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Zone of Interaction Between Hanford Site Groundwater and Adjacent Columbia River

Progress Report
for the Groundwater/River Interface Task
Science and Technology
Groundwater/Vadose Zone Integration Project

R. E. Peterson
M. P. Connelly

October 2001

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RL01830



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Richland, Washington 99352

(a) HydroGeoLogic, Inc., Richland, Washington.

Summary

This report describes results for activities conducted under the Groundwater/River Interface task, which is part of the Science and Technology effort associated with the Groundwater/Vadose Zone Integration Project at the Hanford Site. The goal for the Groundwater/River Interface task is to improve the conceptual model for the zone of interaction and its interfaces with the river. The groundwater flow system beneath the Hanford Site represents a primary pathway for contaminants to migrate away from source areas and, for some contaminants, to ultimately discharge into the Columbia River. Near the river, groundwater flow is strongly influenced by the river stage. The rise and fall of the river stage create a dynamic zone of interaction between the two flow systems, thus influencing flow patterns and transport rates. Also, chemical and biological processes at the various interfaces between the aquifer and river channel may alter the characteristics of contaminants potentially moving with groundwater.

The need for an improved understanding of the Hanford Site's groundwater/river interface is acknowledged in the Integration Project's Science and Technology roadmap (DOE/RL 2000, Appendix B, pp. B-51 to B-67). Technical information gaps identified in the roadmap are an outgrowth of workshops conducted in May 1999 during which several National Laboratories and site contractors collaborated to help define science and technology information needs. Information Need RL-SS37 has been addressed under the Groundwater/River Interface Task. This need is described in the roadmap as follows:

- "Provide methodology to relate information derived from sitewide-scale groundwater flow modeling to the various scales associated with assessing impacts in the river environment."

The roadmap also describes several aspects of research appropriate to address the information need. Two focus areas addressed in this report are:

- "Develop the modeling capabilities to characterize the flow path of water within the zone of interaction, which is strongly influenced by river stage fluctuations."
- "Develop the modeling capabilities to quantify the changes in groundwater characteristics that take place in the zone of interaction between the aquifer and the river."

Water Movement Simulation (Flow Path Modeling Capabilities)

Flow patterns in the zone of groundwater/river interaction (ZOI) are highly variable because of daily and seasonal fluctuations in river stage. Intermingling of groundwater and river water in the zone, along with the locations of groundwater discharge into the river channel, are key issues. The computer code Subsurface Transport of Multiple Phases (White and Oostrom 1996) was used to simulate movement in two dimensions along a cross section oriented perpendicular to the river at the 100-H Area. The simulation covers the entire year of 1998 in hourly increments and includes the transient hydraulic conditions created by the fluctuating river stage. The velocity field was animated using the graphical

display capabilities of TecPlotTM and FramerTM (Amtec Engineering, Bellevue, Washington). In addition to illustrating flow pathlines through the ZOI, flow velocities and water flux through various planes were calculated.

The water movement simulation provides insight on the flow paths followed by groundwater as it moves through the ZOI and discharges into the Columbia River. The velocity field changes dramatically with the daily and seasonal cycles of river stage. Pathlines and flux calculations reveal that river water infiltrates the banks during high stage, moves inland and downward, and subsequently joins the flow of groundwater that discharges through the riverbed. Flow velocities vary from no motion up to 10 meters per day as the direction and rate of flow constantly change under the influence of the fluctuating stage. The water volume flux through planes near or at the actual discharge interface is greater than through planes located farther inland from the interface. This implies that the discharge to the river is a mixture of groundwater and river water. The rate of groundwater discharge from the aquifer to the river along the Hanford Reach from 100-B Area to the 300 Area is in general agreement with previous estimates. The simulation suggests a total discharge from the Hanford aquifer that is approximately 28 cubic feet per second, based on the rate observed at the 100-H Area during 1998.

A comparison was made between running the model using transient river conditions and by assuming steady-state river conditions. The latter is a simplifying assumption that has been used previously in some Hanford applications. Flow directions and velocities under transient river conditions are significantly different from those calculated under a steady-state river condition. One notable difference involves the location where groundwater discharge is focused on the nearshore riverbed. Under transient river stage conditions, flow pathlines discharge somewhat farther offshore as compared to the locations indicated assuming a steady-state condition. However, results from either condition indicate that groundwater discharging from the uppermost hydrologic unit is focused relatively close to the shoreline and is not evenly distributed across the Hanford side of the channel. This finding has implications for monitoring strategies and ecological risk assessments.

The full potential of using the ZOI model to provide greater insight on the physical processes occurring within the ZOI has not yet been realized. Solute transport calculations can be added to the model, which would provide estimates for contaminant dilution and mass transport into the river. Expanding the lateral limits of the model to include flow paths from the Franklin County bank of the river (left bank) would reveal relative discharge from the aquifer on each side of the Hanford Reach. This information is relevant to issues involving water resource management and land-use planning.

Changes in Groundwater Characteristics

The working hypothesis for this focus area is that mixing between groundwater and infiltrating river water causes dilution of contamination potentially present in the groundwater. The degree and timing of dilution prior to discharge into the riverbed substrate and the free stream of the river are key issues. The results of this subtask illustrate the variability of mixing in time and space, thus providing information on the uncertainty associated with dilution coefficients that might be used in numerical models for contaminant transport.

The investigation used several types of observational data to demonstrate the degree and variability of mixing between groundwater and river water. Historical data and interpretations from previous investigations along the Hanford Site shoreline were reviewed and where possible, updated with additional observations. Specific conductance, a measure of the dissolved salt content, was used as the indicator of mixing. The specific conductance of near-shore river water typically falls in the range 130 to 150 $\mu\text{S}/\text{cm}$, while uncontaminated groundwater from the uppermost hydrologic unit ranges between 350 to 450 $\mu\text{S}/\text{cm}$. Observational data came from near-river wells, riverbank seepage sites, near-river aquifer sampling tubes, and riverbed substrate pore water.

Hourly data from two riverbank seepage locations in the 100-H Area reveal the wide variation in dilution that occurs during daily river stage cycles. These data suggest that dilution of groundwater by river water may range from nearly complete to approximately equal parts during the daily cycle at these locations, and during average and low seasonal river conditions. Data assembled to illustrate the geographic distribution included specific conductance values for near-river wells, riverbank seepage, and near-shore river water. The data set was obtained for the shoreline between the 100-B and the 100-F Areas during seasonal low conditions in the fall of 1991. They suggest a minimum of 50% dilution of groundwater by river water for observations made when riverbank seepage was exposed, i.e., during the daily low river stage. Repeated sampling of aquifer sampling tubes installed at three depths in the aquifer near the river shoreline reveals that dilution by river water occurs to significant depths in the aquifer. The tube data also demonstrated how quickly dilution varies within the ZOI in response to seasonal conditions. These data suggest that the ZOI adjusts to seasonal changes in river discharge within the same seasonal cycle.

Where observational data have been collected, the discharge to the river frequently appears to be roughly equal parts of groundwater and river water. This generalization was accepted by the Hanford Site regulatory community as a basis for target compliance concentrations associated with the groundwater interim remedial actions for chromium, which have been underway since 1997 in the 100-K, 100-D, and 100-H Areas.

For modeling contaminant transport to the river, providing for dilution at the interface is contingent on the issue being addressed. Two important near-term issues are: 1) impact on the water quality of the free-flowing stream of the river, and 2) impact on sensitive species at the interface where discharge occurs. For the first issue, dilution may be ignored, because all groundwater in the uppermost hydrologic unit can be assumed to ultimately discharge to the river. For the second issue, dilution is important, because as the results from this investigation reveal, the mixing process in the ZOI strongly influences the concentration of contaminants at the location of exposure. Because of the numerous variables that determine the amount of dilution prior to discharge across an interface, estimates and predictions for dilution are most useful if made at a site-specific scale.

Application of Results

The results to date for the Groundwater/River Interface Task are applicable to the System Assessment Capability (SAC) which is founded on conceptual models for contaminant transport pathways through the natural environment (BHI 2000). The 2-D flow model offers new insight on (a) the movement of water

through the ZOI and (b) locations where discharge to the riverbed occurs. The SAC transport code includes provision for assigning a dilution factor to groundwater at locations where site-specific ecological risk will be assessed. A dilution factor of 50% (i.e., equal parts groundwater and river water) is a reasonable assumption, although the uncertainty in this value is high because of spatial and temporal variability in the amount of mixing. Where contaminant concentrations at the point of exposure are critical for conducting a risk assessment, site-specific observations are needed for the time periods when organisms may be susceptible.

Results are also applicable to regulatory needs for defining locations and standards associated with records-of-decision for environmental restoration. The results of the 2-D flow path model clearly suggest ways to avoid sampling bias when designing sampling and analysis strategies for compliance locations near the river. Longer-term applications are associated with (a) developing strategies and (b) designing sampling and analysis systems for monitoring contaminants moved by groundwater to the Columbia River.

Acronyms

AQST	Aquifer Sampling Tube
BHI	Bechtel Hanford, Inc., Richland, Washington
BPA	Bonneville Power Administration
CD-ROM	Compact Disk-Read Only Memory
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CH2M HILL	CH2M HILL Hanford, Inc., Richland, Washington
DOE-RL	U.S. Department of Energy, Richland
DOH	Washington State Department of Health
Ecology	Washington State Department of Ecology
EPA	Environmental Protection Agency
ER	Environmental Restoration Project
ERC	Environmental Restoration Contractor
FY	Fiscal Year (October 1 to September 30)
GIS	Geographic Information System
GWMP	Groundwater Monitoring Project
GW/VZ IP	Groundwater/Vadose Zone Integration Project (Integration Project)
HEIS	Hanford Environmental Information System
HGL	HydroGeoLogic, Inc., Richland, Washington
HRM	Hanford River Marker
Integration Project	Groundwater/Vadose Zone Integration Project
ISRM	In Situ Redox Manipulation (remediation methodology)
LDRD	Laboratory-Directed Research and Development
NAPL	Non-aqueous Phase Liquid
PNL	Pacific Northwest Laboratory, Richland, Washington (pre-1995)
PNNL	Pacific Northwest National Laboratory, Richland, Washington (post-1995)
RCRA	Resource Conservation and Recovery Act
Redox	Oxidation-reduction
SESP	Surface Environmental Surveillance Project
SAC	System Assessment Capability (Integration Project)
STOMP	Subsurface Transport Over Multiple Phases (computer code)
S&T	Science and Technology (Integration Project)
TPA	Tri-Party Agreement (Hanford Federal Facility Agreement and Consent Order)
ZOI	Zone of Interaction

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1.0 Introduction

This report presents the results of work conducted under the Groundwater/Vadose Zone Integration Project's (Integration Project) Science and Technology effort. The work described pertains to the interface between groundwater in the uppermost hydrologic unit beneath the Hanford Site and the adjacent Columbia River. Additional information on the Integration Project is available at <http://www.bhi-erc.com>.

1.1 Zone of Groundwater/River Interaction

The groundwater flow system beneath the Hanford Site represents a primary environmental pathway for contaminant movement away from source areas. This pathway ultimately discharges into the Columbia River. Near the river, the groundwater flow system is influenced by the river flow system in a zone of groundwater/river interaction (ZOI). The principal features and terminology associated with the ZOI are illustrated in Figure 1.1.

1.1.1 Conceptual Model

Physical, chemical, and biological processes occur within the ZOI that potentially alter the characteristics of the approaching groundwater. Information to date suggests that physical processes are the dominant influence on contaminant concentrations and fluxes at locations of discharge into the free-flowing stream of the river. Physical processes include a) layering and mixing of groundwater and river water, which infiltrates the banks and riverbed sediments, and b) varying hydraulic gradients caused by river stage fluctuations. Chemical processes may change the characteristics of a contaminant in groundwater such that it becomes less mobile (e.g., adsorbs to sediment or precipitates). Biological activity in the zone may (a) capture contaminants and immobilize them or (b) introduce them to the food chain.

Discharge into the river environment occurs across two primary interfaces. The first is the region between high and low river stage – generally referred to as the riparian zone. Within this region, discharge from the ZOI appears as riverbank seepage during periods of low river stage. 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 continues to flow during the period of low river stage, the composition of the seepage may change dramatically from nearly pure river water to primarily groundwater. Riverbank seepage creates the potential for risk associated with (a) human exposure to contaminants and (b) introduction of contaminants to the food chain.

A second interface exists within the river channel substrate that is constantly submerged, i.e., at elevations below the lowest river stage. This region contains sediment pore water that is influenced by the entrainment of river water and the gradual influx of groundwater that upwells from the underlying aquifer. The riverbed provides spawning habitat for fall chinook salmon, and the physical, chemical, and biological characteristics of this interface have been the focus of research in aquatic biology in recent years (e.g., Geist and Dauble 1998; Geist 2000).

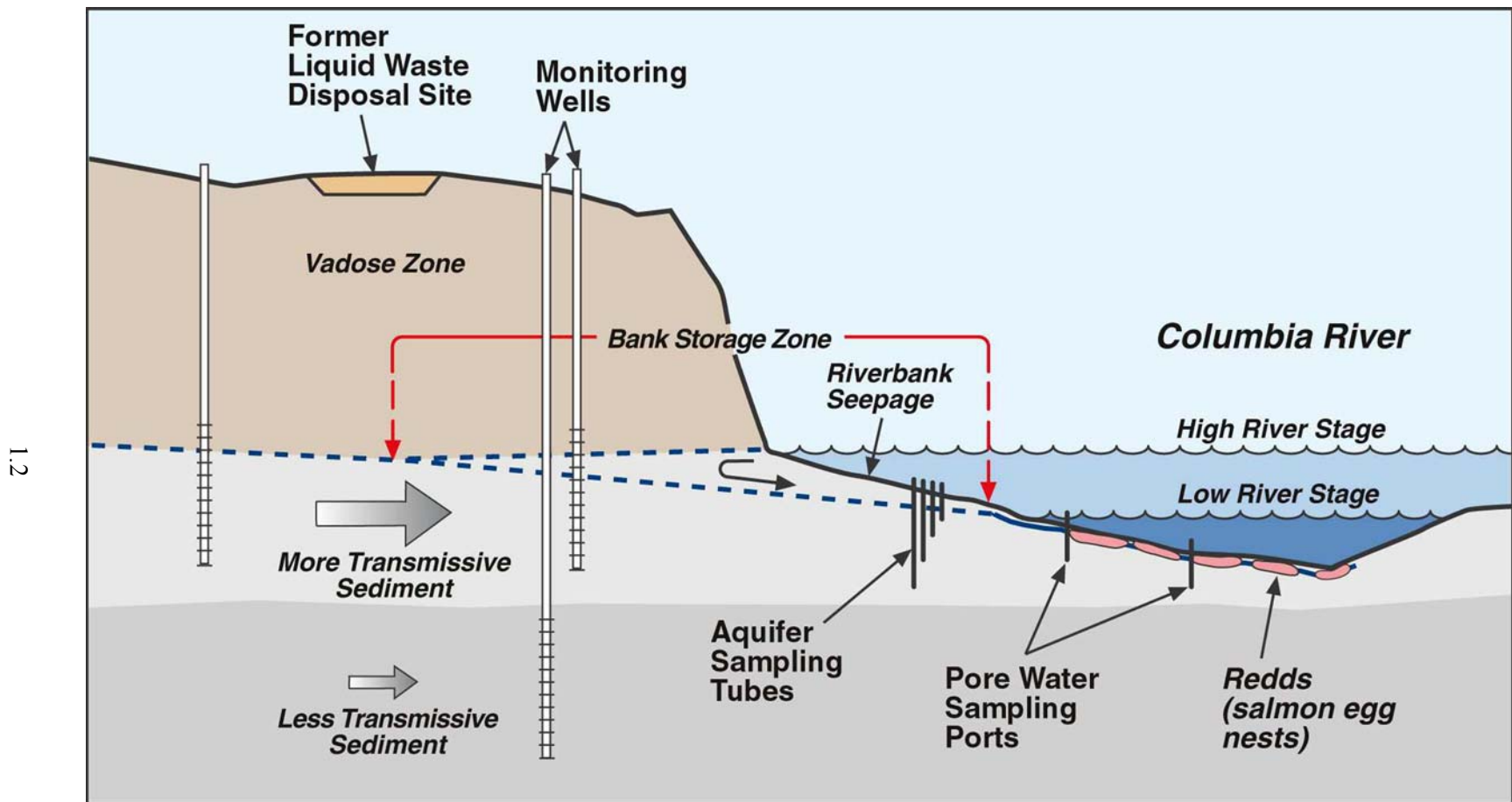


Figure 1.1. Principal Features and Monitoring Sites for Zone of Interaction

1.1.2 Previous Work

Reports describing earlier studies of the influence that the Columbia River has on groundwater beneath Hanford Site facilities provide a basis for the conceptual model for the zone of interaction. Key reports are identified below:

Bank Storage

- *Evaluation of Bank Storage Along the Columbia River Between Richland and China Bar, Washington* (Newcomb and Brown 1961)
- *Ground Water Exchange With Fluctuating Rivers* (Raymond and Brown 1963)

Aquifer Hydraulic Properties

- *Aquifer Characteristics and Ground-Water Movement at Hanford* (Bierschenk 1959)
- *Estimating Aquifer Hydraulic Properties Using the Ferris Method, Hanford Site, Washington* (McMahon and Peterson 1992)

River Influence on Groundwater Characteristics

- *Riverbank Seepage of Groundwater Along the Hanford Reach of the Columbia River, Washington* (Peterson and Johnson 1992)
- *Hydrogeologic Controls on Ground-Water and Contaminant Discharge to the Columbia River Near the Hanford Townsite* (Luttrell et al. 1992)
- *Effects of River Stage and Waste Water Discharges on the Unconfined Aquifer, Hanford, Washington* (Gilmore et al. 1993)

Shoreline Water Quality

- *Investigation of Ground-Water Seepage from the Hanford Shoreline of the Columbia River* (McCormack and Carlile 1984)
- *1988 Hanford Riverbank Springs Characterization Report* (Dirkes 1990)
- *Sampling and Analysis of 100 Area Springs* (DOE/RL 1992)
- *Sampling and Analysis of the 300-FF-5 Operable Unit Springs* (Friant and Hulstrom 1993)

- *Summary of Riverbank Seepage Sampling Event for FY 1997: 100-BC-5, 100-KR-4, and 100-HR-3 Operable Units*^(a)
- *Aquifer Sampling Tube Completion Report: 100 Area and Hanford Townsite Shorelines* (Peterson et al. 1998)

Riverbed Pore Water

- *Chromium Concentrations in 100-H Operable Unit Pore Water Within Chinook Salmon Spawning Habitat of the Hanford Reach, Columbia River* (Hope and Peterson 1996a)
- *Chromium in River Substrate Pore Water and Adjacent Groundwater: 100-D/DR Area, Hanford Site, Washington* (Hope and Peterson 1996b)
- *Redd Site Selection and Spawning Habitat Use by Fall Chinook Salmon: The Importance of Geomorphic Features in Large Rivers* (Geist and Dauble 1998)
- *Hyporheic Discharge of River Water into Fall Chinook Salmon (*Oncorhynchus tshawytscha*) Spawning Areas in the Hanford Reach, Columbia River* (Geist 2000)

1.2 Science and Technology Roadmap Information Needs

The importance of an increased understanding of the features and processes associated with the groundwater/river interface is described in the Integration Project's Science and Technology roadmap (DOE/RL 2000, Appendix B, pp. B-51 to B-67). The technical information gaps identified in the roadmap are an outgrowth of workshops conducted in May 1999 during which several national laboratories collaborated to identify information needs for the Science and Technology effort. Information Need RL-SS37 is being addressed under the Groundwater/River Interface Task. This need is described in the roadmap as follows:

- "Provide methodology to relate information derived from sitewide-scale groundwater flow modeling to the various scales associated with assessing impacts in the river environment."

Three specific aspects of research activities are described in the roadmap as relevant to meeting Information Need RL-SS37:

- "Developing the modeling capabilities to quantify the changes in groundwater characteristics that take place in the zone of interaction between the aquifer and the river."

(a) Peterson, R. E. *Summary of River Bank Seepage Sampling Event for FY1997: 100-BC-5, 110-KR-4, and 100-HR-3 Operable Units*. Attachment to Interoffice Memorandum No. 041996 from M. H. Sturges, CH2M HILL, Hanford, Inc. to A. J. Knepp, Bechtel Hanford, Inc., Richland, Washington, dated March 7, 1997.

- Developing the modeling capabilities to characterize the flow path of water within the zone of interaction, which is strongly influenced by river stage fluctuations.
- Developing the algorithms for estimating contaminant concentrations in the river environment that consider the potential physical and chemical changes that may occur in the zone of interaction. This model will provide the capability to convert a broad-scale groundwater flux into a spatially distributed set of concentrations in three dimensions as the flux enters the river environment. This model will reflect the benthic substrate diversity, river flow, and river physico-chemical characteristics (see RL-SS36) necessary to provide concentration estimates that reflect bioavailability as well as habitat specificity.”

Research activities that contribute to each of these aspects have been conducted by the Groundwater/River Interface Task. Other aspects of research and data gathering activities, which are performed outside of the Science and Technology effort, also contribute to meeting Information Need RL-SS37. Table 1.1 shows how the various aspects of this information need are distributed among various contributors, which include the Groundwater Monitoring, Surface Environmental Surveillance, and Integration Projects, and several additional independent activities.

1.3 Objective and Scope

The objective for the Groundwater/River Interface Study is to improve the current understanding of contaminant transport phenomena that affect the concentration and location of contaminants at key locations along the Columbia River. The study is a multi-year effort, with the first year focusing on refining the conceptual model for the zone of groundwater/river interaction. “Refinement” of the conceptual model means to incorporate additional existing and new data on the ZOI into the conceptual model being used to support the System Assessment Capability (SAC) within the Integration Project.

Two focus areas have been addressed to date: First, a numerical simulation model was developed that illustrates water movement within the ZOI at a representative reactor area location (100-H Area). The framework for the model was constructed from existing geologic records, topographic data, and river channel bathymetric data. Water movement was modeled using the Subsurface Transport of Multiple Phases (STOMP) code (White and Oostrom 1996). An animated sequence of water movement direction, velocity, and volume flux was created for hourly increments during the course of one annual cycle of river discharge. The animation illustrates the dynamic nature of water movement in the ZOI, thus providing insight on contaminant transport to the river. A comparison was made between flow paths that result from modeling under a) transient conditions and b) steady-state river conditions. The consequent difference in where groundwater enters the river is a significant finding that supports use of transient river conditions in flow models. As part of future work, the model will be used to generate refined estimates for contaminant flux through the ZOI and into the river.

Table 1.1. Zone of Interaction Information Needs and Contributors

Zone of Interaction Information Needs (RL-SS37 and -SS38)	Monitoring and Surveillance (Core Projects)	Characterization of Systems and SAC (Integration Project)	Applied Science and Technology (Integration Project)	Potentially Related Activities and Other Contributors
Current distribution of contaminants and trends	<ul style="list-style-type: none"> Groundwater quality characteristics (GWMP) Seeps/river/biota and offsite migration (SESP) Performance evaluation of remediation (ER) 		<ul style="list-style-type: none"> Improved monitoring methods and strategies 	<ul style="list-style-type: none"> Oversight (DOH and Ecology)
Future distribution of contaminants	<ul style="list-style-type: none"> Sitewide groundwater flow and river transport models (GWMP) Residual contamination after remediation (ER) 	<ul style="list-style-type: none"> Contaminant sources–Inventory Disposition of tank wastes 		<ul style="list-style-type: none"> Scenarios for future releases from the 200 Areas
Dimensions associated with contaminated layer	<ul style="list-style-type: none"> Remediation (ER) Sitewide groundwater flow model (GWMP) 	<ul style="list-style-type: none"> Thickness/extent of contaminated layer Intersection of aquifer and river channel 	<ul style="list-style-type: none"> 100-H Area demonstration task 	
Parameters that control water and contaminant movement in ZOI		<ul style="list-style-type: none"> Contaminant transfer coefficients 	<ul style="list-style-type: none"> Hydraulic properties Preferential pathways 	<ul style="list-style-type: none"> Graduate student research on hydraulic properties of ZOI (BPA)
Processes that modify contaminants in ZOI			<ul style="list-style-type: none"> Dilution of ground-water by river water Contaminants-to-biota and to sediments transfer coefficients 	<ul style="list-style-type: none"> Salmon spawning habitat studies (BPA)
Numerical models: water and contaminant movement in ZOI			<ul style="list-style-type: none"> Water/contaminant transport within ZOI Flow net beneath river channel 	<ul style="list-style-type: none"> Groundwater modeling for other applications
Interfaces: Groundwater and river transport models	<ul style="list-style-type: none"> Sitewide groundwater flow and river transport models (GWMP) 		<ul style="list-style-type: none"> Strategy to integrate parameters and boundary conditions for each model 	
BPA = Bonneville Power Administration DOH = Washington State Department of Health Ecology = Washington State Department of Ecology ER = Environmental Restoration Project GWMP = Groundwater Monitoring Project Integration Project = Groundwater/Vadose Zone Integration Project SAC = System Assessment Capability SESP = Surface Environmental Surveillance Project ZOI = Zone of interaction				

The second focus area involved mixing between groundwater and river water within the ZOI. Existing data sets and previous interpretations on mixing between groundwater and river water at the Hanford Site were reviewed. Wherever possible, new data were incorporated. Evidence for dilution was illustrated a) in a temporal sense using hourly data from a single location, b) in a geographic sense by displaying data along the shoreline, and c) in a vertical sense by presenting data from multiple depths in the ZOI. Results suggest that while dilution of groundwater contamination certainly occurs within the ZOI, selecting representative dilution coefficients for use in flow models involves numerous tradeoffs. Because the degree of mixing varies with river stage elevation, duration, and site-specific hydraulic parameters, the coefficient is highly variable in time and space, which increases uncertainty when single values are selected as representative.

Subsequent activities envisioned under the Groundwater/River Interface Task include field investigations that focus on the physical, chemical, and biological processes that occur within the ZOI. Field work includes developing new methods for obtaining observational data and representative samples. Field experiment stations are envisioned that would be equipped with various arrays of sensors and sample collection points for gaining data on the ZOI in three dimensions. The strategy for designing these stations includes provision to make the facility available for subsequent research projects that go beyond Integration Project objectives.

1.4 Relevance to Current Activities

New information generated by the groundwater/river interface task will be useful in several different areas of near-term Hanford Site activities.

1.4.1 System Assessment Capability (SAC)

The SAC includes provision for a dilution coefficient to be assigned in code that links groundwater contaminant concentrations with locations in the river where ecological impact analysis will take place (Kincaid et al. 2000, pg. 3-31). The data presented in Section 3 that illustrate the degree of mixing between groundwater and river water will be used to assign a distribution of dilution factors at locations identified by the SAC risk analysis subtask. A representative distribution will be assigned to these data to aid in quantifying uncertainty in the SAC model. Finally, the refinements for the conceptual model for groundwater/river interaction will be incorporated into future versions of the conceptual models offered in support of the SAC numerical model.

1.4.2 Cleanup Criteria and Compliance Standards

Groundwater remediation activities at sites near the Columbia River are currently being conducted as interim remedial actions under CERCLA records of decision. Objectives for these interim actions include a) reducing the hazard posed by contaminated groundwater and b) acquiring new information that would help prepare subsequent records of decisions. Defining monitoring methods, locations, and concentration levels for compliance will be an important element for the next round of decisions.

Because of the variability in groundwater conditions caused by the influence of the fluctuating river stage, information on the zone of interaction will be crucial in helping to define locations and timing for obtaining representative samples to demonstrate compliance with a record of decision.

1.4.3 Core Monitoring Projects

Two core projects are involved with groundwater and river monitoring: the Groundwater Monitoring Project and the Surface Environmental Surveillance Project. Insight into the influence of the transient river conditions on water quality near the river will aid in designing more effective long-term monitoring strategies for locations near the river. For example, it is apparent from the flow path simulations presented in Section 2 that some locations produce data that are more representative of aquifer conditions than others. Also, the importance of including some measure of groundwater/river water mixing (i.e., specific conductance measurements) in all sampling strategies is apparent. The sitewide groundwater flow model, which is part of the Groundwater Monitoring Project, may benefit from the additional detail now provided to describe flow paths near the boundary between the aquifer and the river channel.

1.5 Report Organization

The report is subdivided into the major focus areas that have been addressed to date. A description of the numerical model assembled to illustrate the movement of water through the ZOI is presented first, followed by a description of dilution within the ZOI. Enhancements to the conceptual model that provides a basis for SAC is presented next. A discussion of future directions for work on the ZOI are presented in the final section of the report.

2.0 Water Movement Within the Zone of Interaction

This section describes activities conducted to develop a numerical model for simulating the flow path of water as it moves through the zone of groundwater/river interaction. Developing this type of model was identified as a high priority research activity under Information Need RL-SS37 in the Science and Technology roadmap (DOE/RL 2000, App. B, pg. B-57). A primary objective for this subtask was to illustrate the water movement pattern in the zone of interaction under the influence of river stage fluctuations. This was completed in hourly intervals for one entire seasonal cycle of the Columbia River (1998 conditions).

Hourly frames of graphics that show features such as gradient direction, flow pathlines, flow velocities, and water volume transport were created. To convey the complex movement pattern created by river stage fluctuations, the hourly frames were sequenced. The resulting animation clearly illustrates the movement of water within the zone of interaction and the changes in patterns that occur during a seasonal cycle.

2.1 Scope of Investigation

The activities involved assembling a three-dimensional model for the topography and subsurface hydrologic units at a 100 Area near-river site and the adjacent Columbia River. Using this spatial framework, a two-dimensional flow model (cross section perspective) was developed that simulates water movement within the zone of interaction between groundwater and river water. The flow model is used to calculate water movement pathlines, pore water velocities, and water volume fluxes. A comparison is made between a) incorporating transient river stage conditions and b) assuming steady-state conditions for river stage.

The 100-H Area was chosen as representative of areas where near-river groundwater is contaminated because of former reactor operations. The number and relatively even distribution of monitoring wells, compared to other reactor areas, reduced the uncertainty in the model. Bathymetric data for the Columbia River along the Hanford Reach are not readily available, so part of the work scope involved creating a topographic surface for the channel adjacent to the 100-H Area. A location map for the 100-H Area is shown in Figure 2.1 and a regional-scale cross section through the 100-H Area is presented in Figure 2.2.

A two-dimensional groundwater flow model was developed for a cross section oriented perpendicular to the river (Figure 2.3). This cross section passes through the chromium plume currently undergoing remediation using pump-and-treat methods (DOE-RL 2000). The two-dimensional flow model simulates the movement of water in the zone of interaction between the unconfined aquifer and the Columbia River. Various flow parameters are calculated in hourly increments for one complete annual cycle of the river. This level of detail allows each of the principal time scales associated with river stage fluctuations (i.e., daily, monthly, and seasonal cycles) to be examined. The year 1998 was selected for this simulation

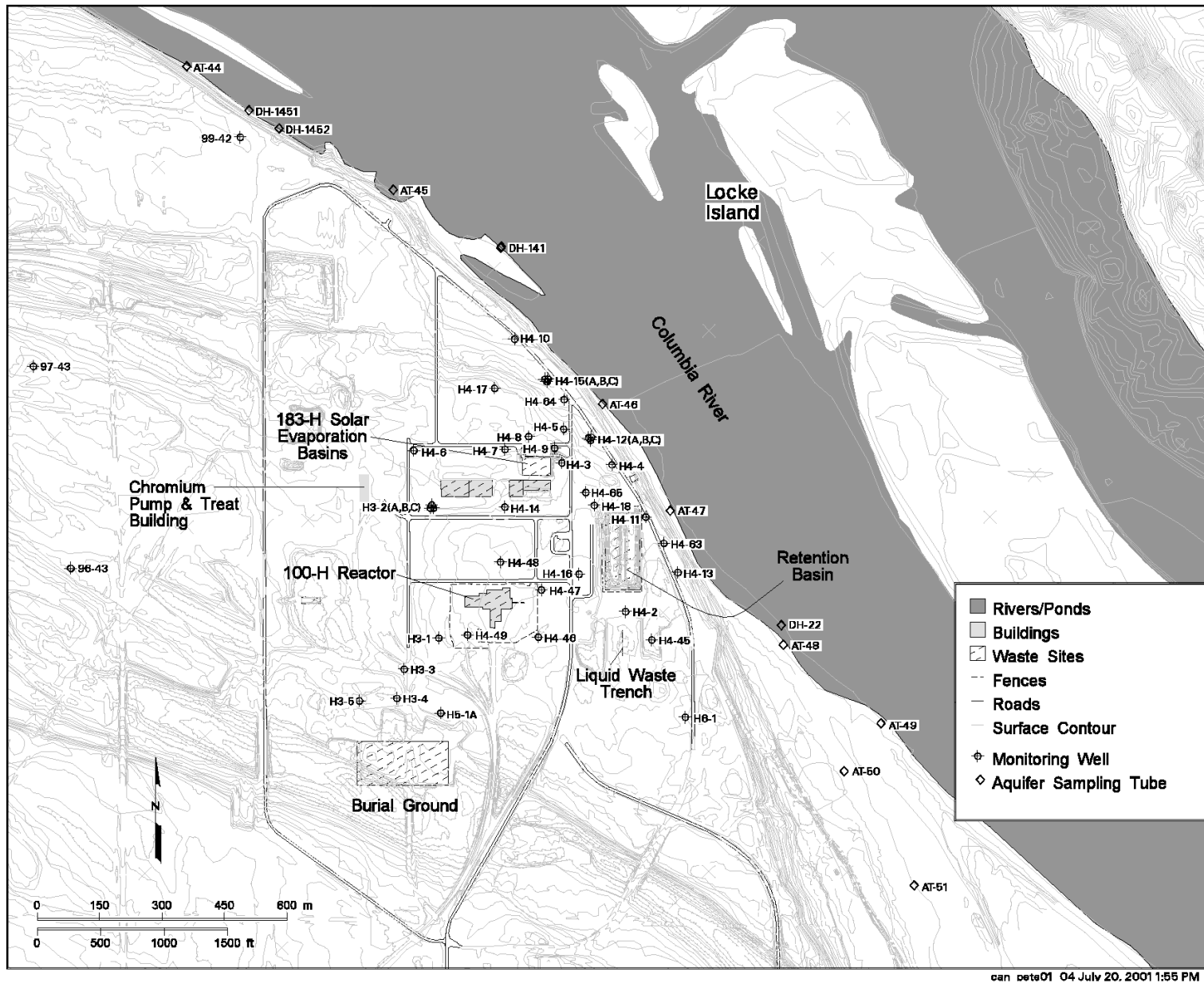


Figure 2.1. Location Map for the 100-H Reactor Area

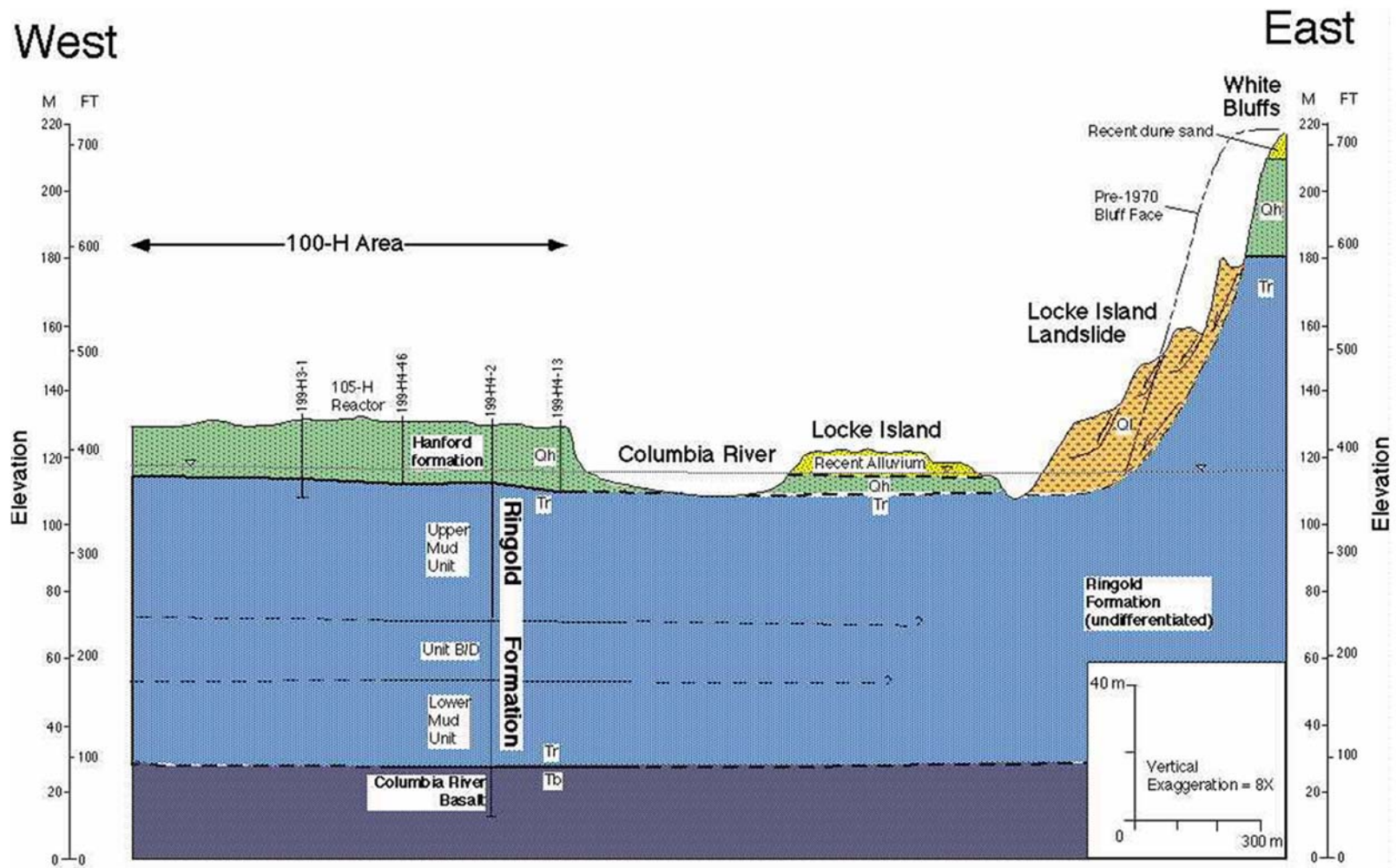


Figure 2.2. Regional Cross Section at the 100-H Area

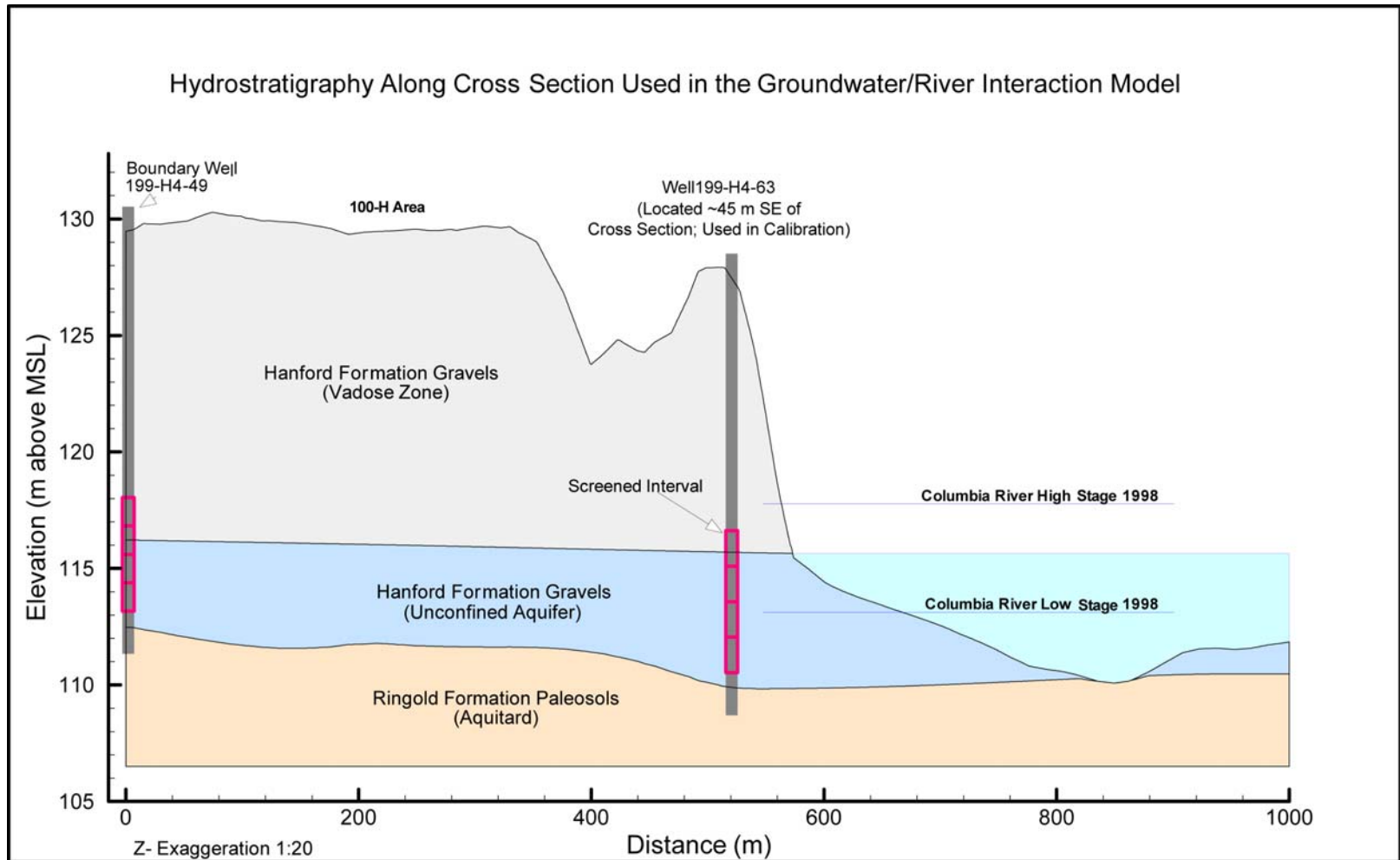


Figure 2.3. Cross Section Modeled at 100-H Area

because it appears to be a relatively typical year for river discharge in terms of volume of water, and for the timing and duration of the cycles. Figure 2.4 is the discharge record for Priest Rapids dam, located immediately upstream of the Hanford Site. The dam's discharge is a good approximation of river discharge along the Hanford Reach.

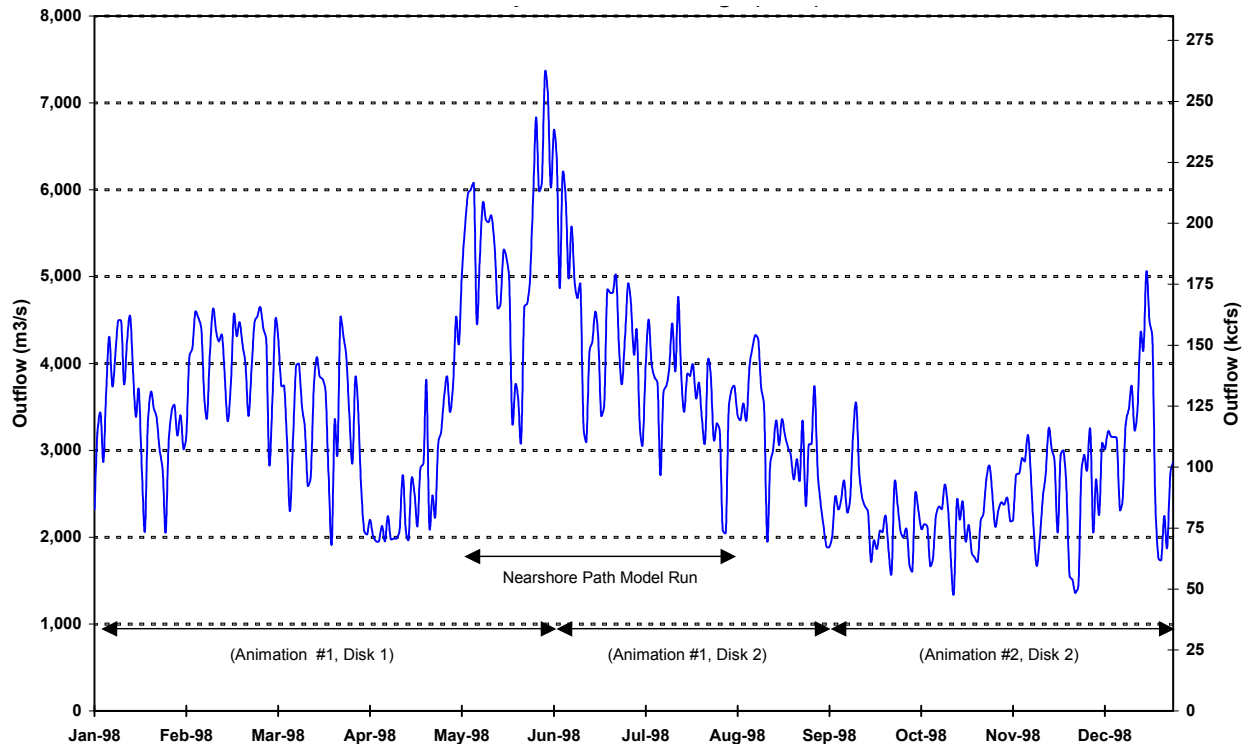


Figure 2.4. Discharge from Priest Rapids Dam Upstream of the Columbia River during 1998

Pressure transducers have been recording water levels in 100-H Area wells since the early 1990's (Campbell 1994). Consequently, a large database is available. The simulation is based on hourly water-level data obtained from transducers installed in well 199-H4-49, which is located approximately 640 meters inland, and in the Columbia River adjacent to the 100-H Area.

Output from the flow model includes the following:

- Flow pathlines for groundwater moving toward the Columbia River.
- Locations in the river channel where groundwater may discharge.
- Groundwater volume flux from the aquifer to the river.
- River water volume flux from the river into the riverbank and aquifer.

- Comparison of results for transient model conditions to steady-state conditions.
- Impacts that river stage fluctuations have on the unconfined aquifer.

The subtask product includes two CD-ROMs containing the simulation showing water movement pathlines, pore water flow velocities, and flux calculations for the cross section through the 100-H Area and adjacent river channel. The simulation covers one entire annual cycle of river discharge at hourly intervals. Instructions for viewing the simulation are provided in Appendix A.

2.2 Previous Work

A similar flow model was constructed to illustrate the interaction between the Columbia River and the unconfined aquifer beneath the 100-N Area^(a). This work was conducted to support decisions involving the Expedited Response Action for strontium-90 (DOE/RL 1994a). The modeling results provided a better understanding of how bank storage influences the release of strontium-90 to the river. The simulation was limited to the May through October 1995 time period and focused on estimating groundwater residence time in the zone of interaction. The stratigraphy beneath the 100-N Area includes a sloping contact between the two principal hydrogeologic units.

2.3 Spatial Framework

The first step in constructing a flow simulation model for the 100-H Area involved creating the spatial framework within which movement occurs. Boundaries within this framework were defined by land topography, river channel topography, and subsurface stratigraphic contacts. Bathymetric profile data, collected by the U.S. Army Corps of Engineers in 1986 (ACOE 1986), were interpolated to develop topographic coverage for the river channel. Geologic information was assembled from drilling records for the numerous 100-H Area monitoring wells to define the lateral and vertical extent of the major lithologic units in the area. (A summary of the geohydrology of the 100-H Area is included as Appendix B to this report).

Figure 2.5 shows four views of the spatial framework. The upper left panel shows the topography of the land surface, locations of monitoring wells, and the border of the 100-H Area. The upper right panel shows the various hydrogeologic units: vadose zone (unsaturated Hanford gravels), uppermost hydrologic unit (saturated Hanford gravels), uppermost aquitard (Ringold Formation Upper Mud Unit; paleosols), and the Columbia River. In this plot, a block has been cut out of the geologic model to show the changes in the thickness of these units across the 100-H Area. (Note: Only the first several meters of the Ringold Upper Mud Unit are shown; the unit extends approximately 15 meters further downward.)

(a) Connelly, M. P., C. R. Cole, and M. D. Williams, CH2M HILL, Hanford, Inc. *Bank Storage Modeling at the 100-N Area*. Letter report to Pacific Northwest National Laboratory, Richland, Washington, dated 1998.

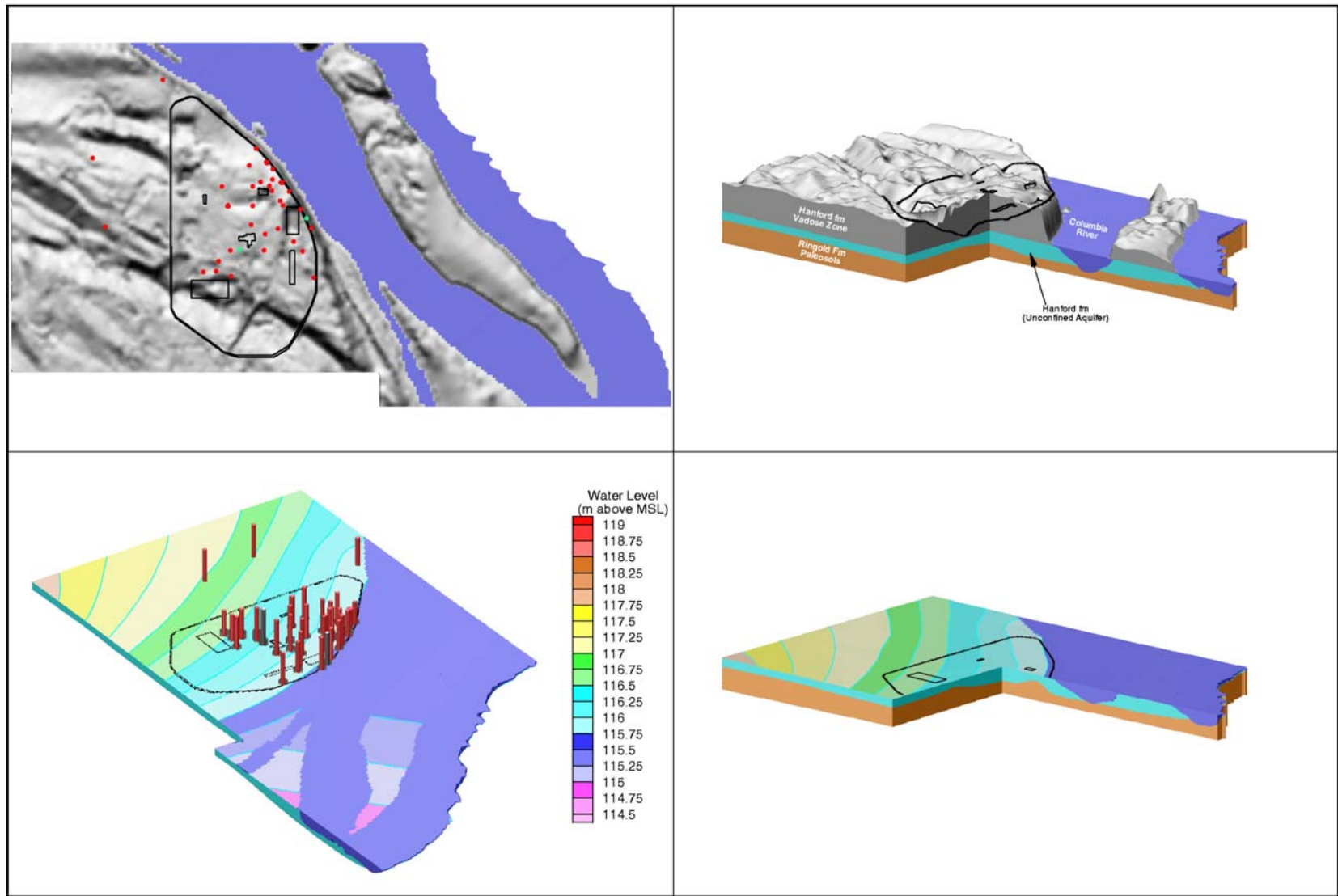


Figure 2.5. Spatial Framework Used for 100-H Area Model

The lower left panel in Figure 2.5 shows the unconfined aquifer and associated monitoring wells. The lower right panel shows another cutout of the geologic model with the vadose zone removed. This illustration reveals a localized relative high on the upper surface (erosional) of the Ringold Upper Mud Unit close to the river. The feature extends from just north of the 107-H Retention Basins in a north-westerly direction for approximately 400 meters.

Numerous cross sections through the spatial framework along the direction of groundwater flow were evaluated to identify a representative cross section for the two-dimensional flow simulation. The following criteria were used to select a representative cross section:

- Availability of a monitoring well with hourly water level data at the inland end of the section – to provide flow boundary conditions.
- Availability of a monitoring well with hourly water level data along the section – to be used for calibrating the model.
- The section should be located as far as possible from pumping and injection wells associated with the interim remedial action that addresses chromium contamination.
- The section should not include atypical stratigraphic features (e.g., not cross the local high on the Ringold Upper Mud contact at the 100-H Area).

Figure 2.6 shows three cross sections through the spatial framework. Cross section B-B' was selected for the groundwater movement model because this location best met the criteria. Cross section A-A' to the south did not have wells available with hourly water level data. Cross section C-C' to the north was impacted by interim action pumping wells and the rise at the Ringold Upper Mud contact, which affects the transmissivity in that area.

2.4 Two-Dimensional Flow Model

The two-dimensional flow model constructed for the 100-H Area takes advantage of many of the same tools used for previous modeling associated with the expedited response action for strontium-90 contamination at the 100-N Area.

2.4.1 Computer Code

The computer code used for this simulation is Pacific Northwest National Laboratory's "Subsurface Transport Over Multiple Phases" (STOMP) (White and Oostrom 1996). This code was selected because of its ability to handle seepage faces along a sloping boundary and previous success with its use in modeling the interaction between the Columbia River and unconfined aquifer at the 100-N Area.^(b) The

(b) Connelly, M. P., C. R. Cole, and M. D. Williams, CH2M HILL, Hanford, Inc. *Bank Storage Modeling at the 100-N Area*. Letter report to Pacific Northwest National Laboratory, Richland, Washington, dated 1998.

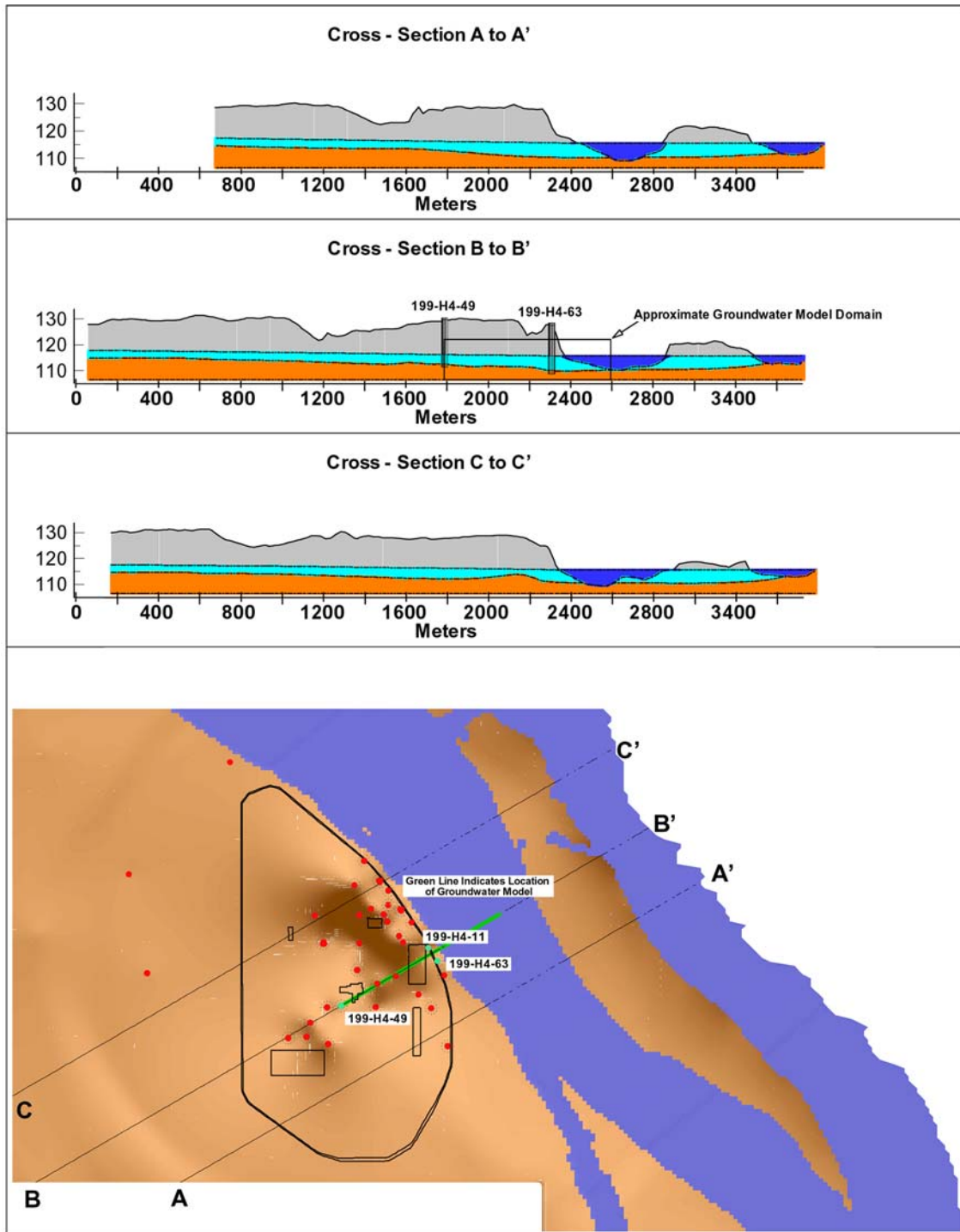


Figure 2.6. Cross Sections Used to Select Location for Two-Dimensional Flow Model

STOMP simulator solves transient flow and transport problems in the subsurface environment in one, two, or three dimensions using an integral-volume, finite-difference approach. Nonlinearities in the discretized equations are resolved through a Newton-Raphson iteration.

2.4.2 Assumptions

The operational mode for this simulation was water, with all other phases ignored. The primary assumptions for this operational mode are: isothermal conditions; passive gas phase; absence of non-aqueous phase liquid (NAPL), dissolved, and brine; and local thermodynamic equilibrium. The model was calibrated under transient conditions that closely approximated water levels in nearby wells.

Construction, analyses, and results associated with the two-dimensional zone of interaction flow model reflect the assumptions and limitations listed in Table 2.1.

Table 2.1. Assumptions for the Two-Dimensional Flow Model

Assumption	Reasoning
No impediment to flow between the Columbia River and the unconfined aquifer (e.g., low transmissivity zone at the river bottom)	Water levels in wells close to the Columbia River respond immediately to changes in river stage
Model has only two property types (Hanford gravels and Ringold Mud Unit paleosols)	Characterization in the vicinity of cross-sectional model indicates the gravels and muds of these formations are the principal lithologic units
Van Genuchten curve used to determine the relationship between moisture content and unsaturated hydraulic conductivity was for the Hanford formation	Site-specific van Genuchten parameters are not available for Hanford formation gravels
Anisotropic ratio of 1:10 for vertical to horizontal hydraulic conductivity was used for both Hanford and Ringold hydrologic units	Typical anisotropic ratio used at the Hanford Site
Base of the unconfined aquifer is the contact with the Ringold Upper Mud Unit; transmissivity in Ringold assumed to be 0.01 that of Hanford gravels	Ringold Upper Mud Unit is approximately 60 meters thick and represents a significant aquitard

2.4.3 Principal Features

The two-dimensional simulations were generated for a cross section that includes the less-than-fully-saturated portion of the vadose zone directly above the uppermost unconfined hydrologic unit. The region simulated extends out into the Columbia River for approximately 320 meters, which is somewhat over half the distance to the shore of Locke Island (see Figure 2.1). The cross section and two-dimensional finite difference grid used for the 100-H Area zone of interaction flow model are shown in Figure 2.7.

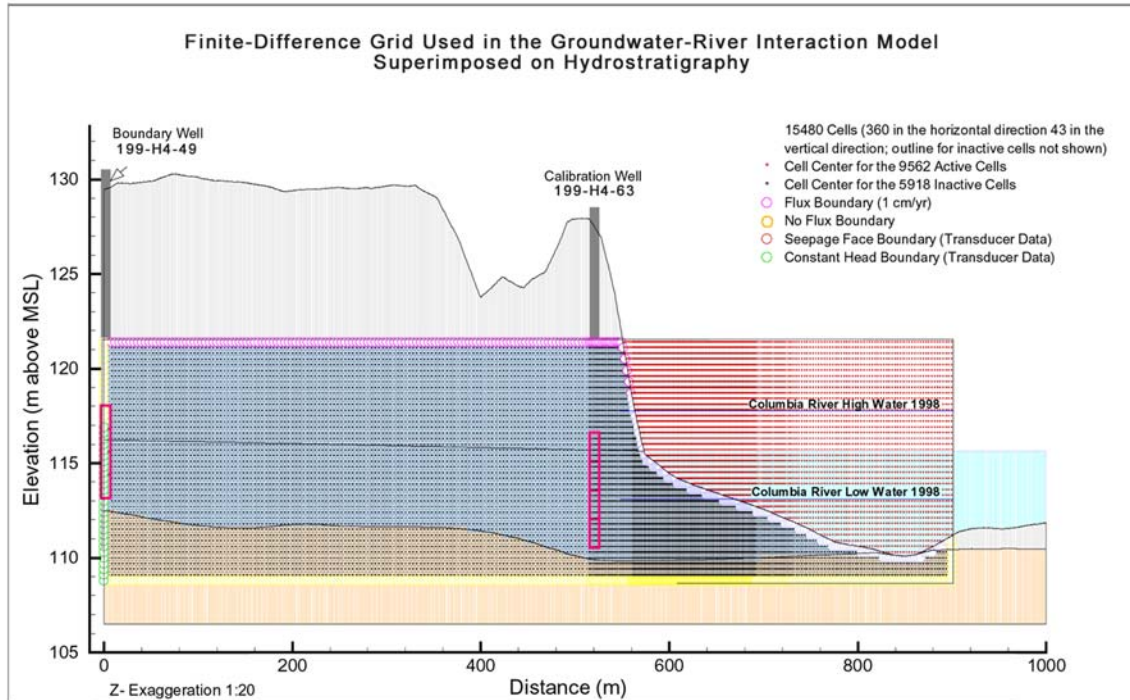


Figure 2.7. Cross Section and Two-Dimensional Finite Difference Grid

A 1-meter width was specified for the cross section (y-direction). The bottom of the grid was set at an elevation of 108.8 meters so that the topography at the contact with the underlying aquitard (i.e., Ringold Upper Mud Unit) could be incorporated into the model. The top of the model extends 5 meters into the vadose zone so that the capillary fringe directly above the water table is included in the model calculations. The eastern portion of the model domain is the unconfined aquifer beneath the Columbia River. While observational data on the stratigraphy beneath the river are not available, it is assumed that the river has incised into the underlying aquitard toward the middle of the channel.

The 900-meter length of the model (x-direction) is the distance between well 199-H4-49 and approximately halfway between the Hanford shoreline and Locke Island, which is located in the middle of the river channel (see Figure 2.2). The distance from well 199-H4-49 to the river shoreline is approximately 643 meters. At that distance, daily river stage fluctuations are not clearly distinguishable from other unspecified causes for fluctuations. Water level response at well 199-H4-49 is apparent, however, for seasonal cycles and extreme events in river stage. The area beneath the river simulated in the model was determined by the geometry of the system. The eastern edge of the model is located beyond where the river is believed to cut into the underlying aquitard.

A variable horizontal grid spacing was used in the flow model. The finest grid spacing is close to the Columbia River, to accommodate the large changes in gradients caused by river stage fluctuations. In the horizontal direction, grid spacing ranged from 1 to 4 meters. In the vertical direction, grid spacing was kept constant at 0.3 meters. Test simulations were run with grids that were both coarser and finer to determine the optimum configuration. The final grid developed contained 360 cells in the x-direction

(along section, perpendicular to the river) and 43 cells in the z-direction (vertical). This resulted in a total of 15,480 cells, of which 9,562 are active. The 5,918 inactive cells are located directly above the bottom of the Columbia River.

2.4.4 Hydraulic Properties

Two hydrogeologic units, each assumed to be homogenous, were used in the simulation. The uppermost unit (Hanford gravels) represents the unconfined aquifer and the lower unit (Ringold Upper Mud Unit) represents the underlying aquitard. The Hanford formation in this area consists mainly of unconsolidated sand and gravel facies that range in thickness from 2 to 6 meters (Peterson and Connelly 1992). The hydraulic conductivity of these facies is high and ranges from 15 to 1,800 meters/day (Liikala et al. 1988). This hydrogeologic unit is underlain by the more consolidated fluvial sands and overbank deposits of the Ringold Formation Upper Mud Unit, which has a much lower hydraulic conductivity. The hydraulic properties adopted for the simulation were derived from results specific to the 100-H Area (summarized in Peterson et al. 1996) or to the Hanford Site (Rockhold et al. 1997). Where necessary, generally accepted values from the open literature were used. No measured values for the Ringold Upper Mud Unit are available. Therefore, the hydraulic conductivity for the Ringold aquitard was set at 1/100 of that for the Hanford unconfined aquifer. The vertical hydraulic conductivity was assumed to be 1/10 of the horizontal value.

Model runs were first made using the published values for the hydraulic conductivity and porosity. These values were later modified during the model calibration process. Model calibration was accomplished by systematically varying the hydraulic conductivity and porosity until model results closely matched the water levels observed at well 199-H4-63, which is located close to the river along the model section. The values listed in Table 2.2 are those subsequently used for the calibrated model. The van Genuchten soil parameters for the less-than-saturated zone above the unconfined aquifer are also listed in Table 2.2.

Table 2.2. Hydraulic Properties for the Hanford and Ringold Units

Hydraulic Property (units)	Hanford Gravels	Ringold Upper Mud
K_h (m/d) ^(a)	106.68	1.0668
K_z (m/d) ^(a)	10.668	0.10668
Porosity ^(a)	0.2	0.15
Particle Density (gm/cm ³) ^(b)	2.65	2.65
Specific Storage (1/m)	1.0E-06	1.0E-06
Van Genuchten Parameters (units) ^(c)		
Alpha (1/cm)	0.0386	0.0386
N	1.6891	1.6891
θ_r	0.04	0.04
(a) Calibrated value.		
(b) Typical particle density for the Hanford and Ringold formations.		
(c) Rockhold et al. 1997.		

2.4.5 Boundary Conditions

The bottom boundary condition for the model was set as a no-flow boundary, because the Ringold Upper Mud Unit is much less transmissive than the Hanford gravels. The upper boundary condition beneath land areas was set to a natural recharge rate of 1 cm/yr (Rockhold et al. 1995). The eastern boundary condition for the nodes directly under the river (at approximate mid-channel) was set as no-flow because of the symmetry in flow from each side of the river. The western boundary condition was set as no-flow for the vadose zone portion and as a time-dependent, prescribed-head boundary for the unconfined aquifer. The time-dependent, prescribed-head boundary was set on an hourly basis using water level data recorded for well 199-H4-49.

The nodes on the riverbed were set to a time-dependent, prescribed-head boundary condition. This boundary condition was applied when the node was below the water table. If the water table dropped, causing the node to be above the water table, a seepage face boundary was applied. The head values applied to these nodes were extrapolated from the 100-D Area river stage monitoring station. Stage data from the 100-H Area river station were not used because during 1998, the stage periodically fell below the 100-H transducer, thus creating data gaps. The following procedure was used to calculate the boundary condition value along the riverbed:

- 1) Obtain the minimum daily water levels for both the 100-H and 100-D Areas for the previous year, during which the 100-H Area river station did not go dry. The correlation between the two river stations) is shown on Figure 2.8.
- 2) Calculate the linear regression for the 100-H river stage as a function of the 100-D river stage and use the regression to calculate the 1998 100-H river stage from 1998 100-D data.
- 3) Extrapolate river stage downstream from the 100-H Area river station to the location of the cross section, using an average river gradient of -0.000344 and a distance of 1,050 meters.

The water levels finally used for the riverbed boundary are shown as a blue line in Figure 2.9. The time-dependent, prescribed-head boundary set for the western end of the cross section (i.e., hourly water level recorded in well 199-H4-49) is shown as an orange line in Figure 2.9.

2.4.6 Initial Conditions

The initial hydraulic heads for all nodes in the simulation must be specified for a transient simulation. The exact initial conditions are unknown at the start of the simulation because of the transient nature of the problem. However, the initial conditions affect the model results, especially during early simulation times, so the following procedure was used to establish the initial conditions for the transient simulation:

- 1) Steady-state conditions were simulated for December 1, 1997. Prescribed-head boundaries were set to the river's water levels (boundary at riverbed) and at well 199-H4-49 (west boundary for the unconfined aquifer) observed at midnight on December 1, 1998.

- 2) The steady-state conditions from the first step were used to begin a transient simulation for one month. The boundary conditions for the transient simulation were set to the hourly water levels observed at the river and in well 199-H4-49 from 12:00 AM December 1, 1997 to 12:00 AM December 31, 1997.

The results of this one-month transient simulation were used as initial conditions for the subsequent simulation of a full year of water level data for 1998.

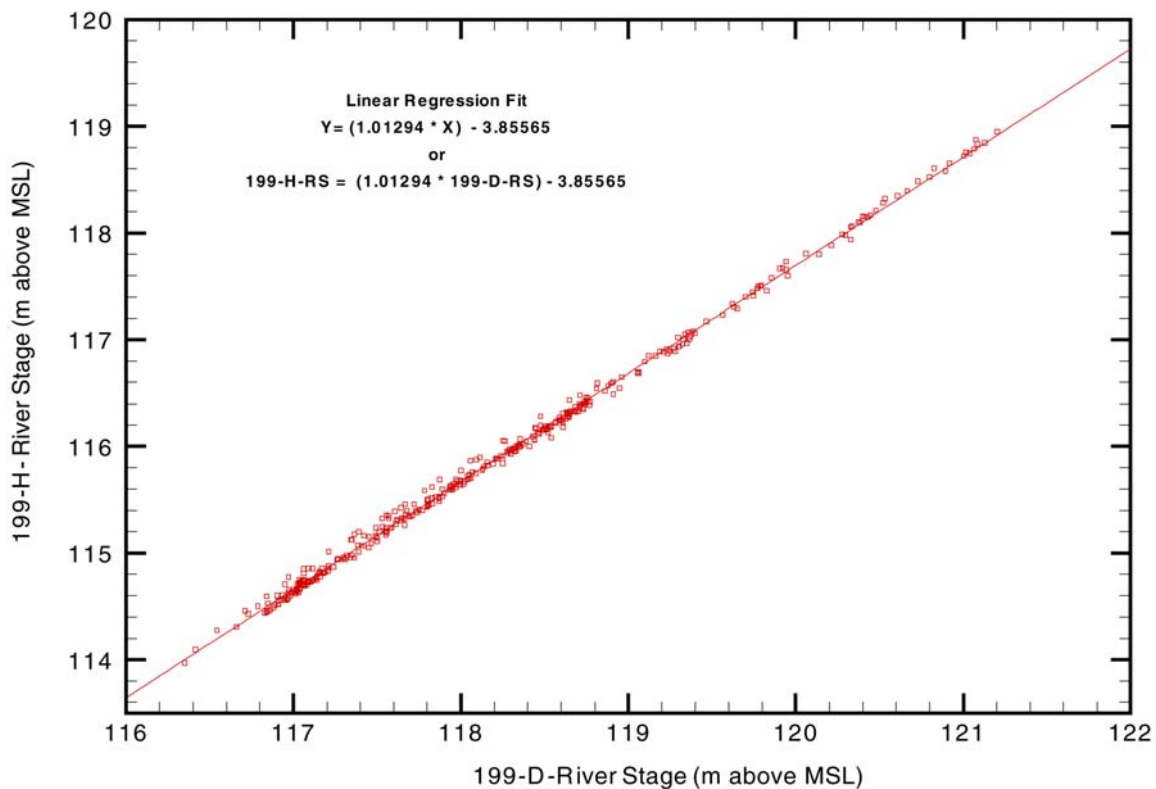


Figure 2.8. Correlation Between River Stage at 100-D and 100-H Areas

2.4.7 Model Calibration

The two-dimensional flow model was calibrated by determining the degree to which the model simulated observed water levels in a well located close to the cross section. The calibration process involved iterative adjustments of hydraulic conductivity and porosity to develop the best correlation between measured and simulated water levels in calibration well 199-H4-63. Wells 199-H4-47 and 199-H4-16 also lie along this section, although they could not be used in the calibration process because they are not part of the hourly water-level recording network. The iterative process started by assuming the Hanford unconfined aquifer a horizontal hydraulic conductivity of 60 m/d, with the Ringold aquitard being set at 1/100 of the Hanford unit's value for all iterations. Because the model is two dimensional, it was not expected that the observed and simulated values would match exactly, although the model should at least be capable of reproducing daily, weekly, and seasonal cycles.

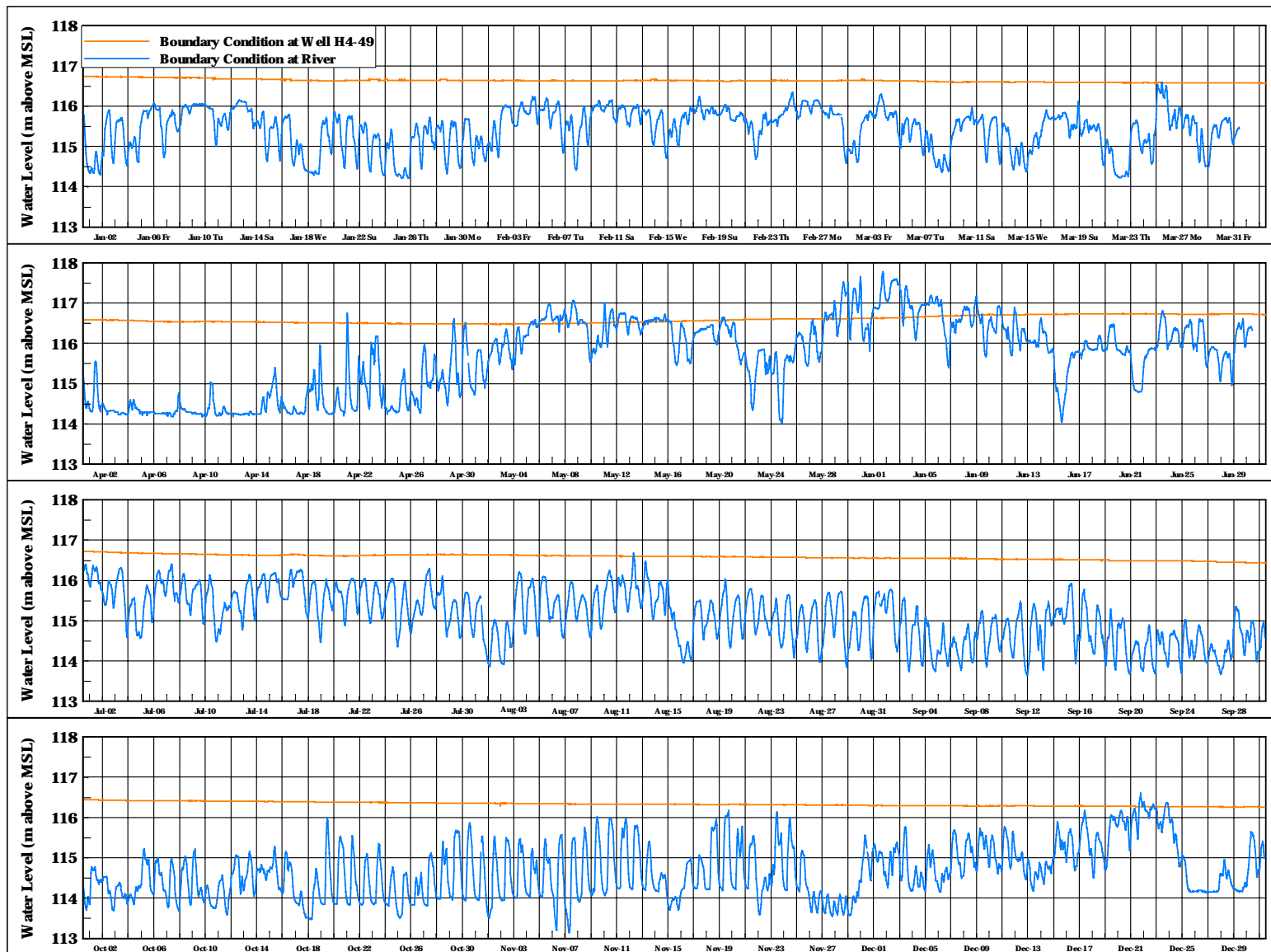


Figure 2.9. Prescribed Head Condition Applied to Western and Riverbed Boundaries

The iterative calibration process proceeded as follows:

1. Set hydraulic conductivity and porosity to initial trial values.
2. Run model to steady-state conditions using boundary conditions for December 1, 1997.
3. Simulate transient conditions for December 1997.
4. Compare water levels measured at calibration well 199-H4-63 to modeled water levels for the last two weeks of December.
5. Repeat the process for a new set of hydraulic parameter values.

A total of six calibration runs were made. Table 2.3 identifies the hydraulic parameters used for each calibration run. Of these calibration runs, calibration run 6 most closely matched the measured water level results at well 199-H4-63. However, the model-simulated water levels were consistently somewhat higher than those observed at the well (Figure 2.10). Lower actual water levels may be a consequence of pumping from well 199-H4-11, located approximately 80 meters northwest of well 199-H4-63. The model did not consider pumping from well 199-H4-11, which produced 0.1 meters of drawdown in the well. Model-simulated results for the year averaged approximately 0.23 meters higher than observed values. The model reproduced the daily, weekly, and seasonal cycles at the well, as anticipated.

Table 2.3. Results of Model Calibration Runs

Calibration Run	Calibration Name	Hanford Gravels		Ringold Upper Mud Unit	
		Hydraulic Conductivity (m/d)	Porosity	Hydraulic Conductivity (m/d)	Porosity
1	60m_por40	60.96	0.40	0.6096	0.15
2	60m_por35	60.96	0.35	0.6096	0.15
3	60m_por20	60.96	0.20	0.6096	0.15
4	75m_por20	76.2	0.20	0.762	0.15
5	90m_por25	91.44	0.20	0.9144	0.15
6	105m_por20	106.68	0.20	1.0668	0.15

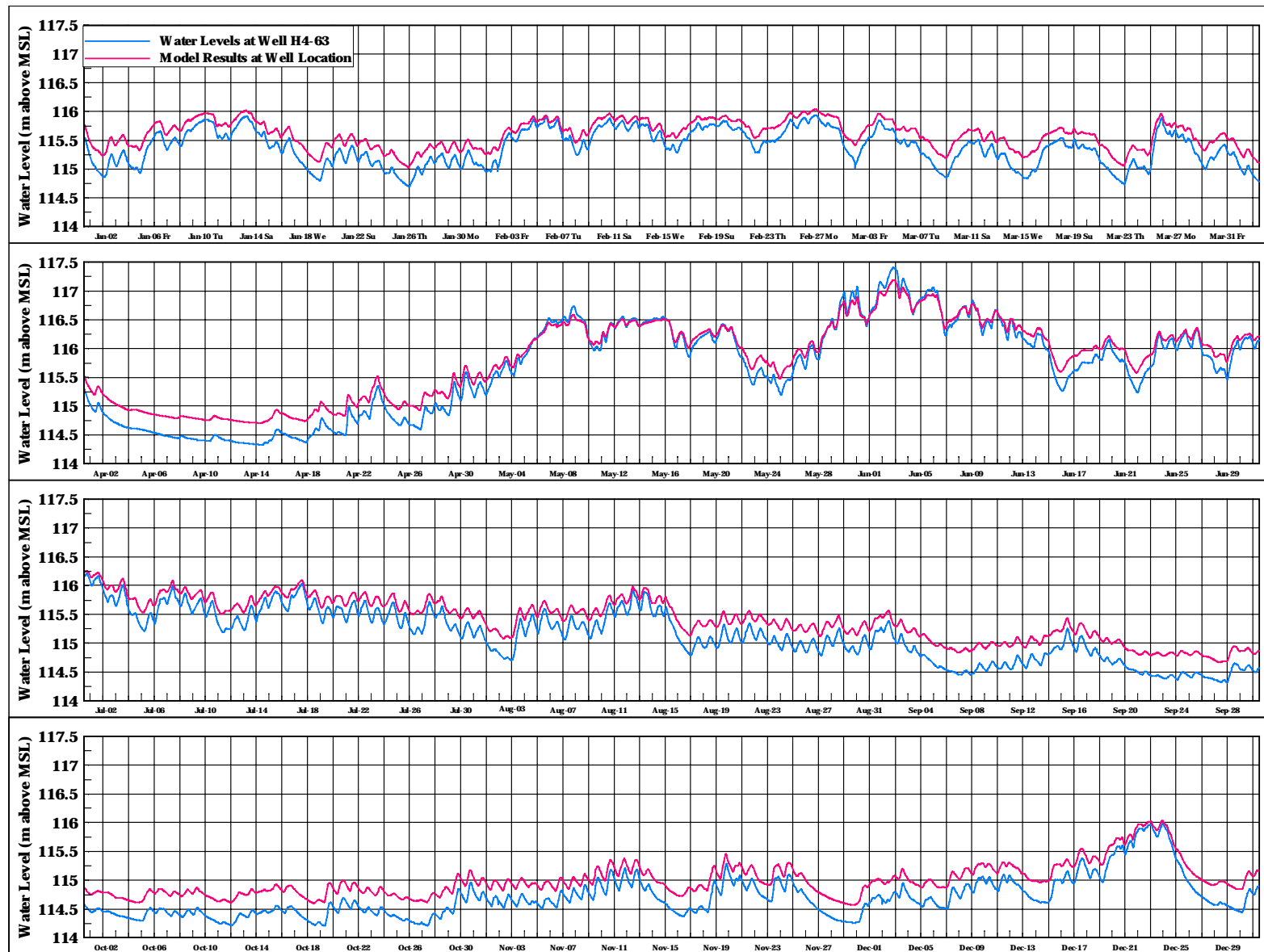


Figure 2.10. Observed and Simulated Water Levels at Well 199-H4-63

A more rigorous approach to calibration would involve examining the residuals (i.e., the difference between the simulated and observed water levels). However, several factors combined to reject using the more rigorous approach, including:

- Difficulty in differentiating differences created by a two-dimensional simulation for a three-dimensional problem.
- Uncertainty introduced by not having the calibration well located directly on the model cross section. (Calibration well 199-H4-63 is located approximately 45 meters to the southeast of the section; see lower panel of Figure 2.6).
- Groundwater withdrawal from well 199-H4-11, which is located approximately 30 meters to the northwest of the section, was not factored into this model.

Because of these factors, examination of residuals was abandoned in favor of pattern matching to daily and weekly cycles.

2.5 Flow Model Results

The water movement simulation was subdivided into three time sequences that illustrate “seasonal” discharge regimes of the river (refer to Figure 2.4 for discharge trend for 1998):

- January through May 1998—Average river flow conditions. Particle movement tracks start approximately 125 meters inland from the shoreline.
- May through August 1998—Seasonal high river-flow conditions, including transition. Particle tracks start close to river (approximately 30 meters inland from the shoreline), move inland approximately 25 meters as the seasonal high occurs, and finally move back toward the river as river levels fall. (Note: May is repeated in this sequence to provide greater detail on the effects of the seasonal high water that begins in late May).
- September through December 1998—Generally low river-flow conditions, including the period mid-October to mid-November when daytime flows are held constant at approximately 1,700 m³/s (60,000 kcfs) to support salmon spawning. Particle tracks start at approximately 125 meters inland from the shoreline.

The simulation generated large volumes of information. The following parameters were computed and saved in 1-hour time steps: pressure head, hydraulic head, moisture content, percent saturation, and pore water velocities in the horizontal and vertical directions. For the year-long simulation, there are 8,760 individual time steps. The data file for each time step is approximately 0.75 megabytes in size.

2.5.1 Time Series Simulation

A single frame from the animation for May 31, 1998, at 11:00 p.m. is shown in Figure 2.11 to illustrate the various types of information developed. Each frame contains four subpanels. The numbers in the following text refer to the yellow-shaded text on this figure.

Panel 1 is the basic display for water movement patterns. The Columbia River (1a) rises and falls during the simulation, creating the transient boundary condition. The colored zones indicate pore water velocity (1b). Small white triangles (1c) indicate instantaneous gradient direction. Red pathlines (1d) show the progression of a water parcel, with red squares at one-month intervals. Values in white boxes are the hydraulic head in meters. Light gray lines show the position of various planes across which water volume flux is calculated. The date and time for each hourly frame is shown in the lower left of the panel (1e). Contours showing partial saturation above the water table are shown as cyan lines (1f). Panel 2 shows the region beneath the shoreline with greater vertical exaggeration than Panel 1. Color coding is used to illustrate elapsed time along the pathlines.

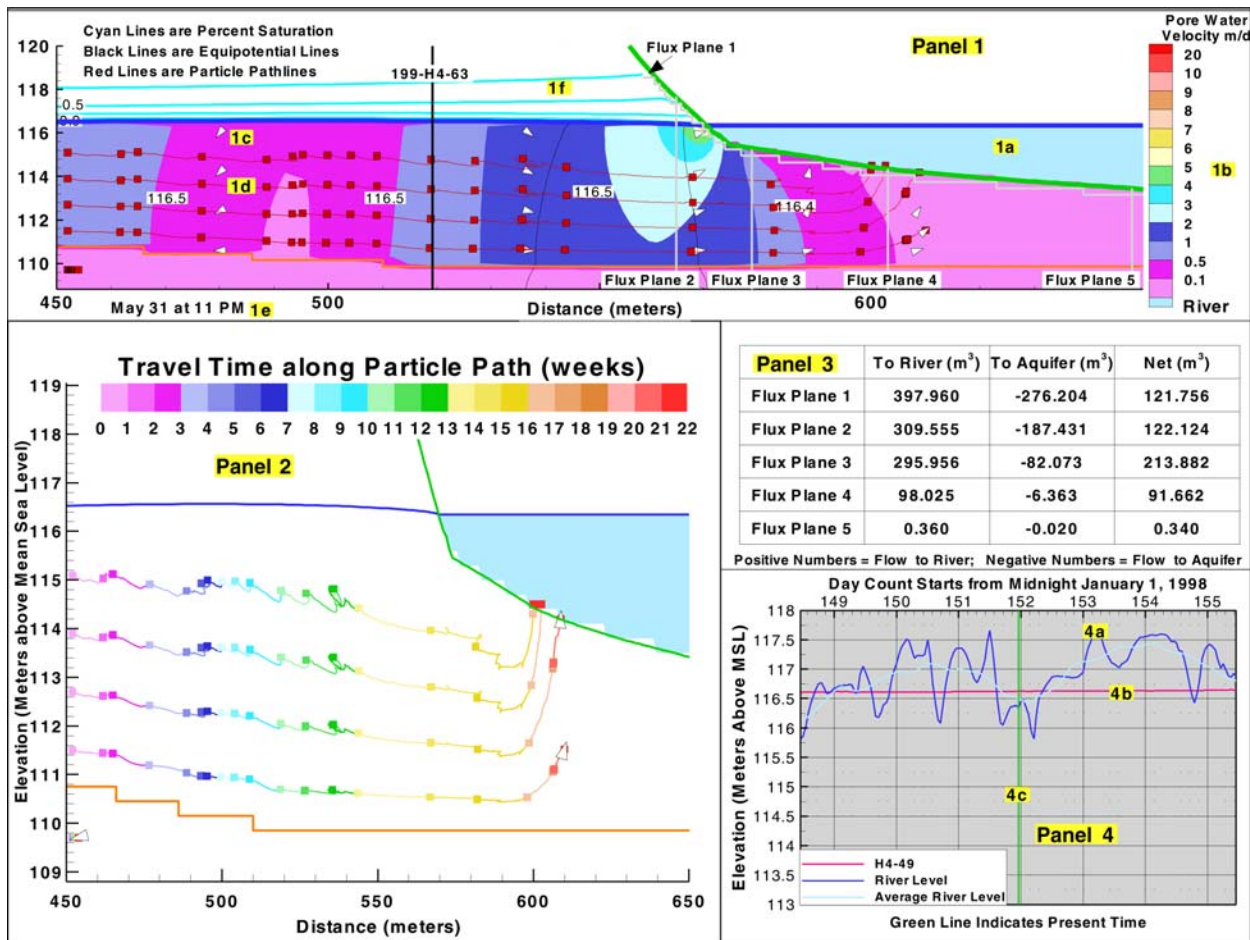


Figure 2.11. Transient Flow Field for May 31, 1998

The subpanel at the middle right of the frame (Panel 3) contains a table of water volumes that are passing through the various flux planes shown in Panel 1. The volume of water is calculated as both an instantaneous flux and a cumulative total volume. An instantaneous flux is the amount of water that passed across the plane (one-meter width) for a particular time step. The sign on the volume indicates which direction the water is moving; if it is positive, water is moving toward the river, if it is negative, water is moving toward the aquifer. The cumulative total volume is the net amount of water that has crossed the flux plane in the direction of the river since the start of the animation.

Finally, the subpanel in the lower right hand corner of Figure 2.11 (Panel 4) is a trend chart that shows the applied boundary conditions for the unconfined aquifer. The dark blue line (4a) represents the boundary condition applied at the nodes located directly below the river. For comparison purposes, the daily average water level for the Columbia River is also included as a light blue line. The magenta line (4b) represents the boundary condition (i.e., water level) being applied on the right boundary at well 199-H4-64. The vertical green line (4c) that runs through the center of the chart indicates the time for which the groundwater flow field is being simulated.

2.5.2 Displaying the Model Results

The simulation files, along with the computer program FRAMER™ (Amtec Engineering, Bellevue, Washington) which is used to animate the simulation, are available on two PC-compatible CD-ROMs, which are included with the distribution of this report. Amtec Engineering licensing allows free distribution of FRAMER™ with the simulation files. Each of the three simulation sequences is between 300 and 400 megabytes in size. The CD-ROMs include the water movement simulation, data files used to develop the geologic model, and various views and cross-sections from the geologic model. Instructions for viewing the animation program are provided in Appendix A, along with a brief description of all the files included on the CD-ROMs.

Briefly, to view the simulation results, double-click on the file called “framer.bat” on the CD-ROM, then select the simulation file for the time period of interest. This file has the proper arguments for the animation program. The animation may be stopped at any point, thereby allowing each hour’s resulting flow field to be examined in detail. Because the animations display a large amount of information in each frame, it is recommended that focus be directed at only one of the several subpanels in the display, then restart the animation to view a different subpanel.

2.6 Groundwater Flow Fields

Water movement in the zone of interaction at the 100-H Area was simulated for 1 year (1998) at hourly intervals, thereby allowing examination of seasonal impacts in considerable detail. The year was subdivided into three time intervals to show the flow patterns that evolve under the various seasonal river conditions: January to May, May to August, and August to December. The following sections describe various features observed in each of the three time intervals—the reader is encouraged to view the animated hourly sequences to obtain a more complete understanding of the characteristics for each interval under transient river stage conditions. Many of the features described below are revealed in previous Figure 2.11.

2.6.1 January to May 1998 Sequence

The flow field for this time interval is shown in the animation file labeled 03Jan-May.rm on the CD-ROM. Particle tracks are strongly influenced by the constantly changing water levels and exhibit a zig-zag motion toward the Columbia River during the first 3 months of the simulation. In April 1998, the Columbia River was kept at a constant elevation of 114.3 meters above mean sea level. This is a relatively low stage elevation; thus the hydraulic gradient in the aquifer increased toward the river. The particle tracks move quickly toward the river, as revealed by the wide spacing between time markers for weeks 13 through 16. Pore water flow velocities along the particle tracks average approximately 1.2 m/d, with maximum velocities approaching 10 m/d beneath the shoreline region. When the particles near the river, they first move vertically downward. The direction reverses to upward, followed by the subsequent exit from the aquifer. Discharge from the aquifer into the riverbed is focused at approximately 30 to 40 meters offshore.

Groundwater flux values for the simulation show a large variation because of the constantly changing flow directions, with water flowing to and from the river. Also, flux planes 1 and 2 have water moving toward the aquifer below the water table, but moving toward the river above the water table, which makes the interpretation of the fluxes complex. It appears that the greatest amount of mixing between river water and groundwater occurs near flux planes 1 and 2. The ratio of river water entering the aquifer compared to exiting the aquifer for flux plane 1 is 0.7 and for flux plane 2 it is 0.6. The ratio for flux plane 3, which is located farther offshore, is 0.3, suggesting less addition of river water to the groundwater that exits the aquifer. These ratios, along with the particle tracks, indicate that most of the mixing is taking place in the upper portion of the aquifer.

2.6.2 May to August 1998 Sequence

For this sequence, particle tracks were started closer to the river than for the January to May sequence, so that the effects of the seasonal high river stage could be better illustrated. During the early part of the May-June period, the hydraulic gradient in the aquifer is reversed because of the seasonal high river discharge. This condition exists for a period of time sufficient for river water to flow some distance into the aquifer. Particles moved inland ~23 meters and upward ~0.8 meters before reversing direction and heading back toward the river as the seasonal high river stage declined. During the later stages of this sequence (i.e., July-August), there is a strong gradient back toward the river as the river level drops during the summer months.

As for the earlier January to May sequence, the particles exit the aquifer at a riverbed location focused approximately 30 to 40 meters offshore. Most of the groundwater/river water mixing occurs in the upper portion of the aquifer, with the mixing ratio of river water entering the aquifer compared to exiting the aquifer for flux plane 1 being 0.8 for flux plane 2 being 0.7. This mixing ratio is higher than for the January to May sequence, which reflects the large influx of river water into the aquifer during seasonal peak discharge of the river.

2.6.3 August to December 1998 Sequence

This sequence is characterized by a relatively steep hydraulic gradient toward the river, with large daily variations for the river's water levels. For the most part, the same patterns observed in the previous time sequences are also observed here (animation file 05Sep-Dec.rm). The average velocity is ~ 2.0 m/d, with a maximum velocity of 16 m/d. During this time sequence, the particle path lines move deeper into the aquifer and enter the river farther offshore than in the previous time sequences (40 to 60 meters offshore, as compared to 30 to 40 meters for the previous two sequences). This is a consequence of the large daily changes in river elevations that occur in late November and early December.

2.6.4 Transient vs. Steady-State Boundary Conditions

Flow fields for each time interval were also calculated under the assumption of steady-state boundary conditions, although these results are not included in the animation files. This was done to illustrate the different information that results from making a steady-state assumption for the river boundary condition, which simplifies the calculations and reduces the number of values generated. For the steady-state calculations, the boundary conditions for the river and well 199-H4-49 were set to their average water level elevations during the time period for the animation.

The flow fields that result from (a) steady-state boundary conditions and (b) transient boundary condition are shown in Figure 2.12, which shows the end of the May to August sequence. The average hydraulic gradient is relatively gentle for the steady-state solution (top half of Figure 2.12), which is deceiving because it does not reveal the strong influence of the seasonal high discharge on water movement. For the steady-state solution, the particles move horizontally, with a slight upward component, until they are within tens of meters of the river shoreline. Once there, they move upward and exit the aquifer fairly close to the shoreline.

In general, the flow patterns derived assuming steady-state river conditions show water parcel flow lines that are essentially horizontal, with a slight downward component, until they approach the river, where they turn upward. Discharge to the riverbed under assumed steady-state river conditions indicated discharge closer to the shore than for the more realistic simulation under transient stage conditions. Under the steady-state assumption, the inference would be that most of the water from the aquifer enters the river within the first 10 meters from the river shore and that groundwater flow velocities range from 0.5 to 1 m/d. This inference is significantly different from the conclusions drawn from the flow paths indicated under the assumption of transient boundary conditions, which better reflect real-world conditions.

2.6.5 Nearshore Particle Paths

The model was run to simulate the movement pattern for two parcels of water that were initially positioned near the shoreline (in contrast to the inland locations adopted for the three seasonal periods). This was done in an attempt to approximate the path followed by river water that infiltrates the bank during high stage. The results are shown in Figure 2.13.

The period selected for the model run was May 1 to July 31, 1998. This period covers the spring high stage condition and the gradual decline in discharge as the seasonal cycle progresses into the summer (see Figure 2.4 for river discharge chart). Parcels of water were started at two near-shore locations (red and green pathlines in Figure 2.13). The initial motion is downward and slightly inland, reflecting the high river stage at the beginning of the simulation. As the river stage falls after approximately 6 weeks, the parcels stop their downward movement and reverse course back toward the river, with subsequent discharge through the riverbed relatively close to shore.

These pathlines represent in a very general way the area within which dilution of groundwater by infiltrating river water is likely to be the greatest during a seasonal cycle. Additional dilution of groundwater following these paths also occurs at the riverbed interface, where river water entrained in riverbed gravels also mixes with the upwelling groundwater.

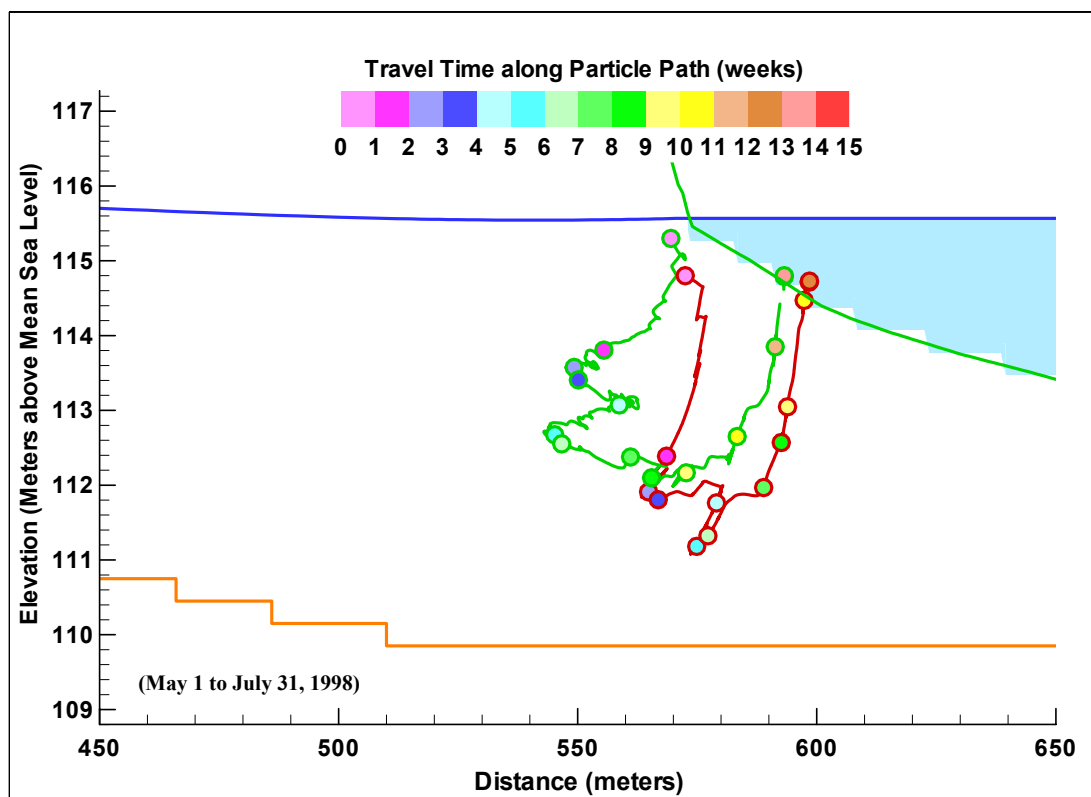


Figure 2.13. Movement Patterns for Water Parcels with Initial Positions Near Shoreline

3.0 Mixing Within the Zone of Interaction

This section describes activities to characterize mixing and contaminant dilution involving groundwater and river water. The need for these activities was identified under Information Need RL-SS37 in the Science and Technology roadmap (DOE/RL 2000, App. B, pg. B-57). The information contributes to developing modeling capabilities to quantify the changes in groundwater characteristics that take place in the zone of interaction between the aquifer and the river.

The working hypothesis for this subtask is that the interaction between groundwater and river water, which infiltrates the bank during high river stage, causes dilution of contamination potentially present in the groundwater. There is abundant evidence to confirm the occurrence of this interaction (e.g., Newcomb and Brown 1961; Raymond and Brown 1963; Peterson and Johnson 1992). However, the ability to quantify the degree and timing of dilution prior to discharge into the free stream of the river is limited to specific locations that can be monitored continuously. The results of this subtask illustrate the variability of mixing in time and space, thus providing information on the uncertainty associated with dilution coefficients used in numerical models for contaminant transport.

3.1 Scope of Investigation

An intensive effort was conducted to compile existing data that would reveal information about the degree of dilution that may occur along the Hanford Reach within the zone of groundwater/river interaction, thus reducing contaminant concentrations as observed in riverbank seepage and riverbed sediment pore water. The search covered the Hanford Environmental Data Base (HEIS), previously published reports on water quality data from riverbank sampling sites, and electronic files from various projects that have not yet become part of the HEIS. Unfortunately, not all of the results from previous investigations have been incorporated into electronic databases, nor has some critical field information been kept with the analytical results.

Measurement results for the specific conductance of water samples collected from various sites near the groundwater/river interface were used as the primary indicator for dilution. A distinct contrast between the specific conductance of groundwater and river water is present along the Hanford Reach, with uncontaminated groundwater typically varying between 350 and 450 $\mu\text{S}/\text{cm}$, while river water is fairly constant in the 130 to 150 $\mu\text{S}/\text{cm}$ range. Specific conductance is measured each time a water sample is collected for nearly any monitoring purpose, so abundant measurements have been made. Although concentration results for non-attenuated dissolved contaminants could also be used to illustrate dilution (e.g., hexavalent chromium), an additional degree of uncertainty is added because of concentration gradients that exist within contaminant plumes (discussed in Section 3.5).

New data sets were compiled and plotted to identify evidence that would help quantify the dilution process. Existing data sets from previous investigations were reviewed and interpreted relative to the objectives for this Science and Technology task. Changes in water quality related to groundwater/river water mixing are described from three perspectives:

- Hourly data from a riverbank seepage location.
- Spatial distribution of several contaminants along the Hanford Reach.
- Periodic measurements from multiple depths in the aquifer near the river during seasonal river flow change.

3.2 Sources for Historical Data

Riverbank seepage of contaminated groundwater was a significant concern during the reactor operating years, especially during the Cold War production period between the early 1950s until the mid-1960s. Intentional and accidental release of huge volumes of liquid effluent created at each reactor to the soil column resulted in groundwater mounds that accentuated flow toward the river (Brown 1963). Because the temperature of the groundwater mounds was well above ambient temperatures, areas of effluent seepage and the resulting thermal plume in the river could be traced using infrared imagery (Eliason 1969). Additional contamination was presented to the shoreline environment by the operation of concrete spillways at each reactor area. These spillways dispersed reactor coolant and other effluents that would normally be discharged to the center of the river channel via outfall pipelines, except when the river stage was too high for flow via the pipelines (HAPO 1963a, pp. 129-136).

Some monitoring of riverbank seepage was conducted during the peak cold war years (i.e., 1950s and 60s), although formal environmental monitoring did not start until the 1970s. By the late 1970s and early 1980s, public awareness of the potential danger created by contaminants exposed along the river shore prompted more comprehensive monitoring, which became the responsibility of Pacific Northwest Laboratory (PNL). However, none of these initial surveys of riverbank seepage focused on the amount of dilution that might be occurring in the zone of interaction. While concentrations of nitrate, tritium, uranium, and gross beta were measured for seepage samples, the specific conductance of the sample, which would provide an indicator for dilution by river water, was apparently not recorded.

Following are descriptions of the principal projects that have collected, or continue to collect, water quality data from sampling sites along the Hanford Reach shoreline.

3.2.1 Sitewide Environmental Surveillance

The first comprehensive survey of riverbank seepage along the Hanford Site shoreline was conducted between fall 1982 and fall 1983 by the Hanford Environmental Surveillance Program (McCormack and Carlile 1984). (Note: The Surveillance Program's objective was to evaluate discharges to the Columbia River that occurred as the result of Hanford operations.) The riverbank seepage study supplemented routine monitoring activities, which focused primarily on analysis of river water.

During 1982, the shoreline from just upstream of the 100-B Area downstream to North Richland was visually inspected. Approximately 115 locations were identified where groundwater appeared at the surface during periods of low river stage. In 1983, many of the previously identified seepage locations were revisited and sampled. River water was collected from within several meters of the shoreline adjacent to each seep sampled. The samples were analyzed for nitrate, tritium, and uranium. The specific conductance of the samples was not reported, so it is not possible to estimate the relative proportions of river water and groundwater in the seepage samples. The results are tabulated in the original report (McCormack and Carlile 1984, Table C.1).

The numbering system for the 1982-1983 seepage investigation used Hanford River Marker (HRM) marker posts, which subdivide the shoreline between Vernita Bridge and North Richland into 46 segments, each approximately 1-mile long. A seepage site name was composed from the nearest upstream marker, to which a suffix was added that indicated the sequence of the seep site downstream of the marker. For example, seepage site "3-5" indicated the fifth seep observed downstream from HRM number 3. No reference to the initial installation of these markers has been identified. They were subsequently reset and surveyed during summer 1999 by the Surface Environmental Surveillance Project (SESP), successor to the original surveillance program.

A second comprehensive survey of riverbank seepage was completed by SESP during 1988 (Dirkes 1990). This study provided a follow-up to the initial 1982/1983 riverbank seepage study, with an expanded geographic coverage and a more extensive suite of analyses. Near-shore river water samples were collected from locations adjacent to where riverbank seepage was collected. Samples were also collected from sites across the river from Hanford facilities and from irrigation return canals. An important discovery was that some radiological constituents that are typical of Hanford Site groundwater were present in irrigation return water at levels higher than Columbia River water.

The location names used for riverbank seepage sites followed the convention established by the earlier 1982 survey. However, the analytical results are tabulated according to HRM position and are not given discreet location names (Dirkes 1990, Tables A.1 and B.1). As for the earlier survey, the specific conductance of the sample is not reported.

3.2.2 Environmental Restoration (Westinghouse Hanford Company)

A third comprehensive survey of riverbank seepage was conducted in fall 1991 as part of the Environmental Restoration project activities (DOE/RL 1992). The work was prompted by an increased need for decision-making information for U.S. Department of Energy and regulatory agencies regarding groundwater contamination near the river. A Tri-Party Agreement major milestone provided impetus for generating this information (major milestone M-30; submilestone M-30-01).

PNL Environmental Surveillance project staff participated in planning the fall 1991 survey. PNL staff outlined all seepage areas previously observed and sampled on the newly-acquired 1:2000 series of topographic maps for the Hanford Site.^(c) A new seepage location numbering system was devised, again based on the HRM marker posts, and attempts were made to associate all previously sampled locations with the new numbering system. The new numbering format consisted of the location to the nearest tenth of a HRM and a suffix used to indicate multiple seeps at the same approximate location (e.g., seeps 057-1, 057-2, etc. would indicate multiple seepage sites at HRM 5.7, which is located between the 100-B and 100-K Areas).

During this project, samples of 1) riverbank seepage, 2) sediment associated with seepage, and 3) nearshore river water adjacent to seepage sites were collected. Twenty-six locations were sampled; analyses included a comprehensive suite of chemical and radiological contamination indicators. The sampling and analysis were completed following *Comprehensive Environmental Response, Compensation and Liability Act of 1980* (CERCLA) protocols for obtaining environmental data to support restoration decisions. An effort was made to determine the relative contributions of groundwater and river water to the seepage sample by recording temperature, pH, and specific conductance for each sample. As a consequence, it became possible to discuss the results not only in terms of concentrations at the location and time of seepage exposure, but also to make qualitative statements regarding how representative the concentrations were of nearby groundwater. The data collected during this project are stored in the HEIS.

The data collected during fall 1991 were further analyzed to better understand the relationship between water quality data obtained from near-river wells, riverbank seepage, and near-shore river water (Peterson and Johnson 1992). Concentrations of various contamination indicators were plotted as a function of distance along the shoreline. This showed good correlation with previously mapped groundwater plumes and also that concentrations in exposed riverbank seepage tended to be midway between values in groundwater and adjacent river water, though considerable variability exists. Additional work to provide consistent names, HRM references, and geographic coordinates was completed during this time period. The results were published in an interpretive report (Peterson and Johnson 1992, Table A-1). The principal conclusions from their analysis are:

- Riverbank seepage concentrations of contamination indicators tend to be intermediate between groundwater and nearshore river water concentrations.
- During diurnal changes in river stage, seepage concentrations also tend to be intermediate between well and nearshore river values.
- Results suggest that the timing of sample collection relative to river characteristics prior to sampling strongly influences observed contaminant concentrations. The height and duration of river stage fluctuations are important influences on the water quality of bank seepage.

(c) R. Dirkes, Pacific Northwest National Laboratory. Personal communication to R. E. Peterson, dated October 1991.

- Bank seepage data are probably not the most representative data to use in modeling groundwater contaminant flux to the Columbia River.

The Environmental Restoration Program re-sampled the 1991 riverbank seepage sites during 1993. There are no published reports that describe the results of this sampling. Many of these sites were then incorporated into the CERCLA remedial investigation sampling and analysis associated with the 100 Area groundwater operable units (see Section 3.2.3).

Shoreline sampling and analysis was also conducted at the 300 Area as part of the limited field investigation associated with the 300-FF-5 groundwater operable unit (Friant and Hulstrom 1993). In that investigation, near-river wells, riverbank seepage, shoreline sediment, and near-shore river water samples were collected during September 1992. The samples were analyzed for radionuclides, metals, and organic constituents. Uranium was identified as the chief contaminant of concern, with the primary source being nuclear fuel fabrication effluent that was discharged to the process trench. The investigation also concluded that shoreline sediment did not appear to be an important sink for contaminants.

3.2.3 Environmental Restoration (ERC Team)

The Environmental Restoration Contractor (ERC) team (Bechtel Hanford, Inc., CH2M HILL Hanford, Inc., and IT Hanford, Inc.) assumed responsibility for the Environmental Restoration Program in 1995. This responsibility included follow-on work to Tri-Party Agreement Milestone M-30-05 that involved the groundwater/river interface. Several projects provided new and unique data from the interface in the 100 Areas. Riverbank seepage sampling has been conducted each fall since 1996.^(d) Sampling logistics have been integrated with the shoreline monitoring activities conducted by PNNL's Sitewide Environmental Surveillance Project.

During spring 1995, ERC divers collected pore water samples from the riverbed adjacent to the 100-H Area (Hope and Peterson 1996a). The area for the investigation included riverbed substrate that is heavily used by fall chinook salmon as spawning habitat. The area is also adjacent to where groundwater contaminated by chromium enters the river. The pore water samples were analyzed for hexavalent chromium using several methods, including adsorptive stripping voltametry,^(e) which offers very low detection levels. At one location within a gravelly area used as a redd, chromium was observed at concentrations up to 130 µg/L, which is well above the federal standard for protecting aquatic organisms (i.e., 11 µg/L). However, the specific conductance of the sample indicated that it contained a significant proportion of river water, so the concentration of groundwater approaching that area might have been even higher than the measured value. The following year, divers returned to this location and installed

(d) Peterson, R. E. *Summary of River Bank Seepage Sampling Event for FY1997: 100-BC-5, 110-KR-4, and 100-HR-3 Operable Units*. Attachment to Interoffice Memorandum No. 041996 from M. H. Sturges, CH2M HILL, Hanford, Inc. to A. J. Knepp, Bechtel Hanford, Inc., Richland, Washington, dated March 7, 1997.

(e) Olsen, K. B., and S. Kucheryavyy, Pacific Northwest National Laboratory, *Determination of Chromium (VI) in Columbia River Pore Water by Adsorptive Stripping Voltametry*. Letter report to the U.S. Department of Energy, Richland, Washington, dated July 1995.

permanent pore water sampling ports, with tubing leading ashore to a point above the high water line.^(f) These tubes, along with additional permanent installations at 100-D and 100-K Areas, may still be viable collection points, although no recent attempt has been made to sample them.

A second field investigation using divers to collect riverbed pore water samples was conducted during the fall 1995 at the 100-D Area (Hope and Peterson 1996b). In addition to collecting pore water samples, numerous aquifer sampling tubes were emplaced in the aquifer at multiple depths along the shoreline. Hexavalent chromium was discovered along one segment of the shoreline at concentrations higher than previously observed in any other water samples from the 100 Area. Peak concentrations in riverbed pore water reached 630 µg/L and 870 µg/L in an aquifer tube adjacent to the pore water site. This discovery led to the installation of new groundwater monitoring wells and vigorous investigation of potential sources, including a reconstruction of the water table that may have existed during the operating years (Connelly 1997a). The newly discovered area of chromium contamination became known as the 100-D “hot spot.” The plume is currently being remediated using in situ Redox treatment technology developed at PNNL (Williams et al. 2000).

3.2.4 Additional Projects Related to the Groundwater/River Interface

Interest in salmon spawning habitat within the Hanford Reach has resulted in projects involving the groundwater/river interface that are supported by organizations outside of the DOE, such as the Bonneville Power Administration (BPA). Methods to identify and characterize the discharge of groundwater in spawning habitat are described in two reports for projects within the Hanford Reach. The first describes a sensor towed along the river bed that measures specific conductance (Lee et al. 1997). The second report describes driving steel tubes into the riverbed to obtain water level and water quality data (Geist et al. 1998). Also, the relationship between geomorphic features on the riverbed and the entrainment of river water in spawning gravels has been studied in the Hanford Reach (Geist and Dauble 1998). That work revealed a possible connection between redd site selection by salmon and whether the pore water in the site gravels was dominated by river water entrained in the gravels or by the influx of groundwater.

Graduate student research during 2000 has produced a new data set for investigating hydraulic properties within the ZOI along the 100-D Area shoreline.^(g) This work used numerous small diameter casings that were driven into the low water shoreline to a) obtain water level measurements and b) conduct hydraulic tests. One of the potential outcomes for this research is a more effective and relatively inexpensive method for obtaining values for hydraulic parameters that are used in flow models.

(f) Hope, S. J. *Installation of Riverbed Pore Water Sampling Ports in the Columbia River at 100-D/DR, 100-H, and 100-K Reactor Areas*. Interoffice Memorandum No. 044041 from M. H. Sturges, CH2M HILL, Hanford, Inc. to A. J. Knepp, Bechtel Hanford, Inc., Richland, Washington, dated March 11, 1997.

(g) Arntzen, E., Portland State University/Pacific Northwest National Laboratory. Personal communication to R. E. Peterson, Pacific Northwest National Laboratory, dated September 2000.

Finally, an FY 2000 Laboratory Directed Research and Development (LDRD) project at PNNL is developing methods to analyze microbial processes and communities within the zone of interaction.^(h) Improved methods will lead to improved characterization of the biological and chemical processes that occur within the ZOI, and the contrasts in processes on either side of the interface with the free stream of the river. This work is intended as a three-year investigation, the results of which provide a direct contribution to the Science and Technology roadmap technical information gap described in Section 1 of this report.

3.3 Access to Existing Data

The first year of the groundwater/river interface investigation relied on existing data sets. New field data were not collected specifically for this study, though some new field data became available as a result of monitoring conducted by core projects. A first step in assembling existing data was to determine what results were available from the HEIS for analyses of riverbank seepage, groundwater from aquifer sampling tubes, and pore water from riverbed sediment.

A problem that appeared early during the project was that many results from previous projects have not been loaded into the HEIS. These data are available only in published reports, field notebooks, and individual investigator records. Therefore, a search was conducted to find electronic records for Environmental Restoration Program projects involving riverbed pore water, aquifer tube sampling, and riverbank seepage, because those data offer the most promise for revealing information about dilution in the zone of interaction. Some files were discovered and the data are used for this task.

A second problem is that many of the riverbank seepage result records that are in HEIS do not contain unique location information, so sorting, or even identifying, locations for some results presents a serious obstacle. The problem has been partially addressed through an integrated effort of the Groundwater Monitoring and Surface Environmental Surveillance projects, with support from the Science and Technology and SAC data gathering tasks.

The first step involved assembling an inventory of riverbank seepage sites from published documents. Geographic coordinates were assigned to each site using an ArcView GIS® (Environmental Systems Research Institute, Redlands, California) coverage for the river shore and the published descriptions for the sites. Maps were then prepared for field use during the fall 2000 riverbank seepage sampling event. Field checking of riverbank seepage sites began in late September 2000 and was completed by late November. Following field investigations to confirm the accuracy of the draft maps, HEIS records were individually reviewed and assigned accurate location information. An inventory of shoreline sampling/monitoring sites was completed following the field checking activities.

(h) Fredrickson, J. K., and D. R. Geist, Pacific Northwest National Laboratory. Personal communication to R. E. Peterson, dated October 1999.

3.4 Evaluation of Mixing Data

The following sections present three different data sets that reveal information on the degree of mixing between groundwater and river water within the zone of interaction, using measurements for specific conductance as the primary indicator of mixing between groundwater and river water. Dilution of groundwater contaminants is a consequence of river water infiltrating the riverbank during periods of high river stage and of river water becoming entrained in the pore space of riverbed sediments. Dilution of contaminants carried by groundwater is controlled by: river stage elevation, stage duration, water table gradient, and hydraulic properties. To provide perspective for the magnitude of seasonal changes in river discharge, the river elevation at 100-H Area during 1993 and 1995 is shown in Figure 3.1.

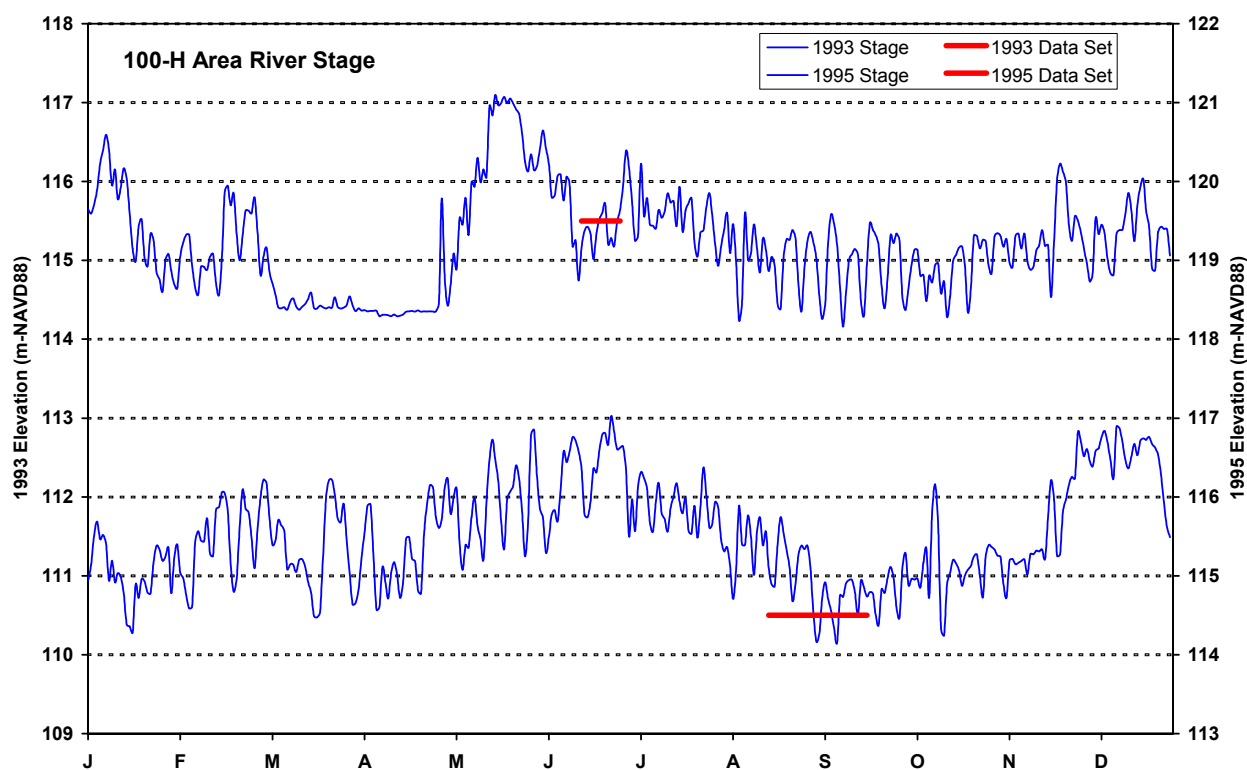


Figure 3.1. River Stage Elevation at 100-H Area

3.4.1 Shoreline Seepage at a Single Location

Starting in 1992, numerous near-river monitoring wells in the 100 Area were equipped with pressure transducers and data loggers to satisfy monitoring requirements created by meeting Tri-Party Agreement Milestone M-30-05. In addition to wells, river stage recorders were also installed at 100-B, 100-H, and 100-F Areas. Some sites were equipped with a specific conductance probe as well, including burial of one probe in a well-established riverbank seepage site in the 100-H Area (seep SH-153).

Figure 3.2 presents a sample of the hourly data recorded at this seepage location, along with hourly records for an adjacent monitoring well and the nearby river stage recorder location. The data source for this and the following figures are electronic archive files currently maintained by the ERC.⁽ⁱ⁾ The data were recorded during the last two weeks of June 1993 and represent average river discharge levels following the annual seasonal high runoff period, which typically starts in May and ends in June (see Figure 3.1). Consequently, in this example, bank storage of river water is relatively high.

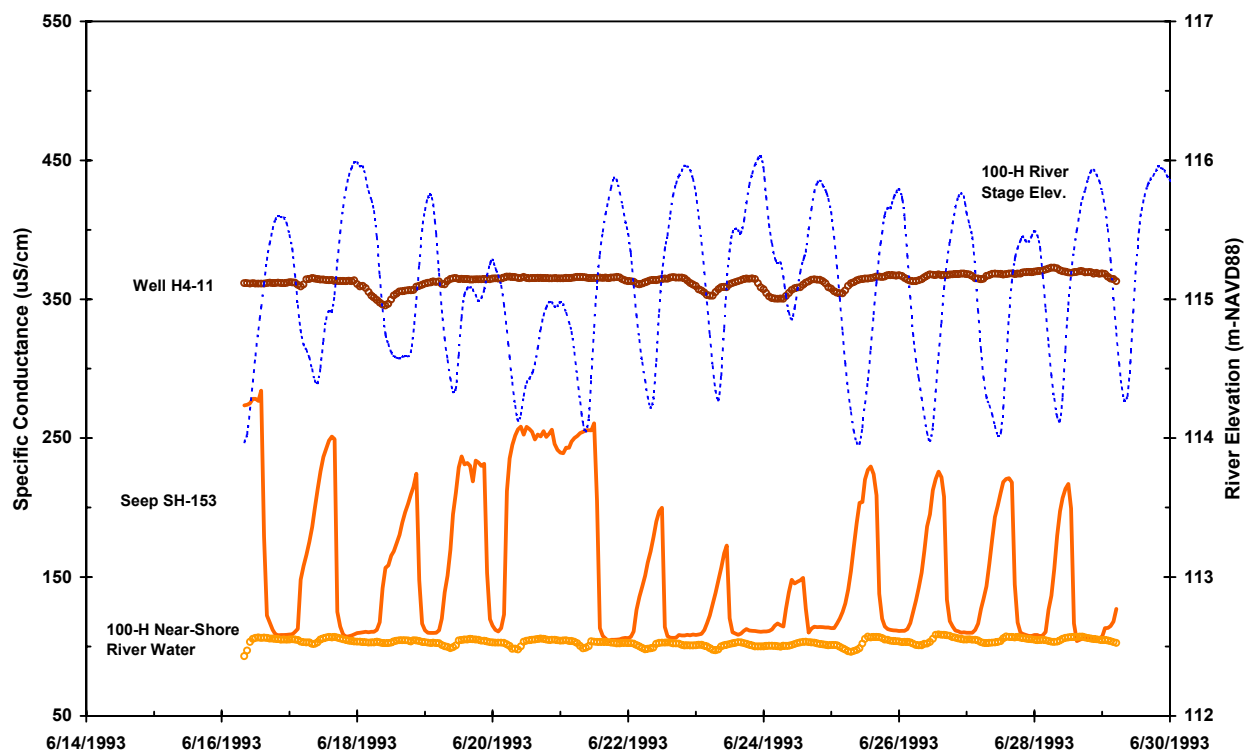


Figure 3.2. Specific Conductance in Seep SH-153 along 100-H Area Shoreline, Summer 1993

The river elevation is superimposed on the specific conductance trends shown in Figure 3.2. The strong negative correlation between river elevation and specific conductance in the riverbank seep is immediately obvious, with specific conductance at the seepage site becoming essentially the same as river water during periods of high river stage, when the seep site is submerged. Conversely, as the river stage falls, the specific conductance increases towards that of groundwater. For this location and period of time, the minimum amount of dilution appears to be approximately 40% river water and 60% groundwater. This minimum persists for only a brief portion of the two-week period shown in the figure. At other times, dilution of groundwater by infiltrating river water is greater. Also, the specific conductance of near-shore river water does not change appreciably with changing river stage, in spite of the increased gradient associated with groundwater flow toward the river during low river stage.

(i) McMahon, W. J., CH2M HILL Hanford, Inc. Personal communication to R. E. Peterson, dated September 2000.

A second sample of hourly data collected in 1995 from an adjacent seepage site (SH-152) reveals a similar but slightly different story. (Note: Data from seep SH-153 for the 1995 time interval could not be used because of specific conductance probe calibration problems). The time period shown in Figure 3.3 represents the seasonal low discharge period for the river, when bank storage of river water is minimal (see Figure 3.1). The seepage from site SH-152 emanates from beneath the concrete spillway at 100-H Area, which was used to discharge reactor coolant into the river during periods of high river stage. The seepage appears to come from a relatively high transmissivity zone of backfill material associated with the reactor coolant outfall structure.

Again, the specific conductance of bank seepage shows a negative correlation with river stage (although the correlation is less distinct than for seep SH-153). Also, bank seepage conductance indicates that dilution for a significant portion of the time portrayed (i.e., five weeks) indicates approximately equal parts groundwater and river water. Groundwater flow at this seepage location appears to be sufficiently strong such that some groundwater is always present in the seepage, even when the seepage site is submerged by the river. This probably indicates a preferential pathway in the aquifer, perhaps as a consequence of engineered structures and backfill.

The differences in dilution characteristics portrayed in Figures 3.2 and 3.3 are best explained by differences in the hydraulic properties of the sediments at the two locations. A secondary influence is that the amount of river water that has infiltrated the bank during the summer period shown in Figure 3.2 is greater than during the late summer/early fall period shown in Figure 3.3.

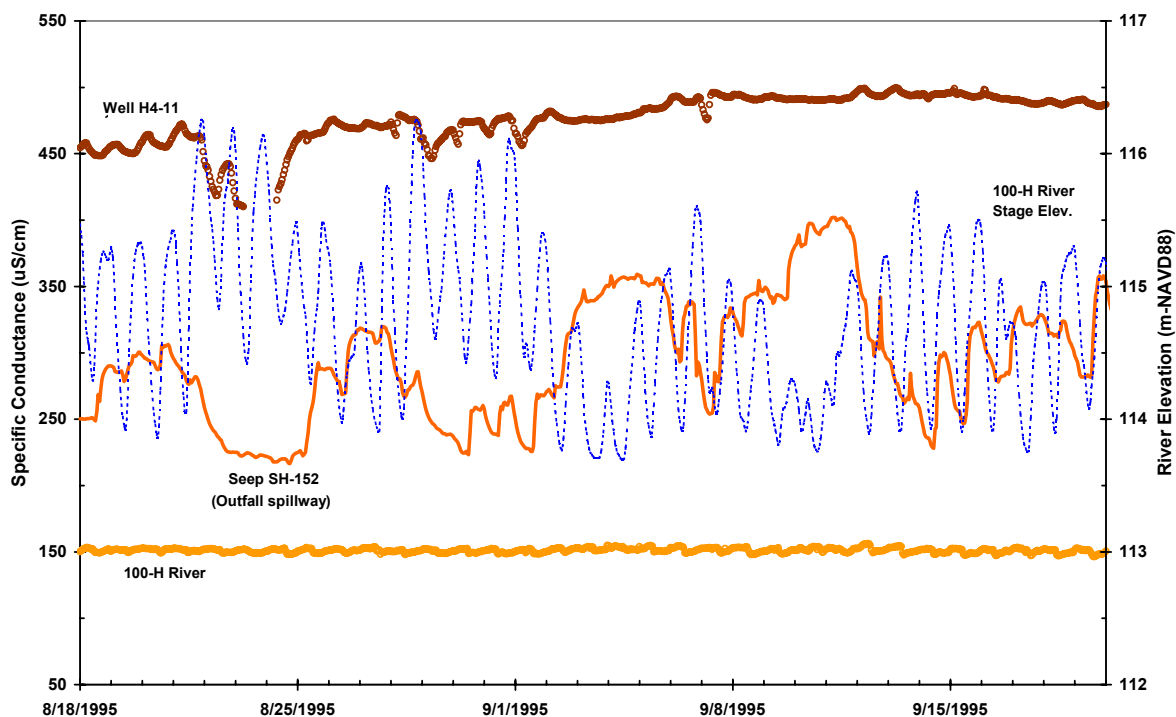


Figure 3.3. Specific Conductance in Seep SH-152 along 100-H Area Shoreline, Fall 1993

The hourly data shown in Figures 3.2 and 3.3 were processed to show the relative proportion of groundwater and river water in each seepage sample, as indicated by the specific conductance values. Frequency distribution charts were prepared for each of the two data sets to provide a sense of how frequently various categories of dilution appear at each seepage site.

Figure 3.4 shows the frequency distribution for seepage site SH-153, where the specific conductance probe is buried approximately 15 centimeters deep in the riparian zone gravels. The horizontal axis is divided into categories of percent river water for each hour's measurement. The vertical axis is the number of hours in each category divided by the total number of hours, thus representing the time element. For example, seepage contained 50 to 54% river water approximately 4% of the time.

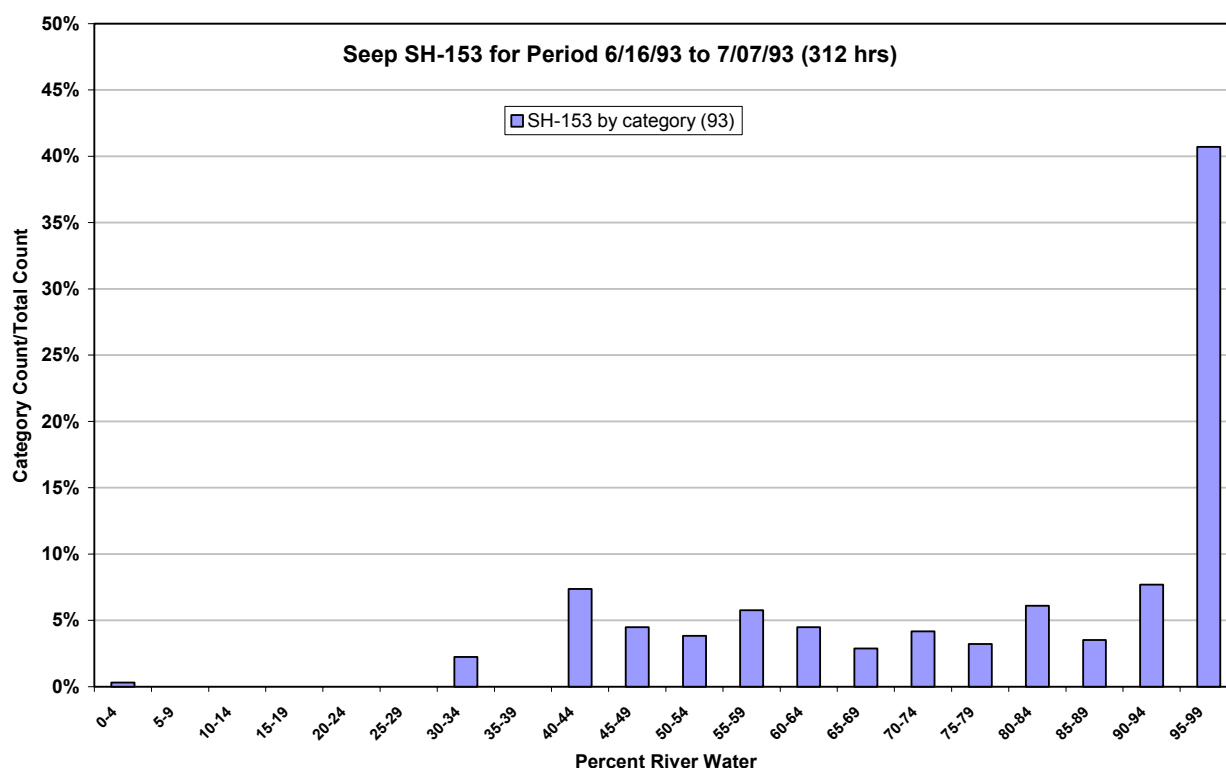


Figure 3.4. Frequency Distribution for Proportion of River Water in SH-153 Seepage

Figure 3.5 shows the distribution for site SH-152, where the specific conductance probe is positioned at an unknown but shallow depth beneath a concrete spillway that is part of an outfall structure. This seepage very likely represents a preferential pathway from the aquifer to the river created by construction of the outfall structure, which involved excavation down to the water table. For this data set, the distribution appears to follow a normal curve, with the most frequent (and probable) proportion of river water being in the 55 to 60% range.

These two examples for the amount and temporal distribution of dilution revealed in seepage by hourly observations at closely spaced locations illustrate the uncertainty associated with assuming a representative coefficient for dilution.

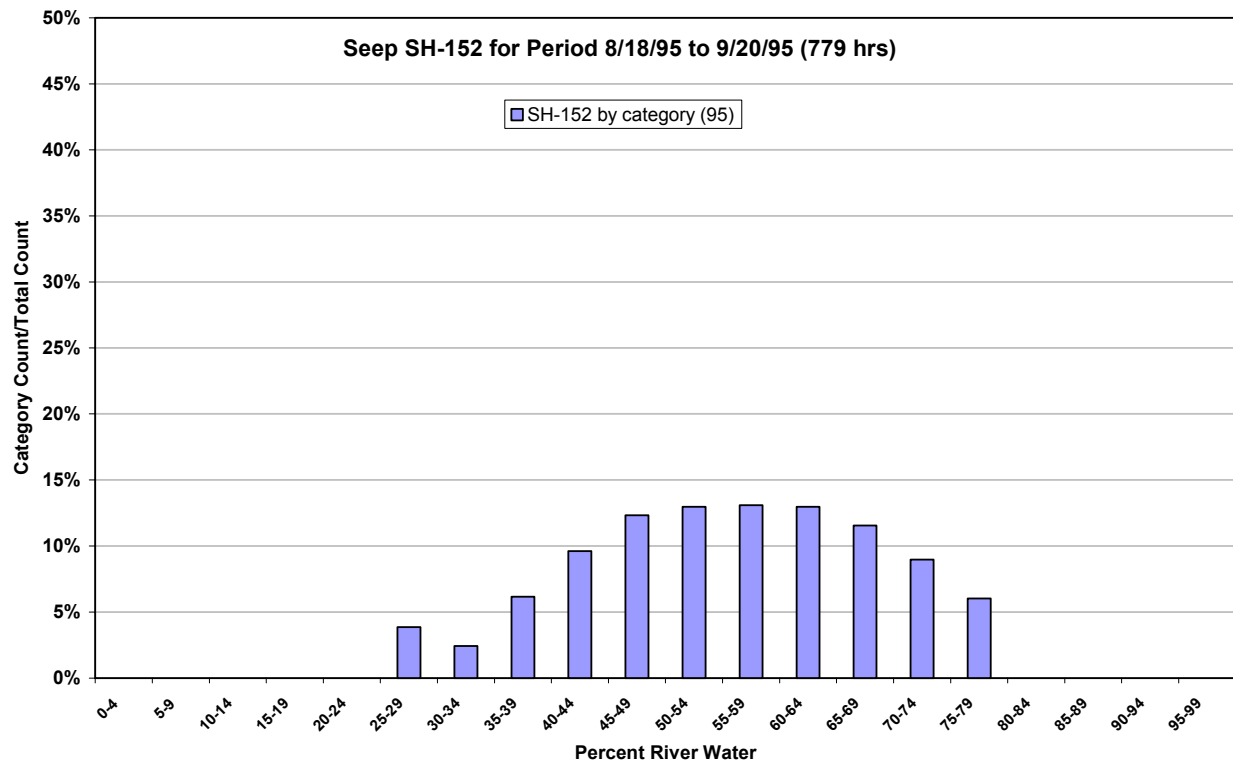


Figure 3.5. Frequency Distribution for Proportion of River Water in SH-152 Seepage

3.4.2 Shoreline Seepage Along the Hanford Reach

A second way to evaluate the effect of dilution near the river involves the spatial distribution of data collected from near- and in-river sampling locations. Very few data sets are available that include results for simultaneous sampling of riverbank seepage, near-shore river water, and nearby monitoring wells. In an attempt to show the relationship between these various monitoring sites, one study combined the sampling results for seeps and near-shore river water from a fall 1991 sampling event (DOE/RL 1992) with estimates for nearby monitoring wells based on projected historical trends for the wells, because current monitoring results were unavailable at the time (Peterson and Johnson 1992).

Shoreline data from the fall 1991 project have been plotted along with actual results from adjacent monitoring wells, to see if the patterns initially displayed become more or less clear. Figure 3.6 is a graph for specific conductance observed in the near-shore river, in riverbank seepage, and in near-river monitoring wells. The geographic area represented extends from the 100-B Area downstream to the 100-F Area. The river condition represented is the seasonal low in discharge that occurs each fall. Typical ranges for specific conductance in uncontaminated groundwater and in near-shore river water are illustrated by the rectangular outlines.

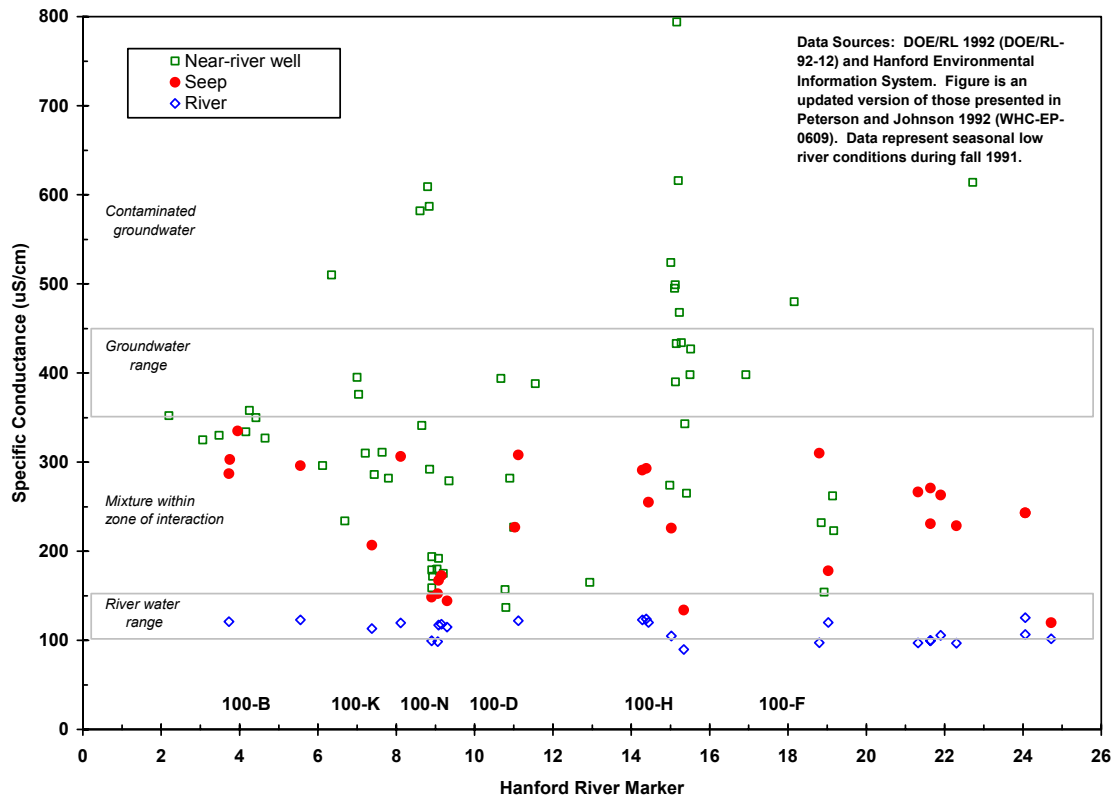


Figure 3.6. Specific Conductance Variability along 100 Area Shoreline, Fall 1991

In Figure 3.6, riverbank seepage appears to be a mixture of groundwater and river water that frequently indicates roughly equal parts from each source. Considerable variability is associated with values for specific conductance in seepage at any particular moment because of the numerous variables that influence the measurement. At any given time of observation, seepage may range in composition from nearly pure groundwater to nearly pure river water. Also, the data plotted in Figure 3.6 are biased in that they represent only the hours between approximately 10 a.m. and 4 p.m. each day when field work is normally conducted, and only when the river discharge is sufficiently low for seepage to appear along the riverbank. In spite of this bias, the generalization that whenever riverbank seepage is exposed during low river stage, its composition reflects some dilution by river water, can be supported. This bias is avoided when data are collected continuously throughout the day and night by in situ sensors and data loggers.

3.4.3 Zone of Interaction Aquifer Samples

In fall 1995, a new method was implemented to obtain samples from the uppermost aquifer at locations as close to the river as possible. The method involved driving a temporary casing into the gravels near the low river stage shoreline and inserting small diameter polyethylene tubing into the casing at multiple depths in the aquifer (Hope and Peterson 1996b). Three horizons in the aquifer were targeted: 1) bottom of the uppermost hydrologic unit, 2) mid-depth in the unit, and 3) two meters below the river elevation.

Specific conductance at one of these locations (site DD-39 along the shoreline near the western boundary of the 100-D Area—the chromium “hot spot”) was measured at periodic intervals following aquifer sampling tube installation in an effort to determine the influence of the river’s seasonal discharge cycle on the aquifer near the river. Planning for future aquifer sampling tube installations required information on how quickly the near-river aquifer would recover from the unusually high river discharge that occurred during 1996 (Peterson et al. 1997). The results of this sampling are shown in Figure 3.7, along with the discharge record for the river. The data are plotted such that results for the shallowest tube are near the top of the graph.

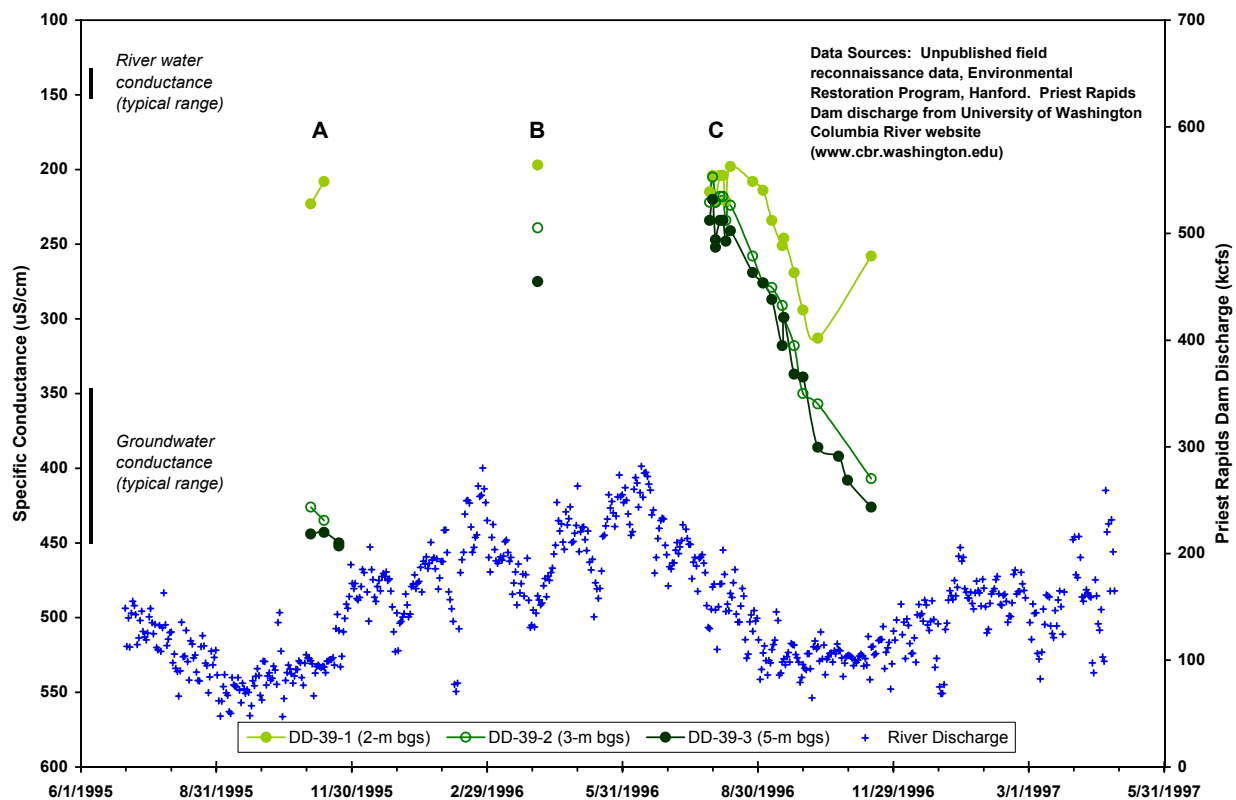


Figure 3.7. Zone of Interaction Response to High Seasonal High River Discharge

Point “A” in Figure 3.7 represents measurements recorded at the time of installation, which occurred just following seasonal low river conditions. The shallowest tube (DD-39-1) shows strong evidence for dilution by river water, while the two deeper tubes appear to be representative of undiluted groundwater. As the discharge of the river increases with progression of the seasonal cycle, the influence of infiltrating river water extends to the deeper sampling tubes (Point B). Samples from the lower two tubes appear to represent roughly equal parts groundwater and river water. This is consistent with the interpretation revealed by the numerical simulation (see previous Section 2) that groundwater flow paths beneath the zone of interaction are displaced downward by infiltration of river water during periods of high river stage.

Finally, starting at Point “C” in Figure 3.7, the degree of dilution by river water in the zone of interaction shows a rapid decrease that continues into the next seasonal low river period. This information provided assurance that the planned installation and sampling of new aquifer tubes along the shoreline during the 1997 field season would produce data that were predominantly representative of groundwater approaching the river. That is, the zone of interaction appears to recover from the influence of unusually high discharge events within the same seasonal cycle of the river.

3.4.4 Dilution of Contaminant Plumes

Additional data for chromium concentrations are available for the 100-D shoreline site described in Section 3.4.3. Numerous chromium concentration and specific conductance measurements were obtained during the period fall 1995 to spring 1996 for water from aquifer sampling tubes and riverbed pore water. Several results for riverbank seepage and groundwater from a near-river well were collected approximately a year later from the same area. The results are plotted in Figure 3.8, which shows chromium concentrations as a function of specific conductance.

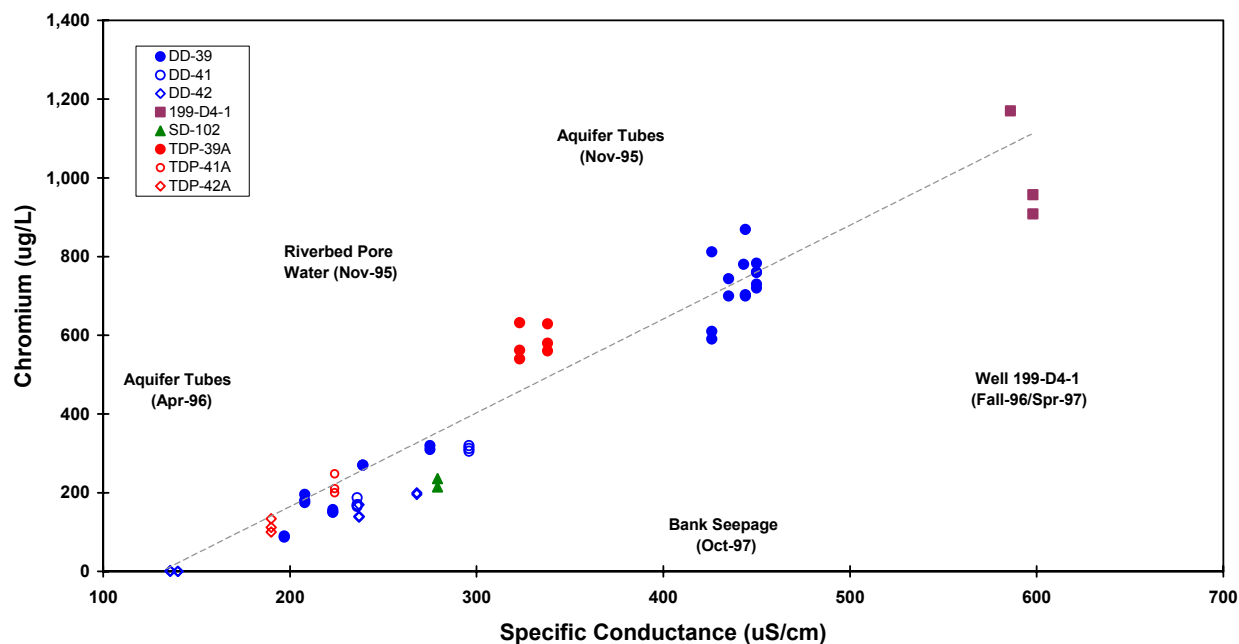


Figure 3.8. Zone of Interaction Mixing Relationship at 100-D Area Chromium Hot Spot

If a homogenous plume of groundwater approaches and mixes with river water, the observed variation in contaminant concentrations should fall along a straight line that represents mixing of the two water types. This appears to be the case at the aquifer sampling tube DD-39 location within the 100-D chromium “hot spot” plume. Repeated measurements of hexavalent chromium and sample specific conductance from aquifer sampling tubes, along with measurements from adjacent riverbed pore water sample sites, riverbank seepage sites, and a near-river monitoring well, all fall along a linear trend. Although not shown on Figure 3.8 to preserve clarity, samples from adjacent locations along the shoreline plot to the right of the trend shown in the figure, indicating the lower chromium concentrations away from the high concentration core of this plume, which passes DD-39.

4.0 Summary and Conclusions

The activities conducted to date under the Groundwater/River Interface task have produced new insight on the movement and mixing of water within the zone of groundwater/river interaction. A discussion of the results and summaries of the key findings are described in the following sections, along with a discussion of the implications of this new information for the Integration Project's System Assessment Capability.

4.1 Two-Dimension Flow Model

The simulation of water movement in the near-river unconfined aquifer demonstrates the strong influence exerted by fluctuations in the Columbia River stage. The rise and fall of the river stage cause the direction and rate of groundwater flow to constantly change, with complete reversals in direction of flow and variability in pore water velocities ranging from nearly motionless to 10 m/d. The simulation files contain a comprehensive record of changes in the groundwater flow field for each hour of simulation, thus allowing a detailed examination of the physical processes associated with the interaction between groundwater and river water.

Water parcel pathlines reveal that a) water flowing from the aquifer to the river is displaced deeper into the aquifer beneath the shoreline, b) discharge of groundwater from the uppermost aquifer occurs relatively close to shore, and c) mixing of groundwater and infiltrating river water occurs in the upper portion of the aquifer. The pathlines suggest that sampling and monitoring activities in the upper portion of the aquifer near the river will produce different information from that which results from sampling at relatively greater depths. This is an important consideration for specifying how to monitor the performance of remedial actions for groundwater near the river.

Water volume flux calculations illustrate that infiltration of river water to the riverbank is an important aspect for calculating total water movement from the aquifer into the river. The amount of water moving across flux plane #2 (see Figure 2.11) can be used to approximate the volume discharged from the aquifer to the river. (Flux planes closer to the river include a component of river water that has infiltrated the bank).

As a test of the credibility of the flux values generated by the model, the flux for the entire Hanford Reach was calculated, using the net transport value across flux plane #2 at the end of the year's simulation. Assumptions include a 7-meter (23-foot) thickness for the aquifer and an interface length of 64 kilometers (40 miles) for the Hanford Reach. At the end of 1998, the cumulative net volume transport across flux plane #2 was 389.876 cubic meters per meter of shoreline (see flux table in CD simulation file for December 31, 1998). This equates to 1.07 cubic meters per day (27.9 cubic feet per second) for the 64 kilometers (40 miles) of shoreline. Previous estimates for the volume flux from the Hanford aquifer to the river are typically quoted as being in the range of 1.53 to 3.82 cubic meters per day (40 to 100 cubic feet per second), though no definitive report on this subject could be located as a reference.

The simulation was run using transient river boundary conditions and a steady-state condition, which simplifies the calculations. The two options produce dramatically different information with regard to the pathlines for water movement, where groundwater is likely to emerge in the river, and the volume flux of water. The simulations emphasize that flow modeling based on steady-state conditions or a time-weighted average (daily, monthly, or seasonal) is not appropriate for examining flow in the near-river unconfined aquifer at scales normally associated with benthic habitat investigations.

Key findings from the model are summarized as follows:

- The two-dimensional flow model for the 100-H Area indicates that as river water infiltrates the bank during high river stage, groundwater flow pathlines are deflected downward beneath the riverbank region.
- Water volume flux across various flux planes indicates that infiltrating river water joins with approaching groundwater and discharges through the riverbed relatively close to the shoreline, i.e., ~40 meters for pathlines from lower part of the unconfined aquifer.
- Flow pathlines become more widely spaced with increased offshore distance, suggesting lower contaminant concentrations at the riverbed interface because of greater surface area. Also, water volume flux horizontally through the aquifer drops off rapidly with increased distance offshore.
- Dilution of groundwater by river water is not evenly distributed within the bank storage zone. The greatest dilution is expected to occur in the immediate vicinity of the shoreline. The degree of dilution is likely to vary widely at a particular location within the zone during each cycle of river stage.
- There are significant differences between pathlines and volume fluxes that result from running the model under transient river conditions (realistic case) compared to steady-state conditions (simplifying assumption). The major differences are
 - The focus of discharge at the riverbed occurs slightly farther offshore under transient conditions than under steady-state conditions, although under either assumption, groundwater discharges relatively near the shoreline.
 - Mixing and dilution are not revealed in model results from computations under the assumption of steady-state conditions, as they are when transient boundary conditions are incorporated.

4.2 Dilution Process

Variations in observed values for specific conductance of samples collected from the zone of groundwater/river interaction are caused by several processes, each having a different time scale. Perhaps the dominant influence is simple mixing between groundwater and river water as the result of infiltration of river water into the banks during periods of high river stage. The degree of mixing that occurs is a function of the stratigraphy at the interface (i.e., how transmissive the bank sediments are); the amplitude

of the river stage change; and the duration of the river stage change. These variables also have temporal aspects that are influenced by daily, seasonal, and climatic cycles.

This investigation has focused on specific conductance measurements to illustrate the degree of dilution that occurs in the zone of interaction, although concentrations of contaminants could also be used. However, except where it can be demonstrated that the particular plume is homogeneous within the area of interest, an additional variable, i.e., concentration gradients within the plume, will influence results. Most contaminant plumes whose sources are reactor area facilities have been migrating to the river for many years. Major inputs to groundwater generally ceased by the mid-1960s as the plutonium production reactors were shut down. Consequently, the highest concentrations associated with a plume may have already passed into the river, and currently-observed plumes near the river should exhibit decreasing concentrations as they pass by monitoring sites near the river.

The principal findings from this analysis are

- Observed water quality characteristics of riverbank seepage nearly always indicate a mixture of river water, which predominates, and approaching groundwater. Exceptions occur in areas where preferential pathways exist, such as zones of very transmissive sediments, backfill, and underground pipelines, which may result in groundwater being the major component.
- The degree of dilution by river water decreases with depth in the aquifer near the river shoreline, as expected. This observation is consistent with the two-dimensional cross-section model for flowpaths beneath the river shoreline. The depth distribution and degree of dilution vary with seasonal river cycles and equilibrium appears to be maintained within the time period of each cycle.
- Contaminant concentrations at the interface vary in response to simple mixing of groundwater and river water where the contaminant plume has a roughly constant concentration over the area of sampling.

4.3 Implications for the System Assessment Capability

The results from the Groundwater/River Interface task contribute to the conceptual model that is part of the Integration Project's System Assessment Capability (SAC) (Kincaid et al. 2000, pg. 3-31). The focus has been to develop a better understanding of how groundwater becomes diluted by river water before being discharged into the river. The new information added to the existing conceptual model for the zone of interaction (described in Section 1.1) pertains to water movement near the shoreline and the uncertainty associated with assigning a dilution coefficient to groundwater as it discharges from the aquifer into the river.

Water Movement

Information on water movement in the aquifer near the river is relevant to SAC with respect to the following: a) grid sizes adopted for the groundwater flow model and b) spatial and temporal scales associated with benthic habitat.

Depending on the grid size adopted for the groundwater flow model in the aquifer near the river, contaminant concentrations predicted at the riverbed interface may be understated because concentrations are averaged over an area larger than the area of focused groundwater discharge. However, if the issue being addressed is that of free-stream water quality, grid size may not necessarily be a crucial factor, because the assumption that all contaminated groundwater from Hanford enters the river is reasonable (i.e., where it enters is not a major factor). Also, the application of a dilution factor for groundwater entering the river is generally not necessary for addressing free-stream water quality issues.

For issues involving benthic habitat and contaminant exposure scenarios for the riparian zone, the “where and when” of groundwater flow discharging to the river environment becomes significant. The two-dimensional model for the 100-H Area indicates a focusing of relatively undiluted flow from the lower part of the aquifer to the riverbed interface at a distance of tens of meters offshore. Beneath the riparian zone, groundwater appears to become diluted by infiltrating river water. The position of focused riverbed discharge relative to sensitive benthic habitat is an important factor for risk analysis. Because the location of focusing changes seasonally, as does the use of benthic habitat, timing becomes an additional factor that is significant for determining risk.

The two-dimensional flow model does not show the influence of river water entrained in riverbed sediment and flowing parallel to the river. This third dimension is undoubtedly important in reducing the concentration of contaminants in groundwater discharging to the riverbed, possibly more so than by the dilution that occurs in the river bank. Adding a third dimension to the flow model would help reveal the relative importance of these two processes in the natural system that cause dilution of contaminants. However, the model becomes much more complex in terms of the number of calculations, calculation time, data file sizes, and assumptions regarding boundary conditions.

Dilution

Any particular observation of the relative proportions of groundwater and river water in a sample at the groundwater/river interface is a product of at least the following variables:

- Volume flux of approaching groundwater.
- Volume flux of infiltrating river water.
- Hydraulic properties in the zone of interaction.
- The amplitude and duration of river stage cycles.
- Site-of-interest position relative to shoreline.

The processes causing dilution in the riverbank, as evidenced by seepage samples, are not necessarily the same as for sediment pore water at the continuously submerged interface. The latter may be strongly

influenced by infiltration of river water moving parallel to the channel (in addition to upwelling groundwater), whereas riverbank seepage observed in the riparian zone is influenced by infiltration of river water moving perpendicular to the channel.

A large portion of the observational data currently available to represent dilution contains additional time and space bias because of the logistics associated with sampling. In situ observational methods are available to reduce this bias. Where accurate contaminant concentration information is required for impact and risk assessment purposes (e.g., benthic habitat), a site-specific analysis of dilution is appropriate for reducing uncertainty.

No simple method is yet apparent to predict a representative coefficient for dilution that reflects all known variables at individual grid locations. However, the assumption that some dilution occurs close to the submerged interface, and is most likely to be approximated by equal parts groundwater and river water, can be supported by observational data. Uncertainty associated with predicting dilution coefficients for specific locations comes primarily from the numerous temporal and spatial variables associated with groundwater/river interaction.

5.0 Directions for Future Research Activities

As described in the Science and Technology roadmap, research activities involving the groundwater/river interface are envisioned to require several years' effort to provide necessary information to various users, and to support established milestones (DOE/RL 2000, Table 4-1). Efforts to date have involved refinements to the conceptual model for the interaction between groundwater and river water at site-specific scales, with emphasis on water movement flowpaths and mixing in the zone of interaction. Subsequent efforts are likely to be directed toward new field studies associated with the various physical, chemical, and biological processes operating within the zone. The results of these investigations will contribute to further improvements in conceptual models that provide the basis for numerical models, which are used for estimating and predicting the characteristics contaminant movement from the aquifer into the Columbia River.

The topical areas where information from field studies is most relevant to near-term information needs include

- Water movement in three dimensions.
- Contaminant attenuation in the zone of interaction.
- Methods to monitor contaminant movement through the zone of interaction.

The following sections offer additional detail on the potential direction for future research activities to support near-term information needs for the Hanford Site. Some of these activities may also contribute to expansion of the fundamental knowledge base for contaminant movement through the natural system.

5.1 Water Movement

Zone of Interaction Hydraulic Test Facility. Installation of new monitoring facilities are envisioned that would allow collection of hourly hydraulic head and specific conductance data from sensors arranged to provide a data set that covers three dimensions. Temporary steel casings can be driven to multiple depths in the aquifer near the river using current Hanford Site technology for installing aquifer sampling tubes. Pressure transducers, specific conductance probes, and other sensors are installed in the casings and connected to data loggers set to capture data at frequent intervals. A station would also be set up in the river adjacent to the array. Collection of data for at least one full seasonal cycle of the river would provide a set of data that could serve multiple objectives—for example, a three-dimensional visualization of water movement within the zone of interaction. The installed casings would be available to other researchers for sample collection and field testing.

Aquifer Hydraulic Properties. Given a data set that covers three dimensions in the uppermost hydrologic unit near the river, high frequency (e.g., hourly) pressure-head measurements can be analyzed to provide detailed information regarding the influence of river stage and atmospheric pressure variations on

the aquifer. Refined estimates for horizontal and vertical hydraulic conductivity can be determined using the pressure pulse created by the fluctuating river stage as the system stressor. The three-dimensional data set might also reveal the degree of heterogeneity in aquifer properties for the volume represented. The results of this effort would strengthen the hydraulic properties assumptions made for groundwater flow and transport models.

Three-Dimensional Simulation of Water Movement. To date, numerical simulation of water movement within the zone of interaction has focused on motion in two dimensions in response to the fluctuating river stage. A three-dimensional water movement simulation would promote a better understanding of the relative importance of a) bank storage of river water and b) entrainment of river water in riverbed sediment, especially with respect to diluting groundwater that discharges to the river. The model could be developed from the existing two-dimensional simulation, which reveals the bank storage aspect of dilution, i.e., the movement of river water perpendicular to the downstream flow. Insight gained is directly relevant to evaluating salmon spawning habitat and whether river water or groundwater plays the more important role in providing a suitable chemical environment for eggs and developing life stages in the substrate.

5.2 Contaminant Attenuation

Dilution of Chromium in the Zone of Interaction. The computer code STOMP, which was used to simulate water movement in two dimensions as described in this report, can accommodate contaminant transport also. Abundant field data on specific conductance and chromium concentrations in near-river wells are available to provide input to the existing two-dimensional simulation. Adding this aspect to the current depiction of mixing, as illustrated by water volume flux calculations, would provide a quantitative visualization of the impact that mixing has on contaminant transport through the groundwater/river interface.

Contaminants and Periphyton at Surface Interface. Periphyton coatings could be collected from riparian zone sediment along both shorelines of the Hanford Reach, from Vernita Bridge downstream to the Richland Pump House. Subsets of organic and inorganic fractions of the coatings would be prepared and the characteristics of each described using microscopy. The subsamples would then be analyzed for metals and radionuclides, and the results compared with adjacent groundwater characteristics. An expected key output from this investigation is information to help differentiate Hanford sources for contamination from other sources, especially with respect to metals in the riparian zone.

Contaminants and Biofilm in Subsurface Interface Zone. The focus of this investigation is to determine if biofilm coatings on subsurface sediments within the zone of interaction concentrate key contaminants (e.g., technetium, uranium, and chromium). Sample collection and analysis methods, such as mechanical harvesting of sediment coatings and artificial media upon which new coatings may accumulate, would have to be developed. Because of the small sample mass expected, micro-analytical methods may be required to evaluate contaminants. An example tool is laser ablation/inductively coupled plasma mass spectroscopy, which can quantify uranium isotopes, technetium-99, and chromium. The chemical characteristics of key contaminants in the dissolved state (i.e., in groundwater) are compared with characteristics in biofilm to determine if chemical changes occur, such as the reduction of hexavalent

chromium to trivalent chromium. An expected output is improved estimates for transfer coefficients (K) to relate contaminant concentrations in groundwater with concentrations per unit mass or unit area of biofilm coatings that accumulate on natural or artificial substrates.

5.3 Monitoring

Design and Test Interface Monitoring Equipment. Chromium and uranium are candidates for analytical systems that would make approximately real-time measurements on samples from the aquifer near the river. Low-flow pumps would be used to obtain water samples from existing facilities, such as aquifer sampling tubes and near-river wells. Sites for chromium sensors include the 100-K, 100-D, and 100-H Areas, and for uranium, the 300 Area. These sites are identified because of a need to evaluate the performance of interim remedial actions currently in progress, and the impending need to develop a strategy (including methods and monitoring sites) for long-term monitoring. Prototype sensors for measuring chromium within a well or temporary casing are under development by various organizations and may become available in the near future for testing at the Hanford Site.

Zone of Interaction Data Collection. Existing sets of simultaneously-collected specific conductance measurements from various portions of the zone of interaction are too limited in duration and distribution to offer detailed information on the predictability of a dilution factor for groundwater-to-river transport models. Installation of *in situ* sensors and data loggers at specific shoreline locations where contamination issues exist would improve the database from which to make estimates/predictions and to characterize the variability of the dilution process. *In situ* sensors at each new station might include a pressure transducer, specific conductance probe (measures temperature also), and hexavalent chromium sensor (dependent on availability). New monitoring equipment could be installed initially along segments of shoreline where groundwater remediation is currently in progress, so that data gathered could satisfy multiple objectives. Subsequent installations might be directed at shoreline segments where current and potential future plumes from the 200 Areas reach the river.

Refinements to Data Management Capabilities. The abundant field data collected by past shoreline monitoring projects are useful for characterizing dilution of groundwater by river water. However, a large amount of data from riverbank seeps and aquifer sampling tubes is not readily available to investigators via electronic databases. Also, documentation for some of the field data and laboratory results stored in the Hanford Environmental Information System (HEIS) is incomplete, creating difficulty in knowing where a particular sample result originated. Many field observations are recorded only in printed reports or field notebooks. Efforts could be directed at a) identifying and compiling historical data from the near-river monitoring activities, b) assisting in formatting the data for the HEIS, and c) recommending procedural controls for entering new shoreline data into the HEIS.

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Appendix A

Instructions for Viewing the Two-Dimensional Simulation

Appendix A

A.1 Instructions for Viewing the Water Movement Animation Files

Insert the CD-ROM into your computer and wait for Windows Explorer to acknowledge its presence. Typically, the contents of the CD will appear on your D: or E: drive. The animation sequences are viewed by running the FRAMER™ program (Amtec Engineering, Bellevue, Washington). This program is distributed for use without cost to view the animations, as long as the licensing agreement file is included with the animation files (see “Frmlic.htm”).

A.2 Starting an animation sequence

Double-click on the file “00Framer.bat” to start the viewing process. A menu will appear that provides a list of several possible files to open. Select the desired sequence (e.g., “03Jan-May.rm”) and click OPEN. Once the initial graphic is displayed, enlarge the window to full screen for easiest viewing.

Use the “GO” and “STEP” menus at the top left of the screen to control the animation. The following keyboard and mouse controls are also available to control the display:

- “F” key = move forward through images
- “B” key = move backward through images
- “C” key = cycle through images first to last, last to first, etc.
- “L” key = loop through images first to last, first to last, etc.

- “1” key = move to first image
- “+” and “-” keys = move forward/backward one image
- “<” and “>” keys = decrease/increase speed

- “S” key or space bar = stop moving through images
- “Q” key or Escape key = exit the current animation; then close FRAMER™

(Mouse control may vary from the following, depending on installed mouse configuration)

- Left mouse button = move backward through images
- Middle (or right) mouse button = move forward through images
- Right (or middle) mouse button = exit the current animation; then close FRAMER™

A.3 To start viewing a different animation sequence

Exit the current animation and close FRAMER™ using one of the several methods listed above. Then restart FRAMER™ by double-clicking on the “00Framer.bat” file and selecting a different time sequence or animation (i.e., the “(sequence).rm files).

A.4 Supplemental technical information on command line options for FRAMER™

Usage: FRAMER™ options rastermetafile

A.4.1 Options

[-b [#]] [-bg color] [-c maxcolors] [-d[#] log] [-f #,#,#] [-g]
[-help] [-geom geometry] [-m] [-sync] [-p #] [-x] [-v]
[-noinfo] [-cycle # | -loop #] [-max #] [-newcmap]
[raster_metafile_name]

-b <i>nf</i>	Use buffered mode reads <i>nf</i> frames into memory and only displays those frames.
-bg color	Change background color
-cycle <i>nn</i>	Cycle through frames <i>nn</i> times
-d <i>dfile</i>	Send debug information to file use -d2 -d3 or -d4 for more information
-f <i>start,stop,skip</i>	Display frames starting with frame number <i>start</i> ending with frame number <i>stop</i> and skipping by <i>skip</i> frames
-g	Use gray scale for image instead of colors
-help	Print help information
-loop <i>nn</i>	Loop <i>nn</i> times through the file
-m	Allow multiple color maps (Needed for these animations)
-max <i>nn</i>	Specify upper limit for number of frames default if 512 (set to 5000 for 100-H Animations)
-noinfo	Don't print copyright notice
-p <i>ms</i>	Pause at least <i>ms</i> milliseconds between frames
-w <i>wc</i>	Width correction for older versions of the raster metafile
-x	Run in full screen

The following files are on the two CD-ROM's included with PNNL-13674:

_readme.txt (Disks 1 and 2): This file provides a listing and description of the files contained on each of the two CD-ROMs.

Framer.exe (Disks 1 and 2): The FRAMER™ (Amtec Engineering, Bellevue, Washington) program is used to animate the hourly graphics displays for each time sequence (i.e., the “__.rm” files).

FramerInstructions.doc (Disks 1 and 2): Instructions for using the FRAMER™ program to control the animations.

Frmlic.htm (Disks 1 and 2): License agreement for the FRAMER™ program. FRAMER™ can be freely distributed provided this file is included in the distribution.

02CrossSection.bat (Disk 1): Batch file that runs the animation file “02CrossSection.rm,” which shows the three-dimensional spatial model for the 100-H Area. Includes a series of cross sections oriented perpendicular to the river channel in full-screen mode. Double-click to start the animation.

02CrossSection.rm (Disk 1): Animation file containing the spatial model and cross sections for the 100-H Area.

01Well_Diagram.bat (Disk 1): Batch file that runs the sequence of construction diagrams and location information for 100-H Area wells that are contained in the animation file “01Well_Diagram.rm.” Runs in full screen mode. Double click to start the animation.

01Well_Diagram.rm (Disk 1): Animation file containing construction diagrams and location information for 100-H Area wells.

00Framer.bat (Disks 1 and 2): Starts animations using the FRAMER™ program with appropriate arguments. This batch file will bypass the FRAMER™ default setting of only 512 frames, which would apply if the sequence files were run directly. This batch file also allows the user to select a sequence file to animate. Double click on “00Framer.bat” to start the FRAMER™ program and view a sequence animation.

03Jan-May.bat (Disk 1): Batch file that runs the animation file “03Jan-May.rm” which shows water movement in the zone of groundwater/river interaction from January through May 1998 in full screen mode. Double click to start the animation.

03Jan-May.rm (Disk 1): Animation file containing water movement simulations at hourly intervals for the period January through May 1998.

04May-Aug.bat (Disk 2): Batch file that runs the animation file “04May-Aug.rm” which shows water movement in the zone of groundwater/river interaction from May through August 1998 in full screen mode. Double click to start the animation.

04May-Aug.rm (Disk 2): Animation file containing water movement simulations at hourly intervals for the period May through August 1998.

05Sep-Dec.bat (Disk 2): Batch file that runs the animation file “05Sep-Dec.rm” which shows water movement in the zone of groundwater/river interaction from September through December 1998 in full screen mode. Double click to start the animation.

05Sep-Dec.rm (Disk 2): Animation file containing water movement simulations at hourly intervals for the period September through December 1998.

Appendix B

Geohydrologic Characterization for the 100-H Area

Appendix B

Geohydrologic Characterization for the 100-H Area

B. N. Bjornstad

A considerable amount of work has been conducted previously to characterize the hydrogeology of the 100-H Area. Three principle driving needs were 1) vadose zone and groundwater contamination associated with the former 183-H Solar Evaporation Basins (Liikala et al. 1988), 2) remedial investigations associated with the 100-HR-3 Groundwater Operable Unit (Peterson et al. 1996), and 3) consideration for using the 100-H Area as a field test facility for bioremediation research. The following summarizes descriptions from some of the numerous previous investigations and provides updates made possible by the recent installation of several new monitoring wells.

B.1 Geomorphology

The 100-H Area lies on an essentially low-relief, semiarid bench south of the Columbia River. The elevation of the area ranges from river level (~116 meters [380 feet]) to 130 meters (425 feet) above mean sea level. The land surface slopes gradually toward the river, with a bank up to 10 meters (30 feet) at the edge of the river. The surface topography of the 100-H Area reflects erosion by the meandering river (i.e., channeling) of the area during periodic floods that occurred prior to construction of upstream dams.

Prior to 1933, when the Columbia River was free flowing, periodic large floods occurred that affected the 100-H Area. This is indicated by a series of fluvial channels that dissect older cataclysmic-flood and fluvial deposits in the 100-H Area. These channels were probably last occupied during the largest known unregulated historical flood, which occurred in 1894 and is estimated to have a discharge of 21,000 m³/s (750,000 ft³/s) (Neitzel 1998). The largest recent flood at the Hanford Site took place in 1948 with an observed peak discharge of 20,000 m³/s (706,280 ft³/s). The 1948 flood did not inundate the 100-H Area. An estimate of the 100-year dam-regulated flood is 12,400 m³/s (440,000 ft³/s) (Neitzel 1998). The 100-year regulated flood would not affect the 100-H Area. The Columbia River flow is now controlled by a series of dams located both upstream and downstream of the Hanford Site. The nearest upstream dam is Priest Rapids, constructed in 1961 and the nearest downstream dam is McNary, constructed in 1952.

The Columbia River channel adjacent to the 100-H Area is up to 1,310 meters wide (4,300 feet) and up to 15 meters deep (50 feet). A mid-channel island (Locke Island) divides the channel in two. The island consists of mostly fine-grained Holocene-age alluvium underlain by coarse-grained cataclysmic-flood deposits (Nickens et al. 1998).

Since the 1970s, irrigation-induced landslides have been slumping into the river across from the 100-H Area (Schuster et al. 1987). These landslides are coming off a 100-meters embankment (300-feet) referred to as the White Bluffs, which run along the northeast bank of the river. The slides have been deflecting the river to the southwest, thus restricting the channel adjacent to Locke Island and causing significant erosion of the island's northeast bank (Nickens et al. 1998).

A dramatic set of gravel bedforms exists within the river channel at the north end of Locke Island, just upstream from the 100-H Area. The bedforms are up to 3 meters in height (10 feet) and spaced approximately 30 meters apart (100 feet). They appear to be relict giant-current ripple marks created by floods associated with the last ice-age (Nickens et al. 1998). These partially submerged, coarse-textured bedforms appear in some locations to have been modified by contemporary river processes. They probably extend laterally beneath the Holocene alluvium that blankets most of Locke Island. They also are likely to exist elsewhere within the Hanford Reach and may play a role salmon spawning habitat (Geist and Dauble 1998).

B.2 Stratigraphy

Bedrock beneath the Hanford Site and the 100-H Area consists of the Miocene Columbia River Basalt Group and its interbedded sedimentary deposits of the Ellensburg Formation. Overlying this bedrock are suprabasalt sediments that reach approximately 100 meters (300 feet) in thickness. These sediments belong to the Miocene-Pliocene Ringold Formation and Pleistocene Hanford formation (not yet formalized nomenclature).

The Columbia River Basalt Group consists of continental flood basalts, which erupted from linear vents within northeastern Oregon, eastern Washington, and western Idaho between 17 to 6 million years ago. The Saddle Mountains Basalt forms the uppermost basalt unit in the Pasco Basin except along some of the bounding ridges where Wanapum and Grande Ronde Basalt flows are exposed.

The fluvial-lacustrine Ringold Formation was deposited in generally east-west trending valleys by the ancestral Columbia River and its tributaries in response to development of the Yakima Fold Belt. Ringold sediments are dominated by lacustrine and overbank deposits and associated paleosols in the 100-H Area, with very little appearance of gravel facies, which characterize the Ringold Formation elsewhere in the Pasco Basin.

The Ringold Upper Mud Unit comprises the upper 30-38 meters (100-125 feet) of the Ringold Formation. In a hydrologic sense, the upper mud unit is roughly equivalent to hydrostratigraphic unit 4, as defined by Thorne et al. (1993) for the Hanford sitewide groundwater flow model. The unit has a total thickness between 75 and 82 meters (250-270 feet) within the 100-H Area. Much of the Upper Mud appears to represent weathered fluvial and overbank deposits, including caliche and other types of paleosols. The unit is described as a moderately consolidated, yellowish, reddish, and brown sand, silt and/or clay. The average grain size distribution is reported as approximately 20% sand, 55% silt, and 25% clay (Fruchter et al. 1996). It is an aquitard and represents the bottom boundary for the potentially contaminated uppermost hydrologic unit beneath the 100-H Area.

The upper surface of the Ringold Upper Mud Unit was scoured out during Pleistocene cataclysmic flooding, which subsequently deposited the Hanford formation. The relief created on the top of the Ringold suggests the presence of northwest-southeast trending flood channels, with at least two buried ridges observable beneath the 100-H Area. Along these ridges, the contact between the Ringold and overlying Hanford formation comes close to the water table. The undulating surface at this contact may have a significant influence on flow geometry and transmissivity within the uppermost hydrologic unit beneath the 100-H Area, as will be illustrated in Section 2.3.

Differences in color, degree of consolidation, and sedimentary particle size between the Ringold and the overlying Hanford formation usually make identifying the contact between the two units easy in the 100-H Area. However, at some locations fine-grained Ringold material appears to have been ripped up during flooding and incorporated into the overlying Hanford sediments during their deposition. Where this has occurred, it may be more difficult to distinguish the contact.

The Hanford formation consists primarily of the gravel-dominated facies, with local occurrences of the sand-dominated or silt-dominated facies. The Hanford formation generally thickens from north to south, ranging from 10-20 meters (30-65 feet), and disconformably overlies fine-grained facies of the Ringold Formation. The average grain-size distribution for the Hanford formation is 43% gravel, 50% sand, and 7% silt and clay (Vermeul et al. 1995).

B.3 Hydrology

The hydrologic units beneath the 100-H Area include the a) uppermost unconfined unit that resides primarily in the Hanford formation gravels, b) semi-confined units in more transmissive facies of the Ringold Formation, and c) confined aquifers near the base of the Ringold Formation and in the underlying Columbia River Basalt Group.

The hydraulic parameters of saturated hydraulic conductivity (K) and transmissivity are summarized in Table 2.1. As shown in the table, the Hanford formation generally has up to an order-of-magnitude greater K and transmissivity than the Ringold Formation. Because the Ringold sediments are finer grained, more consolidated, and, in places, partially cemented, they are generally much less permeable than the sediments of the overlying Hanford formation. Within the 100-H Area saturated hydraulic conductivities within the Ringold Formation (upper mud unit) generally range from about $9.9\text{E-}07$ to $2.5\text{E-}03$ m/s ($2.6\text{E-}06$ to $8.2\text{E-}03$ ft/s) compared to $3.5\text{E-}04$ to $4.2\text{E-}02$ m/s ($1.1\text{E-}03$ to $1.4\text{E-}01$ ft/s) for the Hanford formation. Transmissivity values average $64\text{ m}^2/\text{d}$ ($690\text{ ft}^2/\text{d}$) for the Ringold upper mud unit compared to $259\text{-}672\text{ m}^2/\text{d}$ ($2790\text{-}7230\text{ ft}^2/\text{d}$) for the Hanford formation.

The water table ranges in depth from near 0 meters at the river edge to 30 meters (107 feet) across the 100-H Area. Groundwater flow direction is generally towards the river. Groundwater flow near the river is strongly influenced by fluctuations in Columbia River stage, which is controlled by dams. River stage can vary 1.8 to 2.4 meters daily (6 to 8 feet) and 2.4 to 3.0 meters seasonally (8 to 10 feet). The hydraulic gradient is greatly increased near the river during periods of low flow. As the river stage increases, the gradient becomes less and may even reverse direction in response to the highest stages that occur.

Table B.1. Saturated Hydraulic Conductivity and Transmissivity Values Measured for Suprabasalt Sediments Within the 100-H Area

Saturated Hydraulic Conductivity			
Hanford formation			
Average (m/s [ft/s])	Range (m/s [ft/s])	n	Reference
7.3E-04 (2.4E-03)	2.5E-04 to 1.1E-03 (8.2E-04 to 3.6E-03)	6	Vermeul et al. (1995)
1.1E-03 (3.6E-03)	3.5E-04 to 5.6E-03 (1.1E-03 to 1.8E-02)	10	DOE/RL (1994)
5.4E-03 (1.8E-02)	3.5E-04 to 4.2E-02 (1.1E-03 to 1.4E-01)	13	Liikala et al. (1988)
Ringold Formation			
Average (m/s [ft/s])	Range (m/s [ft/s])	n	Reference
2.5E-04 (8.2E-04)	7.1E-05 to 4.2E-04 (2.3E-04 to 1.4E-03)	7	DOE/RL (1994)
7.9E-04 (2.5E-03)	9.9E-07 to 2.5E-03 (2.6E-06 to 8.2E-03)	4	Liikala et al. (1988)
Transmissivity			
Hanford formation			
Average (m ² /d [ft ² /d])	Range (m ² /d [ft ² /d])	n	Reference
259 (2,790)	158-297 (1,700-3,200)	11	Vermeul et al. (1995)
672 (7,230)	51-4,970 (550-53,480)	13	Liikala et al. (1988)
Ringold Formation			
Average (m ² /d [ft ² /d])	Range (m ² /d [ft ² /d])	n	Reference
64 (690)	0.09-164 (1-1,760)	4	Liikala et al. (1988)

Normal peak discharge occurs during June while normal low flow occurs in October and November. River stage fluctuations can be detected in wells up to 610 meters (2,000 feet) inland from the river. Confined aquifer layers have potentiometric surfaces that are generally above those of the unconfined aquifer. The groundwater gradient varies depending on the distance from the river and the time of year. The hydraulic gradient ranges from 0.0006 to 0.0020 m/m (average = 0.0009) across the site (DOE/RL 1994; Fruchter et al. 1996).

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