

## 2.0 Overview of Hanford Hydrogeology and Geochemistry

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This chapter discusses the hydrogeologic setting of the Hanford Site. The deposition and later removal of sedimentary units in certain areas by cataclysmic flooding contribute to the complex hydrogeology. The regional geologic setting of the Pasco Basin and the Hanford Site has been described in the documents listed in Section 2.6. The following sections provide a basic summary of Hanford Site geology, hydrology, and geochemistry.

### 2.1 Stratigraphic Setting

This section discusses the geology of the Hanford Site. The Hanford Site lies within the Pasco Basin (Figure 2-1). The geology of the Site has been studied extensively over the years. The simplified “layer cake” depositional model of basalt bedrock that is overlain by Ringold Formation sediments, overlain by Cold Creek sediments, overlain by Hanford formation sediments has been complicated by the method of deposition, and later removal, of some of the sedimentary units. During deposition of the Ringold Formation sediments, actions of the ancestral Columbia and Salmon/Clearwater River systems resulted in deposition of a thick sequence of alternating river gravels and sands, as well as overbank flood deposits, and alluvial fans shed from the surrounding hillsides. During the Cold Creek depositional cycle, while the activities in the ancestral river systems continued, large portions of the Pasco Basin remained stable. This stability allowed for the formation of structured soil horizons that can still be identified today in certain areas as the “early Palouse soil.” During the last ice age, cataclysmic flooding deposited the coarse gravel to boulder sediments of the Hanford formation, while simultaneously scouring channels of varying depth into the previously deposited Cold Creek and Ringold sediments. As the multiple flooding events waned, and slack water conditions prevailed, fine sands to silts and clays were deposited over much of the Pasco Basin. All of these events contribute to the complex hydrogeology of the Hanford Site.

*Miocene- to Pliocene-Aged Suprabasalt Sediments of the Hanford Site, South-Central Washington*, (BHI-00184) provides a stratigraphic interpretation for the Ringold Formation based on facies associations and defines the areal extent of these suprabasalt units in the Pasco Basin. *Standardized Stratigraphic Nomenclature for Post-Ringold-Formation Sediments Within the Central Pasco Basin* (DOE/RL-2002-39) presents the standardized stratigraphic nomenclature for post-Ringold Formation sediments. A generalized stratigraphic column showing the nomenclature is provided in Figure 2-2. The following subsections discuss the various stratigraphic layers, from oldest (deepest) to youngest (shallowest).

#### 2.1.1 Columbia River Basalt Group

The lowest geologic unit of interest for this report is the Columbia River Basalt Group. Within the Pasco Basin, the Elephant Mountain flows of the Saddle Mountains Basalt formation are generally the uppermost basalt flows. Beneath the Hanford Site’s 200 Area, the Elephant Mountain Member consists of two flows and ranges in thickness from 20 to 30 meters (RHO-BWI-ST-14, *Subsurface Geology of the Cold Creek Syncline*). The earlier basalt flows below the Elephant Mountain Member are locally important but will not be discussed here.

The uppermost surface of the Elephant Mountain Member (basalt) is considered the base of the suprabasalt aquifer system (bedrock) because of its low permeability relative to the overlying sediments. This surface can be interpreted as either a groundwater no-flow boundary or a prescribe-flux boundary, depending on whether leakage between the confined and unconfined aquifers is considered significant (PNL-8971, *Three-Dimensional Conceptual Model for the Hanford Site Unconfined Aquifer System, FY 93 Status Report*). In areas where the Elephant Mountain Basalt has been partially eroded (e.g., north of the 200 East Area), a similar boundary exists at the contact between the Rattlesnake Ridge interbed to the top of the Pomona basalt. In some areas, the upper surface of the Elephant Mountain Basalt is sufficiently fractured or rubbly to allow it to transmit water. In these areas the unconfined aquifer may extend into the upper portion of the basalt, and the massive flow interior acts as the no-flow boundary.

The basalt surface beneath the 200 Area dips south, forming the southern limb of the Gable Mountain anticline/northern limb of the Cold Creek syncline (“Paleodrainage of the Columbia River System on the Columbia Plateau of Washington State -- A Summary” [Fecht et al., 1987]). Two smaller basalt folds or anticlinal ridges trending northwest-southeast extend above the water table and create barriers to groundwater flow (Figure 2-3).

Sedimentary interbeds, collectively referred to as the Ellensburg Formation, were deposited between many of the flows of the Saddle Mountains Basalt. The Ellensburg Formation includes fluvial and lacustrine sediments consisting of muds, sands, and gravels. The Rattlesnake Ridge interbed is the uppermost and most laterally extensive of these interbeds on the Hanford Site, and several wells are completed in this confined aquifer.

Intercommunication of groundwater between the uppermost basalt-confined aquifer (the Rattlesnake Ridge interbed) and overlying suprabasalt aquifer system has been documented in some areas of the Hanford Site, most notably beneath the B Pond (RHO-BWI-ST-14) (see Chapter 15.0). Another area of intercommunication is near Gable Gap, where the upper basalt units have been eroded, exposing the lower units and interbeds to the uppermost unconfined aquifer (PNL-10817, *Hydrochemistry and Hydrogeologic Conditions Within the Hanford Site Upper Basalt Confined Aquifer System*). The dominant vertical flow is now upward in most of these intercommunication areas.

### 2.1.2 Ringold Formation

The thick sedimentary sequence of the Ringold Formation overlies the basalt. The Ringold Formation can be divided into three broad facies types, depending on the proximity to the ancient river systems and basaltic ridges of the time (Figure 2-4):

- **Type I facies:** Consists of gravel and associated sand and silt representing a migrating channel deposit of the ancestral Columbia and/or Salmon/Clearwater River systems. This type of sediment is generally confined to the central portion of the Pasco Basin.
- **Type II facies:** Comprises mainly overbank sand, silt, and clay deposited around the margins of the basin, away from the main fluvial channel system.
- **Type III facies:** A fanglomerate facies comprising angular basaltic debris derived from side-stream alluvium shed from the flanks of the basalt ridges. This facies occurs only locally around the extreme margins of the basin.

To date, two separate Hanford Site stratigraphic classifications have been used to describe Ringold Formation sediments. One classification, developed in BHI-00184, is based on lithology; the second classification, developed by Pacific Northwest National Laboratory (PNNL-10886, *Development of a Three-Dimensional Ground-Water Model of the Hanford Site Unconfined Aquifer System: FY 1995 Status Report*; PNL-8971), is based primarily on hydrostratigraphy (also see PNNL-10886). This report uses the hydrostratigraphic classification because it is more applicable to the issue of addressing groundwater movement in the suprabasalt sediments (Figure 2-2). A hydrogeologic summary of these units is presented below.

The Ringold Formation is broadly divided into two units: an upper unit, consisting of lacustrine deposits and intercalated fluvial sands; and a lower unit that is subdivided into five subunits. BHI-00184 provides a detailed description of the upper Ringold unit. The upper Ringold unit forms the bluffs along the Columbia River north and east of the Hanford Site but has largely been removed by erosion from the site itself.

The lower Ringold Formation is subdivided into five subunits (units 5 through 9) and is discussed below, from deepest to shallowest.

#### **2.1.2.1 Ringold Formation Unit 9**

The deepest Ringold sediments belong to unit 9, which is a mixture of clay, silt, fine- to coarse-grained sand, and granule to cobble gravel. In the eastern portion of the 200 East Area, unit 9 can be further subdivided into three hydrogeologic units based on markedly different lithologies and hydraulic properties. The primary subunit is characterized as a silt to clay-rich confining zone with low permeability, classified as unit 9B. Subunits 9A and 9C have much higher permeabilities and lower clay content. Subunits 9A, 9B, and 9C can be differentiated and mapped as separate units using geophysical logs, lithologic logs, and drillers' reports based on the correlation of unit 9B where it is laterally continuous.

Unit 9 dips consistently to the south-southwest, roughly comparable to the basalt structure. Unit 9 increases in thickness from north to south into the Cold Creek syncline, suggesting deposition of Ringold unit 9 in an environment of continued structural growth of the Pasco Basin (SD-BWI-DP-039; DOE/RW-0164, *Site Characterization Plan, Reference Repository Location, Hanford Site, Washington*).

The north-northeastern extent of unit 9 is approximate and is delineated as the erosional limit of cataclysmic flooding that traversed across the uplifted Gable Butte anticlinal area (PNNL-12261, *Revised Hydrogeology for the Suprabasalt Aquifer System, 200-East Area and Vicinity, Hanford Site, Washington*). In the scoured area (interpreted to be north of the erosional boundary), most of the Ringold Formation has been all or partially removed and/or reworked within the area of erosion. Data from north and east of the B Pond suggest that only portions of units 9A/9C and 9B are preserved on the lee side and between the smaller anticlinal ridges within this erosional area (PNNL-12261).

In the northern Hanford Site, unit 9 is present beneath the 100-B/C, 100-K, and 100-N Areas.

#### **2.1.2.2 Ringold Formation Lower Mud Unit (Unit 8)**

The Ringold lower mud unit is composed of a thick sequence of fluvial overbank, paleosol, and lacustrine silts and clay, with minor sand and gravel. A more detailed description of the lower mud unit is presented in BHI-00184.

The Ringold lower mud unit is the most significant confining unit within the suprabasalt aquifer system on the Central Plateau. The lower mud unit separates

the saturated sediments of the suprabasalt aquifer system into (1) an uppermost unconfined aquifer system often referred to as the Hanford unconfined aquifer, and (2) a lower confined aquifer system referred to as the confined Ringold aquifer system. In the 200 East Area, a secondary confined Ringold aquifer system is composed of subunit 9A/9C gravels separated by subunit 9B. The uppermost unconfined aquifer system includes saturated sediments above the lower mud unit or the top of subunit 9B, or the top of basalt in the areas where the lower mud unit is absent.

BHI-00184 indicates that east of B Pond and south of the 200 East Area, the lower mud unit is regionally continuous throughout the Pasco Basin. However, as BHI-00184 and other publications describe, the lower mud unit is not present on the Gable Mountain anticline, including Gable Gap and the region to the south, extending to the northern boundary of the 200 West Area and including most of the 200 East Area. BHI-00184 suggests that the absence of the lower mud unit is due to either depositional thinning onto the basalt structure or truncation by Ringold unit 5 or Hanford formation sediments. Geologic, geophysical, and hydraulic data indicate that where channeling occurs, erosion appears to have scoured into and/or completely removed all the lower mud unit and unit 5, with the possible exception of small, localized remnants (Figure 2-5).

Where the lower mud unit is present, the maximum thickness is between 26 meters (in the 200 West Area) and up to 29 meters (in the 200 East Area), and it dips south to southwest into the Cold Creek syncline, roughly paralleling the basalt structure. The revised structural map of the Ringold lower mud unit illustrates that it is elevated above the groundwater surface east and south of the B Pond and between the 200 East and 200 West Areas (Figure 2-6). In these areas where the Ringold lower mud unit is at or above the water table, it is mapped as a hydraulic barrier similar to the basalt surface (PNNL-13858, *Revised Hydrogeology for the Suprabasalt Aquifer System, 200-West Area and Vicinity, Hanford Site, Washington*).

The hydrogeologic continuity and thickness of the lower mud unit indicate that groundwater within the Hanford unconfined aquifer and confined Ringold aquifer system does not flow vertically through this unit. However, flow along the lateral boundary of the lower mud unit does occur, and where it has been removed by erosion, groundwater from the confined Ringold aquifer system may be in communication with groundwater from the uppermost unconfined aquifer. Along the May Junction Fault where uplift has juxtaposed the lower mud unit adjacent to the unconfined aquifer, intercommunication between the Ringold confined and the upper unconfined aquifers may also occur.

### **2.1.2.3 Ringold Formation Units 6 and 7, Overbank Deposits and Upper Mud Unit**

Unit 7 consists of fluvial gravels overlain by the fine-grained overbank and lacustrine deposits (clay, silt, silty fine-grained sand, and paleosols) of Ringold unit 6. The shallowest overbank deposits are known informally as the Ringold upper mud unit in the 100 Area, where this unit forms the bottom of the unconfined aquifer. These units have been largely removed by later flooding from beneath the 200 Area or were possibly never deposited in this area.

### **2.1.2.4 Ringold Formation Unit 5**

Unit 5 is the uppermost of the Ringold Formation units in the unconfined aquifer (Figure 2-2) and is composed primarily of fluvial gravels that grade upward into the interbedded fluvial sand and silt of the upper Ringold unit (BHI-00184). The unconfined aquifer resides in Ringold unit 5 beneath the 100-B, 100-N, and

100-K Areas; most of the 200 West Area; and the southern and western portions of the 200 East Area.

In the 200 Area, unit 5 overlies the lower mud unit and is present everywhere, except the very northeastern portion of the 200 West Area and in the northern portion of the 200 East Area. Within the 200 East Area, unit 5 is present only in the southern portion because the unit has been removed by erosion (PNNL-13858).

Ringold unit 5 has also been removed from the Gable Gap and most of the 200 East Area to approximately the May Junction Fault. Unit 5 was not removed from the downthrown side of the fault because of structural displacement into the basin and distance away from the highest forces of the Pleistocene floods (PNNL-12261).

Ringold unit 5 is also absent beneath the eastern part of the “horn” area of the Hanford Site (i.e., the 100-H and 100-F Areas) and beneath the 300 Area.

### 2.1.3 Cold Creek Unit

After deposition of the Ringold Formation sediments, a period of regional incision occurred, followed by soil development and deposition of windblown sediments during the late Pliocene to early Pleistocene (“Late-Cenozoic Stratigraphy and Tectonic Evolution Within a Subsiding Basin, South-Central Washington” [Bjornstad, 1985]). These deposits are referred to as the Cold Creek unit (CCU). In the eastern portion of the Pasco Basin, the CCU is not found and, therefore, was either not deposited or was eroded later by the Columbia River or cataclysmic flooding.

Several different facies associations are represented by the CCU, including (1) mainstream alluvial, (2) calcic-paleosol, (3) side-stream-alluvial, (4) colluvial, and (5) overbank-eolian facies associations (Figure 2-7). The CCU in the 200 West Area is represented by the calcic paleosol (the early Palouse soil) and overbank/eolian facies (Cold Creek silt unit [CCU<sub>z</sub>]), which is a silt and/or well-sorted, fine sand.

In much of the 200 East Area and elsewhere in the Pasco Basin, a quartzo-feldspathic sandy gravel above the Ringold Formation and below the more basaltic Hanford formation has been identified. This intermediate gravel is referred to as the Cold Creek gravel unit (CCU<sub>g</sub>) (PNNL-19277, *Conceptual Models for Migration of Key Groundwater Risk Contaminants Through the Vadose Zone and into the Upper Unconfined Aquifer Below the B-Complex*). The CCU<sub>g</sub> is mineralogically similar to the Ringold Formation, with the exception that it often caves and heaves during drilling. The loose, unconsolidated nature of these sediments suggests that they are post-Ringold in age and belong to a mainstream gravel facies of the CCU. These most likely represent fluvial deposits from the ancestral Columbia River, perhaps equivalent to the pre-Missoula gravels (PSPL, 1982) identified east of the 200 Area. The upper surface of the CCU<sub>g</sub> unit shows ~10 meters of relief.

### 2.1.4 Hanford Formation

The “Hanford formation” is the informal name given to Pleistocene-age cataclysmic flood deposits in the Pasco Basin (DOE/RL-2002-39, RHO-BWI-ST-4, *Geological Studies of the Columbia Plateau – A Status Report*; DOE/RW-064; “Quaternary Geology of the Columbia Plateau” [Baker et al., 1991]; “Geohydrologic Setting of the Hanford Site, South-Central Washington” [Lindsey et al., 1994]). Sources for the floodwaters included Glacial Lake Missoula, pluvial Lake Bonneville, and ice-margin lakes that formed around the margins of the Columbia Plateau (Baker et al., 1991). These floods periodically inundated the Pasco Basin during the Pleistocene, often eroding existing sediments (“Pre-Wisconsin Glacial Outburst Floods: Pedogenic and Paleomagnetic Evidence from the Pasco Basin and Adjacent Channeled Scabland”

[Bjornstad and Fecht, 1989]). As the floodwaters encountered restricted flow through Wallula Gap, both coarse- and fine-grained sediments entrained in the floodwaters were deposited within the basin. As the floodwaters gradually drained away, both deposition and erosion occurred. This sequence of events occurred a number of times, leaving behind distinct geomorphic features (Figure 2-8) and creating a complex stratigraphy within the Hanford formation, with lenses of sand and silt surrounded by sand and gravel. However, fine-grained sediments are mainly found near the margins of the basin, and coarse-grained sediments are found in the central portion where the flood currents were stronger.

The Hanford formation forms a nearly continuous blanket over the entire Hanford Site, except near flood-scoured Gable Butte/Gable Mountain and other basalt outcrops. In the northern portion of the 200 West Area, the Hanford formation directly overlies basalt; further to the south, it overlies the CCU and Ringold Formation. The Hanford formation consists predominantly of unconsolidated sediments covering a wide range in grain size: from boulder-size gravel to sand, silty sand, and silt. Gravel clasts are composed of mostly sub-angular to sub-rounded basalt. Mineralogically, the sand fraction of the Hanford formation averages ~50% mafic rock fragments (i.e., basalt) and ~50% quartz feldspar (RHO-ST-23, *Geology of the Separations Areas, Hanford Site, South-Central Washington*).

Cataclysmic flood deposits of the Hanford formation have been classified into three facies types (gravel, sand, and interbedded sand- and silt-dominated), which grade into one another both vertically and laterally. The three facies may interfinger with or grade from gravel to sand, or sand to fine-grained facies, but rarely from gravel to fine-grained facies.

#### **2.1.4.1 Gravel-Dominated Facies**

The gravel-dominated facies of the Hanford formation (designated as “H1” in the cross sections) consists of coarse-grained basaltic sand and granule- to boulder-size gravel. These deposits display an open-framework texture, plane to low-angle massive bedding, and large-scale planar cross-bedding in outcrop. Gravel-dominated beds sometimes grade upward into sand- and silt-dominated facies. Gravel clasts are dominantly basalt with lesser amounts of Ringold Formation clasts, granite, quartzite, and gneiss (WHC-SD-EN-TI-012, *Geologic Setting of the 200-East Area: An Update*). The gravel-dominated facies was deposited by high-energy floodwaters in or immediately adjacent to the main cataclysmic flood channels (i.e., the Pasco Basin channel way [Figures 2-8, 2-9, and 2-10]).

#### **2.1.4.2 Sand-Dominated Facies**

The sand-dominated facies of the Hanford formation (designated as “H2” in the cross sections) consists of fine- to coarse-grained sand and granule gravel. The sands typically have high basalt content and are commonly referred to as black, gray, or “salt-and-pepper” sands. The sands may contain small pebbles and rip-up clasts, pebble-gravel interbeds, and often grade upward into thin (less than 1 meter) zones of silt-dominated facies. This facies commonly displays plane lamination and bedding, and also less flood channels during the waning stages of flooding. This facies is transitional between the gravel-dominated facies and the silt-dominated facies, and it is the major component of the Hanford sand plain (Figures 2-8 and 2-11).

#### **2.1.4.3 Interbedded Sand- and Silt-Dominated Facies**

The interbedded sand and silt-dominated facies of the Hanford formation (designated as “H3” but not occurring in any of the cross sections) consists

of thin-bedded, plane-laminated, and ripple cross-laminated silt and fine- to coarse-grained sand. Beds are typically a few centimeters to a meter in thickness and commonly display normally graded bedding (WHC-SD-EN-TI-012). Sediments of this facies were deposited under slack water conditions and in back-flooded areas (DOE/RW-0164; Baker et al., 1991). This facies is typified by the stratigraphy found through the various flood bars (Figure 2-8).

### 2.1.5 Clastic Dikes

Clastic dikes are vertical to sub-vertical sedimentary structures that crosscut normal sedimentary layering. Clastic dikes are a common geologic feature of the Hanford formation in the 200 Area, especially in the sand- and silt-dominated facies. Clastic dikes are much less common in the gravel-dominated facies of the Hanford formation.

Clastic dikes occur in swarms and form four types of networks (BHI-01103, *Clastic Injection Dikes of the Pasco Basin and Vicinity: Geologic Atlas Series*): (1) regular-shaped polygonal patterns, (2) irregular-shaped polygonal patterns, (3) pre-existing fissure fillings, and (4) random occurrences. Regular polygonal networks resemble four- to eight-sided polygons and typically range from 3 centimeters to 1 meter in width, 2 meters to greater than 20 meters in depth, and 1.5 to 100 meters along strike. Smaller dikelets, sills, and small-scale faults and shears are commonly associated with master dikes that form the polygons.

In general, a clastic dike has an outer skin of clay with coarser infilling material. Clay linings are commonly 0.03 to 1.0 millimeters in thickness, but linings up to ~10 millimeters are known. The width of individual infilling layers ranges from as little as 0.01 millimeters to more than 30 centimeters, and their length can vary from ~0.2 meters to more than 20 meters. Infilling sediments are typically poorly sorted to well-sorted sand but may contain clay, silt, and gravel (HNF-4936, *Subsurface Conditions Description Report for the S-SX Waste Management Area*). The importance of clastic dikes in determining the migration potential of contaminants from the near-surface disposal facilities to the water table is still debated.

### 2.1.6 Holocene Surficial Deposits

Holocene surficial deposits consisting of silt, sand, and gravel form a thin (less than 5-meter) veneer across much of the Hanford Site. In the 200 West Area and the southern portion of the 200 East Area, these deposits consist dominantly of laterally discontinuous sheets of windblown silt (loess) and fine-grained sand (PNNL-12086, *Hanford Site Groundwater Monitoring for Fiscal Year 1998*).

## 2.2 Tectonic Setting

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Tectonic activity has occurred in the Pasco Basin throughout its history but has become fairly stable since the deposition of the CCU sediments. The Columbia River Basalt and Ringold Formation sediments both show extensive structural development in the form of anticlines and synclines (folded ridges and valleys). The larger of these structures on the Hanford Site are shown in Figure 2-3. From a hydrogeologic perspective the Umtanum Ridge-Gable Mountain anticline is the more important feature. This anticline is an upward flexure of the Columbia River Basalt that creates Gable Butte and Gable Mountain and has smaller anticlines associated with its limbs that place the basalt at or above the water table in areas to the southwest.

As an additional visual guide to the key stratigraphic elements, three cross sections from *Hydrogeologic Model for the Gable Gap Area, Hanford Site* (PNNL-19702) are

provided in this chapter. Although of limited extent, these cross sections provide a view of the complex geology of the Hanford Site resulting from structural deformation as well as from cataclysmic floods during the last ice age. Cross-section 1 (A-A') (Figure 2-10) is along a roughly north-south line from the upstream edge of the horn flood bar south through Gable Gap to the southern end of Waste Management Area B-BX-BY (Figure 2-9). Cross-section 2 (B-B') (Figure 2-11) is an east-west line across Gable Gap showing the paleochannels incised into the basalts. Cross-section 3 (C-C') (Figure 2-5) is another roughly east-west line located further south than cross-section 2; it clearly shows how the incised paleochannels left remnants of Ringold Formation sediments and places Hanford formation sediments in direct communication with the basalt-confined aquifers.

## 2.3 Hydrologic Setting

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Both unconfined and confined aquifer systems lie beneath most of the Hanford Site. The unconfined aquifer system is located in unconsolidated to semiconsolidated sediments of the Hanford and Ringold formations overlying the basalt bedrock. In some areas, the unconfined aquifer extends into the fractured upper zone of the underlying basalt. Parts of this aquifer are locally semiconfined or confined (confined Ringold). However, because the entire suprabasalt aquifer system is interconnected on a Hanford Site-wide scale, this system has commonly been referred to as the Hanford unconfined aquifer. Aquifers located within the Columbia River Basalt Group are referred to as the basalt-confined aquifer system.

### 2.3.1 Confined Aquifer

Confined aquifers within the Columbia River Basalt Group are composed of relatively permeable sedimentary interbeds and the brecciated tops of basalt flows. The horizontal hydraulic conductivities of most of these aquifers range from  $10^{-4}$  to  $10^{-10}$  meters per second. Dense interior sections of the basalt flows have horizontal hydraulic conductivities ranging from  $10^{-9}$  to  $10^{-15}$  meters per second, about five orders of magnitude lower than those of the confined aquifers (DOE/RW-0164). Groundwater in the confined aquifers underlying the Hanford Site results mainly from infiltration of precipitation and stream flow, within recharge areas along the periphery of the Pasco Basin (DOE/RW-0164). Hydraulic head information indicates that groundwater in the confined aquifers flows generally toward the Columbia River and, in some places, toward areas of enhanced vertical flow communication with the unconfined system (*Maps Showing Ground-Water Levels in the Columbia River Basalt and Overlying Materials, Spring 1983, Southeastern Washington* [Bauer et al., 1985]; SD-BWI-TI-335, *Fresh-Water Potentiometric Map and Inferred Flow Direction of Ground Water Within the Mabton Interbed, Hanford Site, Washington State -- January 1987*; DOE/RW-0164).

With regard to development of a conceptual model for groundwater flow and contaminant migration in the unconfined aquifer, the confined aquifer system is important because the two systems are known to be in hydraulic communication in the area northwest of the 200 East Area (RHO-RE-ST-12P, *An Assessment of Aquifer Intercommunication in the B Pond-Gable Mountain Area of the Hanford Site*; DOE/RL-2008-01, *Hanford Site Groundwater Monitoring for Fiscal Year 2007*). Although the dominant gradient is now upward in the confined aquifer system (flow moving from the confined to the unconfined aquifer), the potential also exists for significant downward groundwater leakage between the two systems in areas where

hydraulic heads in the unconfined aquifer were artificially increased (see Chapter 15.0, Section 15.2).

### 2.3.2 Unconfined Aquifer

Groundwater in the unconfined aquifer at the Hanford Site generally flows from recharge areas in the elevated region near the western boundary of the Site, toward the Columbia River on the eastern and northern boundaries. The Columbia River is the primary discharge area for the unconfined aquifer. The Yakima River borders the Hanford Site on the southwest and is generally regarded as a source of recharge. Natural areal recharge across the entire Hanford Site depends on a number of variables, most notably soil type and vegetation cover. Thus, recharge ranges from a general low of 1.5 millimeters per year for areas with a natural shrub-steppe vegetation cover to a high of 52 centimeters per year for unvegetated areas in the 100-H Area and eastern 200 Area (PNNL-14702, *Vadose Zone Hydrogeology Data Package for Hanford Assessments*). It should also be noted that recharge can be artificially reduced/enhanced to as low as 0.04 millimeters per year for engineered evapotranspiration covers or as high as 92 millimeters per year for unvegetated gravel areas. Since 1944, the artificial recharge from Hanford Site wastewater disposal operations has been greater than the natural recharge, estimated at 17.2 millimeters per year (PNNL-18807, *Soil Water Balance and Recharge Monitoring at the Hanford Site – FY09 Status Report*). An estimated  $1.68 \times 10^{12}$  liters of wastewater were discharged to disposal ponds, trenches, and cribs to date. The volumes of wastewater discharged to the ground surface have steadily declined, from ~14 billion liters in 1990, to ~0.6 billion liters by 2000. The greatest decreases occurred in 1996, when all major waste streams were discontinued and combined into very few Washington State Permitted liquid discharges. In calendar year 2010, ~333 million liters of wastewater were discharged to the ground surface. The two largest discharge locations are on the Central Plateau at the 200 Area Treated Effluent Disposal Facility (~93% of the total site-wide discharge) and the State-Approved Land Disposal Site (~6% of the total). The remaining ~1% of artificial recharge comes from releases to the 400 Area process ponds and the 100-N Area filter backwash pond and sanitary sewage lagoon.

The unconfined aquifer at the Hanford Site lies mainly within the Ringold Formation and Hanford formation. Horizontal hydraulic conductivities of sand and gravel facies within the Ringold Formation generally range from  $\sim 10^{-4}$  to  $10^{-5}$  meters per second (DOE/RW-0164). Because the Ringold sediments are more heterogeneous and consolidated, contain more silt, and are not as well sorted, these sediments are approximately three times less permeable than the sediments of the overlying Hanford formation along the River Corridor and up to 1,000 times less permeable than the Hanford formation sediments in the Central Plateau. Wastewater discharges increased the water table elevation and created groundwater mounds under the two main wastewater disposal areas near the 200 East and 200 West Areas. Because of the increased groundwater elevation during site operations, the unconfined aquifer extended upward into the Hanford formation. This change resulted in increased transmissivity. Since large wastewater discharges ceased, water levels have declined and are approaching pre-Hanford conditions, as well as an associated decrease in transmissivity.

From 1944 through 1989, the largest water table increase of ~24 meters occurred under the 216-U-10 Pond in the 200 West Area, while an increase of ~9 meters occurred under the 216-B-3 Ponds near the 200 East Area. The volume of water discharged to the ground at the 200 West Area is actually less than that discharged at the 200 East Area; however, the lower permeability of the aquifer in the vicinity

of the 200 West Area has inhibited groundwater movement in this area and resulted in a higher groundwater mound. The presence of the groundwater mounds also affected the direction of groundwater movement, causing radial flow from the discharge areas. In *Hanford Site Water-Table Changes, 1950 Through 1980 -- Data Observations and Evaluation* (PNL-5506), changes documented in the water table elevation showed that the edge of the mounds migrated outward from the sources over time until about 1980. Water levels have declined in most areas since 1980 due to decreased wastewater discharges (PNL-7498, *Evaluation of Hanford Site Water-Table Changes -- 1980 to 1990*).

Since non-permitted discharges of wastewater to unlined ponds ceased in 1996, groundwater levels have been declining across the Hanford Site. The water table has decreased 3 meters in the 200 East Area and 13 meters in the 200 West Area. Although some permitted discharges continue today (e.g., Treated Effluent Disposal Facility and State-Approved Land Disposal Site), the water table continues to decline. As a result, groundwater flow directions around the Hanford Site are also changing to a more regional direction (see discussion in Chapter 3.0).

In the 1950s through 1960s, groundwater mounds of 6 to 9 meters were present in each of the 100 Areas (WHC-SD-EN-TI-023, *Hydrologic Information Summary for the Northern Hanford Site*). A mound persisted in the 100-N Area until 1991.

### 2.3.3 Vadose Zone

The Hanford formation and CCU comprise most of the vadose zone. The CCU (both CCU<sub>z</sub> and CCU<sub>g</sub>) represents relatively thin, but significant, depositional units of post-Ringold and pre-Hanford sedimentation. The vadose zone ranges in thickness from less than 1 meter near the Columbia River to greater than 50 meters beneath the Central Plateau.

### 2.3.4 Groundwater/River Interactions

It is widely accepted that the typical groundwater flow system is influenced by the river flow system near the Columbia River. This influence takes the form of a dynamic “zone of interaction,” where mixing of groundwater and river water occurs. Physical, chemical, and biological processes occur within the zone of interaction that potentially alter the characteristics of the approaching groundwater. Physical processes include layering and mixing of groundwater and river water (tending to dilute contaminants to lower concentrations), which infiltrates the banks and riverbed sediments, as well as varying hydraulic gradients caused by river-stage fluctuations. Chemical processes may change the characteristics of a contaminant in groundwater so it becomes less mobile (e.g., adsorbs to sediment or precipitates) or more mobile (bonds to non-ionic organic material). Biological activity in the zone may capture and immobilize contaminants, or it may introduce the contaminants into the food chain. Current information to date suggests that physical processes are the dominant influence on contaminant concentrations and fluxes at locations of discharge of the unconfined aquifer at the Hanford Site into the free-flowing stream of the Columbia River.

A number of reports have been issued that address various aspects of the zone of interaction. One of the more detailed of reports, *Zone of Interaction Between Hanford Site Groundwater and Adjacent Columbia River* (PNNL-13674), discusses modeling the flow and determining the mixing efficiencies within the zone of interaction. PNNL-13674 notes that discharge into the river environment occurs across two primary interfaces: (1) the region between high and low river stage, generally referred to as the “riparian zone”; and (2) an interface that exists within

the river channel substrate that is constantly submerged (i.e., at elevations below the lowest river stage), known as the “hyporheic zone.”

Within the riparian zone, river water infiltrates the banks during periods of high river stage and forms either a layered system or a mixture during interaction with the approaching groundwater. As seepage from the bank occurs during the period of low river stage, the composition of the seepage may change dramatically from nearly pure river water to primarily groundwater.

In the hyporheic zone, sediment porewater is influenced by the entrainment of river water and the gradual influx of groundwater that upwells from the underlying aquifer. As this zone is constantly submerged, the composition is thought to be more stable, although it is possible for areas of preferential upwelling to be present.

Groundwater flow near the river is strongly influenced by fluctuations in Columbia River stage, which in turn is controlled by dams. River stage can vary 1.8 to 2.4 meters daily and 2.4 to 3.0 meters seasonally (PNNL-13647). As a result of these fluctuations, the dynamics of groundwater flow near the river change on multiple scales (hourly, daily, and seasonally). Normal peak discharge occurs during June, and normal low flow occurs in October and November. During low river stage in the fall and winter, the groundwater flow is toward the river; as the river stage increases in the spring and summer, the gradient becomes less and may even reverse direction in response (SGW-46279, *Conceptual Framework and Numerical Implementation of 100 Areas Groundwater Flow and Transport Model*). These observations suggest that the Columbia River is primarily a gaining reach during times of low flow and may become primarily a losing reach during times of high flow.

While the aquifer response is most pronounced near the shoreline within several tens of meters of the Columbia River, effects can extend inland of the shore up to several hundreds of meters or more. River-stage fluctuations can be detected in wells up to 610 meters inland from the river. Because of the very flat gradient between the river and the 200 East Area, the resulting pressure head changes during the highest stages can effect water levels (and the subsequent gradient) as far as 11 kilometers from the river (see Chapter 3.0, Section 3.2).

The importance of groundwater/river interactions in the 100 Area was the subject of a 3-day workshop where an expert panel of scientist from academia, government, and the consulting industry, and not associated with Hanford, reviewed the current understanding of interactions at Hanford (SGW-39305, *Technical Evaluation of the Interaction of Groundwater with the Columbia River at the Department of Energy Hanford Site, 100-D Area*). A total of twelve recommendations were made on topics from the base conceptual model framework, network design, data acquisition, and analysis, as well as the role of modeling in understanding of groundwater/river interactions and the role that the interactions have on the selection of remedial alternatives. One important concern was regarding the conceptual model. The two-dimensional model results presented in PNNL-13674 indicated that “mixing” occurred throughout the thickness of the unconfined aquifer and provided a 1:1 dilution of contaminated groundwater. This model does not account for the potential existence of an armored layer along the riverbed or the role that geologically controlled preferential pathways might play. The concern was that riverbed armoring and/or aquifer heterogeneities leading to preferential pathways may “short circuit” the mixing zone and allow discharge of contaminated groundwater directly into the Columbia River.

## 2.4 Physical and Hydraulic Properties

The determination of physical and hydraulic properties and parameters for use at the Hanford Site has a long history dating back to the late 1950s with publication of *Hydraulic Characteristics of Hanford Aquifers* (HW-48916). A number of flow and transport parameters are needed for characterizing and modeling contaminant movement in the subsurface. In general, the physical and hydraulic properties of the sediments present in the subsurface at the Hanford Site have not changed over the Site's operational history; therefore, it could be assumed that the assignment of a single, site-wide, best-estimate value to an individual stratigraphic unit would not be difficult to determine. However, as new data are collected and new methods for determining the properties are developed, the values applied to these properties may change, in some cases significantly. This has been further complicated by (1) the many different contractors and principal investigators that have performed studies at the site over its operational lifetime, (2) the changing nomenclature and descriptions of stratigraphic units and how those descriptions are applied, and (3) the differing approaches used to estimate these properties. In addition to the complications stated above is the tremendous spatial variability and geologic heterogeneity inherent among the various units across the Hanford Site. Determining these properties is also traditionally driven by site-specific workscope and project funding. Therefore, the assignment of a single, site-wide value to an individual stratigraphic unit is difficult.

Because of the difficulties in assigning a single value to any one property (as noted in the previous paragraph), this section introduces the range of values for select physical and hydraulic properties and the parameters encountered at the Hanford Site that affect contaminant fate and transport in both the vadose zone and in the unconfined aquifer. Another key issue when reviewing the physical and hydraulic properties and the parameters on the Hanford Site is that these properties can vary significantly within hydrogeologic formations, making the collection and derivation of these properties location-specific. Many of the properties and parameters are not only location-specific but also scale-specific. Values for some of these properties that are made in the laboratory can bear little resemblance to the same parameter when defined at the field scale. Therefore, it is critical to be aware of how the small-scale laboratory measurements were obtained and what, if any, upscaling techniques are needed to adequately characterize and/or model the large-scale flow and transport behavior.

### 2.4.1 Vadose Zone Properties

A number of physical and hydraulic properties are necessary to characterize and/or model the movement of contaminants in the vadose zone. All of these properties relate to how moisture containing a contaminant, usually as a component of some type of fluid (e.g., wastewater), moves through the vadose zone. Properties such as bulk density, effective porosity, saturated and unsaturated hydraulic conductivity, and soil moisture content as a function of matric potential have traditionally been defined using a best estimate based on the average of the individual samples tested. Historically, the extent of this testing is based on site-specific workscope and project funding. Factors complicating the derivation of a general site-wide value for any one property arise for many reasons, as noted above. Considering these differences, the Soil and Groundwater Remediation Project set out to re-evaluate and establish a set of consistent and defensible values that could be traced back to their raw data sets, which was completed in 2009 (PNNL-18564, *Selection and Traceability of Parameters to Support Hanford-Specific RESRAD Analyses*). Tables 2-1 and 2-2

present the hydrostratigraphic units for which the various properties are defined, as well as the range in values for a few select properties from that report.

Other references containing information on vadose zone properties include the following:

- PNNL-14702, *Vadose Zone Hydrogeology Data Package for Hanford Assessments*
- PNNL-17154, *Geochemical Characterization Data Package for the Single-Shell Tank Waste Management Areas at the Hanford Site*
- RPP-23748, *Geology, Hydrogeology, Geochemistry, and Mineralogy Data Package for the Single-Shell Tank Waste Management Areas at the Hanford Site*
- RPP-RPT-35222, *Far-Field Hydrology Data Package for the RCRA Facility Investigation (RFI) Report*
- WHC-EP-0883, *Variability and Scaling of Hydraulic Properties for 200 Area Soils, Hanford Site.*

## 2.4.2 Saturated Zone (Unconfined Aquifer) Properties

A similar number of physical and hydraulic properties is also necessary for the saturated zone (the zone below the water table) to characterize and/or model contaminant movement. Properties such as transmissivity, hydraulic gradient, effective porosity, adsorption coefficients, and both horizontal and vertical hydraulic conductivity relate directly to the movement of a contaminant, again usually as a component of some type of fluid (e.g., wastewater), through the porous material of the saturated zone. Other parameters such as storativity and specific yield have to do with the physical property of the aquifer itself. As for the vadose zone these properties have traditionally been extrapolated from individual well samples and/or testing. Historically, the extent of this testing was based on site-specific workscope and project funding. The overriding factor complicating the derivation of a general site-wide value for any one saturated zone property comes from an increased understanding of the complexity of the Hanford Site's subsurface, which reduces the distance that values can be reliably extrapolated from for any given test well. Similar to vadose zone properties, the key properties for the unconfined aquifer sediments cover a range of values linked to the sediment type and contaminants present, and also vary with the particular location, both vertically and horizontally, within the aquifer.

To aid in predicting future contaminant spread and the effectiveness of remedial actions to be used when assessing past practice sites at the Hanford Site, the Soil and Groundwater Remediation Project began developing a site-wide groundwater model in 2005. An initial effort for this work involved reviewing and compiling aquifer testing data to date for use in the 2005 site-wide groundwater model. This information was published in *Groundwater Data Package for Hanford Assessments* (PNNL-14753). Figure 2-12 shows the hydrogeologic units present at the water table in 2005. Table 2-3 presents the minimum and maximum values for horizontal hydraulic conductivity for the different hydrogeologic units that make up the unconfined aquifer, while Table 2-4 presents minimum and maximum values for other selected saturated parameters. As an example of the variability of these properties, Figure 2-13 shows the distribution of horizontal hydraulic conductivity within the upper 10 meters of the hydrogeologic units at the water table, while Figure 2-14 (a and b) shows the vertical distribution of hydraulic conductivity along the two cross sections marked in Figure 2-13.

Additional references containing information on aquifer properties include the following:

- PNNL-14058, *Prototype Database and User's Guide of Saturated Hydraulic Properties for the Hanford Site*
- PNNL-14753, *Groundwater Data Package for Hanford Assessments*
- PNNL-15837, *Data Package for Past and Current Groundwater Flow and Contamination Beneath Single-Shell Tank Waste Management Areas*
- SGW-42736, *Geohydrologic Data Package in Support of 200-ZP-1 Modeling*
- SGW-46279, *Conceptual Framework and Numerical Implementation of 100 Areas Groundwater Flow and Transport Model*
- SGW-47040, *Geohydrologic Data Package in Support of 100-FR-3 Modeling.*

## 2.5 Geochemical Overview of Selected Hanford Site Groundwater Contaminants

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### ***J. Blount***

The groundwater of the unconfined aquifer at the Hanford Site can be generally described as a calcium-magnesium-bicarbonate-type water that is approximately saturated with respect to calcium carbonate. The groundwater is typically slightly basic with a pH range generally between 7.5 and 8.5. Dissolved oxygen (DO) concentrations generally range between 6 to 12 mg/L, but localized low DO conditions are present in some areas. Exceptions to all of these general characteristics are observed locally as a result of previous waste disposal practices, as well as leaks and spills of contaminated solutions during operations, affecting local groundwater chemistry where applicable.

Although the extent of groundwater contamination for any given Hanford Site contaminant will vary in response to the nature of the waste site and the underlying vadose zone, once a contaminant enters the groundwater, the nature and extent of the resulting plume is controlled by the geochemical characteristics of the contaminant under the local aquifer conditions. Consequently, the fate and transport of the primary groundwater contaminants of concern at the Hanford Site will vary across the Site. It is important to understand the nature of these local and regional variations to develop valid conceptual site models. These models help identify chemical sources for the plumes and guide the development of remedial solutions or identify the need for alternative remediation. Thus, understanding the groundwater chemistry is key to moving toward final cleanup of a site.

The mobility of constituents such as uranium, chromium, and nitrate are sensitive to the reduction-oxidation state of the aquifer. These constituents are typically highly mobile under the oxidizing conditions of the unconfined aquifer. These constituents, however, can undergo chemical or biochemical transformations to much less mobile forms in areas of the aquifer where reducing conditions predominate. The fate and transport characteristics of some contaminants are not directly affected by changes in groundwater reduction-oxidation conditions, but these characteristics are affected by other factors (e.g., changes in groundwater pH or aquifer matrix composition). For example, changes in groundwater pH can increase or decrease the extent of sorption of iodide or the precipitation of strontium-90 as a solid carbonate or phosphate phase. The following subsections present a general overview of the geochemical characteristics of groundwater contaminants in the Hanford unconfined aquifer.

### 2.5.1 Uranium

During the period of active Hanford Site operations, large amounts of uranium metal were used to fuel the reactors and to produce plutonium. Large-scale reprocessing of spent fuel rods and related waste disposal activities generated hundreds of thousands of kilograms of dissolved uranium in large volumes of waste solutions that were primarily released to the vadose zone in the 200 and 300 Areas (PNNL-17031, *A Site-Wide Perspective on Uranium Geochemistry at the Hanford Site*). Based in part on the high volume of the waste solutions discharged, the generally high concentrations in those waste solutions, and the mobility of uranium, a substantial component of the discharged uranium was transported through the vadose zone and into the unconfined aquifer. The component of uranium retained in the vadose zone remains a potential future source of groundwater contamination. A simplified summary of the geochemical characteristics of uranium that contributed to the development of large uranium plumes in the unconfined aquifer are summarized below.

Depending on the reduction-oxidation/pH conditions, dissolved uranium in aqueous solutions can exist in the +3, +4, +5, and +6, oxidation states. In most groundwater environments uranium will exist predominantly in the tetravalent (+4) or in the hexavalent (+6) states (uranium[IV] or uranium[VI]). The high pH (greater than 7.5) and calcium bicarbonate concentrations in most Hanford Site groundwater, combined with the prevalent oxidizing conditions, suggest that uranium(VI) should predominately occur as carbonate complexes; this form of uranium is relatively mobile. However, carbonate complexes of uranium(VI) are sensitive to spatial or temporal changes in groundwater pH. For example, the dominant aqueous uranium species will generally change from the neutral uranyl mono-carbonate complex ( $\text{UO}_2\text{CO}_3$ ) at a pH of  $\sim 5.5$  to 6, to the divalent anionic uranyl di-carbonate complex [ $\text{UO}_2(\text{CO}_3)_2^{-2}$ ] at a pH of  $\sim 7$  to 8, and to the anionic tetravalent uranyl tri-carbonate complex [ $\text{UO}_2(\text{CO}_3)_3^{-4}$ ] at a pH above 8.5 (EPA 402-R-99-004B, *Understanding Variation in Partition Coefficient,  $K_d$ , Values*). All of these neutral to anionic complexes are slightly absorbing on the aquifer matrix materials, resulting in some degree of retardation of uranium but generally allowing uranium to be mobile enough to form groundwater plumes within the Hanford Site aquifer.

Under reducing conditions with pH values near 8.0, aqueous complexes of uranium(VI) convert to uranium(IV), which tends to precipitate insoluble uranium oxides. Thus, the resulting groundwater concentrations of uranium are very low when uranium(IV) complexes dominate. However conditions sufficiently reducing to convert uranium(VI) to uranium(IV) are rare in any aquifer, especially at the Hanford Site, which has almost universally oxygen-rich groundwater. Several small uranium plumes exist in the groundwater within the 200 West Area with a larger plume under the B Complex in the 200 East Area. Both areas were the site of chemical processing plants, where plutonium and eventually uranium were separated from irradiated fuel rods. The plume with the greatest areal extent is located under the 300-FF-5 Operable Unit area, where uranium rich fuels rods were manufactured for use in the Hanford Site reactors.

### 2.5.2 Chromium

Chromium typically occurs in the natural environment as trivalent chromium (chromium[III]). Hexavalent chromium (chromium[VI]) is the common form in waste streams and is the most mobile form of chromium. The aqueous mobility of chromium introduced into the unconfined aquifer at the Hanford Site is highly

dependent upon (1) the valence state of the chromium in the waste solution, (2) the chemical characteristics and volume of the waste solution that is transporting the chromium into the aquifer, and (3) the chemistry of the groundwater and associated aquifer matrix.

Cationic chromium(III) species (e.g.,  $[\text{Cr}(\text{OH})]^{2+}$ ) are stable in strongly acidic solutions, while anionic chromium(III) species ( $[\text{Cr}(\text{OH})_6]^{3-}$ ) are stable in strongly basic aqueous solutions. Chromium(III) species are not stable in typical Hanford Site groundwater, with a pH range that is intermediate between these two extremes (e.g., pH between 6.5 and 9). Consequently, if chromium(III) in a disposal area's soil or waste material is mobilized by either a strongly acidic (e.g., less than pH 5) or basic (e.g., greater than pH of 12) solution and subsequently transported to the unconfined aquifer, the chromium(III) will begin to precipitate as low-solubility solid phases, such as  $\text{Cr}(\text{OH})_3$ . This is the result of either the strongly acidic or basic pH of the waste solution being neutralized by interaction with the groundwater and the aquifer matrix. However, the presence of organic acids and other organic complexing agents in the waste solution or in the local groundwater can increase the solubility of chromium(III) somewhat in near neutral groundwater ("The Role of Metal-Organic Complexes in the Treatment of Chromium Containing Effluents in Biological Reactors" [Remoudaki et al., 2003]). Barring the presence of elevated concentrations of organic complexing agents (e.g., acetate), the precipitation of very low solubility chromium(III) phases (e.g.,  $\text{Cr}(\text{OH})_3$ ) should keep the concentrations of dissolved chromium(III) below the drinking water standard ("Environmental Chemistry of Chromium" [Rai et al., 1989]). Thus, carbonate-buffered aquifers, such as the Hanford unconfined aquifer, are unlikely to support dissolved chromium(III) plumes, even if the aquifer was receiving substantial volumes of acidic or strongly basic waste solutions with elevated concentrations of dissolved chromium(III).

The aqueous chemistry of chromium(VI) is very different than chromium(III) and chromium(VI) forms very stable, highly mobile anionic species (typically chromate  $[\text{CrO}_4^{2-}]$ ) in oxidizing soil porewater and groundwater over a range of pH conditions.

The vadose zone and the unconfined aquifer at the Hanford Site contain very little natural organic material, and the vadose zone porewater and underlying groundwater are not sufficiently reducing to convert mobile chromium(VI) to the relatively immobile chromium(III). Consequently, oxidizing waste solutions have the potential to transport substantial amounts of chromium(VI) into the vadose zone where subsequent natural or manmade recharge events can transport much of the chromium(VI) to the unconfined aquifer. The stability and mobility of chromium(VI) complexes in the vadose zone and in the unconfined aquifer at the Hanford Site are supported by (1) the results of saturated flow-leaching tests performed on Hanford soils containing chromium(VI) (PNNL-17674, *Geochemical Characterization of Chromate Contamination in the 100 Area Vadose Zone at the Hanford Site*), and (2) by the existence of the extensive and long-lived hexavalent chromium plumes within the groundwater operable units in the 100 and 200 Areas.

Although chromium(VI) is stable under oxidizing groundwater conditions, it may be readily converted to chromium(III) if sufficiently reducing conditions are either naturally present in the aquifer or if reducing conditions are imposed on the aquifer system by the implementation of an engineered system. Numerous studies and field applications have demonstrated that the addition of simple organic carbon compounds (e.g., lactate or ethanol) to an aquifer contaminated with chromium(VI) will stimulate the natural microbial assemblage in an aquifer to produce reducing conditions. This bioremediation approach has been used at numerous sites to convert toxic and mobile

chromium(VI) to less toxic and much less mobile chromium(III). In situ chemical methods can also be used to create reducing conditions. The injection of zero-valent iron at the 100-HR-3 Operable Unit has been shown to create reducing conditions and convert chromium(VI) to chromium(III) (DOE/RL-2009-35, *Treatability Test Report on Mending the In Situ Redox Manipulation Barrier Using Nano-Size Zero Valent Iron*). Once chromium(VI) is converted to chromium(III), it will typically rapidly precipitate as a highly insoluble phase such as  $\text{Cr}(\text{OH})_3$  that will not redissolve once treatment is terminated.

### 2.5.3 Nitrate

Nitrate occurs naturally in soil when free-living or symbiotic bacteria combine gaseous nitrogen with hydrogen to produce ammonia. This process of fixation is an integral part of the nitrogen cycle. Whether by decomposition of organic material or by nitrogen-fixing bacteria in legume root nodules, the ammonium is further converted to nitrite ( $\text{NO}_2^-$ ) and then nitrate ( $\text{NO}_3^-$ ). Nitrogen as nitrate is stable and mobile in oxygenated environments, and the amount not taken up by plants is leached to the local aquifer.

The elevated nitrate concentrations observed in some Hanford groundwater are primarily the result of plutonium and uranium separations waste streams released to the ground in very large volumes in the early days of processing. Nitric acid was used to deacid and dissolve the irradiated fuel rods throughout the history of Hanford Site operations. During the time that waste was retrieved from the single-shell tanks for use in the uranium recovery process and to recover strontium-90 from the B Plant waste fractionation campaign, nitric acid was also used to dissolve solids in the feed stock solution.

Additional sources of nitrate result from many of the later plutonium separations processes used at the Hanford Site. Although the reduction-oxidation process (active from 1952 to 1958) used methyl isobutyl ketone as the solvent extractor, aluminum nitrate nonahydrate was used as the source for the nitrate ion (DOE/RL-2000-60, *Uranium-Rich/General Process Condensate and Process Waste Group Operable Units RI/FS Work Plan and RCRA TSD Unit Sampling Plan Includes: 200-PW-2 and 200-PW-4 Operable Units*). Aluminum nitrate nonahydrate was added to the processing stream to drive uranium and plutonium into a solution phase for later chemical removal. Another example of nitrate added to the waste stream is during the uranium recovery process. The final product from the tri-butyl phosphate uranium recovery process was uranyl nitrate hexahydrate. By using calcinators, the uranyl nitrate hexahydrate was converted to uranium trioxide for shipment to plants that processed it to the metal form of uranium for use in reactors. Thus, nitrates were part of the waste streams resulting from the nitrification of the uranyl nitrate hexahydrate to uranium trioxide. This process was conducted at U Plant from 1958 until 1972, and the again from 1984 to 1988.

The only other source of nitrate may be upgradient agricultural use of nitrogen-rich fertilizers. However results from wells monitoring upgradient of the 100 Area and the 200 West Area Central Plateau do not show agricultural activities as a major nitrate source, although several have shown steady increases in nitrate levels that remain below regulatory levels. In the southern Hanford Site around the 300 and 1100 Areas elevated nitrate is from offsite agricultural and industrial sources. However, nitrate in the groundwater beneath most of the Hanford Site is primarily the result of Hanford operations.

### 2.5.4 Carbon-14

Carbon-12 and carbon-13 are stable nonradioactive isotopes of carbon that account for ~99% and 1%, respectively, of all carbon. Carbon-14 is a radioactive isotope of carbon that is produced naturally in the upper atmosphere, primarily by the interaction of cosmic rays and atmospheric nitrogen, that makes up less than one trillionth ( $1 \times 10^{-10}$ ) of natural carbon. Carbon-14, which decays to nitrogen-14 by beta emission, has a half-life of ~5,700 years.

At the Hanford Site, carbon-14 was produced as a byproduct during plutonium production at the reactors in the 100 Area. Sources of carbon-14 contaminated groundwater include wastes associated with previous reactor operation decommissioning activities (*Radiological and Chemical Fact Sheets to Support Health Risk Analyses for Contaminated Areas*). Several other radioactive isotopes of carbon exist, but their half-lives are extremely short and they are not a health concern for DOE environmental management sites.<sup>1</sup>

The environmental chemistry of carbon-14 is virtually identical to that of common carbon, and it can migrate either as a gas (i.e., carbon dioxide) or in solution as carbonate or bicarbonate species (INEEL/EXT-04-01793, *Multiphase Carbon-14 Transport in a Near-Field-Scale Unsaturated Column of Natural Sediments, Idaho National Engineering and Environmental Laboratory*). The fate and transport characteristics of carbon-14 as carbon dioxide in the vadose zone within or beneath a waste site will reflect a range of factors, including unsaturated water content, extent of microbial biomass production, microbial carbon dioxide production, temperature, diffusion rates, and carbonate equilibria. These and other factors that affect the transport of carbon dioxide into or out of the vadose zone will be subject to the same gas/water/solid exchange processes as carbon dioxide containing only stable carbon.

Once carbon-14 reaches the water table, the effects of retardation processes such as adsorption and gas/water exchange rates are influenced by the pH and carbonate alkalinity of the groundwater. For example, depending on the pH, carbon-14 in a groundwater plume may be present primarily as carbonic acid, bicarbonate, or carbonate; each of these carbonate species would be subject to somewhat different retardation factors in the aquifer.

### 2.5.5 Technetium-99

Technetium-99 is a radioactive metal with a half-life of 210,000 years. Technetium-99 is found primarily in radioactive wastes from nuclear processing facilities as a byproduct (or fission product) of reactor operations. Technetium can exist in valence states ranging from 1- to 7+ and is strongly sensitive to oxidation-reduction conditions. Under oxidizing conditions typical of the Hanford Site aquifer, technetium-99(VII) forms the chemically stable pertechnetate anion ( $\text{TcO}_4^-$ ). Pertechnetate is generally not adsorbed by inorganic aquifer materials under near neutral or higher pH conditions, so is highly mobile in groundwater under these conditions.

When pertechnetate is exposed to reducing conditions, technetium-99 changes from 7+ to 4+ valence state and normally precipitates to the solid  $\text{TcO}_2$ , removing technetium-99 from the groundwater. This reduction could occur in a natural

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1 *Radiological and Chemical Fact Sheets to Support Health Risk Analyses for Contaminated Areas* (March 2007), J. Peterson, M. MacDonell, L. Haroun, and F. Monette, Argonne National Laboratory, Environmental Science Division, in collaboration with the U.S. Department of Energy, Richland Operations Office.

environment (e.g., groundwater passing through an area enriched in organic material) or an imposed one. A common remediation technique for a contaminant that behaves in this manner is to reduce the aquifer by injecting a chemical reductant, or by introducing a carbon source into the aquifer, which stimulates indigenous microbes that in turn create reducing conditions in the groundwater and aquifer materials. This will reduce the technetium-99(VII) to technetium-99(IV), which is largely immobile in groundwater. Unlike hexavalent chromium, which remains in the reduced state when conditions return to oxidizing, reduced technetium-99(IV) readily returns to the mobile pertechnetate ion under oxidizing conditions.

### 2.5.6 Tritium

Tritium is a radioactive isotope of hydrogen with a half-life of 12.3 years that is created naturally in the upper atmosphere and by anthropogenic sources such as nuclear reactors and nuclear weapons testing. The nucleus of a tritium atom consists of one proton and two neutrons and undergoes beta decay to form stable helium-3. The chemistry of tritium is essentially identical to common hydrogen, and it can migrate in soils as a gas and readily reacts with oxygen to form what is known as heavy water (H<sub>3</sub>O). Once tritium atoms have been incorporated into water molecules, they will be subject to the same dispersive, advective, and other transport processes as common water and will migrate at the same average velocity (EPA 402-R-99-004B).

The fate and transport of tritium in the subsurface at the Hanford Site is primarily controlled by radioactive decay and by the hydrologic characteristics of the affected vadose or groundwater systems. Although no sorption or precipitation processes are known to retard the movement of tritiated water in the environment, some studies have reported a small but notable retardation of tritium relative to bromide during long-term (~500 days) column testing (INEEL/EXT-04-01793). The modest retardation of tritium (estimated distribution coefficient of ~0.08) in these column tests was speculated to be due to the fixation of tritiated water on clays and other hydrated soil minerals. The 12.3-year half-life of tritium is relatively long compared to the groundwater travel times in many areas of the unconfined aquifer. Consequently, for a given waste site, the extent and magnitude of tritium activity that defines the resulting plume primarily reflects the age and longevity of the contamination event and the local hydraulic properties of the aquifer (e.g., groundwater velocity).

### 2.5.7 Strontium-90

Strontium is an alkaline earth element that occurs naturally in only the divalent state (2+). Because of the similar size and charge to calcium, these two elements can and commonly do substitute for each other in natural systems. Strontium has four naturally occurring stable isotopes (strontium-84, -86, -87, and -88). Of these, strontium-88 comprises ~82.5% of the total mass of strontium. Numerous short-lived strontium isotopes have been identified as byproducts of nuclear fission (fission products), but strontium-90 (with a half-life of 28.78 years by beta decay) is the only strontium isotope identified as a potential health concern in Hanford Site groundwater.

Strontium forms weak complexes with most inorganic anions (e.g., carbonate, sulfate, chloride, and nitrate) (EPA 402-R-99-004B) and the uncomplexed Sr<sup>2+</sup> ion typically predominates in groundwater over a wide range of pH conditions. In sufficiently high pH, carbonate-rich environments, the precipitation of strontium carbonate may serve as control on the maximum concentrations in groundwater. Ion exchange of divalent strontium (Sr<sup>2+</sup>) onto clays and other aquifer phases is a significant mechanism of retardation of strontium transport in groundwater. Although strontium has a higher affinity than calcium for the exchange site of many minerals,

the much greater abundance of calcium in most groundwater commonly results in the preferential displacement of  $\text{Sr}^{2+}$  from exchange sites by  $\text{Ca}^{2+}$ . This effect would appear to be substantially more pronounced for strontium-90, which would be several orders of magnitude lower in concentration than common strontium and calcium (EPA 402-R-99-004B). Studies on contaminated soils taken from the 100-N Area indicate that because of strong strontium-90 absorption by ion exchange to sediments (distribution coefficient is  $25 \text{ cm}^3/\text{g}$  in groundwater, yielding a retardation factor of approximately 100 (PNNL-16891, *Hanford 100-N Area Apatite Emplacement: Laboratory Results of Ca-Citrate-PO4 Solution Injection and Sr-90 Immobilization in 100-N Sediments*), approximately 1% of the strontium-90 is in groundwater and 99% is adsorbed onto sediments. The strong affinity for  $\text{Sr}^{2+}$  to exchange with  $\text{Ca}^{2+}$  is the basis for the success of the apatite barrier in the 100-N Area (see Chapter 6.0, Section 6.2.4).

### 2.5.8 Iodine-129s

Iodine has one stable isotope (iodine-127) and 36 known radioactive isotopes. Iodine-129 is by far the longest lived, with a half-life of 15.7 million years. The other isotopes have half-lives ranging from about 100 microseconds (iodine-109) to 59 days (iodine-125). Iodine-129 is produced in small quantities in nature (e.g., by spontaneous fission of natural uranium) but in much larger quantities as a fission product in nuclear reactors. Iodine occurs in +7, +5, +3, +1, and -1 valence states and typically occurs as the diatomic molecule ( $\text{I}_2$ ) in the atmosphere. In groundwater, iodine most commonly occurs as iodide ( $\text{I}^-$ ), although in marine environments the prevalent form is as  $\text{I}^{5+}$  in the iodate ( $\text{IO}_3^-$ ) complex. As with other similar anionic halogen species (e.g.,  $\text{Cl}^-$ ), iodine is relatively mobile in most groundwater environments and displays very little sorption on the organic-poor sediments and moderately basic groundwater in the unconfined aquifer at the Hanford Site (“Linearity and Reversibility of Iodide Adsorption on Sediments from Hanford, Washington Under Water Saturated Conditions” [Um et al., 2004]).

### 2.5.9 Carbon Tetrachloride

Carbon tetrachloride is a semi-volatile organic liquid that was used in the Plutonium Finishing Plant in association with plutonium production at the Hanford Site. The carbon tetrachloride molecule is nonpolar, which makes it only sparingly soluble in water (approximately 800 milligrams per liter of water). That characteristic, along with a density of  $1.6 \text{ g/cm}^3$ , classifies it as a dense, nonaqueous phase liquid. Partition coefficients published in the literature for carbon tetrachloride in groundwater range from 0 to 0.83 liters per kilogram; values obtained from contaminated Hanford sediments range from  $5.21 \times 10^{-5}$  to 0.367 liters per kilogram (PNNL-16100, *Carbon Tetrachloride Partition Coefficients Measured by Aqueous Sorption to Hanford Sediments from Operable Units 200-UP-1 and 200-ZP-1*),

Carbon tetrachloride in the subsurface can exist as a vapor phase, as a dissolved aqueous phase, as an adsorbed phase on solid matrices, and as a separate organic phase as a dense, nonaqueous phase liquid. In the Hanford Site vadose zone, all of these phases have been detected, although only a very small amount of dense, nonaqueous phase liquid is present. In groundwater, only the dissolved phase has been detected.

## 2.6 Selected Bibliography

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Additional information on the regional geologic setting of the Pasco Basin and the Hanford Site can be found in the following documents:

- BHI-00184, *Miocene- to Pliocene-Aged Suprabasalt Sediments of the Hanford Site, South-Central Washington*, 1995
- DOE/RL-2002-39, *Standardized Stratigraphic Nomenclature for Post-Ringold-Formation Sediments Within the Central Pasco Basin*, 2002
- DOE/RW-0164, *Site Characterization Plan, Reference Repository Location, Hanford Site, Washington*, 1988
- “Geohydrologic Setting of the Hanford Site, South-Central Washington” (Lindsey et al., 1994)
- RHO-BWI-ST-4, *Geological Studies of the Columbia Plateau – A Status Report*, 1979
- WHC-SD-ER-TI-003, *Geology and Hydrology of the Hanford Site: A Standardized Text for Use in Westinghouse Hanford Company Documents and Reports*, 1993
- WHC-SD-EN-EE-004, *Revised Stratigraphy for the Ringold Formation, Hanford Site, South-Central Washington*, 1991.

The geologic setting for the 200 Area has been described in the following documents:

- HW-61780, *Subsurface Geology of the Hanford Separations Area*, 1959
- PNL-6820, *Hydrogeology of the 200 Areas Low-Level Burial Grounds – An Interim Report*, 1989
- PNNL-12261, *Revised Hydrogeology for the Suprabasalt Aquifer System, 200-East Area and Vicinity, Hanford Site, Washington*, 2000
- PNNL-13858, *Revised Hydrogeology for the Suprabasalt Aquifer System, 200-West Area and Vicinity, Hanford Site, Washington*, 2002
- PNNL-17913, *Hydrogeology of the Hanford Site Central Plateau – A Status Report for the 200 West Area*, 2009
- PNNL-19277, *Conceptual Models for Migration of Key Groundwater Contaminants Through the Vadose Zone and into the Unconfined Aquifer Below the B-Complex*, 2010
- PNNL-19702, *Hydrogeologic Model for the Gable Gap Area, Hanford Site*, 2010
- RHO-BWI-ST-5, *Hydrologic Studies Within the Columbia Plateau, Washington: An Integration of Current Knowledge*, 1979
- RHO-BWI-ST-14, *Subsurface Geology of the Cold Creek Syncline*, 1981
- RHO-ST-23, *Geology of the Separations Areas, Hanford Site, South-Central Washington*, 1979
- RHO-ST-42, *Hydrology of the Separations Area*, 1981
- WHC-SD-EN-TI-012, *Geologic Setting of the 200-East Area: An Update*, 1992.

The geology of the 100 Area has been described in the following documents:

- WHC-SD-EN-EV-027, *Hydrogeology of 100-N Area, Hanford Site, Washington*, 1993
- WHC-SD-EN-TI-132, *Geologic Setting of the 100-HR-3 Operable Unit, Hanford Site, South-Central Washington*, 1993
- WHC-SD-EN-TI-133, *Geology of the 100-B/C Area, Hanford Site, South-Central Washington*, 1993

- WHC-SD-EN-TI-221, *Geology of the 100-FR-3 Operable Unit, Hanford Site, South-Central Washington*, 1994
- WHC-SD-EN-TI-294, *Hydrogeology of the 100-K Area, Hanford Site, South-Central Washington*, 1994.

The geology of the 300 Area is described in *Geology and Hydrology of the 300 Area and Vicinity, Hanford Site, South-Central Washington* (WHC-EP-0500). Updated geologic information is presented in *Volatile Organic Compound Investigation Results, 300 Area, Hanford Site, Washington* (PNNL-17666).

**Table 2-1. Hydrostratigraphic Units for Which Physical, Hydrologic, and Geochemical Data Can Be Defined**

Formation/Unit	Subunit (Symbol)	Representative Hydraulic Property Sediment Class		Qualitative Sediment Description
		After PNNL-14702, Rev. 1	After RPP-17209, Rev. 1, RPP-13310, Rev. 1	
Holocene deposits	Backfill (Bf)	Bf	Backfill	Poorly sorted sand and gravel mixed with finer fraction.
Hanford formation	Unit H1a (H1a)	Hfs, Hcs	NA	Mostly sand-dominated sediment with some silt but may contain some gravelly sediments.
	Unit H1 (H1)	Hgs, Hg	Gravelly sand H1	Gravel-dominated sediments with coarse sand found in 200 West Area.
	Unit H2 (H2)	Hfs, Hcs	Sand H2	A mixture of sandy and silty sediment in 200 West Area.
	Unit H2a (H2a)	--	--	A transitional sand and gravel unit between H2 and H3.
	Unit H3 (H3)	Hgs, Hg	Gravelly sand H3	Laterally discontinuous gravelly sediment at the base of the Hanford formation.
	Unit H4 (H4), undifferentiated Hanford/Cold Creek unit (Hf/CCU)	Hss, Hcs	NA	Laterally discontinuous silty sediment at the base of the Hanford formation, including undifferentiated silty Hanford/CCU sediments.
Cold Creek unit (CCU)	Cold Creek unit silt (CCUz)	PPlz	Cold Creek (Unit 4)	Stratified very fine sand to clayey silt at least partially correlative with the "early Palouse" soils.
	Cold Creek unit carbonate (CCUc)	PPlc	Cold Creek (Unit 4)	Calcium-carbonate cemented clay, silt, sand, and/or gravel.
	Cold Creek unit gravels (CCUg)	NA	Cold Creek (pre-Missoula gravels)	Gravelly sand to gravel equivalent to the pre-Missoula gravels.
Ringold Formation	Member of Taylor Flat (Rtf)	PPlz	NA	Well-bedded fine to coarse sand to silt.
	Member of Wooded Island, subunit E (Rwi[e])	Rg	Ringold sandy gravel	Fluvial gravel, moderate to strongly cemented, and interstratified with finer grained deposits.
	Ringold Formation lower mud unit (Rlm)	NA	NA	--
	Member of Wooded Island, subunit A (Rwi[a])	NA	NA	--
Saddle Mountains formation	Elephant Mountain Member (Tem)	NA	NA	--

Note: The information provided in this table is from PNNL-18564, *Selection and Traceability of Parameters To Support Hanford-Specific RESRAD Analyses: Fiscal Year 2008 Status Report*.

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Table 2-2. Best Estimate for Selected Site-Wide Vadose Zone Properties

Sediment Class – Description <sup>a</sup>	Bulk Density (g/cm <sup>3</sup> )				Total Porosity (cm <sup>3</sup> /cm <sup>3</sup> )				Effective Porosity (cm <sup>3</sup> /cm <sup>3</sup> )				Saturated Water Content, $\theta_s$ (cm <sup>3</sup> /cm <sup>3</sup> ) <sup>b</sup>				Saturated Hydraulic Conductivity, $K_s$ (cm/s) <sup>b</sup>			
	Minimum	Maximum	Minimum Location	Maximum Location	Minimum	Maximum	Minimum Location	Maximum Location	Minimum	Maximum	Minimum Location	Maximum Location	Minimum	Maximum	Minimum Location	Maximum Location	Minimum	Maximum	Minimum Location	Maximum Location
Bf – Backfill	2.13	2.13	S-SX Tank Farms	C Tank Farm	NA <sup>c</sup>	0.21	--	<sup>d</sup>	NA	0.158	--	<sup>d</sup>	0.138	0.2688	South, S-SX Tank Farms	North, B-BX-BY Tank Farms	5.60E-04	5.94E-04	South, S-SX; North B-BX-BY, & C Tank Farms	<sup>d</sup>
Hss – Hanford formation silty sand	1.58	1.8	S 200 W	N 200W	0.329	0.392	N 200 W	S 200 W	0.282	0.326	N 200 W	S 200 W	0.351	0.437	North, 200-ZP-1; 200NW	South, 200-U1 & U2	6.55E-06	2.40E-04	North, 200-ZP-1	North, B-BX-BY Tank Farms
Hfs – Hanford formation fine sand	1.65	1.76	S 200 E	S-SX Tank Farms	0.318	0.422	N 200 W	BC	0.277	0.388	N 200 W	BC	0.347	0.394	South, 200-U1 & U2	South, IDF	1.71E-05	4.15E-03	South, 200-U1 & U2	South, IDF
Hcs – Hanford formation coarse sand	1.56	1.67	N 200 W	S 200 E	0.384	0.41	200 W	N 200 W	0.348	0.395	200 W	N 200 W	0.292	0.357	North, 200-ZP-1	South, BC	1.09E-03	5.32E-03	200W	South, BC
Hgs – Hanford formation gravelly sand	1.81	1.94	200 W	S-SX & C Tank Farms	0.3	0.335	BC	200 W	0.26	0.305	BC	200 W	0.2126	0.273	South, S-SX Tank Farms	200W	2.35E-04	5.15E-04	200W	North, B-BX-BY & C Tank Farms
Hg – Hanford formation sandy gravel	1.79	2.09	N 200 W	S 200 W	0.231	0.237	S 200 W	N 200 W	0.202	0.218	S 200 W	N 200 W	0.15	0.2126	South, 200-U1 & U2	South, S-SX; North B-BX-BY, & C Tank Farms	2.62E-04	3.65E-03	South, S-SX; North B-BX-BY, & C Tank Farms	North, 200-ZP-1
Hrg – Hanford formation gravel (>60% gravel)	NA	1.97	--	<sup>d</sup>	NA	0.259	--	<sup>d</sup>	NA	0.239	--	<sup>d</sup>	0.102	0.138	<sup>d</sup>	South, IDF	5.60E-04	1.46E-03	South, IDF	<sup>d</sup>
CCUz – Cold Creek unit silt	1.58	1.71	N 200 W	S 200W	0.355	0.452	S 200 W	N 200 W	0.308	0.42	S 200 W	N 200 W	0.398	0.448	South, 200-U1 & U2	North, 200-ZP-1	7.27E-06	7.11E-04	South, 200-U1 & U2; 200WS	North, 200-ZP-1
CCUc – Cold Creek unit carbonate	1.65	1.71	S-SX Tank Farms	200W	0.34	0.352	200 W	N 200 W	0.288	0.297	200 W	N 200 W	0.281	0.286	200 W	South, S-SX Tank Farms	5.00E-04	1.03E-03	200W	North, 200-ZP-1
CCUg – Cold Creek unit gravels	2.13	2.13	C Tank Farm	C Tank Farm	NA	NA	--	--	NA	NA	--	--	0.138	0.138	North, C Tank Farm	North, C Tank Farm	5.60E-04	5.60E-04	North, C Tank Farm	North, C Tank Farm
Rg – Ringold Formation sandy gravel	1.82	2.13	S 200 W	S-SX & C Tank Farms	0.299	0.313	200 W	S 200 W	0.258	0.266	200 W	S 200 W	0.138	0.315	South, S-SX; North B BX-BY, & C Tank Farms	South, 200-U1 & U2	7.83E-05	5.60E-04	South, 200-U1 & U2	South, S-S; North B-BX-BY, & C X Tank Farms

a. Values shown are from PNNL-18564, *Sediments and Traceability of Parameters to Support Hanford-Specific RESRAD Analyses*. See Table 2-1 in this document and Table 6.1 in PNNL-18564 for details on the sediment classes.

b. Saturated water content and saturated hydraulic conductivity values are from the limited data set of samples tested to date.

c. "NA" indicates not available; total porosity has not been determined for the various types of backfill.

d. After *Vadose Zone Hydrogeology Data package for Hanford Assessments* (Last et. al., 2006)

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**Table 2-3. Ranges of Horizontal Hydraulic Conductivity Values for Each Hydrostratigraphic Unit**

Unit <sup>a</sup>	Unit Description <sup>b</sup>	Minimum $K_h$ <sup>c</sup>	Maximum $K_h$
1	Hanford formation sands, silts, and gravels	6.06	20195
2	Cold Creek unit fluvial facies (CCU <sub>c</sub> )	NA <sup>d</sup>	NA
3	Cold Creek unit coarse grained facies (CCU <sub>2</sub> )	1.84	5717
4	Upper Ringold Formation silts and clays	0.0005	0.0005
5	Upper Ringold Formation sands and gravels	0.239	2562
6	Ringold Formation middle fines	0.01	0.01
7	Ringold Formation middle coarse	0.0227	101
8	Ringold Formation lower mud unit	0.00001	0.00001
9	Ringold Formation basal sands and gravels	0.00051	4.24

a. Units are as defined in PNNL-14753, *Groundwater Data Package for Hanford Assessments*.

b. Unit descriptions are from Figure 2-2.

c.  $K_h$  = horizontal hydraulic conductivity. Values are in meters per day.

d. "NA" indicates that unit is not found below the water table.

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Table 2-4. Best Estimate for Selected Site-Wide Saturated Zone Properties

Single-Shell Tank Farm – Description	Aquifer Thickness (m)		Effective Porosity <sup>b</sup>		Horizontal Hydraulic Conductivity <sup>c</sup> (m/day)		Transmissivity <sup>c</sup> (m <sup>2</sup> /day)		Specific Yield <sup>c</sup> (unitless)		Flow Direction Azimuth (degrees)		Flow Direction		Gradient		Flow Rate <sup>b</sup> (m/day)		Calculated Maximum Flow Rate <sup>d</sup> (m/day)	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum		
<b>200 East Area</b>																				
A	26.09	27.33	<sup>e</sup>	0.3	49.3 <sup>d</sup>	109 <sup>d</sup>	30 <sup>f</sup>	160 <sup>f</sup>	NA <sup>g</sup>					Southeast			0.00016	0.026	1.06	0.058
B-BX-BY (northern half)	0.70	5.80		0.3					2.80E-6 <sup>h</sup>	1.53E-4 <sup>h</sup>				West-southwest <sup>i</sup>	Southwest <sup>i</sup>					0.169 (0.045) <sup>j</sup>
(southern half)	1.26	7.61			22 <sup>d</sup>	2,520 <sup>d</sup>	15.77 <sup>j</sup>	2,527.60 <sup>j</sup>						South-southeast <sup>i</sup>	Southeast <sup>i</sup>		0.00002	0.0049	0.17	
C	8.65	9.33		0.3	1,900 <sup>d</sup>	6,900 <sup>d</sup>	0.024 <sup>k</sup>	2,070 <sup>k</sup>	NA					Southwest			0.0001	2.13E-5	3.68	2.3 (0.76) <sup>j</sup>
<b>200 West Area</b>																				
S-SX	70	75	0.02	0.671	1.33	14.4	91	1,035	0.09	0.12	82	115	East	East-southeast	0.00164	0.00209	0.013	0.179	0.172	
T	50	55	0.045	1.1	0.85	2.02	44	103	0.1	0.11	85	98	5 degrees north of east	8 degrees south of east	0.00114	0.00172	0.022	0.029	0.28	
TX-TY (northern half)	50	58	0.002	0.068	1.49	19.6	82	1,130	0.1	0.14	116	162	18 degrees east of south	43 degrees east of south	0.00073	0.0014	0.122	1.1	2.46	
(southern half)													South	South-southwest						
U	60	70	0.027		1.18	6.12	345		0.17		76		East		0.00184			0.419	0.352	

a. Values shown are from PNNL-15837, *Data Package for Past and Current Groundwater Flow and Contamination Beneath Single-Shell Tank Waste Management Areas*.

b. Data from tracer pump-back tests.

c. Data from constant-rate pumping test.

d. Data from slug and/or constant-rate pumping tests.

e. Blank cells indicate that only a single value was determined for this parameter.

f. Calculated by multiplying hydraulic conductivity by thickness of the test interval using pre-1997slug test data.

g. "NA" indicates not available; a specific yield has not been calculated for this unit.

h. Calculated from specific storage and storativity.

i. Flow directions are from the above referenced report and are based on determinations up through 2006; prior to the intensive low-gradient study now underway (see Chapter 3.0, Section 3.2). It is now accepted that the general flow direction for the B-BX-BY Tank Farm as a whole is to the northwest.

j. Values are averages. Given due to high variability in values.

k. Calculated by multiplying hydraulic conductivity of the test interval by thickness of the test interval using pre-1997slug test data.

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Figure 2-1. Location of the Pasco Basin and Hanford Site

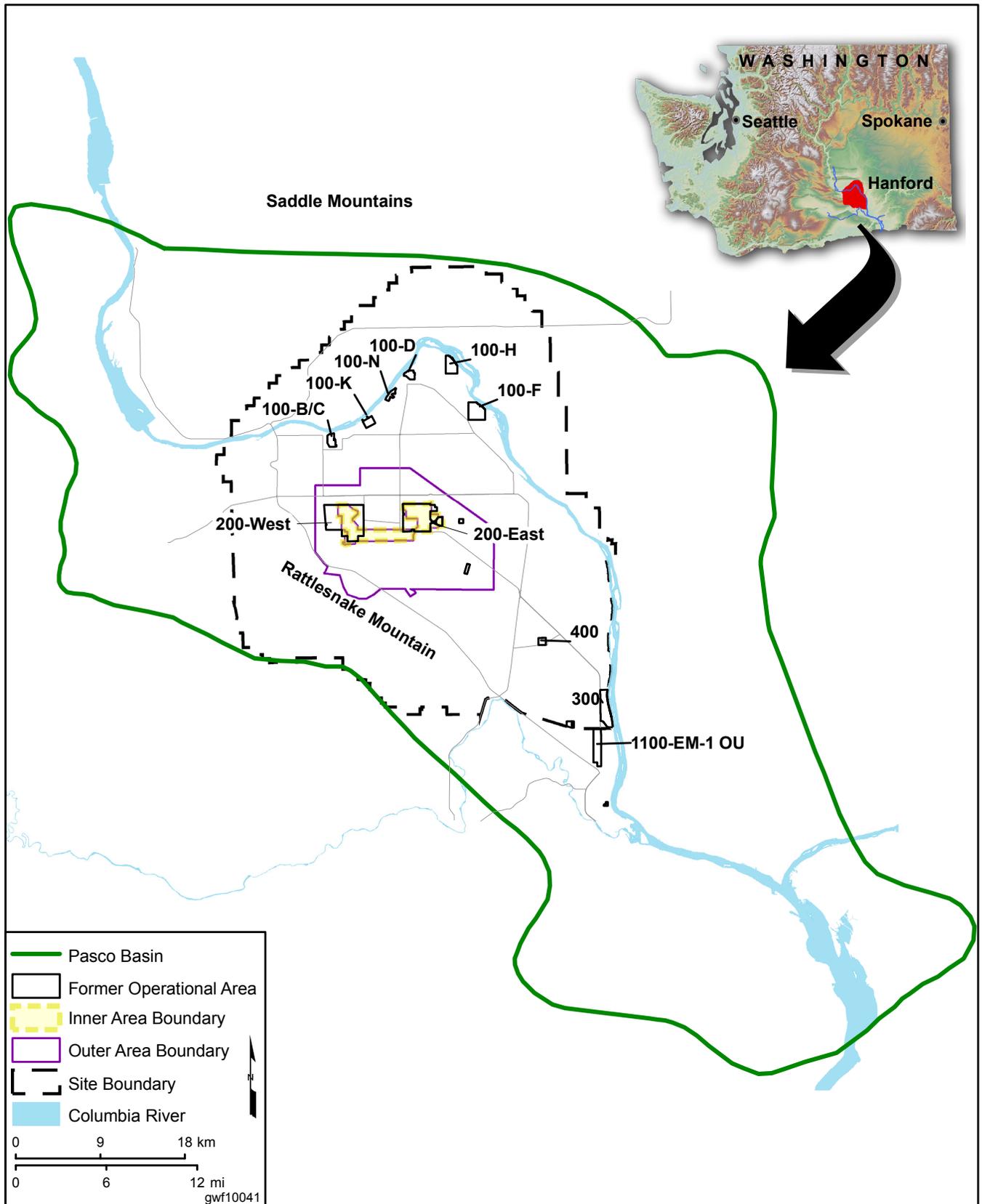


Figure 2-2. Stratigraphic Column for the Hanford Site Showing Nomenclature

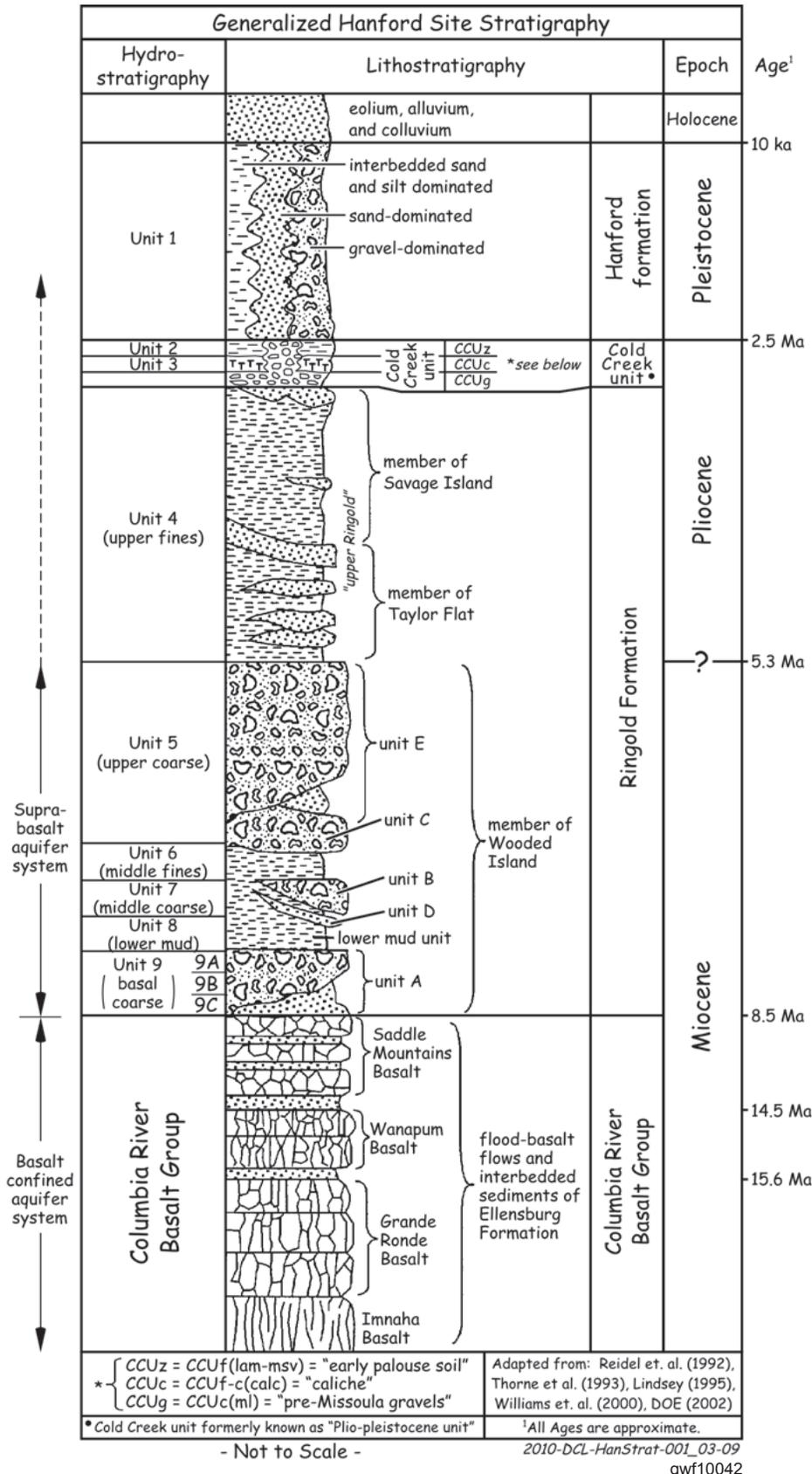


Figure 2-3. General Geologic Structures of the Pasco Basin and Hanford Site

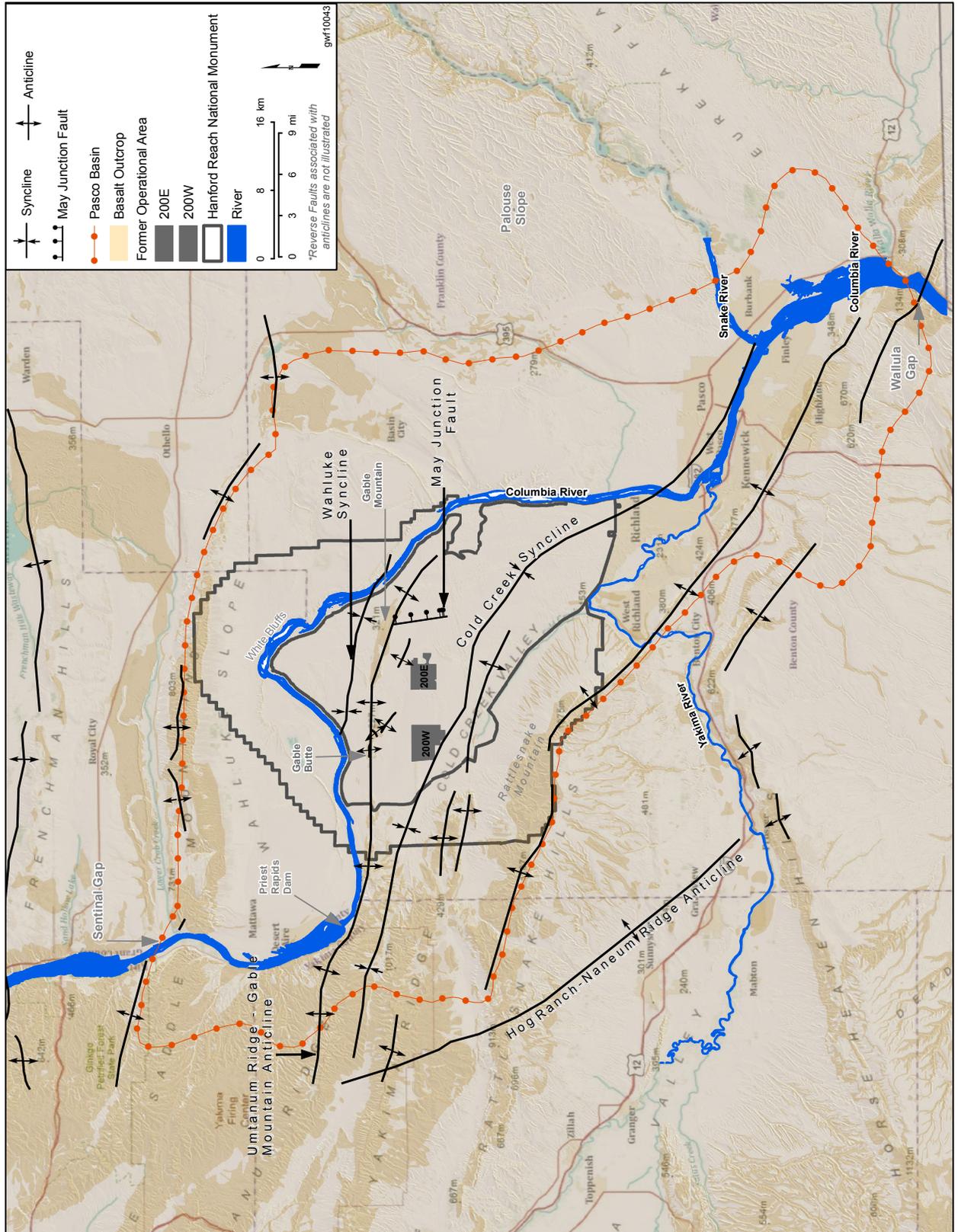
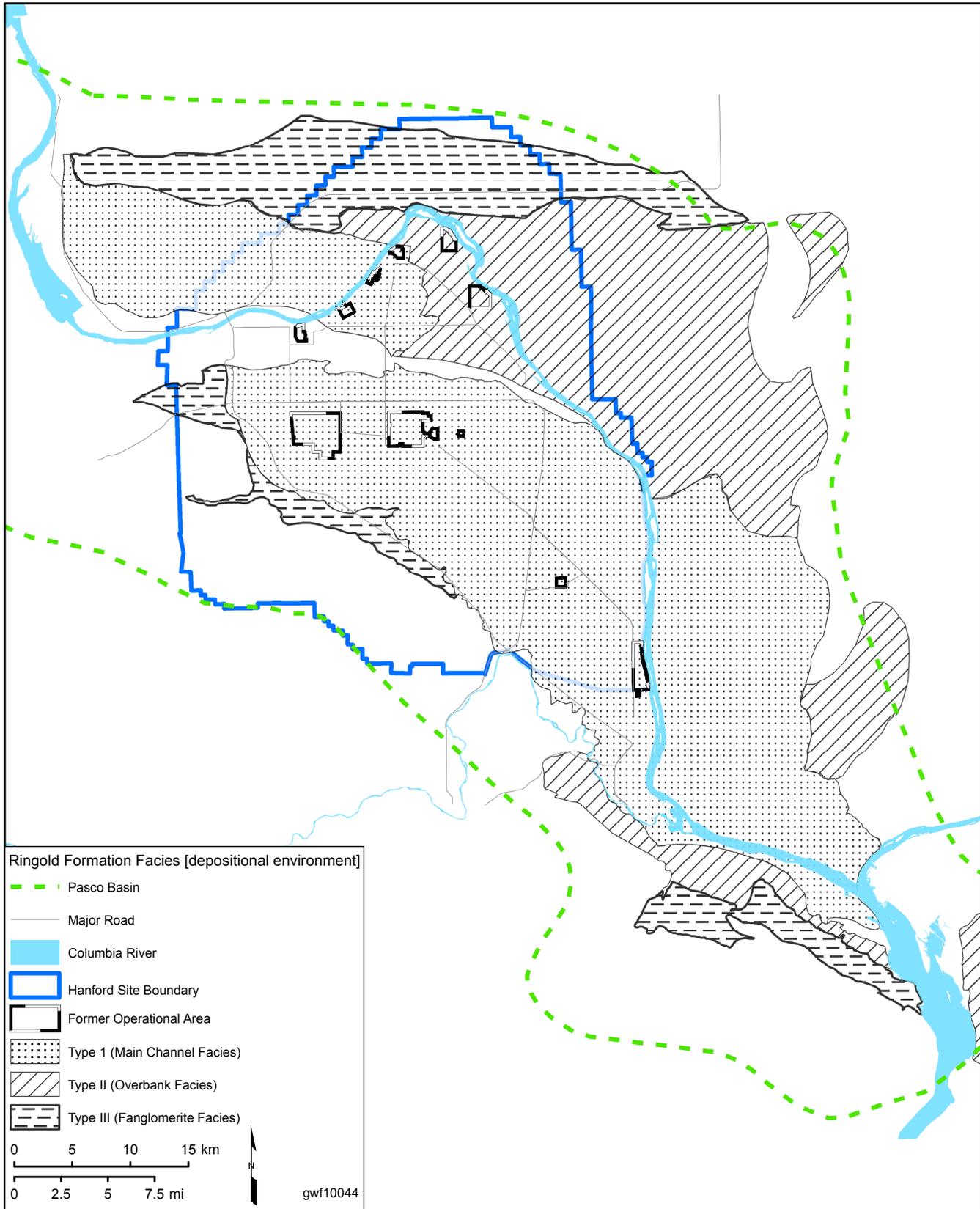


Figure 2-4. Facies of the Ringold Formation Within the Central Pasco Basin





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Figure 2-6. Lower Ringold Formation Beneath the 200 East Area

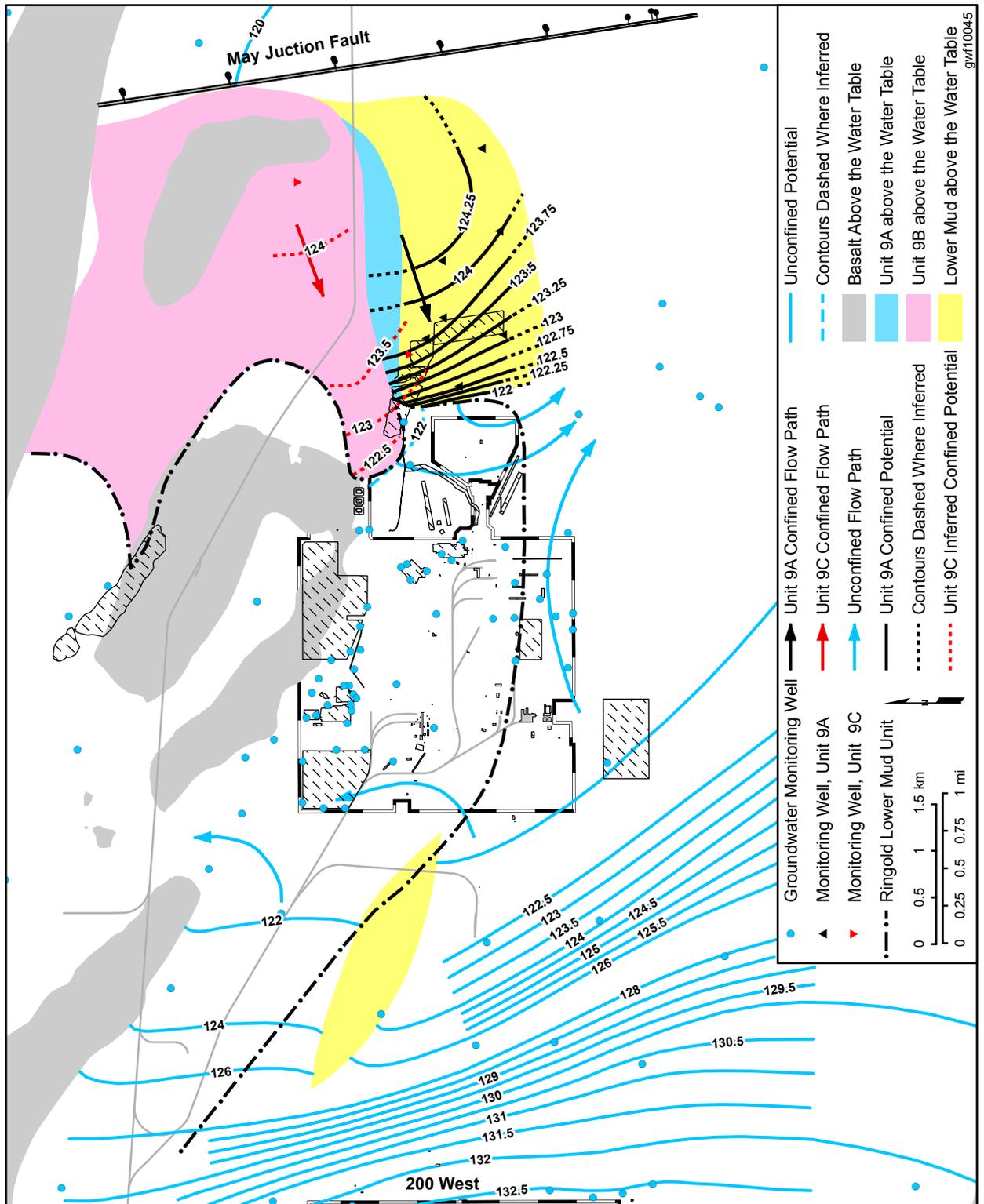


Figure 2-7. Facies Distribution for the Cold Creek Unit Within the Central Pasco Basin

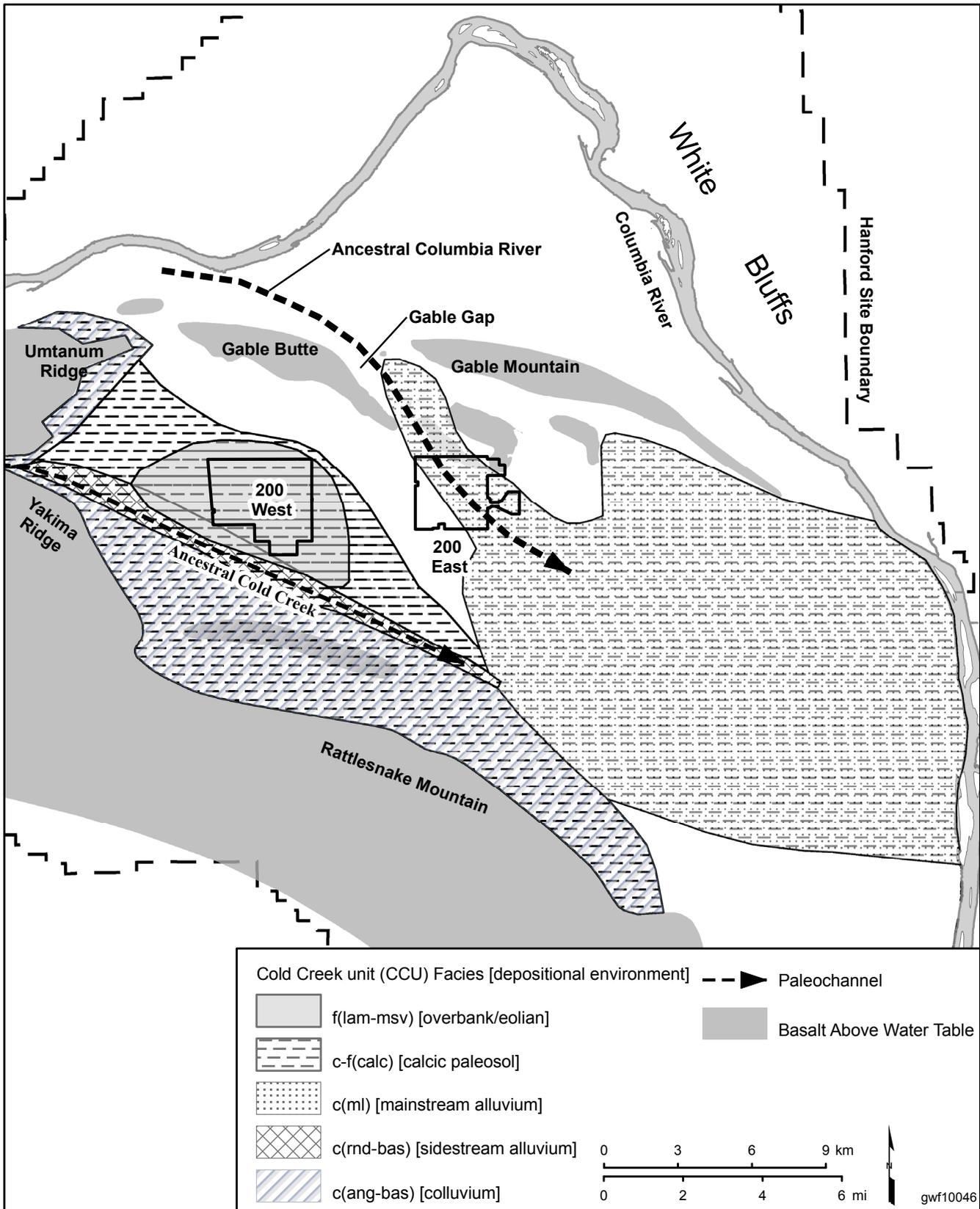


Figure 2-8. Ice Age Flood Geomorphic Features of the Pasco Basin

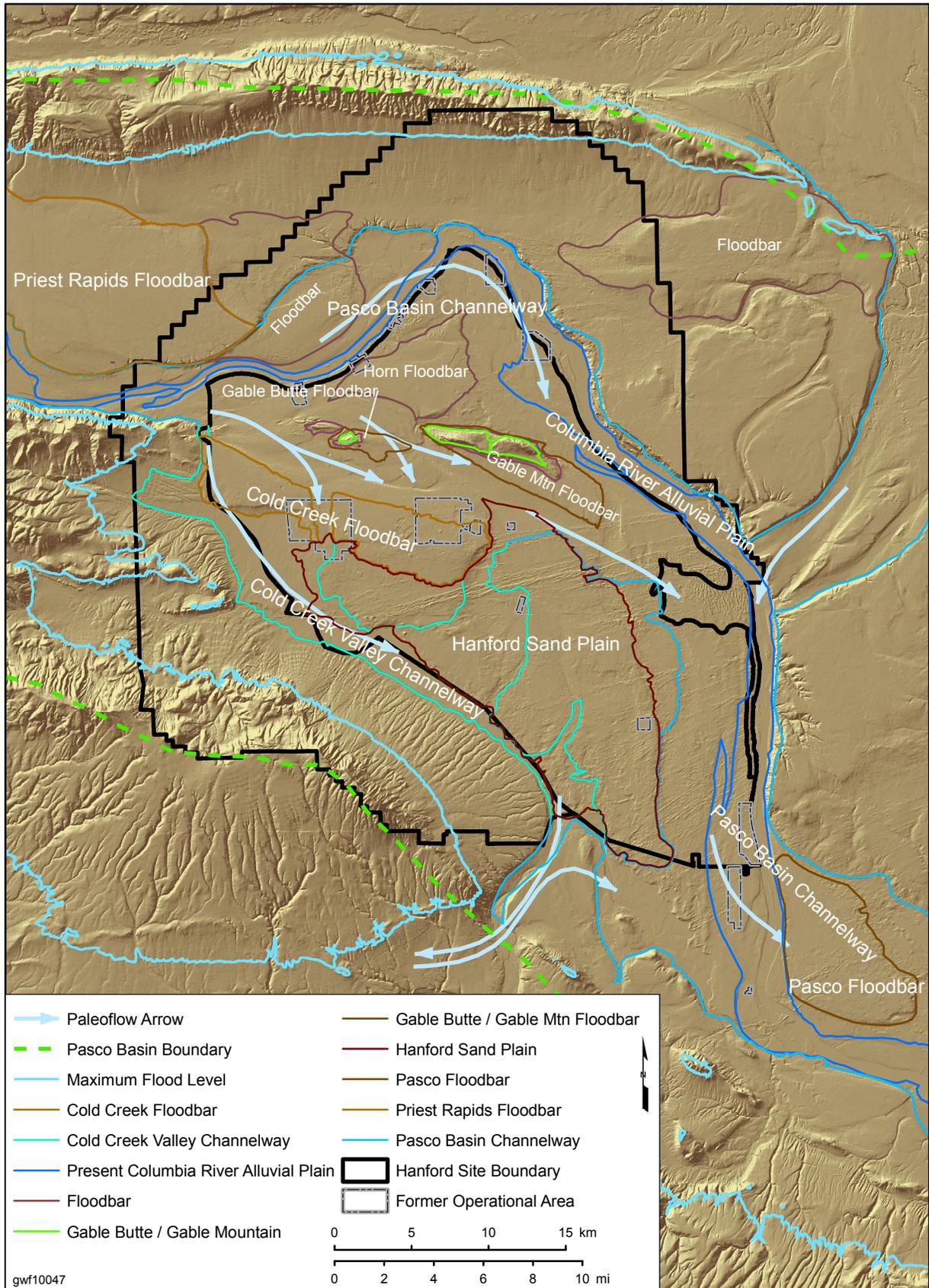
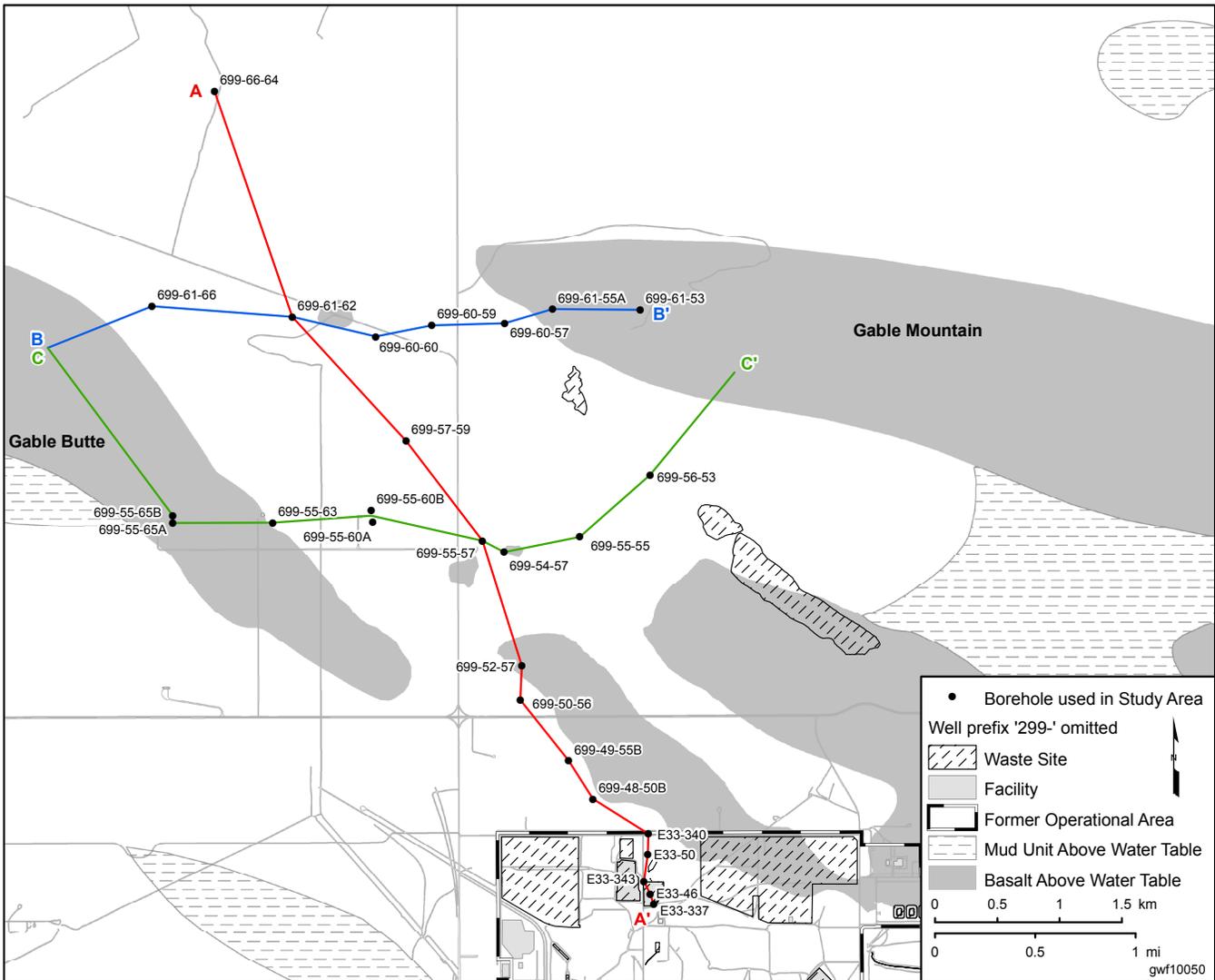


Figure 2-9. Cross-Section Location Map





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Figure 2-11. Hydrogeologic Cross-Section 2 (B-B')

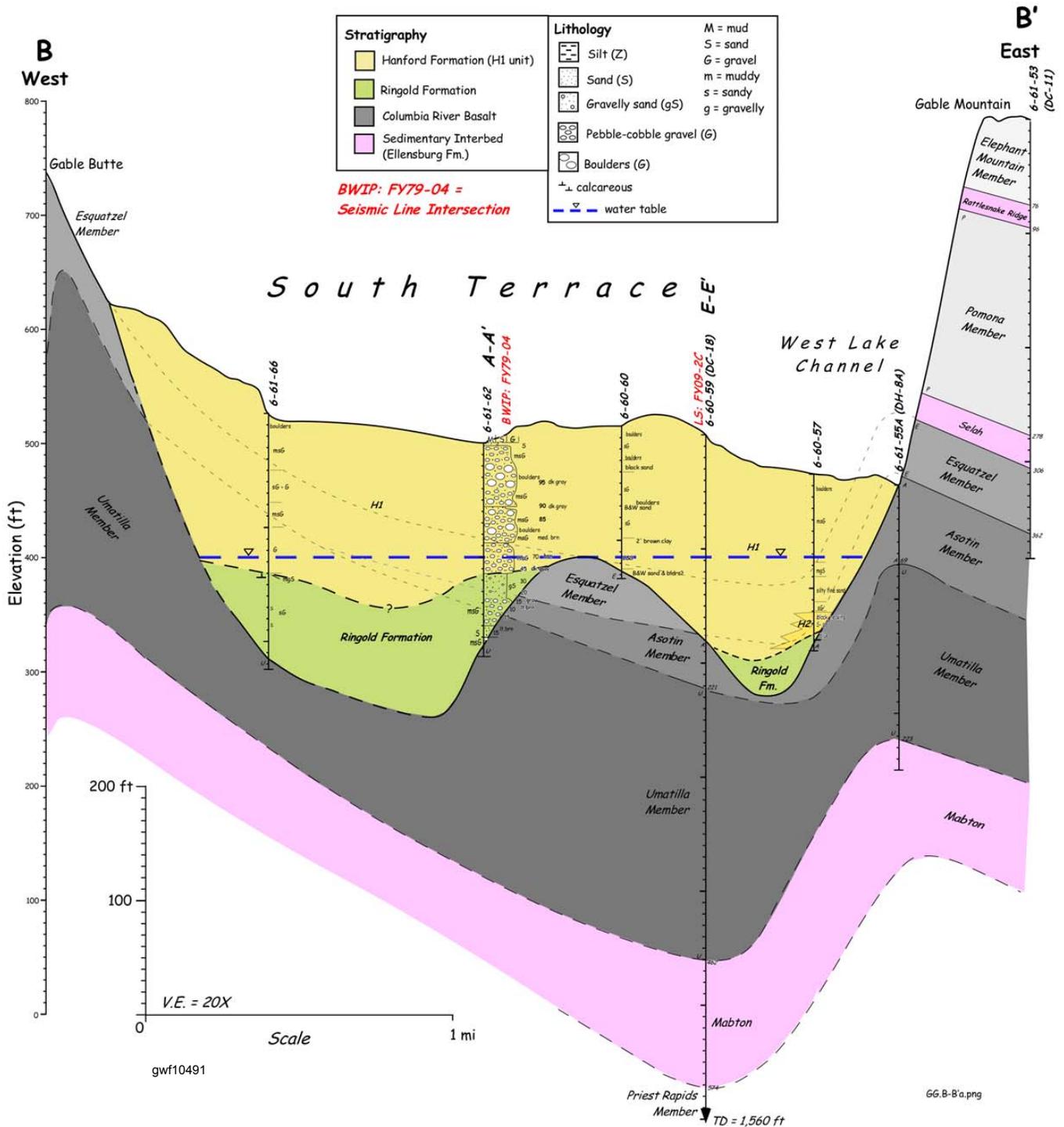
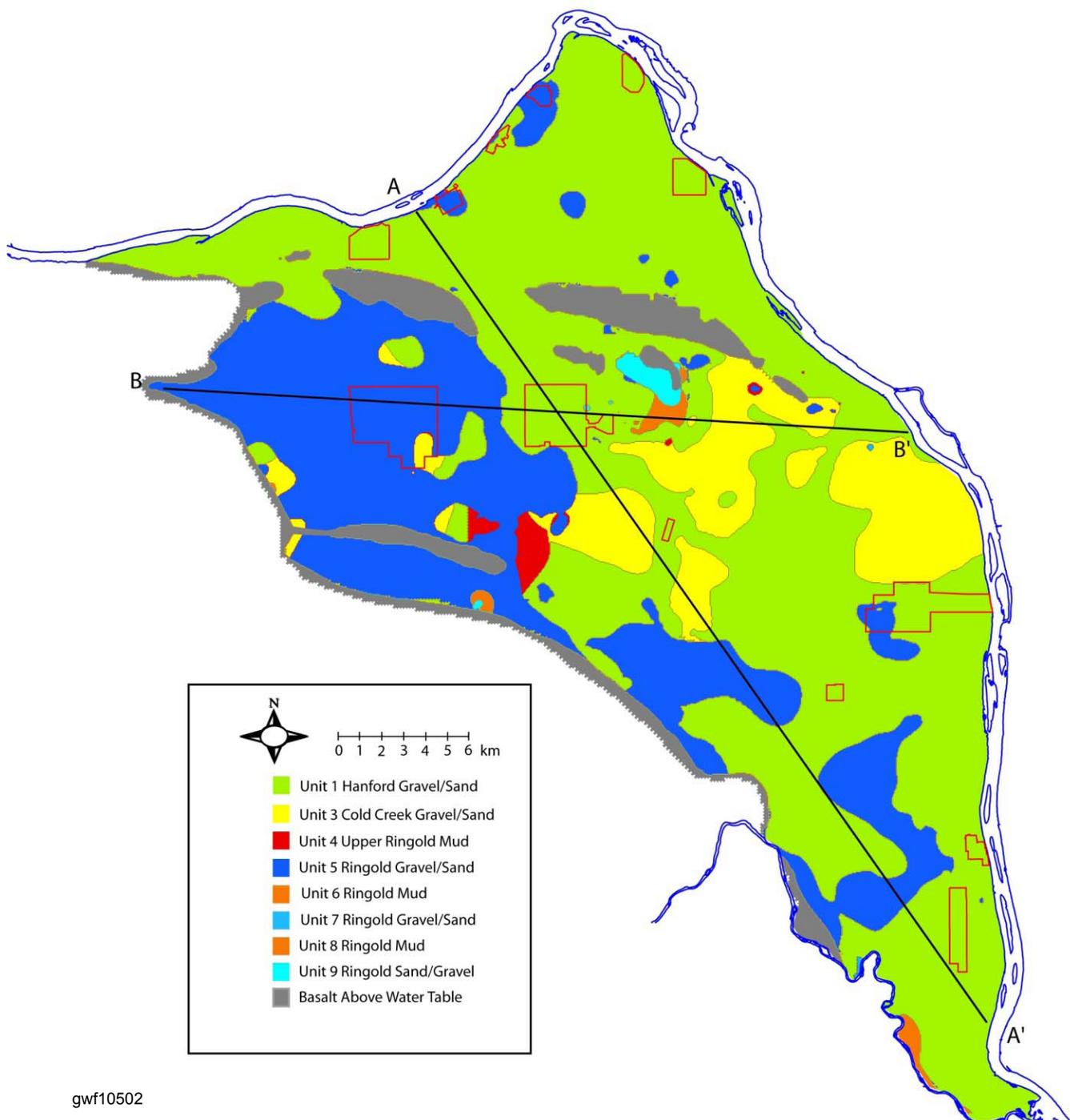


Figure 2-12. Distribution of Hydrogeologic Units at Maximum Water Table (after PNNL-14753)



gwf10502

Figure 2-13. Hydraulic Conductivity Distribution at Maximum Water Table (after PNNL-14753)

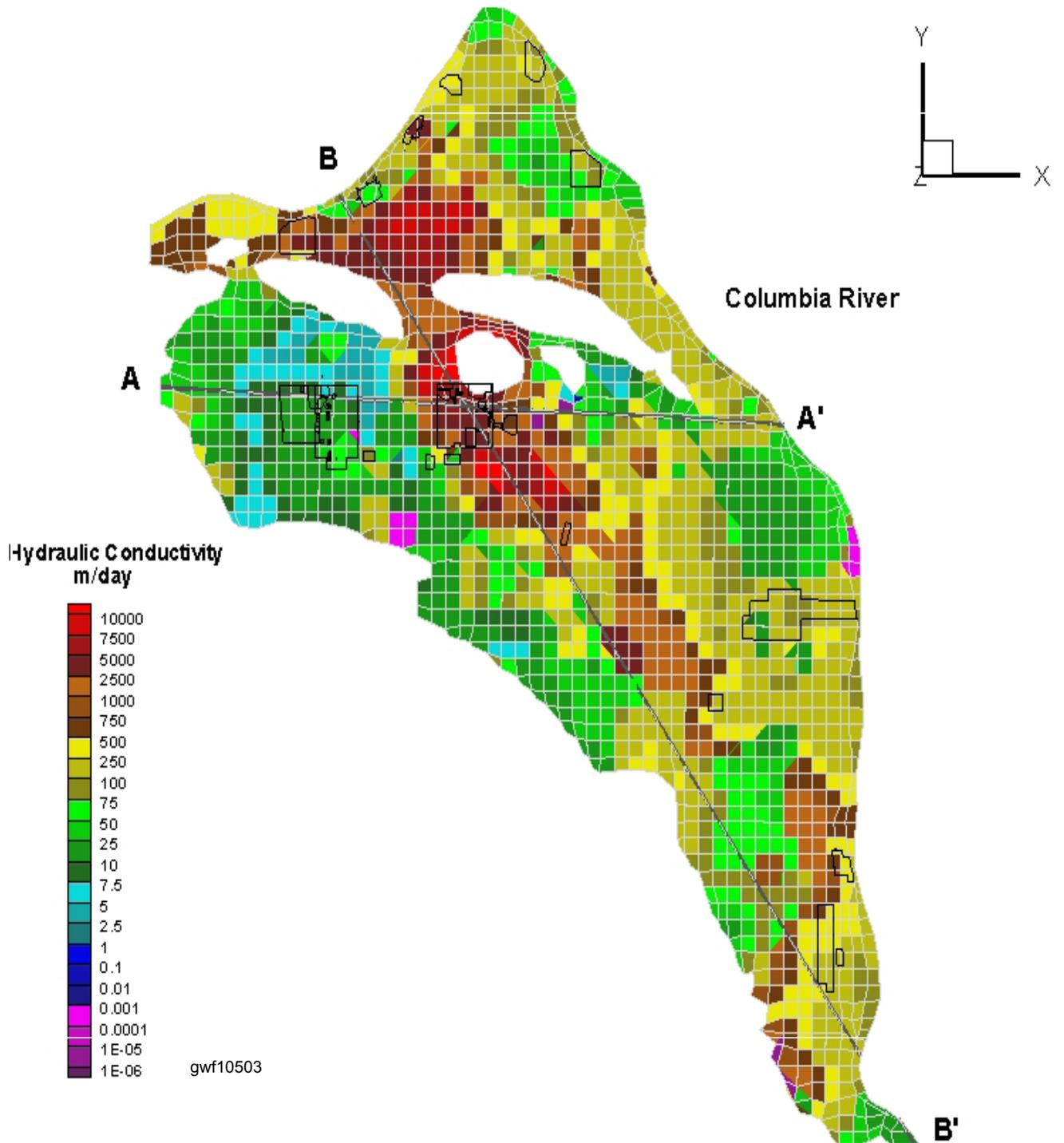
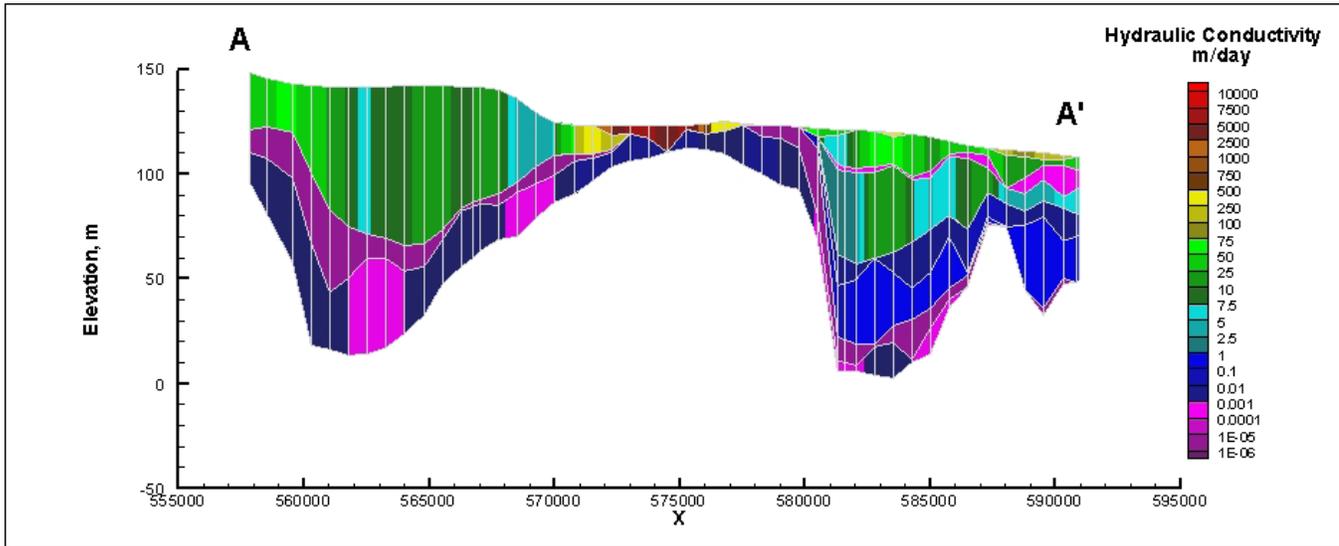
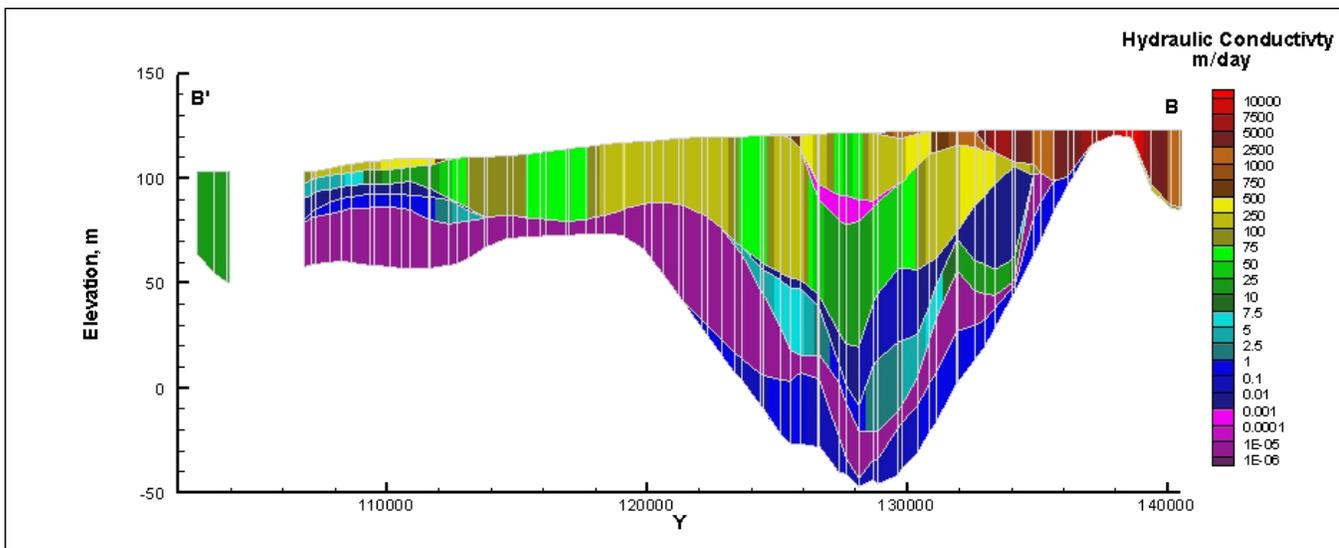


Figure 2-14. Hydraulic Conductivity Distribution Along Cross-Section (a) A-A' and (b) B-B' at the Maximum Water Table (after PNNL-14753)



(a)



(b)

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