensional model was constructed that assumes the trench is infinite in length, and that lateral spreading is strictly perpendicular to the trench length axis.

Table C.1. BC Trenches (data from Maxfield 1979)

WIDS Identification	Area (square meters)	Discharge Volume (liters)
216-B-20	152.4×3.0 = 457.2	4.68×10^6
216-B-21	152.4×3.0 = 457.2	4.67×10^6
216-B-22	152.4×3.0 = 457.2	4.74×10^6
216-B-23	152.4×3.0 = 457.2	4.52×10^6
216-B-24	152.4×3.0 = 457.2	4.7×10^6
216-B-25	152.4×3.0 = 457.2	3.76×10^6
216-B-26	152.4×3.0 = 457.2	5.88×10^6
216-B-27	152.4×3.0 = 457.2	4.42×10^6
216-B-28	152.4×3.0 = 457.2	5.05×10^6
216-B-29	152.4×3.0 = 457.2	4.84×10^6
216-B-30	152.4×3.0 = 457.2	4.78×10^6
216-B-31	152.4×3.0 = 457.2	4.74×10^6
216-B-32	152.4×3.0 = 457.2	4.77×10^6
216-B-33	152.4×3.0 = 457.2	4.74×10^6
216-B-34	152.4×3.0 = 457.2	4.87×10^6
216-B-52	176.8×3.0 = 530.4	8.53×10^6
216-B-53A	18.3×3.0 = 54.9	5.49×10^5
216-B-53B	45.7×3.0 = 137.2	1.51×10^4
216-B-54	61.0×3.0 = 182.9	9.99×10^5
216-B-58	61.0×3.0 = 182.9	4.13×10^5
WIDS – Waste Information Data Systemc		

The SAC one-dimensional model for each BC trench with a substantial inventory of technetium-99 (trenches below 216-B-34 in Table C.1 did not have a large disposal of technetium-99) was expanded into a two-dimensional axial-symmetric model (half the trench represented, with results scalable to represent the whole trench). The vertical resolution (580 0.15-meter grid cells) was retained, and the x-axis was resolve into 96, 0.15-meter grid cells. This yielded a model grid of 55,680 grid nodes. The liquid and analyte discharges were converted to density-type sources and assigned to the topmost nodes in the grid index range from 1 to 10 (inner 1.5 meters), representing half the source term (again, consistent with the axial-symmetric treatment).

Hanford soils are anisotropic, considered about 10 times more conductive in the horizontal dimension than in the vertical. To consider this feature, each trench was modeled twice, once with isotropic properties and once with 10:1 anisotropy in saturated hydraulic conductivity.

Once the release histories for the multidimensional model runs were available, the one-dimensional model was rerun with several 'AreaX' (area scaling parameter) values. By trial-and-error, an 'AreaX' scaling factor that would cause the one-dimensional model to produce releases similar to the two-dimensional model (with explicit treatment of lateral flow) was determined. For all BC trenches, the value AreaX = 3.0 provided the best match for isotropic conductivity and AreaX = 6.5 provided the best match for anisotropic (10:1 ratio) conductivity.

Figures C.1 through C.15 provide the modeling results for the BC trenches with substantial technetium-99 inventory (216-B-20 through 216-B-34, inclusive). Each figure depicts the release from the VADER vadose zone release model (i.e., the "input signal"), the release from the various Subsurface Transport Over Multiple Phases (STOMP) one-dimensional models (with variable AreaX factor values), and from the STOMP two-dimensional models (with isotropic and anisotropic conductivity).

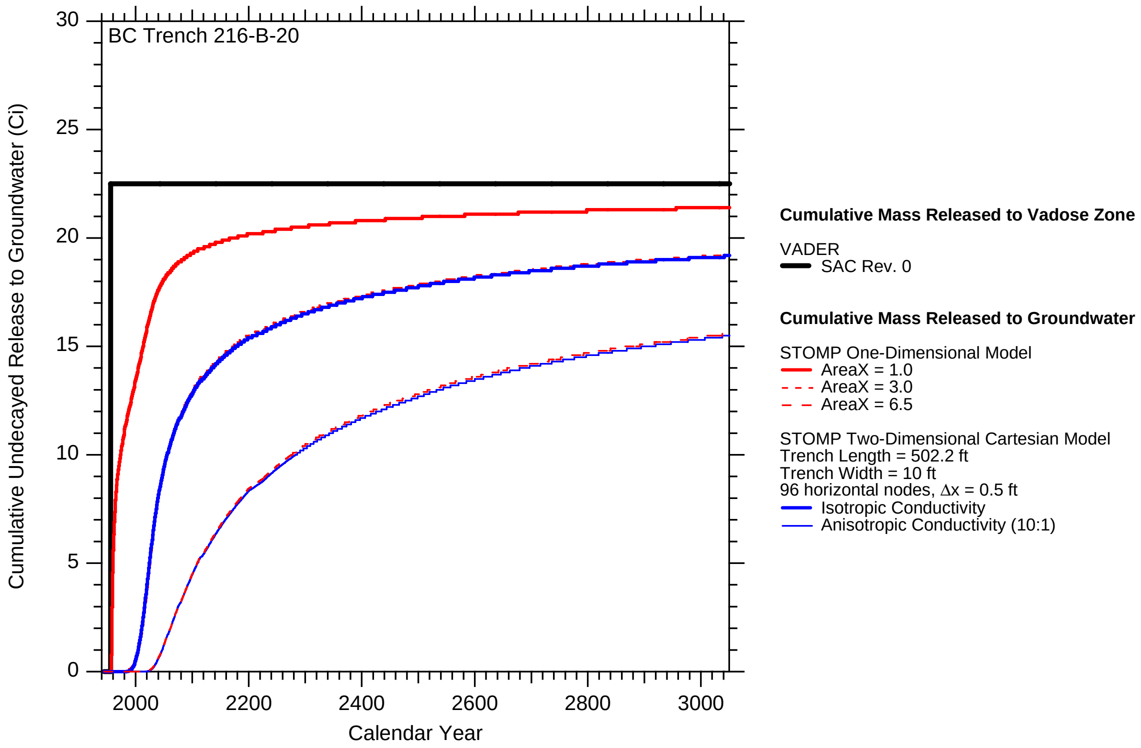

Figure C.1. Vadose Zone Cumulative Release to Groundwater Modeled for Trench 216-B-20

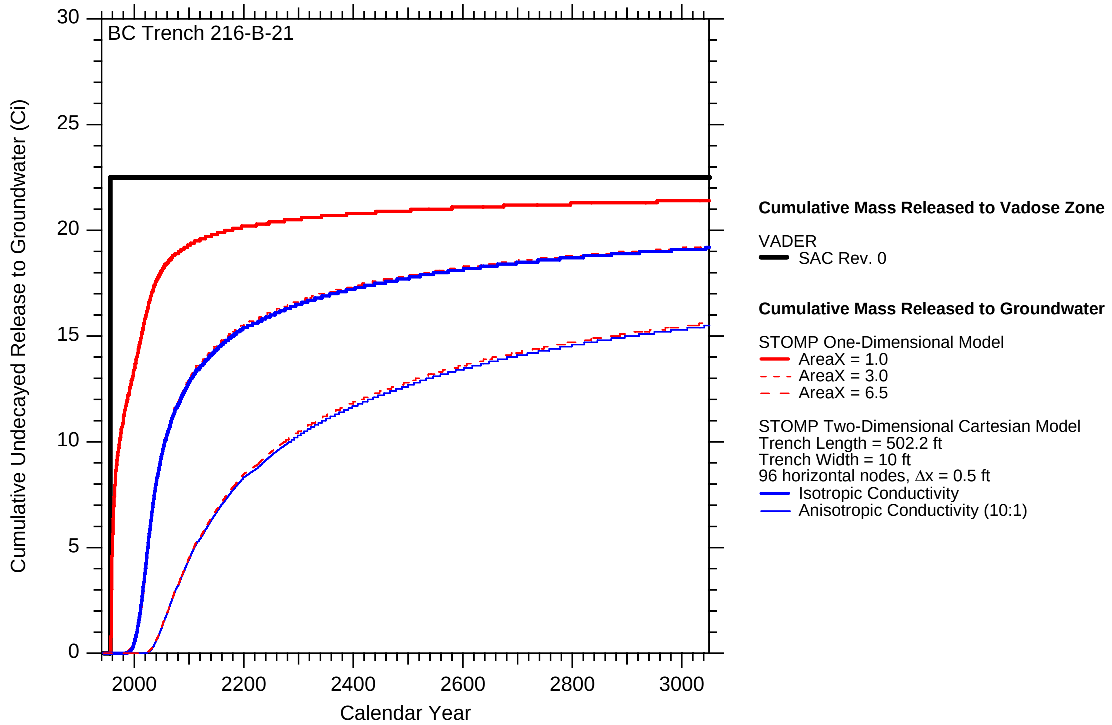

Figure C.2. Vadose Zone Cumulative Release to Groundwater Modeled for Trench 216-B-21

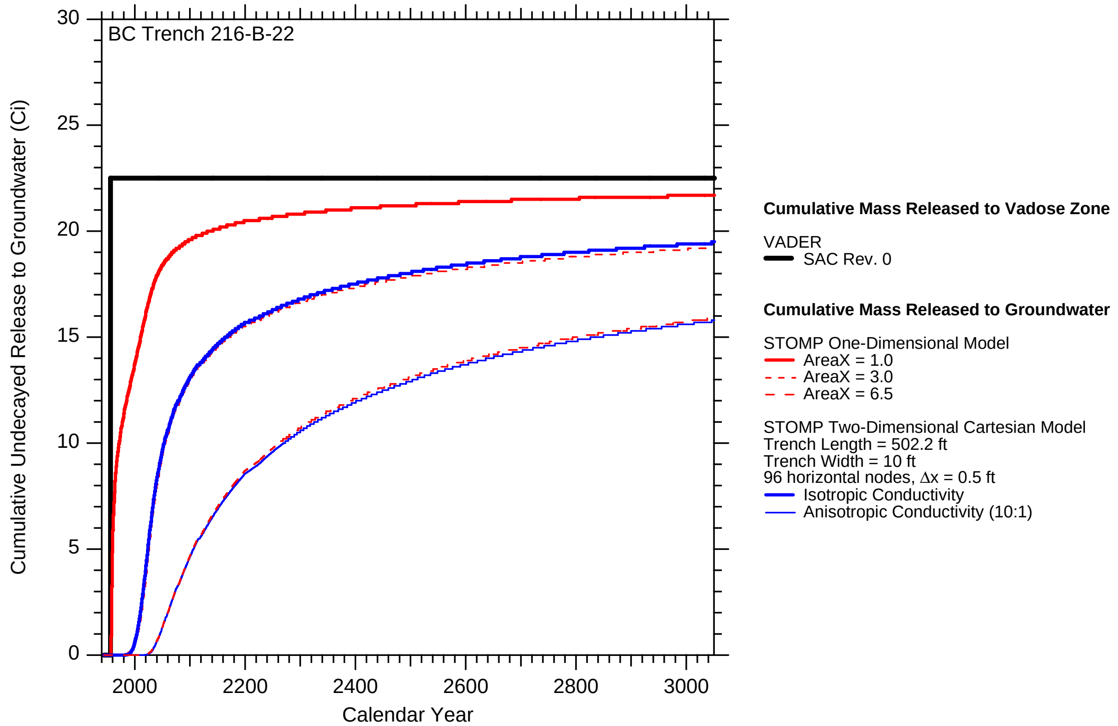

Figure C.3. Vadose Zone Cumulative Release to Groundwater Modeled for Trench 216-B-22

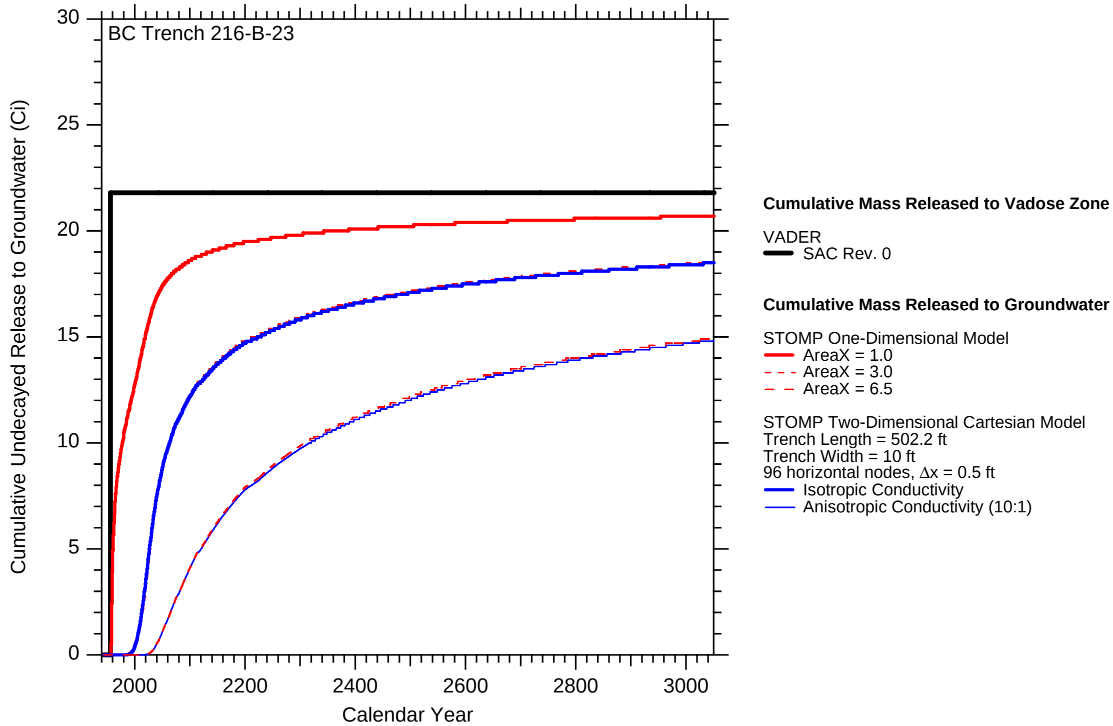

Figure C.4. Vadose Zone Cumulative Release to Groundwater Modeled for Trench 216-B-23

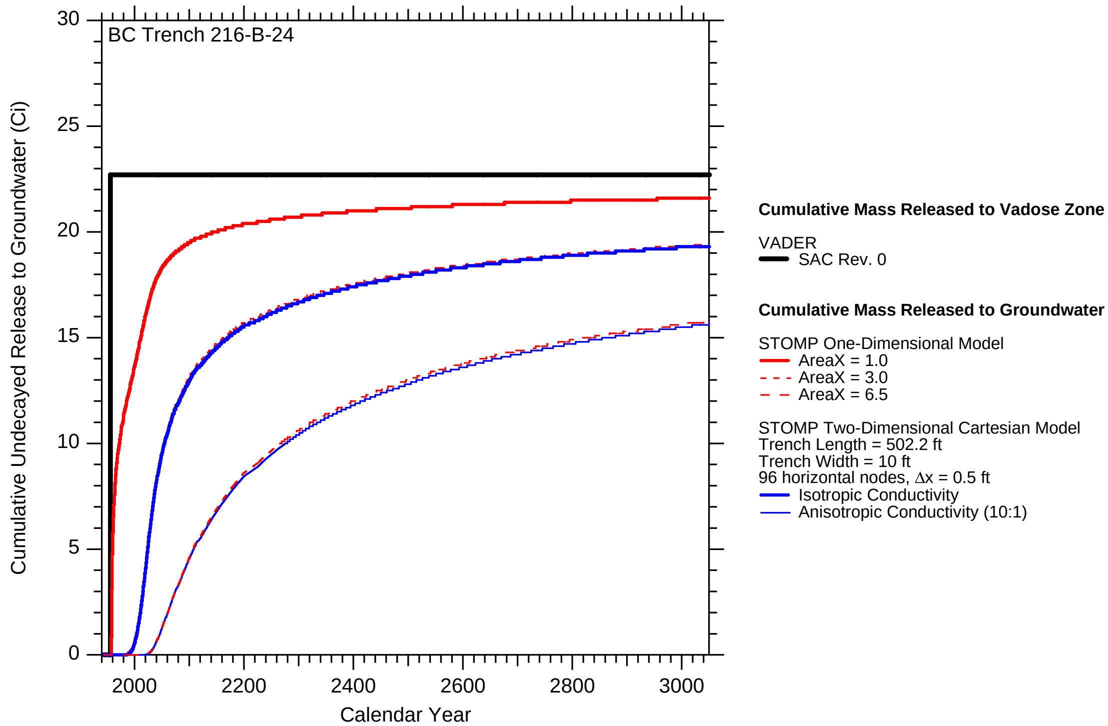

Figure C.5. Vadose Zone Cumulative Release to Groundwater Modeled for Trench 216-B-24

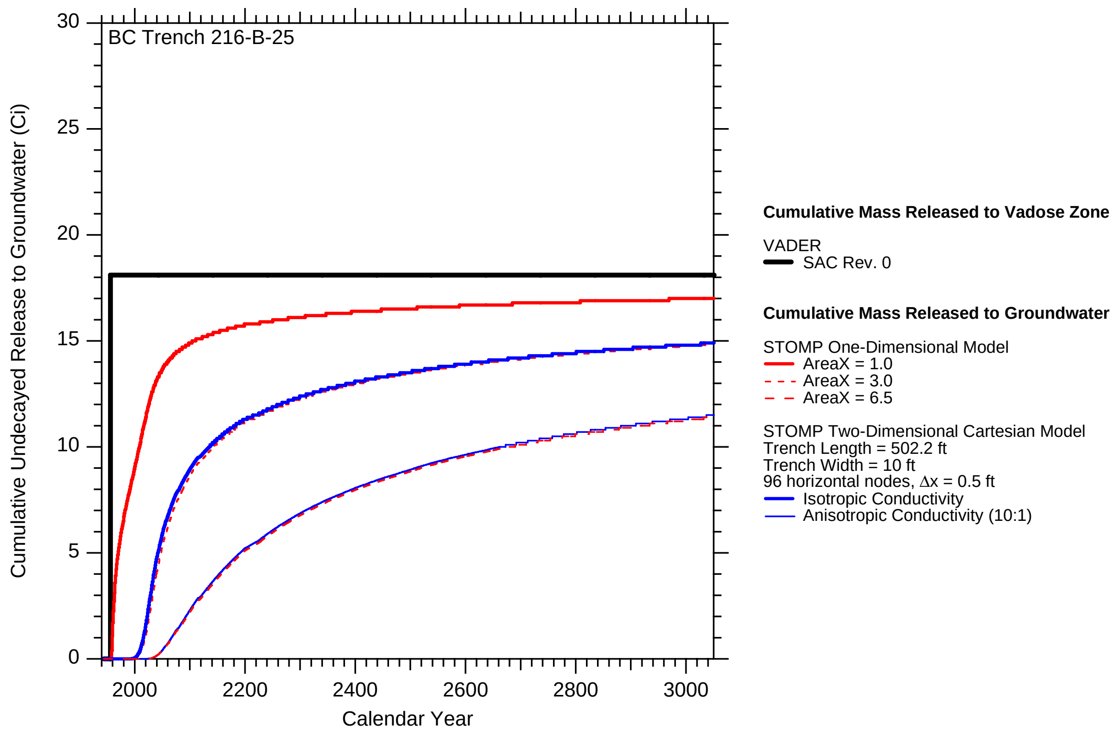

Figure C.6. Vadose Zone Cumulative Release to Groundwater Modeled for Trench 216-B-25

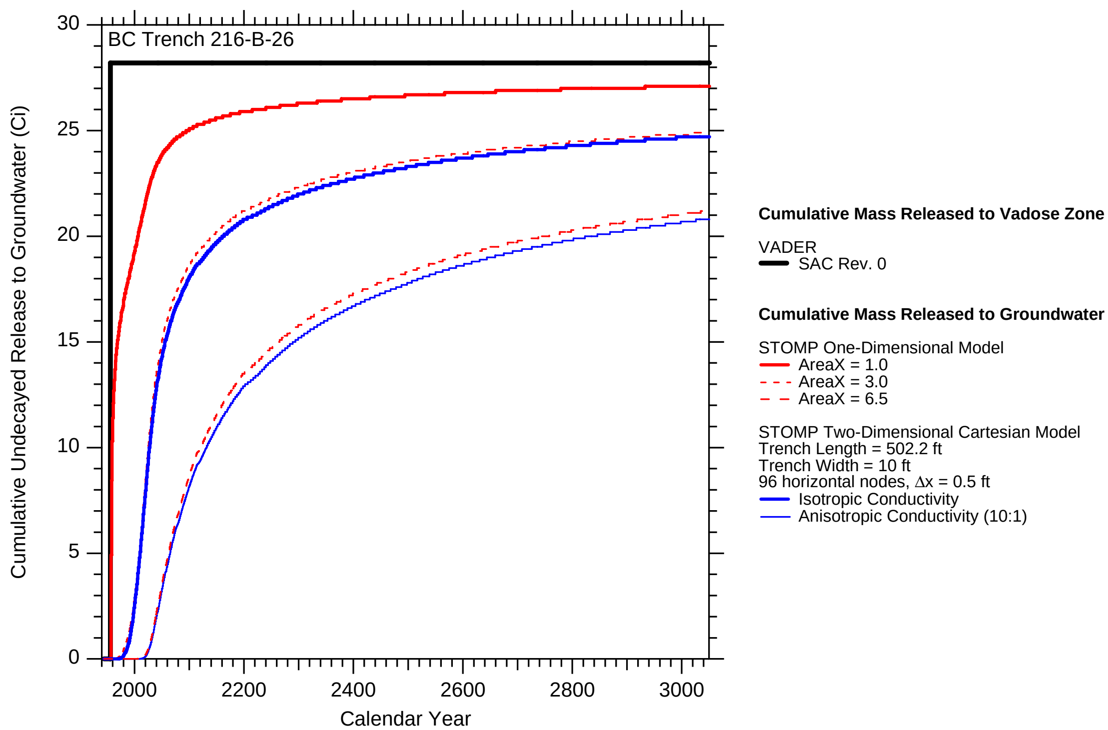

Figure C.7. Vadose Zone Cumulative Release to Groundwater Modeled for Trench 216-B-26

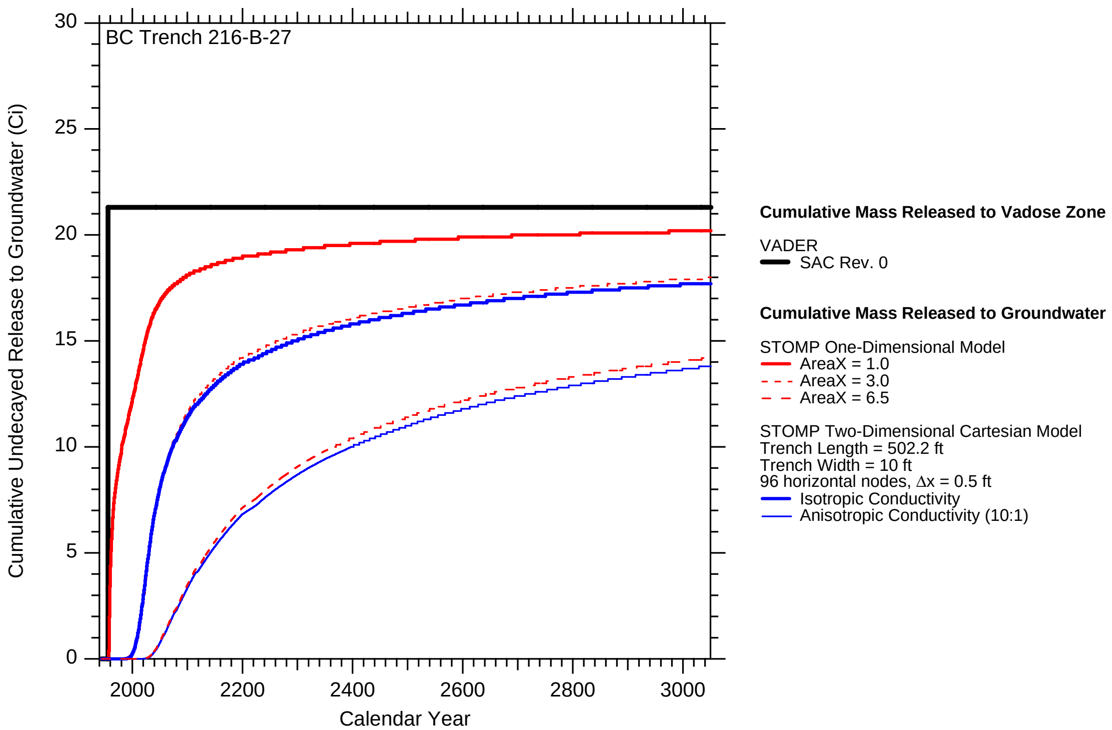

Figure C.8. Vadose Zone Cumulative Release to Groundwater Modeled for Trench 216-B-27

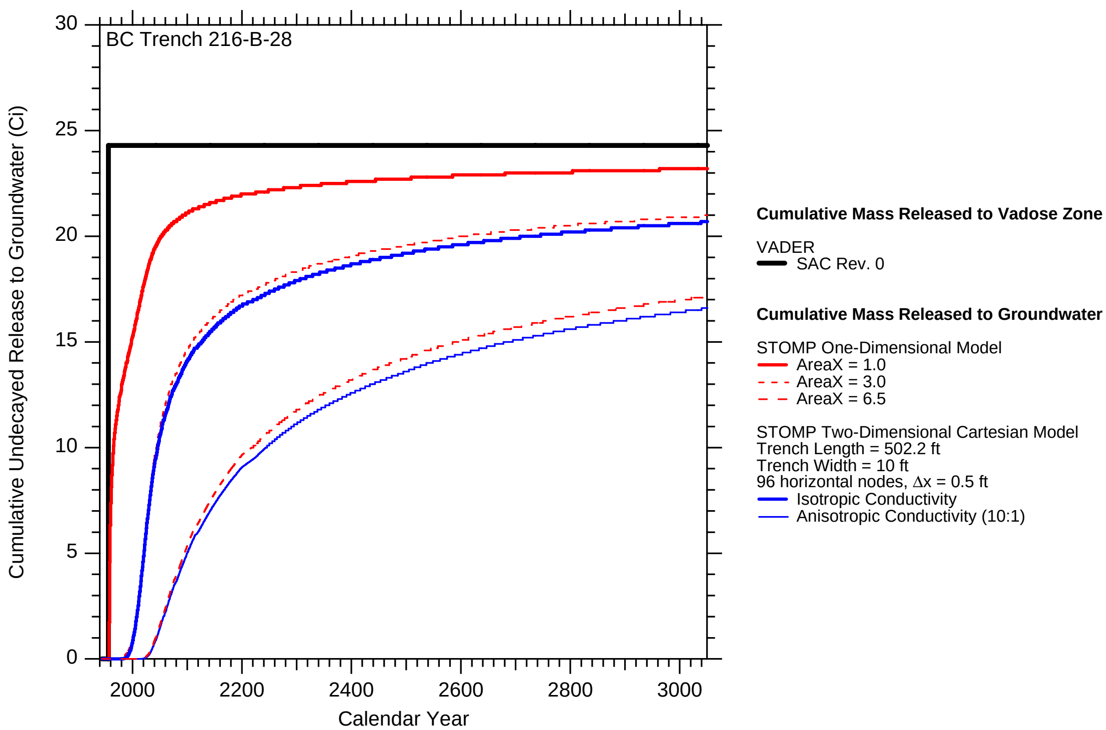

Figure C.9. Vadose Zone Cumulative Release to Groundwater Modeled for Trench 216-B-28

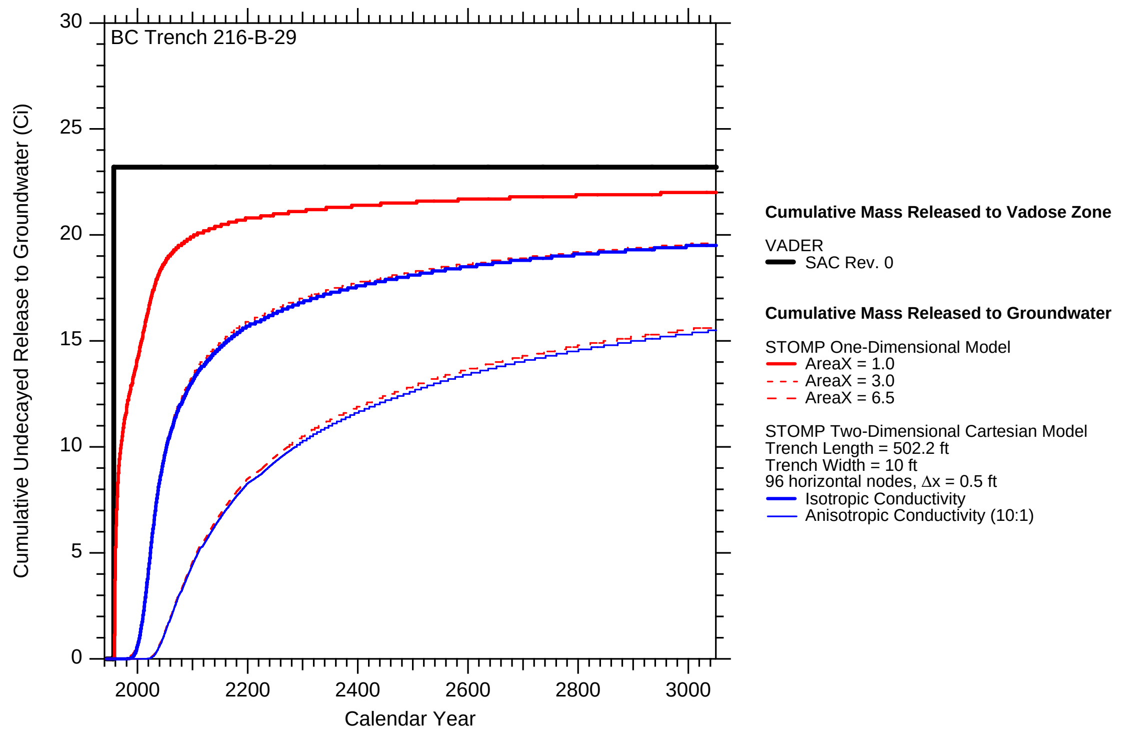

Figure C.10. Vadose Zone Cumulative Release to Groundwater Modeled for Trench 216-B-29

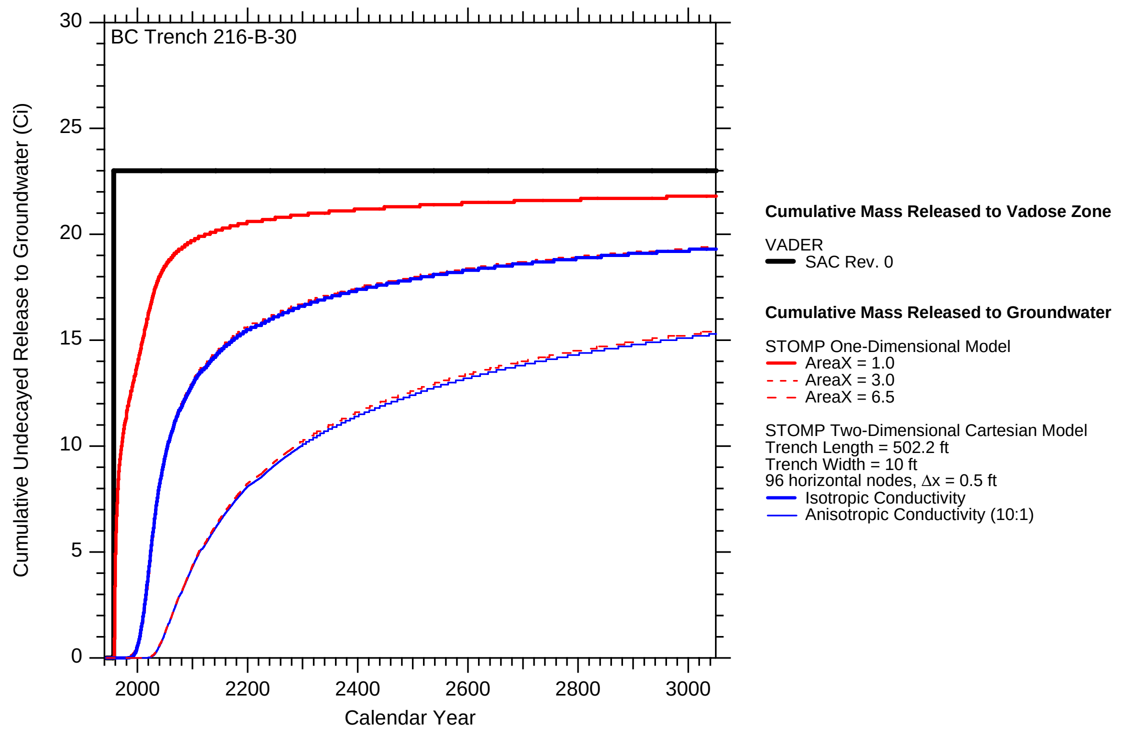

Figure C.11. Vadose Zone Cumulative Release to Groundwater Modeled for Trench 216-B-30

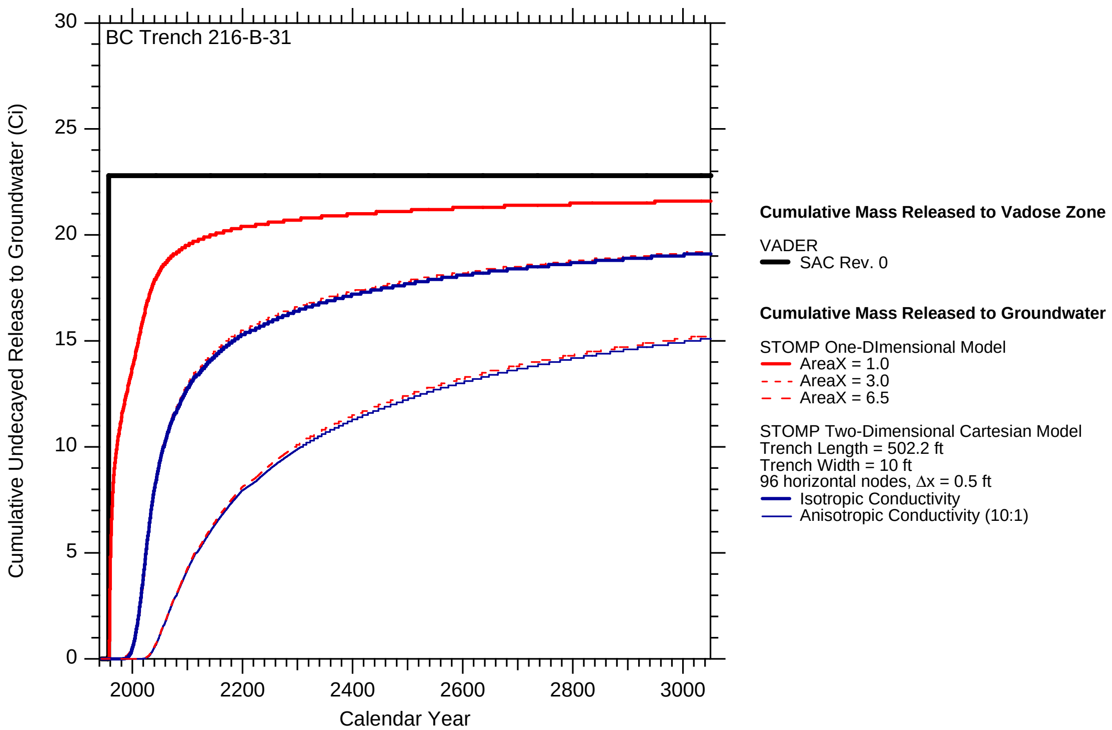

Figure C.12. Vadose Zone Cumulative Release to Groundwater Modeled for Trench 216-B-31

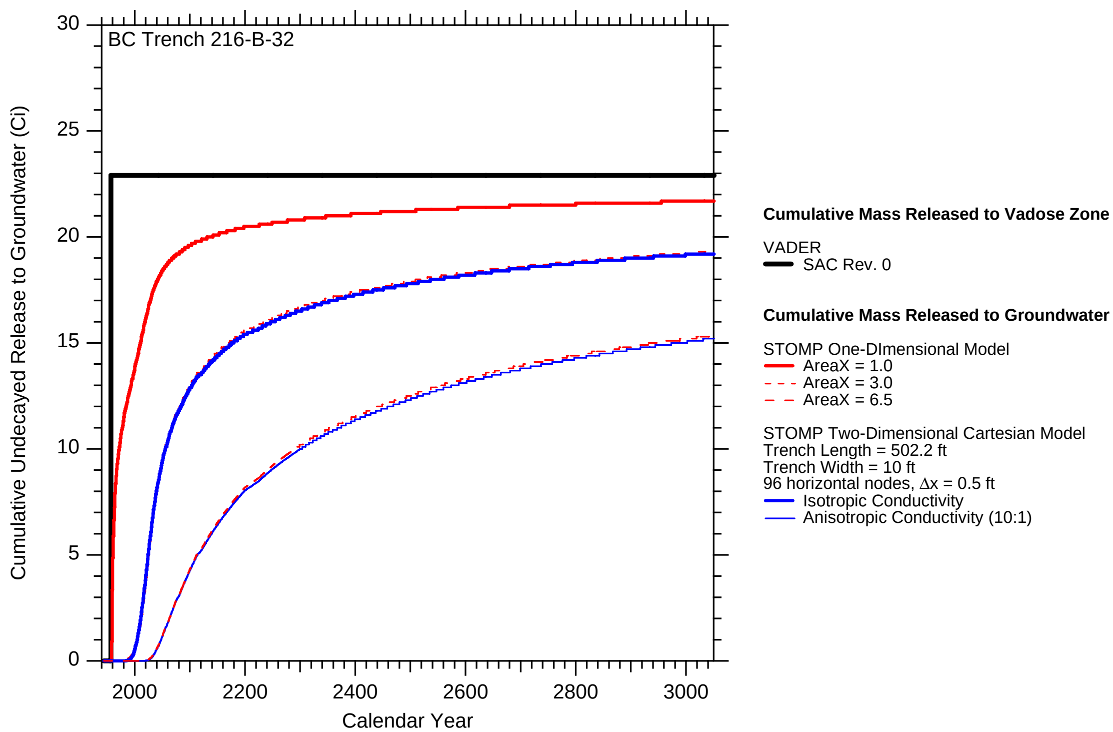

Figure C.13. Vadose Zone Cumulative Release to Groundwater Modeled for Trench 216-B-32

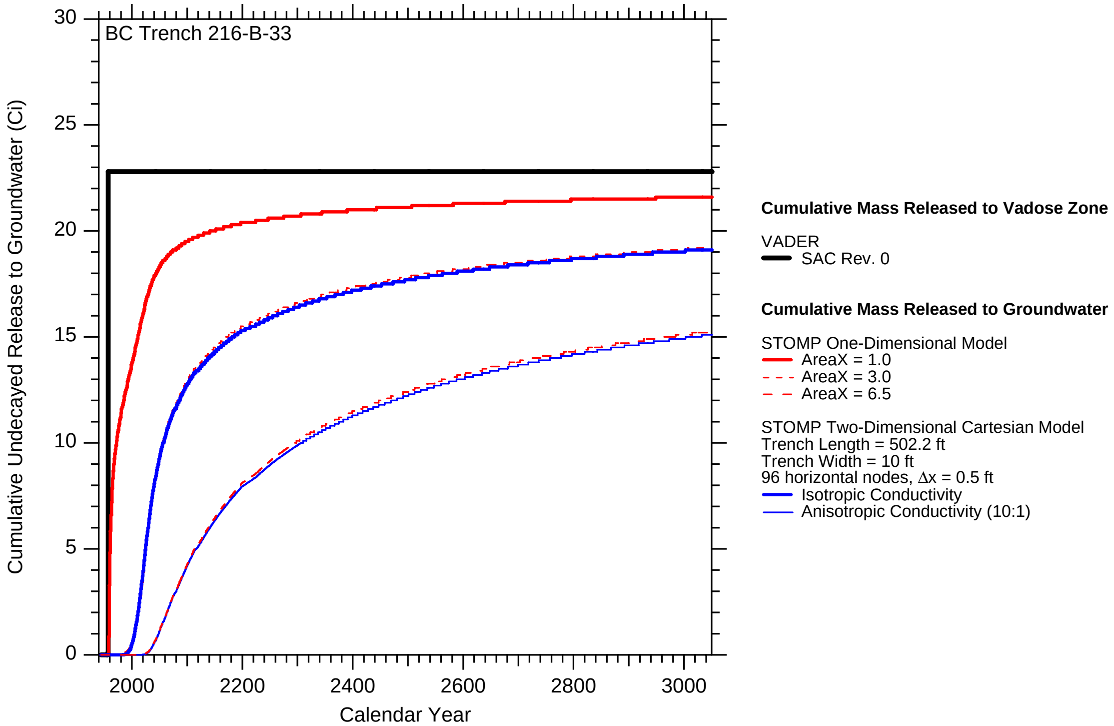

Figure C.14. Vadose Zone Cumulative Release to Groundwater Modeled for Trench 216-B-33

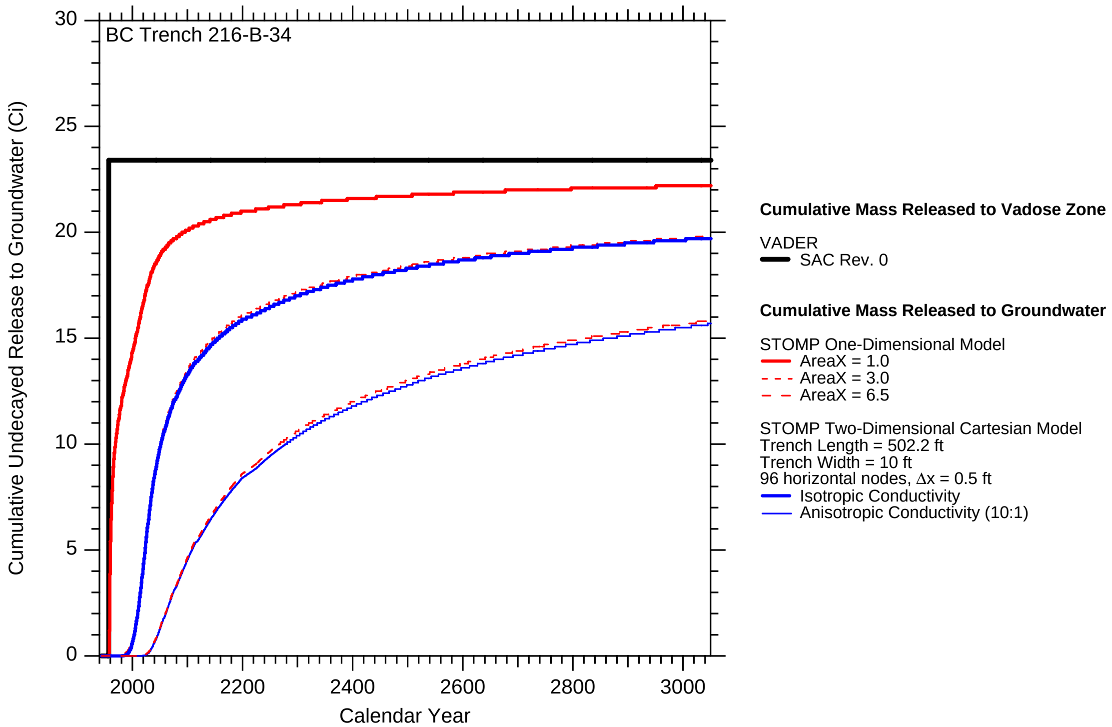

Figure C.15. Vadose Zone Cumulative Release to Groundwater Modeled for Trench 216-B-34

C.3 Multidimensional Modeling of BC Cribs

The BC cribs and their respective areas and discharge volumes are listed in Table C.2. The BC cribs are essentially square and were idealized as a two-dimensional circular feature symmetric about the diameter. An idealized two-dimensional cylindrical model was constructed that assumes lateral spreading will be strictly radial outward.

Table C.2. BC Cribs (data from Maxfield 1979)

WIDS Identification	Area (square feet)	Discharge Volume (liters)
216-B-14	40×40 = 1600	8.71×10^6
216-B-15	40×40 = 1600	6.32×10^6
216-B-16	40×50 = 2000	5.6×10^6
216-B-17	40×40 = 1600	3.41×10^6
216-B-18	40×40 = 1600	8.52×10^6
216-B-19	40×40 = 1600	6.4×10^6
WIDS = Waste Information Data System.		

The SAC one-dimensional model for each BC crib was expanded into a two-dimensional axial-symmetric cylindrical model (a 180-degree arc, or half the crib, represented with results scalable to represent the whole crib). The vertical resolution (580, 0.15-meter-grid cells) was retained, and the x-axis was resolved several ways. Ideally, the model should be resolved to the same degree horizontally (0.15 meter) as vertical to avoid numerical dispersion, but for the high volume (relative to disposal area) the number of nodes necessary to accomplish this leads to a model too large to solve practically with available computer systems. Instead, several successively finer resolutions were simulated for the first crib (216-B-14) to demonstrate convergence in the release history with finer resolution. It is notable that lower resolution leads to greater lateral flow (due to numerical dispersion in the horizontal dimension), which in turn leads to lower release predictions. This indicates the need to use full resolution in two-dimensional models if release is not to be systematically under-predicted in SAC analyses.

Liquid and analyte discharges were converted to density-type sources and assigned to the topmost nodes in the grid index range covering the inner 13.7 meters (the radius of a circle with the same area as a typical BC crib), representing half the source term (again, consistent with the axial-symmetric treatment). Note that the area given in Table C.2 does not match the area declared in WIDS and the SAC database; often the WIDS area is larger than the true footprint.

Hanford soil is anisotropic, considered about 10 times more conductive in the horizontal dimension than in the vertical. To consider this feature, each crib was modeled twice, once with isotropic properties and once with 10:1 anisotropy in saturated hydraulic conductivity.

Once the release histories for the multidimensional model runs were available, the one-dimensional model was rerun with several AreaX (area scaling parameter) values. By trial-and-error, an AreaX scaling factor that would cause the one-dimensional model to produce releases similar to the two-dimensional model (with explicit treatment of lateral flow) was determined. For all BC cribs, the value AreaX = 1.5 provided the best match for isotropic conductivity and AreaX = 3.0 provided the best match for anisotropic (10:1 ratio) conductivity.

Figures C.16 through C.24 shows simulated vadose zone release to groundwater results for BC crib 216-B-14 for various horizontal resolutions of the two-dimensional cylindrical model for the early years 1944 to 2000 for both isotropic and anisotropic (10:1) conductivity. Note that increasing release with increasing resolution, showing the need for a highly resolved two-dimensional model to preclude substantially under predicting release. The highest model resolution simulated was 580 vertical (0.15 meter) by 192 horizontal (0.43 meter) nodes, for a total model grid of 111,360 nodes. Ideally, the horizontal should be resolved to 0.15-meter nodes also, but this would yield a model domain of more than 300,000 nodes, too large to simulate with available equipment in a reasonable time. As it was, the final resolution (111,360 nodes) could only be simulated on the analysis stations (paper.pnl.gov or plastic.pnl.gov) and not on any RANSAC compute node due to the memory demands of such a large domain. Hence, the release for the highest resolution should be seen as close, but not quite as high as the release that would be predicted for the fully resolved (0.15-meter grid) model if it were run.

Also displayed in Figure C.16 are the release results for the one-dimensional model for AreaX = 1.0 (SAC Rev. 0 default) and for AreaX = 1.5, which approximates the isotropic release history, and AreaX = 3.0, which approximates the anisotropic (10:1) release history. The one-dimensional model is shown to slightly under predict annual releases from the crib in early years (up to about 1980) and slightly over predict annual releases thereafter.

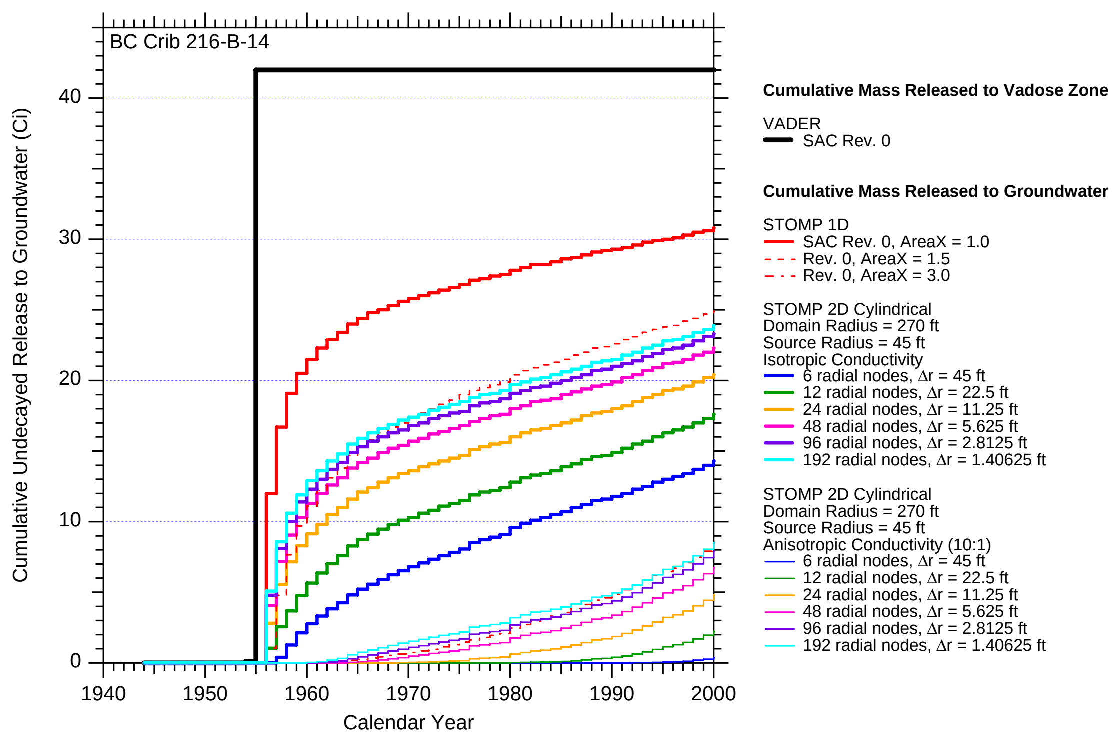

Figure C.16. Vadose Zone Cumulative Release to Groundwater Modeled for Crib 216-B-14 (1944 to 2000)

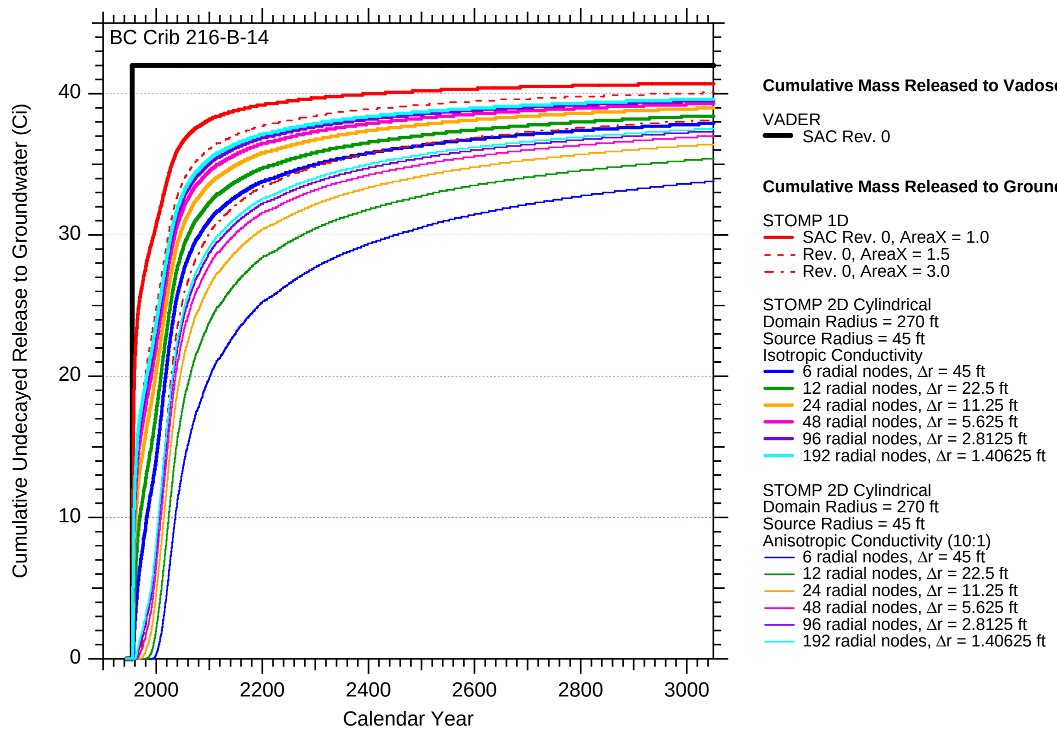

Figure C.17. Vadose Zone Cumulative Release to Groundwater Modeled for Crib 216-B-14

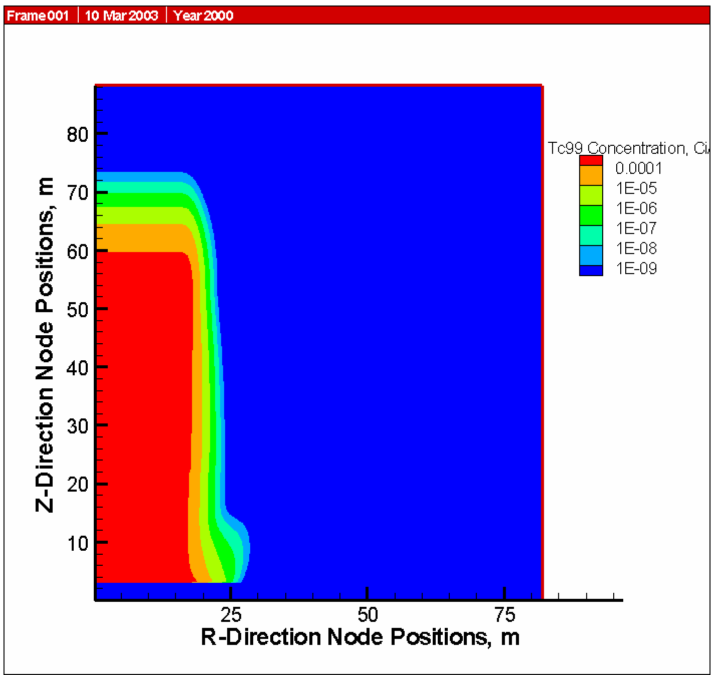

Figure C.18. Tc-99 Concentration (Ci/m^3) of Two-Dimensional Axial-Symmetric (192 radial nodes) Isotropic Model of Crib 216-B-14 (center of crib is the left-hand side and the water table is the bottom of the domain)

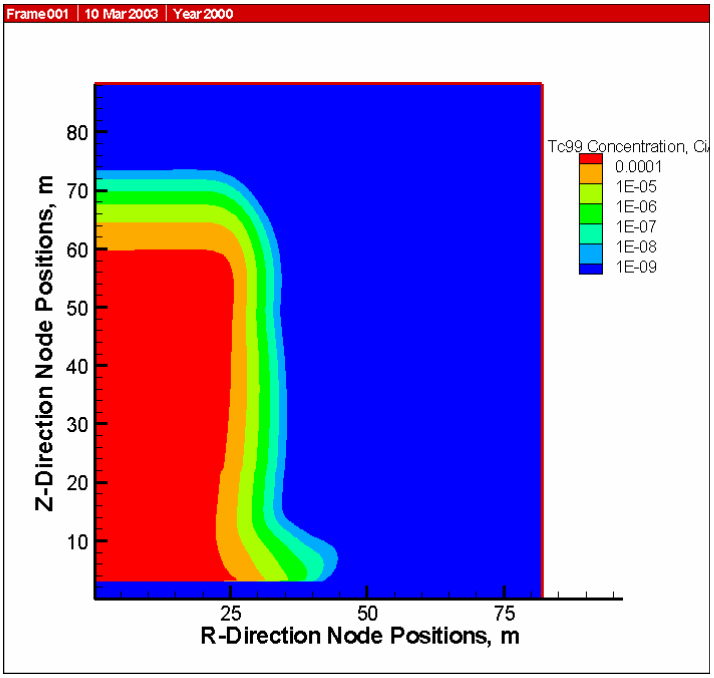

Figure C.19. Tc-99 Concentration (Ci/m^3) of Two-Dimensional Axial-Symmetric (192 radial nodes) Anisotropic (10:1 conductivity ratio) Model of Crib 216-B-14 (center of crib is the left-hand side and the water table is the bottom of the domain)

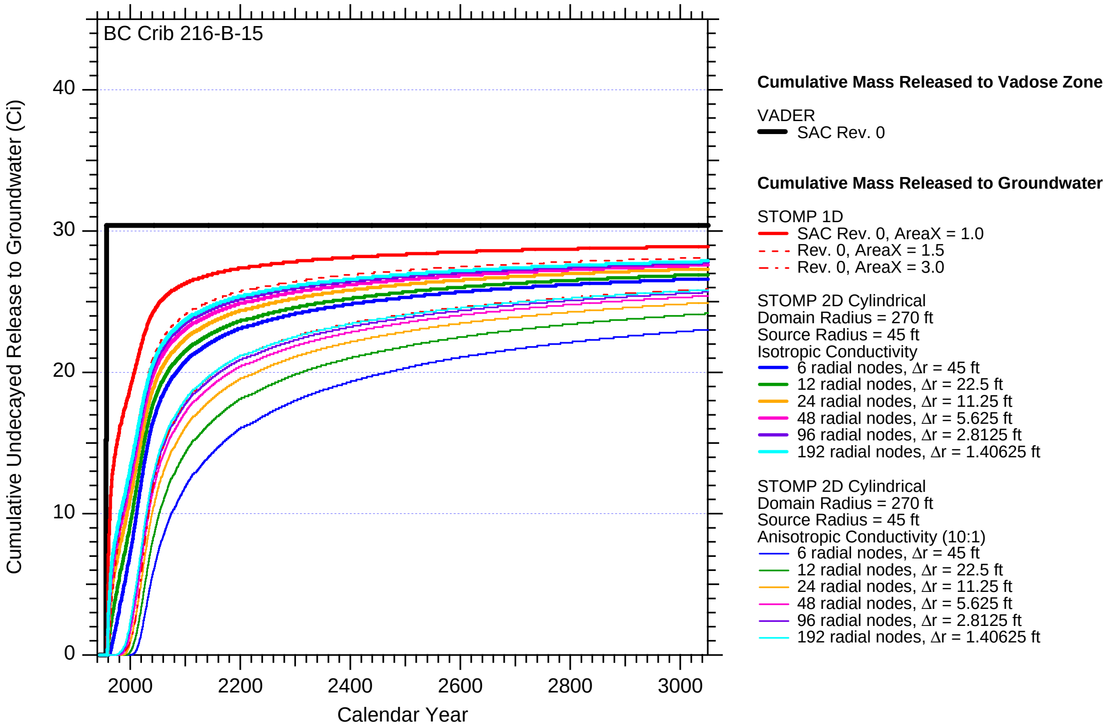

Figure C.20. Vadose Zone Cumulative Release to Groundwater Modeled for Crib 216-B-15

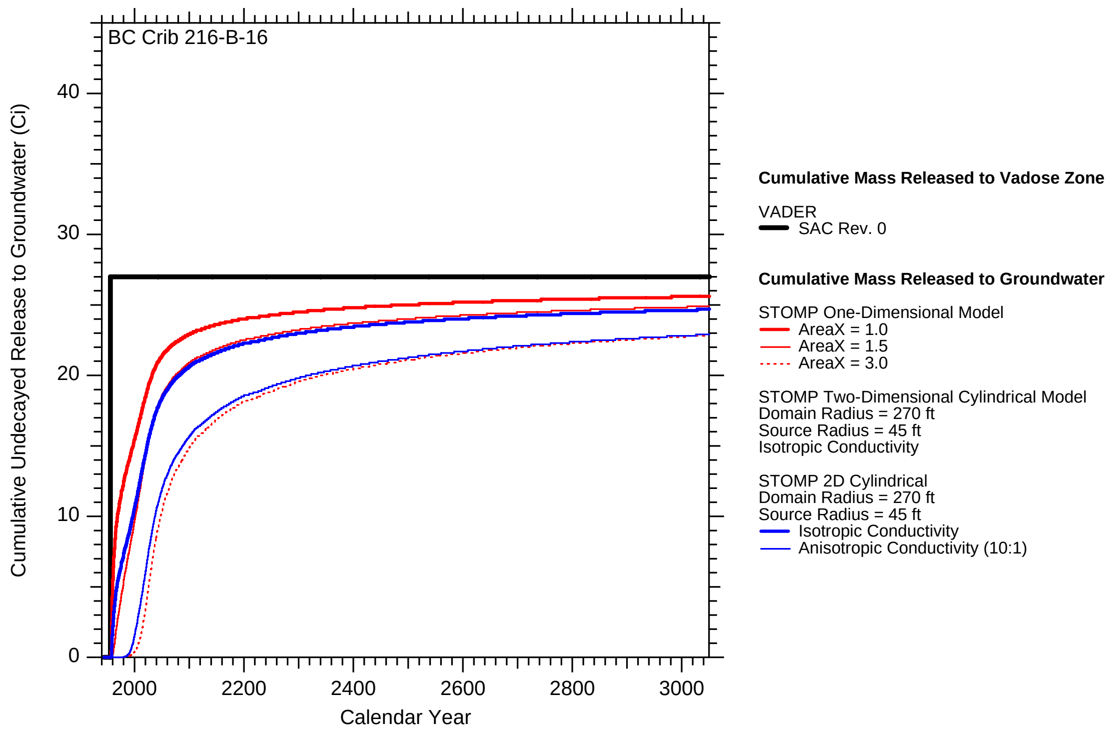

Figure C.21. Vadose Zone Cumulative Release to Groundwater Modeled for Crib 216-B-16

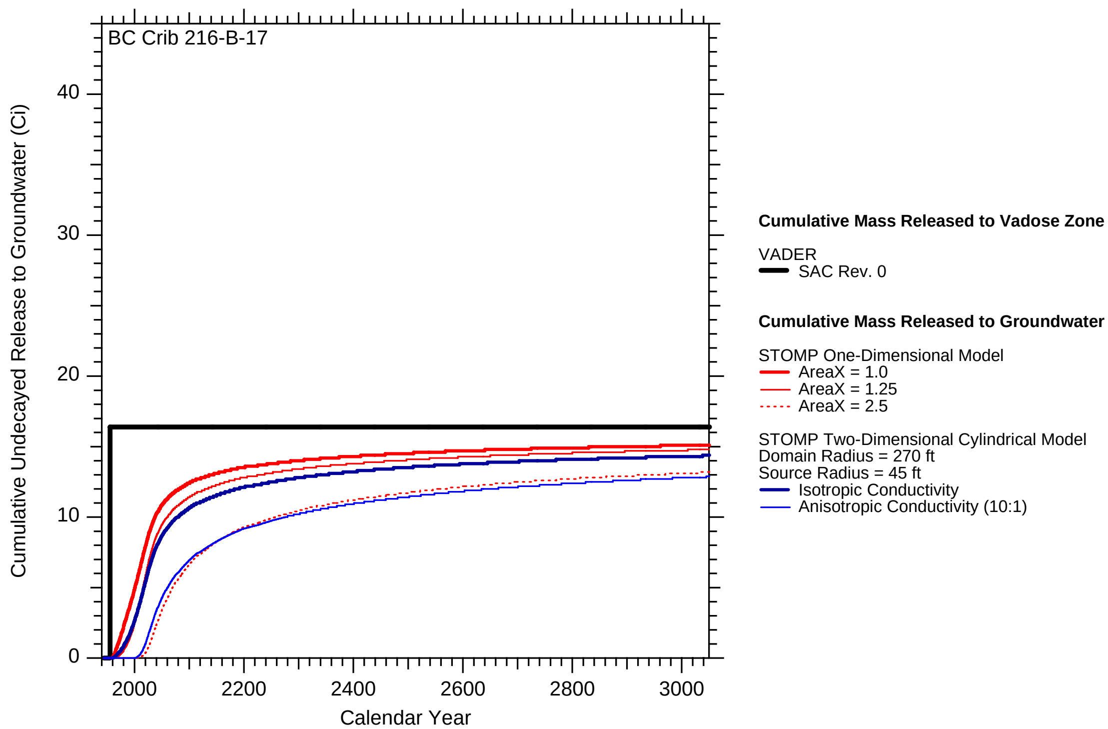

Figure C.22. Vadose Zone Cumulative Release to Groundwater Modeled for Crib 216-B-17

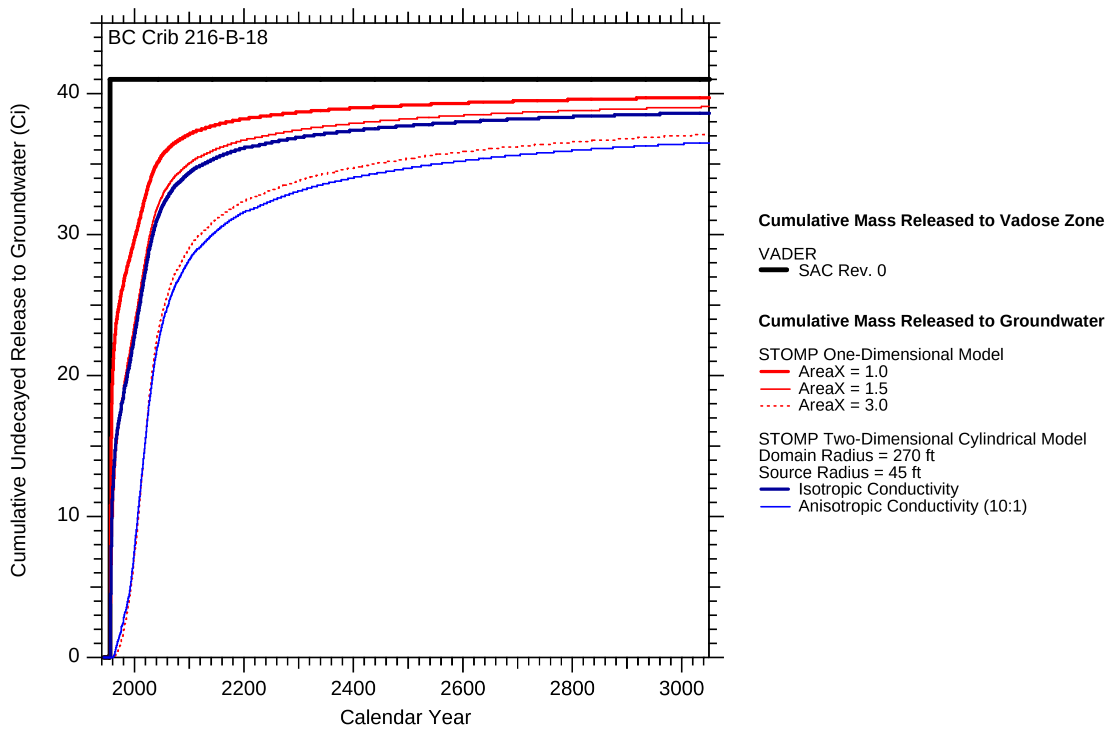

Figure C.23. Vadose Zone Cumulative Release to Groundwater Modeled for Crib 216-B-18

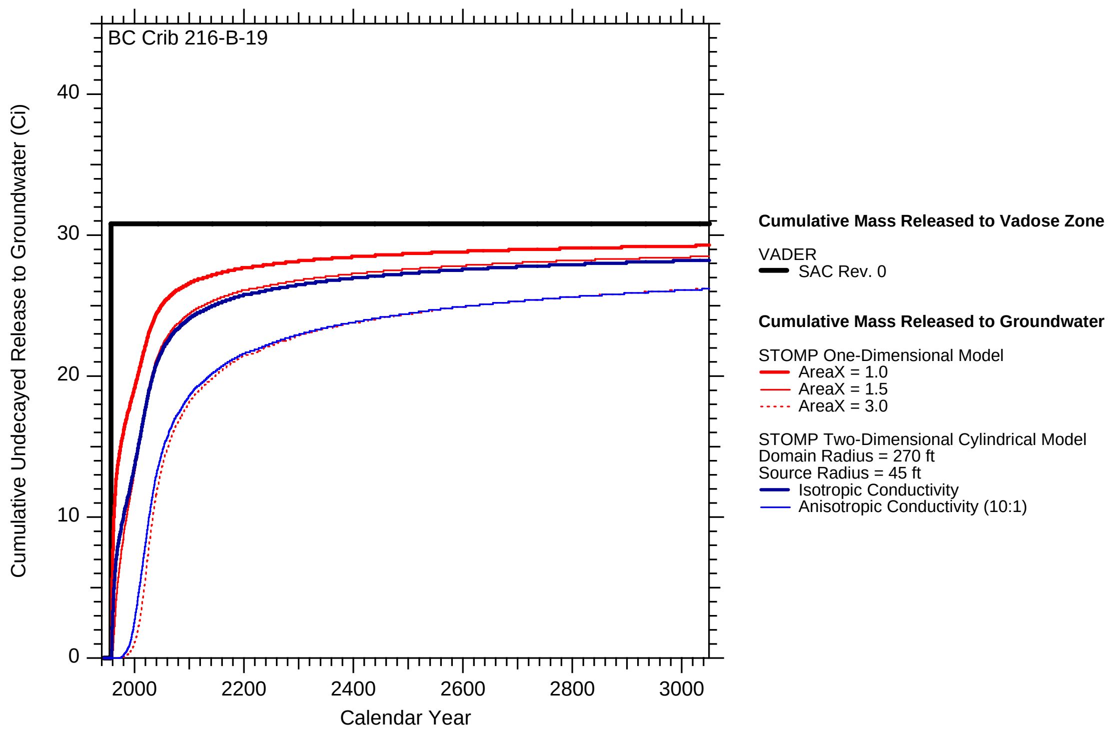

Figure C.24. Vadose Zone Cumulative Release to Groundwater Modeled for Crib 216-B-19

C.4 Computer Simulation Time

An important implication of two-dimensional simulation in the SAC context is the simulation time required to solve for vadose zone transport of analytes. As a stochastic simulator, SAC will invoke a STOMP model of a vadose zone site for a number of cases equal to the number of realizations times the number of analytes. Ideally, locations with liquid discharges (such as the BC cribs and trenches) would be modeled as two-dimensional features. However, if the computer time required to perform the number of two-dimensional cases required is too great, a problem of feasibility arises.

The times required to solve the various one- and two-dimensional simulations of the crib 216-B-14 provides a basis for consideration. Table C.3 provides the timing results. Note all time are for simulations on a Pentium 4 processor, except the highest resolution grid which had to be run on a SAC analysis node due to the high RAM requirements of this resolution grid. The highest resolution two-dimensional model, with 111,360 nodes, was too large to run on any RANSAC compute node as it required more RAM than any of the compute nodes are equipped with. The high memory demand of this size model has important implications for inclusion in SAC of a two-dimensional model of the BC cribs. Moreover, this model still wasn't sufficiently resolved (that would require a model with more than 300,000 nodes).

C.5 Summary

Based on the simulation times in Table C.3 and the simulation results shown earlier, several points can be made with respect to SAC Rev. 1 implementation:

1. If a two-dimensional capability is desired, the SPLIB solver is substantially faster for grid domains over 20,000 nodes and should be made standard for STOMP in SAC.

2. If a two-dimensional model were to be used directly in SAC, the time required to solve the vadose zone segment of SAC would increase starkly. For crib 216-B-14, more than 15 hours were required at a grid resolution that was nearly sufficient. In a production run with 25 realizations and 10 analytes, this would imply 3,750 hours of computer time for just one crib, or 22,500 hours for the six BC cribs. Spread over 132 compute nodes (assuming these were equipped with enough RAM to carry the problem), it would take 170 hours, or about one week, just to solve for the six BC cribs. Worse, these time estimates were based on runs on 2.2-GHz processors; 128 of the 132 compute nodes on RANSAC are 1.0-GHz processors (about three times slower). And this only for the BC cribs; there are many other liquid-discharge sites that make good candidates for two-dimensional simulation in SAC. It is clear that direct two-dimensional treatment of liquid discharge waste sites remains impractical, requiring at least RAM upgrades to the entire SAC cluster and unacceptably long simulation times to solve.

3. However, the results also demonstrate that the one-dimensional model can be made to approximate the direct two-dimensional model by selecting an appropriate value of the vadose zone wetted area based on detailed two-dimensional modeling.

Table C.3. Computer Simulation Time for Various One- and Two-Dimensional STOMP Models of 216-B-14 Crib (Pentium 4, 2.2-GHz processor running under Linux)

Number of Nodes in Direction			Total Number of Nodes	Solution Time(s)	
r	θ	Z		Banded Matrix Solver	SPLIB Solver
1	1	580	580	137	129
6	1	580	3,480	960	955
12	1	580	6,960	2,081	2,055
24	1	580	13,920	4,910	4,501
48	1	580	27,840	21,835	9,522
96	1	580	55,680		20,588
192	1	580	111,360		55,748[(a)]

(a) Simulated on Pentium III, 1.3-GHz processor instead because RAM was insufficient on any RANSAC compute node for this large of grid domain.

It is recommended that for the BC cribs and trenches the one-dimensional model continue to be used in SAC Rev. 1, but with vadose zone wetted area scaling factors derived from the simulations performed in this report.

C.6 Projected Impact on Initial Assessment

To demonstrate the change from following these calibration factors, the total technetium-99 release from all BC cribs and trenches was simulated both using the SAC Rev. 0 approach (effectively AreaX = 1.0) and with the vadose zone wetted area scaling parameters derived in this study. The results are shown in Figure C.25. Note the difference predicted by year 2000; 449 curies released to the aquifer in the initial assessment model (one-dimensional model, AreaX = 1.0) compared to only 18.2 curies released in the one-dimensional model with scaling factors drawn from the detailed two-dimensional models. Based on the more detailed modeling, the absence of a detected technetium plume in groundwater monitoring data for this area, the much lower release is considered much more realistic.

C.7 References

Bryce RW, CT Kincaid, PW Eslinger, and LF Morasch (eds.). 2002. *An Initial Assessment of Hanford Impact Performed with the System Assessment Capability*. PNNL-14027, Pacific Northwest National Laboratory, Richland, Washington.

Maxfield HL. 1979. *Handbook – 200 Areas Waste Sites*. RHO-CD-673, Volumes I and II, Rockwell Hanford Company, Richland, Washington.

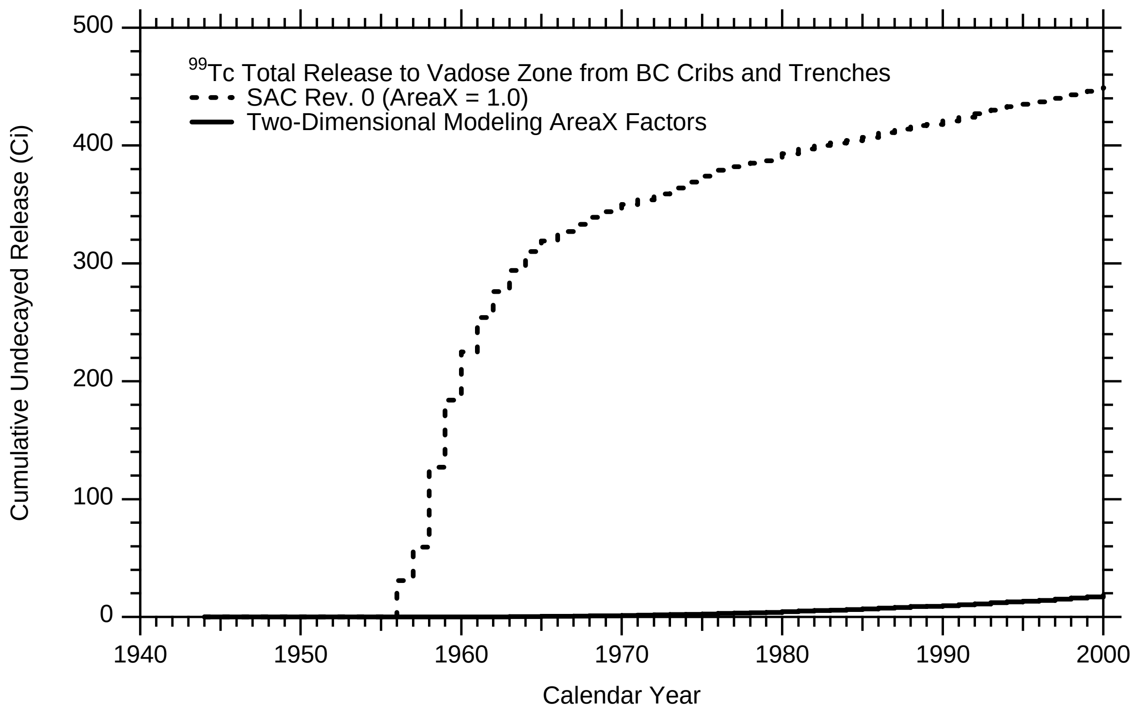

Figure C.25. Total Annual Release from all BC Cribs and Trenches Simulated in SAC Rev. 0 Initial Assessment and with Vadose Zone Wetted Area Scaling Parameters Conditioned to Direct Two-Dimensional Simulations

Distribution

(Distribution is by electronic copy.)

No. of Copies		
3	**DOE Office of River Protection**	
	M.E. Burandt	H6-60
	R. W. Lober	H6-60
	S.A. Wiegman	H6-60
6	**DOE Richland Operations Office**	
	B. L. Charboneau	A6-33
	B. L. Foley	A6-38
	R. D. Hildebrand	A6-38
	J. G. Morse	A6-38
	K. M. Thompson	A6-38
	DOE Public Reading Room	H2-53
5	**CH2M HILL Hanford Group, Inc.**	
	M. Connelly	H6-03
	J. G. Field	H6-62
	J. G. Kristofzski	H6-03
	F. M. Mann	H6-03
	W. J. McMahon	H6-03
3	**Washington Closure**	
	K. R. Fecht	H4-21
	E. T. Feist	H4-22
	S. G. Weiss	H4-22
2	**Fluor Federal Services**	
	R. Khaleel	E6-17
	R. J. Puigh	E6-17
6	**Fluor Hanford, Inc.**	
	B. A. Austin	H8-68
	J. V. Borghese	E6-35
	L. R. Fitch	E6-35
	B. H. Ford	E6-35
	T. W. Fogwell	E6-35
	J. Hoover	E6-35

No. of Copies		
47	**Pacific Northwest National Laboratory**	
	R. L. Aaberg	K3-54
	M. P. Bergeron	K9-36
	B. N. Bjornstad	K6-81
	C. A. Brandt	K9-04
	R. W. Bryce (5)	E6-35
	A. L. Bunn	K6-85
	K. J. Cantrell	K6-81
	D. W. Engel	K5-12
	P. W. Eslinger	K6-04
	J. C. Evans, Jr.	K6-96
	M. J. Fayer	K9-33
	E. J. Freeman	K9-36
	V.L. Freedman	K9-36
	M. D. Freshley	K9-33
	G. W. Gee	K9-33
	T. J. Gilmore	K6-96
	D. G. Horton	K6-81
	C. T. Kincaid	K9-33
	G. V. Last (5)	K6-81
	C. A. LoPresti	K5-12
	B. A. Napier	K3-54
	W. J. Martin	K6-81
	T. B. Miley	K6-04
	C. J. Murray	K6-81
	I. C. Nelson	K3-54
	W. E. Nichols	K9-33
	B.E. Opitz	K6-75
	G. W. Patton	K6-75
	C. L. Rakowski	K9-33
	J. V. Ramsdell, Jr	K3-54
	R. G. Riley	K6-96
	M. L. Rockhold	K9-36
	P. A. Scott	K9-46
	R. J. Serne	P7-22
	D. L. Strenge	K3-54
	P. D. Thorne	K9-33
	M. D. Williams	K6-96
	S. K. Wurstner	K9-36
	Hanford Technical Library	H2-53