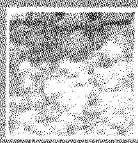
STRATUS CONSULTING



Hanford Site Natural Resource Damage Assessment Conceptual Site Model

Prepared for:

Hanford Natural Resource Trustees:
Confederated Tribes and Bands of the Yakama Nation, Confederated Tribes of the Umatilla Indian Reservation, National Oceanic and Atmospheric Administration, Nez Perce Tribe, State of Oregon, State of Washington, U.S. Department of Energy, U.S. Fish and Wildlife Service

Hanford Site Natural Resource Damage Assessment Conceptual Site Model

Prepared for:

Hanford Natural Resource Trustees:
Confederated Tribes and Bands of the Yakama Nation
Confederated Tribes of the Umatilla Indian Reservation
National Oceanic and Atmospheric Administration
Nez Perce Tribe
State of Oregon
State of Washington
U.S. Department of Energy
U.S. Fish and Wildlife Service

Prepared by:

Stratus Consulting Inc.
PO Box 4059
Boulder, CO 80306-4059
303-381-8000

Contacts:

Joshua Lipton
Jamie Holmes

July 1, 2009
SC11654

Contents

Figures

Tables

List of Acronyms and Abbreviations

ALE	Arid Lands Ecology
BEHP	bis-(2-ethylhexyl) phthalate
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
cfs	cubic feet per second
CRBG	Columbia River Basalt Group
CSM	conceptual site model
CTUIR	Confederated Tribes of the Umatilla Indian Reservation
CWA	Clean Water Act
D4	decommission, deactivation, decontamination, and demolition
DDD	dichlorodiphenyldi-chlorethane
DDE	dichlorodiphenyldichloro-ethylene
DDT	dichlorodiphenyltrichloro-ethane
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOI	U.S. Department of the Interior
EPA	U.S. Environmental Protection Agency
ERDF	Environmental Restoration Disposal Facility
FFTF	Fast Flux Test Facility
FS	Feasibility Study
gpm	gallons per minute
HEDR	Human Environmental Dose Reconstructions
HNRTC	Hanford Natural Resource Trustee Council
IDF	Integrated Disposal Facility
kg/yr	kilograms per year
km/hr	kilometers per hour

LAW	low activity waste
LIGO	Laser Interferometer Gravitational-wave Observatory
LLRW	low-level radioactive waste
μCi/g	microcuries per gram
μg/L	micrograms per liter
m/d	meters per day
m^3/s	cubic meters per second
mCi/g	millicuries per gram
MEI	maximum exposed individual
mg/L	milligrams per liter
MLLW	mixed low level waste
mm/year	millimeters per year
mmho/cm	millimhos per centimeter
NAPL	non-aqueous phase liquid
NARM	naturally-occurring and accelerator-produced material
NEPA	National Environmental Policy Act
NOAA	National Oceanic and Atmospheric Administration
NPL	National Priorities List
NRDA	natural resource damage assessment
OPA	Oil Pollution Act
PAH	polycyclic aromatic hydrocarbon
PCB	polychlorinated biphenyl
pCi/L	picocuries per liter
PFPP	Plutonium Fuels Pilot Plant
ppb	parts per billion
ppm	parts per million
PRB	permeable reactive barrier
PRTR	Plutonium Recycle Test Reactor
PUREX	Plutonium-Uranium Extraction
RCRA	Resource Conservation and Recovery Act
REDOX	Reduction-Oxidation
RI	Remedial Investigation
ROD	Record of Decision

SALDS	State-Approved Land Disposal Site
SDWA	Safe Drinking Water Act
SESP	Surface Environmental Surveillance Project
SWDA	Solid Waste Disposal Act
2,4-D	2,4-dichlorophenoxyacetic acid
TBq/yr	terabecquerel per year
TEDF	Treated Effluent Disposal Facility
TNC	The Nature Conservancy
TSP	Technical Steering Panel
USBOR	U.S. Bureau of Reclamation
USFWS	U.S. Fish and Wildlife Service
VOC	volatile organic compound
WDFW	Washington Department of Fish and Wildlife
WIDS	Waste Information Data System
WIPP	Waste Isolation Pilot Plant

1. Introduction

This report contains a conceptual site model (CSM) for the Hanford natural resource damage assessment (NRDA). The CSM was prepared on the behalf and with the active participation of the Hanford Natural Resource Trustee Council (HNRTC). The natural resource trustee agencies and tribal governments that comprise the Trustee Council include the Confederated Tribes and Bands of the Yakama Nation, the Confederated Tribes of the Umatilla Indian Reservation (CTUIR), the Nez Perce Tribe, the Washington Department of Ecology and Department of Fish and Wildlife (WDFW) (on behalf of the State of Washington), the Oregon Department of Energy (on behalf of the State of Oregon), the U.S. Department of Energy (DOE), the U.S. Fish and Wildlife Service (USFWS) (on behalf of the U.S. Department of the Interior, DOI), and the National Oceanic and Atmospheric Administration (NOAA) (on behalf of the U.S. Department of Commerce). The Hanford Site ("the Site"), located in southeastern Washington State, was developed as a plutonium production facility beginning in 1943. Since production ended in the late 1980s, the DOE has led a large cleanup effort at the Site. The purpose of the CSM is to describe a conceptual model of the site that will aid in assessing natural resource injuries.

1.1 Overview

The NRDA CSM has been developed to assist injury assessment planning, coordination between Remedial Investigation/Feasibility Study (RI/FS) and natural resource damage data collection and analysis, and data review, including future identification of potential data gaps. The NRDA CSM has been designed to address the fundamental elements of NRDA and therefore integrates individual CSMs that address the stressors associated with contaminant releases and subsequent response actions; the pathways by which stressors affect natural resources and the services they provide (including how substances are transported in the environment); where and how natural resources and the services they provide may be adversely affected (both directly and indirectly) by those stressors; and the nature of adversely affected ecological and human services.

Figure 1.1 presents a simple depiction of the relationship between the seven individual CSMs that comprise the overall NRDA CSM. These CSMs include the Stressor CSM, which addresses various environmental stressors at the site (including contaminant releases of and subsequent effects from response actions); the Pathway CSM, which considers the pathways through which natural resources and humans may be exposed to or adversely affected by stressors; the Natural Resources CSMs, which address the resources that may have been exposed to and potentially injured by stressors from the Site; and the Human Services CSM, which considers human use services associated with natural resources at the Site.

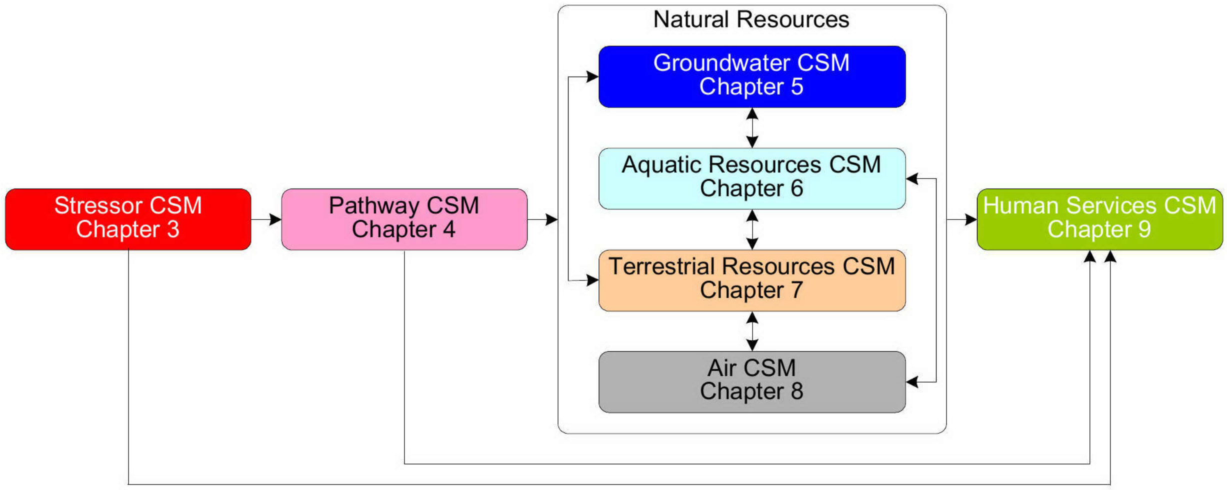


Figure 1.1. Relationship between individual CSMs that make up the NRDA CSM.

The CSM is intended to frame issues that the Trustees will need to address as part of the injury assessment. Although based on review of a considerable amount of existing information and data together with detailed technical input from Trustee representatives during CSM planning workshops, the CSM is not a comprehensive review of all literature pertaining to Hanford operations or potential releases, nor is it intended to serve as a blueprint for an injury assessment plan. Rather, the CSM provides an overview of how site information relates to key steps in the injury assessment process, including releases of hazardous substances, transport and exposure processes, and potential injuries to natural resources.

1.2 Temporal Scope of the CSM

The temporal scope of the CSM explicitly recognizes that natural resource damage authorities enable the Trustee Council to quantify damages for losses that have occurred in the past, are ongoing at the present time, and may reasonably be expected to occur or continue to occur in the future. The CSM contemplates and provides for consideration of past, present, and future injuries and damages.

1.3 Spatial Scope of the CSM

The spatial scope of the CSM includes the entire Hanford assessment area, encompassing the full geographic extent of the areas where hazardous substances (and their by-products) released from the Site may have come to be located, as well as the geographic extent of natural resources that may have been injured as a result of exposure to those stressors. A CSM for natural resource injury assessment considers such a comprehensive geographic scope to facilitate thoughtful assessment planning; it is not intended to draw or imply conclusions about the spatial extent of natural resource injuries. The spatial scope of potential environmental exposures and natural resource injuries is dynamic and must reflect temporal changes in site operations, releases and transport of hazardous substances, as well as potential natural resource injuries that may occur in the future.

1.4 Other NRDA Documents

The Hanford Natural Resources Trustees have published several preassessment screen documents for the Hanford Site. The purpose of a preassessment screen is to provide a rapid review of readily available information to ensure that there is a reasonable probability of making a successful claim for natural resource damages. A preassessment screen is typically more narrowly focused than a CSM, and it focuses specifically on the likelihood of natural resource injuries resulting from contaminant releases. This CSM has a broader focus, with the goal of assisting the Trustees with future injury assessment planning.

Some existing preassessment screens from the Site include:

- A 100 Area draft preassessment screen (HNRTC, 1998) that concluded that the criteria for pursuing NRDA in the 100 Area had been met.

- An 1100 Area preassessment screen (HNRTC, 2000) conducted prior to its deletion from the Federal list of Superfund sites (see Chapter 3). This document concluded that the criteria for pursuing NRDA in the 1100 Area had been met, but rather than pursuing an assessment at that time, the Trustees accepted a proposal for additional sampling and monitoring.

- A draft preassessment screen for the entire Hanford assessment area that Ridolfi (2006) authored on behalf of the Yakama Nation. This preassessment screen is considerably more detailed than the previous ones. Ridolfi (2006) concluded that criteria had been met for pursuing a site-wide NRDA. This preassessment screen was apparently not made final and has not yet been endorsed by all Trustees. The Ridolfi (2006) preassessment screen contains site data and a CSM that are useful for injury assessment planning. Relevant information from that preassessment screen is included in this document.

- A preassessment screen for the Hanford assessment area drafted by the CTUIR (2008). The CTUIR preassessment screen largely adopts the content of the Ridolfi (2006) preassessment screen, with a different cover page and some additional language and sections specific to the CTUIR.

1.5 Existing Site CSMs

In developing this document, we have reviewed and relied upon existing CSMs prepared for the site, including CSMs developed as part of Hanford RI/FS activities or other activities at the Site, CSMs developed for Tribal risk scenarios, and a CSM developed for a draft Hanford NRDA preassessment screen (see below).

The CSM presented herein is intended as an NRDA planning tool to help facilitate injury assessment planning. Consequently, certain elements differ from existing Site CSMs. This does not imply that the existing CSMs, which are designed to address different needs, are flawed. The goals and needs in NRDA differ from those in other planning processes, and the Trustee Council has a specific set of objectives that must be considered. To the extent, however, that the NRDA and existing CSMs share common attributes, these commonalities should be used to facilitate efficiencies in data collection and analysis.

Selected existing CSMs for the Site, in chronological order, include the following:

- A generic human exposure CSM developed to assess past exposure to Hanford radionuclide releases (Napier, 1991)
- An aquatic ecological CSM in the Columbia River Comprehensive Impact Assessment (PNNL, 1998)
- A Tribal services CSM developed for assessing risks to Tribal community health and culture (Harper and Harris, 2000)
- CSMs describing the environmental pathways of Site contamination and associated risk implications in a Hanford impact assessment (Bryce et al., 2002)
- A CSM guidance document for Hanford, presenting methods for using process relationship diagrams (Last et al., 2004)

- CSMs describing the fate of tritium discharged from the 200 Area Effluent Treatment Facility into the State-Approved Land Disposal Site (Barnett et al., 2004)
- CSMs for aquatic and terrestrial ecological and human receptors in the 100 Area developed for the 100-B/C pilot project (Doctor et al., 2004)
- A CSM for a uranium plume in the 300 Area and tritium in the 618-11 Burial Ground, developed for the annual groundwater monitoring report (Freeman et al., 2005)
- A CSM for contamination in liquid waste disposal facilities in the 100-N Area, developed for the 100-NR-2 groundwater operable unit risk assessment (Fluor Hanford, 2005; U.S. DOE, 2005)
- A geospatially-based general Site CSM for ecological and human exposure, published in a peer-reviewed journal (Mayer and Greenberg, 2005)
- A groundwater flow CSM for the Site (Thorne et al., 2006)
- A CSM developed in a draft Hanford preassessment screen on behalf of the Yakama Nation (Ridolfi, 2006)
- General CSMs for Site contaminant transport to the Columbia River, as well as a human health exposure CSM, developed for the Columbia River corridor (Hulstrom, 2007; Hulstrom and Lerch, 2007)
- CSMs for aquatic and terrestrial ecological and human receptors developed for the River Corridor Baseline Risk Assessment (U.S. DOE, 2007)
- A CSM linking contaminant releases to Tribal exposure, developed for the Yakama Nation exposure scenario (Ridolfi, 2007)
- A general Site CSM for ecological and human exposure, included in a book on radiological risk assessment (Rocco et al., 2008)
- CSMs describing contaminant fate and transport from the 100-D/H decision unit (U.S. DOE, 2009a) and the 100-K decision unit (U.S. DOE, 2009b).

Several of these existing CSMs contain useful process relationship diagrams for envisioning environmental processes in the Hanford assessment area. We have included several example diagrams from other CSMs in the appendix.

1.6 Level of Detail

This CSM has been prepared during the initial phase of NRDA planning. Consequently, although the CSM has been developed based on a review of existing information about the Site, it is not intended to provide the level of site detail or injury analysis that might be feasible following completion of the NRDA. Moreover, since the purpose of the CSM is to assist in planning the NRDA, an overly prescriptive or precise level of detail is neither required nor necessarily desirable.

1.7 Potential Injury Definitions

Potential definitions of injury to natural resources are presented in Chapters 5–8. These potential injury definitions include definitions that are contained explicitly in federal NRDA regulations, as well as alternative injury definitions discussed during CSM planning workshops. This information is intended to assist the Trustees with assessment planning and do not represent a final or consensus list of potential injuries that will be assessed. Ultimate selection of injury definitions will be undertaken during development of injury assessment plans.

1.8 Dynamic and Flexible Document

The CSM is intended to be dynamic and flexible. As new information becomes known, the CSM may be modified to reflect evolution in the Trustees' thinking about the Site NRDA.

1.9 Report Organization

Chapter 2 presents an overview of the Site, including its national and regional context and history. **Chapter 3** presents the Stressor CSM and **Chapter 4** presents the Pathway CSM. Chapters 5–8 present the natural resource CSMs; with **Chapter 5** covering groundwater; **Chapter 6** covering aquatic resources associated with the Columbia River; **Chapter 7** covering terrestrial resources, including ponds and ephemeral streams found in upland areas; and **Chapter 8** describing potentially affected air resources. Finally, **Chapter 9** presents the Human Services CSM.

References

Barnett, D.B., M.P. Bergeron, and E.J. Freeman. 2004. *Results of Groundwater Modeling for Tritium Tracking at the Hanford Site 200 Area State-Approved Land Disposal Site – 2004.* PNNL-14898. Prepared for the U.S. Department of Energy. Pacific Northwest National Laboratory, Richland, WA.

Bryce, R.W., C.T. Kincaid, P.W. Eslinger, and L.F. Morasch (eds.). 2002. *An Initial Assessment of Hanford Impact Performed with the System Assessment Capability.* PNNL-14027. Prepared for the U.S. Department of Energy. Pacific Northwest National Laboratory, Richland, WA. September.

CTUIR. 2008. Preassessment Screen for the Hanford Facility. Prepared by the Confederated Tribes of the Umatilla Indian Reservation. May 23.

Doctor, P.G., K.A. Gano, and J.K. Linville. 2004. Conceptual Site Model for the 100-B/C Pilot Project Risk Assessment. Rev. 0. BHI-01706. Prepared by Bechtel Hanford, Inc. for the U.S. Department of Energy, Richland Operations Office. March.

Freeman, E.J., M.J. Truex, S.M. Yabusaki, J.P. McDonald, C.J. Murray, V.R. Vermeul, J.M. Zachara, P.D. Thorne, M.D. Williams, and J.L. Lindberg. 2005. Contaminants of Potential Concern in the 300-FF-5 Operable Unit: Expanded Annual Groundwater Report for Fiscal Year 2004.

Fluor Hanford. 2005. 100-NR-2 Groundwater Operable Unit Ecological Risk Assessment Data Quality Objectives Summary Report. Fluor Hanford, Inc.

Harper, B.L. and S.G. Harris. 2000. Measuring risks to tribal community health and culture. In *Environmental Toxicology and Risk Assessment: Recent Achievements in Environmental Fate and Transport. Volume 9*, F.T. Price, K.V. Brix, and N.K. Lane (eds.). ASTM, West Conshohocken, PA. pp. 195–211.

HNRTC. 1998. Preassessment Screen Determination. In Hanford 100 Area National Priority List (NPL) Site, Washington. Draft. January 7.

HNRTC. 2000. Preassessment Screen Determination for the Hanford 1100 Area (National Priority List) Site. Final. August 9.

Hulstrom, L.C. 2007. *Columbia River Component Data Gap Analysis.* WCH-201. Rev. 0. Prepared by Washington Closure Hanford for the U.S. Department of Energy, Richland Operations Office. October.

Hulstrom, L.C. and J.A. Lerch. 2007. *Integrated Strategy for Achieving Final Cleanup Decisions in the River Corridor.* WCH-71. Rev. 0. Prepared by Washington Closure Hanford for the U.S. Department of Energy, Richland Operations Office. February.

Last, G.V., V.J. Rohay, F.J. Schelling, A.L. Bunn, M.A. Delamare, R.L. Dirkes, R.D. Hildebrand, J.G. Morse, B.A. Napier, R.G. Riley, L. Soler, and P.D. Thorne. 2004. A comprehensive and systematic approach to developing and documenting conceptual models of contaminant release and migration at the Hanford Site. *Stochastic Environmental Research and Risk Assessment* 18(2):109–116.

Mayer, H.J. and M.R. Greenberg. 2005. Using integrated geospatial mapping and conceptual site models to guide risk-based environmental clean-up decisions. *Risk Analysis* 25(2):429–446.

Napier, B.A. 1991. *Selection of Dominant Radionuclides for Phase I of the Hanford Environmental Dose Reconstruction Project*. PNL-7231 HEDR. Pacific Northwest Laboratory, Richland, WA. Prepared for the Technical Steering Panel. July.

PNNL. 1998. *Screening Assessment and Requirements for a Comprehensive Assessment: Columbia River Comprehensive Impact Assessment.* DOE/RL-96-16. Revision 1, Final. Pacific Northwest National Laboratory.

Ridolfi. 2006. Preassessment Screen for the Hanford Facility. Public review draft. Prepared for the Confederated Tribes and Bands of the Yakama Nation. Ridolfi Inc. October 18.

Ridolfi. 2007. Yakama Nation Exposure Scenario for Hanford Site Risk Assessment, Richland, Washington. Prepared for the Yakama Nation ERWM Program. Ridolfi Inc. September.

Rocco, J.R., E.A. Stetar, and L.H. Wilson. 2008. Site conceptual exposure models. In *Radiological Risk Assessment and Environmental Analysis,* J.E. Till and H.A. Grogan (eds.). Oxford University Press, New York. pp. 376–388.

Thorne, P.D., M.P. Bergeron, and V.L. Freedman. 2006. *Groundwater Data Package for Hanford Assessments*. PNNL-14753, Rev. 1. Prepared for the U.S. Department of Energy. Pacific Northwest National Laboratory, Richland, WA. January.

U.S. DOE. 2005. Aquatic and Riparian Receptor Impact Information for the 100-NR-2 Groundwater Operable Unit. Richland, WA. U.S. Department of Energy. October 31.

U.S. DOE. 2007. Risk Assessment Report for the 100 Area and 300 Area Component of the River Corridor Baseline Risk Assessment. U.S. Department of Energy.

U.S. DOE. 2009a. Integrated 100 Area Remedial Investigation/Feasibility Study Work Plan Addendum 1: 100-D/H Decision Unit. Prepared for the U.S. Department of Energy Assistant Secretary for Environmental Management. May.

U.S. DOE. 2009b. Integrated 100 Area Remedial Investigation/Feasibility Study Work Plan Addendum 2: 100-K Decision Unit. Prepared for the U.S. Department of Energy Assistant Secretary for Environmental Management. May.

2. Hanford Background and History

The Hanford assessment area, including the Site, surrounding areas where contaminants may have come to be located, and the Columbia River, have a rich history and significance for Native Americans and for later European settlers. From the viewpoint of biodiversity, this area includes unique high-quality shrub-steppe, riverine, and riparian habitats, with conservation values of regional and national importance. Moreover, much of the 586 acres of the Site served as a buffer around industrial operations; these areas were protected from urban and agricultural development. Thus, the Hanford Reach of the Columbia River, 51 miles of unimpounded, uninterrupted aquatic habitat, bisects large swathes of contiguous and largely undeveloped shrub-steppe habitat. This is one of the only remaining areas in the United States where the Columbia River and its surrounding habitat resemble conditions that were present prior to industrialization, dam construction, and large-scale irrigated agriculture. Viewed as a whole, this largely unfragmented natural ecosystem is capable of providing ecological and human services that exceed those services provided by individual and fragmented natural resources and habitats.

Hanford is located in the southeastern, shrub-steppe zone of Washington State. The Columbia River flows through the north part of the Site and forms its eastern boundary before continuing south and west to the Pacific Ocean (Figure 2.1). The Site is divided into several areas defined by current and past land uses (Figure 2.2). The Hanford Operations Area is the area still under the active control and management of DOE. Surrounding the Hanford Operations Area on several sides are management units of the Hanford Reach National Monument, including the Hanford Reach River Corridor Unit, the Arid Lands Ecology (ALE) Reserve Unit to the west, the McGee Ranch and Riverlands Unit to the northwest, and the Wahluke Slope and Saddle Mountain Units to the north and east of the river (USFWS, 2008). The Yakima River flows just south of the Site. The Tri-Cities – Kennewick, Pasco, and Richland – and the towns of West Richland and Benton City are at the southern end of the Site (Burk et al., 2007).

The Hanford Operations Area includes the areas that were the sites of the primary nuclear production activities (described in more detail in Section 2.4). These were the 100 Area, where the reactors were located; the 200 Area, where the separation plants were located; the 300 Area, where fuel fabrication took place; and the 400 Area, which housed the Fast Flux Test Facility (FFTF). The 600 Area includes all Hanford lands not included in the 100, 200, 300, and 400 areas. The 1100 Area has been decommissioned and is no longer part of the Site (Burk et al., 2007), and the 700 Area comprises only a Federal office building. The 100, 200, 300, and 1100 areas were designated Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) Superfund sites on the National Priorities List (NPL) in 1989; the 1100 Area was deleted from the NPL in 1996 and parts of the 100 Area were deleted from the NPL in 1998, after the remedies were complete. Some of these deleted areas became part of the Hanford Reach National Monument in 2000.

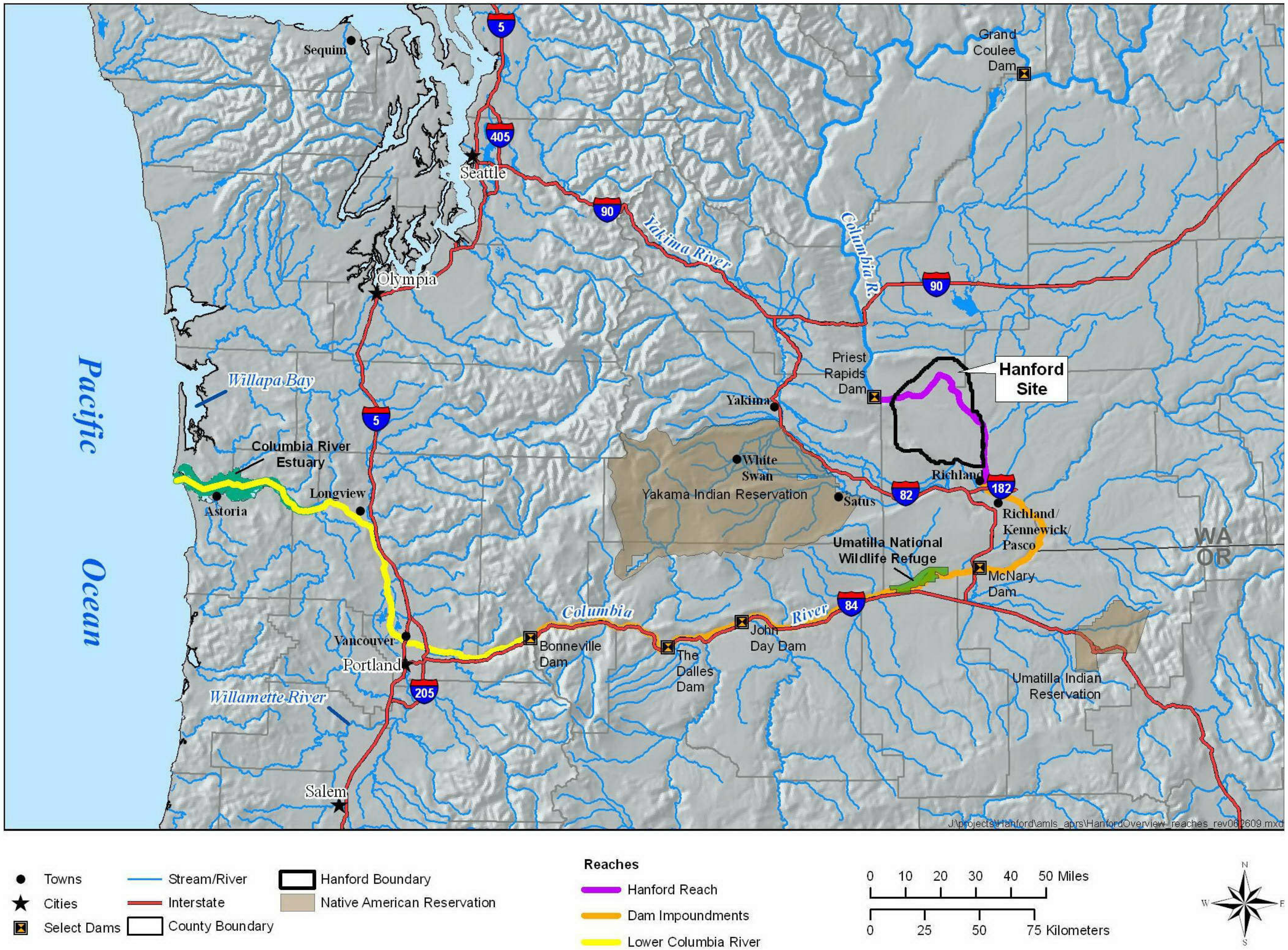


Figure 2.1. The Hanford Site, Columbia River, and surrounding area, from the Grand Coulee Dam to the Pacific Ocean.

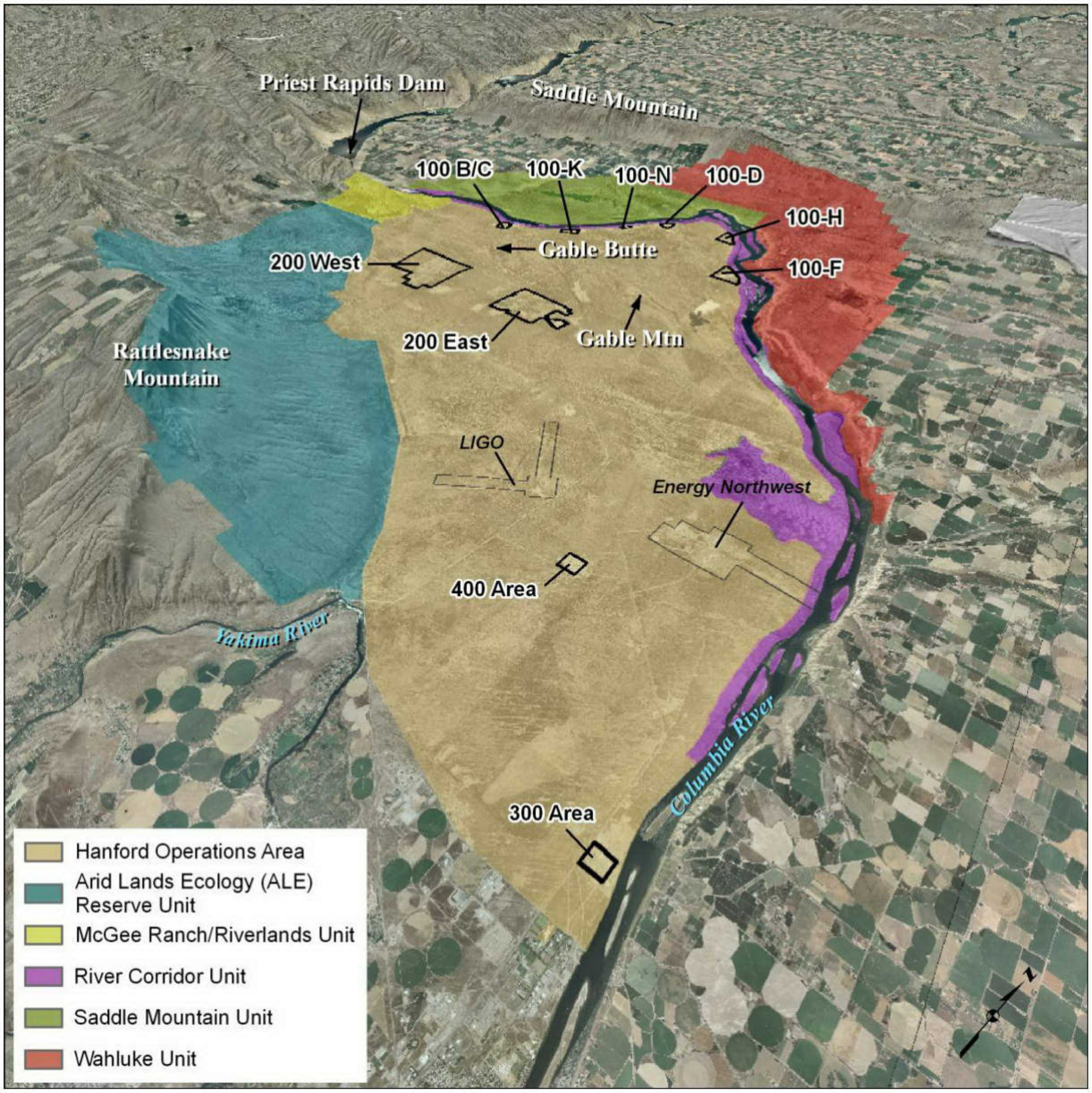


Figure 2.2. Aerial view of the Site, including units of the Hanford Reach National Monument, and its immediate environs. The figure shows two non-DOE facilities on-site: the Laser Interferometer Gravitational-wave Observatory (LIGO), a research facility jointly operated by the California Institute of Technology and the Massachusetts Institute of Technology; and Energy Northwest, a nuclear power plant.

This chapter presents an overview of the Site, its national and regional context, and its history in relation to developing the NRDA CSM. Specifically, Section 2.1 describes the national, regional, and local context of the Site; Section 2.2 describes the natural history of the Site; Section 2.3 describes the indigenous history of the Site; Section 2.4 describes the history of plutonium production at the Site; Section 2.5 describes the history of response actions at the Site; and Section 2.6 presents a timeline of major events at the Site.

2.1 National, Regional, and Local Context

The context for the NRDA CSM is set by the national, regional, and local importance and value of the Site, the Columbia Basin, and the Columbia River. Historically, the Columbia Basin ecosystem consisted of more than 23,000 square miles of steppe and shrub-steppe habitat throughout southeastern Washington and north central Oregon (U.S. DOE, 2001b). Protected from development for national security reasons, the 586 square miles of the Site now include one of the largest contiguous tracts of intact shrub-steppe ecosystem remaining in the Columbia Basin (Soll et al., 1999). The Site's regional and national importance for protecting key habitat and biodiversity has increased as the surrounding area has been developed for agricultural, commercial, and residential uses. For example, before European settlement the Site accounted for 3.6% of big sagebrush steppe habitat within the Columbia Basin Ecoregion; it now accounts for 8.3% of that habitat in the ecoregion (U.S. DOE, 2001b). In fact, after conducting a detailed inventory of Hanford's rare species and ecosystems, Soll et al. (1999) concluded that:

> In its present condition the Hanford Site is not only a refuge, but also a genetic bank for both the common and rare plants and animals that are integral components of the shrub-steppe and Columbia River ecosystems. From a conservation standpoint, the Hanford Site is a vital – and perhaps the single most important – link in preserving and sustaining the biodiversity of the Columbia Basin's shrub-steppe region.

The Columbia River, flowing adjacent to the Site, is a resource of national importance. It is the largest river in the Pacific Northwest, with a drainage area that encompasses more than 250,000 square miles. The Columbia River provides habitat for more than 1,000 species, including at least 19 state- and federally-listed endangered and threatened species (USFWS, 2008). At the Site, the Columbia River came to play a significant role in the history of the United States because it enabled the production of plutonium through the Manhattan Project.

At a regional level, the Columbia River helps structure the ecology of the Pacific Northwest, and has influenced human settlement and development patterns since the first days of human settlement in the area, approximately 11,000 years ago. The Columbia River has value to humans as an important resource for navigation, food, drinking water, irrigation, and recreation – as well as providing traditional medicinal, religious, and cultural services to Native Americans, and ecological and habitat services for a wide variety of fish and wildlife. Anadromous fish runs in the Columbia River at the turn of the 20th century were estimated to range from 15 to 20 million fish per year, and even after significant habitat impacts, the average annual run size at the turn of the 21st century was estimated at about 2.5 million fish (Dauble et al., 2003). Hydropower dams in the Columbia River Basin are estimated to produce approximately 14,000 megawatts of electricity per year, which is enough power for more than 13 cities the size of Seattle (Northwest Power and Conservation Council, Undated). The Columbia River also absorbs municipal and industrial waste, with numerous wastewater treatment plants and permitted outflows into the river.

At a local level, the Columbia River provides drinking water, food, irrigation, recreational, and cultural services to the citizens of the Tri-Cities area. The geographic areas, habitats, and resources of the Columbia River through the Hanford Reach are particularly important for the members of the Yakama Nation, the Umatilla and Nez Perce tribes, and the Wanapum Band, whose tribal culture evolved around the resources and historic salmon runs of the Columbia River. The river is an important resource for a wide variety of fish and wildlife, and supports many aspects of the lifecycles of local fauna, including fish spawning, rearing of young, feeding, and migration. The Hanford Reach is especially important for ecological and human use services because it is the only stretch of the Columbia River in the United States upstream of the Bonneville Dam that is not impounded by a dam, retaining the full diversity of native riverine habitat types (USFWS, 2008). The Hanford Reach provides essential habitat for fall Chinook salmon (Dauble, 2000). A study of wildlife along the Hanford Reach in 1982 noted its status as a refuge for numerous wildlife species, especially for bald eagles, mule deer, coyote, and resident Great Basin Canada Goose (Rickard et al., 1982). The importance of the Hanford Reach is summarized in the vision statement for the Hanford Reach National Monument (USFWS, 2008):

> The Hanford Reach, the last free-flowing non-tidal stretch of the Columbia River, is the ribbon that weaves shrub-steppe and riverine communities together, defining an irreplaceable landscape – a place to discover the richness of life, to reflect upon history, and to experience nature in solitude.
>
> The Monument's diversity of plants and wildlife are critical to the biological integrity of the Columbia Basin. The unique combination of an expansive and increasingly rare shrub-steppe ecosystem, the free-flowing river, and the last major salmon spawning grounds in the Columbia River create a diverse and precious mosaic of habitats. The Monument is a refuge for a multitude of species, many new to science.

2.2 Natural History

This section provides a brief overview of the physical, climatic, and ecological features of the Hanford assessment area. This includes the Site as well as locations downwind and downstream of the Site where contaminants may have come to be located. However, more data are available from the Site itself, and thus in the following sections we generally include more information about the Site than surrounding areas. This should not imply that the natural resource injury assessment should be confined to the Site.

2.2.1 Physical environment

The Site lies within the Pasco Basin in the Columbia Basin Ecoregion and is the structural and topographic low-point of the Columbia Plateau (Sackschewsky and Downs, 2001). The Site is underlain by Columbia River Basalts, emplaced by lava flows that occurred between 17 and 2 million years ago. The ancient basalt surface has subsequently been modified by tectonic activity, volcanism, weathering, and erosion. Massive flood events that occurred periodically until approximately 12,000 years ago covered most of the Site with a thick sequence of fluvial, overbank, and lacustrine sedimentary units (Wurstner et al., 1995) and deep sandy, loamy, and gravelly soils. Basalt ridges across the Site provide topographic relief (Chatters et al., 1991). In particular, Rattlesnake Mountain, which is the highest point on the Site at 3,450 feet, forms the southwest and western boundary of the Site along with Yakima Ridge and Umtanum Ridge (Figure 2.2; Burk et al., 2007). Saddle Mountain forms the northern boundary of the Site (north of the Columbia River), and Gable Butte and Gable Mountain are important features in the central portion of the Site (Figure 2.2; Burk et al., 2007).

Fifteen different soil types have been described at the Site, ranging from sand to sandy loam to silt (Chatters et al., 1991). Sandier soils tend to be found at lower elevations closer to the river, while silt loam soils tend to be found on the slopes and higher elevation areas. There are large, active dune fields on both sides of the river. Intermittent streams (Rattlesnake and Snively springs) originate on the Site in the higher elevation areas, but no perennial streams exist other than the Columbia River (Chatters et al., 1991; Burk et al., 2007).

The Hanford Reach of the Columbia River flows unimpounded through Hanford, beginning at the base of the Priest Rapids Dam and extending for 51 miles downstream to Lake Wallula, the reservoir upstream of the McNary Dam (U.S. DOE, 2008b). As mentioned previously, this is the longest unimpounded stretch of the Columbia River in the United States upstream of the Bonneville Dam. Flow through the Site is regulated primarily by the upstream Grand Coulee Dam and the Priest Rapids Dam, although downstream dams may also influence flow (U.S. DOE, 2001b; USFWS, 2008). Because of variability in the operations of the Priest Rapids

Dam, river levels can vary by up to 3 meters within a few hours in the Hanford Reach (PNNL, 1998).

2.2.2 Climate

The climate at the Site is semi-arid; it is located within the hottest and driest part of the Columbia Basin Ecoregion (O'Connor and Wieda, 2001; U.S. DOE, 2001b). The Pacific Ocean and Cascade Mountain range are major influences on local and regional climate. The Pacific Ocean moderates temperatures throughout the Pacific Northwest. The Cascade Mountain range creates a rain shadow, limiting rain and snowfall in the Hanford area and acting as a cold air drainage source, which also influences local wind patterns (Sackschewsky and Downs, 2001; Burk et al., 2007; USFWS, 2008).

Average annual precipitation on the Site is approximately 6.3 inches, occurring primarily in the late fall and winter. Precipitation varies with elevation and geography, ranging between 3 and 18 inches across the Site. Snowfall constitutes approximately 38% of winter precipitation, occurring primarily during December through February (Burk et al., 2007; USFWS, 2008). Average monthly temperatures range from 31°F in January to 76°F in July. Daily maximum temperatures range between 35°F in late December and January to 96°F in July. Monthly average temperatures from mid-November to early March are below freezing (Burk et al., 2007). The prevailing wind direction at the Site is from the northwest, and the secondary wind direction is from the southwest (Dirkes and Hanf, 1996). A 1995 study of wind at the Site found an average annual wind speed of 12.6 kilometer per hour (km/hr), with peak gusts in that year of 98 km/hr on December 12.

2.2.3 Ecology

Before European settlement, the Site was integrated into the larger steppe and shrub-steppe habitat of the Columbia Basin ecosystem. The early European settlers used the land for agriculture and grazing, which, along with fire, degraded much of the habitat (Sackschewsky and Downs, 2001; U.S. DOE, 2001b). Because the Site has been protected from civilian uses since 1943, many areas have recovered naturally and the shrub-steppe habitat is of high quality, supporting wildlife and human uses (O'Connor and Wieda, 2001; U.S. DOE, 2001b). The following sections give a brief overview of the ecology of the Site; more detail is provided in Chapter 6 (Aquatic Resources CSM) and Chapter 7 (Terrestrial Resources CSM).

Riverine habitat

Important riverine habitat features found in the Hanford Reach include islands, cobble shorelines, riffles, gravel bars, and backwater sloughs (O'Connor and Wieda, 2001; U.S. DOE, 2001b). These habitats are rare or absent in the impounded, downstream portions of the river. The Hanford Reach supports a wide variety of native fish and wildlife dependent on a healthy river ecosystem, including essential spawning and rearing habitat for fall Chinook salmon (*Oncorhynchus tsawytscha*) (U.S. DOE, 2001b; USFWS, 2008). It is also an important area for white sturgeon (*Acipenser transmontanus*), steelhead trout (*Oncorhynchus mykiss*), and the Columbia pebblesnail (*Fluminicola columbianus*) (U.S. DOE, 2001b). Additionally, the Hanford Reach supports diverse benthic fauna and more than 40 species of fish (Becker et al., 1996).

Riparian habitat

Riparian habitats on the Site are rare but important. In the arid to semi-arid shrub-steppe ecosystem, riparian habitats are areas of plentiful water, shelter, and food. Many wildlife species live exclusively in the riparian habitats (e.g., amphibians and some birds), but many if not all upland species may also use riparian habitats for water, food, and shelter (O'Connor and Wieda, 2001). The characteristic native riparian species on the Site are willow (*Salix* L.) and black cottonwood (*Populus balsamifera* L. ssp. *Trichocarpa*) (O'Connor and Wieda, 2001; Sackschewsky and Downs, 2001). A variety of introduced species, such as mulberry (*Morus* L.) and Russian olive (*Eleagnus angustifolia*), are prevalent along the Hanford Reach (and downstream); many of these were planted as shade trees by homesteaders and farmers prior to 1943 (O'Connor and Wieda, 2001; U.S. DOE, 2001b). While the majority of riparian habitat is associated with the Columbia River, smaller upland springs and artificially-created ponds also support riparian vegetation and wildlife.

Upland habitat

Shrub-steppe habitat comprises four main vegetation layers: shrubs, grasses, forbs, and biological soil crusts. It is characterized by widely spaced shrub species in the overstory associated with one or more main grass species and various forbs present in the understory. These shrub-grass associations (sometimes called "fertile islands") are surrounded by interspaces that support cryptobiotic soil crusts. These crusts are associations of algae, fungi, and bryophytes that transform bare soil into productive components of the ecosystem (O'Connor and Wieda, 2001; Sackschewsky and Downs, 2001; USFWS, 2008).

A wide diversity of vegetation community types exist within shrub-steppe habitat. The common overstory shrub species found at Hanford is big sagebrush (*Artemisia tridentata*). It may be associated with a number of grasses depending on local factors such as temperature, soil-type, and precipitation (which are closely related to elevation; O'Connor and Wieda, 2001). Some of the most common native understory grasses found on the Site include Sandberg's bluegrass (*Poa secunda*), bluebunch wheatgrass (*Pseudoroegneria spicata*), needle-and-thread grass (*Stipa comata*), and Indian ricegrass (*Oryzopsis hymenoides*). Cheatgrass (*Bromus tectorum*), a common invasive grass, is found throughout much of the Site, especially in disturbed areas (O'Connor and Wieda, 2001; Sackschewsky and Downs, 2001; U.S. DOE, 2001b).

Shrub-steppe habitat supports a wide diversity of wildlife including invertebrates, reptiles, birds, and mammals. According to a comprehensive species list for the Site developed by Ridolfi (2004), the Hanford area contains 870 plant, 13 algae, 56 fish, 7 amphibian, 14 reptile, 64 aquatic invertebrate, 13 terrestrial invertebrate, 269 bird, and 52 mammal species.

2.3 Indigenous History

The region surrounding the Site has been inhabited for some 11,000 years. Early inhabitants lived in small shelters near the Columbia River and relied heavily on aquatic resources, including salmon and other species of fish (Landeen and Crow, 1997). Hunting and gathering helped supplement the diets of these early people with terrestrial meats, roots, and berries (Ames and Maschner, 1999). Tribes moved frequently to coincide with the seasonal availability of resources and transitioned into more permanent lifestyles as their abilities to store and preserve foods became more sophisticated (Landeen and Crow, 1997).

This lifestyle evolved over time, but was shaped most significantly by contact with Euro-American settlers. While European trappers and traders first exposed the indigenous peoples of the region to Euro-American culture and disease, the expedition of Lewis and Clark in 1805–1806 served as a catalyst for the eventual relocation of the Columbia Plateau tribes (U.S. DOE, 1997). In 1855, territorial governor and Superintendent of Indian Affairs Isaac Stevens signed treaties with the tribes of the region that ceded tribal lands to the United States, and in return the United States provided designated tribal reservations and "the right of taking fish at all usual and accustomed places in common with citizens of the Territory; and of erecting temporary buildings for curing, together with the privilege of hunting, gathering roots and berries, and pasturing their horses and cattle upon open and unclaimed land" [12 Stats. 945, 951, 957].

This stipulation allowed the tribes to continue their major subsistent and cultural activities of the time (Harper and Harris, 2009). As had been the tradition for centuries, tribal interaction with the natural environment was characterized by a deep dependence and respect for the various resources used to support tribal lifeways. Tribes depended on a wide range of resources at the Site and surrounding area for sustenance, as well as for cultural and religious activities. This holistic tradition continues today and underscores the importance of the Hanford area to the Tribes.

2.4 Plutonium Production History

Operations at the Site began in 1943 with the production of plutonium for atomic bombs as a part of the World War II Manhattan Project. The Site was selected in part because of its proximity to the Columbia River, which provided water and hydroelectric power for operations (Harvey, 2000). After the end of World War II, plutonium production continued at Hanford until the last reactor was shut down in 1988. Discrete steps in the plutonium production process occurred at different areas across the Site. These include fuel rod fabrication (300 Area), fuel irradiation (100 Area), and chemical separation/extraction processes (200 Area). In addition to plutonium production for atomic bombs, other activities that occurred at the Site include research activities, site maintenance, and defense activities. In this section, we provide a brief summary of the historical plutonium operations. A discussion of these operations as potential sources of hazardous substances, as well as other potential on-site sources, is provided in Chapter 3.

Fuel fabrication (300 Area)

Fuel fabrication, the first step in the plutonium production process, occurred in the 300 Area adjacent to the Columbia River (Figure 2.2). Nuclear fuel rods were fabricated from metallic uranium transported from off-site facilities. The metallic uranium was machined into cylindrical cores and encapsulated in protective cladding, or "jackets." The encapsulation was necessary to facilitate heat conduction from the uranium rods to circulated coolant waters in the nuclear reactors to avoid overheating. The jackets also reduced the release of highly radioactive fission products to the coolant water and prevented corrosion of the uranium by the water, which would inhibit the irradiation process. Different encapsulation processes were used at the Site over time:

- Originally, the jackets were made of aluminum-formed cylinders, or cans. The uranium rods were heated, then placed into heated aluminum cans, and the top was welded closed with an aluminum lid.
- In the early 1950s, a lead-dip process was developed in which the uranium cores were first dipped in molten lead, then molten aluminum, and finally a molten aluminum-silicon bath. Later, a hot die size process was developed that replaced the aluminum-silicon method. Between 1955 and 1964, about 30,000 single-pass reactor fuel elements were canned each week using this method.
- A co-extrusion fabrication process was developed in the 1960s. This process used a zirconium alloy that provided a more uniform bond between the uranium fuel rod and the alloy. Only the newest reactor was fueled with rods jacketed in the zirconium alloy. The first eight reactors were fueled with aluminum-clad uranium rods (Harvey, 2000).

After encapsulation, the fuel elements were trimmed to a specified diameter and cut to a required length to fit in the reactors. They were then shipped by rail to the reactors in the 100 Area for irradiation, the second step in the plutonium production process (Harvey, 2000).

In addition to fuel fabrication, activities in the 300 Area included research and development related to improving the fuel fabrication, irradiation, and separation process, as well as investigating alternative nuclear fuel materials, developing commercial applications of nuclear energy, and other research activities (Harvey, 2000). The 300 Area included several test reactors and separation plants; many of the techniques ultimately used in the 100 Area reactors and 200 Area separation plants were first developed in the 300 Area test reactors and test separation plants (Marceau et al., 2002).

Fuel irradiation (100 Area nuclear reactors)

In the 100 Area, the fuel rods produced in the 300 Area were placed in nuclear reactors to generate weapons-grade plutonium. The first nuclear reactor was completed in 1944, with additional reactors coming online throughout the late 1940s and 1950s (U.S. DOE, 2008b). The reactors consisted of a large stack of graphite blocks (or "pile") with many cylindrical openings. The uranium fuel rods were inserted into the openings. The large numbers of uranium fuel rods held within the reactor pile created an intense radiation field, and a nuclear fission chain reaction converted some uranium atoms in the fuel elements to plutonium atoms. The highest production of plutonium at the Site occurred between 1954 and 1970, with output ranging from approximately 1,000 and 4,700 kilograms per year (kg/yr) (U.S. DOE, 2008b).

A by-product of the nuclear chain reaction was heat. To cool the reactors, large volumes of Columbia River water were passed through the reactors to absorb and remove the heat. Pump houses located along the river pumped river water up to storage reservoirs located next to the reactors. The reservoirs each stored about 25 million gallons of water. The water was treated and filtered to remove particulate matter, dissolved gases (i.e., carbon dioxide and oxygen), and chemicals prior to circulation in the reactors. The water was then injected into the reactors (U.S. DOE, 2008b). Each reactor was originally designed to use 35,000 gallons of water per minute (gpm) (or 78 cubic feet per second, cfs) from the Columbia River, but eventually used up to 105,000 gpm (234 cfs) as the power output of the reactors increased (Gerber, 1996). For comparison, the minimum flow from Priest Rapids Dam is set at 36,000 cfs.

There were eight single-pass reactors, which used purified Columbia River water for direct cooling of the reactors once before the water was released back to the river. These reactors were in operation up until the early 1970s. The ninth reactor, 105-N (or N Reactor), recirculated purified water through the reactor core in a closed-loop cooling system and was in operation until 1986 (U.S. DOE, 2008b).

Fuel processing/reprocessing (200 Area Central Plateau)

After irradiation in the 100 Area reactors, the irradiated fuel elements were taken to the 200 Area to extract the plutonium. These processes began in 1944 and were carried out in plutonium separation facilities (U.S. DOE, 2001a). The extraction (or separation) process involved dissolving the irradiated fuel rods in nitric acid to remove the protective outer jacket and to convert the rods to liquid. The plutonium was extracted from the solution in the form of liquid plutonium nitrate, then purified (finishing process) and converted into plutonium metal. When operations first began, the plutonium finishing process consisted of drying the plutonium in a building in the 200 West Area. It was then shipped to the weapons assembly facilities at Los Alamos, New Mexico, where it was made into metallic plutonium and formed for use in nuclear weapons. On-site processing of the plutonium nitrate into metallic form began with construction of the T Plant and B Plant complexes in 1944 and 1945, respectively (Harvey, 2000; U.S. DOE, 2006d).

Over time, different methods were used to extract (or separate) the dissolved plutonium from the nitric acid solution:

- Originally, the plutonium was extracted using a bismuth phosphate process, which occurred in the B Plant in the 200 East Area and the T Plant in 200 West Area (U.S. DOE, 2001a).
- In 1951, a Reduction-Oxidation (REDOX) Extraction Plant (also known as the S Plant) became operational in the 200 West Area. The REDOX Plant recovered both plutonium and uranium using an organic solvent extraction process, replacing the bismuth phosphate process employed in the B and T plants (Harvey, 2000).
- In 1955, the Plutonium-Uranium Extraction (PUREX) Plant became operational. It used a continuous solvent flow extraction process to separate plutonium, uranium, and neptunium. It was the last and most advanced separation plant constructed at Hanford (U.S. DOE, 2001a).

Starting in the 1950s, liquid wastes generated by the separation plants were reprocessed to recover uranium and other metals. For example, the Z Plant isolated metallic plutonium and plutonium oxides from various types of processed plutonium solutions from 200 Area separation plants (U.S. DOE, 2001a). Liquid wastes stored in underground tanks were retrieved and the uranium and metals were recovered, employing an extraction method that used tributyl phosphate as the solvent. Recovery operations occurred in the 200 West Area at the U Plant (1944 through 1951) and Z Plant (1949 through 1990) (U.S. DOE, 2001a).

As a result of these operations, many hazardous substances are known or suspected to have been released to the environment, including radionuclides, organic chemicals, and metals. In addition to the on-site sources, some hazardous substances at the Site may have originated from non-Hanford sources. For example, global fallout from atmospheric nuclear testing in the United States, China, and the Soviet Union, and the Soviet nuclear reactor accident at Chernobyl in 1986, likely released radionuclides to the Site. Hazardous substances may have also come to be located at the Site from upriver industrial sources, including smelting, pulp and paper production, mining activities, and wastewater treatment plants. Agriculture activities are widespread in the Central Washington Plateau and may have resulted in the release of agricultural chemicals to the Site (U.S. DOE, 2008b). Notwithstanding these potential off-site sources, the majority of the contamination at the Site is known or suspected to have originated from the nuclear operations and other on-site activities. As a result of this contamination, numerous response actions have occurred and are underway at the Site. A brief summary of Site environmental response actions are presented in the next section.

2.5 Response Actions

By the late 1980s, plutonium production had ceased at Hanford, and environmental cleanup activities under CERCLA began. In 1989, the Hanford Federal Facility Agreement and Consent Order (or Tri-Party Agreement), was signed between DOE, the U.S. Environmental Protection Agency (EPA), and the State of Washington Department of Ecology. The agreement defines and ranks cleanup commitments, allows integration of CERCLA and Resource Conservation and Recovery Act (RCRA) activities, establishes cleanup responsibilities, provides a basis for budgeting, and ensures regulatory compliance. During operations, some waste management activities were managed and permitted by the Washington Department of Ecology under RCRA. The Tri-Party Agreement allows for coordination and integration of RCRA permitting and closure activities with CERCLA cleanup activities (U.S. DOE, 2007b).

Shortly after implementing the Tri-Party agreement in 1989, the 100, 200, 300, and 1100 areas (Figure 2.3) were placed on the NPL. Some of the areas, or portions of them, have since been removed from the NPL:

- The 1100 Area was deleted from the NPL in 1996, after a Record of Decision (ROD) was reached in 1993, and cleanup was completed in 1995 (U.S. DOE, 2006d; U.S. EPA, 2007; Duncan et al., 2008a)

- Portions of the 100 Area were deleted from the NPL in 1998, including the Wahluke Slope area north of the Columbia River (Figure 2.3; U.S. DOE, 2006d).

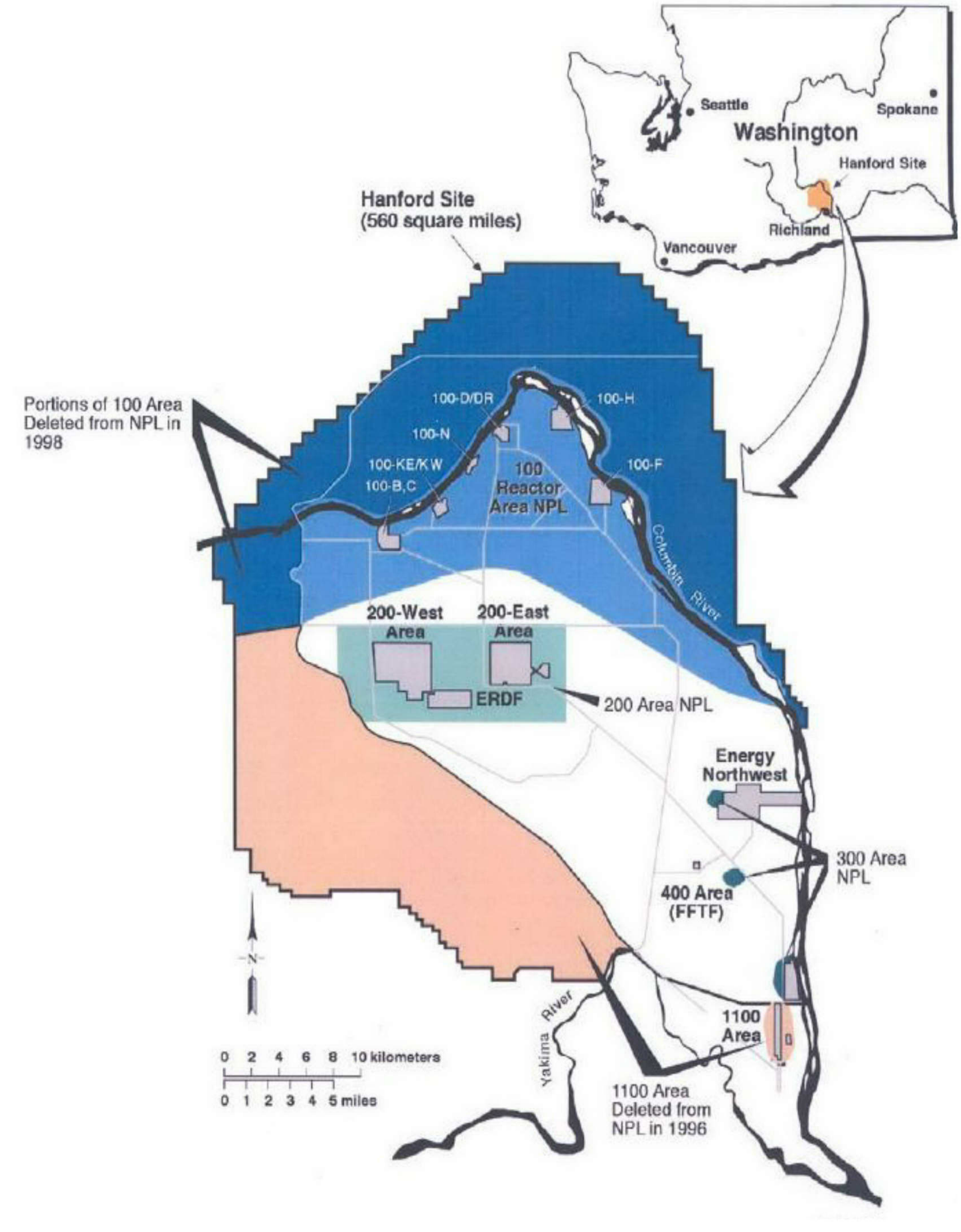


Figure 2.3. The 100, 200, 300, and 1100 NPL areas at the Hanford Site.

Source: U.S. DOE, 2006d.

Thus, the current NPL areas include the 300 Area, the 200 Area, and portions of the 100 Area south and west of the Columbia River which contain the nuclear reactors. Response actions that have taken place thus far in the 100 and 300 areas, either as interim actions or based on RODs, have mainly focused on the removal of solid waste, debris, and contaminated soil, and on groundwater treatment. Most of the removed solid materials are transported to treatment and long-term disposal facilities in the Central Plateau area, such as the Environmental Restoration Disposal Facility (ERDF). Some of the transuranic waste has been shipped off-site to the DOE Waste Isolation Pilot Plant (WIPP) repository in New Mexico. In the 200 Area, response actions are focused on treating groundwater and removing liquid wastes from underground storage tanks. These liquid wastes are also being treated placed in disposal facilities in the 200 Area (Bryce et al., 2002).

The following section provides additional details on the timeline of response actions. Chapter 3 discusses the details of the contaminant releases that resulted in these response actions.

2.6 Timeline

Industrial activities at the Site began in 1943; remedial actions are scheduled through 2036, a period of over 100 years. Table 2.1 presents an overview timeline that includes milestones of industrial history, major release events, key waste management practices, and important remedial actions, as well as the dates of dam construction on the Columbia River. Table 2.1 is not intended to be a comprehensive listing of all events that are relevant for the NRDA. In addition, it should be noted that target dates for future cleanup frequently change at the Site.

References

Ames, K.M. and H.D.G. Maschner. 1999. *Peoples of the Northwest Coast: Their Archaeology and Prehistory*. Thames & Hudson, NY.

Ballinger, M.Y. and R.B. Hall. 1991. *A History of Major Hanford Facilities and Processes Involving Radioactive Material. Hanford Environmental Dose Reconstruction Project.* PNL-6964. Hanford Environmental Dose Reconstruction Project. Prepared by the Pacific Northwest Laboratory, Richland, WA. March.

Becker, J.M., C.A. Brandt, D.D. Dauble, A.D. Maughan, and T.K. O'Neil. 1996. *Species for the Screening Assessment, Columbia River Comprehensive Impact Assessment*. Revision 0. DOE/RL-96-16-b. Prepared by the Pacific Northwest National Laboratory, Richland, WA.

Table 2.1. Timeline of industrial operations, release/spill events, waste management and remedial activities at the Site, with dates of Columbia River dam completion

Year	Columbia River dams	General Hanford operations	Release/spill event	Waste management	Remedial actions	Reference(s)
Early industrial history (1937–1954)						
1937	Bonneville Dam completed (downstream of Hanford)					U.S. DOE, 2008b
1941	Grand Coulee Dam completed (upstream of Hanford)					U.S. DOE, 2008b
1943		Start of 300 Area fuel element production				Harvey, 2000
1944		Start of 100 Area nuclear reactor operations				Gerber, 1993; Harvey, 2000; U.S. DOE, 2008b
1944		Start of 200 Area fuel separation operations				Harvey, 2000; U.S. DOE, 2001a, 2008a
October 1948			300 Area South Process Pond fails, releasing 14.5 million gallons of uranium-contaminated water into the Columbia River			U.S. DOE, 2008b
1949			"Green Run" occurs, releasing iodine-131 into the air to test surveillance/monitoring equipment			Washington Department of Health, 2002

Table 2.1. Timeline of industrial operations, release/spill events, waste management and remedial activities at the Site, with dates of Columbia River dam completion (cont.)

Year	Columbia River dams	General Hanford operations	Release/spill event	Waste management	Remedial actions	Reference(s)
1949		Start of 200 Area plutonium recovery and finishing operations				Ballinger and Hall, 1991
1952		Start of 200 Area uranium recovery operations				Ballinger and Hall, 1991
1954	McNary Dam completed (downstream of Hanford)					U.S. DOE, 2008b
1954				Ten 3.8 million liter tanks constructed in the 200 Area (A and AX Tank Farms)		U.S. DOE, 2008a
1954				Opening of 618-11 and 618-10 burial grounds, receiving radioactive waste from 300 Area		U.S. DOE, 2008a
1954				200 Area REDOX facility wastes diverted to S-5 and S-6 Cribs		U.S. DOE, 2001a
Active operations (1955–1980)						
Mid to late 1950s		Start of 1100 Area missile defense				Harvey, 2000
1957	The Dalles Dam completed (downstream of Hanford)					U.S. DOE, 2008b

Table 2.1. Timeline of industrial operations, release/spill events, waste management and remedial activities at the Site, with dates of Columbia River dam completion (cont.)

Year	Columbia River dams	General Hanford operations	Release/spill event	Waste management	Remedial actions	Reference(s)
1958		End of 200 Area uranium recovery operations				Ballinger and Hall, 1991
1960		End of 1100 Area missile defense				Harvey, 2000
1961	Priest Rapids Dam completed (upstream of Hanford)					U.S. DOE, 2008b
1966			100 Area spill from a sodium dichromate storage tank			U.S. DOE, 2008b
1967				Ending of 618-11 and 618-10 burial grounds receiving radioactive waste from 300 Area		U.S. DOE, 2008a
December 1969			200 Area Tank Farm pipeline leak of approximately 2,600 gallons of cesium-137 recovery process solution			Brown et al., 2008
1971		End of operation of 100 Area single pass reactors				U.S. DOE, 2008b
1971	John Day Dam completed (downstream of Hanford)					U.S. DOE, 2008b

Table 2.1. Timeline of industrial operations, release/spill events, waste management and remedial activities at the Site, with dates of Columbia River dam completion (cont.)

Year	Columbia River dams	General Hanford operations	Release/spill event	Waste management	Remedial actions	Reference(s)
1973				300 Area Waste Acids Treatment System constructed, replacing settling pond treatment		Harvey, 2000
Post-CERCLA operations (1981–2009)						
1982		Start of 400 Area FFTF operations				Dirkes and Hanf, 1998; Poston et al., 2003
1986		End of 100 Area nuclear reactor operations				Gerber, 1993; Harvey, 2000; U.S. DOE, 2008b
1988		End of 200 Area fuel separation operations				U.S. DOE, 2001a, 2006d
1989					National Priorities Listing of the 100, 200, 300, and 1100 areas	U.S. DOE, 2006d, 2007a; U.S. EPA, 2001
1990		End of 200 Area plutonium recovery and finishing operations				U.S. DOE, 2001a, 2006d
1992					Remedial investigations begin in 200 Area	U.S. EPA, 2001

Table 2.1. Timeline of industrial operations, release/spill events, waste management and remedial activities at the Site, with dates of Columbia River dam completion (cont.)

Year	Columbia River dams	General Hanford operations	Release/spill event	Waste management	Remedial actions	Reference(s)
1992					200 Area memorandum issued requiring soil vapor extraction system to remove carbon tetrachloride from vadose zone	U.S. EPA, 2001
1993		End of 400 Area FFTF operations				Dirkes and Hanf, 1998; Poston et al., 2003
1994				Liquid waste stopped being discharged to unlined ponds and trenches just north of the 300 Area		U.S. DOE, 2007a
1995					1100 Area remedial actions completed	U.S. EPA, 2007
1996					200 Area ERDF opened	U.S. DOE, 2006b
September 1996					1100 Area deleted from NPL	U.S. DOE, 2006d; U.S. EPA, 2007
July 1996			Tritium originating from the 200 Area Effluent Treatment Facility detected in site wells			U.S. DOE, 2006d

Table 2.1. Timeline of industrial operations, release/spill events, waste management and remedial activities at the Site, with dates of Columbia River dam completion (cont.)

Year	Columbia River dams	General Hanford operations	Release/spill event	Waste management	Remedial actions	Reference(s)
1997					100 Area pump-and-treat systems initiated to treat chromium in groundwater at the 100-D, 100-H, and 100-K areas	Duncan et al., 2008b
1997					200 West Area disposal facility began operations	Poston et al., 2003
May 1997			Chemical explosion occurred at the Plutonium Reclamation Facility in the 200 West Area			Dirkes and Hanf, 1998
1998					100 Area 105-C reactor ”cocooned”	U.S. DOE, 2006c
1998 to 2003			Soil sampling in the 1100 Area Horseshoe Landfill detected dichlorodiphenyltrichloro-ethane (DDT) above the 1 parts per million (ppm) cleanup level			U.S. DOE, 2006d
2002					100 Area 105-DR reactor “cocooned”	U.S. DOE, 2006c
January 2003			200 Area spill of approximately 200 gallons of diesel fuel at the 242-S Facility			Poston et al., 2004

Table 2.1. Timeline of industrial operations, release/spill events, waste management and remedial activities at the Site, with dates of Columbia River dam completion (cont.)

Year	Columbia River dams	General Hanford operations	Release/spill event	Waste management	Remedial actions	Reference(s)
2004					100 Area 105-F and 105-D reactors "cocooned"	U.S. DOE, 2006c
May 2005					1100 Area DDT-contaminated soil removed to achieve 0.75 ppm ecological protection cleanup level	U.S. DOE, 2006d
2005					100 Area 105-H reactor "cocooned"	U.S. DOE, 2006c
2006					100-N Area installation of permeable reactive barrier (PRB) near the Columbia River shoreline to target strontium-90 groundwater plume	Duncan et al., 2008b
April 2006					200 Area Integrated Disposal Facility (IDF) completed	U.S. DOE, 2008a
July 2007			200 Area spill of 85 gallons of radioactive waste at the S Tank Farm			Poston et al., 2008
2007					200 East Area Hanford Tank Waste Treatment and Immobilization Plant construction started	Duncan et al., 2008b

Table 2.1. Timeline of industrial operations, release/spill events, waste management and remedial activities at the Site, with dates of Columbia River dam completion (cont.)

Year	Columbia River dams	General Hanford operations	Release/spill event	Waste management	Remedial actions	Reference(s)
August 2008					300 Area 300-FF-1 OU waste site remedial actions completed	U.S. DOE, 2007a
September 2008					300 Area target date for completing source unit cleanup actions	U.S. DOE, 2007a
Future scheduled activities (2010–2032)						
September 2009					400 Area FFTF systems and equipment planned deactivation date	Duncan et al., 2008b
2010					200 Area IDF scheduled to begin operations	U.S. DOE, 2008a
2011					100 Area 105-KE and 105-KW reactors "cocooning" scheduled to be completed	U.S. DOE, 2006c
2012					100 Area 105-N reactor "cocooning" scheduled to be completed	U.S. DOE, 2006c
2015					100 and 300 Area Columbia River Corridor cleanup planned completion	U.S. DOE, 2006c
2019					Startup of Vitrification Plant to treat tank wastes	Bechtel, 2009

Table 2.1. Timeline of industrial operations, release/spill events, waste management and remedial activities at the Site, with dates of Columbia River dam completion (cont.)

Year	Columbia River dams	General Hanford operations	Release/spill event	Waste management	Remedial actions	Reference(s)
2032					200 Area Central Plateau Remediation project planned completion	U.S. DOE, 2006a
2040					Waste retrieval from single shell tanks completed	
2047					Treatment of all tank wastes completed	

Bechtel. 2009. Hanford Vitrification Plant. Available: http://www.bechtelvitplant.com. Accessed 5/4/2009.

Brown, C.F., R.J. Serne, B.N. Bjornstad, M.M. Valenta, D.C. Lanigan, T.S. Vickerman, R.E. Clayton, K.N. Geiszler, C. Iovin, E.T. Clayton, I.V. Kutnyakov, S.R. Baum, M.J. Lindberg, and R.D. Orr. 2008. *Characterization of Vadose Zone Sediments from C Waste Management Area: Investigation of the C-152 Transfer Line Leak.* Rev. 1. PNNL-15617. Pacific Northwest National Laboratory, Richland, WA. Prepared for CH2M HILL Hanford Group, Inc. and the U.S. Department of Energy.

Bryce, R.W., C.T. Kincaid, P.W. Eslinger, and L.F. Morasch (eds.). 2002. *An Initial Assessment of Hanford Impact Performed with the System Assessment Capability*. PNNL-14027. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. September.

Burk, K.W., M.A. Chamness, R.A. Fowler, B.G. Fritz, P.L. Hendrickson, E.P. Kennedy, G.V. Last, T.M. Poston, M.R. Sackschewsky, M.J. Scott, S.F. Snyder, M.D. Sweeney, and P.D. Thorne. 2007. *Hanford Site National Environmental Policy Act (NEPA) Characterization.* Rev. 18. PNNL-6415. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. September.

Chatters, J.C., D.L. Hadley, D.J. Hoitink, S.J. Marsh, T.M. Poston, A.C. Rohay, and R.W. Wallace. 1991. *Characterization of the Hanford Site and Environs.* PNL-7668. Pacific Northwest Laboratory, Richland, WA. Prepared for the U.S. Department of Energy.

Dauble, D. 2000. Assessment of the Impacts of Development and Operation of the Columbia River Hydroelectric System on Mainstem Riverine Processes and Salmon Habitats, 1998–2000 Final Report, Project No. 199800402. Columbia River Research Laboratory, BPA Report DOE/BP-08104-1. Available: http://pisces.bpa.gov/release/documents/documentviewer.aspx?pub = H08104-1.pdf. Accessed 2/17/2009.

Dauble, D.D., T.P. Hanrahan, D.R. Geist, and M.J. Parsley. 2003. Impacts of the Columbia River hydroelectric system on main-stem habitats of fall Chinook salmon. *North American Journal of Fisheries Management* 23(3):641–659.

Dirkes, R.L. and R.W. Hanf (eds.). 1996. *Hanford Site Environmental Report for Calendar Year 1995*. PNNL-11139. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. June. Available: http://hanford-site.pnl.gov/envreport/. Accessed 4/1/2009.

Dirkes, R.L. and R.W. Hanf (eds.). 1998. *Hanford Site Environmental Report for Calendar Year 1997*. PNNL-11795. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. September. Available: http://hanford-site.pnl.gov/envreport/. Accessed 4/1/2009.

Duncan, J.P., T.M. Poston, and R.L. Dirkes (eds.). 2008a. *Hanford Site Environmental Report for Calendar Year 2007* (Including Some Early 2008 Information). PNNL-17603. Pacific Northwest National Laboratory, Richland, WA. Prepared for U.S. Department of Energy. September. Available: http://hanford-site.pnl.gov/envreport/2003/Hanford04/index.htm. Accessed 4/1/2009.

Duncan, J.P., T.M. Poston, and R.L. Dirkes (eds.). 2008b. *Summary of the Hanford Site Environmental Report for Calendar Year 2007*. PNNL-17603-SUM. Pacific Northwest National Laboratory, Richland, WA. Prepared for U.S. Department of Energy. September.

Gerber, M.S. 1993. History of 100-B/C Reactor Operations, Hanford Site. Westinghouse Hanford Company. Facility Operations Division. WHC-SD-EN-RPT-004. April. Available: http://b-reactor.org/hist-toc.htm. Accessed 2/17/2009.

Gerber, M.S. 1996. The Plutonium Production Story at the Hanford Site: Processes and Facilities History. Westinghouse Hanford Company, Richland, WA. Prepared for the U.S. Department of Energy. June.

Harper, B.L. and S.G. Harris. 2009. Human Services, Risk Assessment, Lost Use & Injury. Review Draft. PowerPoint Presentation. Confederated Tribes of the Umatilla Indian Reservation.

Harvey, D. 2000. History of the Hanford Site, 1943–1990. Pacific Northwest National Laboratory, Richland, WA.

Landeen, D. and J. Crow. 1997. *I Am of this Land: Wetes pe m'e wes*. A Nez Perce Nature Guide. Conceived and Produced by Nez Perce Tribe Environmental Restoration and Waste Management Department. Western Printing, Clarkston, WA.

Marceau, T.E., D.W. Harvey, D.C. Stapp, S.D. Cannon, C.A. Conway, D.H. Deford, B.J. Freer, M.S. Gerber, J.K. Keating, C.F. Noonan, and G. Weisskopf. 2002. *History of the Plutonium Production Facilities at the Hanford Site Historic District, 1943–1990.* DOE/RL-97-1047. Hanford Cultural and Historic Resources Program, U.S. Department of Energy. June.

Northwest Power and Conservation Council. Undated. Columbia River History: Hydropower. Portland, OR. Available: http://www.nwcouncil.org/history/Hydropower.asp. Accessed 4/17/2009.

O'Connor, G. and K. Wieda. 2001. *Northwest Arid Lands: An Introduction to the Columbia Basin Shrub-Steppe*. Battelle Press, Columbus, OH.

PNNL. 1998. *Screening Assessment and Requirements for a Comprehensive Assessment: Columbia River Comprehensive Impact Assessment.* Revision 1, Final. DOE/RL-96-16. Pacific Northwest National Laboratory, Richland, WA.

Poston, T.M., J.P. Duncan, and R.L. Dirkes. 2008. *Hanford Site Environmental Report for Calendar Year 2007* (Including Some Early 2008 Information). Report PNNL-17603. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. September.

Poston, T.M., R.W. Hanf, R.L. Dirkes, and L.F. Morasch (eds.). 2003. *Hanford Site Environmental Report for Calendar Year 2002*. PNNL-14295. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. September. Available: http://hanford-site.pnl.gov/envreport/. Accessed 4/1/2009.

Poston, T.M., R.W. Hanf, R.L. Dirkes, and L.F. Morasch. 2004. *Hanford Site Environmental Report for Calendar Year 2003*. Pacific Northwest National Laboratory, Richland, WA.

Rickard, W.H., W.C. Hanson, and R.E. Fitzner. 1982. The non-fisheries biological resources of the Hanford Reach of the Columbia River. *Northwest Science* 56(1):62–76.

Ridolfi. 2004. Draft Natural Resources Studies Matrix: Biota Studies. Prepared for the Hanford Natural Resources Trustees. Ridolfi Inc.

Sackschewsky, M.R. and J.L. Downs. 2001. *Vascular Plants of the Hanford Site.* PNNL-13688. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. September.

Soll, J., J.A. Hall, R. Pabst, and C. Soper (eds.). 1999. *Biodiversity Inventory and Analysis of the Hanford Site: Final Report, 1994–1999*. Prepared by the Nature Conservancy of Washington, Seattle, WA. October 15.

U.S. DOE. 1997. *National Register of Historic Places Multiple Property Documentation Form Historic, Archaeological and Traditional Cultural Properties of the Hanford Site, Washington.* Revision 0. DOE/RL-97-02. U.S. Department of Energy. Available: http://www.hanford.gov/doe/history/mpd/toc.htm. Accessed 4/10/2009.

U.S. DOE. 2001a. *Ecological Evaluation of the Hanford 200 Areas: Phase I. Compilation of Existing 200 Areas Ecological Data.* DOE/RL-2001-54. Draft A. U.S. Department of Energy, Richland, WA.

U.S. DOE. 2001b. *Hanford Site Biological Resources Management Plan.* Revision 0. DOE/RL 96-32. U.S. Department of Energy. August.

U.S. DOE. 2006a. Central Plateau. Restore the River Corridor Fact Sheet. U.S. Department of Energy, Richland Operations Office, WA. July.

U.S. DOE. 2006b. Environmental Restoration Disposal Facility (ERDF). Restore the River Corridor Fact Sheet. U.S. Department of Energy, Richland Operations Office, WA. August.

U.S. DOE. 2006c. The Columbia River Corridor. Restore the River Corridor Fact Sheet. U.S. Department of Energy, Richland Operations Office, Richland, WA. August.

U.S. DOE. 2006d. *The Second CERCLA Five-Year Review Report for the Hanford Site.* Revision 1. DOE/RL-2006-20. U.S. Department of Energy, Richland, WA.

U.S. DOE. 2007a. *Risk Assessment Report for the 100 Area and 300 Area Component of the River Corridor Baseline Risk Assessment.* DOE/RL-2007-21. Draft A. U.S. Department of Energy, Richland, WA.

U.S. DOE. 2007b. *Supplemental Remedial Investigation/Feasibility Study Work Plan for the 200 Areas Central Plateau Operable Units. Volume II: Site-Specific Field-Sampling Plan Addenda.* Revision 0. DOE/RL-2007-02. U.S. Department of Energy, Richland, WA. November.

U.S. DOE. 2008a. *Hanford Site Groundwater Monitoring for Fiscal Year 2007.* DOE/RL-2008-01. U.S. Department of Energy. March.

U.S. DOE. 2008b. *Remedial Investigation Work Plan for Hanford Site Releases to the Columbia River.* Rev. 0. DOE/RL-2008-11. U.S. Department of Energy. September.

U.S. EPA. 2001. USDOE Hanford Site First Five Year Review Report. Prepared by U.S. Environmental Protection Agency Region 10 Hanford Project Office. April.

U.S. EPA. 2007. Hanford 1100-Area (USDOE): Site Description. U.S. Environmental Protection Agency Region 10 Benton County Richland, WA. Available: http://yosemite.epa.gov/r10/nplpad.nsf/88d393e4946e3c478825631200672c95/20ad495477c76cb285256592007b5d06?OpenDocument. Accessed 2/13/2009.

USFWS. 2008. Hanford Reach National Monument Final Comprehensive Conservation Plan and Environmental Impact Statement; Adams, Benton, Grant and Franklin Counties, Washington. U.S. Fish and Wildlife Service. August.

Washington Department of Health. 2002. The Release of Radioactive Materials from Hanford: 1944–1972. Office of Radiation Protection, Olympia, WA. Available: www.doh.wa.gov/hanford/publications/history/release.html. Accessed 2/13/2009.

Wurstner, S.K., P.D. Thorne, M.A. Chamness, M.D. Freshley, and M.D. Williams. 1995. *Development of a Three-Dimensional Ground-Water Model of the Hanford Site Unconfined Aquifer System: FY 1995 Status Report*. PNL-10886. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. December.

3. Stressors

This chapter presents a Stressor CSM that describes known and potential Site stressors that may have resulted in injuries to natural resources. Figure 3.1 illustrates the relationship between this CSM and the other CSMs provided in this document. Chapter 4 describes pathways through which stressors may expose natural resources, Chapters 5–8 describes those resources and the nature of potential injuries, and Chapter 9 discusses potential human losses caused by Site stressors.

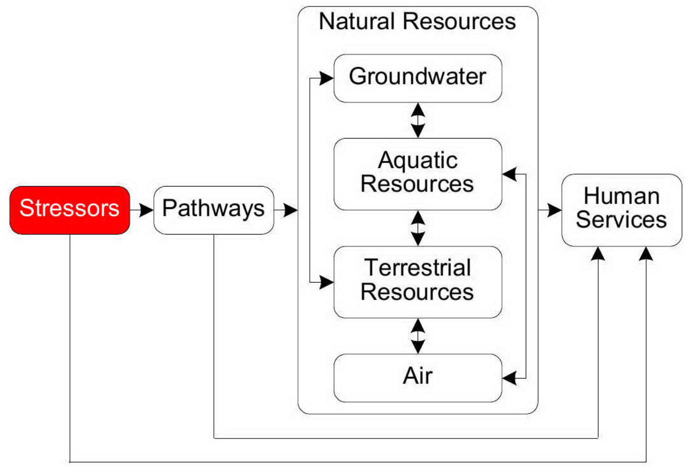


Figure 3.1. Relationship between the Stressor CSM and other CSMs that together make up the NRDA CSM.

In this document, we use the term "stressors" to broadly refer to substances or activities that may have caused injuries to natural resources for which the Trustee Council may quantify damages. Thus, stressors may include:

- Hazardous substances[1]
- By-products of hazardous substances
- Response actions that result in unavoidable injuries to natural resources [43 CFR § 11.15(a)]
- Secondary sources (contaminated natural resources).

Figure 3.2 shows the main categories of operational, response action, and secondary stressors at the Site. As briefly discussed in Chapter 2, there may also be stressors that have come to be located on-site that originated from off-site sources. Such non-Hanford sources are not addressed here, but may also need to be explicitly addressed in future NRDA activities to help define baseline conditions for injury and damage quantification.

---

1. For purposes of this conceptual site model, we use the term "hazardous substances" broadly to refer to chemical substances that may have caused injuries to natural resources. The use of this term does not imply Trustee consensus regarding the potential for natural resource damage liability. At a later stage in the assessment process, Trustees may choose to narrow the suite of stressors for which damages are quantified.

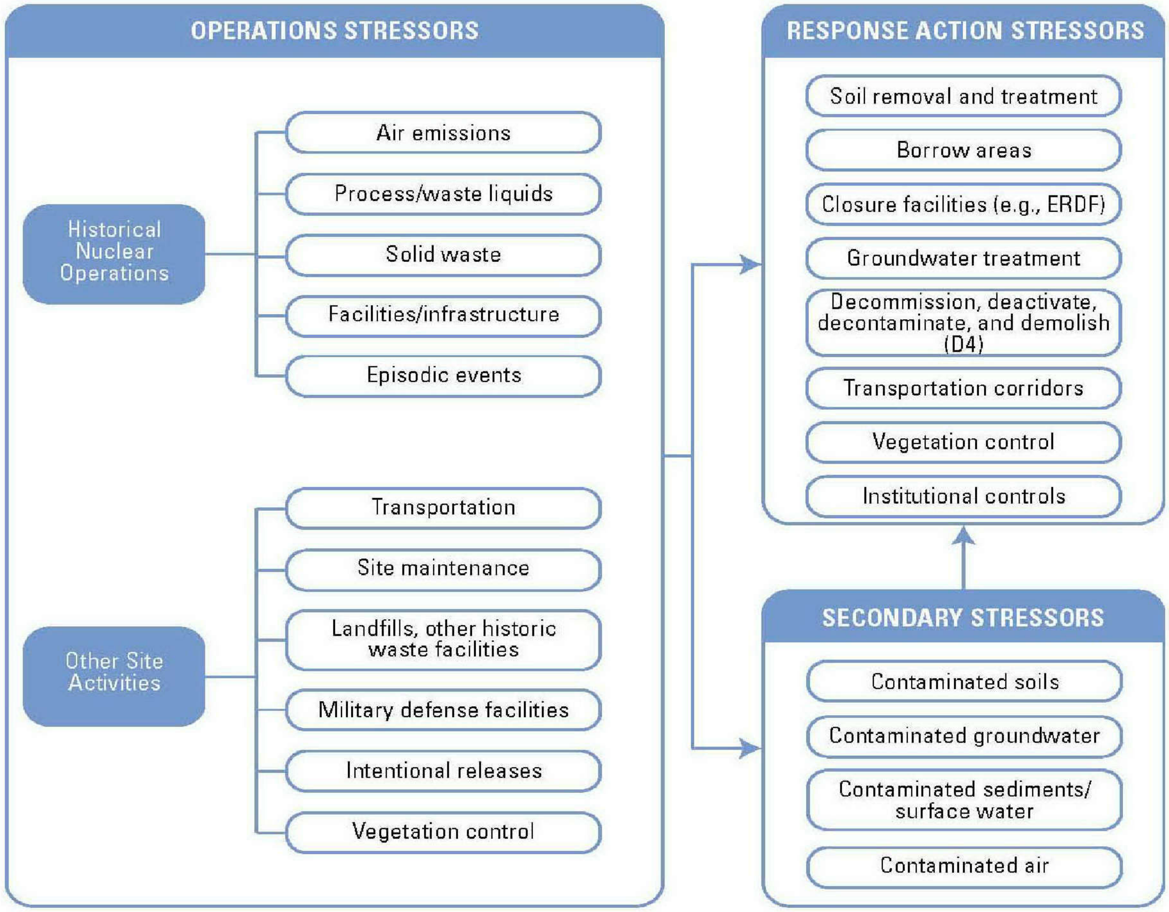


Figure 3.2. Stressor CSM diagram showing operational, response action, and secondary stressors at the Site.

Section 3.1 provides descriptions of stressors associated with historical nuclear operations and other site activities. Section 3.2 provides a summary of contaminated natural resources that act as secondary stressors. Section 3.3 summarizes stressors associated with response actions, and Section 3.4 provides a list of known hazardous substances used or produced at the Site, including whether they have been found in the environment. The stressors discussed in this chapter are intended to provide the Trustees with guidance for planning an injury assessment. This chapter does not contain a comprehensive list of all past, present, and potential future stressors at the Site.

3.1 Operations Stressors

3.1.1 Historical nuclear operations

Chapter 2 provides a description of the plutonium production process. Briefly, uranium ore shipped from off-site sources was formed into rods and encapsulated in the fuel fabrication area (300 Area). The rods were then shipped by rail to the 100 Area nuclear reactors for irradiation to create plutonium through nuclear fission. The irradiated fuel was then transported to the 200 Area by rail for chemical treatment to isolate and purify the plutonium. Research activities related to different aspects of plutonium production were also historically carried out in these areas. In this section, we describe potential sources of releases and stressors associated with nuclear production and research activities, including air emissions, process waters/liquid waste, solid waste, facilities/infrastructure, and episodic events.

Note that while fabrication, irradiation, and separation/purification occurred in "operational areas" with defined geographical boundaries, our discussion of sources associated with historical operations encompasses all areas where the sources were located, without regard to the NPL area designations at the Site.

3.1.2 Air emissions

Hazardous substances were released to air during plutonium production operations. Sources of airborne hazardous substances include stacks, incinerators and open burn pits, as well as other sources such as electrical and diesel generators.

Stack emissions from plutonium production operations were a significant source of airborne contaminants. The vast majority of airborne radionuclides releases from the Site occurred in the 1940s (Napier, 1991, 2002). Emissions were significantly reduced with the introduction of air filtration devices on stacks and stricter operating procedures in the late 1940s and early 1950s. The filtration devices underwent numerous changes and improvement throughout the period of operations (Ballinger and Hall, 1991).

The separation facilities in the 200 Area were the largest contributors of radionuclide emissions from stacks, particularly iodine-131 (U.S. DOE, 2005b). Non-radionuclide hazardous substances were also released to air from 200 Area stacks, including volatile organic compounds (VOCs), nitrate compound particulates, and gaseous ammonia produced during chemical separation operations (U.S. DOE, 2005b).

Stacks in the 100 Area also released radionuclides and other hazardous substances to air. Filtration systems were installed on the stacks in the 1960s which reduced the amount of emissions (Ballinger and Hall, 1991). In the 300 Area, air emissions were associated with fuel fabrication and research activities; the 324 Waste Technology Engineering Laboratory, 325 Applied Chemistry Laboratory, 327 Post-Irradiation Laboratory, and 340 Vault and Tanks are known to have released airborne radionuclides (Dirkes et al., 1999). Hazardous substances were also likely released from stacks associated with other research activities, including the FFTF and support facilities in the 400 Area.

Another source of releases of radionuclides, organics, metals and other hazardous substances to air were incinerators and open burn pits in the 100 Area (Duncan et al., 2008). Radioactive solid wastes in the 100 Area were segregated into soft waste (combustibles) and hard waste (greater than 99% metallic). Most of the combustible wastes from reactor operations were burned in open pits or in an incinerator in the 100-K Area. The radioactive hard waste that was not burned included fuel rod jackets, fuel element spacers, equipment, tools, and control rods. The hard waste was either disposed of in burial grounds or, if it contained alpha emitters, cobalt-60 at activity greater than 1 millicurie per gram (mCi/g), or beryllium, was shipped to the 200 Area for burial in designated trenches (U.S. DOE, 2006d).

Other sources of airborne releases of hazardous substances include on-site diesel-powered and electrical generation plants located across the Site. These facilities released particulate matter, sulfur and nitrogen oxides, VOCs, carbon monoxide, and lead (Dirkes et al., 1999).

3.1.3 Process and waste liquids

Examples of sources of process and waste liquids include discharge pipelines, surface impoundments, and underground storage tanks. Waste liquids were also discharged to groundwater via injection wells (also called reverse wells). Pipelines in the 100 Area were direct sources of process waters to the Columbia River. Some of the surface impoundments, including cribs, French drains, and trenches were deliberatively designed to allow for disposal of liquids through infiltration into the underlying soil; others unintentionally leaked into the ground. The surface impoundments were also sources of hazardous substances to air through evaporation. Many of the underground storage tanks that were used to store highly radioactive wastes are known or suspected to have leaked over time, and thus were also sources of hazardous substances releases. Here we provide a brief description of these sources.

Direct discharge

Direct discharge of process waters via to the Columbia River occurred during operation of the reactors. Process waters used to cool the eight single-pass nuclear reactors were sent to retention basins for cooling and then discharged to the river via outfall structures and underground pipelines that emerged mid-channel in the river (U.S. DOE, 2008c). Each reactor was originally designed to use 35,000 gpm from the Columbia River (Gerber, 1996) but eventually used up to 105,000 gpm as the power output of the reactors increased (Gerber, 1996). The water temperature was elevated when discharged to the river, with temperatures as high as 70–90°C (Eliason, 1967; Kannberg, 1992). Discharged cooling water often contained radionuclides, chromium, and other hazardous substances (Gerber, 1996). Direct discharges of hazardous substances to the river also occurred during purges of the reactors, which cleaned the process tubes of the surface film of minerals, elements, and other suspended solids that built up during operations (Gerber, 1996).

The N reactor was the last production reactor to be built. It was constructed with recirculating coolant water, and thus required much less water, just 100–1,500 gpm, versus the tens of thousands of gallons for the single-pass reactors (Gerber, 1996). Effluent from the reactor was released to the river until trenches were dug in the 1970s to receive the reactor effluent. Hazardous substances also were released to the river during purges of the reactor until a tank was constructed for this effluent in the 1970s (Gerber, 1996).

Retention basins

As mentioned above, retention basins were used in the 100 Area to temporarily store process waters from the single-pass reactors while it cooled, and to allow for decay of short-lived radionuclides prior to discharge the Columbia River (U.S. DOE, 2008c). The basins were lined with concrete, but thermal shock from the hot process waters often cracked the basin walls, allowing potentially contaminated cooling water to leak into underlying soils (U.S. DOE, 2008c). On occasions where failures in the reactors exposed cooling waters to high levels of radioactivity, the highly contaminated cooling water was sent to trenches and allowed to infiltrate into the ground, rather than being discharged directly to the Columbia River.

Cribs, French drains, trenches, ponds

Cribs, French drains, and trenches were all used for the disposal of liquid wastes at operations across the Site. Cribs were designed to inject or percolate wastewater into the soil column. They were shallow excavations that were either backfilled with permeable material or created with intentional void space from wooden or concrete structures (U.S. DOE, 2001a). It is reported that most cribs were designed to receive liquid until a specific soil retention volume or radionuclide capacity was reached, though it is not specified how this was determined. French drains were generally constructed of steel or concrete pipe and served a similar purpose as cribs (U.S. DOE, 2001a). Trenches were shallow, long, narrow, unlined excavations that were used to dispose of various process waters and liquid wastes (U.S. DOE, 2001a).

Ponds were also used to dispose of low-level radioactive and other liquid wastes in the 300 Area and the 200 Area, and to a lesser extent in the 100 Area and the 600 Area (U.S. DOE, 2001a). The primary pond in the 300 Area was located east of the 300 Area near the Columbia River. The laboratories and fuel manufacturing facilities located in the area were connected to a common process sewer that collected low-level radioactive liquid waste. The process sewer routed the liquid waste streams to the south process pond (Harvey, 2000). Discharge to this large unlined pond ceased in the late 1960s. However, other ponds in the 300 Area were still used after this time.

Ponds were also used in the 200 Area to dispose of waste waters (U.S. DOE, 2006e), including the U, B, S, T, and Gable ponds, as well as West Lake. The U Pond in 200 West and B Pond in 200 East were constructed in the mid-1940s (U.S. DOE, 2008a). The B Pond had three additional lobes that were added on to the original pond as the volume of liquid wastes increased over time (U.S. DOE, 2001a). The S Pond received wastes from the REDOX facility between 1951 and 1954, after which the waste stream was diverted to cribs (U.S. DOE, 2001a). The T Pond was located near the T Plant and received more than 11 billion gallons of waste discharge (Gerber, 2008). Gable Pond was constructed in 1957 and was the largest of the 200 Area ponds. West Lake was not constructed and did not directly receive effluent, but it was fed by elevated groundwater levels caused by operations discharges (Emery and McShane, 1978).

In the 100 Area, a percolation pond received coolant water from the N reactor between 1977 and 1990 (U.S. DOE, 2008a). There is also a pond in the 600 Area that was a disposal site for process waters from the FFTF (Duncan et al., 2008). The FFTF was constructed in the 1980s, and thus this pond may be a less significant source than the other ponds, though we have not reviewed groundwater or soil sampling data from this area.

Underground storage tanks

Underground storage tanks were used to store high-level radioactive liquid waste in the 200 and 300 areas (Dirkes et al., 1999). Collections of underground storage tanks, referred to as tank farms, were used to store the large amount of high-level radioactive waste liquid waste generated at the five chemical separation plants (T, B, U, REDOX, and PUREX) in the 200 Area (Harvey, 2000). There are 177 single-shell and double-shell high-radioactivity storage tanks in the 200 Area, ranging in capacity from 55,000 to approximately 1 million gallons (U.S. DOE, 2001a, 2006e). The storage tanks were used to settle the heavier constituents out of the liquid effluents, forming sludge. The liquid supernatants in the tanks were then discharged to the soil column via surface impoundments such as cribs, drains, trenches, and injection/reverse wells. Underground storage tanks were also used in the 300 Area to store radioactive acidic liquid wastes (U.S. DOE, 2009a). These underground storage tanks are known to have leaked hazardous substances to the subsurface (U.S. DOE, 2008a). Waste evaporators were also used to dispose of liquid wastes. These were known sources of radionuclide emissions in the 200 Area (Dirkes et al., 1999).

Injection wells (reverse wells)

Injection wells, or reverse wells, were used during operations to dispose of liquid wastes through direct injection into groundwater. Injection wells were used in the 100 Area and in the 200 Area. Injection of process waters that were in contact with irradiated fuel rods occurred in the 100 Area during operation of the reactors, and is suspected to be one source of strontium-90 in groundwater in the 100 Area (U.S. DOE, 2008a).

Reverse wells were used in early operations in the 200 Area to inject liquid wastes into deeper groundwater. Numerous contaminants are associated with these wells. For example, elevated concentrations in groundwater of uranium, cesium-137, plutonium, strontium-90, and other hazardous substances are associated with the 216-B-5 injection well, which was used in the 1940s (U.S. DOE, 2008a).

3.1.4 Solid waste

Numerous types of solid wastes were generated during Site operations, with several methods of handling the waste. Solid waste was disposed of in burial grounds. It was incinerated in open pits and incineration facilities, as described above. Highly radioactive irradiated materials were stored in the K basins in the 100 Area. Pieces of failed equipment and other large solid waste materials were stored in railcars at different locations on-site. Hazardous substances are known or suspected to have been released from all of the historical solid waste disposal sites described below.

Burial grounds were trenches in the ground which were used to dispose of intermediate- and low-level wastes such as laboratory supplies, tools, clothing, machinery, paper, wood, etc. (Dirkes et al., 1999). Some examples of specific burial grounds across the Site include the 118-F-1 (100 Area); 218-E-10, 218-E-12B (200 East Area); 218-W-3A, 218-W-3AE, 218-W-5 (200 West Area); and 618-10 (600 Area) (Dirkes et al., 1999). Solid wastes were historically packaged in wood, metal, or plastic containers for burial (U.S. DOE, 2001a). In later years, more care was given to separating solid wastes, and in 1970, special containers were used to package solid wastes that contained plutonium and other transuranic materials which were then stored in soil-covered trenches for possible later retrieval (Dirkes et al., 1999). As described above, there were also open burn pits and an incinerator in the 100 Area that were used to dispose of solid wastes by incineration (U.S. DOE, 2006d).

The K basins in the 100 Area were used to temporarily store spent fuel toward the end of nuclear operations. It is estimated that 105,000 irradiated, solid uranium metal fuel assemblies, representing approximately 2,100 metric tons of spent nuclear fuel, were generated and stored in the 100 Area, representing almost 80% of DOE's nationwide inventory of spent fuel (U.S. DOE, 2006d). The fuel stored in the K West Basin was packaged and sealed in canisters, while fuel in the K East Basin was stored in open canisters exposed to the basin water. Much of the irradiated fuel that was stored in the K basins became severely corroded and damaged over time. Some of the fuel was so corroded, especially in the K East Basin, that it disintegrated into small particles which collected at the bottom of the basins as a layer of radioactive sludge. The sludge contained fuel corrosion particles, fuel fragments, corrosion particles from metal products and equipment, wind-blown sand, pieces of corroded fuel cladding, and polychlorinated biphenyls (PCBs). A substantial amount of larger debris also accumulated in the basins. This material has been transferred to closure facilities in the 200 Area for treatment and long-term storage as a part of site closure operations (U.S. DOE, 2006d).

Railroad flatcars were used to store high-level solid waste, such as large pieces of machinery and equipment, at different locations across the Site. For example, in 1992, highly contaminated railroad cars were kept on railroad spurs and fenced off with a chain link fence and posted with warnings such as "Contamination Area and Radiation Area," "Radiological Materials Area," and "High Radiation Area." These zones were created as temporary waste storage sites until proper disposal of the railroad cars could occur (Henning, 1992). Railcars containing highly radioactive failed equipment were also stored in tunnels in the PUREX Plant area (U.S. DOE, 1999b). The PUREX Tunnels were built in the 1950s and 1960s (U.S. DOE, 1999a) and contain over 30 railcars filled with highly radioactive waste equipment that is also contaminated with lead, silver, mercury, cadmium, chromium, barium, and oil (Washington Department of Ecology, 2006; U.S. DOE, 2009a). The tunnels are now closed and the railcars will remain in storage until the waste materials can be processed and repackaged for disposal (U.S. DOE, 1999b).

3.1.5 Facilities/infrastructure

Operations and research facilities include the physical buildings that housed the nuclear operations. Examples of such facilities include fuel fabrication buildings, nuclear reactor buildings, chemical separation plants, associated support infrastructure (including pipelines, and tanks and other containers used to store chemicals), as well as research facilities. Numerous hazardous substances were used and produced in the Site facilities, and thus the buildings and support infrastructure are potential historical and ongoing sources of hazardous substances. In this section, we provide a brief summary of Site facilities and examples of hazardous substances stored, used, and produced within them. Note that maintenance facilities are discussed in Section 3.1.7; in this section we focus on nuclear operations and research activities.

Many metals and other substances were stored, used, and produced in the fuel fabrication facilities (300 Area), including, for example, beryllium, zirconium, lead, and aluminum. Copper sulfate, nitric acid, and sulfuric acid were used in the rod fabrication process, and trichloroethylene was commonly used to remove lubricants (Gray and Becker, 1993).

During fuel irradiation in the nuclear reactor facilities (100 Area), plutonium was generated from uranium fuel rods. Many other radionuclides were also generated as side-products. In addition, many other chemicals were stored and used in the nuclear reaction operations. For example, sodium dichromate was used as an antioxidant in the reactors, and sulfuric acid was used to control the pH of the reactor coolant water. Chromic, oxalic, and nitric acid decontaminated inactive fuel elements used as spacers. Chlorine and/or copper sulfate were used to control the algal growth in settling ponds (Gray and Becker, 1993). Other facilities in the 100 Area also may have released hazardous substances, including the cold vacuum drying facility, and the 107-N basin recirculation building (Duncan et al., 2008).

The 200 Area housed facilities used in the chemical separation (or extraction) of plutonium from irradiated fuel elements. These facilities are potential historical and ongoing sources of radionuclides and chemicals used in the chemical separation processes. The major chemical processing plants in the 200 East Area were the PUREX and B plants, and in the 200 West Area, the REDOX, U, and Z plants. Numerous hazardous substances were stored, used, and produced in these plants, including metals, organic solvents, and other substances. For example, in the B Plant, plutonium was separated from uranium fuel using an extraction process that used many different chemicals. A sodium hydroxide-sodium nitrate solution was first used to dissolve the aluminum fuel jacket. Nitric acid was then used to dissolve the fuel, followed by the complexation of uranium by sulfuric acid. Lastly, sodium bismuthate, sodium dichromate, sodium nitrate, oxalic acid, ammonium nitrate, hydrofluoric acid, potassium hydroxide, ammonium sulfate, hydrogen peroxide, hydrogen fluoride, and lanthanum salt were used in a series of extractions, ion exchanges, and washes to recover the plutonium oxide or metal (Ballinger and Hall, 1991; Gray and Becker, 1993).

Activities at the Site also included research and development work. Biological research was initiated in the 1950s which involved investigating the effect of radioactive contamination on biological species. This research was conducted at fish-rearing ponds and sheep pens in the 100-F Area. Other research and development practices were directed at investigating advances of various nuclear technologies. The Plutonium Fuels Pilot Plant (PFPP) and the Plutonium Recycle Test Reactor (PRTR) were built in the 1950s in the 300 Area to investigate non-defense uses of plutonium, including nuclear energy production. The Radiometallurgy Laboratory and the High-Level Radiochemistry Laboratory are examples of other research facilities constructed in the 1950s. Vitrification processes were also investigated to stabilize radioactive waste in glass or glass-like materials in the 1960s. In the 100 Area, research was conducted on the irradiation of lithium and thorium to produce tritium and uranium-233, respectively. In the 1980s, the FFTF

(400 Area) was developed which used sodium to cool the reactor (Ballinger and Hall, 1991). Each of these test facilities had associated hazardous substances that may have been released into the environment.

3.1.6 Episodic events

There have been numerous documented episodic events at the Site, such as overland flow, spills, leaks, explosions, and wildfires that may have resulted in the release of hazardous substances into the environment. Here we briefly provide some illustrative examples.

Numerous overland flow events have occurred at the Site. For example, in October 1948, the failure of the South Process Pond, one of the large liquid waste ponds in the 300 Area, resulted in the release of 14.5 million gallons of uranium-contaminated water down a natural channel into the river. As a result, 12 to 16 pounds of elemental uranium entered the Columbia River (U.S. DOE, 2008c).

Chemical spills have also been documented at the Site. An example of a large documented chemical spill is the sodium dichromate solution spill which occurred in the 100 Area in 1966. The spill released 140,000 pounds of sodium dichromate, much of which reached the Columbia River, as a result of a storage tank transfer pump malfunction at the 183-C Building. It was estimated that the concentration of hexavalent chromium in Richland and Pasco drinking water supplies from the river climbed to 50 parts per billion (ppb) before the pumps were shut down (Gerber, 1993).

Other illustrative examples of spills and leaks include the following:

- In 1953, an unintentional chemical reaction resulted in the violent ejection of metal waste spray from a vault in one of the tank farms in the 200 area. The spray rose about 30 feet (9 meters) into the air for 30 seconds. The volume of waste released was unspecified but should not have exceeded the 15,000 gallon storage capacity of the vault. The contamination spread to the southeast, and covered the eastern half of the tank farm (CH2M Hill, 2003).

- In 1956, 500 gallons of metal waste overflowed from the 241-UR-151 diversion box at the northeast corner of the U tank farm. In the same year, tank U-104 leaked an estimated 55,000 gallons of metal waste (CH2M Hill, 2003).

- Approximately 322 liters (85 gallons) of radioactive waste spilled from Tank 241-S-102 at the S Tank Farm on July 27, 2007 (Duncan et al., 2008).

- A spill of 346,700 liters (91,600 gallons) of supernatant containing 20.4 metric tons (22.5 tons) of uranium at Tank BX-102 (Sobczyk, 2004) in the 200 East Area.
- Approximately 2,600 gallons of cesium-137 recovery process feed solution leaked in December 1969 in the 200 West Area, near the 241-C-152 Diversion Box. This event, referred to as the "UPR 200-E-82 waste-loss event," created a temporary ground-surface puddle measuring 100 gallons in volume. It is estimated that 11,300 curies of cesium-137, 18.3 kilograms of uranium, and 5.01 curies of technetium-99 were released to the subsurface (Brown et al., 2008).
- On January 1, 1997, leachate tanks at the ERDF leaked approximately 190 liters (50 gallons) (Dirkes and Hanf, 1998) of contaminated leachate.
- Approximately 757 liters (200 gallons) of diesel fuel leaked from a 242-S Facility tank on January 22, 2003. Contaminated soil was excavated and moved to a remediation area (Poston et al., 2004).

Explosions may also have resulted in the release of hazardous substances. Numerous explosions have occurred on-site. Examples include a chemical explosion at the 200 West Area Plutonium Reclamation Facility which occurred in May 1997. After the explosion, a yellow-brown-colored gaseous plume was emitted from the facility stack and water was discharged from a severed line (Dirkes and Hanf, 1998). An explosion also occurred in the REDOX Plant in the 200 Area in 1953, which likely resulted in the release of hazardous substances (McCullugh, 1968).

Wildfires which occurred periodically throughout the history of operations may also have been episodic sources of hazardous substances. Wildfires may have burned contaminated vegetation, releasing contaminants to air. They also likely created heat updrafts and dust dispersion that released and distributed hazardous substances.

3.1.7 Other Site activities

In addition to stressors associated with nuclear operations at the Site, other related support activities may also have released stressors to the environment, and potentially caused injury to natural resources. Examples include transportation, site maintenance, landfills and other historic waste management facilities, military defense facilities, intentional releases, and vegetation controls.

Transportation

There is an extensive system of railroads and highways, as well as a small airstrip at the Site, with many associated known and suspected releases of hazardous substances.

Railroads were used extensively throughout the Site to transport materials related to the nuclear operations. There are 205 kilometers (127 miles) of rail line at the Site, linking the different operational areas. Fuel rods manufactured in the 300 Area were transported by rail to the 100 Area for irradiation, with irradiated rods subsequently transported by rail to the 200 Area for extraction of plutonium (U.S. DOE, 1999a). Numerous hazardous substances are known or suspected to have been released to the environment during transport by rail. For example, in 1957 a railcar which was transporting failed equipment from the REDOX Plant to the T Plant was derailed, releasing contamination to the ground (McCullugh, 1968). Other examples include:

- Spills of sodium dichromate and mercury (Henning, 1992)
- Various chemicals, such as sulfuric acid and sodium hydroxide, detected on the ground surface near facilities which remove liquids from railroad cars (e.g., 108-N Chemical Unloading Facility) (Henning, 1992)
- Railcars transporting material from the PUREX Plant to a burial ground reportedly had fission products dripping from the car (Henning, 1992).

Leakage of hazardous substances from pipelines that connected railroad and storage tanks in the different operational area are also suspected to have occurred. These pipelines transported numerous substances from the railcars to storage facilities, including mercury, lead, sodium silicate, and sodium dichromate (Henning, 1992). Finally, in addition to the release of transported hazardous substances as a result of spills and derailments, and leaky transfer pipes, the railroads were also likely sources of polycyclic aromatic hydrocarbons (PAHs) and other substances related directly due to the operation of the railroad. Underground storage tanks were used to store fuel for railroad cars (and vehicles), with many documented instances of hydrocarbons leaking into the environment from these tanks (Henning, 1992).

Vehicles (cars and trucks) were also used for transportation on 464 kilometers (288 miles) of road at the Site (U.S. DOE, 1999a). Numerous releases of hazardous substances are known or suspected to have occurred as a result of vehicular transportation and maintenance. Contaminants known or suspected to have been released associated with vehicle and road maintenance include lubricating fluids, battery acid, lead, ethylene glycol, total petroleum hydrocarbons, and PCBs (Henning, 1992). As mentioned above, underground storage tanks were used to house fuel for vehicles and railroad cars, with many documented instances in which oil had been released into the environment from these tanks (Henning, 1992). Though we did not find any documentation, it is also likely that hazardous substances transported by vehicles may have leaked during transport.

Aviation transportation also occurred at the Site, with an airstrip located between the 200 East and 200 West areas. Hazardous substances associated with aviation, including fuels and other substances, may have released as a result of this transportation mechanism.

Site maintenance

Many site maintenance activities are known or suspected to have resulted in the release of hazardous substances to the environment, and potentially injured natural resources. Site maintenance services and infrastructure was mainly located in the 1100 Area. This included warehousing and property receiving and distribution, mail services, vehicle maintenance, a landfill (described in Section 3.1.2), and other infrastructure services (U.S. DOE, 2006a). There was also a demolition area in the 1100 Area, in which detonation of nonradioactive explosive, ignitable, shock-sensitive, and/or reactive discarded chemical products took place. These were either excess materials or chemicals beyond the designated shelf life. Examples of the compounds detonated include but are not limited to 2,4,6-trinitrorescorcinol, alpha-nitrosomethylisobutylketone, trinitrotolue, tetrahydrofuran, perchloric acid, and benzene with b-butyl lithium (Henning, 1992). Disposal pits and dumping areas in the 1100 Area were used to discard maintenance materials, including paint, solvent, thinners, construction debris such as concrete rubble, asphalt, and wood. Concrete, glass, dry cell batteries, and other materials were also disposed of in these areas (Henning, 1992).

In addition to maintenance activities in the 1100 Area, there were also releases of hazardous substances associated with site-wide maintenance activities. One of the more notable examples is PCBs. Leaks and spills from capacitors, transformers, and hydraulics found in operational equipment likely released PCBs to the environment. Other common site-wide sources of PCBs include fluorescent light ballasts, paint, and sealants. In addition, a common practice at the Site in the past was to apply PCB oils to unpaved roads to suppress dust (Herman, 2007).

Other contaminants such as pesticides and herbicides have been detected at different locations across the Site as a result of their storage and use (Dirkes et al., 1999). Pesticides have been detected in sanitary sewer pipelines in the 100 Area (Henning, 1992) which may be a source to nearby soils or groundwater.

Landfills and other historic waste facilities

There are a number of landfills and other waste treatment facilities at the Site that may be sources of hazardous substances. Here we provide brief descriptions of illustrative examples of such facilities, including the US Ecology low-level radioactive waste (LLRW) disposal facility, the Horseshoe and Horn Rapids and Hanford Central landfills, and the Wahluke Slope burial ground.

The US Ecology site houses a LLRW disposal facility currently operated by US Ecology Inc. Packaged waste is disposed of in unlined trenches which are approximately 240 meters (800 feet long), 46 meters (150 feet) wide, and 14 meters (45 feet) deep. The packaged waste includes LLRW, such as trash clothing, tools, hardware, and equipment that has been contaminated by radioactive substances; and naturally-occurring and accelerator-produced radioactive material (NARM), such as pipe scale from oil and gas pipelines, soils from cleanup of mineral processing sites, measuring devices and gauges, non-radioactive hazardous, and mixed waste. Only LLRW and NARM have been disposed of at this site since 1985. Waste is accepted from off-site sources, including nuclear power plants, industrial users, government and military organizations, academic institutions, and the medical community (Washington Department of Ecology, 2009). For example, in 2000, the core of the Trojan nuclear reactor, which is a commercial nuclear reactor in Oregon used to produce electric power, was buried at this site (U.S. DOE, 2006b). This facility is expected to close in 2056 (Washington Department of Ecology, 2009).

The Horseshoe Landfill (600-720 waste site) is approximately 6.9 acres and is located in the former 1100 Area (see Section 3.3). DDT-contaminated soil (~ 13,500 tons) was disposed of in the Horseshoe Landfill. Miscellaneous solid wastes, such as used oil and hydraulic fluids, decontamination fluids, and used batteries were also disposed of at the landfill. The Horseshoe Landfill was remediated in 1994 under CERCLA. Although the 1100 Area was taken off the NPL in 1996, continued monitoring from 1993 to 2000 demonstrated that the residual levels of DDT in landfill soils exceeded the cleanup level of 0.75 ppm. Therefore, further soil remediation was completed as described in the approved Richland Environmental Restoration Project Fiscal Year 2005/2006 Detailed Work Plan (U.S. DOE, 2005a). As of 2006, the cleanup actions were completed and the Site was awaiting backfill and revegetation (U.S. DOE, 2006e).

The Horn Rapids Landfill is located in the 1100 Area (see Section 3.3). Asbestos was disposed of at this landfill (U.S. DOE, 2006e). Trichloroethene (and its breakdown products such as vinyl chloride and 1,1-dichlorethene), nitrate, and technetium-99 are other chemicals that have been identified at this site (U.S. DOE, 2008a). This landfill was sealed and capped in 1995 and was removed from the NPL in 1996 (U.S. EPA, 2009).

The Hanford Central Landfill was established in the early 1970s in the 200 East Area. In the late 1980s, this landfill received 40 cubic meters (1,424 cubic feet) of asbestos which originated from the demolition of facilities in the 100 Area (Henning, 1992). The Hanford Central Landfill was closed on March 31, 1996 (Author unknown, 1999).

In 1967, the Wahluke Slope Burial site, located on the north side of the Columbia River, was used to dispose of 11 known or suspected leaking tanks which contained the herbicide 2,4-dichlorophenoxyacetic acid (2,4-D), as well as 38 cubic meters (50 cubic yards) of contaminated soil. The U.S. Bureau of Reclamation (USBOR) commonly used this herbicide to control vegetation growth along the irrigation canals on the Wahluke Slope and stored this chemical in underground storage tanks 3.7 meters (12 feet) in length and 1.2 meters (4 feet) in diameter. Sampling in 1997 detected concentrations of 2,4-D of 17,000 ppm in soils. Dioxins were also detected as contaminants in these soils. Bioremediation was proposed as the dominant remediation technique to be employed for treatment of the 2,4-D contamination. Much of the remaining debris such as tanks were proposed to either be disposed of at the ERDF or other off-site disposal facilities (U.S. DOE, 1997). This area was listed on the NPL in 1989 and deleted by 2006 (U.S. DOE, 2006e).

Military defense facilities

Military defense facilities were housed at different locations at the Site, and are also a potential source of stressors to natural resources. Here we briefly describe the military facilities and provide examples of some of the hazardous substances that were known to be used at these sites.

In order to protect the reactors and chemical separation plants from airplane attack, Army troops were permanently stationed at 16 anti-aircraft artillery sites which encircled the 100 and 200 areas beginning in 1951. These sites were approximately 20 acres in size and contained four gun emplacements as well as buildings such as wooden structures, prefabricated metal buildings, and permanent concrete block structures (Harvey, 2000). A Nike, Ajax, and Hercules missile launching facility was installed during the mid-1950s, which replaced the 16 anti-aircraft artillery sites. Installation included assembly, fueling, maintenance, and launching facilities. The deployment of these missiles occurred at three locations on the Wahluke Slope and one on the Fitzner-Eberhardt Arid Lands Ecology Reserve (Harvey, 2000).

Wastes associated with military activities included missile components, propellants, solvents, fuels, and other support materials. Solvents such as carbon tetrachloride, trichloroethylene, and trichloroethane were commonly used for cleaning and maintenance activities. Petroleum products were also used and stored at these sites, including JP-4 jet fuel, gasoline, diesel fuel, fuel oil, hydraulic fluid, and motor oil. Other examples of substances used at these sites include nitrate, dimethyl hydrazine, and aniline, which were commonly found in starter fluids, and lead associated with lead batteries. Many of the liquids were routinely dumped into sumps. Sumps were excavated pits (1–2 cubic meters) backfilled with gravel where liquids were placed and allowed to soak into the ground. Fuel components were also disposed of in this manner, but to a more limited extent. Wastes were also disposed of in burial grounds and landfills (McMaster et al., 1984).

Intentional releases

On December 2–3, 1949, a U.S. Air Force experiment at Hanford resulted in the intentional release of 7,000 to 12,000 curies of iodine-131 into the air, purportedly to test radioactivity monitoring equipment being developed to assess the Soviet Union's nuclear weapons program. The normal practice in 1949 was to cool the irradiated fuel 90 to 100 days before processing. The longer cooling time allowed for radionuclides with short half lives, including iodine-131, to decay to lower levels. This intentional release was called the "Green Run" because it involved a processing "run" of uranium fuel that had been cooled for only 16 days, and was, therefore, "green" (Washington Department of Health, 2002).

Vegetation control

Vegetation control measures, including mechanical, chemical, and biological methods, have been employed at the Site to control the spread of contamination through vegetation. Mechanical control of vegetation is the physical removal (e.g., cutting) of plants. Chemical controls involve the use of herbicides to reduce the number and size of plant populations. Biological controls involve the use of specific organisms to reduce the seed production of plants (Duncan et al., 2008). Vegetation control measures may result in the injury of natural resources, either through the release of hazardous substances to the environment, or through the physical removal and disturbance of habitat.

The potential for the spread of contamination by vegetation at the Site had been identified since the late 1960s, when "hot" tumbleweeds were found growing in solid waste burial grounds (Millikin and Brannan, 2002). Since then, there have been numerous observations of contaminated vegetation at the Site. In the early 1970s, many burial grounds, trenches and ponds were capped with a thick soil layer to reduce radioactive contamination and to prevent deep-rooted plants from penetrating into buried wastes. Other historical vegetation controls included spraying of herbicides, physically removing vegetation using heavy equipment, planting of other vegetation, using snow fencing to control tumbleweed movement, and covering contaminated soils with impermeable materials (Millikin and Brannan, 2002). Vegetation control measures have also been used to control noxious weeds at the Site. Noxious weeds are typically nonnative species which when established are highly destructive to and competitive with native species (Duncan et al., 2008).

3.2 Secondary Stressors

Natural resources, including air, soils, groundwater, surface water, sediments, and biotic resources, which are contaminated by hazardous substances released from Site sources may in turn act as sources of contamination (or secondary stressors) to other resources. For example, soil contamination can occur as a result of the release of hazardous substances from ponds, cribs, and other surface impoundments. The contaminated soil may then act as a secondary stressor by exposing other natural resources, including biologic receptors such as plants and animals, through, for example, uptake and dermal contact. The contaminated soil may also be a source of hazardous substances to the underlying groundwater. In turn, the contaminated groundwater may come into contact with and expose sediments and surface waters of the Columbia River. Thus contaminated groundwater may also act as a secondary source to other natural resources. Contaminated vegetation can also be a secondary stressor, exposing grazers that ingest the contamination, and potentially re-releasing contaminants to air during wildfires. Secondary stressors are discussed in further detail in the Pathway chapter (Chapter 4).

3.3 Response Action Stressors

In this section, we summarize and provide examples of response action stressors at the Site. The main response activities on-site thus far have focused on treating and/or removing contaminated soils and groundwater. Response actions for contaminated soils have mainly consisted of removal actions that remove the most contaminated soil (with potential residual contamination). Clean fill materials have been excavated from borrow areas to replace excavated contaminated soils and for other remedial purposes. Waste treatment facilities have been constructed to treat and store contaminated soils and other Site waste materials, with a network of roads constructed to link these facilities to the waste sites. Pump and treat and re-injection systems have been installed to treat groundwater. In addition, demolition of facilities is underway, as well as vegetation control activities and plans for institutional controls. All of these response actions likely will cause unavoidable injuries to natural resources.

Figure 3.3 shows historical landfill sites, current closure facilities, and waste areas where removal actions have occurred or are planned.[2] While the waste and closure areas shown in Figure 3.3 have not been verified and may not be complete, this preliminary map shows that the total area likely to be disturbed by response actions (and thus, the total area of injuries unavoidable as a result of response action) is quite extensive. As such, these response action stressors are included in this CSM.

3.3.1 Soil removal and treatment

Soil removal is a part of the soil remediation process, which according to U.S. DOE (2006e), involves quantifying contaminants, excavating, treating, disposing of contaminated soil, regrading, and revegetating. Soil removal activities thus far have been focused on the 100 and 300 areas. The removed soils have been transported to the closure facilities located in the 200 Area, primarily the ERDF, for treatment and long-term storage. The ERDF currently holds 7.2 million tons of material, much of which has come from the River Corridor. As of 2006, roughly 4.7 million metric tons of soil and debris have been removed from the 100 Area waste

---

2. The waste areas shown in Figure 3.3 are listed in the Waste Information Data System (WIDS) as any of the following: Burial Ground, Burial Vault, Crib, Drain/Tile Field, Dumping Area, Process Pit, Radioactive Process Sewer, Retention Basin, Sanitary Landfill, Spoils Pile/Berm, Trench, or Unplanned Release. Figure 3.3 also includes waste area information that Washington Closure Hanford provided to Stratus Consulting.

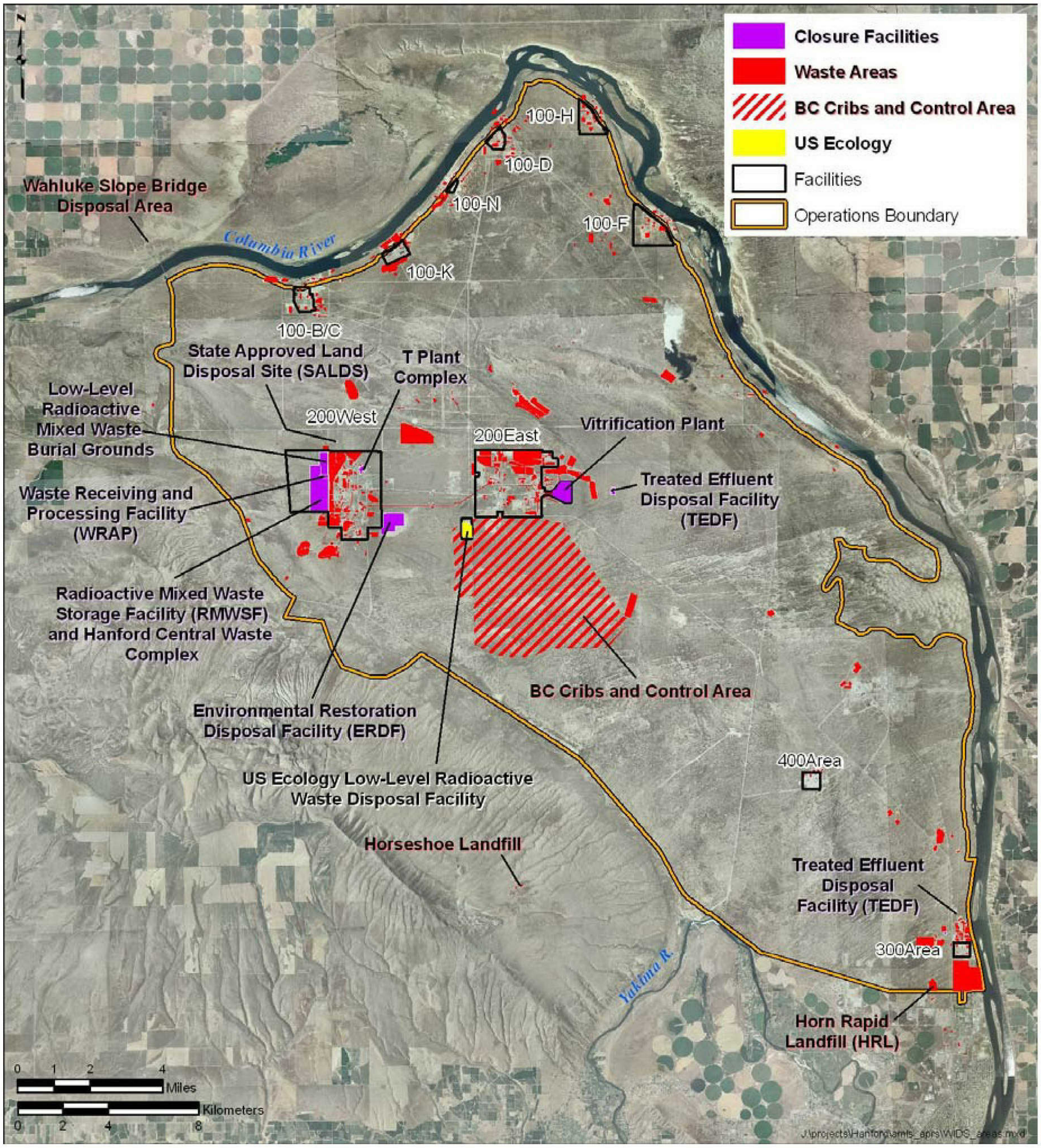


Figure 3.3. Hanford historical landfill sites, waste areas, and closure facilities constructed to process or store Hanford contaminants. The BC Cribs and Control Area includes some areas that require complete soil removal and other areas slated for hotspot removal only. The US Ecology facility is not a DOE facility, and it receives low level radioactive waste from sources outside of Hanford.

Source: Hanford WIDS and Washington Closure Hanford – see footnote 2 in text.

sites, and transported to the ERDF (U.S. DOE, 2006e). More than 553,382 metric tons (610,000 tons) of contaminated soil and debris have been excavated from the 300 Area (mainly from the 300-FF-1 OU waste sites) and transported to ERDF for disposal (U.S. DOE, 2007). In the 1100 Area, 130 cubic yards of soil with bis-(2-ethylhexyl) phthalate (BEHP) were excavated and sent to an incineration facility and 165 cubic yards of soil contaminated with PCBs were removed and disposed of at a permitted facility. As a result of the soil removal actions, very large surface areas have been physically disturbed and potentially injured.

We are aware of one in situ soil treatment process installed at the Site. A vapor extraction system was installed in 1991 as a CERCLA-expedited response action in the 200 Area to treat soils contaminated with carbon tetrachloride. Since extraction operations began in 1991, ~79,200 kilograms of carbon tetrachloride have been removed, which is roughly 9%–14% of the estimated amount of carbon tetrachloride discharged to the soil column (U.S. DOE, 2006e, 2008a). According to Dirkes et al. (1999), releases of carbon tetrachloride to the air have occurred during vapor extraction.

3.3.2 Borrow areas

Borrow areas, or borrow pits, are areas where material, usually soil, gravel, or sand, have been dug for use at another location. The material may be used to backfill an area where soil removal has occurred, as road construction materials, or for other reasons (U.S. EPA, 2001a). Clean fill is and will continue to be used extensively in Site response actions. The borrow areas represent areas that have been injured as a result of response actions.

3.3.3 Closure facilities

There are many on-site closure facilities for the treatment of contaminated wastes. Examples include the ERDF, the Treated Effluent Disposal Facility (TEDF), the Central Waste Complex, the Waste Receiving and Processing Facility, the T Plant Complex, the Integrated Disposal Facility, the Radioactive Mixed Waste Disposal Facility, the Vitrification Plant, and Low-Level Burial Grounds (Duncan et al., 2008). Biological and other mitigation activities were performed at many of these sites. Nevertheless, construction of these facilities has disturbed large areas of land, resulting in disturbance of natural habitat and potential injuries to natural resources. The facilities are also potential sources of future hazardous substance releases that could injure natural resources, including potential air emissions. Here we provide brief descriptions of example waste treatment closure facilities at the Site.

Environmental Restoration Disposal Facility

Soil and/or debris that has been contaminated by hazardous, low-level radioactive, or mixed waste that has been dug up or removed from demolition sites is mainly disposed of at the ERDF located on the Central Plateau near the center of the Site. The ERDF consists of multiple cells which are each 150 meters (500 feet) wide at the bottom, 20 meters (70 feet) deep, and over 300 meters (1,000 feet) wide at the surface (U.S. DOE, 2006c, 2009b). It is a lined facility with a leachate collection and recovery system (U.S. EPA, 1998). An expansion was recently approved that will expand ERDF from eight to ten cells; based upon a 1995 ROD, the ERDF can expand up to 2.6 kilometers (1.6 miles) in length, with a total of 28 cells (Duncan et al., 2008). Since this work began in 1996, more than 8 million tons of material have been placed in the ERDF. About 3,000 tons of contaminated soil and materials go into the ERDF each day and this facility is expected to hold a total of about 11 million tons of this low-level waste from cleanup. Once filled, the ERDF will be capped with an engineered barrier to prevent the release of waste and the infiltration of rain (U.S. DOE, 2009b; Washington Closure Hanford, 2009).

Treated Effluent Disposal Facility

The TEDF, located in the 300 Area, collects and treats industrial (non-radioactive and radioactive) wastewater generated throughout the Site related to recent closure operations. The volume of industrial wastewater treated and disposed of during 2007 was 44.4 million gallons (Duncan et al., 2008).

Central Waste Complex

Most of the waste received at the Central Waste Complex, which is located in the 200 West Area, comes from Site operations such as ongoing cleanup and research and development activities, as well as off-site waste from other DOE and the U.S. Department of Defense (DOD) facilities. The volume of waste stored as of 2007 was approximately 7,930 cubic meters out of a total storage capacity of 20,796 cubic meters. The waste disposed of at the Central Waste Complex includes low-level, transuranic, mixed waste, and radioactively contaminated PCBs (Duncan et al., 2008).

Waste Receiving and Processing Facility

The Waste Receiving and Processing Facility is located in the 200 West Area and began operations in 1997. Waste entering this facility primarily includes contaminated cloth, paper, rubber, metal, and plastic as a result of stored waste and newly generated waste from Hanford cleanup activities (Duncan et al., 2008).

T Plant Complex

The T Plant Complex, built in 1944, is located in the 200 West Area and was used as a plutonium separation facility, similar to the B Plant (U.S. DOE, 2008b). However, it is currently run under RCRA interim status. This complex provides waste treatment, storage, and decontamination services for both the Site and off-site facilities (Duncan et al., 2008).

Integrated Disposal Facility

The construction of the IDF, which is located in the 200 East Area, was completed in 2006. This RCRA-compliant landfill is 460 meters (1,500 feet) wide, 230 meters (765 feet) across, and 13 meters (42 feet) deep, and was developed for the disposal of LLRW, mixed LLRW, and low activity waste (LAW). The IDF currently contains two cells: one for LLRW from Site cleanup activities and the other for mixed low level waste (MLLW), which is anticipated to come from the Waste Treatment Plant and Hanford's Demonstration Bulk Vitrification Plant. The landfill is expandable, but at its current size it has a disposal capacity of 153,000 cubic meters (200,000 cubic yards) of waste (CH2M Hill, 2006).

Vitrification Plant

The Vitrification Plant is located in the Central Plateau, adjacent to the 200 East Area (see Figure 3.3). The plant will be used to vitrify approximately 53 million gallons of radioactive wastes stored in 177 of the underground storage tanks in the 200 Area. The vitrified waste materials will be placed in stainless steel canisters for long-term storage. Construction began in 2001 on the 65-acre complex, with a planned completion date of 2019, and a planned operating life of 30 years (Bechtel, 2009).

Low-Level Burial Grounds and Radioactive Mixed Waste Disposal Facility

The Low-Level Burial Grounds are located in the 200 East and West areas and consist of eight burial grounds which are used for the disposal of low-level and mixed waste. The Radioactive Mixed Waste Disposal Facility is designated as Trenches 31 and 34 in the Low-Level Burial Grounds. Disposal in Trench 34 began in 1999 and Trench 31 in 2005 (Duncan et al., 2008).

3.3.4 Groundwater treatment

Groundwater treatment at the Site includes pump and treat systems installed to fulfill CERCLA requirements, in situ treatments that are a part of interim actions, and treatability tests. These are summarized here. Surface areas where treatment takes place, and other physical disturbances associated with groundwater treatment represent unavoidable injuries associated with response actions.

Pump and treat systems

Pump and treat systems are being used to treat groundwater in the 100 and 200 areas to fulfill CERCLA requirements. Pump and treat systems use physical and chemical treatments to remediate chemicals from water. The groundwater is pumped to the surface, treated, and then re-injected. Table 3.1 provides a summary of pump and treat systems at the Site.

Table 3.1. 100 and 200 areas pump and treat systems

Year initiated	Event	Reference
1994	Initiation of pump and treat systems to target carbon tetrachloride in the 200 West Area at the 200-ZP-1 and 200-UP-1 units. Total carbon tetrachloride treated as of 2007 is 10,950 kg and 34.6 kg, respectively. Treatment ongoing as of 2008.	Duncan et al., 2008
1994	Pump and treat systems initiated at the 200-UP-1 unit to target nitrate, technetium-99, and uranium. Total treated as of 2007: nitrate – 35,072 kg, technetium-99 – 119.1 kg, and uranium – 1.13 kg. Treatment ongoing as of 2008.	Duncan et al., 2008
1995	Pump and treat systems which targeted strontium-90 from 100 Area have removed a total of 1.83 curies of radionuclides. Activities stopped in 2006.	U.S. DOE, 2008a
1997	Initiation of pump and treat systems in the 100 D Area, 100 H Area, and 100 K Area to target chromium; total removed 423.7 kg, 49 kg, and 327.8 kg of chromium, respectively. Treatment ongoing as of 2008.	Duncan et al., 2008

Interim actions

Numerous interim actions have also taken place at the Site. These include:

- An in-situ REDOX manipulation system was installed in 2000 to target chromium at the 100-HR-3-D OU (U.S. DOE, 2008a)
- In the 100 N Area, a 90-meter apatite PRB installed near the Columbia River shoreline in 2006 to target strontium-90 (U.S. DOE, 2008a)
- Four cylinders of a selective polymer were lowered into wells to remove petroleum products from groundwater in 2007 in the 100 N Area (U.S. DOE, 2008a)
- The interim action for the groundwater contamination in the 300 Area involves natural attenuation of the dichloroethylene, trichloroethylene, and uranium (U.S. DOE, 2008a).

Treatability tests

Many experimental treatability tests have been implemented and are underway at the Site. Examples include:

- In the 100 K Area, calcium polysulfide treatability tests were initiated in 2005 for chromium (U.S. DOE, 2008a)
- In the 100-D Area, electro-coagulation tests were conducted in summer 2007 to treat chromium (U.S. DOE, 2008a)
- In the 200 Area, a treatability test of the Purolite resin-based ion exchange system to remove technetium-99 started in late April 2007 (U.S. DOE, 2008a)
- In the 300 Area, a uranium treatability test was conducted which injected polyphosphate into the aquifer in June 2007 (U.S. DOE, 2008a).

In addition, a suite of treatability tests were conducted in the 200 Area to evaluate remediation methods for the treatment of carbon tetrachloride, trichloroethene, chromium, nitrate, technetium-99, iodine-129, uranium, and tritium. Table 3.2 summarizes reported results (Truex et al., 2006).

Table 3.2. Treatability tests

Test	Description	Outcome
Physical Containment (injectable grout walls and freeze walls)	Injectable grout walls were made by injecting a cement mixture into the ground. Freeze walls used heat transfer devices to freeze soil pore water.	Rejected as a potential remediation strategy
Chemical Oxidation	This remediation strategy uses strong oxidants to degrade organic contaminants.	Considered a potential remediation action to target carbon tetrachloride
Injectable Apatite Solution	This method uses hydroxyapatite as a means to immobilize aqueous uranium species.	Considered a potential remediation technique for treatment of uranium
Stabilization by Polyphosphate	This method uses polymers of phosphate, which release phosphate in a more controlled manor to encourage formation of autinite which has a very low solubility.	Considered a potential remediation technique for treatment of uranium
Injectable Zero-Valent Iron	This method places particles of zero-valent iron into the subsurface to dechlorinate carbon tetrachloride, trichloroethene, and reduce chromium, nitrate, technetium-99, and uranium.	Rejected as a possible remediation strategy

Table 3.2. Treatability tests (cont.)

Test	Description	Outcome
Surfactant Flushing	Surfactant mixtures promotes the solubilization of non-aqueous phase liquids (NAPLs). After the microemulsions form they are treated using ex situ treatment processes.	Considered a potential source of remediation of carbon tetrachloride
In-Well Air Stripping (and thermally enhanced in-well air stripping)	This process pumps air into a well creating recirculation of groundwater and creates mass transfer between volatile organic species from the groundwater to the gas phase which could then be captured by vacuum extraction.	Considered a potential remediation strategy for treatment of carbon tetrachloride and/or trichloroethene.
Down-Well System	This technique employs a bioreactor of adsorption media in a well.	Eliminated as a potential remediation strategy
Air Sparging	This process injects gas (usually air/oxygen) under pressure into the saturated subsurface that volatilizes organic contaminants which can then be collected by vacuum.	Considered a potential remediation technique
Anaerobic Bioremediation	Anaerobic bacteria have the ability to reduce and degrade organochlorines.	Considered a potential remediation strategy to target carbon tetrachloride or trichloroethene
Aerobic Bioremediation (co-metabolism)	Some bacteria can co-metabolically oxidize trichloroethene with other compounds such as methane. Therefore, by injecting methane into the target zone, this would help to stimulate microbial activity and oxidize trichloroethene.	Considered a potential remediation strategy to target trichloroethene
In Situ Thermal Treatment	This remediation strategy uses electrical resistance heating or steam injections which promote the hydrolysis of carbon tetrachloride.	Retained as a potential remediation technique
Permeable Reactive Barrier	In general these are large structures designed to treat contaminated water as it passes through the barrier. Most are similar to techniques described above but are more or less a “barrier.” ▸ Zero-valent iron PRB ▸ In situ redox manipulation PRB ▸ In situ anaerobic bioremediation PRB ▸ Injectable apatite PRB ▸ Polyphosphate PRB.	All systems retained as possible remediation techniques with the exception of the zero-valent iron PRB

3.3.5 Facility decommission, deactivation, decontamination, and demolition (D4)

Four hundred and eighty-six facilities at the Site will be demolished. This includes facilities in the 100 Area (except the retired reactors), facilities in the 300 Area, and facilities in the 400 Area (except the FFTF). The facilities range from small mobile offices to highly contaminated multi-structured facilities, waste storage pads, sewage treatment structures, stacks, and tanks. D4 specifically refers to ending existing operations or processes (deactivation), removal of energy sources (decommissioning), removal or stabilization of radioactive and hazardous contaminated materials (decontamination), and removal of building structures and slab or foundations (demolition) (U.S. DOE, 2009c).

While final closure decisions for the reactors have not yet been made, the reactors are currently undergoing a process called “cocooning.” Cocooning involves demolishing all ancillary and exterior structures at the reactor complex, leaving only the reactor core and its surrounding shield walls. Loose contamination is removed or stabilized. The remaining structure receives a 75-year roof, as well and lighting and electrical receptacles designed to provide adequate illumination for entry and exit during surveillance and maintenance activities (U.S. DOE, 2006f). A system is also installed to monitor for potential flooding in below-grade areas (U.S. DOE, 2007). From 1998 to 2005, the C, DR, F, and H reactors were “cocooned.” The cocooning of the K East and K West reactors is expected to be completed in 2011, and the N reactor is scheduled to be cocooned in 2012 (U.S. DOE, 2006f).

Deactivation of the FFTF in the 400 Area is planned to be completed by September 2009. This requires removing all nuclear fuel, draining the sodium systems, and deactivating systems and equipment to place the facility in a low-cost, long-term surveillance and maintenance condition (Duncan et al., 2008).

3.3.6 Transportation corridors

Roadways have been constructed as a part of response activities at the Site. These transportation corridors and associated ancillary stressors such as dust creation, dust suppression, and noise, cause disturbances that may act as barriers to natural habitats and may injure natural resources. Hazardous substances released as a result of vehicle operation and maintenance may injure natural resources.

3.3.7 Vegetation control

Recent vegetation control at the Site includes controlling or preventing the growth or re-growth of plants in contaminated or potentially contaminated areas on the Site. Contaminated plants may expose other natural resources to hazardous substances, providing a pathway to spread contamination. For example, at one time contaminated mulberry bushes grew in the N-Springs area along the Hanford Reach shoreline near the N-Reactor. In 1991, these bushes were removed to reduce exposure to wildlife(Nord and Day, 1991; Izatt and Lerch, 1992). In 1999, The Integrated Biological Control Program was established to address the spread of radioactive contamination by biological vectors such as noxious weeds (Poston et al., 2000). The purposes of the Integrated Biological Control program are to control the transport of radioactive contamination by biological vectors outside of radiological control areas, and to provide non-radiological biological control services, such as noxious weed control and pest control (U.S. DOE, 2001b). This program is responsible for the integration of monitoring, controlling, cleaning up, and restoring areas affected by radioactive contaminants spread by plants or animals. In addition to herbicide application, recent controls have included installing herbicide-impregnated fabrics to stop vegetation and insects from burrowing into waste sites, and planting bunchgrass to inhibit the growth of deep-rooted noxious vegetation (Duncan et al., 2008).

3.3.8 Institutional controls

Institutional controls are put in place to limit or prohibit activities that would interfere with interim or cleanup actions, and to protect human health from exposure to hazardous substances (HAB, 2004). They are required when residual concentrations of hazardous substances are above cleanup standards and may include physical closures or legal measures. Examples of physical controls include fencing and posting property; legal control can include land zoning and lease restrictions. Controls can also be applied to surface- and groundwater.

Two types of institutional controls have been put in place in the 1100 Area, including restricted groundwater use because of trichloroethylene contamination, and physical access controls to the Horn Rapids landfill. The U.S. DOE (2003) reports that additional institutional controls will likely be required at the Site. Potential institutional controls that are being considered for the 100 Area include legal and administrative restrictions on activities which disturb soils that are deeper than 4.5 meters (15 feet) below the surface. Restricted use of the groundwater is also anticipated, with restrictions only to be removed if contaminant levels in the groundwater drop below drinking water standards. The 200 Area will likely be designated for long-term waste management activities. Institutional controls will likely be both physical, legal, and permanent, over many square kilometers. Controls may also be needed in the 300 Area. Finally, DOE anticipates that site-wide groundwater restrictions will likely be needed because of contamination. Such institutional controls may result in disturbance to habitats, injuries to natural resources, and service loss.

3.4 Hazardous Substances Known or Suspected to Have Been Released from Site Sources

This section provides a list of contaminants known or suspected to have been released from the operations described in Sections 3.1–3.3. Table 3.3 provides a preliminary list of contaminants that have been used or produced at the Site. Those that have been found in the environment at or above analytical detection limits are indicated by an "X." The contaminants are listed by operational area, and by groups of operational areas, as reported by the citations provided in the table. While this list is representative, it does not represent the full suite of stressors released into the environment, nor does it represent a consensus amongst the Trustees of contaminants that should be examined in the natural resource injury assessment.

Table 3.3. Hazardous substances known to have been used or produced in the different operational areas. X indicates that the compound has been used or produced at the Site and confirmed in the environment.

			Operational area(s)					
Contaminant class	**Contaminant**	**Listed hazardous substance?[a]**	**100 Area**	**200 Area**	**300 Area**	**600 Area**	**100, 300, and 1100 areas**	**100 and 300 areas and nearby Columbia River surface water samples**
Radionuclides[b]	Actinium-228	Y						X
	Americium-241	Y	X	X			X	X
	Americium-242	Y						
	Americium-243	Y						
	Antimony-123	Y						
	Antimony-124	Y					X	
	Antimony-125	Y					X	X
	Barium-137	Y						
	Barium-137m	Y						
	Barium-140	Y	X					X
	Beryllium-7	Y						X
	Bismuth-214	Y						X
	Cadmium-113m	Y						
	Carbon-14	Y	X				X	X
	Cerium-141	Y						X
	Cerium-144	Y						X

Table 3.3. Hazardous substances known to have been used or produced in the different operational areas (cont.). X indicates that the compound has been used or produced at the Site and confirmed in the environment.

Contaminant class	Contaminant	Listed hazardous substance?[a]	Operational area(s)					
			100 Area	200 Area	300 Area	600 Area	100, 300, and 1100 areas	100 and 300 areas and nearby Columbia River surface water samples
Radionuclides[b] *(cont.)*	Cesium-134	Y					X	X
	Cesium-135	Y						
	Cesium-137	Y	X	X			X	X
	Chromium-51	Y						
	Cobalt-57	Y						X
	Cobalt-58	Y	X					X
	Cobalt-60	Y	X	X			X	X
	Curium-242	Y						
	Curium-243	Y						X
	Curium-244	Y						X
	Curium-245	Y						
	Europium-152	Y	X	X			X	X
	Europium-154	Y	X	X			X	X
	Europium-155	Y	X	X			X	X
	Iodine-127	Y						X
	Iodine-129	Y		X			X	X
	Iodine-131	Y						X
	Iron-59	Y						X
	Lanthanum-140	Y						X
	Lead-210	Y						
	Lead-212	Y						X
	Lead-214	Y						X
	Manganese-54	Y						X
	Neodymium-147	Y						
	Neptunium-237	Y		X			X	X
	Neptunium-239	Y						
	Nickel-59	Y						
	Nickel-63	Y	X				X	X

Table 3.3. Hazardous substances known to have been used or produced in the different operational areas (cont.). X indicates that the compound has been used or produced at the Site and confirmed in the environment.

Contaminant class	Contaminant	Listed hazardous substance?[a]	Operational area(s)					
			100 Area	200 Area	300 Area	600 Area	100, 300, and 1100 areas	100 and 300 areas and nearby Columbia River surface water samples
Radionuclides[b] *(cont.)*	Niobium-93m	Y						
	Niobium-94	Y	X					
	Niobium-95	Y						X
	Niobium-98	Y						
	Palladium-107	Y						
	Plutonium-238	Y	X	X			X	X
	Plutonium-239/240	Y	X	X			X	X
	Plutonium-241	Y						
	Plutonium-242	Y						
	Potassium-40	Y	X	X			X	X
	Praseodymium-143	Y						
	Praseodymium-144	Y						
	Promethium-147	Y						
	Radium-224	Y						X
	Radium-226	Y	X	X			X	X
	Radium-228	Y	X	X				X
	Rhodium-106	Y						
	Ruthenium-103	Y						X
	Ruthenium-106	Y					X	X
	Samarium-149	Y						
	Samarium-151	Y						
	Selenium-79	Y						
	Silver-108m	Y						
	Sodium-22	Y	X					X
	Strontium-89	Y						X
	Strontium-90	Y	X	X	X		X	X
	Technetium-99	Y		X	X		X	X
	Tellurium-129	Y						
	Tellurium-129m	Y						

Table 3.3. Hazardous substances known to have been used or produced in the different operational areas (cont.). X indicates that the compound has been used or produced at the Site and confirmed in the environment.

Contaminant class	Contaminant	Listed hazardous substance?[a]	Operational area(s)					
			100 Area	200 Area	300 Area	600 Area	100, 300, and 1100 areas	100 and 300 areas and nearby Columbia River surface water samples
Radionuclides[b] (cont.)	Thallium-208	Y						X
	Thorium-228	Y	X	X			X	X
	Throium-230	Y		X				X
	Thorium-232	Y	X	X			X	X
	Thorium-234	Y					X	X
	Tin-113	Y						
	Tin-123	Y						
	Tin-123m	Y						
	Tin-125	Y						
	Tin-126	Y						
	Tritium (H-3)	Y	X	X	X		X	X
	Uranium-232	Y						
	Uranium-233/234	Y	X	X	X		x	X
	Uranium-235	Y	X	X			X	X
	Uranium-236	Y						X
	Uranium-238	Y	X	X	X		X	X
	Yttrium-90	Y						
	Yttrium-91	Y						
	Zinc-65	Y	X				X	X
	Zirconium-93	Y						
	Zirconium-95	Y					X	X
Inorganics	Aluminum[c]		X	X			X	X
	Ammonia	Y					X	X
	Ammonium[c]						X	
	Antimony	Y	X	X	X		X	X
	Arsenic	Y	X	X	X		X	X
	Barium		X	X	X		X	X
	Beryllium	Y	X	X			X	X
	Bismuth							

Table 3.3. Hazardous substances known to have been used or produced in the different operational areas (cont.). X indicates that the compound has been used or produced at the Site and confirmed in the environment.

			Operational area(s)					
Contaminant class	**Contaminant**	**Listed hazardous substance?[a]**	**100 Area**	**200 Area**	**300 Area**	**600 Area**	**100, 300, and 1100 areas**	**100 and 300 areas and nearby Columbia River surface water samples**
Inorganics (cont.)	Boron							X
	Cadmium	Y	X	X			X	X
	Calcium		X				X	
	Cerium							X
	Chloride[c]		X				X	
	Chromium	Y	X	X	X		X	X
	Cobalt	Y	X	X			X	X
	Copper	Y	X	X			X	X
	Cyanide	Y		X			X	
	Fluoride	Y	X	X			X	
	Gallium							X
	Hydrazine	Y					X	
	Iodine							
	Iron		X				X	X
	Lanthanum							X
	Lead	Y	X	X			X	X
	Lithium							X
	Neodymium							X
	Magnesium		X				X	
	Manganese	Y	X	X			X	X
	Mercury (organic)	Y	X	X			X	X
	Mercury (inorganic)	Y	X					
	Molybdenum							X
	Neodymium							X
	Nickel	Y	X	X			X	X
	Niobium							X
	Nitrate[c]		X	X	X		X	
	Nitrite[c]						X	
	Orthophosphate							X

Table 3.3. Hazardous substances known to have been used or produced in the different operational areas (cont.). X indicates that the compound has been used or produced at the Site and confirmed in the environment.

			Operational area(s)					
Contaminant class	**Contaminant**	**Listed hazardous substance?[a]**	**100 Area**	**200 Area**	**300 Area**	**600 Area**	**100, 300, and 1100 areas**	**100 and 300 areas and nearby Columbia River surface water samples**
Inorganics (cont.)	Phosphate	Y					X	
	Potassium		X				X	
	Scandium							X
	Selenium	Y	X	X	X		X	X
	Silicon							X
	Silver	Y	X	X			X	X
	Silver chloride						X	
	Sodium	Y	X				X	
	Strontium						X	X
	Sulfate[c]		X				X	
	Sulfide[c]						X	
	Technetium							
	Thallium	Y	X	X			X	X
	Thorium	Y						X
	Tin			X				X
	Titanium							X
	Uranium	Y		X	X			X
	Vanadium		X	X	X		X	X
	Ytterbium							X
	Yttrium							X
	Zinc	Y	X	X			X	X
	Zirconium						X	X
Organics[d]	Acenaphthene	Y		X			X	X
	Acetone	Y	X				X	X
	Anthracene	Y					X	X
	Aroclor-1016	Y						
	Aroclor-1221	Y						
	Aroclor-1232	Y						
	Aroclor-1242	Y						

Table 3.3. Hazardous substances known to have been used or produced in the different operational areas (cont.). X indicates that the compound has been used or produced at the Site and confirmed in the environment.

Contaminant class	Contaminant	Listed hazardous substance?[a]	Operational area(s): 100 Area	200 Area	300 Area	600 Area	100, 300, and 1100 areas	100 and 300 areas and nearby Columbia River surface water samples
Organics[d] (*cont.*)	Aroclor-1248	Y					X	
	Aroclor-1254	Y	X					X
	Aroclor-1260	Y	X					X
	Benzene	Y	X				X	X
	Benzo(a)anthracene	Y	X				X	X
	Benzo(a)pyrene	Y		X			X	X
	Benzo(b)fluoranthene	Y					X	X
	Benzo(k)fluoranthene	Y	X				X	X
	Benzo(ghi)perylene	Y					X	X
	Benzoic acid	Y	X				X	X
	Benzyl alcohol							
	Biphenyl	Y						
	Bromodichloromethane	Y						
	Bromoform	Y						
	Bromomethane	Y						
	4-bromophenylphenylether	Y						
	2-butanone (MEK)	Y	X				X	
	Butylbenzylphthalate	Y	X					
	Carbazole							
	Carbon disulfide	Y	X					X
	Carbon tetrachloride	Y		X	X			X
	Chlorinated dibenzofurans (total)							
	Chloroacetamide							
	3-chloroanaline							
	4-chloroaniline	Y						
	Chlorobenzene	Y		X				
	3,3'-dichlorobenzidine	Y						
	Chloroethane	Y						

Table 3.3. Hazardous substances known to have been used or produced in the different operational areas (cont.). X indicates that the compound has been used or produced at the Site and confirmed in the environment.

			Operational area(s)					
Contaminant class	**Contaminant**	**Listed hazardous substance?[a]**	**100 Area**	**200 Area**	**300 Area**	**600 Area**	**100, 300, and 1100 areas**	**100 and 300 areas and nearby Columbia River surface water samples**
Organics[d] (cont.)	Bis(2-chloroethoxy)methane	Y						
	Bis(2-chloroethyl)ether	Y						
	Chloroform	Y	X	X	X	X	X	X
	Chloromethane	Y						
	Bis(2-chloro-1methylethyl)ether							
	4-chloro-3-methylphenol							
	2-chloronaphthalene	Y						
	2-chlorophenol	Y						
	3-chlorophenol							
	4-chlorophenylphenylether	Y	X					
	Chrysene	Y	X				X	X
	Dibenz[a,h]anthracene	Y						X
	Dibenzofuran	Y					X	X
	Dibromochloromethane							
	Dibutyl-chlorendate							X
	1,2-dichloroaniline				X			
	2,4-dichloroaniline							
	3,4-dichloroaniline							
	1,2-dichlorobenzene	Y						
	1,3-dichlorobenzene	Y						
	1,4-dichlorobenzene	Y		X				X
	1,2-dichloroethane	Y						X
	1,1-dichloroethane	Y				X		
	1,1-dichloroethylene	Y						
	1,2-dichloroethylene	Y		X	X	X	X	X
	2,4-dichlorophenol	Y						
	3,4-dichlorophenol							

Table 3.3. Hazardous substances known to have been used or produced in the different operational areas (cont.). X indicates that the compound has been used or produced at the Site and confirmed in the environment.

Contaminant class	Contaminant	Listed hazardous substance?[a]	Operational area(s)					
			100 Area	200 Area	300 Area	600 Area	100, 300, and 1100 areas	100 and 300 areas and nearby Columbia River surface water samples
Organics[d] *(cont.)*	1,2-dichloropropane	Y		X				
	1,3-dichloropropene	Y						
	Diesel range organics	Y					X	
	Diethylphthalate	Y	X	X				X
	2,4-dimethylphenol	Y						
	Dimethylphthalate	Y						X
	Di-n-butylphthalate	Y	X	X				X
	2,4-dinitrophenol	Y						X
	2,4-dinitrotoluene	Y						
	2,6-dinitrotoluene	Y						
	4,6-dinitro-2-methylphenol	Y						
	Di-n-octylphthalate	Y						
	Dioxins	Y						X
	Ethylbenzene	Y					X	
	Bis(2-ethylhexyl)phthalate	Y	X				X	X
	Fluoranthene	Y	X				X	X
	Fluorene	Y		X			X	X
	Furan	Y						
	Gasoline range organics	Y						
	Hexachlorobutadiene	Y						
	Hexachlorocyclopentadiene	Y						
	Hexachloroethane	Y						
	Hexadecanoic acid							X
	Hexane	Y	X					
	2-hexanone							X
	Indeno(1,2,3-cd)pyrene	Y					X	X
	Isophorone	Y						X
	Kerosene	Y					X	
	Methylene chloride	Y	X				X	X

Table 3.3. Hazardous substances known to have been used or produced in the different operational areas (cont.). X indicates that the compound has been used or produced at the Site and confirmed in the environment.

Contaminant class	Contaminant	Listed hazardous substance?[a]	Operational area(s) 100 Area	200 Area	300 Area	600 Area	100, 300, and 1100 areas	100 and 300 areas and nearby Columbia River surface water samples
Organics[d] *(cont.)*	2-methylnaphthalene					X	X	X
	4-methyl-2-pentanone	Y					X	X
	2-methylphenol (cresol, 0-)	Y						X
	4-methylphenol (cresol, p-)	Y						
	Naphthalene	Y						X
	2-nitroaniline							
	3-nitroaniline							
	4-nitroaniline	Y						
	2-nitrophenol	Y						
	4-nitrophenol	Y		X				
	N-nitroso-di-n-propylamine	Y						
	N-nitrosodiphenylamine	Y	X					
	Nitrobenzene	Y						
	Pentachloroaniline							
	Pentachlorobenzene	Y						
	Pentachlorophenol	Y	X					X
	Phenanthrene	Y					X	X
	Phenol	Y		X				X
	Pyrene	Y	X				X	X
	Perylene							X
	Styrene	Y		X				
	2,3,4,6-tetrachloroaniline							
	1,2,4,5-tetrachlorobenzene	Y						
	1,1,2,2-tetrachloroethane	Y						X
	Tetrachloroethene	Y			X	X	X	X
	2,3,4,6-tetrachlorophenol	Y						

Table 3.3. Hazardous substances known to have been used or produced in the different operational areas (cont.). X indicates that the compound has been used or produced at the Site and confirmed in the environment.

			Operational area(s)					
Contaminant class	**Contaminant**	**Listed hazardous substance?[a]**	**100 Area**	**200 Area**	**300 Area**	**600 Area**	**100, 300, and 1100 areas**	**100 and 300 areas and nearby Columbia River surface water samples**
Organics[d] (cont.)	Toluene	Y	X	X			X	X
	Total petroleum hydrocarbon	Y					X	
	Tributyl phosphate				X			
	1,1,2-trichloroaniline				X			
	2,4,5-trichloroaniline							
	1,2,3-trichlorobenzene							
	1,2,4-trichlorobenzene	Y						
	1,1,1-trichloroethane	Y				X		
	1,1,2-trichloroethane	Y						X
	Trichloroethene (TCE)	Y		X	X	X	X	X
	2,4,5-trichlorophenol	Y						
	2,4,6-trichlorophenol	Y						
	Vinyl acetate	Y						
	Vinyl chloride	Y						
	Xylenes (total)	Y					X	X
Pesticides/ herbicides	Aldrin	Y						X
	Benzene hexachloride	Y		X				X
	Beta-l,2,3,4,5,6hexa-chlorocyclohexane	Y						X
	Bromoxynil							X
	Chlordane	Y					X	X
	Dichlorodiphenyldi-chlorethane (DDD)	Y		X				X
	Dichlorodiphenyldichloro-ethylene (DDE)	Y		X				X
	Dichlorodiphenyltrichloro-ethane (DDT)	Y		X				X
	Dieldrin	Y						X

Table 3.3. Hazardous substances known to have been used or produced in the different operational areas (cont.). X indicates that the compound has been used or produced at the Site and confirmed in the environment.

Contaminant class	Contaminant	Listed hazardous substance?[a]	Operational area(s)					
			100 Area	200 Area	300 Area	600 Area	100, 300, and 1100 areas	100 and 300 areas and nearby Columbia River surface water samples
Pesticides/ herbicides (cont.)	Endosulfan I	Y						X
	Endosulfan II	Y						
	Endrin	Y						
	Endrin aldehyde	Y					X	
	Endrin ketone	Y						
	Heptachlor/heptachlor epoxide	Y		X				X
	trans-Nonachlor							X
	Methoxychlor	Y						
	Toxaphene	Y						

a. Listed in Table 302.4: List of Hazardous Substances and Reportable Quantities [40 CFR § 302.4].
b. All radionuclides are listed in Table 302.4.
c. Specific compounds with this contaminant are listed in Table 302.4.
d. Many organic contaminants have multiple synonyms. Here we use the name as it appears in Table 302.4.

Sources: Napier et al., 1995; U.S. DOE, 2001a; U.S. EPA, 2001b; Doctor et al., 2003; Freeman et al., 2005; Hulstrom, 2007.

References

Author unknown. 1999. Fall 1998 200 East Area Biological Vector Contamination Report. HNF-3628.

Ballinger, M.Y. and R.B. Hall. 1991. *A History of Major Hanford Facilities and Processes Involving Radioactive Material*. Hanford Environmental Dose Reconstruction Project. PNL-6964. Hanford Environmental Dose Reconstruction Project. Prepared by the Pacific Northwest Laboratory, Richland, WA. March.

Bechtel. 2009. Hanford Vitrification Plant. Available: http://www.bechtelvitplant.com. Accessed 5/4/2009.

Brown, C.F., R.J. Serne, B.N. Bjornstad, M.M. Valenta, D.C. Lanigan, T.S. Vickerman, R.E. Clayton, K.N. Geiszler, C. Iovin, E.T. Clayton, I.V. Kutnyakov, S.R. Baum, M.J. Lindberg, and R.D. Orr. 2008. *Characterization of Vadose Zone Sediments from C Waste Management Area: Investigation of the C-152 Transfer Line Leak.* PNNL-15617, Rev. 1. Pacific Northwest National Laboratory, Richland, WA. Prepared for CH2M HILL Hanford Group, Inc. and the U.S. Department of Energy.

CH2M HILL. 2003. Site-Specific Single-Shell Tank Phase I RCRA Facility Investigation/Corrective Measures Study: Work Plan Addendum for Waste Management Areas C, A-AX, and U. RPP-16608, Rev. 0. CH2M Hill Hanford Group, Richland, WA. August 4.

CH2M HILL. 2006. CH2M HILL Completes State-of-the-Art Landfill at Hanford. State of Washington Issues Permit for Hanford's first RCRA Compliant Landfill. Immediate Release. May.

Dirkes, R.L. and R.W. Hanf (eds.). 1998. *Hanford Site Environmental Report for Calendar Year 1997*. PNNL-11795. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. September. Available: http://hanford-site.pnl.gov/envreport/. Accessed 4/1/2009.

Dirkes, R.L., R.W. Hanf, and T.M. Poston (eds.). 1999. *Hanford Site Environmental Report for Calendar Year 1998*. PNNL-12088. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. September. Available: http://hanford-site.pnl.gov/envreport/. Accessed 4/1/2009.

Doctor, P.G., K.A. Gano, R.G. Bauer, J.K. Linville, and T.M. Poston. 2003. 100-B/C Area Ecological Risk Assessment Data Quality Objectives. BHI-01673. Rev. 0. Prepared for the U.S. Department of Energy, Richland Operations Office, Richland, WA. March.

Duncan, J.P., T.M. Poston, and R.L. Dirkes (eds.). 2008. *Hanford Site Environmental Report for Calendar Year 2007* (Including some early 2008 information). PNNL-17603. Pacific Northwest National Laboratory, Richland, WA. Prepared for U.S. Department of Energy. September. Available: http://hanford-site.pnl.gov/envreport/2003/Hanford04/index.htm. Accessed 4/1/2009.

Eliason, J.R. 1967. Thermal Mapping of the Columbia River at Hanford suing an Infrared Imaging System. Prepared by BATELLE for the US Atomic Energy Commission under contract AT(45-1)-1830.

Emery, R.M. and M.C. McShane. 1978. *Comparative Ecology of Nuclear Waste Ponds and Streams on the Hanford Site*. PNL-2499. Pacific Northwest Laboratory. Prepared for the U.S. Department of Energy.

Freeman, E.J., M.J. Truex, S.M. Yabusaki, J.P. McDonald, C.J. Murray, V.R. Vermeul, J.M. Zachara, P.D. Thorne, M.D. Williams, and J.L. Lindberg. 2005. *Contaminants of Potential Concern in the 300-FF-5 Operable Unit: Expanded Annual Groundwater Report for Fiscal Year 2004*. PNNL-15127. Pacific Northwest National Laboratory. Prepared for the U.S. Department of Energy. March.

Gerber, M.S. 1993. History of 100-B/C Reactor Operations, Hanford Site. Westinghouse Hanford Company. Facility Operations Division. WHC-SD-EN-RPT-004. April. Available: http://b-reactor.org/hist-toc.htm. Accessed 2/2009.

Gerber, M.S. 1996. The Plutonium Production Story at the Hanford Site: Processes and Facilities History. Westinghouse Hanford Company, Richland, WA. Prepared for the U.S. Department of Energy. June.

Gerber, M.S. 2008. Final Frontier at Hanford: Tackling the Central Plateau. HNF-36881. Prepared by Fluor Hanford, Inc. for U.S. Department of Energy. March.

Gray, R.H. and C.D. Becker. 1993. Environmental cleanup: The challenge at the Hanford Site, Washington, USA. *Environmental Management* 17(4):461–475.

HAB. 2004. Information Sheet on Institutional Controls. September Hanford Advisory Board. Available: file://L:\DOE-hanford.gov\public\boards\hab\advice\advice63a.htm. Accessed 4/16/2009.

Harvey, D. 2000. History of the Hanford Site, 1943–1990. Pacific Northwest National Laboratory, Richland, WA.

Henning, J.M. 1992. Letter Regarding the Request for Approval to Install Lonber Well Screens in Non-Radioactive Dangerous Waste Landfill Groundwater Monitoring Wells addressed to Jansen, D.B., Hanford Project Manager.

Herman, R.M. 2007. Polychlorinated Biphenyl Presence in the Columbia River Corridor. WCH-208. Prepared for the U.S. Department of Energy, Richland Operations Office. Office of Assistant Manager for River Corridor. September.

Hulstrom, L.C. 2007. Columbia River Component Data Gap Analysis. WCH-201 Rev. 0. Prepared for the U.S. Department of Energy, Richland Operations Office. October.

Izatt, R.D. and R.E. Lerch. 1992. Letter regarding the Cutting of Mulberry Bushes at Hanford addressed to P.T. Day and T.L. Nord. January.

Kannberg, L.D. 1992. Hanford Production Reactor Heat Releases 1951–1971. Prepared by BATELLE for the US DOE under contract DE-AC06-76RLO 1830.

McCullugh, R.W. 1968. Memo re: Chronological Record of Significant Events in Chemical Separations Operations. To W.M. Harty. August 30.

McMaster, B.N., J.B. Sosebee, W.C. Fraser, K.C. Govro, C.F. Jones, S.A. Grainger, and K.A. Civitarese. 1984. Historical Overview of the Nike Missile System. Final Report ESE-A016. December.

Millikin, E.G. and P.B. Brannan. 2002. Root Cause Analysis of Contaminated Vegetation at Low-Level Burial Grounds on the Hanford Site. HN F-SA-3215-FP. Prepared by Fluor Hanford. Richland, Washington for US. Department of Energy. August.

Napier, B.A. 1991. Selection of Dominant Radionuclides for Phase I of the Hanford Environmental Dose Reconstruction Project. PNL-7231 HEDR. Pacific Northwest Laboratory, Richland, WA. Prepared for the Technical Steering Panel. July.

Napier, B.A. 2002. A re-evaluation of the ^{131}I atmospheric releases from the Hanford Site. *Health Physics* 83(2):204–226.

Napier, B.A., N.C. Batishko, D.A. Heise-Craff, M.F. Jarvis, and S.F. Snyder. 1995. *Identification of Contaminants of Concern, Columbia River Comprehensive Impact Assessment.* PNL-10400. Pacific Norwest Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. January.

Nord, T.L. and P. Day. 1991. Letter re: Removal of Mulberry Trees and Vegetation in the 100-NR-1 Operable Unit. To Steve Wisness, Hanford Project Manager, U.S. Department of Energy. October 4.

Poston, T.M., R.W. Hanf, and R.L. Dirkes (eds.). 2000. *Hanford Site Environmental Report for Calendar Year 1999*. PNNL-13230. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. September. Available: http://hanford-site.pnl.gov/envreport/. Accessed 4/1/2009.

Poston, T.M., R.W. Hanf, R.L. Dirkes, and L.F. Morasch (eds.). 2004. *Hanford Site Environmental Report for Calendar Year 2003*. PNNL-14687. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. September. Available: http://hanford-site.pnl.gov/envreport/2003/Hanford04/index.htm. Accessed 4/1/2009.

Sobczyk, S.M. 2004. Interpreted Extent of Subsurface Contamination Resulting from the 241-BX-102 Tank Leak, 200 East Area, Hanford Site, Washington. Prepared for Confederated Tribes of the Umatilla Indian Reservation Department of Science and Engineering, Mission, OR. November 9.

Truex, M.J., P.E. Dresel, M.J. Nimmons, C.J. Murray, and C.D. Johnson. 2006. *Screening of Potential Remediation Methods for the 200-ZP-1 Operable Unit at the Hanford Site*. Pacific Northwest National Laboratory. Prepared for the U.S. Department of Energy. August.

U.S. DOE. 1997. Action Memorandum: USDOE Hanford 100 Area NPL 100-IU-3 Operable Unit (Wahluke Slope) Hanford Site Adams, Grant, and Franklin Counties, Washington.

U.S. DOE. 1999a. *Hanford Comprehensive Land Use Plan Environmental Impact Statement,* DOE-EIS-0222-F, U. S. Department of Energy, Richland, WA. Available: http://www.hanford.gov/doe/eis/hraeis/section4.pdf. Accessed 4/10/2009.

U.S. DOE. 1999b. *Radioactive Air Emissions Notice of Construction for Reactivation of the PUREX Storage Tunnel Number 2*. DOE/RL-99-67. U.S. Department of Energy, Richland, WA. September.

U.S. DOE. 2001a. *Ecological Evaluation of the Hanford 200 Areas: Phase I. Compilation of Existing 200 Areas Ecological Data*. DOE/RL-2001-54. Draft A. Richland, WA.

U.S. DOE. 2001b. Washington Closure Hanford. 2009. River Corridor Closure Project Monthly Progress Report, April 2009. Available: http://www.washingtonclosure.com/news/docs/reports/empr/2009/RCCrpt-apr09.pdf. Accessed 6/29/2009.

U.S. DOE. 2003. *Sitewide Institutional Control Plan For Hanford CERCLA Response Actions.* DOE/RL-2001-41. Prepared by Fluor Hanford, Inc. for U.S. Department of Energy, Richland, WA. July.

U.S. DOE. 2005a. Horseshoe Landfill Waste Management Plan. Approved by J. Zeisloft and D. Einan. May.

U.S. DOE. 2005b. *RCBRA Stack Air Emissions Deposition Scoping Document*. DOE/RL-2005-49 Revision 0. June.

U.S. DOE. 2006a. Hanford Site Virtual Tours. 1100 Area. December. Available: http://www.hanford.gov/?page = 334&parent = 326. Accessed 4/10/2009.

U.S. DOE. 2006b. Hanford Site Virtual Tours. US Ecology. December. Available: http://www.hanford.gov/?page = 353&parent = 326. Accessed 4/23/2009.

U.S. DOE. 2006c. Environmental Restoration Disposal Facility (ERDF) (Fact Sheet).

U.S. DOE. 2006d. K Basin Closure Project (Fact Sheet).

U.S. DOE. 2006e. Soil Remediation. Restore the River Corridor Fact Sheet. U.S. Department of Energy, Richland Operations Office, Richland, WA. August.

U.S. DOE. 2006f. The Columbia River Corridor. Restore the River Corridor Fact Sheet. U.S. Department of Energy, Richland Operations Office, Richland, WA. August.

U.S. DOE. 2007. *Risk Assessment Report for the 100 Area and 300 Area Component of the River Corridor Baseline Risk Assessment*. DOE/RL-2007-21. Draft A. Richland, WA.

U.S. DOE. 2008a. *Hanford Site Groundwater Monitoring for Fiscal Year 2007*. DOE/RL-2008-01. March.

U.S. DOE. 2008b. Manhattan Project Signature Facilities. T Plant, Chemical Separation Building, Hanford, Washington. Adapted from Department of Energy's Manhattan Project "Signature Facilities." Available: http://www.atomicarchive.com/History/sites/T_plant.shtml. Accessed 4/15/2009.

U.S. DOE. 2008c. *Remedial Investigation Work Plan for Hanford Site Releases to the Columbia River*. DOE/RL-2008-11. Rev. 0. September.

U.S. DOE. 2009a. *Hanford Site Waste Management Units Report*. DOE/RL-88-30. CH2M HILL, Richland, WA. Prepared for the U.S. Department of Energy. January.

U.S. DOE. 2009b. Washington Closure Hanford – New Room Reports. Available: http://www.washingtonclosure.com/news/reports.html. Accessed 4/15/2009.

U.S. DOE. 2009c. Washington Closure Hanford – Projects D4 Project (Decommission, Deactivate, Decontaminate, Demolish). Available: http://www.washingtonclosure.com/projects/D4.html. Accessed 4/15/2009.

U.S. EPA. 1998. Environmental Restoration Disposal Facility Leachate De-Listing Proposal. Focus Sheet. Available: http://www5.hanford.gov/pdw/fsd/AR/FSD0001/FSD0026/D198208190/D198208190_18406_2.pdf. Accessed 4/15/2009.

U.S. EPA. 2001a. *EPA Superfund Record of Decision: Hanford 300-Area (US DOE)*. Benton County, WA. EPA/ROD/R10-01/119. April.

U.S. EPA. 2001b. Table 302.4. 40 CFR Ch. I (7-1-01 Edition).

U.S. EPA. 2009. Hanford 1100 Area Case Study. January. Available: http://www.epa.gov/superfund/programs/recycle/live/casestudy_hanford.html. Accessed 4/15/2009.

Washington Closure Hanford. 2009. ERDF Expansion Completed. Available: http://www.hanfordnews.com/releases/story/13180.html. Accessed 5/1/2009.

Washington Department of Ecology. 2006. PUREX Storage Tunnels – WA7890008967, Part III, Operating Unit 2. Revision 6. Available: http://www.ecy.wa.gov/programs/nwp/Public%20File%20OU-2%20PUREX%20Tunnels/Part%20III_OU-02_PUREX%20Storage%20Tunnels_2006-10.pdf. Accessed 4/16/2009.

Washington Department of Ecology. 2009. About the Commercial Low-Level Radioactive Waste Disposal Facility. Available: http://www.ecy.wa.gov/programs/nwp/llrw/use.htm. Accessed 4/1/2009.

Washington Department of Health. 2002. The Release of Radioactive Materials from Hanford: 1944–1972. Office of Radiation Protection, Olympia, WA. Available: http://www.doh.wa.gov/hanford/publications/history/release.html. Accessed 2/13/2009.

4. Pathways

This chapter presents an overview of the pathways through which natural resources and humans may be exposed to stressors. Figure 4.1 illustrates the relationship between the pathway CSM and the other CSMs provided in this document. Stressors (discussed in Chapter 3) include hazardous substances and their by-products that may have been released from Site operations (operational stressors), contaminated resources which may act as a secondary source of contamination (secondary stressors), as well as response actions that may cause unavoidable injuries to natural resources (response action stressors). Figure 4.2 shows these general categories of stressors and associated exposure pathways to natural resources and humans.

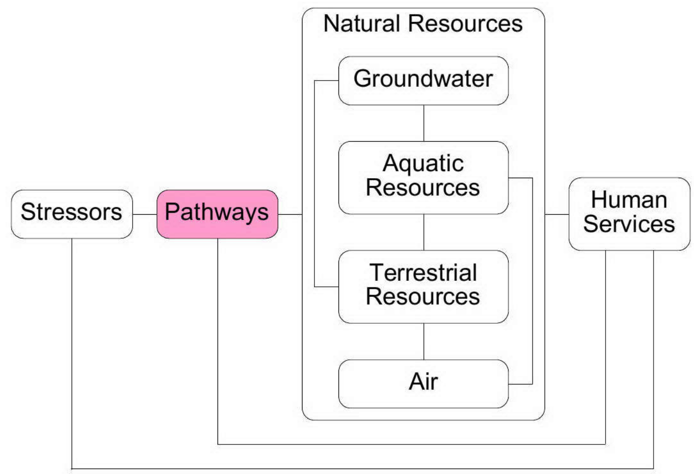


Figure 4.1. Relationship between the pathway CSM and other CSMs that together make up the NRDA CSM.

Figure 4.3 details the specific physical, biological, and response action pathways that are known or suspected to expose natural resources and humans to Site stressors. Examples of operational stressors, include those associated with air emissions, process wastes/liquids, and solid wastes. These stressors may adversely effect natural resources such as sediments, soils, groundwater, surface water, and humans and other biota through direct contact, and through the physical disruption of habitat. In addition, hazardous substances released can be transported through biotic and abiotic pathways and expose and potentially injure abiotic and biotic natural resources and humans. Examples of biotic pathways include dermal contact; respiration and inhalation; ingestion of food, water, or soils; uptake from soils by plants; decomposition of plants and animals; and the distribution of hazardous substances by the physical movement of biota (biotic vectors). Examples of abiotic components of pathways include processes such as volatilization, evaporation, aeolian transport, infiltration, runoff, flooding, and irrigation.

Natural resources that are exposed to hazardous substances through both biotic and abiotic pathways may in turn act as secondary stressors, or secondary sources of contaminants. For example, contaminated soils may expose groundwater through infiltration mechanisms, or the air through aeolian transport. Contaminated groundwater may enter the hyporheic zone and then expose surface water and sediments, which may in turn lead to the exposure of aquatic biota and humans.

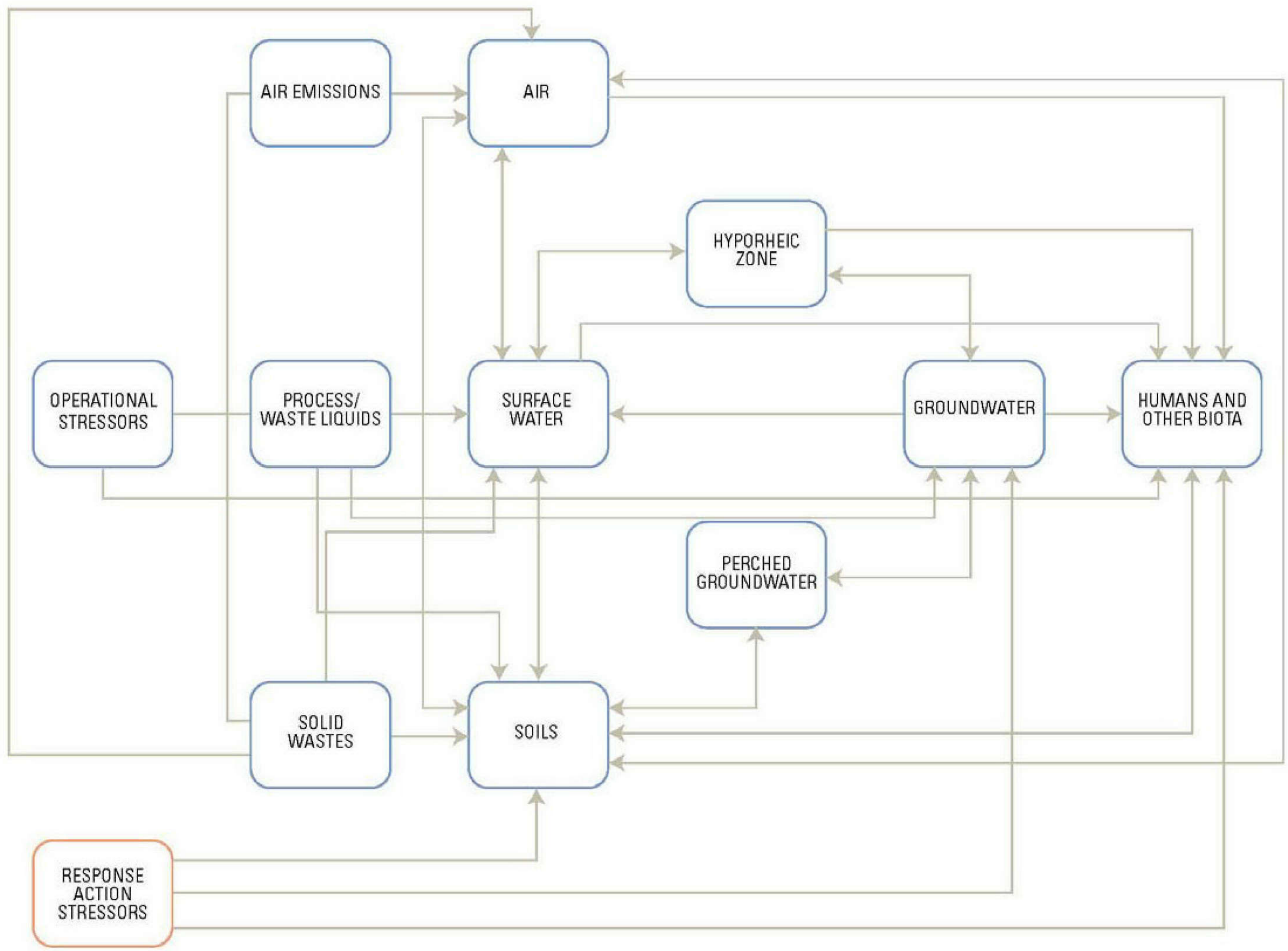


Figure 4.2. Sources, natural resources, and transport pathways.

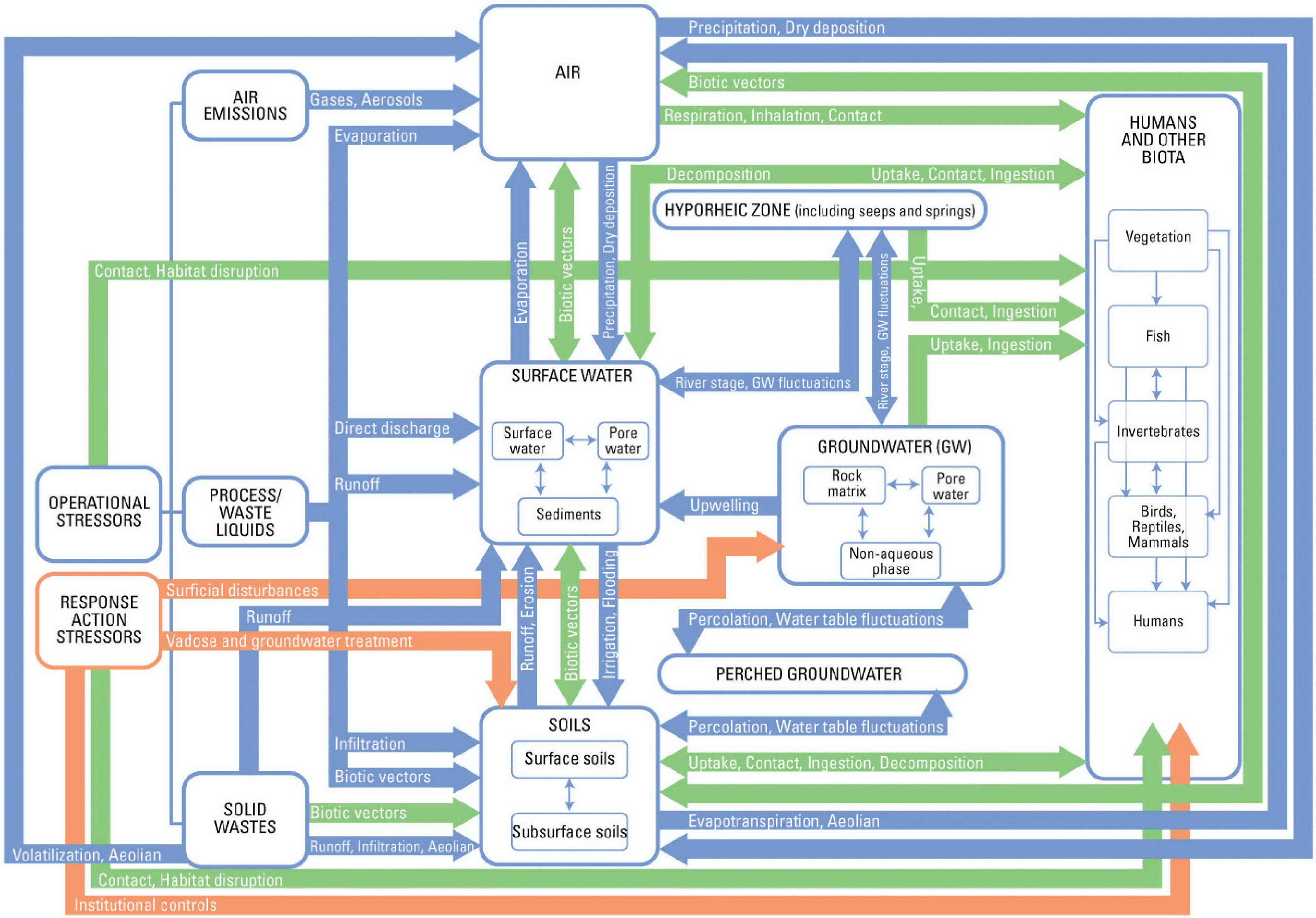


Figure 4.3. Physical (blue arrows), biological (green arrows), and response action (orange arrows) pathways between sources of hazardous substances, natural resources, and humans at the Site.

Response actions may inadvertently facilitate contaminant transport. They may also cause direct physical disruption of habitat, potentially resulting in injuries to natural resources and in human service loss. Pump and treat and re-injection systems that are designed to treat a specific contaminant may inadvertently transport and disperse other contaminants. Tritium is an example of a contaminant that may be redistributed by groundwater by pump and treat systems (Peterson et al., 2002). Surficial disturbances, such as the physical removal and displacement of contaminated soils and road construction are examples of response actions that cause physical disruptions of habitat which may result in injuries to natural resources.

In this chapter we present pathways from operational stressors (Section 4.1); pathways from secondary stressors (Section 4.2); and pathways associated with remedial stressors (Section 4.3). The overview of pathways provided here focuses on abiotic components of pathways and biotic vectors. The biotic component of pathways shown in the far right box in Figure 4.3 will be addressed in the aquatic and terrestrial CSMs (Chapters 6 and 7). Chapters 5 and 8 also provide overviews of natural resources that may be exposed and injured as a result of the pathways discussed here, and Chapter 9 provides an overview of potentially associated human service losses.

4.1 Pathways from Operational Stressors

As shown in Figure 4.2, we have organized operational stressors at the Site into three major categories. These include air emissions, process/waste liquids, and solid wastes. Natural resources and humans can be injured by all three categories of operational stressors through direct contact and through the physical disruption of habitat. In addition, there are specific pathways from each category of operational stressor that can transport hazardous substances to natural resources. In this section, we describe these pathways and identify factors that influence transport.

4.1.1 Air emissions

Sources of air emissions at the Site are described in Chapter 3, and include:

- Stacks associated with historical nuclear operations
- Waste incinerators and open burn pits associated with historical nuclear operations
- Other Site operations sources, including electric and diesel generators
- Episodic events, such as explosions, fires, and dust storms
- Intentional releases, such as the Green Run.

Hazardous substances released to air from these sources are discussed in Chapter 3, and include historical, on-going, and potential future releases of radionuclides, VOCs, metals, and other substances. Numerous factors and processes can affect the release of hazardous substances to air as gases and aerosols, including the duration and amount of the release, and the configuration of the emitting source (point source versus diffuse non-point sources). Other factors that may influence the release of hazardous substances to air include wind speed and direction, seasonal and diurnal changes, atmospheric stability (inversions), air temperature and humidity, and precipitation.

The physical and chemical properties of substances released, including their volatility, solubility, and physical state, may also influence transport. These properties may also influence the interaction of hazardous substances with atmospheric constituents (e.g., their sorption to particulate matter, and interactions with atmospheric constituents such as ozone and nitrogen oxides). Other phenomena that may influence the release of hazardous substances to air include effects of wildfires and dust storms. Wildfires may be a source of hazardous substances to the air through the burning of contaminated vegetation. Both wildfires and dust storms can produce updrafts that entrain contaminants in soils and influence the transport of hazardous substances in air. Exposure to hazardous substances and the potential injury of the air resource is discussed further in Chapter 8.

4.1.2 Process/waste liquids

Sources of liquids, process waters, and liquid wastes are described in Chapter 3, and include:

- Reactor coolant water discharge pipelines in the 100 Area
- Liquid waste injection wells (also referred to as reverse wells)
- Surface impoundments, including cribs, trenches, French drains, retention basins, and ponds
- Underground radioactive liquid waste storage tanks in the 200 and 300 areas
- Waste evaporators and evaporation basins
- Liquid chemical containers and distribution infrastructure (e.g., pipelines) associated with Site operations
- Liquid chemical containers (e.g., PCB storage tanks) and distribution infrastructure associated with general site maintenance

- Underground storage tanks for gasoline and diesel, and other transportation sources
- Episodic events, including spills, leaks, and explosions from Site facilities
- Leachate from landfills and other waste facilities.

Hazardous substances known or suspected to have been released from these sources are discussed in Chapter 3, and include, but are not limited to, radionuclides, metals, organics, and other substances. As shown in Figure 4.2, transport pathways from process/waste liquids sources to natural resources include evaporation to air, direct discharge, and overland flow (runoff) to surface water, infiltration to soils, and transport by biotic vectors.

Evaporation to air

The evaporation pathway may be influenced by many factors, including the exposed surface area of the liquid, and the concentration and volatility of the hazardous substance. Other atmospheric properties listed in Section 4.1.1 may also influence the evaporation pathway, including the temperature and humidity of the air, and dispersion factors such as wind speed and direction (including seasonal and diurnal changes), inversions, and precipitation.

Infiltration through soils (surface soils and the vadose zone)

The infiltration pathway may transport hazardous substances into and through biologically active surface soils, as well as subsurface (vadose zone) soils that are below surface soils and above groundwater. Here we discuss surface soils and the vadose zone from the context of their role as a pathway for hazardous substances. We describe surface soils in greater detail in Chapter 7 (Terrestrial Resources) and vadose zone soils together with groundwater in Chapter 5, noting that soils serve both as pathways by which hazardous substances are exposed to other natural resources, and as geological resources that can themselves be injured by hazardous substance releases.

There are many different factors that can influence infiltration through soils, including physical and chemical properties of the soils and of the hazardous substances. Physical characteristics of the surface soils and the vadose zone that may influence infiltration include:

- Horizontal and vertical heterogeneities and discontinuities (e.g., horizontal caliche layers, vertical clastic dykes)
- Soil moisture/vapor pressure/presence of nonaqueous phases
- Grain size distribution

- Soil mechanics (disturbed versus undisturbed)
- Permeability
- Shallow referential pathways caused by roots and burrowing animals
- Natural and enhanced recharge
- Response actions (e.g., soil vapor extraction).

The structure of surface soils and the vadose zone can influence contaminant pathways. Horizontal and vertical heterogeneities and discontinuities can influence the path of infiltrating water and hazardous substances. Perched groundwater lenses may form and preferential lateral migration may occur when infiltrating water encounters low permeability units. Vertical features may also influence pathways. For example, vertical dykes of low permeability may slow lateral migration, and vertical dykes of higher permeability may create preferential pathways. The horizontal layering of the sedimentary units beneath the Site leads to strong anisotropy for fluid flow, particularly in the vadose zone. As a result, radionuclides and other hazardous substances have spread further laterally in the vadose zone than anticipated (Ward, 2006; Conrad et al., 2007).

In surface and subsurface soils, pores between soil or rock grains are partially filled with air and other gases, partially filled with water, and in some cases can be partially filled with NAPL (including light and dense NAPL). Thus, hazardous substances can be transported in different phases through soils, including aqueous, gaseous, NAPL, and colloidal phases (natural organic matter or inorganic particles) (Bryce et al., 2002). Non-aqueous phases may also enhance the transport of co-mingled radionuclides through the vadose zone.

Grain size distribution influences porosity and infiltration rates; lower porosity and slower migration are associated with more poorly sorted soils, because the finer grains fill in the space between the larger grains. Mechanical disturbance of soils (either due to historical operations or recent response actions) may change its permeability. Preferential pathways can develop in the unconsolidated or loosely consolidated vadose zone material. Plant roots and animal burrows may also create preferential pathways surface soils and in the upper part of the vadose zone (Bryce et al., 2002).

Natural recharge to soils can mobilize hazardous substances and carry them downward, either as a dissolved phase or as colloids. At the Site, natural recharge results from infiltration of rainfall and snowmelt and infiltration of surface runoff in the Cold and Dry creek basins. Estimates of total recharge through the vadose zone to groundwater at the Site range from about 0.2 to 0.6 cubic meters per second (m^3/s) (6,000 to 15,500 acre-feet/year) (Wigmosta and Guensch, 2005). The introduction of large amounts of liquid wastes at the ground surface can increase the degree of saturation in the vadose zone and thereby increase the effective permeability and drainage rates. Drainage rates through the vadose zone were estimated by Singleton et al. (2006) to be < 1 millimeters per year (mm/yr) at the Site. Other studies predicted variable vadose zone drainage rates of 0 to 100 mm/yr, depending on soil cover and vegetation (Singleton et al., 2006). Vegetative cover can also influence infiltration rates. In the tank farm areas in the 200 Area, surface vegetation has largely been removed to prevent uptake of radionuclides by plants (Gee et al., 2007). Net infiltration is therefore higher than would otherwise be expected, which may enhance mobilization of contaminants from the vadose zone.

Certain response actions may also influence transport in the vadose zone. For example, solvent extraction treatment systems, such as the one installed in the 200 Area to remove carbon tetrachloride from the vadose zone (Rohay, 1993; U.S. DOE, 2008a), can influence fluid flow directions, soil vapor pressure, the phases present in the pore space, and thus hazardous substance transport.

Biogeochemical processes and properties of contaminants, soils, and pore water can affect contaminant transport, including:

- Mineralogy
- Organic carbon content
- Pore water pH
- Reducing/oxidizing conditions
- Adsorption/desorption
- Complexation (or aqueous speciation) of contaminants with solutes in pore water
- Precipitation (formation of a solid from solution) and dissolution processes
- Ion-exchange reactions
- Microbial processes that change the chemical form of the hazardous substance, such as bacterial oxidation of iron or incorporation of metals into bacteria structures
- Radioactive decay of radionuclides
- Thermal effects (temperature).

Mineralogy, organic carbon content, pore water pH, and whether reducing or oxidizing conditions exist, are all properties of soil systems that may influence the transport of hazardous substances. These properties determine the ability of soils to adsorb and form complexes with hazardous substances. They also influence precipitation and ion-exchange reactions with hazardous substances. These soil properties can also influence microbially-mediated hazardous substances reactions.

The ion-exchange capacity of soils can influence contaminant migration. At Hanford, the ion-exchange capacity of Site soils was central to the design of early liquid waste disposal practices. Many liquid wastes were disposed of in cribs and trenches, which were designed to dispose of the liquids through infiltration into the ground. The assumption was that the soil would act as a large ion-exchange column and immobilize infiltrating radionuclides. However, Hanford soils generally have relatively low cation exchange capacity, and the discharged wastes typically had extremely high concentrations of sodium and other cations which frequently overwhelmed the available exchange capacity of vadose zone soils (Gee et al., 2007). Thus, while some radionuclides that infiltrated into the vadose zone were immobilized through ion exchange, large contaminant plumes reached the groundwater because the ion-exchange capacity of the soil was exceeded.

In addition to ion-exchange, adsorption and precipitation can also be important controls on the movement of hazardous substances in soils. These processes can slow the migration of stressors such as cesium-137, plutonium-239, plutonium-240, and strontium-90. In contrast, iodine-129, technetium-99, tritium, and nitrate are not as readily retained on aquifer or soil materials and can move more rapidly through the vadose zone and groundwater (Dirkes and Hanf, 1995).

Temperature can also influence biogeochemical processes. Pore water and groundwater temperatures in the 100 Area under the reactors were elevated as a result of reactor operations. Water was circulated in the reactors to dissipate excess heat generated during the irradiation process. This water was normally sent to retention basins to cool before discharge to the Columbia River. However, if a failure occurred in the reactors, releasing radioactivity, the coolant water was diverted to trenches and allowed to infiltrate into the soil. In addition, process waters leaked to underlying soils through discharge pipes and from retention basins cracked by thermal shocking (U.S. DOE, 2007). The water that was discharged to the trenches and that leaked from the retention basins was hot, with groundwater temperatures reported to have been exceeded 70°C under the reactor retention basins throughout the 1950s and 1960s (Kannberg, 1992). These temperatures may have been high enough to influence geochemical and microbially mediated reaction rates, including dissolution/precipitation, complexation, and other reactions. Thus, elevated temperatures in waste water may have influenced the transport of hazardous substances through surface soils, the vadose zone, and groundwater in the 100 Area.

Direct discharge and runoff to surface water, direct injection to groundwater

Process and waste liquids were released to the Columbia River during Site operations as a result of direct discharge and overland flow (runoff) events. Both of these pathways likely discharged radionuclides and other hazardous substances to the river. Liquid wastes were also directly discharged to groundwater through injection (reverse) wells.

Process waters were discharged directly to the Columbia River during operation of the reactors. The water that was circulated in the reactors to dissipate the large amount of heat generated during operations was first sent to retention basins for cooling and then returned to the river via outfall structures and underground pipelines that emerged mid-channel in the river (U.S. DOE, 2008b). The eight single-pass reactors used up to 105,000 gpm of water in this cooling process (Gerber, 1996). The water temperature was still elevated when discharged to the river, as high as 70–90°C (Eliason, 1967; Kannberg, 1992) and contained radionuclides, chromium, and other hazardous substances (Gerber, 1996). The N reactor was the last reactor to be built; it was constructed with recirculating coolant water and required and discharged much less water, just 100–1,500 gpm (Gerber, 1996). Coolant waters from the N reactor were discharged to the river up until the 1970s, when trenches were dug to receive the reactor effluent. Hazardous substances also were released to the river during purges of the reactors that were conducted to clear out suspended solids and precipitates (Gerber, 1996). Thus, during operations, the discharge pipes were a direct pathway transporting hazardous substances to the river.

Hazardous substances were also transported to the Columbia River from process/waste liquid sources via surface water runoff associated with rain events. Overland flow (runoff) was historically a significant pathway in the 100 and 300 areas, and a significant source of contamination to the Columbia River. Historic information including aerial photographs show water seepage from the reactor cribs and trenches flowing across the land surface and discharging directly to the Columbia River (U.S. DOE, 2008b). Areas of suspected overland flow have been evaluated in various 100 Area investigations. As discussed in Chapter 3, one significant overland flow event in 1948 resulted in the release of an estimated 12 to 16 pounds of uranium (elemental) to the river when a pond was breached in the 300 Area (U.S. DOE, 2008b).

Liquid wastes were also disposed of directly to groundwater through injection (reverse) wells. A number of such wells were operated in the 100 and 200 areas (U.S. DOE, 2008a). These wells were direct pathways for hazardous substances to groundwater.

Biotic vector transport to soils

Biotic vectors can be a pathway for the transport of hazardous substances from liquid waste sources to natural resources. The BC control area on the Central Plateau is an example of the distribution of radionuclides by biotic vectors. The BC control area (see Figure 3.3) has been monitored as a radiologically controlled contamination area since 1958. The area is largely undisturbed by Site operations but has been contaminated by animal feces from local wildlife that came into contact with salt precipitates and liquid wastes at the BC cribs and trenches, or through the ingestion of contaminated prey (Rucker and Sweeny, 2004; Fluor Hanford, 2003). Fluor Hanford (2003, p. 3) stated:

> In 1958, rabbit and coyote contaminated feces were found south, east, and west of the BC Crib site. A badger burrow was found in one of the trenches, and the burrow became a salt lick for the native wildlife. This lead [*sic*] to a four square mile area becoming sparsely contaminated with radioactive feces. The contaminated area was posted as a radiologically contaminated area. The burrow hole was sealed to prevent further spread of contamination.

Although it is likely that wind and water dispersal also played a role, this example illustrates how biotic vectors can be a transport pathway for radionuclides from process/waste liquids to soils and other natural resources at the Site.

More recently, Washington Closure Hanford engineers discovered that mud dauber wasps built nests in the 100-H area during demolition in 2003. The demolition included watering the surrounding soils for dust suppression, which created mud dauber habitat. The wasp nests contain radionuclide contamination sufficient to require complete removal of the top 6 to 12 inches of soil over six acres near 100-H (Cary, 2009).

4.1.3 Solid waste

There were numerous types of solid waste generated at the Site. These wastes were handled in different ways:

- Burial grounds were used to dispose of solid waste materials, including intermediate- and low-level wastes such as laboratory supplies, tools, clothing, machinery, paper, wood, etc.
- Irradiated fuel in large quantities was stored in the K basins in the 100 Area
- Failed equipment and other solid wastes were stored in railcars and placed in closed off areas and 200 Area tunnels
- Solids wastes were also disposed of in landfills and other Site closure facilities.

Solid wastes and their disposal are described in greater detail in Chapter 3. In addition, operational facilities, including buildings, pipelines, and other support infrastructure can be considered a form of solid waste. Many of the Site facilities have been removed and disposed of through the D4 process, and those that remain standing may continue to be stressors to the environment.

Hazardous substances, including radionuclides, metals, organics, and other substances are known or suspected to have been released from these solid waste sources. Pathways that can transport hazardous substances from solid waste sources to natural resources include (Figure 4.2):

- Infiltration to soils
- Runoff to soils and surface water
- Aeolian transport to soils and air and surface water
- Volatilization to air
- Biotic vectors to soils
- Direct contact with humans and biota.

The factors influencing infiltration and runoff transport pathways from solid wastes are similar to those described above in Section 4.1.2. In addition, solid hazardous substances may volatilize and be transported by air. Many of the factors that discussed in Section 4.1.1 also apply to volatilized substances, and to aeolian transport of hazardous substances from solid wastes. Hazardous substances from solid waste sources may also be transported to natural resources by biotic vectors. For example, hazardous substances may be transported through uptake by plants from soils, and wind dispersion of plant materials. Hazardous substances may also be distributed in feces excreted by animals that have ingested contaminated plants or other contaminated animals. Finally, humans and other biota may be exposed to hazardous substances by coming into direct contact with solid wastes.

4.2 Secondary Stressor Pathways

Natural resources, including air, soils, groundwater, surface water resources (including sediments and pore water), and biotic resources that are contaminated by hazardous substances released from Site sources may in turn act as sources of contamination (or secondary stressors) to other resources. Here we present a summary of secondary pathways from air, soils, surface water, the hyporheic zone, and groundwater.

4.2.1 Air

Air that has been contaminated by emissions from the Site can serve as a secondary stressor to other natural resources and humans. Once released to air, hazardous substances may expose surface water, soils, humans, and other biota through dry deposition and precipitation pathways. Biota in contact with contaminated air may also serve as vectors, physically transporting hazardous substances to soils and surface water. Humans and other biota may be directly exposed to hazardous substances in air through respiration, inhalation, or direct contact. Many of the factors that influence the release of hazardous substances to air that were summarized in Section 4.1.1 also control their migration through air to other resources.

4.2.2 Surface and subsurface (vadose zone) soils

Surface soils can be a secondary source of hazardous substances to biota, and potentially to air during episodic events such as wildfires or dust storms. The vadose zone can be a pathway for and a secondary source of hazardous substances to groundwater (including perched groundwater), air, and surface water.

Infiltration of liquid wastes and process waters, or leaching of soil-bound contaminants by infiltrating precipitation can carry hazardous substances through the vadose zone to groundwater. The infiltrating substances may reach the water table directly, or may encounter groundwater perched on low permeability layers within the vadose zone. As mentioned previously, clastic dikes may form communication conduits within the vadose zone soils and between vadose zone soils and underlying groundwater. Hazardous substances in the vadose zone may also be leached to groundwater by fluctuating water table levels. For example, in the 100 Area, fluctuations in strontium-90 concentrations in the groundwater are attributed to rising groundwater coming into contact with and leaching soil-bound strontium from the vadose zone (U.S. DOE, 2008a). Water table fluctuations occur at the Site in response to changes in river stage, which occur on both a seasonal and diurnal basis (U.S. DOE, 2008a). River stage at the Site is controlled by the Grand Coulee Dam and the Priest Rapids Dam. Operation of the Priest Rapids Dam can result in variations in river levels of up to 3 meters within a few hours (PNNL, 1998). Thus, stressors can be exchanged between the vadose zone and groundwater as the water table responds to river stage changes.

Soils can be a secondary source to surface water. The runoff pathway described in Section 4.1.3 can also transport contaminated soil particulate matter, and dissolved substances from surface soils to surface waters. In addition, the erosion pathway can transport hazardous substances from soil to surface waters. Evapotranspiration from contaminated plants, and aeolian transport pathways (discussed in Section 4.1.3) can expose air to hazardous substances originating from soils.

Humans and other biota can be exposed to hazardous substances in soils through contact, ingestion, and uptake. In turn, exposed biota can contaminate soils when they die and their bodies decompose. Biotic vectors can physically transport hazardous substances between soils and surface waters, and between soils and air by dispersion and movement through the environment

4.2.3 Surface water resources (including sediment and pore water)

Contaminated surface water resources – including surface water, sediments, and pore water – can serve as a secondary stressor to other natural resources, as well as to humans. Here we discuss pathways through which surface water may expose other natural resources and humans. In Chapter 6 (Aquatic Resources), we discuss surface water resources in greater detail.

As illustrated in Figure 4.2, there are numerous pathways through which surface water may expose other natural resources and humans. Hazardous substances can be transported from surface water to air by evaporation. Surface water can be a source to soil through irrigation and flooding pathways. It can also be a source of stressors to the hyporheic zone, and to a lesser extent, to groundwater, depending upon river stage and groundwater elevation that influence the relative hyporheic exchange. Humans and biota can be exposed to hazardous substances through direct contact with and by ingesting water. In turn, contaminated biota can expose surface water resources through decomposition. In addition, biotic vectors can come into contact with hazardous substances and physically transfer them between surface water and other media.

The principal surface water body at the Site is the Columbia River. The flow of surface water in the Columbia River has transported hazardous substances downstream as far as the Pacific Ocean (Nelson, 1961). Contaminants can move back and forth between the suspended, bed, bank, and dissolved load in the river. There are many physical characteristics and processes that may influence the transport of hazardous substances in river surface waters:

- Hydraulic parameters (stream flow characteristics)
- Dams: flow rates, river stage, retention of surface water and sediment behind dams
- Bank storage/groundwater-surface water interactions (hyporheic exchange)
- Tidal flux and current directions and rates in marine-influenced waters
- Irrigation
- Flooding
- Direct discharge of process effluent
- Transport and exchange between dissolved, suspended, and bed loads
- Bed, bank, and suspended sediment grain size, mineralogy
- Riverbed morphology
- Flux of hazardous substances to/from sediment pore water
- Mixing and dilution

- Sediment "dilution," or mixing with cleaner sediment
- Sedimentation rates (e.g., erosion)
- Physical disturbances (e.g., rip-rap, channelization)
- Bioturbation
- Biogeochemical properties
- Thermal effects (temperature).

Many of these processes are described by Bryce et al. (2002), as depicted in Figure 4.4. The hydraulic properties of a river, including channel dimensions, morphology, gradient, and the river bottom profile, will influence flow rates and thus the transport of hazardous substances. In addition, anthropogenic features such as dams can control flow rates and thus will also influence transport of hazardous substances. The retention of water and sediments behind dams may also be a significant control on the migration of hazardous substances. Hazardous substances may be introduced to and released from bank storage (the hyporheic zone) with fluctuations in river stage. The hyporheic zone plays a significant role in contaminant transport between groundwater and surface water, and is discussed in further detail in Section 4.2.4. In marine-influenced areas, transport may also be influenced by tidal flux and current directions and rates. As well as being pathways to/from the river, irrigation, flooding, and direct discharge may influence contaminant transport within the river. They may alter flow rates, disturb/resuspend/ deposit sediments, and have other effects on river dynamics.

Surface water pathways can be influenced by physical mixing and dilution. For example, radionuclide concentrations in the Columbia River vary with flow rates, with the lowest dissolved concentrations occurring during high flow conditions when river stage reduces groundwater exchange and river water dilutes contamination seeping into the river (Nelson, 1961). Contaminants may be transported and exchanged between the dissolved, suspended and bed loads of rivers. The grain size distribution and mineralogy of the different loads, river bottom and bank sediments will influence adsorption, complexation, precipitation, and colloidal interactions with hazardous substances. For example, because cadmium and zinc preferentially sorb to fine particles, cadmium concentrations were found to be preferentially associated with fine sand fractions in the Hanford Reach, and cadmium and zinc were associated with silt and clay fractions near the downstream McNary Dam (Patton and Crecelius, 2001).

Contaminant concentrations in sediments can be diluted through mixing with uncontaminated sediments downstream and/or through deposition of clean sediment through erosion and other processes. The rate of sedimentation will influence the degree of dilution that occurs. Bioturbation can disturb, redistribute, and mix deposited contaminated sediments, causing re-suspension into the water column. As releases of hazardous substances from the Site have decreased over time and new sediment continues to be introduced from upstream, sediment stressor concentrations have decreased in the Columbia River. Deeper sediment generally has higher concentrations of hazardous substances than shallower sediment. Surface sediment in the

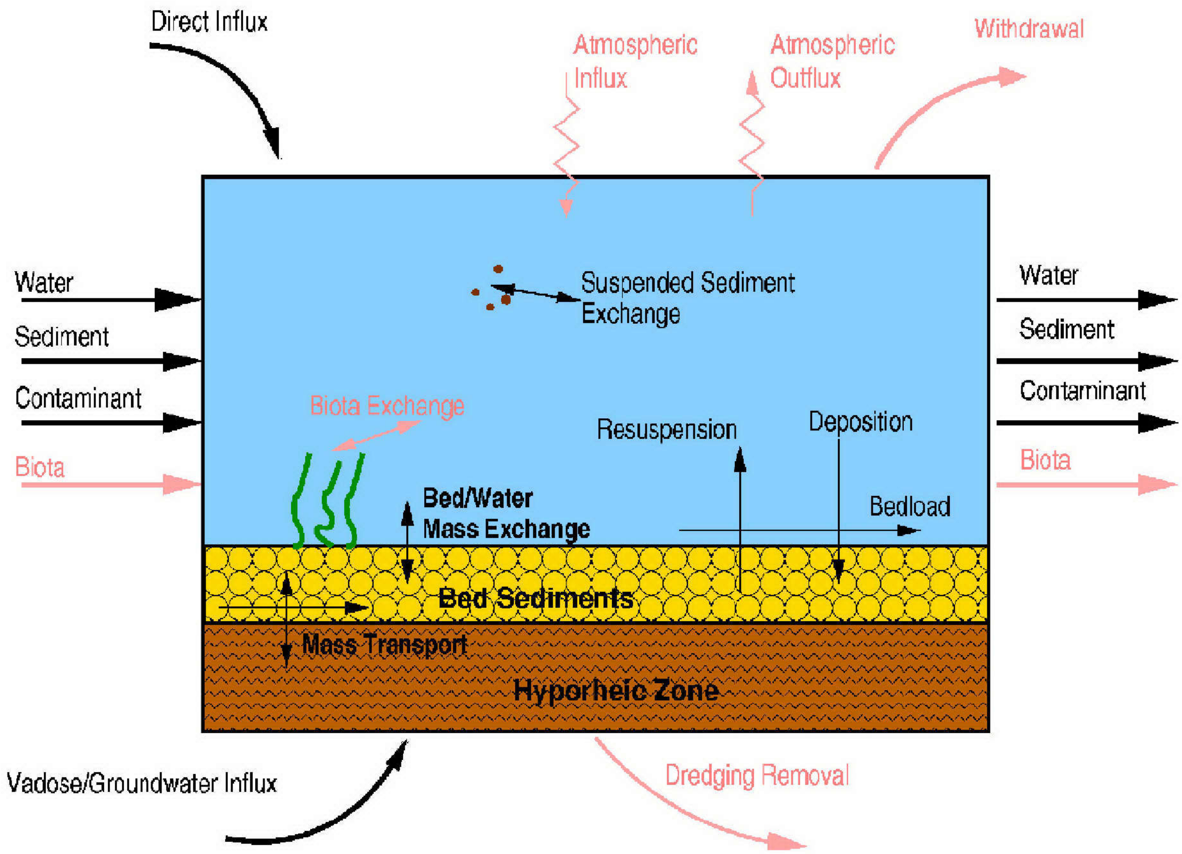


Figure 4.4. Fate and transport processes in the Columbia River.

Source: Bryce et al., 2002, Figure 8.6.

Lake Wallula located downstream of the Site has lower radionuclide concentrations than deeper sediment because from 40 to 80 centimeters of less contaminated sediment has been deposited in the reservoir since 1971 (Robertson and Fix, 1977). Only the longer-lived radionuclides (e.g., manganese-54; iron-55; cobalt-60; cesium-137; europium-152 and -154; plutonium-238, -239, and -240; and americium-241) remain buried in the sediment; shorter-lived radionuclides have decayed to levels close to background values (Robertson and Fix, 1977).

Other features of a river system that can influence contaminant migration include physical disturbances, such as the installation of rip-rap to create artificial shorelines. The potential removal of effluent pipelines from the river would also cause physical disruption in the river (U.S. DOE, 2007).

Biogeochemical properties of the surface water, pore water, and hazardous substances can affect contaminant transport. The biogeochemical properties and processes that influence transport in the vadose zone, discussed in Section 4.1.1, also apply to transport in surface water. Thermal effects may have influenced biogeochemical processes in the river. As mentioned above (Section 4.1.2), process waters discharged to the river from the nuclear reactors were as hot as 70–90ºC. Such elevated temperatures likely affected geochemical reactions and microbially-mediated processes. For example, they may have accelerated precipitation/dissolution reactions, and other processes that influence contaminant transport.

4.2.4 Hyporheic zone

The hyporheic zone is the subsurface volume of sediment and porous space located adjacent to a river or stream through which surface water and groundwater can readily exchange. Hyporheic flow can be vertical or lateral, and it can involve very short (a few meters) or very long (kilometers) distances. It can be a pathway for hazardous substance transport from groundwater to surface water, and to a lesser extent, from surface water to groundwater. The morphology and architecture of river bars and other sedimentary features influence the hyporheic exchange into and out of the river, further complicating transport pathways.

The hyporheic zone of the Columbia River along the Hanford Reach is alternatively fed by surface water and groundwater, depending upon the river bed and bank morphology (including curvature) and the relative elevation of the water table and the river stage. River levels fluctuate dramatically in the Hanford Reach and can change on the order of meters in the span of a few hours. These river level changes have been shown to strongly influence flow in the hyporheic zone. River water flows into the hyporheic zone as the river stage rises and flows back into the river as the river stage lowers. The contribution of groundwater (vs. stored river water) to the hyporheic zone increases as the river level lowers (Dirkes and Hanf, 1996).

There are many springs (or seeps) along the riverbank associated with the hyporheic zone that emerge at low river stage. These springs initially release stored river water, with the contribution of groundwater increasing as the stored river water drains, as evidenced by increasing contaminant levels. In 1983, 115 riverbank springs were identified along the 66 km (41 mile) Hanford Reach. Since discharge at springs is influenced by both river stage and groundwater elevations, decreasing groundwater mounding since the reactors were shut down has decreased the number of riverbank springs in the 100-N Area (Dirkes and Hanf, 1996).

Thus, groundwater can be a source of contamination to surface water through the hyporheic zone and seeps and springs, particularly when the river stage is falling. Surface water may dilute contaminant concentrations in the hyporheic zone when the river stage is rising (Fritz et al., 2007).

4.2.5 Groundwater

The groundwater resource includes groundwater and the aquifer materials that contain the groundwater. Hazardous substances can be transported into groundwater via infiltration from the overlying vadose zone. Stressors may also reach groundwater to a limited extent via surface water/groundwater interactions through the hyporheic zone. Historically, hazardous substances were directly discharged to groundwater through waste injection (reverse) wells. Poorly constructed wells can also provide preferential pathways for contaminant transport. Contaminated groundwater in turn can act as a pathway (secondary stressor) to other natural resources.

Chapter 5 provides a description of groundwater resources, including a description of the hydrogeologic units present at the Site and the physical groundwater flow system. Here we focus on groundwater as a pathway to other natural resources and humans, as well as factors that influence the groundwater pathway.

Hazardous substances can flow through groundwater and reach surface water through shallow and deep upwelling of groundwater to the river. In addition, groundwater can transport hazardous substances to surface water through the hyporheic zone. The vadose zone can be exposed to contaminants in groundwater through fluctuating water table levels, creating a “smear zone” that is alternatively saturated and unsaturated. Groundwater aquifer materials can be source of hazardous substances to clean downgradient groundwater.

Some of the primary aquifer characteristics that influence the transport of hazardous substances through groundwater include:

- Hydraulic conductivity
- Porosity
- Hydraulic gradient
- Saturated thickness
- Areal extent of the geologic units (aquifer continuity)
- Groundwater flow direction and velocity
- Dispersion (spreading) of contaminants
- Dilution (advective and diffuse mixing) of contaminants with clean groundwater
- Inter-aquifer connectivity/confinement
- Historical mounding due to infiltration and injection of liquid wastes and process waters
    - Natural/erosional mound at N. Gable Mountain
    - “Rebound” of confining layer after mound dissipates
- Mounding and cones of depression from pump/treat/re-injection
- Perched groundwater

- Groundwater/surface water interactions (hyporheic zone)
  - River stage fluctuations
  - Discharge as seeps, springs
  - Upwelling to the river
- Vertical gradients in confined aquifers
- Biogeochemical properties and processes of the groundwater and hazardous substances
  - Adsorption/desorption, absorption
  - Colloidal transport, especially for radionuclides
  - Radioactive decay rates
  - Degradation rates (e.g., carbon tetrachloride to chloroform)
  - Biochemical degradation
- Changes in mineral structure as a result of contact with acidic liquid wastes
- Thermal effects (temperature).

The primary hydrologic aquifer and groundwater characteristics that determine transport of hazardous substances are hydraulic conductivity, hydraulic gradient, and the thickness and areal extent of the geologic units. In general, more contamination will be transported more quickly and to a greater distance through an aquifer or geologic unit with higher hydraulic conductivity, higher gradient, and greater thickness and areal extent. The hydraulic gradient also controls the direction and velocity in which groundwater flows and thus the specific receptors it may expose. During advective transport, diffusion and dispersion of contaminants also occurs, resulting in some degree of mixing and dilution of hazardous substances. Inter-aquifer connectivity and the presence or absence of low permeability confining layers can also allow the migration of hazardous substances. For example, in the Central Plateau area, carbon tetrachloride is reported to be migrating from the upper Ringold aquifer to the underlying lower Ringold aquifer through gaps in the low permeability rock that separates the upper and lower aquifers (U.S. DOE, 2008a).

Historical groundwater mounding associated with the very large volume of liquid wastes and process waters that were released to the ground during operations at the Site has also influenced the transport of hazardous substances in groundwater. Groundwater levels in the Central Plateau area mounded as high as 20 meters (66 feet) during the peak of operations. Since the cessation of operations, the mounding has decreased to approximately 11 meters (36 feet) (U.S. DOE, 2008a). Historical deep waste injection wells also caused groundwater mounding during operations. Mounding can influence the fate and transport of groundwater contaminants. It can cause steeper groundwater gradients, and thus can increase flow rates. It also can cause changes in groundwater flow directions, thereby influencing the pathway of contaminants (U.S. DOE, 2008a). As discussed in greater detail in Chapter 5, there is currently some uncertainty with respect to which way groundwater will flow in parts of the Central Plateau area with further dissipation of mounding. More recently, pump and treat and re-injection systems have been installed to treat groundwater in the 100 and 200 areas. These have created localized cones of depression where the water is being pumped up to the surface for treatment, and mounds where it is re-injected.

Perched groundwater lenses, formed when infiltrating liquid wastes and process waters encounter low permeability units in the vadose zone such as caliche units, can affect contaminant transport. They can result in much greater lateral flow in the vadose zone of hazardous substances than would otherwise be predicted (Ward, 2006; Conrad et al., 2007). Also, as saturated thicknesses increases with increasing infiltration, the saturated lens can exceed the capacity of the low-permeability unit on which it is perched, resulting in further vertical migration towards the water table, essentially acting as a “delayed yield” secondary source.

Other factors that may influence contaminant migration in groundwater includes groundwater – surface water interactions. Groundwater gradients and flow directions have been demonstrated to respond to changes in river stage. For example, groundwater flow through the Gable Gap shifts seasonally as a result of changes in river water levels. Low river stage results in steeper groundwater gradients, and more groundwater flows north through the Gap and toward the river. When the river stage rises again, the groundwater gradient and velocity decrease, and some groundwater flow diverts to a northeast trajectory (U.S. DOE, 2008a). Such shifts in groundwater flow directions can influence the transport pathway of hazardous substances, and the resources that they expose.

Vertical gradients that are present in the confined aquifers at the Site (discussed further in Chapter 5) may also influence contaminant migration. Upward gradients causing outward flow from confined aquifers can inhibit the contamination of deeper aquifers by dissolved-phase contaminants in overlying aquifers.

Biogeochemical properties of hazardous substances, groundwater, and aquifer materials can affect contaminant transport. In addition to those properties presented in the Section 4.1.2, reduction-oxidation (redox) reactions that change the oxidation state of an element can have significant effects on transport in groundwater [e.g., reduced uranium (IV) is immobile, while oxidized uranium (VI) is mobile in groundwater] can play an important role in groundwater contaminant transport. Adsorption of hazardous substances (measured by retardation factors) to aquifer materials can also play an important role in contaminant mobility in groundwater. Radioactive decay and abiotic and biochemical degradation (e.g., carbon tetrachloride to chloroform) can also affect the fate and transport of contaminants in groundwater. These properties are discussed in greater detail in Chapter 5.

4.3 Response Action Stressors

Response actions may inadvertently facilitate contaminant transport and may cause direct physical disruption of habitat, potentially resulting in injuries to natural resources and in human service loss. Figure 4.2 shows three main pathways through which response action stressors may injure natural resources at the Site: direct contact, groundwater and vadose zone treatment systems, and surficial disturbances. Direct exposure of humans and other biota to hazardous substances as a result of response actions may occur, potentially resulting in injury. For example, soil removal actions may disturb and disperse soil and dust particles into the air and expose biota. Response actions also result in the physical disruption of habitat, such as soil removal from contaminated sites or the construction of a repository for hazardous substances. In addition, institutional controls, such as restricting access to lands and groundwater, may also adversely impact the flow of services provided by natural resources.

The treatment of groundwater and vadose zone soils may inadvertently facilitate the transport of hazardous substances. For example, pump and treat and re-injection systems that are designed to treat a specific contaminant such as strontium-90 may inadvertently transport and disperse another contaminant such as tritium. Chapter 3 presents a summary of current treatment systems at the Site. Hazardous substances transported through treatment systems may then cause additional injuries to the groundwater where they are re-injected, and may also expose other resources at the location of re-injection, including soils and surface water.

Surficial disturbances that have occurred thus far at the Site and may have injured natural resources include:

- The physical removal and displacement of contaminated soils
- The creation of borrow areas where clean materials have been excavated to replace excavated contaminated soils, and for other remedial purposes
- The creation of transportation corridors to facilitate access areas where response action activities take place
- The clearing and use of land for closure facilities, including treatment and storage facilities such as ERDF
- Vegetation control measures
- Dust suppression with water (attracting various biota to contaminated areas, including mud dauber wasps as mentioned previously)

- Dust suppression by spraying oils containing PCBs
- Soil treatment methods (e.g., soil vapor extraction) that may disrupt surface and subsurface soils.

These activities are described in greater detail in Chapter 3. The total area of surficial disturbances at the Site is quite extensive. For example, ERDF, the disposal facility receiving most of the low-level radioactive soil and debris from cleanup activities, currently comprises 8 cells which are each 150 meters (500 feet) wide at the bottom, 20 meters (70 feet) deep, and over 300 meters (1,000 feet) wide at the surface. ERDF expansion to 10 cells was recently approved, and it could potentially expand to as much as 28 cells that will be several kilometers in length (U.S. DOE, 2006; Washington Closure Hanford, 2009). In the previous chapter, Figure 3.3 showed hundreds of acres of surface area potentially impacted by response actions and closure activities. This illustrates the potential for extensive injured surface area as a result of response actions at the Site.

References

Bryce, R.W., C.T. Kincaid, P.W. Eslinger, and L.F. Morasch (eds.). 2002. *An Initial Assessment of Hanford Impact Performed with the System Assessment Capability.* PNNL-14027. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. September.

Cary, A. 2009. Sting planned on radioactive wasp nests at Hanford. Available: http://www.tri-cityherald.com/901/story/609825.html. Accessed 6/29/2009.

Conrad, M.E., D.J. DePaolo, K. Maher, G.W. Gee, and A.L. Ward. 2007. *Field Evidence for Strong Chemical Separation of Contaminants in the Hanford Vadose Zone*. Lawrence Berkeley National Laboratory, Berkeley, CA and Pacific Northwest National Laboratory, Richland, WA.

Dirkes, R.L. and R.W. Hanf (eds.). 1995. *Hanford Site Environmental Report for Calendar Year 1994*. PNNL-10574. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. June. Available: http://hanford-site.pnl.gov/envreport/. Accessed 4/1/2009.

Dirkes, R.L. and R.W. Hanf (eds.). 1996. *Hanford Site Environmental Report for Calendar Year 1995.* PNNL-11139. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. June. Available: http://hanford-site.pnl.gov/envreport/. Accessed 4/1/2009.

Eliason, J.R. 1967. *Thermal Mapping of the Columbia River at Hanford Using an Infrared Imaging System*. BNWL-CC-1074. Pacific Northwest Laboratory, Richland, WA. February 28.

Fluor Hanford. 2003. *Radiological Review of Conditions Created During and After a Fire on the Hanford Site in the BD Crib Controlled Area and Areas of Radiological Concern in the 600 Area (TBD-HSO-RC-013)*. HNF-15850. Prepared for the U.S. Department of Energy. April.

Fritz, B.G., N.P. Kohn, T.J. Gilmore, D. McFarland, E.V. Arntzen, R.D. Mackley, G.W. Patton, D.P. Mendoza, and A.L. Bunn. 2007. *Investigation of the Hyporheic Zone at the 300 Area, Hanford Site*. PNNL-16805. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. October.

Gee, G.W., M. Oostrom, M.D. Freshley, M.L. Rockhold, and J.M. Zachara. 2007. Hanford Site vadose zone studies: An overview. *Vadose Zone Journal* 6:899–905.

Gerber, M.S. 1996. The Plutonium Production Story at the Hanford Site: Processes and Facilities History. Westinghouse Hanford Company, Richland, WA. Prepared for the U.S. Department of Energy. June.

Kannberg, L.D. 1992. Hanford Production Reactor Heat Releases 1951–1971. Prepared by BATELLE for the U.S. DOE under contract DE-AC06-76RLO 1830.

Nelson, I.C. (ed.). 1961. *Evaluation of Radiological Conditions in the Vicinity of Hanford for 1960*. HW-68435. General Electric, Hanford Atomic Products Operation, Richland, WA. June 1. Available: http://hanford-site.pnl.gov/envreport/. Accessed 4/1/2009.

Patton, G.W. and E.A. Crecelius. 2001. *Simultaneously Extracted Metals/Acid-Volatile Sulfide and Total Metals in Surface Sediment from the Hanford Reach of the Columbia River and the Lower Snake River*. PNNL 13417. Pacific Northwest National Laboratory. Prepared for the U.S. Department of Energy. January.

Peterson, R.E., F.A. Spane, K.B. Olsen, and M.D. Williams. 2002. *Evaluation of Potential Sources for Tritium Detected in Groundwater at Well 199-K-111A, 100-K Area.* PNNL-14031. Pacific Northwest National Laboratory. Prepared for the U.S. Department of Energy. September.

PNNL. 1998. *Screening Assessment and Requirements for a Comprehensive Assessment: Columbia River Comprehensive Impact Assessment.* DOE/RL-96-16. Revision 1, Final. Pacific Northwest National Laboratory.

Robertson, D.E. and J.J. Fix. 1977. *Association of Hanford Origin Radionuclides with Columbia River Sediment*. BNWL-2305. Battelle Pacific Northwest Laboratories. Prepared for the Energy Research and Development Administration.

Rohay, V.J. 1993. Tracer gas diffusion sampling test plan. WHC-SD-EN-TP-035. Westinghouse Hanford Co., Richland, WA. October.

Rucker, D.F. and M.D. Sweeney. 2004. *Plume Delineation in the BC Cribs and Trenches Area*. PNNL-14948. Prepared by Pacific Northwest National Laboratory Richland, Washington, for the U.S. Department of Energy. December.

Singleton, M.J., K. Maher, D.J. DePaolo, M.E. Conrad, and P.E. Dresel. 2006. Dissolution rates and vadose zone drainage from strontium isotope measurements of groundwater in the Pasco Basin, WA unconfined aquifer. *Journal of Hydrology* 321:39–58.

U.S. DOE. 2006. Environmental Restoration Disposal Facility (ERDF) (Fact Sheet). Richland, WA. August.

U.S. DOE. 2007. *Risk Assessment Report for the 100 Area and 300 Area Component of the River Corridor Baseline Risk Assessment.* DOE/RL-2007-21. Draft A. Richland, WA.

U.S. DOE. 2008a. Hanford Site Groundwater Monitoring for Fiscal Year 2007. DOE/RL-2008-01. March.

U.S. DOE. 2008b. *Remedial Investigation Work Plan for Hanford Site Releases to the Columbia River.* DOE/RL-2008-11. Rev. 0. September.

Ward, A.L. 2006. *Vadose Zone Transport Field Study Summary Report*. PNNL-15443. Pacific Northwest National Laboratory, Richland, WA. Prepared for U.S. Department of Energy.

Washington Closure Hanford. 2009. River Corridor Closure Project Monthly Progress Report, April 2009. Available http://www.washingtonclosure.com/news/docs/reports/empr/2009/RCCrpt-apr09.pdf, accessed June 29, 2009.

Wigmosta, M.S. and G.R. Guensch. 2005. *FY 1999 Progress Report On: Potential Groundwater Recharge from the Infiltration of Surface Runoff in Cold and Dry Creeks*. PNNL-15534. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. December.

5. Groundwater Resources

This chapter presents a CSM for groundwater resources for the Hanford assessment area. Figure 5.1 illustrates the relationship to the other CSMs provided in this document.

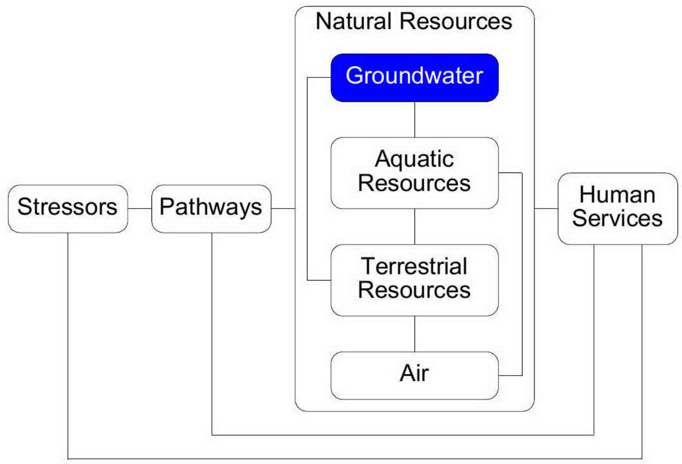


Figure 5.1. Relationship between the groundwater resources CSM and other CSMs that together make up the NRDA CSM.

This groundwater CSM addresses both groundwater resources (water and aquifer materials), *per se*, and vadose zone soils. Aquifer materials and vadose zone soils may also be considered geologic resources. Both groundwater resources and geologic resources in the vadose zone have been exposed to, and potentially injured by, stressors at the Site. Figure 5.2 shows the main elements of the groundwater CSM. As described in Chapter 3, site stressors include:

- Hazardous substances
- By-products of hazardous substances
- Response actions that may cause unavoidable injuries to natural resources
- Secondary sources (contaminated resources).

Hazardous substances and their by-products have been released to the vadose zone and to groundwater from site operations. They have infiltrated into the ground from cribs, trenches, ponds, and other surface impoundments; leaked from underground storage tanks and other containers; and have been injected at reverse wells. Response actions, such as the installation of groundwater pump and treat systems and soil vapor extraction systems, and the implementation of institutional controls to prevent groundwater use, can also cause injuries to the vadose zone soils, groundwater, and the services they provide.

Other natural resources are likely secondary sources of hazardous substances to the vadose zone and groundwater. For example, hazardous substances may be deposited on the ground surface from the air, and then infiltrate through surface soils with precipitation. Further, the vadose zone and groundwater may be secondary sources to each other. Contaminants bound to soil in the vadose zone may be leached and transported to groundwater by percolation. Contaminated groundwater may expose the vadose zone as a result of fluctuating water table levels. Finally, the vadose zone and groundwater may be secondary sources and pathways to other natural resources such as surface water.

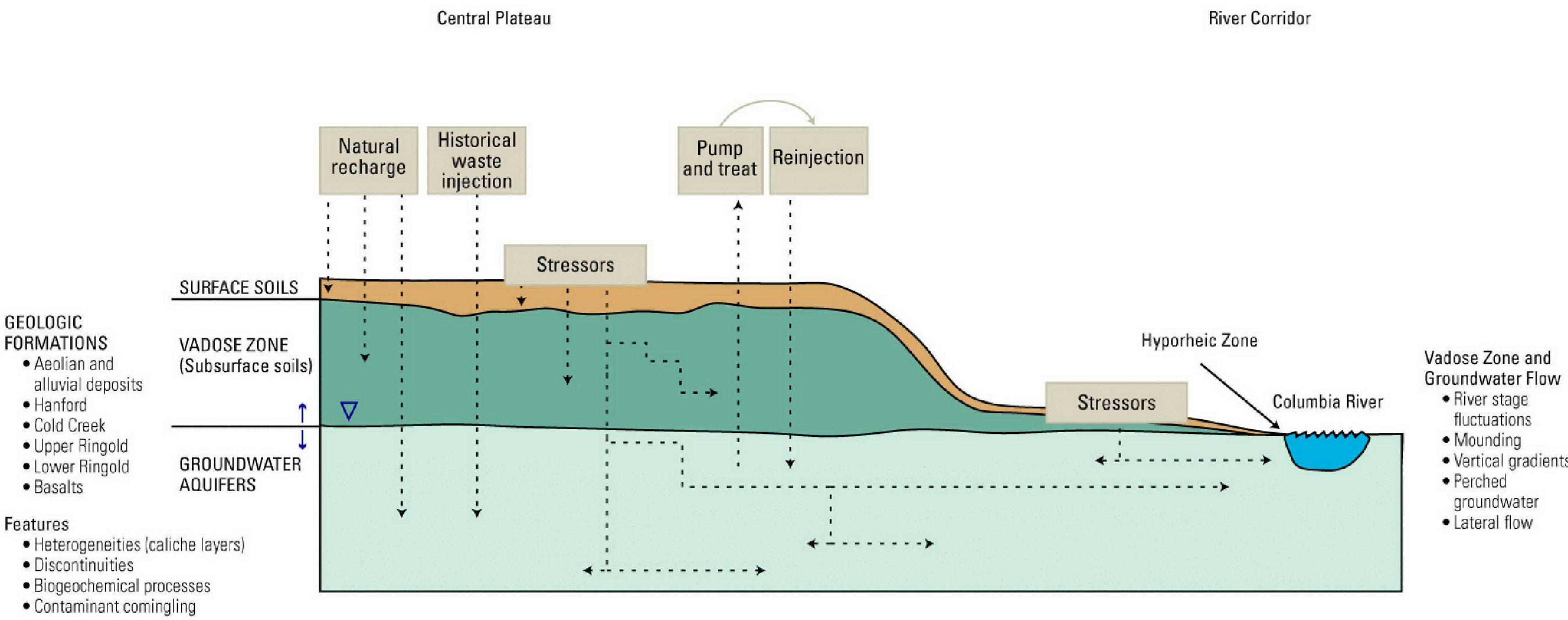


Figure 5.2. Factors influencing contaminant fate and transport in vadose soils and groundwater. Human-created factors include both surface and subsurface releases of contaminants as well as pump and treat systems. Physical factors include the properties of the vadose soils and aquifer (geologic formation) materials, as well as vertical and horizontal discontinuities that result in less predictable vertical and lateral groundwater flow.

Groundwater flow and contaminant transport through the vadose zone and groundwater at the Site is complex and may be influenced by many factors. As indicated in Figure 5.2, some of the features that may influence contaminant transport include geologic heterogeneities and discontinuities, biogeochemical processes, and contaminant co-mingling. Transport may also be influenced by river stage fluctuations, mounding, vertical gradients, and lateral flow effects.

In this chapter we provide a definition and description of the groundwater and vadose zone natural resources (Sections 5.1 and 5.2), a brief summary of stressors that may have exposed and/or injured groundwater and the vadose zone (Section 5.3), factors influencing contaminant migration through these resources (Section 5.4), a summary of the known extent of contamination (Section 5.5), and a description of potential approaches to characterize and quantify injuries (Section 5.6).

Although groundwater and vadose soil resources could potentially be injured in areas outside the Site, this chapter focuses on the Site primarily because of the extent of information available, the fact that groundwater and vadose zone soils at the Site are known to be contaminated in many areas, and the proximity of Site groundwater and vadose zone resources to stressors. However, groundwater and vadose zone resources may also be influenced by site stressors in the broader assessment area; the conceptual approaches described in this chapter are generally applicable to the full assessment area.

5.1 Vadose Zone Soils and Groundwater Resources

This CSM addresses groundwater and associated aquifer materials, as well as geologic resources (soils) in the vadose zone. The DOI regulations for conducting NRDAs define groundwater resources as water in a saturated zone or stratum beneath the surface of land (including land below surface water), and the rocks or sediments through which groundwater moves [43 CFR § 11.14(t)]. Geologic resources, including unsaturated soils of the vadose zone, are defined in the DOI regulations as elements of the Earth's crust such as soils, sediments, rocks, and minerals that are not included in the definitions of ground and surface water resources [43 CFR § 11.14(s)]. As previously described in this document, we define surface soils as the biologically active soil layer, and subsurface soils (the vadose zone) as the soils below surface soils and above the groundwater table. Surface soils are addressed in the terrestrial CSM (Chapter 7).

Below we provide a description of the geologic and groundwater resources at the Site, including the geologic units that comprise the vadose zone and the groundwater aquifers.

Vadose and groundwater geologic units

The Site lies within a structural basin known as the Pasco Basin, which has accumulated a thick sequence of fluvial, overbank, and lacustrine sedimentary units over the past 2 million years (Wurstner et al., 1995). The major geologic units that host the vadose zone and groundwater aquifers at the Site, as shown in Figure 5.3, include the:

- Hanford Formation (unconsolidated alluvial sand and gravel)
- Ringold Formation (variably cemented gravel, sand, silt, and clay deposited by the ancestral Columbia and Snake rivers and associated lakes)
- Columbia River Basalt Group (CRBG; up to 50 layers of basalt flows).

There are also localized surface aeolian and alluvial deposits at the Site. The Cold Creek unit is also locally present between the Hanford and Ringold formations, and was formed by erosion of the Ringold Formation (Bunn et al., 2005; Hartman and Webber, 2008).

The geologic units are not uniformly distributed across the Site, and may alternatively be a part of the vadose zone or groundwater aquifer(s), depending on the elevation of the water table. For example, as shown in the generalized cross-section in Figure 5.4, the unconfined aquifer in the western part of Central Plateau largely occurs in the Ringold Formation. Thus, in this area, the overlying vadose zone is comprised of the portion of the Ringold Formation located above the water table, the Cold Creek unit (i.e., palouse soil and plio-pleistocene unit), the Hanford Formation, and locally present alluvial and aeolian deposits, while the groundwater lies in the Ringold Formation and underlying basalts. In contrast, in the eastern part of the Central Plateau area, the water table is in the Hanford Formation. Thus, in this illustrative example, the vadose zone is comprised solely of the upper part of the Hanford Formation and locally deposited Aeolian and alluvial deposits, while the groundwater is within the portion of the Hanford Formation below the water table, the Ringold Formation, and underlying basalt layers. In the northern part of the Site, both the vadose zone and the saturated aquifer materials lie mainly within the Hanford Formation.

Each of the geologic units present at the Site has different hydrologic and geochemical characteristics that will affect the transport of hazardous substances in the vadose zone and groundwater. For example, the Hanford Formation gravels are the most permeable units in the aquifer system, and mud units in the Ringold Formation can form localized confining layers. Permeable units will generally facilitate contaminant transport, while low permeability units may slow or hinder downward migration, and may result in greater lateral distribution of contaminants.

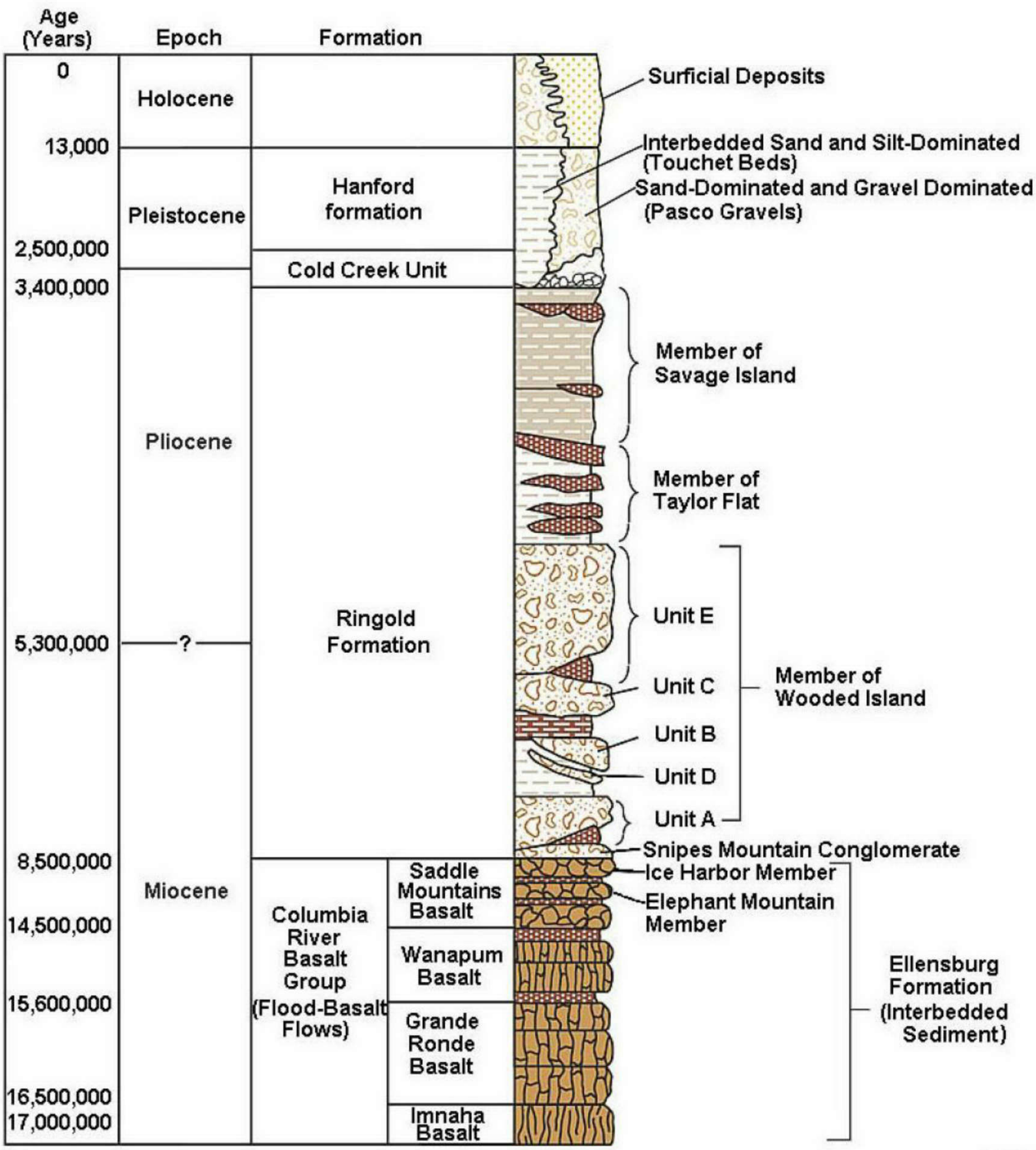


Figure 5.3. Generalized hydrogeologic and geologic stratigraphy.

Source: Bunn et al., 2005, Figure 4.3-5.

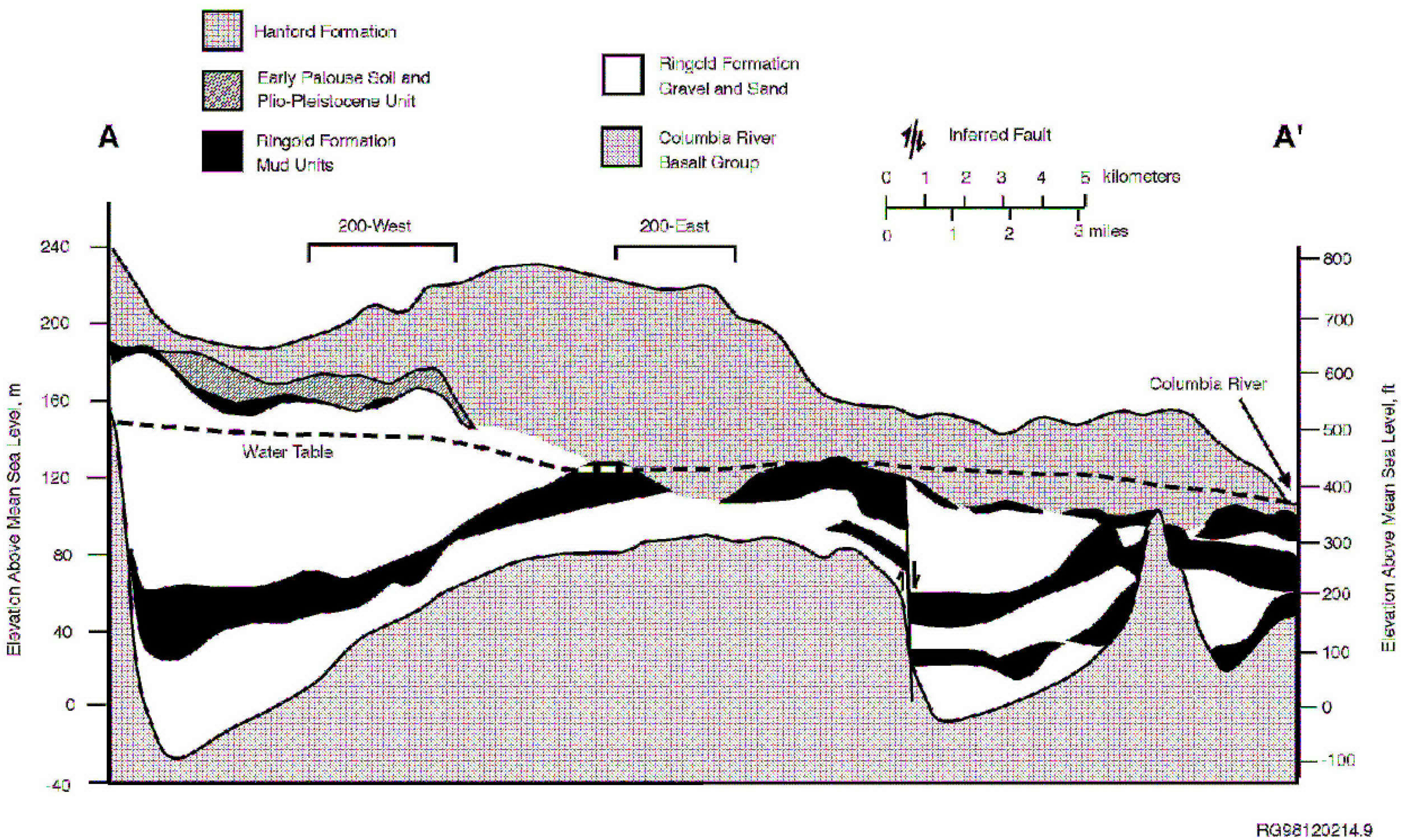


Figure 5.4. Generalized west to east hydrogeologic cross section through the Site with 1999 water table.

Source: Bryce et al., 2002, Figure 7.6.

Hanford Formation

The Hanford Formation comprises a series of coarse flood deposits, the majority of which were deposited during the catastrophic Lake Missoula outburst floods during the Pleistocene. These floods occurred multiple times during the Pleistocene as ice dams were repeatedly breached and reformed at the mouth of Lake Missoula. The Hanford Formation deposits therefore alternate between very coarse grained, high energy gravel deposits left behind by these catastrophic floods, and substantially finer-grained waning flow deposits (Hartman, 2000).

The total thickness of the Hanford Formation on the Site ranges from less than 1 meter to greater than 100 meters. Three facies are generally recognized within the Hanford Formation, dominated by coarse gravels, laminated sands, and silts, respectively (Hartman, 2000). Because of this variation, individual beds within the Hanford Formation are heterogeneous, with widely variable hydraulic conductivities ranging from 0.04 to 15,000 meters per day (m/d). The presence of fine-grained layers within the Hanford Formation leads to some anisotropy within the unit, with hydraulic conductivity values in the horizontal direction as much as an order of magnitude higher than those in the vertical direction (Wurstner et al., 1995).

The Hanford Formation also contains clastic dikes. Where present, these structural features may influence contaminant migration in the vadose zone and in groundwater. The dikes are fissures filled with sand, silt, clay, and coarser debris, and formed during the period of lake formation and flooding. These sharp-walled, near-vertical tabular structures range in thickness from less than 1 centimeters up to 2 meters thick, and can range in vertical extent from 1 to 50 meters. They are often characterized by low permeability thin clay/silt outer margins. Clastic dikes may facilitate or retard the migration of contaminants. Notably, they may limit the lateral spread of contaminants caused by the horizontal anisotropy of the Hanford Formation (Bunn et al., 2005 and references therein).

Cold Creek Unit

The Cold Creek unit is locally present at the Site, varying in thickness from 0 to 20 meters. The unit underlies the Hanford Formation and overlies the Ringold Formation and is known to be present in the 200 West Area. Erosion of the Ringold Formation was followed by deposition of fluvial, colluvial, and aeolian sediments. The Cold Creek unit typically has paleosols and low-permeability caliche (or hardpan) layers that formed when precipitation evaporated and left behind layers of hard minerals. The caliche layers are significant because they can influence contaminant migration by slowing the rate of downward movement, resulting in greater lateral migration than would otherwise be anticipated (Bunn et al., 2005).

Ringold Formation

Underlying the Hanford Formation is an older (Pliocene) sequence of fluvial-lacustrine deposits laid down by the ancestral Columbia and Snake rivers and referred to as the Ringold Formation. The ancestral Columbia River flowed into the Pasco Basin during the Pliocene-Pleistocene, episodically becoming dammed and forming large lakes. The Ringold Formation therefore also comprises a variety of facies, including fluvial gravels, fluvial sands, overbank deposits, lacustrine deposits, and an alluvial fan facies (Hartman, 2000). Subsidence of the Pasco Basin continued at least through the deposition of the middle Ringold Formation, causing strong spatial variations in total thickness of the unit.

The Ringold Formation includes five distinct units (see Figure 5.3), which have been broadly grouped into two aquifers; the "Upper" and "Lower" Ringold (Bunn et al., 2005). The uppermost of the five units comprises fine-grained lacustrine and overbank deposits. Immediately beneath this upper fine-grained sequence is a relatively thick, coarse-grained fluvial deposit. This upper coarse unit is the Upper Ringold; in the western part of the Central Plateau area (see Figure 5.4), the Upper Ringold behaves as an unconfined aquifer (Spane et al., 2003). In locations where the water table is higher and lies in the overlying Hanford Formation, the Ringold lacustrine unit acts a confining layer, and the Upper Ringold is a confined aquifer. The Ringold Formation has not been as well characterized as the Hanford Formation. However, available hydraulic testing results suggest that the hydraulic conductivities in the Upper Ringold are typically at least one to two orders of magnitude lower than the conductivities in the Hanford Formation, and range from ~0.05 to 150 m/d (Wurstner et al., 1995).

Beneath the upper coarse Ringold unit is a sequence of alternating fine and coarse grained facies, with the lowermost Ringold Formation being a basal coarse-grained facies. This basal coarse-grained unit is the Lower Ringold. The Lower Ringold has been even less well characterized than the upper Ringold, but available data suggest that hydraulic conductivities are slightly higher than in the Upper Ringold, and lower than in the Hanford (Wurstner et al., 1995). Immediately above the Lower Ringold basal coarse grained unit is a relatively impermeable mud facies. Where this mud is present, for example in the southern and eastern parts of the 200 East Area, it can act as a local confining unit, and the lowermost Ringold Formation behaves as a confined aquifer. However, this lower permeability mud is absent in many portions of the Site, including other parts of the 200 Area. The absence of these muds in this area allows for hydraulic communication between the lowermost Ringold and overlying units and may represent a window or gap for the vertical migration of contaminants, as discussed below.

Available data suggest that horizontal anisotropy in the Ringold Formation is also higher than in the Hanford Formation, with vertical conductivities as much as one to two orders of magnitude lower than horizontal conductivities (Wurstner et al., 1995). The total thickness of the Ringold

Formation ranges from less than 30 meters (100 feet) to more than 150 meters (500 feet), with the deposit generally thickening to the west (see Figure 5.4).

Columbia River Basalt Group

The bedrock underlying the Ringold Formation is the CRBG, comprising a thick sequence of flood basalts. There are a minimum of 50 discrete CRBG flows, which erupted between 14 and 16 million years ago. The periods between discrete flood basalt eruptions allowed lakes and rivers to occupy the landscape, depositing thin sedimentary interbeds within the CRBG. These sedimentary interbeds are collectively known as the Ellensburg Formation (Hartman, 2000). Some of these sedimentary interbeds act as confined aquifers, transmitting water within the CRBG. One of these sedimentary interbeds, known as the Rattlesnake Ridge interbed, is a laterally extensive confined aquifer on the Site, and lies near the top of the CRBG (Spane and Vermeul, 1994). The CRBG comprises generally dense, impermeable basalt that have more permeable top and bottom portions. Zones between the basalt flows and the sedimentary interbeds are commonly water-bearing and are used as water sources near the Site. Hydrologic connection between the basalt aquifers and the surficial aquifer occurs along faults that bring a water-bearing interbed in contact with overlying sediments, or where the basalt flows have been eroded down to an interbed (Dirkes and Hanf, 1995).

5.2 Groundwater Flow

Unconfined aquifer

Most of the groundwater investigations and remediation efforts at the Site have focused on the unconfined aquifer because it is the shallowest aquifer and therefore assumed to be the primary aquifer contaminated by Site activities. In this aquifer, groundwater is recharged in the upland areas and flows toward the Columbia River. A generalized water table elevation map is shown in Figure 5.5 (Hartman and Webber, 2008). Groundwater in the unconfined aquifer generally flows west to east in the southern part of the Site toward the Columbia River, and in a more northerly direction toward the Columbia River in the northern part of the Site.

The water table is within the sands and gravels of the Hanford Formation throughout much of the Site (Figure 5.6). These high permeability sands and gravels result in low hydraulic gradients, particularly along the river to the north (100 Areas), and in the eastern Central Plateau area, including the 200 East Area. However, some areas to the west and east exhibit steep gradients, as a result of the relatively low permeability units in the Ringold Formation being present at the water table and higher topographic gradients in these areas (Hartman and Webber, 2008).

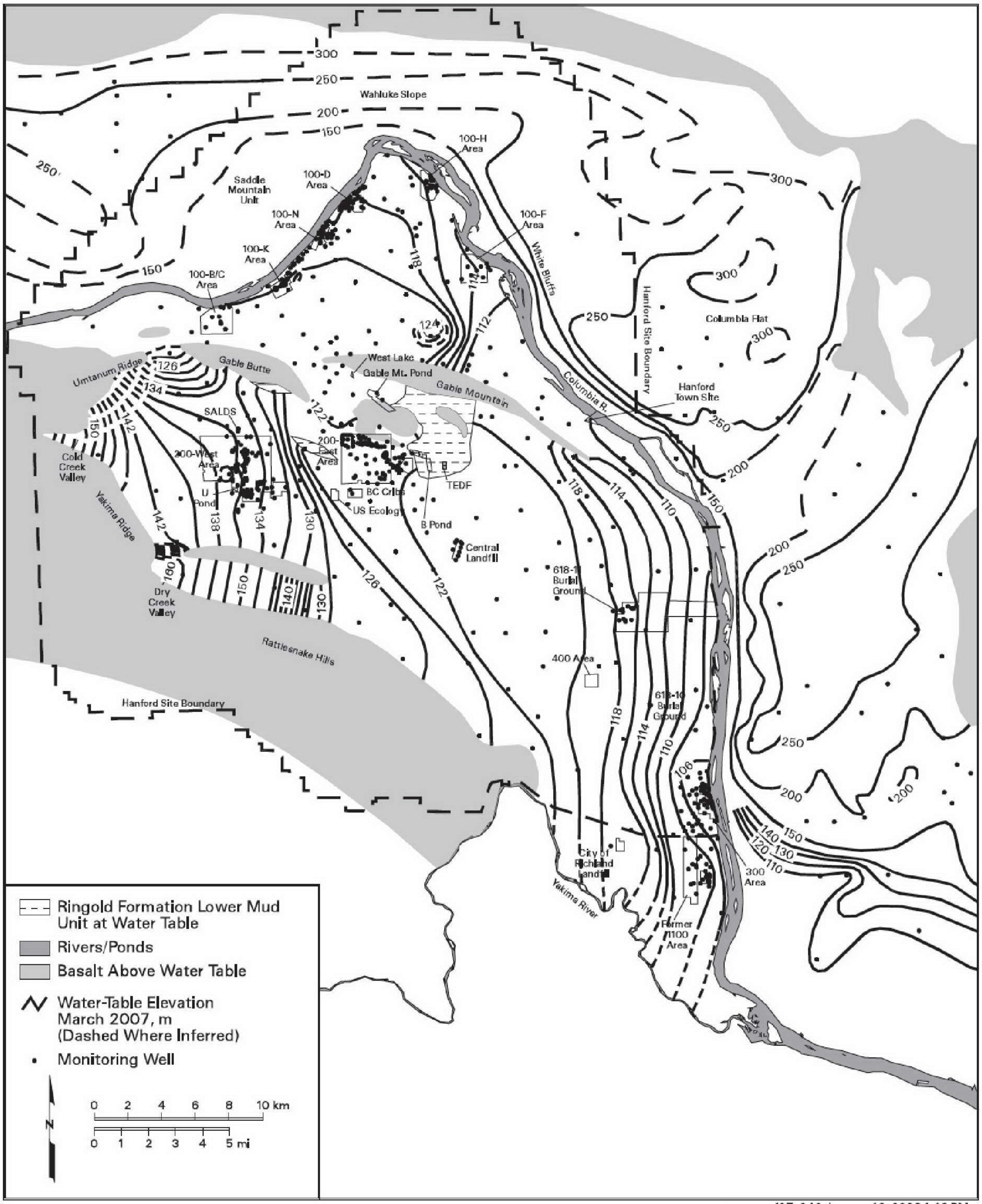


Figure 5.5. Water table at the Site and surrounding areas, March 2007.

Source: Hartman and Webber, 2008, Figure 2.1-2.

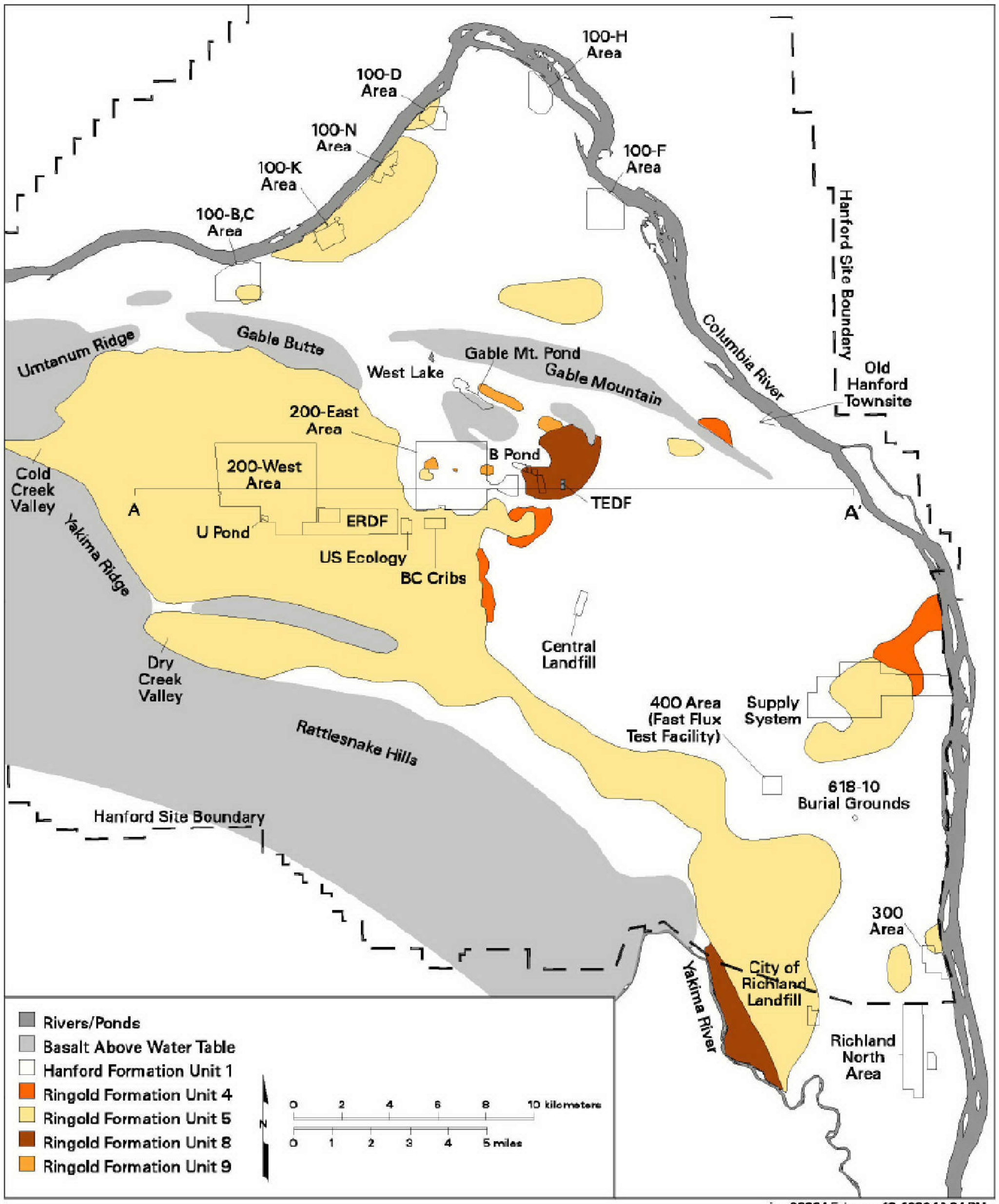


Figure 5.6. Geologic units in which the unconfined aquifer resided in 1999.

Source: Bryce et al., 2002, Figure 7.5.

The highest hydraulic conductivities are generally in the Central Plateau area and north of Gable Mountain, where the water table lies within the Hanford Formation gravels. The hydraulic conductivity in the unconfined aquifer exceeds 50 m/d across the majority of the Site (Figure 5.7).

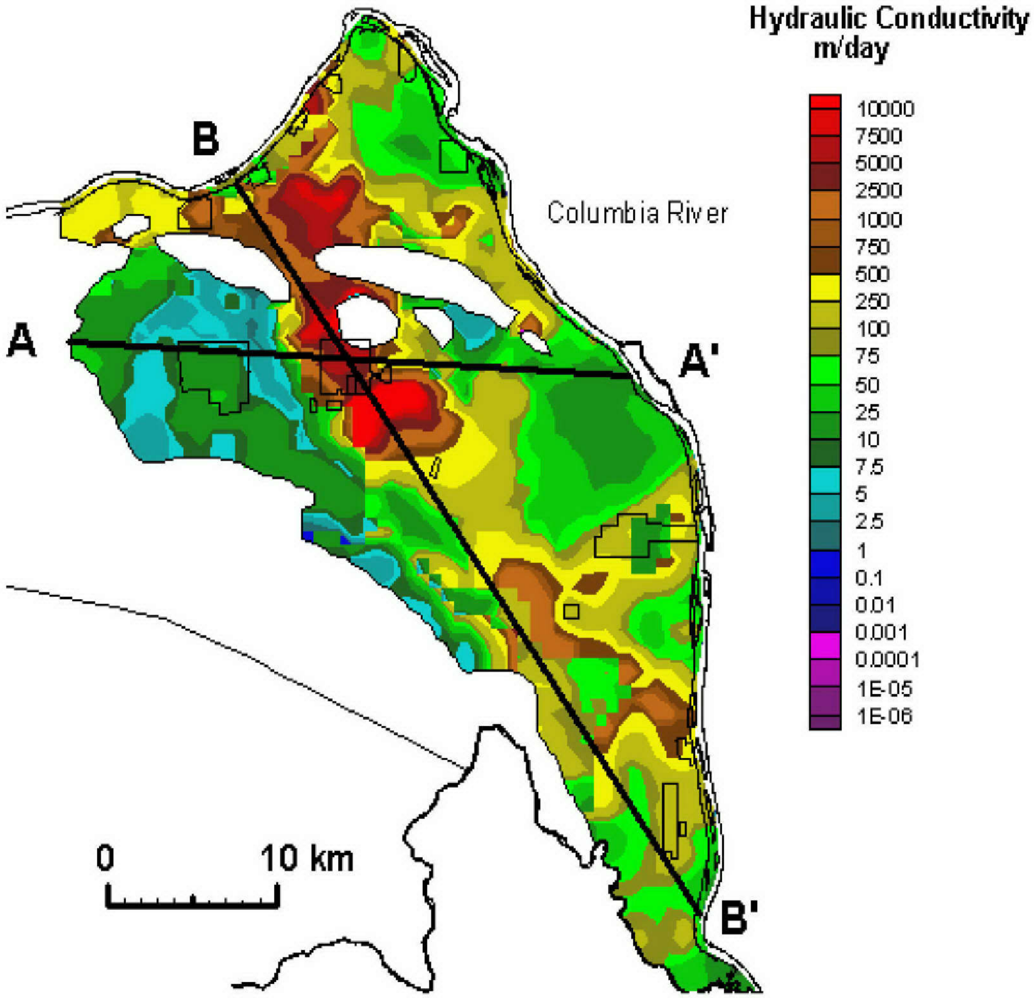


Figure 5.7. Distribution of estimated hydraulic conductivities at water table from best-fit inverse calibration of Site-wide groundwater models. The cross sections shown are discussed in the original document, but those discussions are not included in this generalized groundwater CSM.

Source: Bergeron and Freeman, 2005, Figure 2.4 (based on Cole et al., 2001).

The saturated thickness of the unconfined aquifer is largely unknown across the Site. Most wells were not completed to an underlying aquitard, and thus the aquifer thickness is not known. Groundwater plume data from the unconfined aquifer generally specify that the reported contaminant concentrations are from the top of the aquifer (e.g., Hartman and Webber, 2008).

Central Plateau

Under current conditions, groundwater in the northern and central parts of the 200 West Area generally flows from west to east, although a component of the flow from the 200 West Area is directed through Gable Gap (Hartman and Webber, 2008). The water table and most of the groundwater flow in this area are in the sands and gravels of the upper Ringold Formation. Beneath this unit, the lower Ringold Formation mud unit forms a confining layer that separates the unconfined aquifer from the underlying basalts (Horton, 2007).

Historic mounding of the water table in this area resulted from liquid waste discharges to groundwater. Artificial recharge due to liquid waste discharge in the past was up to three times the natural recharge (Thorne et al., 2006), creating a groundwater mound approximately 20 meters higher than pre-Hanford conditions. Steeper hydraulic gradients resulting from this recharge in the past caused groundwater to move more quickly in these areas. This mounding has dissipated in the years since the 1970s, when effluent discharge rates decreased substantially (Figure 5.8). However, mounding relative to pre-Hanford conditions is still estimated to be as high as ~11 meters in some areas (Figure 5.9; Hartman and Webber, 2008). Continued dissipation of the groundwater mound in the 200 West Area is likely to continue changing groundwater flow patterns here. Groundwater modeling suggests that this mound will never fully dissipate; however, it remains unclear whether this model prediction reflects a shortcoming of the model assumptions or a real change in hydrologic conditions since pre-Hanford times. Hence, there are uncertainties associated with future flow directions and the portioning of flow to the north and to the east. Currently, groundwater flow patterns in the 200 West Area are also influenced by discharges from the State-Approved Land Disposal Site (SALDS) and a pump-and-treat remediation system (Hartman and Webber, 2008).

Groundwater flow in the 200 East Area is significantly affected by the presence of a buried flood channel, which creates a preferential flow path in a northwest to southeast orientation (Williams et al., 2002). The water table in this area is within the high permeability units of the Hanford Formation, and the gradient currently is nearly flat. Groundwater flow in this region is also influenced by the local presence of low permeability sediment (i.e., muds) of the Ringold Formation at the water table east and northeast of the 200 East Area, as well as basalt exposures above the water table. These features constitute local barriers to groundwater flow (see Figure 5.4; Hartman and Webber, 2008). Whereas the Ringold lower mud is present beneath most of 200 West Area, it has been eroded away beneath almost all of the 200 East Area. Thus the unconfined aquifer extends from the water table to the top of basalt (Horton, 2007).

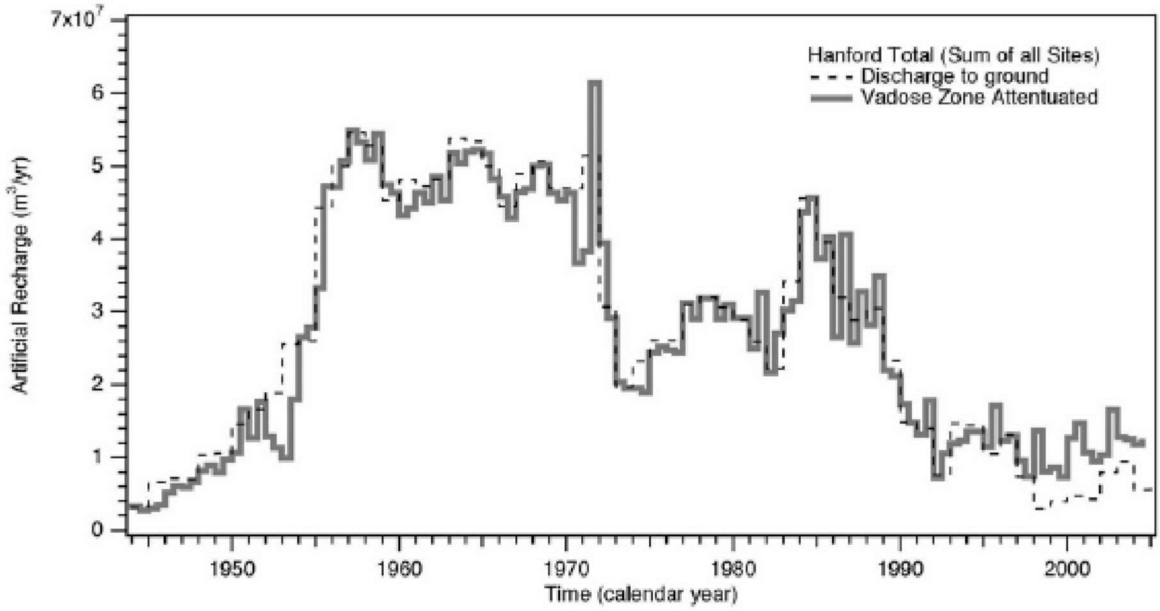


Figure 5.8. Artificial recharge to the unconfined aquifer from Site activities, 1944–2005.

Source: Eslinger et al., 2006, Figure 3.12.

Groundwater enters the 200 East Area and vicinity from the west and southwest, as well as from beneath the mud units to the east and the underlying aquifers where the confining units have been removed or thinned by erosion. At 200 East, the flow of water divides, with some migrating to the north through Gable Gap and some moving southeast toward the central part of the Site (see Figure 5.5; Hartman and Webber, 2008).

The water table to the northeast of the 200 East Area is essentially flat (i.e., measured water levels only varied by 4 centimeters across the area in 2007, within the uncertainty of the measurements), so it has been difficult to determine groundwater gradients or velocities (Hartman and Webber, 2008). Various groundwater conceptual models are currently being evaluated for this area. In the southern parts of the 200 Area, groundwater flow in the uppermost unconfined aquifer is to the east (see Figure 5.5). Flow directions have generally changed from southeast in the 1980s to east over time.

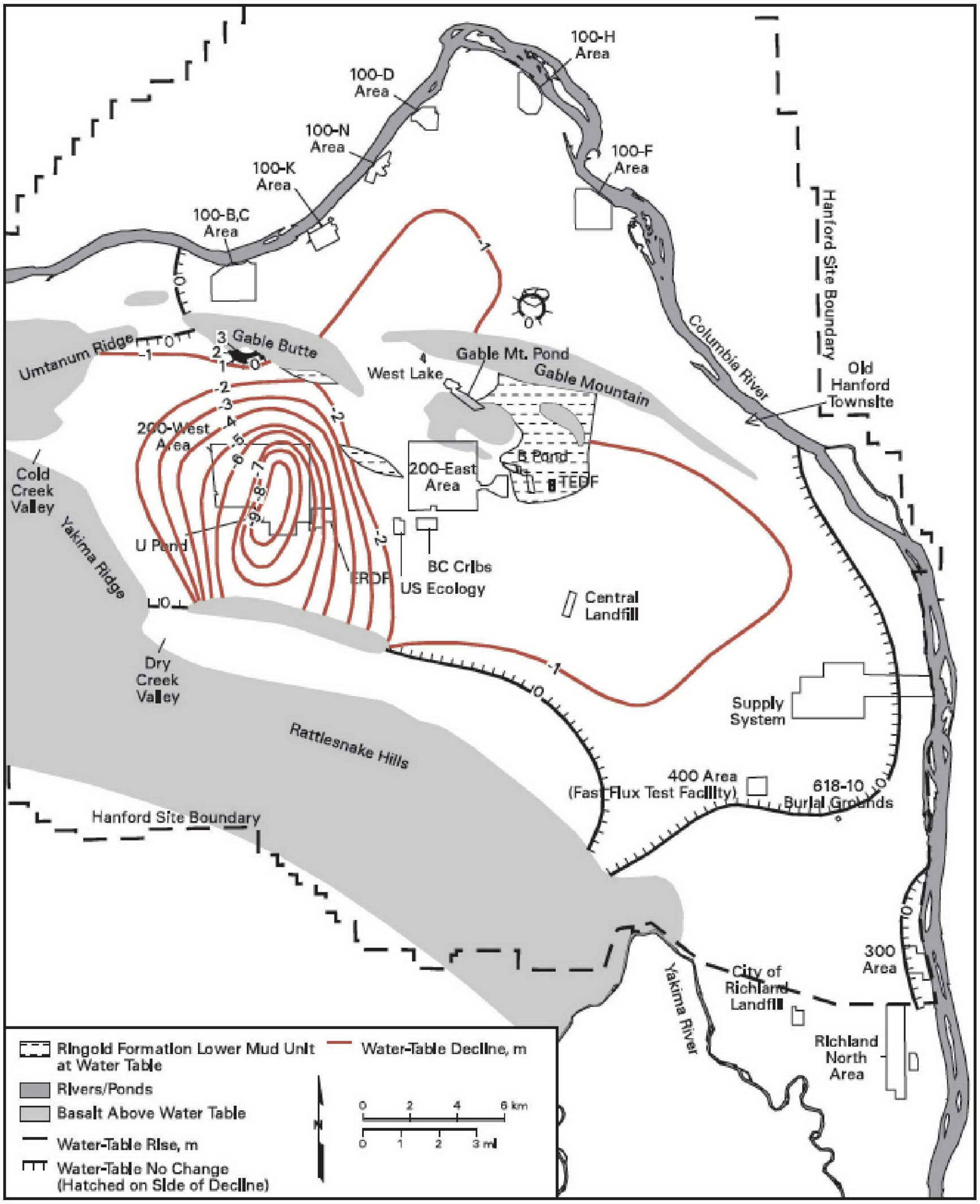


Figure 5.9. Changes in groundwater elevation in the unconfined aquifer, 1970s to present.

Source: Hartman and Webber, 2008, Figure 2.1-4.

Much of the area between the 200 East Area and the Columbia River comprises the 200-P0-1 operable unit. Groundwater in the unconfined aquifer in this area generally flows southeastward in the west portion of the operable unit and northeastward, eastward, and southeastward in the east portions of the operable unit, as groundwater approaches the Columbia River. Groundwater flow is primarily in the high permeability Hanford Formation, but in places the Ringold Formation is present at the water table (see Figure 5.6).

River Corridor area

The depth to the water table along the River Corridor generally ranges from ~1 meter to ~20 meters (Hartman, 2000). The water table is typically in the Hanford Formation along the river, but locally occurs within the Ringold Formation, as in the 100 Areas in the northwestern part of the Site (see Figure 5.6). Groundwater flow in the River Corridor areas is, and has historically been, directed from the Site northward and eastward toward the river. Groundwater flow modeling for the Site indicates that an average of 31,000,000 cubic meters per year (35 cfs) of groundwater was discharged to the Columbia River along the Hanford Reach between 1944 and 2000 (Peterson et al., 2007).

Pump and treat systems installed to treat groundwater contamination along the River Corridor create localized water table depressions, and groundwater injection systems have created localized groundwater mounding. Locations where pump and treat systems currently influence groundwater flow include the 100-K, 100-D, and 100-H nuclear reactor areas. Locations where groundwater mounding historically occurred due to infiltration of process waters include the 100-K, 100-N, 100-D, and 100-H areas. Mounding associated with landfill operations is also reported to have occurred in the 1100 Area (Hartman and Webber, 2008). These activities have created localized changes in groundwater flow directions over the history of plant operations, sometimes pushing or pulling portions of contaminant plumes away from the river. However, the overall regional pattern of groundwater flow in the unconfined aquifer system is northward and eastward toward the river. The installation of reactive permeable barriers and flow barriers in groundwater remediation sites has slowed groundwater velocity and altered flow directions. As localized groundwater mounds dissipate, hydraulic gradients are likely to turn back towards the river. In addition, changes in river stage due to water control activities on the Columbia River lead to temporal changes in the magnitude and direction of hydraulic gradients, discussed in more detail below.

Along the eastern side of the Site adjacent to the Columbia River (300 Area), groundwater flow converges and then moves east toward the river (Hartman and Webber, 2008). Sediments overlying basalt bedrock in the 300 Area consist primarily of the Ringold Formation, the Hanford Formation, and a thin veneer of wind-blown and Columbia River deposits. Reports based on aquifer testing in 300 Area wells indicate average hydraulic conductivity values of 14,000 m/d for the Hanford Formation gravels, and 125 m/d for the underlying Ringold Unit E gravels and associated sands (Peterson et al., 2005; Fritz et al., 2007). The water table aquifer is within high permeability sands and gravels of the Hanford Formation. Consequently, the gradients in the 300 Area are low, and groundwater flow velocities can be high (15 m/d; Vermeul et al., 2007).

Groundwater flows south- and eastward in the southern 1100 Area, away from the Yakima River and toward the Columbia River. The Yakima River recharges groundwater in this area. In the northern part of the 1100 Area, southerly regional flow converges with groundwater from the 300 Area before discharging to the Columbia River. The City of Richmond's recharge ponds create a local groundwater mound in the east-central part of the 1100 Area, which splits the overall eastward flow of groundwater to the north and south of the eastern central 1100 Area (Hartman and Webber, 2008).

Because flow in the Columbia River is controlled along the Hanford reach by upstream dams, rapid changes in river level are common. Releases from dams upstream of the Site can result in water level changes on the order of meters in the span of a few hours. These river level changes strongly influence flow in the hyporheic zone, forcing water from the river into the adjacent riverbank during high flows and flushing it back out during low flows. Thus, the hyporheic zone serves as a bank storage mixing zone of surface water and potentially contaminated groundwater (Fritz et al., 2007).

The changes in groundwater chemistry that result from these water level fluctuations could have substantial implications for the mobilization of contaminants from groundwater to the river, or for contamination of vadose zone soils due to episodic contact with contaminated groundwater (Fritz et al., 2007). In addition, flushing of contaminants by river water could influence the characterization of concentrations of dissolved constituents reaching the river by diluting the concentrations in groundwater prior to sampling.

Confined Ringold aquifer

Few wells are completed in the Ringold confined aquifer. Information on groundwater flow patterns in the confined Ringold is available only for portions of the Central Plateau, including the 200 Areas and the inactive B Pond system. The available data on groundwater elevations in the confined Ringold aquifer suggest that groundwater flow is generally from west to east in the 200 West Area (Figure 5.10). In the 200 East Area, it appears that flow in the Ringold Formation confined aquifer converges from the west, south, and east before discharging to the unconfined aquifer where the confining mud is absent (Hartman and Webber, 2008). However, these inferences are based on very limited monitoring well information, and the conceptual model is incomplete.

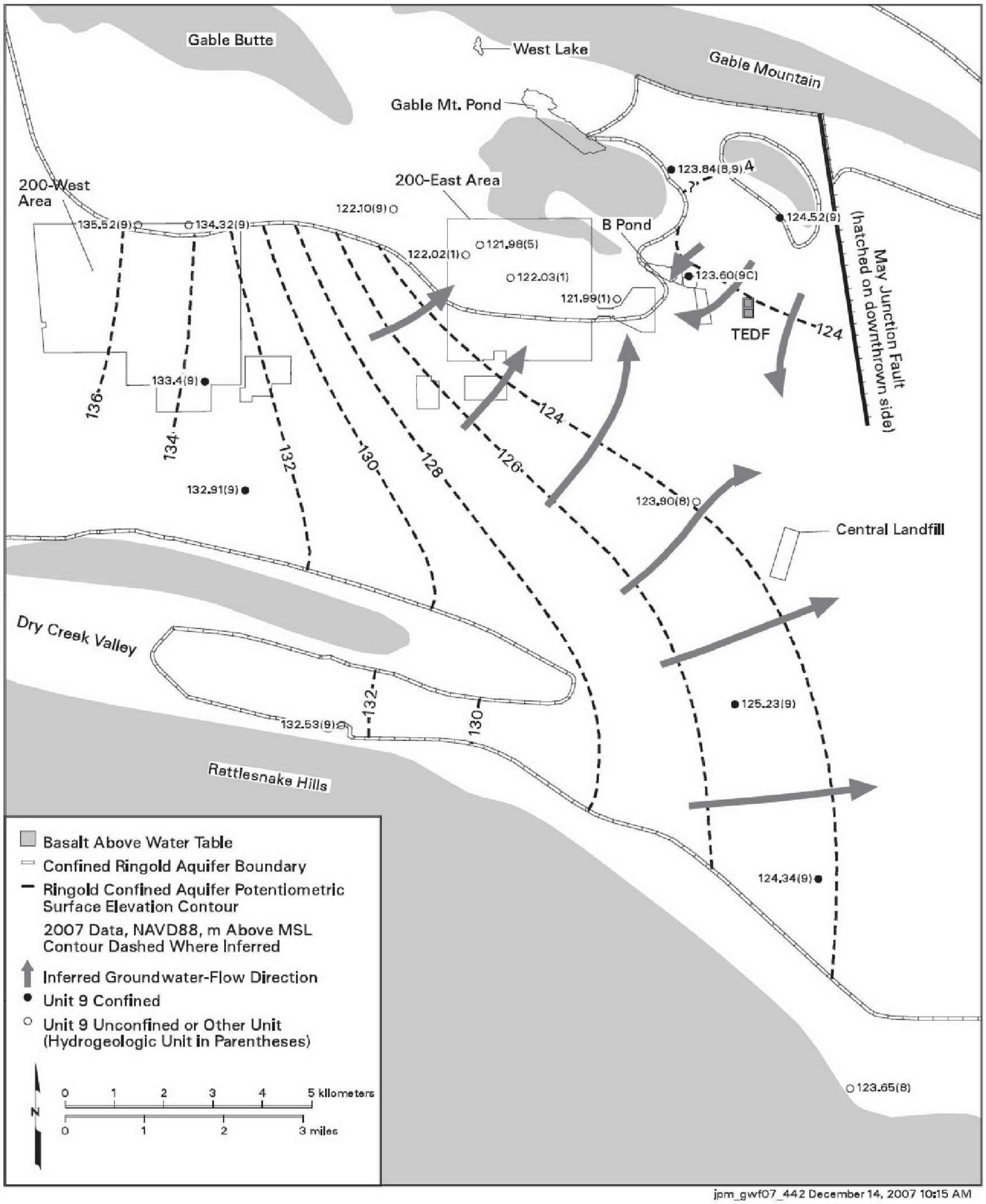


Figure 5.10. Potentiometric surface of Ringold confined aquifer, 2007.

Source: Hartman and Webber, 2008, Figure 2.14-2.

The confining unit within the Ringold Formation is absent in parts of the Site, resulting in hydraulic communication between the lower and upper Ringold aquifers. The confining unit is demonstrably absent beneath the 200 West Area, where boring 299-W13-1 penetrated to bedrock without encountering any fine-grained confining units. This has allowed communication between the Upper and Lower Ringold units, including transport of a carbon tetrachloride plume into the lower Ringold Formation.

Confined basalt aquifer

Many of the basalt layers have low permeability, and significant groundwater flow occurs only within basalt fractures and joints, interflow contacts, and sedimentary interbeds within the upper Saddle Mountains Basalt. Three primary interbeds have been identified at the Site. The thickest and most widespread sedimentary unit in this system is the Rattlesnake Ridge interbed, which is present beneath much of the Site, although groundwater also occurs within the Levey interbed, which occurs only in the south portion of the Site and in an interflow zone within the Elephant Mountain Member of the upper Saddle Mountains Basalt (Hartman and Webber, 2008).

Groundwater flow in the confined basalt aquifers is generally from northwest to southeast across the Site. Recharge to the basalt aquifer occurs from infiltration in areas where permeable units within the basalts crop out at the surface, and may also locally recharge from the Yakima River along the southwestern edge of the Site (Hartman and Webber, 2008). Discharge of groundwater from the basalt aquifer to the Columbia River occurs in the southeastern portion of the Site, but does not appear to occur in other parts of the Site (Spane and Raymond, 1993). Discharge from basalts may also recharge the unconfined aquifer near Gable Butte, where basalt layers have been eroded away (Hartman and Webber, 2008). Vertical hydraulic gradients between the confined basalt aquifer and the overlying unconfined units are typically downward in the northern and western parts of the Site, and upward to the south and east (Hartman et al., 2009).

Intercommunication between the upper basalt-confined aquifer and the overlying sedimentary aquifer system may occur where there is a pathway for the movement of water as well as a difference in hydraulic head between the two systems. The 200 Area Central Plateau meet these criteria. For example, communication between the Basalt and Ringold aquifers is believed to occur directly to the north and east of the 200 East Area, where there are downward hydraulic gradients, and where the uppermost basalt layer appears to be absent (Hartman et al., 2009). In the Gable Gap region, upward hydraulic gradients and a missing Elephant Mountain Basalt member suggest that bedrock groundwater discharges back to the overlying aquifer (Hartman et al., 2009).

5.3 Groundwater and Vadose Stressors

The vadose zone and groundwater have been exposed to stressors at the Site. These include hazardous substances and their by-products released from Site operations (operational stressors, or primary stressors), hazardous substances and by-products released from contaminated resources (secondary stressors), as well as response actions that cause unavoidable injuries to natural resources (response action stressors). As described in Chapters 3 and 4, these stressors include but are not limited to liquid and process waste sources, solid waste sources, air emissions, and response action stressors.

Liquids and process waste sources that are known or suspected of releasing hazardous substances to the vadose zone and groundwater include:

- Liquid waste injection (reverse) wells
- Surface impoundments, including cribs, trenches, French drains, retention basins, and ponds
- Underground radioactive liquid waste storage tanks in the 200 and 300 areas
- Waste evaporators and evaporation basins
- Liquid chemical containers and distribution infrastructure (e.g., pipelines) associated with Site operations
- Liquid chemical containers (e.g., PCB storage tanks) and distribution infrastructure associated with general site maintenance
- Underground storage tanks for gasoline and diesel, and other transportation sources
- Episodic events, including spills, leaks, and explosions from Site facilities.

Leaching from solid waste sources likely also released hazardous substances to the subsurface. Examples include, but are not limited to:

- Burial grounds
- Failed equipment and other solid wastes stored in railcars in closed off areas and tunnels
- Operational facilities, including buildings, pipelines, and other support infrastructure
- Landfills and other waste facilities.

Releases of hazardous substances from other natural resources (secondary sources) have also likely adversely affected the vadose zone soils and groundwater resources. Releases from air emissions, including stacks and waste incinerators and open burn pits associated with historical nuclear operations; other Site operations sources such as electric and diesel generators; episodic (accidental) events, such as explosions and fires, as well as wildfires; and intentional releases, such as the Green Run, may have deposited hazardous substances on surface soils, which then may have been carried into the vadose zone and groundwater by infiltrating precipitation. As previously mentioned, the vadose zone and groundwater may also be secondary sources to each other as well.

Response actions may also result in adverse effects to the vadose zone and groundwater. The treatment of groundwater and vadose zone soils may inadvertently facilitate the transport of hazardous substances. For example, pump and treat and re-injection systems that are designed to treat a specific contaminant such as strontium-90 may inadvertently transport and disperse another contaminant, such as tritium. Hazardous substances transported through treatment systems may then cause additional injuries to the groundwater where they are re-injected, and may also expose other resources at the location of re-injection. Groundwater mounding from pump and treat injection alters the flow scheme locally, which may redirect contaminant plumes into less contaminated or uncontaminated aquifers. Response actions may also result in the physical disruption of habitat. Furthermore, institutional controls, such as restricted access to lands and groundwater, may also cause long term service loss from the vadose zone and groundwater.

5.4 Contaminant Transport Pathways

Vadose zone

As described in the pathways CSM (Chapter 4), numerous factors may influence the transport of hazardous substances in the vadose zone, including the amount of water present, the physical and chemical properties of the soils and of the hazardous substances. Examples of physical characteristics of the vadose zone soils that may influence infiltration include: horizontal and vertical heterogeneities and discontinuities (including horizontal caliche layers and vertical clastic dikes); soil moisture/vapor pressure/presence of nonaqueous phases; grain size distribution; soil mechanics (disturbed versus undisturbed); permeability; shallow preferential pathways caused by roots and burrowing animals; natural and enhanced (artificial) recharge, and response actions (e.g., soil vapor extraction). There are also numerous biogeochemical processes and properties of contaminants, soils, and pore water that can affect contaminant transport; these are also described in further detail in Chapter 4.

Groundwater

Hazardous substances have reached groundwater via infiltration from the overlying vadose zone, surface water/groundwater interactions through the hyporheic zone, and direct discharge to groundwater through waste injection (reverse) wells. Some of the primary aquifer characteristics that influence the transport of hazardous substances through groundwater are described in the pathways CSM (Chapter 4) and include hydraulic conductivity, porosity, hydraulic gradient, saturated thickness, and areal extent of the geologic units (aquifer continuity). Groundwater flow direction, dispersion (spreading) of contaminants, dilution (mixing due to advection and diffusion) of contaminants with clean groundwater, and inter-aquifer connectivity/confinement will also influence contaminant migration.

Historical mounding from infiltration and injection of liquid wastes and process waters, as well as mounding and cones of depression from pump and treat and re-injection systems, influence groundwater gradients and flow directions and thus contaminant transport. Mounding can cause steeper groundwater gradients, increasing flow rates, as well as change groundwater flow direction. Perched groundwater in the vadose zone can result in greater lateral distribution of contaminants than would otherwise be predicted, and may also act as a secondary source, or "delayed yield" to groundwater. Other factors that likely influence contaminant migration at the Site include surface water – groundwater interactions, vertical gradients, and biogeochemical processes (see Chapter 4).

5.5 Exposure to Stressors

Vadose zone soils and groundwater resources at the Site have been exposed to and possibly injured by site stressors, including the historical operations and ongoing response actions described in Section 5.3. Here we present a summary of vadose and groundwater contamination at the Site, as presented primarily in DOE annual groundwater reports. These reports present delineations of the current estimated spatial extent of contaminant plumes at the Site, based on exceedences of drinking water standards, or, for plumes in the River Corridor, aquatic life criteria. The reproduction of current conditions from the DOE reports is meant to be illustrative, providing information to help the Trustees assess groundwater injuries. The contaminant plumes depicted in this section do not represent Trustee consensus of the spatial extent of groundwater contamination or groundwater injury. It is anticipated that the groundwater injury assessment will assess both the spatial and volumetric extent of contaminated groundwater, as well as contaminant concentrations that represent groundwater injury and service loss, and the past and future extent of injury.

The plumes in the DOE reports are identified using average contaminant concentrations in wells. The contaminant plumes encompass areas where the concentration of a contaminant is above that of drinking water standards, with two exceptions. For chromium, the plume was delineated in the 100-B, 100-K, 100-H, and 100-F areas using a cleanup level of 20 micrograms per liter (μg/L), which was established based on aquatic criteria, rather than the drinking water standard of 100 μg/L. For tritium, the 200 East Area plume was delineated based on an 80,000 picocuries per liter (pCi/L) concentration threshold rather than the drinking water standard of 20,000 pCi/L (Hartman and Webber, 2008). The Trustees may choose to use other methods to delineate groundwater plumes and the extent of groundwater injuries in the injury assessment (see Section 5.6 for a discussion of potential injury definitions).

Using the above approaches, the most recent estimate of the total surface area of the plumes on the Site is ~183 square kilometers (71 square miles) (Hartman et al., 2009). The largest of these plumes are tritium (Figure 5.11) and iodine-129 plumes that extend east and southeastward from the 200 East Area on the Central Plateau (Hartman et al., 2009). Large nitrate plumes originate in the 100-F, 200 West, and 300 Areas. Cyanide, carbon tetrachloride, strontium-90, technetium-99, trichloroethene, and uranium are present in smaller plumes at the Site, primarily sourced in the 200 and 100 areas.

Central Plateau area

Groundwater contamination beneath the 200 West Area includes large plumes of carbon tetrachloride, chromium, iodine, nitrate, and tritium, and smaller plumes of technetium-99, trichloroethene, and uranium. Table 5.1 lists Hartman and Webber's (2008) estimate of the extent of contaminant plumes in the Central Plateau area, while Figures 5.12 and 5.13 show these estimated radioactive and non-radioactive plumes, respectively.

Because of pump-and-treat remediation activities in the 200 West Area, Hartman et al. (2009) reports that some of the plumes beneath this area may have decreased in size and/or concentration through time. For example, they report that the technetium-99 plume in the 200 West Area decreased in size between 1995 and 2008. Other plumes have changed less substantially through time, and others may be growing (Hartman et al., 2009).

Contamination beneath the Central Plateau is dominated by two large plumes of tritium and iodine-129 that extend east from the 200 East Area (Figure 5.11). Other plumes beneath the 200 East Area include nitrate and technetium-99, with smaller plumes of strontium-90, cyanide, and uranium (Table 5.1).

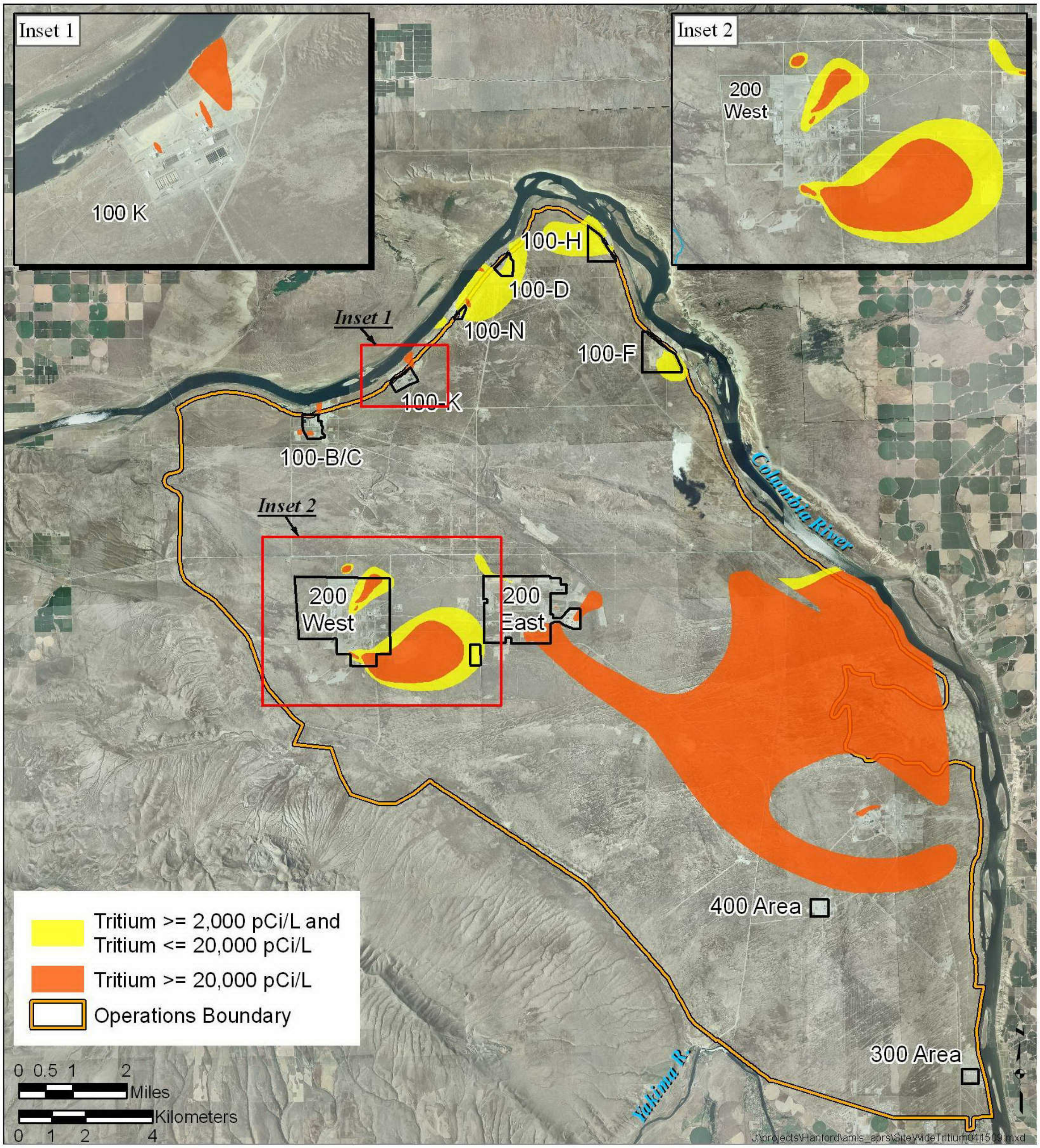


Figure 5.11. Estimated extent of tritium plumes on the Site, fiscal year 2007.

Sources: Hartman and Webber, 2008; CHPRC, 2009.

Table 5.1. Estimated areal extent of (and maximum contaminant concentrations in) groundwater plumes in the Central Plateau area in fiscal year 2007 based on DOE reports

Contaminant (concentration)	Total area of plumes (km^2)	Maximum concentration	Areas
Cyanide ≥ 200 μg/L	0.07	3,990 μg/L	200 East
Iodine-129 ≥ 1 pCi/L	64.41	45.4 pCi/L	200 East, 200 West
Nitrate ≥ 45 mg/L	17.88	8,630 mg/L	200 East, 200 West
Strontium-90 ≥ 8 pCi/L	0.66	4,130 pCi/L	200 East
Technetium-99 ≥ 900 pCi/L	2.31	113,000 pCi/L	200 East, 200 West
Tritium ≥ 20,000 pCi/L	125.79	1,760,000 pCi/L	200 East, 200 West
Tritium ≥ 80,000 pCi/L	17.8	1,760,000 pCi/L	200 East
Uranium ≥ 30 μg/L	0.9	935 μg/L	200 East, 200 West
Carbon Tetrachloride ≥ 5 μg/L	10.1	3,400 μg/L	200 West
Chromium ≥ 100 μg/L	1.14	798 μg/L	200 West
Trichloroethene ≥ 5 μg/L	0.44	21 μg/L	200 West

Source: Hartman and Webber, 2008.

The estimated areal extent of the tritium plume has not decreased substantially through time, although the tritium concentrations in the core of this plume decreased between 1980 and 2008 (Hartman et al., 2009). German-Heins (2002) suggested that the tritium follows two major pathways from the 200 East Area, one toward the east and one toward the southeast. This study further suggested that transport times from the 200 East Area eastward to the Columbia River could be as short as two years.

Notable amounts of plutonium-239, cesium-137, cobalt-60, ruthenium-101, molybdenum, antimony, arsenic, mercury, and fluoride are also present beneath the 200 Areas (Dresel et al., 2002; Hartman and Webber, 2008). A uranium plume beneath the northwestern 200 East Area increased in size between 1997 and 2008 (Hartman et al., 2009).

River Corridor

Nearly all of the 100 Areas along the River Corridor have associated contaminant plumes, but the plume constituents vary from site to site. Because hydraulic gradients are directed towards the river through most of the River Corridor areas, most of these plumes lie between the nuclear reactor facilities and the Columbia River, as well as in the "horn" between the 100-D and 100-H reactors. Table 5.2 lists Hartman and Webber's (2008) estimate of the areal extent of contaminant plumes in the River Corridor area, while Figures 5.14 and 5.15 show these estimated radioactive and non-radioactive plumes, respectively.

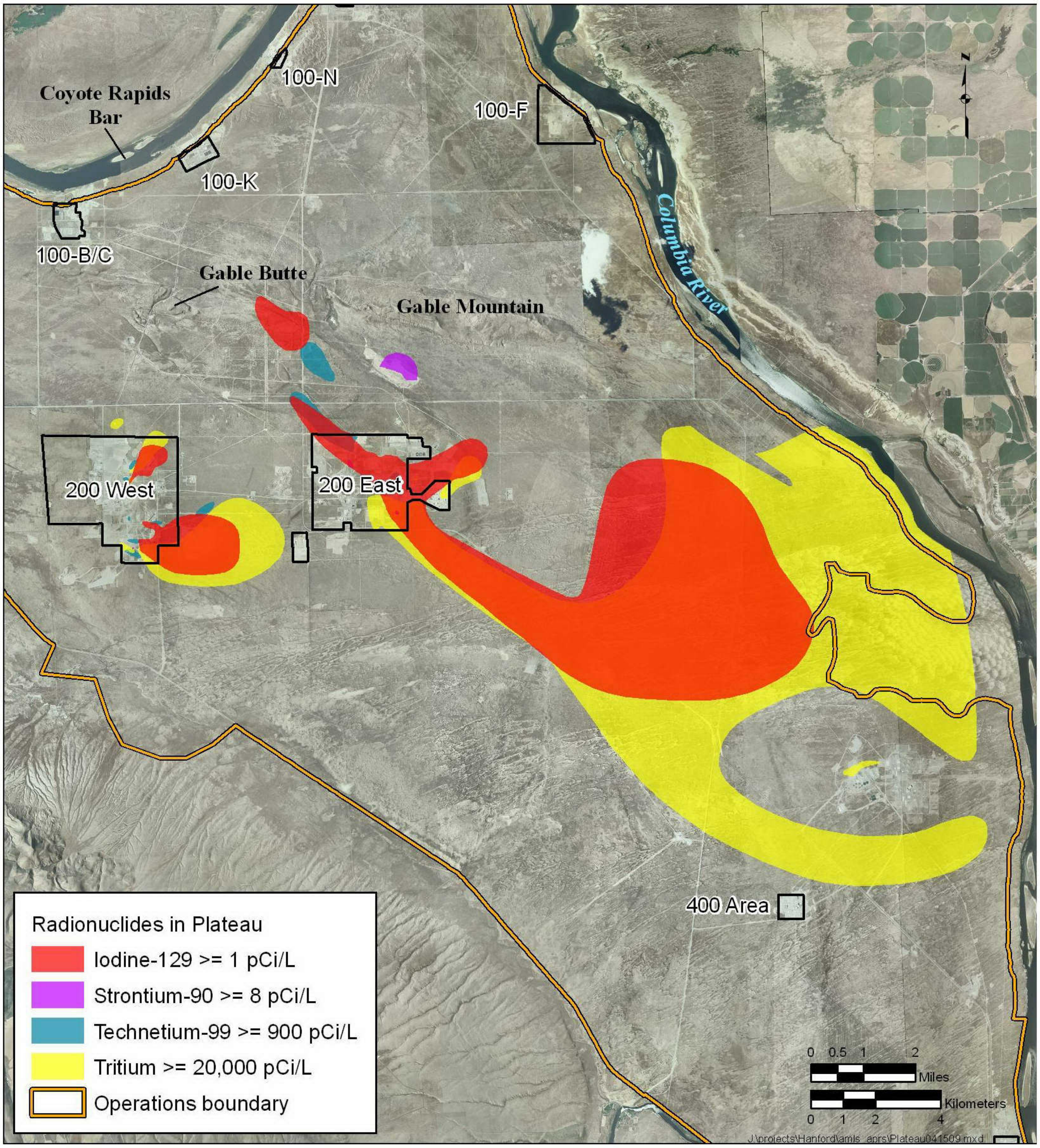


Figure 5.12. Estimated extent of radionuclide plumes beneath the Central Plateau area in fiscal year 2007.

Sources: Hartman and Webber, 2008; CHPRC, 2009.

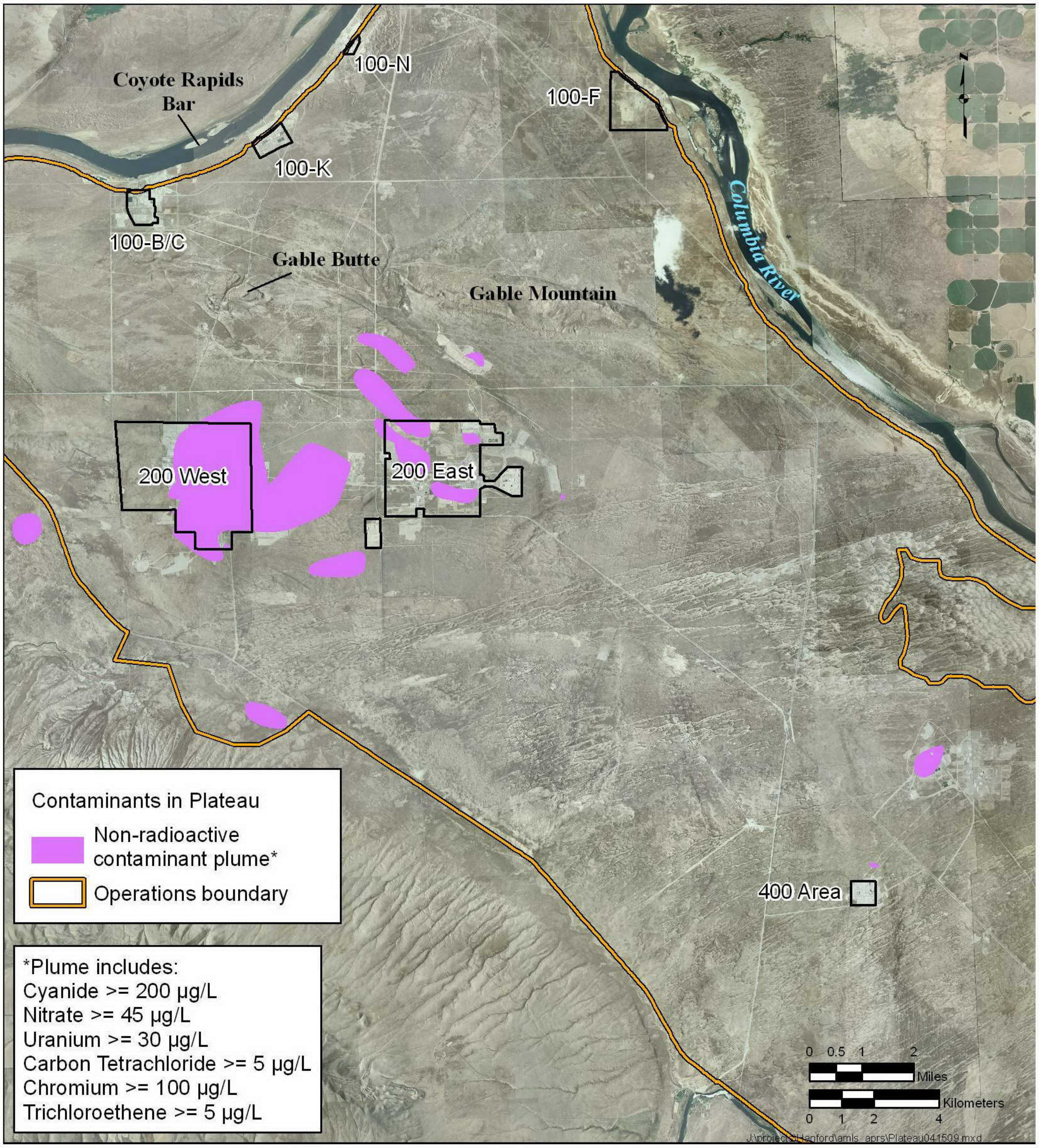


Figure 5.13. Estimated extent of non-radioactive plumes beneath the Central Plateau area in fiscal year 2007.

Sources: Hartman and Webber, 2008; CHPRC, 2009.

Table 5.2. Estimated areal extent of (and maximum contaminant concentrations in) groundwater plumes in the River Corridor area in fiscal year 2007 based on DOE reports

Contaminant (concentration)	Total area of plumes (km^2)	Maximum concentration	Areas
Uranium > 30 µg/L	0.05	218 µg/L	300 Area
Tritium > 20,000 pCi/L	0.74	1,060,000 pCi/L	300 Area, 100 Areas
Chromium ≥ 20 µg/L	10.29	7,290 µg/L	100 Areas
Chromium ≥ 100 µg/L	0.91	7,290 µg/L	100 Areas
Strontium-90 ≥ 8 pCi/L	1.04	757 pCi/L	100 Areas
Carbon-14 > 2,000 pCi/L	0.09	12,400 pCi/L	100 Areas
Nitrate ≥ 45 mg/L	18.57	294 mg/L	100 Areas
Trichloroethene ≥ 5 µg/L	2.2	3.3 µg/L	100 Areas

Source: Hartman and Webber, 2008.

Strontium-90 and chromium plumes are extensive, with concentrations that greatly exceed that of drinking water standards (8 pCi/L and 100 µg/L, respectively). Plumes containing tritium, carbon-14, nitrate, and trichloroethene are also present in this area. Other reported hazardous substances detected in groundwater in the 100 Area include technetium-99, sulfate, nitrite, chloroform, fluoride, iodine-129, petroleum hydrocarbons, carbon tetrachloride, methylene chloride, manganese, iron, antimony, and arsenic (Hartman and Webber, 2008).

Pump and treat systems purportedly have decreased the size and concentration of some of the contaminant plumes in the 100 Areas, including the chromium plumes beneath the 100-K and 100-H Areas. Treatment has been less effective and the River Corridor plume sizes and concentrations have remained relatively constant for other plumes, such as the strontium-90 plume in the 100-N Area (Hartman et al., 2009).

The 300 Area contains plumes of tritium and uranium. Table 5.2 lists contaminants that have been identified in the groundwater underlying the 300 Area, along with estimated plume size, potential source(s), and other information summarized by Hartman and Webber (2008). Tritium and uranium in these plumes exceed their applicable drinking water standards of 20,000 pCi/L and 30 µg/L, respectively (Hartman et al., 2009).

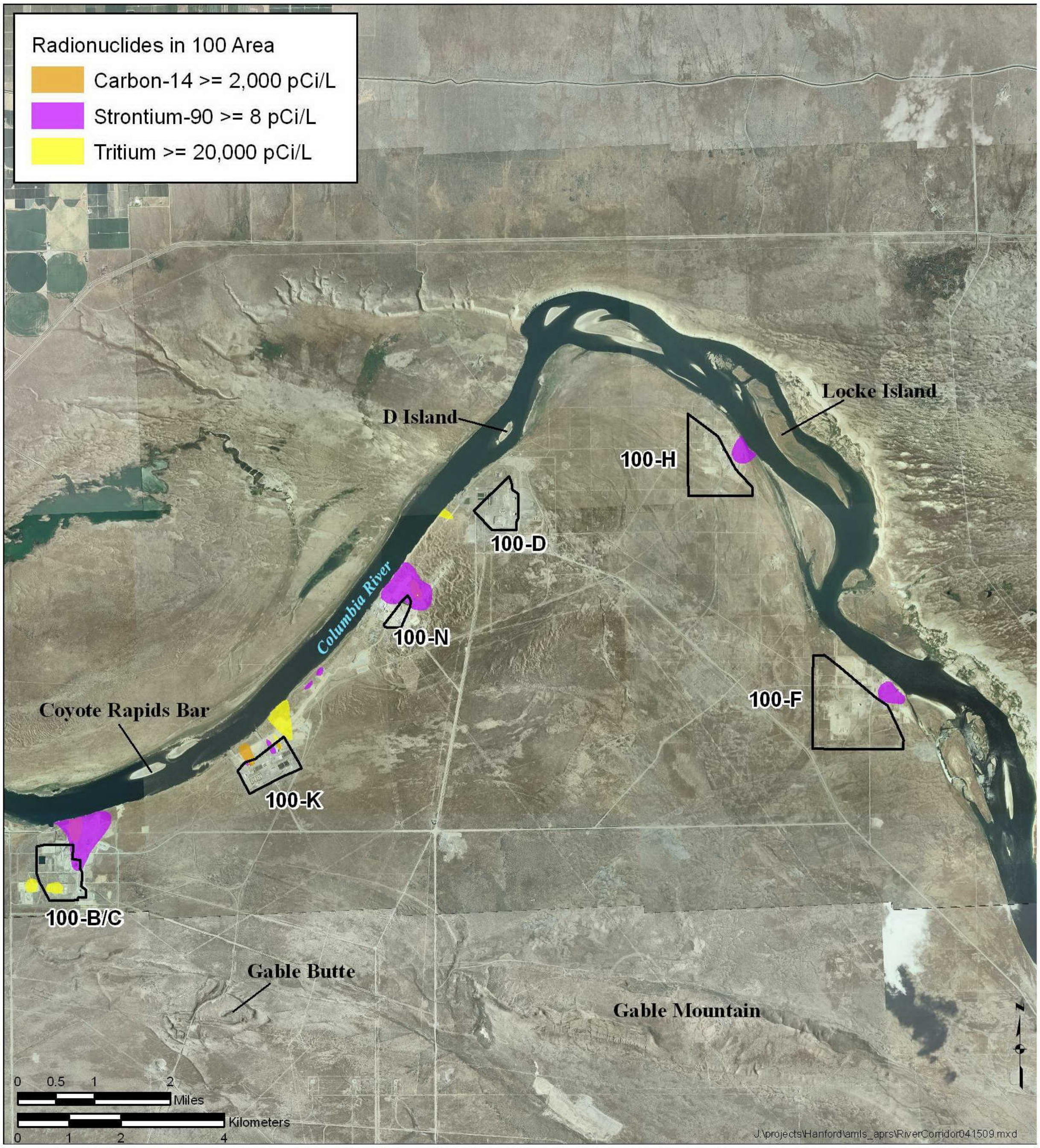


Figure 5.14. Estimated extent of radionuclide plumes beneath the River Corridor area in fiscal year 2007.

Sources: Hartman and Webber, 2008; CHPRC, 2009.

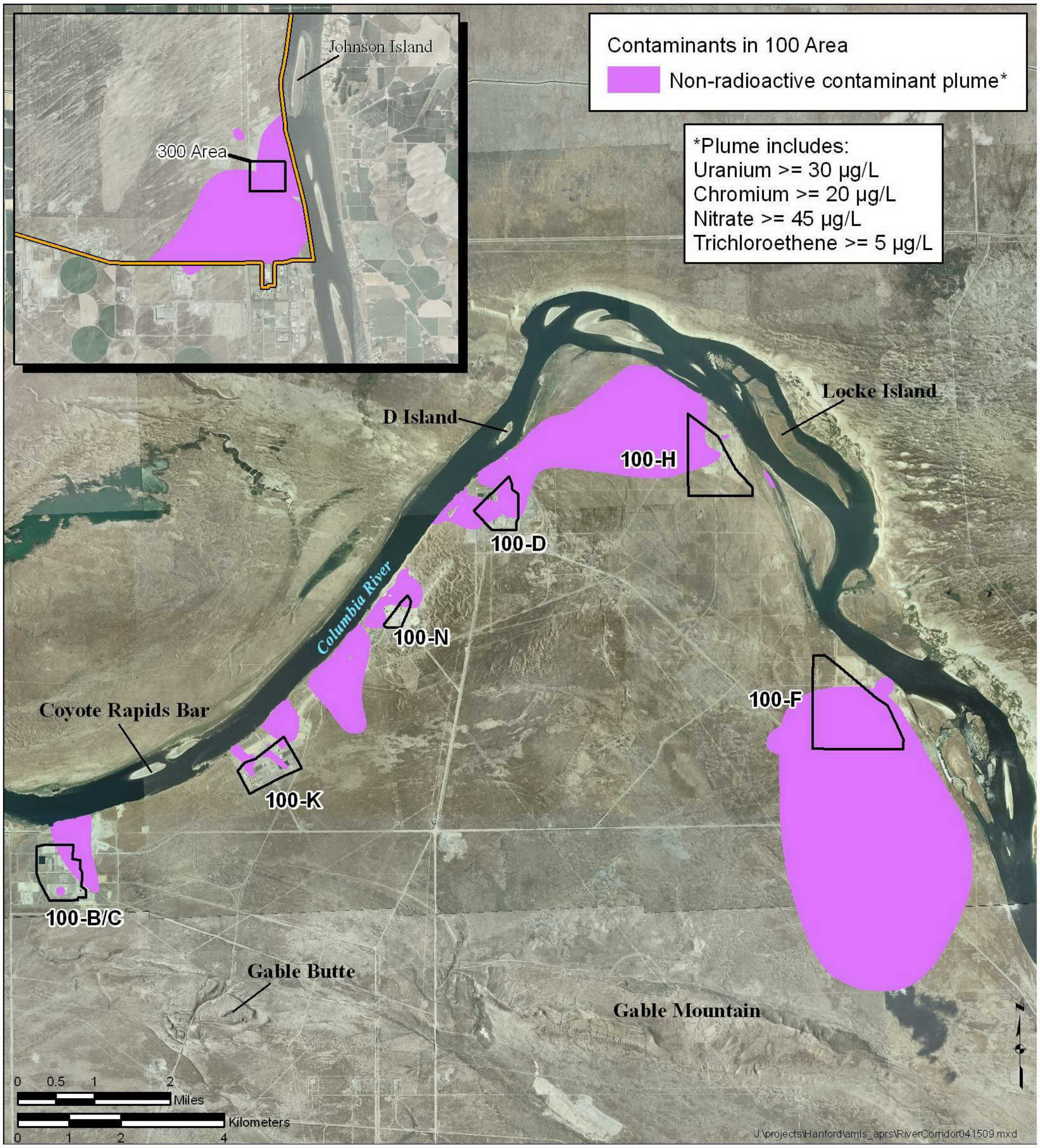


Figure 5.15. Estimated extent of non-radionuclide plumes beneath the Central Plateau area in fiscal year 2007.

Sources: Hartman and Webber, 2008; CHPRC, 2009.

Other contaminants identified in groundwater in the 300 Area (Hartman and Webber, 2008) include:

- Strontium-90
- Chlorine-36
- Cis-1,2-dichloroethene
- Tetrachloroethene
- Trichloroethene.

Measured concentrations for these hazardous substances have not exceeded drinking water standards, though this does not preclude the potential for injury.

In the 1100 Area, Hartman and Webber (2008) delineated a nitrate plume with concentrations exceeding 45 milligrams per liter (mg/L) over an area of 4.5 square kilometers. The maximum reported concentration for this plume is 536 mg/L. Other identified groundwater contaminants occurring at concentrations below drinking water criteria in this area include trichloroethylene, tritium, uranium, and technetium-99.

5.6 Potential Injury Definitions

As described above, this CSM addresses both saturated aquifer materials (groundwater resources) and the unsaturated vadose zone soils (geologic resources). The DOI regulations define groundwater resources as water in a saturated zone or stratum beneath the surface of land (including land below surface water), and the rocks or sediments through which groundwater moves [43 CFR § 11.14(t)]. Geologic resources, including unsaturated soils, are defined as elements of the Earth's crust such as soils, sediments, rocks, and minerals that are not included in the definitions of ground and surface water resources [43 CFR § 11.14(s)].

It is helpful to understand potential approaches to defining groundwater or vadose soil injuries when developing a CSM for an NRDA. The following sections discuss potential injury definitions for these resources. The potential injury definitions presented below include both injury definitions that are explicitly contained in federal regulations, as well as other potential injuries discussed during CSM planning workshops. This information is intended to assist the Trustees with assessment planning and does not represent a final or consensus list of injuries that will be assessed. Ultimate selection of injury definitions will be undertaken during development of injury assessment plans.

Groundwater injury

Regulatory definitions of injury to groundwater are listed below. Generally, these definitions state that groundwater is injured if hazardous substance concentrations exceed threshold concentrations established under the Safe Drinking Water Act (SDWA), Clean Water Act (CWA), or applicable state regulations.

- Concentrations and duration of hazardous substances in excess of drinking water standards as established by Sections 1411–1416 of the SDWA, or by other federal or state laws or regulations that establish such standards for drinking water, in groundwater that was potable before the release [43 CFR § 11.62(c)(1)(i)]

- Concentrations of substances in excess of water quality criteria, established by Section 1401(1)(d) of the SDWA, or by other Federal or State laws or regulations that establish such criteria for public water supplies, in ground water that before the discharge or release met the criteria and is a committed use . . . as a public water supply [43 CFR § 11.62(c)(1)(ii)]

- Concentrations of substances in excess of applicable water quality criteria, established by Section 304(a)(1) of the CWA, or by other Federal or State laws or regulations that establish such criteria for domestic water supplies, in ground water that before the discharge or release met the criteria and is a committed use as a domestic water supply [43 CFR § 11.62(c)(1)(iii)].

The applicable criteria for Washington State are the Ground Water Quality Standards [WAC 173-200]. These standards include a specific non-degradation criterion:

- Existing and future beneficial uses shall be maintained and protected. Degradation of ground water quality that would interfere with or become injurious to beneficial uses shall not be allowed [WAC 173-200-030 (2)(a)].

The implementation guidance for the Ground Water Quality Standards further specifies:

> At a minimum all ground water should be protected as a potential source of drinking water. Not all ground water is presently used for drinking water, nor do the standards presume that all ground water is suitable as a drinking water source. However, the Ground Water Quality Standards recognize the potential for future use of these sources to be used for drinking water purposes if other sources become diminished or the demand for water increases (Washington Department of Ecology, 2005, p. 17).

Thus, according to the above definitions, groundwater is injured if hazardous substance concentrations exceed SDWA, CWA, or Washington Ground Water Quality Standards [WAC 173-200-040]. Groundwater may also be injured if it is shown that releases of contaminants to groundwater interfere with or become injurious to beneficial uses of the groundwater, even if the concentrations of contaminants are below a prescribed injury threshold criterion.

The injury definition at 43 CFR § 11.62(c)(1)(i) specifies that groundwater must have been "potable before the release." No definition of potability is provided in either the Federal or the Washington [WAC 173-200] regulations. The implementation guidance for the Washington standards defines nonpotable groundwater as groundwater with "water quality which does not meet the drinking water standards, such that it is not suitable for human consumption" (Washington Department of Ecology, 2005, p. 122). This issue may require additional research as part of the injury assessment, although the data reviewed for this CSM do not indicate that groundwater from the Site was not potable before the release.

The injury definitions at 43 CFR § 11.62(c)(1)(ii) and (iii) specify that the groundwater must have been a "committed use" as a public or domestic water supply. In the DOI regulations, committed use means either an existing public use or a documented planned public use of the resource prior to the release [43 CFR § 11.14(h)]. Some of the past, present, and future committed uses of groundwater at the Site include:

- Drinking water supply
- Irrigation water
- Aquifer storage
- Fire suppression
- Geothermal/tropical fish rearing at McGee Ranch
- Assimilative capacity to treat contaminated water.

Finally, the DOI regulations also include an injury definition that acknowledges the role of groundwater as a secondary stressor:

- Concentrations and duration of hazardous substances sufficient to have caused injury to other resources when exposed to groundwater [43 CFR § 11.62(c)(1)(iv)].

Thus, according to the above definitions, groundwater is injured if hazardous substance concentrations are sufficient to injure another natural resource, regardless of whether those concentrations exceed a regulatory criterion.

Vadose soil injury

Vadose soils are geologic resources that can be injured by hazardous substance releases. The DOI regulations include several criteria that meet the definition of injury to geologic resources. Relevant definitions are summarized below.

- Concentrations of substances sufficient for the materials in the geologic resource to exhibit characteristics identified under or listed pursuant to Section 3001 of the Solid Waste Disposal Act (SWDA), 42 USC 6921 [43 CFR § 11.62(e)(1)].

The characteristics identified in this section of SWDA are "toxicity, persistence, and degradability in nature, potential for accumulation in tissue, and other related factors such as flammability, corrosiveness, and other hazardous characteristics" [42 USC § 6921(a)].

Vadose soils may also be injured if concentrations of substances are sufficient to:

- Raise the soil pH to above 8.5 or to reduce it below 4.0 [43 CFR § 11.62(e)(2)]
- Yield a salt saturation value greater than 2 millimhos per centimeter (mmho/cm) in the soil or a sodium adsorption ratio of more than 0.176 [43 CFR § 11.62(e)(3)]
- Cause a toxic response or inhibit growth in plants, invertebrates, or microbes [43 CFR § 11.62(e)(4, 5, 9,10)]
- Decrease water holding capacity [43 CFR § 11.62(e)(4)]
- Impede carbon mineralization because of decreased microbial respiration or growth [43 CFR § 11.62(e)(5,6)]
- Restrict the ability to access, develop, or use mineral resources within or beneath the exposed geologic resource [43 CFR § 11.62(e)(7)]
- Cause injury to other natural resources, including groundwater [43 CFR § 11.62(e)(8,11)].

Other potential groundwater injury definitions

Trustees are not required to use the definitions of natural resource injuries put forth in the DOI regulations [43 CFR § 11.10]. The Trustees discussed alternative injury definitions during CSM workshops. The injury definitions presented herein do not represent a consensus list of potential injuries. As stated previously, ultimate selection of injury definitions will be undertaken during development of injury assessment plans.

Examples of alternative injury definitions that may be considered in injury assessment planning include:

- Impairment of groundwater use services for any domestic, livestock, or agricultural purpose
- Unusable water supply because of proximity to contamination (to prevent lateral migration of a groundwater plume into a previously uncontaminated aquifer area)
- Unusable water supply because response actions such as rubble barriers or institutional controls prevent groundwater use regardless of contaminant concentrations
- Degradation of groundwater quality in violation of Native American treaties
- Concentrations of contaminants exceeding a Federal, State, or Tribal risk-based threshold
- Reduction in groundwater services because of the presence of contamination, regardless of the contaminant concentrations
- Reduction in surface services because of the stigma of underlying groundwater contamination.

Groundwater services

Groundwater provides many ecological and human services. This section provides some examples, but it is not complete and does not go into detail. A more thorough examination of groundwater services will be undertaken during injury assessment planning.

Some examples of human groundwater services include the committed human uses mentioned in the previous section, as well as services specific to Tribal lifeways such as religious, ceremonial, or medicinal groundwater use, or passive (nonuse) services such as a clean water supply for future generations (groundwater services for humans, including both use and nonuse services, are described in detail in Chapter 9). Ecological services that groundwater provides include subsurface habitat for certain biota; a water source for rivers, seeps, and springs; and a water source for vegetation and biota in aquatic habitat.

References

Bergeron, M.P. and E.J. Freeman. 2005. *Estimating Groundwater Concentrations from Mass Releases to the Aquifer at the Integrated Disposal Facility and Tank Farms in the Hanford Central Plateau*. PNNL-14891. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy.

Bryce, R.W., C.T. Kincaid, P.W. Eslinger, and L.F. Morasch (eds.). 2002. *An Initial Assessment of Hanford Impact Performed with the System Assessment Capability*. PNNL-14027. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. September.

Bunn, A.L., S.D. Cannon, J.P. Duncan, R.A. Fowler, B.G. Fritz, D.W. Harvey, P.L. Hendrickson, D.J. Hoitink, D.G. Horton, G.V. Last, T.M. Poston, E.L. Prendergast-Kennedy, S.P. Reidel, A.C. Rohay, M.R. Sackschewsky, M.J. Scott, and P.D. Thorne. 2005. *Hanford Site National Environmental Policy Act (NEPA) Characterization.* PNNL-6415 Rev. 17. Pacific Northwest National Laboratory. Prepared for the U.S. Department of Energy. September.

CHPRC. 2009. Geographic Information System (GIS) files depicting groundwater plumes from Fiscal Year 2007. Sent by Bill Webber, CH2M Hill Plateau Remediation Company, to Jamie Holmes, Stratus Consulting Inc., April 15.

Cole, C.R., M.P. Bergeron, S.K. Wurstner, P.D. Thorne, S. Orr, and M.I. McKinley. 2001. *Transient Inverse Calibration of the Site-Wide Groundwater Flow Model to Hanford Operational Impacts from 1943 to 1996*. PNNL-13447. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. May.

Dirkes, R.L. and R.W. Hanf (eds.). 1995. *Hanford Site Environmental Report for Calendar Year 1994*. PNNL-10574. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. June. Available: http://hanford-site.pnl.gov/envreport/. Accessed 4/1/2009.

Dresel, P.E., J.C. Evans, and O.T. Farmer III. 2002. *Investigation of Isotopic Signatures for Sources of Groundwater Contamination at the Hanford Site*. PNNL-13763. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy.

Eslinger, P.W., C.T. Kincaid, W.E. Nichols, and S.K. Wurstner. 2006. *A Demonstration of the System Assessment Capability (SAC) Rev. 1 Software for the Hanford Remediation Assessment Project*. PNNL-16209. Pacific Northwest National Laboratory, Richland, WA.

Fritz, B.G., N.P. Kohn, T.J. Gilmore, D. McFarland, E.V. Arntzen, R.D. Mackley, G.W. Patton, D.P. Mendoza, and A.L. Bunn. 2007. *Investigation of the Hyporheic Zone at the 300 Area, Hanford Site*. PNNL-16805. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. October.

German-Heins, J. 2002. Visualization and Analysis of Tritium Transport from Historical Data at the Hanford Nuclear Reservation, Washington. Nez Perce Tribe ERWM Program, Lapwai, ID. January.

Hartman, M.J. (ed.). 2000. *Hanford Site Groundwater Monitoring: Setting, Sources and Methods*. PNNL-13080. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. February.

Hartman, M.J. and W.D. Webber (eds.). 2008. *Hanford Site Groundwater Monitoring for Fiscal Year 2007.* DOE/RL-2008-1. Prepared for the U.S. Department of Energy.

Hartman, M.J., J.A. Rediker, and V.S. Richie. 2009. *Hanford Site Groundwater Monitoring for Fiscal Year 2008.* DOE/RL-2008-66. Prepared for the U.S. Department of Energy. March.

Horton, D.G. 2007. *Data Package for Past and Current Groundwater Flow and Contamination Beneath Single-Shell Tank Waste Management Areas*. PNNL-15837. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. January.

Peterson, R.E., M.D. Williams, and G.W. Patton. 2007. Hanford Site Groundwater and the Columbia River, South-Central Washington (Presentation). In *6th Washington Hydrogeology Symposium*, May 1–3, 2007, Tacoma, WA. Abstract: PNNL-SA-56038.

Peterson, R.E., E.J. Freeman, P.D. Thorne, M.D. Williams, J.L. Lindberg, C.J. Murray, M.J. Truex, S.B. Yabusaki, J.P. McDonald, V.R. Vermeul, and J.M. Zachara. 2005. *Contaminants of Potential Concern in the 300-FF-5 Operable Unit: Expanded Annual Groundwater Report for Fiscal Year 2004*. PNNL-15127. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. March.

Spane Jr., F.A. and R.G. Raymond. 1993. *Preliminary Potentiometric Map and Flow Dynamic Characteristics for the Upper-Basalt Confined Aquifer System*. PNL-8869. Pacific Northwest Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. September.

Spane Jr., F.A. and V.R. Vermeul. 1994. *Summary and Evaluation of Hydraulic Property Data Available for the Hanford Site Upper Basalt Aquifer Confined System*. PNL-10158. Pacific Northwest Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. September.

Spane Jr., F.A., D.R. Newcomer, and P.D. Thorne. 2003. *Results of Detailed Hydrologic Characterization Tests – Fiscal Year 2002*. PNNL-14186. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. February.

Thorne, P.D., M.P. Bergeron, and V.L. Freedman. 2006. *Groundwater Data Package for Hanford Assessments*. Rev. 1. PNNL-14753. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. January.

Vermeul, V.R., M.D. Williams, B.G. Fritz, R. Mackley, D.P. Mendoza, D.R. Newcomer, M.L. Rockhold, B.A. Williams, and D.M. Wellman. 2007. *Treatability Test Plan for 300 Area Uranium Stabilization Through Polyphosphate Injection*. PNNL-16571. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. May.

Washington Department of Ecology. 2005. *Implementation Guidance for the Ground Water Quality Standards*. Publication 96-02. October.

Williams, B.A., B.N. Bjornstad, R. Schalla, and W.D. Webber. 2002. *Revised Hydrogeology for the Suprabasalt Aquifer System, 200-West Area and Vicinity, Hanford Site, Washington*. PNNL-13858. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. May.

Wurstner, S.K., P.D. Thorne, M.A. Chamness, M.D. Freshley, and M.D. Williams. 1995. *Development of a Three-Dimensional Ground-Water Model of the Hanford Site Unconfined Aquifer System: FY 1995 Status Report*. PNL-10886. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. December.

6. Aquatic Resources

This chapter presents a CSM for aquatic resources potentially exposed to and/or injured by stressors at the Site. Figure 6.1 illustrates the relationship between the aquatic resource CSM and the other CSMs provided in this document. As discussed previously in this document, we use the term "stressors" to refer to substances or activities that can cause injuries to natural resources for which the Trustee Council may quantify damages. Specifically, stressors include:

- Hazardous substances as defined in Section 101(14) of CERCLA
- By-products of hazardous substances [43 CFR § 11.14(v)]
- Response actions that may cause unavoidable injuries to natural resources [43 CFR § 11.15].

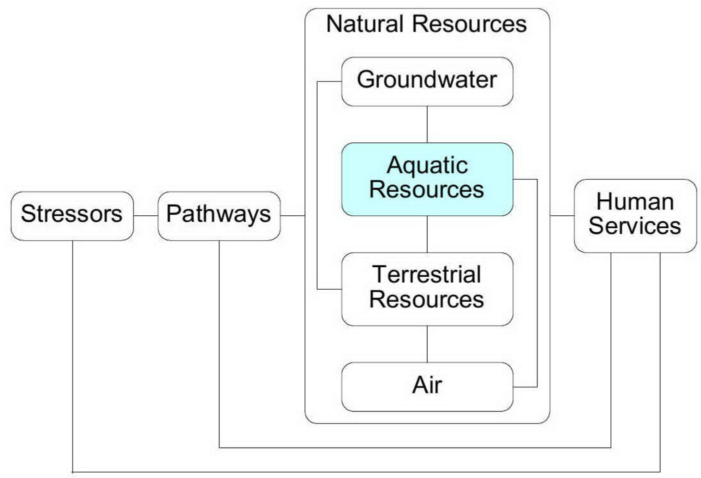


Figure 6.1. Relationship between the aquatic resource CSM and other CSMs that together make up the NRDA CSM.

Adverse effects to aquatic resources can occur through direct exposure to a stressor, including exposure to radiation or other hazardous substances released from the Site. Adverse effects to aquatic organisms also can occur through indirect effects if stressors from the Site result in a loss of habitat, a loss of prey base, changes in the food-web structure, or other impacts to an organisms' physical or biological environment.

Although we differentiate aquatic and terrestrial resource CSMs, there are many points of connection between aquatic and terrestrial food-webs. Many different wildlife species at the Site include both aquatic and terrestrial prey items in their diets, with the relative proportion of aquatic versus terrestrial prey varying across different seasons and through an animal's life-cycle. For example, predators such as raccoons, skunks, bald eagles, and hawks will consume small fish, reptiles, amphibians, and birds that are part of the aquatic food web, as well as consuming small mammals and birds that are part of the terrestrial food web. These ecological connections may influence pathways of contaminant transport and the type and degree of injury experienced by aquatic or terrestrial resources. Traditional tribal practices also integrate aquatic and terrestrial resources throughout the "seasonal round" of the year, with consumption and cultural use of both aquatic and terrestrial flora and fauna. Thus, understanding the interconnections at the Site between aquatic and terrestrial resources will be essential for assessing injury as well as for restoration planning.

6.1 Aquatic Natural Resources

Aquatic resources include biological resources and surface water resources. Biological resources are defined in the DOI regulations as ". . . fish and wildlife and other biota. Fish and wildlife include marine and freshwater aquatic and terrestrial species; game, nongame, and commercial species; and threatened, endangered, and State sensitive species. Other biota encompass shellfish, terrestrial and aquatic plants, and other living organisms not otherwise listed in this definition" [43 CFR § 11.14(f)]. Surface water resources are "the waters of the United States, including the sediments suspended in water or lying on the bank, bed, or shoreline and sediments in or transported through coastal and marine areas" [43 CFR § 11.14(pp)].

This aquatic resources CSM focuses on surface water resources, including sediments, and on aquatic, riparian, wetland, and hyporheic biological resources. These resources include riparian and aquatic plants (including rooted plants and plankton); aquatic biota, including finfish, shellfish, invertebrates, and microbes; and birds and mammals that are either partly or wholly dependent on aquatic or riparian resources, including shorebirds, waterfowl, and fish-eating birds and mammals. The aquatic resources CSM considers surface water; hyporheic water; bed, bank, and floodplain sediments; and pore water in sediments both as potentially injured natural resources and as pathways of contaminant transport to aquatic biological resources and their supporting habitat.

Riparian resources are considered in both the aquatic resources CSM and the terrestrial resources CSM because of their role in linking aquatic and terrestrial ecosystems. For the aquatic resources CSM, riparian resources are considered on their own as well as in the context of how they affect the functioning of the aquatic habitats they border.

6.2 Geographic Scope

The geographic scope for the aquatic resources CSM includes all the locations where hazardous substances released from the Site may have come to be located. The geographic scope includes the Columbia River, beginning upstream of the Site where contaminants could have been transported by aerial deposition or movement of biota and continuing through the Hanford Reach, downstream through a series of dam impoundments, and finally to the Pacific Ocean, including the ocean zone influenced by discharge from the Columbia River (Figure 6.2). The remainder of this chapter focuses primarily on the Hanford Reach and points downstream, because the vast majority of aquatic studies have focused on these areas. Although this CSM does not discuss specific aquatic habitat or biota upstream of Priest Rapids Dam, it does not imply that these upstream areas should not be considered for examination of potential aquatic resource injuries.

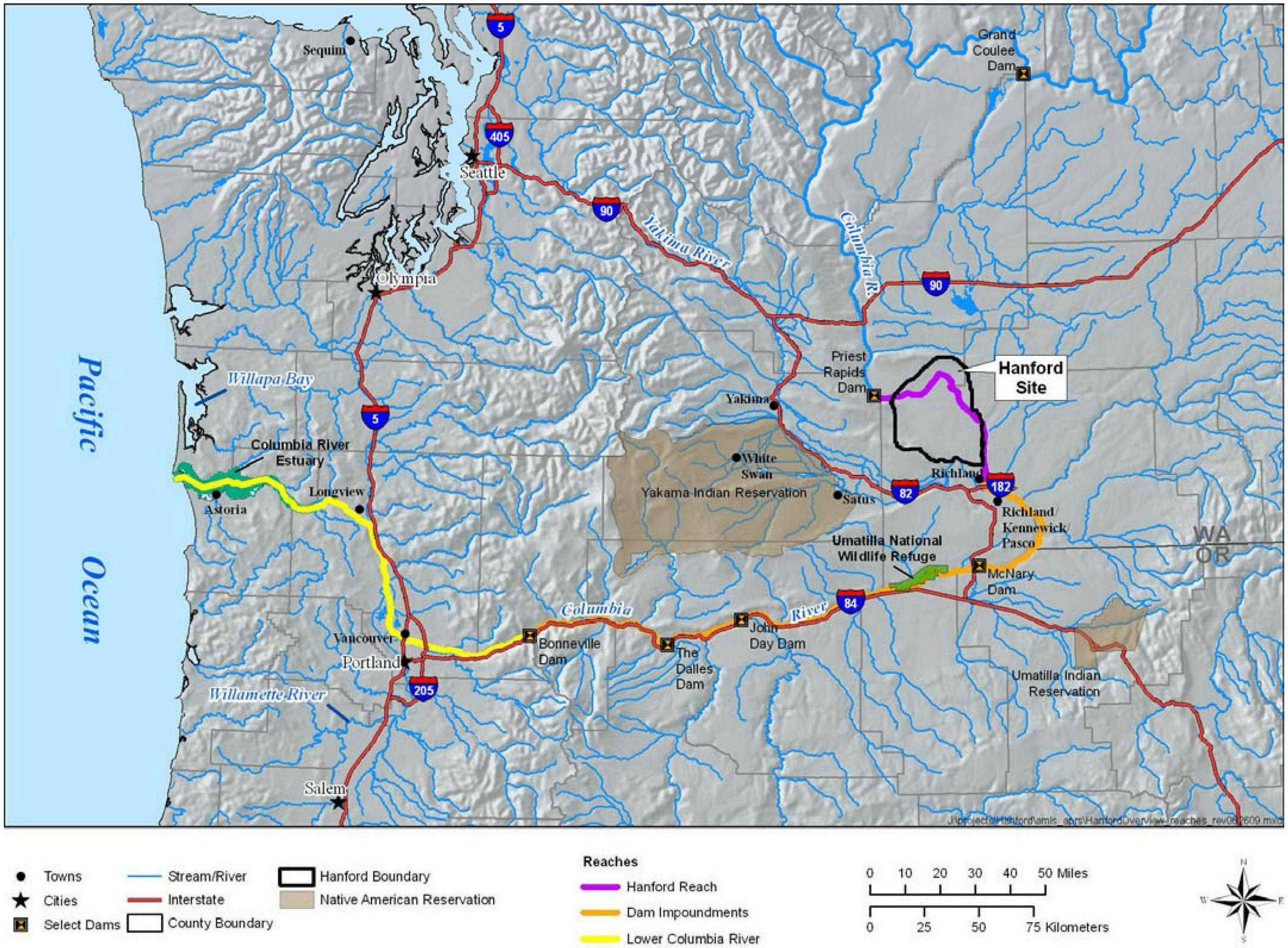


Figure 6.2. The Hanford Site, Columbia River, and surrounding area from the Grand Coulee Dam to the Pacific Ocean. Willapa Bay and Sequim, Washington, were the sites of oyster collection for evaluation of radionuclides in 1958.

The geographic scope presented in this chapter may change in the future as more information is gained about contaminant transport and natural resource injury. Smaller surface water bodies on and around the Site and the resources they support are discussed in the terrestrial CSM described in Chapter 7, because of their important connections to the terrestrial ecology and food-webs of the Site.

6.2.1 Hanford Reach

The Hanford Reach was under the sole management and control of the DOE from 1943 to 2000, at which point the Hanford Reach National Monument was created by presidential proclamation. The USFWS, under permit from the DOE, administers the monument as an "overlay" national wildlife refuge and is responsible for protecting and managing Monument resources. The USFWS manages the north shore of the Columbia River as part of the "River Corridor Unit" (USFWS, 2008a). The DOE manages the islands within the monument, while WDFW manages the riverbed and shorelines up to the ordinary high water mark (USFWS, 2008b). The vision statement for the Hanford Reach National Monument (USFWS, 2008b) states:

> The Monument's diversity of plants and wildlife are critical to the biological integrity of the Columbia Basin. The unique combination of an expansive and increasingly rare shrub-steppe ecosystem, the free-flowing river, and the last major salmon spawning grounds in the Columbia River create a diverse and precious mosaic of habitats. The Monument is a refuge for a multitude of species, many new to science.

The Columbia River flows without impoundments through the Hanford Reach, which begins at the base of the Priest Rapids Dam and extends for 51 miles downstream to Lake Wallula, the reservoir upstream of the McNary Dam (U.S. DOE, 2008). This is the only unimpounded stretch of the Columbia River in the United States upstream of the Bonneville Dam. Although the Hanford Reach is not impounded by a downstream dam, seasonal and daily flows are controlled by the upstream dams. Thus, the volume and velocity of the water in the Columbia River, as well as the depth and width of the river, are largely determined by the amount and timing of water releases from upstream dams. More specifically, the Grand Coulee Dam establishes the daily flow through the Hanford Reach, while operation of the Priest Rapids Dam affects hourly flows through the Hanford Reach (USFWS, 2008a). River levels can vary by up to 3 meters within a few hours as a result of variability in the operation of the Priest Rapids Dam (PNNL, 1998).

The physical and ecological characteristics of the Hanford Reach are described in more detail in Section 6.3.

6.2.2 Dam impoundments

Both upstream and downstream of the Hanford Reach, the Columbia River has been transformed through hydropower development into a series of reservoir impoundments. Upstream of the Hanford Reach is Priest Rapids Lake (created by Priest Rapids Dam), which extends 28 miles upstream to Wanapum Dam.

Downstream of the Hanford Reach, the dam impoundments are, in order, Lake Wallula (created by the McNary Dam), Lake Umatilla (created by the John Day Dam), Lake Celilo (created by The Dalles Dam), and Bonneville Reservoir (created by the Bonneville Dam). Downstream of Bonneville Dam, the river flows without impoundment into the Pacific Ocean.

Lake Wallula extends for 64 miles on the Columbia River from the end of the Hanford Reach to the McNary Dam (USACE, 1997). This stretch includes portions of the McNary National Wildlife Refuge and its adjacent habitat management areas. Habitats along this reach include Columbia River shoreline, wetlands, backwater sloughs, and riparian hardwood forest (USFWS, Undated). Lake Umatilla extends for approximately 76 miles from the base of the McNary Dam to the John Day Dam. This stretch includes the Umatilla National Wildlife Refuge, with open water, shallow marsh, backwater slough, and island habitat. Lake Celilo extends for approximately 24 miles from the base of the John Day Dam to The Dalles Dam. In this area, most of the shoreline is bordered by highways and railroads, although there is some riparian habitat along the shoreline (Raub, 2008). The Bonneville Reservoir (also called Lake Bonneville) extends for approximately 46 miles from the base of The Dalles Dam to the Bonneville Dam (USACE, Undated). Bonneville Reservoir falls within the Columbia Gorge National Scenic Area, with a landscape characterized by steep forested hillsides (Topinka, 2008).

Downstream of Bonneville Dam, the Lower Columbia River flows freely for 146 miles to the Pacific Ocean. The river is 925 feet wide at the base of the Bonneville Dam and then broadens into a wider floodplain with islands, sloughs, and side-channels (Lower Columbia River Estuary Program, 1999). The confluence with the Willamette River, a major tributary to the Columbia, occurs near river mile 100 (U.S. EPA, 2009). The National Estuary Program considers the entire reach downstream of the Bonneville Dam to be part of the Columbia River estuary because the area is influenced by tides and ocean conditions (Lower Columbia River Estuary Program, 1999).

6.2.3 Pacific Ocean

The Columbia River enters the Pacific Ocean just west of the City of Astoria, Oregon; it accounts for 77% of the coastal drainage to the Pacific Ocean from the United States (Garcia Berdeal et al., 2002). Discharge is affected by runoff, snowmelt, and dam operations. Hickey et al. (1998) estimate the average annual discharge to be 250,000 cfs (reported as 7,000 m^3/s), with a range of 106,000–600,000 cfs (3,000–17,000 m^3/s). The plume of freshwater entering the Pacific Ocean from the Columbia River can extend up to 50 miles wide, 150 miles long, and 60 feet thick, and plays an important role in transporting dissolved and particulate organic mater, plankton, larvae, and contaminants (Hines, 2001). The location of the plume also influences fish behavior (Hines, 2001). The position of the plume depends on wind and coastal flow conditions and can vary dramatically between winter and summer (Garcia Berdeal et al., 2002).

6.3 Hanford Reach

This subsection focuses on the Hanford Reach and presents a discussion of relevant stressors, habitats, and trophic relationships. The Hanford Reach has unique habitat value for aquatic resources in the region, including essential spawning and rearing habitat for fall Chinook salmon (Dauble et al., 2003a). This section contains more detail than the subsequent sections addressing other geographic regions because the Hanford Reach has had the greatest direct exposure to Site stressors and because more information is available for the Hanford Reach. However, the detail in this section is not meant to suggest that other resources or locations are less important than the Hanford Reach or that these other resources or locations have not also been exposed to Site stressors and contaminant releases.

The Columbia River in the Hanford Reach is a large, low-gradient river. The elevation of the river only drops approximately 100 feet from the Priest Rapids Dam to the McNary Dam (based on NOAA weather station locations; NOAA, 2009). Through the Hanford Reach, the Columbia River varies from 1,000 feet to 3,300 feet wide (USFWS, 2008a). The minimum flow at Priest Rapids Dam is required to be at least 36,000 cfs, with targeted flows of 50,000–70,000 cfs from October to May to help protect fall Chinook salmon spawning. The average daily flow rate from 1993 to 2003 was approximately 120,000 cfs (USFWS, 2008a). The depth and width of the river can change quickly depending on upstream water releases.

6.3.1 Description of stressors

As described in Chapters 3 and 4, stressors include releases of hazardous substances, by-products of releases, and response actions. Releases can be classified as either primary (direct discharges) or secondary (discharges that occur through pathways from other natural resources).

Examples of primary releases to the Hanford Reach were described in detail in Chapter 3. Some of these sources include, but are not limited to, the following:

- Single-pass nuclear reactors (1944–1971)

    - Releases of radionuclides, chromium, other hazardous substances, and heat (hot water) directly to the river channel. Cooling water was discharged through pipes into the center of the river channel, after brief storage in retention basins (Gerber, 1996). Discharge was estimated to be 78–234 cfs per reactor (Gerber, 1996, converted from gpm).
    - Releases of radionuclides, chromium, other hazardous substances, and heat (hot water) indirectly to the river channel via shoreline discharge and retention basin leakage. When cooling water effluent volume exceeded the capacity of the discharge pipes, the effluent was discharged along the shoreline.
    - Releases of radionuclides, other hazardous substances, and heat (hot water) directly into the river channel when the reactors were purged to clean the process tubes of surface film (Gerber, 1996).

- N-reactor, with recirculating coolant water

    - Releases of radionuclides, chromium, and other hazardous substances, from 1964 to the mid-1970s, from discharge of reactor effluent directly to the river. Though most of the coolant water was recirculated, some coolant water was released and new coolant water added on a continuous basis as part of operations. Discharge to the river was estimated to be 0.2–3.3 cfs (Gerber, 1996, converted from gpm). Starting in the mid-1970s, reactor effluent was discharged to trenches instead of directly to the river (Gerber, 1996).
    - Releases of radionuclides, other hazardous substances, and heat (hot water) occurring during purges of the reactor. Starting in the mid-1970s, purges were directed to a tank instead of directly to the river (Gerber, 1996).

- Episodic events and spills

    - Failure of the South Process Pond in October 1948, resulting in the release of 14.5 million gallons of uranium-contaminated water to the river (U.S. DOE, 2008).
    - Sodium dichromate spill in 1966, releasing 140,000 pounds of sodium dichromate solution, necessitating the shutdown of the Richland and Pasco drinking water plants (Gerber, 1993).

- Continuous leaching of uranium at the 300 Area (Hartman and Webber, 2008).

- Transport of contaminants east from the central plateau, and through the Gable Mountain gap toward the B/C and K reactors.
    - Contaminants on the central plateau include tritium, nitrates, technetium-99, and iodine-131.

Secondary releases to the Hanford Reach have occurred from sources that include, but are not limited to, the following:

- Aerial deposition and precipitation
- Erosion, runoff, and Aeolian transport from soils
- Movement of biotic vectors
- Discharge of contaminated groundwater into the river
    - Groundwater plumes mix with surface water in the hyporheic zone and are subsequently released to surface water through upwellings, seeps, and springs
    - As described in Chapter 5, contaminants in groundwater plumes in the River Corridor area include moderate- and long-lived radionuclides such as strontium-90 and carbon-14, as well as uranium, tritium, chromium, nitrate, and trichloroethene (Table 5.4; Figures 5.20 and 5.21). Gross alpha and gross beta activity in groundwater in excess of drinking water standards also has been measured at the Site (Ridolfi, 2006).

Response actions that can serve as a source of stress to aquatic resources include, but are not limited to, the following:

- Creation of artificial shoreline through the placement of riprap in the 100-N and 100-B/C areas
- Location and activities at groundwater pump and treat facilities along the shoreline
- Potential removal of effluent pipelines from the river that would disrupt riparian, shoreline, and benthic habitat (U.S. DOE, 2007).

6.3.2 Habitats

The Hanford Reach contains the full diversity of native habitat types for this stretch of the Columbia River, including features such as islands, cobble shorelines, riffles, gravel bars, and backwater sloughs (USFWS, 2008a) (Figure 6.3). Many of these features have been lost downstream of the Hanford Reach through the construction of dams and the associated impounding of the Columbia River.

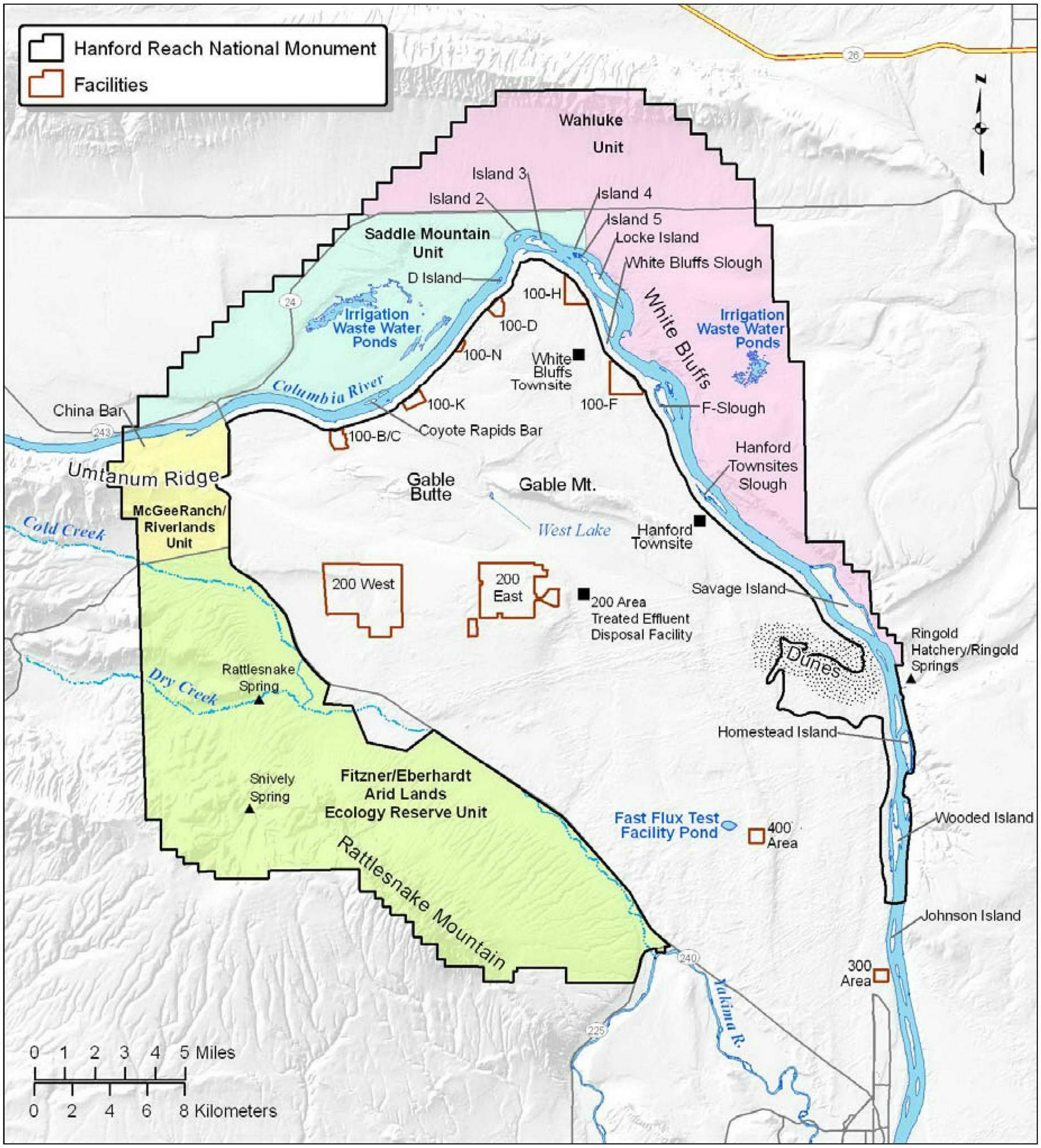


Figure 6.3. Prominent islands and sloughs along the Hanford Reach of the Columbia River.

This section describes the general physical and ecological characteristics of hyporheic, aquatic, riparian, and wetland habitats in the Hanford Reach – the four major habitat types included in the aquatic resources CSM. Although described individually below, these habitats are not isolated from each other but are interconnected to form a comprehensive aquatic ecosystem.

Hyporheic

The hyporheic zone in the Hanford Reach can be lateral to or below the river bed. Hyporheic water can emerge as a seep or spring at low river stage (see Figure 5.10). Thus, there are hyporheic habitats associated with the riverbank, where groundwater and surface water can actively mix, and hyporheic habitats associated with the river bottom.

Hyporheic habitats associated with the riverbank can be visible as riverbank springs when the water level of the river drops. More than 115 springs were identified along the Hanford Reach in the early 1980s (Dirkes and Hanf, 1996). Springs are fed by a mixture of groundwater and bank storage of river water. The presence of springs varies with river stage; as the river stage falls, hyporheic water that was stored in the riverbank seeps out and is visible as a spring. Riverbank springs have been monitored extensively for contamination and are an important pathway of contamination to the river and its associated aquatic resources (Dirkes and Hanf, 1996). The location of riverbank springs with respect to the river's water level will depend on groundwater elevation, river stage (influenced by dam operation), and on the locations where aquifers intersect with the river.

Hyporheic habitats are important for microbial biota that inhabit the hyporheic zone, for aquatic biota that come into contact with the hyporheic water when it enters the river, for terrestrial biota that make use of riverbank seeps and springs when they emerge above the river, and for humans who make use of seeps and springs for drinking water or other purposes. Upwelling of hyporheic water into a cobble or gravel bed can be important for salmon reproduction, since hyporheic water upwelling into redds can carry dissolved minerals that are important for chemical imprinting and dissolved oxygen essential for developing embryos (Geist, 2000).

Aquatic habitat

Aquatic habitats in the Hanford Reach of the Columbia River include all areas of the river, including the nearshore aquatic zone up to the ordinary high water mark (Figure 6.4). The diverse habitat types within the Hanford Reach provide distinct habitat services to a wide variety of fish and wildlife species, as well as providing essential human services including drinking water and irrigation (see Chapter 9). Examples of specific aquatic habitat types in the Hanford Reach[1] include the following:

---

1. Other reaches of the Columbia River contain these habitat types as well.

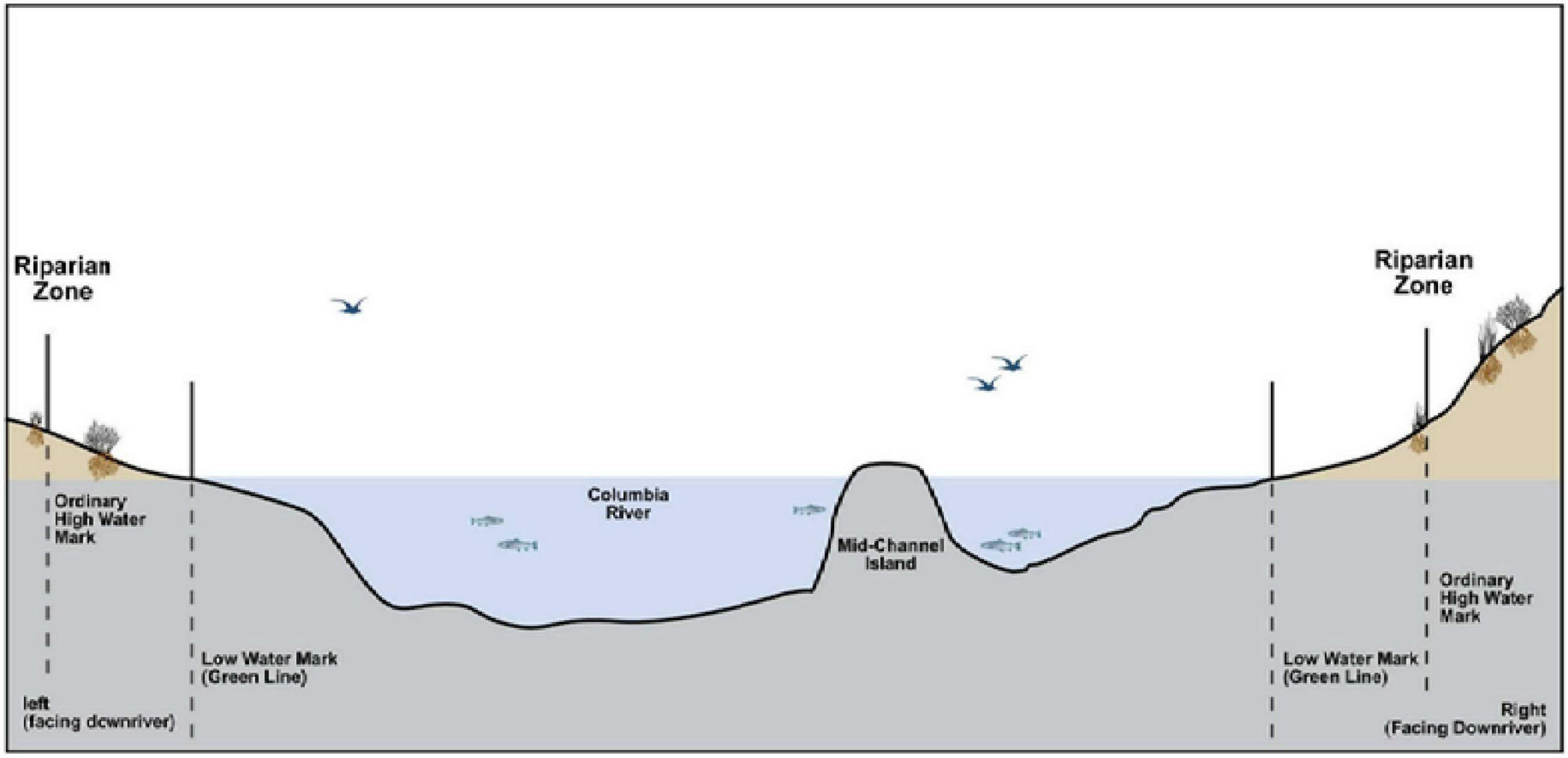


Figure 6.4. Simple conceptual diagram of habitats associated with the Columbia River.

Source: U.S. DOE, 2008, Figure 1-3.

- **Open-water.** This habitat type is characterized by open, flowing water year round. Within this habitat type, there are open-water pelagic habitats as well as benthic habitats associated with the river bottom. Open-water habitat also has different characteristics based on its distance from shore, with near-shore habitats providing different habitat functions from habitat in the middle of the river. This habitat is highly influenced by the flow and discharge rate of the river. In the Hanford Reach, open-water flowing habitat is important for a large number of migratory and resident fish. For example, white sturgeon require swiftly flowing water for spawning; known spawning locations in the Hanford Reach include a site immediately downstream of Priest Rapids Dam and a second location upstream of the Vernita Bridge, with other locations likely used for spawning as well (USFWS, 2008a). Benthic habitats are important for invertebrates, benthic-dwelling fish, and as spawning locations for some species.

- **Riffles.** This habitat type is characterized by swiftly flowing, turbulent water, with some substrate exposed. This habitat type is found in the Hanford Reach, especially associated with the islands and is important for fish spawning. Riffle habitat has been lost in the downstream impounded reaches of the Columbia River. Salmon spawning redds are often found at the transition between pools and riffles (Dauble, 2000).

- **Gravel and cobble beds.** This habitat type forms in shallow-water areas of the river, often downstream of islands. The size of gravels and cobbles plays an important role in influencing habitat use. Spawning habitat for salmonids usually occurs in areas where there is upwelling of groundwater into a gravel or cobble bed. Salmon spawning redds may be associated with deposition areas for lateral bars, and with the presence of long gravel bars and islands such as Locke Island (Dauble, 2000; Visser et al., 2002). A map of fall Chinook salmon redds around Locke and Wooded islands is presented in Figure 6.5. As described previously, the Hanford Reach is the only significant reach of the Columbia River in the United States upstream of the Bonneville Dam that contains these physical habitat characteristics necessary for spawning of fall Chinook salmon (Dauble, 2000).

- **Backwater sloughs.** Sloughs are areas with slow-moving water, where macrophytes (rooted plants) are commonly present along the shorelines. Macrophytes modify the river habitat and can provide food and shelter for juvenile fish and spawning locations for warm-water fish (Burk et al., 2007). Backwater sloughs in the Hanford Reach (such as the F Slough and associated wetland – see Figure 6.3) and other areas of slower-moving water can provide important resting and rearing habitat for fish, amphibians, and other organisms.

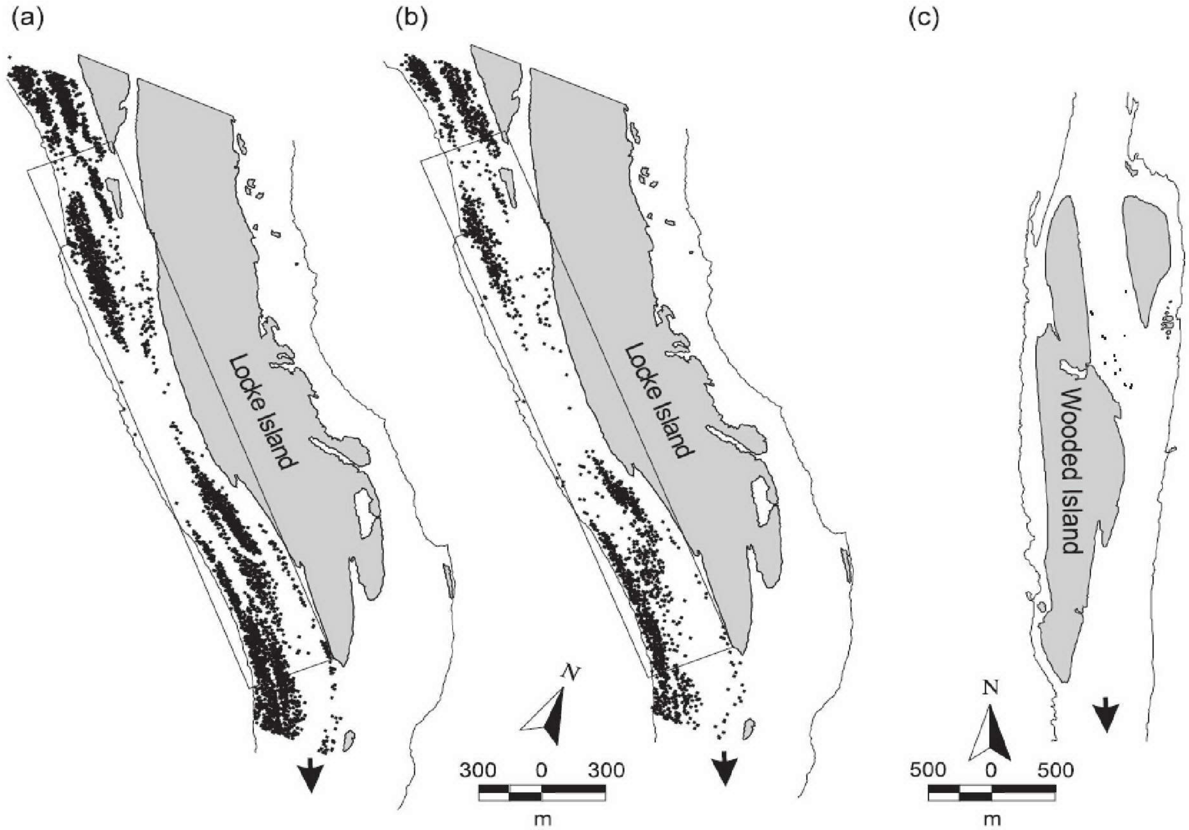


Figure 6.5. Distribution of fall Chinook salmon redds following peak spawning at (a) Locke Island in 1994, (b) Locke Island in 1995, and (c) Wooded Island in 1995. In each panel, a black dot represents a salmon redd, and an arrow indicates the flow direction of the river.

Source: Geist et al., 2000, Figure 2.

In general, the specific hydrological and morphological characteristics of aquatic habitat affect how that habitat is used by different aquatic organisms at different stages in their life-history. Important characteristics include the volume and seasonality of flow, the vertical gradient of the river, the degree of sinuosity versus channelization, water depth (deep versus shallow habitat), water movement (fast- versus slow-moving reaches), and other attributes that influence how biota use aquatic habitat. Preferences for different habitat characteristics vary by species, by season, and by the life-stage of an organism (e.g., most migratory fish require distinct spawning, rearing, and migrating habitat).

The Hanford Reach has rapid fluctuations in streamflow because of operations at the Priest Rapids Dam. These fluctuations affect the quality of the habitat for aquatic organisms and also influence exposure through potential rapid changes in the concentration of hazardous substances in the river. A wide range of stream flows between day and night can shift the location of suitable spawning habitat on a daily basis, as river depth and velocity changes (USFWS, 2008a).

Water fluctuations have resulted in the mortality of rearing fish that are stranded on shorelines and gravel bars or become vulnerable to predators and high temperatures in small, shallow depressions created by the receding water (USFWS, 2008a). Estimates of juvenile fall Chinook salmon annual mortality from stranding or entrapment have ranged from approximately 45,000 to over 1.6 million dead fish per year between 1999 and 2003 (USFWS, 2008a). These mortality rates have decreased recently because of new regulations of water discharge for the Priest Rapids Dam. Water level fluctuations also can stimulate downstream movement of juvenile fall-run Chinook salmon, resulting in their displacement to less desirable reservoir habitat downstream of the Hanford Reach (USFWS, 2008a).

Riparian and wetland habitat

Wetland habitats are transitional areas between aquatic and terrestrial systems, where the land is either saturated by a shallow water table or covered by shallow water for some period of the year, including at least part of the growing season (Cowardin et al., 1979). Riparian habitat can be defined as vegetated wetlands that are associated with rivers and streams.

Adjacent to the open-water aquatic habitat of the Columbia River, riparian areas play an important role in providing habitat to a large variety of organisms, as well as influencing the structure and quality of the aquatic habitat itself. Along the Columbia River, riparian habitat occurs in association with riffles, gravel bars, backwater sloughs, side channels, and cobble shorelines (Burk et al., 2007).

Riparian habitat is structured by the physical and hydrological characteristics of the associated aquatic habitat. Riparian vegetation is sensitive to the duration and frequency of flooding and drought cycles and the depth to the water table. In the Hanford Reach, these parameters are controlled in large part by dam operations, with rapid fluctuations in water level that create unusual stresses for riparian vegetation.

Riparian habitat is found along the main shoreline, along the shoreline of islands, and associated with gravel bars within the Hanford Reach. The characteristics of riparian vegetation varies through the reach depending on the shape and width of the river canyon and particular flow patterns through an area. For example, there is a narrow, wooded riparian zone in the 100 Area, where the river banks are steep. Riparian vegetation also is affected by sediment erosion and aggradation. In areas that are relatively unstable, riparian vegetation along the Columbia River can be dominated by grasses, rushes, and sedges. Woody vegetation tends to develop in more stable locations and then plays a feedback role in further promoting streambank stability.

Wetlands found along the Hanford Reach are of particularly high value because dam impoundments have inundated many historical wetlands downstream. Important wetland areas include China Bar, Islands 2–5, Locke Island, White Bluffs Slough, 100-F Slough, and the Hanford Townsite Slough (Burk et al., 2007; USFWS, 2008a) (see Figure 6.3).

Riparian and wetland habitats provide important functions for fish and other aquatic organisms. Shoreline vegetation shades the river channel, moderates the temperature of shallow water areas, and provides shelter and physical substrate for invertebrate populations, which are important food sources for fish. In some of the slough areas, vegetation may become overly dense and limit open water habitat (USFWS, 2009).

6.3.3 Biota

This section provides examples of aquatic and riparian/wetland species found in the Hanford Reach, including special status species, and then gives an overview of trophic relationships and representative species in different trophic categories. Stressors in the Hanford Reach can potentially affect not only the river-dwellers, such as benthic invertebrates and fish, but also river-dependent species such as osprey that consume fish, and river users such as bald eagles that consume aquatic and terrestrial resources. Species that integrate terrestrial and aquatic resources in their life-history are also discussed in the terrestrial CSM (Chapter 7).

The Hanford Reach contains a high diversity of organisms, including both native and introduced species. Ridolfi Inc. compiled a comprehensive list of species in the Hanford area, showing the interconnected biodiversity of species potentially been exposed to and/or injured by stressors at the Site. In total, this list includes 13 algae species, 56 fish species, 269 bird species, 52 mammal species, 21 amphibian and reptile species, over 800 aquatic and terrestrial plant species, and dozens of orders, families, and genera of aquatic and terrestrial insects. Of these, most of the fish species were identified as inhabiting the Hanford Reach, and 17 of 48 waterfowl species have nests in the vicinity of the Site.

Rather than transcribe the Ridolfi Inc. biota list here, we provide examples of individual species in the text as illustrations of categories of biota and trophic relationships. If a particular species is mentioned herein, it does not imply that is more important than other species or necessarily should be a focus for the injury investigation. Similarly, if a particular species is not mentioned in the text, it does not imply that the species should be excluded from the injury investigation.

Most of the species discussed herein and included in the Ridolfi Inc. list are species that have been identified in the vicinity of Hanford in recent times. It should be noted that some species (including snails and mussels) may have been present historically but may have been locally extirpated or suffered severe population declines. Historically, these species may also have been exposed to and/or injured by Site stressors.

Example species

Forty-nine species of fish have been documented in the Hanford Reach, inhabiting a range of habitat types. Beach seine catches in the spring (April–June) are dominated by subyearling fall Chinook salmon, with significant numbers of redside shiners, carp, largescale suckers, northern pikeminnow, and peamouth also present (USFWS, 2009). There is a recreational fishery for mountain whitefish and for smallmouth bass which also are common in the Hanford Reach. Other species such as tench and three-spine stickleback are caught more rarely (USFWS, 2009).

There are many special status species found in aquatic habitats of the Hanford Reach, including plants, invertebrates, and fish (Table 6.1). For example, the Hanford Reach is an important migratory corridor for white sturgeon, Upper Columbia River spring Chinook, Middle Columbia River steelhead, Upper Columbia River steelhead, and lamprey; all except sturgeon are listed as federally threatened species (USFWS, 2009). These fish must pass through the Hanford Reach en route to their tributary spawning areas (Upper Columbia Salmon Recovery Board, 2007).

Riparian plant communities in the Hanford Reach include a mixture of native and non-native species. Though a large amount of riparian habitat contains non-native plant species, these areas can still provide important habitat functions for wildlife. The characteristic native riparian species are willow (*Salix* L.), black cottonwood (*Populus balsamifera* L. ssp. *Trichocarpa*), and various cattails, sedges, and rushes (O'Connor and Wieda, 2001; Sackschewsky and Downs, 2001). A variety of introduced species, such as mulberry (*Morus* L.) and Russian olive (*Eleagnus angustifolia*), are prevalent along the Hanford Reach (and downstream) of the Columbia River; many of these were planted as shade trees by homesteaders and farmers prior to 1943 (O'Connor and Wieda, 2001; U.S. DOE, 2001). Reed canarygrass (*Phalaris arundinacea*) is another prominent invasive species on the Site (U.S. DOE, 2001).

Aquatic and riparian habitat associated with the Columbia River support a significant diversity of non-fisheries biological resources. A study of wildlife along the Hanford Reach in 1982 noted the Hanford Reach's status as a refuge for wildlife, especially for bald eagles, mule deer, coyote, and resident Great Basin Canada Goose (Rickard et al., 1982).

Table 6.1. Special status species found in aquatic habitats in the Hanford Reach

Scientific name	Common name	Federal status	State status
Plants			
Ammannia robusta	Ammania (also known as Scarlet Ammania and Grand Redstem)		Rare/threatened
Artemisia campestris ssp. borealis var. wormskioldii	Northern wormwood	Candidate	Endangered
Centunculus minimus	Chaffweed		Rare/threatened
Hypericum majus	Canadian St. John's-Wort		Sensitive
Limosella acaulis	Southern mudwort		Watch list
Lipocarpha (= Hemicarpha) aristulata	Small-flowered hemicarpha		Rare/threatened
Oenothera cespitosa ssp. Cespitosa	Desert (Cespitose) eveningprimrose		Sensitive
Rorippa columbiae (also *Rorippa calycina)*	Persistent-sepal Yellowcress	Species of concern	Endangered
Rotala ramosior	Toothcup		Rare/threatened
Wildlife			
Catastomus platyrhynchus	Mountain sucker	Threatened	Candidate/special concern
Cicindela columbica	Columbia River tiger beetle		Candidate/special concern
Fisherola (Lanx) nuttalli	Giant Columbia River limpet (a.k.a. Shortface lanx)		Candidate/special concern
Fluminicola (= Lithoglyphus) columbiana	Giant Columbia River spire snail	Species of concern	Candidate/special concern
Lampetra ayresii	River lamprey	Species of concern	Monitored
Lampetra tridentate	Pacific lamprey	Species of concern	Monitored
Oncorhynchus mykiss	Steelhead trout	Endangered	Candidate/special concern
Oncorhynchus tshawytscha	Spring-run Chinook	Endangered	Candidate
Rhinichthys flacatus	Leopard dace	Threatened	Candidate/special concern
Salvelinus confluentus	Bull trout	Threatened	Candidate

Sources: Sackschewsky and Downs, 2001, Table 4.1; Burk et al., 2007, Table 4.5.1; USFWS, 2008a, Tables 3.3 and 3.5.

Trophic relationships

A generalized food-web diagram that illustrates trophic relationships for aquatic resources in the Hanford Reach is presented in Figure 6.6, and a more intricate aquatic food web from the Columbia River Comprehensive Impact Assessment (PNNL, 1998) is shown in Figure 6.7. Arrows between food-web categories in Figure 6.6 indicate possible pathways for contaminant transport as well as ecological relationships. For example, contaminants in hyporheic water can be transported to surface water, taken up by algae, consumed by fish, consumed by aquatic birds, and then ingested by humans. Surface water and sediments are direct routes of exposure for all of the categories of biota (macrophytes, algae, benthic invertebrates, fish, aquatic birds, mammals, and humans) because of the potential for ingestion or contact. The degree of complexity of other pathways depends on the particular species involved. For example, there can be a complex set of trophic relationships as small fish such as slimy sculpin are consumed by juvenile Chinook salmon which in turn are consumed by larger predatory fish.

At a general level, the aquatic food-web includes primary producers, primary consumers, and secondary and tertiary consumers:

- Primary producers provide the energetic foundation of any ecosystem, using energy from the sun to support their biological functions. In the Hanford Reach, the predominant aquatic primary producers include phytoplankton (free-floating algae), periphyton (an assemblage of attached algae and associated micro-organisms), and macrophytes (PNNL, 1998). Riparian vegetation also provides energy to the river in the form of leaf-fall and other debris. Many of the species of plankton found in the Hanford Reach are from the Priest Rapids Dam reservoir and move downstream with the flow of water (Burk et al., 2007). Rooted macrophytes are important in sloughs and other locations of slow-moving water where these plants can survive. Native macrophytes include rushes (*Juncus* spp.) and sedges (*Carex* spp.), while shoreline areas in the floodplain zone can include duckweed (*Lemna* spp.); native rooted pond weeds *(Potamogeton* spp. and *Elodea canadensis*); and exotic species such as reed canary grass and Eurasian watermilfoil (*Myriophyllum spicatum*) (Burk et al., 2007).

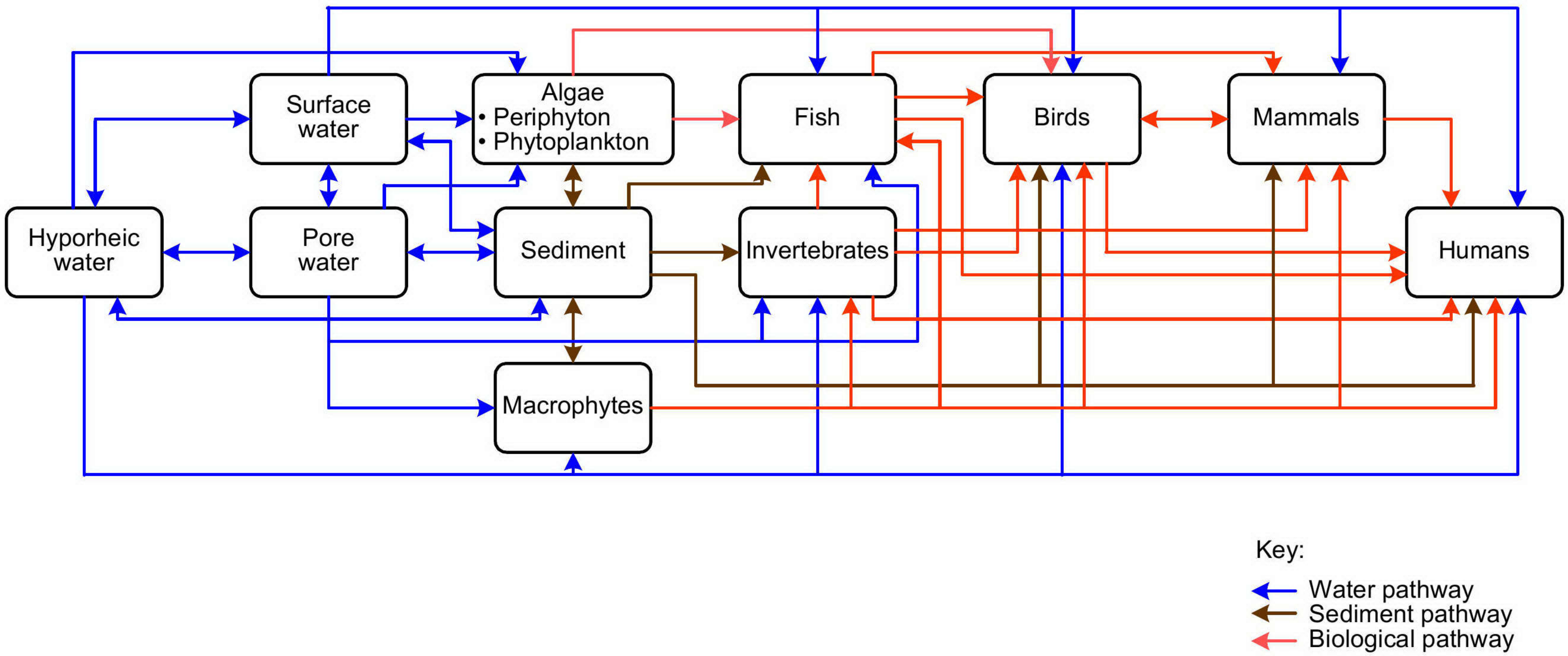


Figure 6.6. Generalized food-web diagram for aquatic and riparian resources in the Hanford Reach.

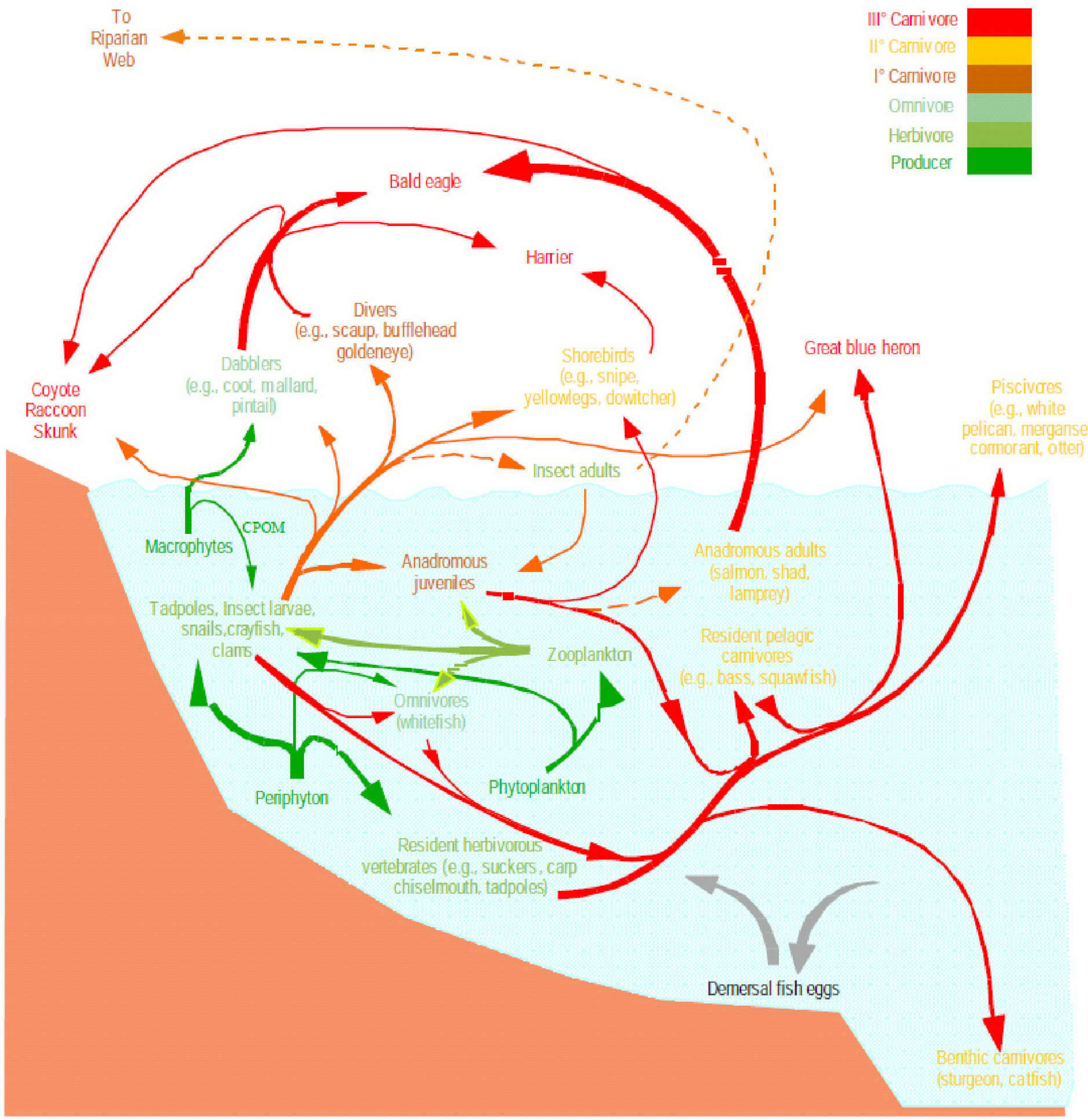


Figure 6.7. Aquatic food web for the Columbia River in the Hanford area, from the Columbia River Comprehensive Impact Assessment. Line widths represent the approximate level of biomass flow. Dashed lines indicate developmental transformation to a different life style. Legend colors apply only to organisms' names, not to the arrows. Detrital/decomposing components are not represented.

Source: PNNL, 1998, Figure 4.2.

- Primary consumers are those organisms that feed on primary producers. Primary consumers can be obligate herbivores or omnivores. Aquatic primary consumers in the Hanford Reach include zooplankton, aquatic invertebrates, fish, aquatic birds, and mammals. Many aquatic primary consumers also consume sediment and silt when foraging for algae, phytoplankton, and other plant material (this is particularly true for benthic invertebrates).

    - Invertebrate primary consumers identified in the Hanford Reach include invasive species such as Asian clams, as well as crayfish and caddisflies, fresh water shrimp, mayflies, midges, clams, mussels, snails, and water fleas (Becker et al., 1996; Doctor et al., 2004; Downs et al., 2004).

    - Vertebrate primary consumers found in the Hanford Reach include fish such as bridgelip sucker and largescale sucker (Becker et al., 1996; Doctor et al., 2004; Downs et al., 2004); birds that primarily eat plant material, such as American coot; and mammals that will forage in the riparian zone, such as elk. These birds and mammals form a link between aquatic and terrestrial environments, because they can depend on both terrestrial and aquatic resources to complete their lifecycle. Humans function as primary consumers when they consume roots, berries, or other plant material from the aquatic environment.

- Secondary and tertiary consumers include carnivores (eat only other animals), predators (hunting live prey), scavengers (eating dead prey), and omnivores. Secondary and tertiary consumers in aquatic environments include fish, benthic invertebrates, amphibians, reptiles, and mammals. Some terrestrial animals such as birds and land-based mammals also feed on aquatic organisms. Humans are important omnivorous consumers and should be considered in trophic evaluations.

    - Secondary and tertiary consumers include fish that prey on benthic invertebrates, fish, and other small vertebrates. Relevant fish species in the Hanford Reach include (but are not limited to) carp, mountain whitefish, salmon, sturgeon, trout, pacific lamprey, lake whitefish, smallmouth bass, speckled dace, walleye, and yellow perch (Becker et al., 1996; Doctor et al., 2004; Downs et al., 2004).

    - Birds may consume insects, invertebrates, fish, and other small vertebrates, depending on their relative size and dietary preferences. Osprey are obligate fish-eaters (piscivores). Other carnivorous avian species found in the Hanford area or downstream on the Columbia River include great blue heron, belted kingfisher, bald eagle, American white pelican, Caspian tern, common loon, double-crested cormorant, Forster’s tern, glaucous-winged gull, hooded merganser, and western grebe (Becker et al., 1996; Doctor et al., 2004; Downs et al., 2004).

- Carnivorous mammals that live and feed in the Hanford Reach include the river otter and mink (Downs et al., 2004). Other birds and mammals, such as bald eagles and raccoons, will consume prey from aquatic or riparian habitats as well as terrestrial prey. These species form a link between aquatic and terrestrial environments and need to be considered in both aquatic and terrestrial assessments of injury.

- Omnivorous birds eat vegetation as well as invertebrates and small fish when other food is not available. These species include Barrow's goldeneye, blue-winged teal, California gull, horned grebe, lesser scaup, northern pintail duck, red-necked grebe, ruddy duck, spotted sandpiper, and wood duck (Becker et al., 1996; Doctor et al., 2004; Downs et al., 2004).

6.3.4 Fish species in the Hanford Reach

Table 6.2 identifies 49 fish species thought to be present in the Hanford Reach, compiled from multiple sources. Gray and Dauble (1977) provided the first published list of fish species, mainly from field sampling conducted in 1973 to 1975 at two sampling stations, combined with fish collections at Pacific Northwest National Laboratory dating back to 1943. The Hanford fish species list was later updated by Becker et al. (1996) to include species from the Columbia River far downstream of the Hanford Reach (Lewis and Clark National Wildlife Refuge) and input from resource management agencies associated with the Columbia River natural resources. We screened this list and only considered fish species that were located in the Hanford Reach or Columbia River backwater south of Richland. Thus, we did not include chum salmon, longfin smelt, and shiner perch on our list, because they inhabit downstream locations. Such species would be relevant, however, to injury assessment planning in these downstream reaches. We also excluded fathead minnow, because they do not occur naturally in the Hanford Reach.

Table 6.2. Residency status and diet for fish species that have been observed in or near the Hanford Reach

Family/species	Scientific name	Resident (R) or migratory (M)	Diet
Acipenseridae (sturgeons)			
White sturgeon	*Acipenser transmontanus*	M	F, Bi, Sm
Catostomidae (suckers)			
Bridgelip sucker	*Catostomus columbianus*	R	Bi, V
Largescale sucker	*Catostomus macrocheilus*	R	Bi, V, Sm
Mountain sucker	*Catostomus platyrhynchus*	R	V, Bi

Table 6.2. Residency status and diet for fish species that have been observed in or near the Hanford Reach (cont.)

Family/species	Scientific name	Resident (R) or migratory (M)	Diet
Centrachidae (sunfishes)			
Pumpkinseed	*Lepomis gibbosus*	R	Bi, F
Bluegill	*Lepomis macrochirus*	R	Bi, F
Smallmouth bass	*Micropterus dolomieu*	R	Bi, F
Largemouth bass	*Micropterus salmoides*	R	F, Bi
White crappie	*Pomoxis annularis*	R[a]	Bi, F
Black crappie	*Pomoxis nigromaculatus*	R	Bi, F
Clupeidae (herrings)			
American shad	*Alosa sapidissima*	M[b]	juv – Pi, F
Cottidae (sculpins)			
Prickly sculpin	*Cottus asper*	R	Bi
Mottled sculpin	*Cottus bairdii*	R	Bi, F, V
Paiute sculpin	*Cottus beldingii*	R	Bi, V
Reticulate sculpin	*Cottus perplexus*	R	Bi
Torrent sculpin	*Cottus rhotheus*	R	Bi, F
Cyprinidae (carps and minnows)			
Chiselmouth	*Acrocheilus alutaceus*	R	V, Bi
Common carp	*Cyprinus carpio*	R	Bi, V, Sm
Peamouth	*Mylocheilus caurinus*	R	Bi, Pi, F
Northern pikeminnow	*Ptychocheilus oregonensis*	R	F, Bi, Pi
Longnose dace	*Rhinichthys cataractae*	R	Bi
Leopard dace	*Rhinichthys falcatus*	R	Bi
Speckled dace	*Rhinichthys osculus*	R	Bi, V
Redside shiner	*Richardsonius balteatus*	R	Bi, F
Tench	*Tinca tinca*	R[a]	Bi, V
Gadidae (cods)			
Burbot	*Lota lota*	R[a]	Bi, F
Gasterosteidae (sticklebacks)			
Threespine stickleback	*Gasterosteus aculeatus*	R	Bi
Ninespine stickleback	*Pungitius pungitius*	R[c]	Bi
Ictaluridae (catfishes)			
Black bullhead	*Ameiurus melas*	R	Bi, V, F
Brown bullhead	*Ameiurus nebulosus*	R	Bi, V, F
Yellow bullhead	*Ameiurus natalis*	R	Bi, V
Blue catfish	*Ictalurus furcatus*	R[c]	F, Bi
Channel catfish	*Ictalurus punctatus*	R	F, Bi

Table 6.2. Residency status and diet for fish species that have been observed in or near the Hanford Reach (cont.)

Family/species	Scientific name	Resident (R) or migratory (M)	Diet
Percidae (perches)			
Yellow perch	*Perca flavescens*	R	Bi, F
Walleye	*Sander vitreus*	R	Bi, F
Percopsidae (trout-perches)			
Sand roller	*Percopsis transmontana*	R	Bi, Pi
Petromyzontidae (lampreys)			
River lamprey	*Lampetra ayresii*	M[a,d]	juv – Sm
Western brook lamprey	*Lampetra richardsoni*	R[c]	Sm
Pacific lamprey	*Lampetra tridentata*	M[d]	juv – Sm
Poeciliidae (livebearers)			
Western mosquitofish	*Gambusia affinis*	R[c]	Bi
Salmonidae (trouts and salmons)			
Lake whitefish	*Coregonus clupeaformis*	R[a]	Bi, F
Cutthroat trout	*Oncorhynchus clarkii*	R[a]	F, Bi
Coho salmon	*Oncorhynchus kisutch*	M[d]	juv – Bi
Steelhead trout	*Oncorhynchus mykiss*	M[b]	juv – Bi
Rainbow trout		R	Bi, F, Pi
Sockeye salmon	*Oncorhynchus nerka*	M[d]	juv – Bi
Fall Chinook	*Oncorhynchus tshawytscha*	M[b]	juv – Bi
Spring Chinook		M[d]	juv – Bi
Summer Chinook		M[d]	juv – Bi
Mountain whitefish	*Prosopium williamsoni*	R	Bi, F
Bull trout	*Salvelinus confluentus*	M[e,f]	Bi, F
Dolly Varden	*Salvelinus malma*	M[d,f]	Bi, F

Dietary codes: F = fish, Bi = benthic invertebrate, S = sediment microbes, V = vegetation, juv = juvenile only, Pi = planktonic invertebrate.

a. Fish species that Gray and Dauble (1977) did not sample but report as inhabitants of the Hanford Reach.
b. Migratory fish that spawn in the Hanford Reach.
c. Fish species that Gray and Dauble (1977) report as being observed south of Richland or occasionally caught by sport fishermen and known to inhabit the lower Snake and Yakima Rivers that may be present in the Hanford Reach.
d. Migratory fish have egg, larval, and juvenile stages resident in the river for varying times.
e. Observed in the Hanford Reach on very rare occasions, usually associated with the spring freshets, and are not considered to be residents of the Site (Bunn et al., 2005).
f. Bull trout and Dolly Varden are very closely related char species. Genetic reconnaissance has demonstrated that the two species ranges overlap (WDFW, 2000). Given the level of taxonomy used by supporting references, both species may have been observed in the Hanford Reach.

Residency status information obtained from Mueller and Geist (1999), Dauble et al. (2003b), Bunn et al. (2005), and U.S. DOE (2005). Diet referenced from Froese and Pauly (2009).

The common and scientific names of the species in Table 6.2 are based on current American Fisheries Society naming conventions (Nelson et al., 2004). Not all species listed in Table 6.2 are permanent residents of the Hanford reach. For example, fall Chinook salmon are the only anadromous salmon species to spawn in the Hanford Reach; other anadromous stocks migrate upstream through the reach as adults or downstream as juveniles. Hanford Reach fish species residency status information was obtained from Mueller and Geist (1999), Dauble et al. (2003a), Bunn et al. (2005), and U.S. DOE (2005).

A summary of each species' diet is also provided in Table 6.2. Diets were referenced from Froese and Pauly (2009) and are summarized according to five non-specific categories. Note that for migratory species, diet has been characterized for juvenile life stages only, as most adult anadromous salmonid and lamprey species do not feed during their spawning migrations.

6.4 Downstream of Hanford Reach

The Columbia River downstream of Hanford Reach, from Lake Wallula to the Pacific Ocean, is included within the geographic scope of the aquatic resources CSM because of evidence that contaminants from the Site have been transported downstream through the Columbia River and into the Pacific Ocean (Foster and Junkins, 1960; Junkins et al., 1960). Until the completion of the McNary Dam in 1956, the first dam downstream of the Site was the Bonneville Dam. Thus, hazardous substances released from the Site prior to 1956 would not have encountered a dam impoundment until Bonneville Reservoir. Contaminated sediments can potentially serve as ongoing sources of hazardous substance releases and exposure. Because dams can be effective sediment traps, there are likely to be fewer Hanford-generated hazardous substances behind the Dalles Dam or the John Day Dam, both of which were constructed after the completion of the McNary Dam. Downstream of the Hanford Reach, non-Hanford stressors to aquatic resources include dam impoundments, industrial and agricultural activities, urbanization, and habitat modification.

6.4.1 Dam impoundments

As described in Section 6.2.2, the Columbia River downstream of the Hanford Reach consists of a series of interconnected reservoir impoundments (i.e., the reservoirs extend upstream to the next dam), followed by the tidally-influenced Lower Columbia River and Estuary downstream of the Bonneville Dam. Aquatic habitat types in the downstream reach of the Columbia River include open-water aquatic habitat as well as riparian and wetland habitats. Specific habitat types include, but are not limited to the following:

- **Open-water aquatic habitat.** River impoundment habitat behind the four downstream dams (McNary, John Day, The Dalles, and Bonneville) contains deep water that moves more slowly and has a wider temperature range than the unimpounded Hanford Reach (Tanner et al., 2005). The dams are operated as run-of-the-river, thus generally allowing for downstream water movement. The river impoundments, although not natural, nevertheless are home to a wide variety of fish, birds, and other wildlife. For example, Lake Wallula provides habitat for a variety of cold-water and warm-water fish species. Juvenile fall Chinook salmon must pass through the relatively unfavorable impoundment habitat before arriving at the ocean; they make particular use of wetlands and shoreline bays which can serve as nursery habitat (Dauble, 2000; USFWS, Undated). River impoundments also provide habitat for wildlife, such as piscivorous mammals, and for birds, including waterfowl, spring and fall migrating shorebirds, wading birds, and raptors (USFWS, Undated). River impoundments provide less habitat diversity compared to the Hanford Reach, as riffles, gravel bars, islands, and cobble shorelines have been largely inundated (Dauble, 2000).

- **Riparian shoreline.** Riparian habitat is found along the shorelines of many of the impounded areas. Macrophytes are restricted to areas near shorelines because of the depth of the water in the reservoirs. Riparian habitat in the downstream reaches is heavily influenced by human activity, including road and railway construction along the river.

- **Wetlands and shallow marsh.** There are some extensive areas of wetland and shallow marsh associated with the downstream impoundments, especially at the McNary and Umatilla National Wildlife Refuges. These areas can be highly productive for waterfowl and other wildlife.

In general, the types of trophic relationships described for the Hanford Reach also apply to the impoundment areas, with differences in the particular species that make up the trophic categories and differences in the physical parameters that affect biota. For example, the slower-moving water of the reservoirs tends to allow for greater development of phytoplankton populations. The biological diversity of the downstream reaches is also generally lower than in the Hanford Reach, because of the simplification of habitat types and the widespread loss of native aquatic habitat types such as riffles, gravel bars, and cobble shorelines.

6.4.2 Lower Columbia River and Estuary

Downstream of the Bonneville Dam, the lower Columbia River enters a relatively wide, brackish estuary. The salt water wedge can extend upstream as far as the dam. The river, riparian area, and watershed of the Lower Columbia River and Estuary have been influenced by agricultural, urban, and industrial activities. A number of problems affect this area, including a loss of biological integrity, habitat loss and modification, and poor water quality from both conventional pollutants such as nutrients and toxic contaminants such as PCBs, DDE, and dioxins (Lower Columbia River Estuary Program, 1999). Non-native species also create problems for native biota (Sytsma et al., 2004).

The Columbia River estuary historically had extensive areas of tidal marsh and swamp. Since 1948, as much as 70% of the historic tidal wetlands in the Columbia River estuary have been lost. Much of the remaining wetlands are protected by two National Wildlife Refuges. These wetlands provide important feeding, spawning, nursery, and migratory habitat for fish, birds, and wildlife. At the confluence with the Willamette River, the floodplain of the river expands and contains the last major remnants of the historic swamp riparian system (Lower Columbia River Estuary Program, 1999).

Despite the loss of habitat and water quality problems, the Lower Columbia River and Estuary provides habitat for hundreds of year-round or migratory species, including more than 175 species of birds, as well as rare and endangered species (Lower Columbia River Estuary Program, 1999). Shorebirds migrating along the Pacific Flyway use the Lower Columbia River and Estuary as an important stopover point, with peak counts of almost 150,000 birds. Wintering waterfowl populations in the lower Columbia area can exceed 200,000 birds (Lower Columbia River Estuary Program, 1999). Marine mammals, including California and Stellar's sea lions and harbor seals, feed on fish (particularly salmon) in the estuary and use the jetties at the river's confluence as haul-out sites (important habitat locations where they leave the water for reproduction, rest, or predator avoidance) (Lower Columbia River Estuary Program, 1999). Other mammals and wildlife also make use of the habitat resources of the Lower Columbia River and Estuary. Finally, the coastal and ocean habitat influenced by the Columbia River discharge provides habitat for aquatic vegetation such as kelp, fin-fish, shellfish, seabirds, and marine mammals.

Trophic relationships in the Lower Columbia River and Estuary again follow the same general relationships as described for the Hanford Reach, with the exception of species that are not tolerant of salt water and the addition of large marine mammals such as seals and sea lions and additional species of invertebrates such as clams and crabs.

6.5 Pacific Ocean

The Pacific Ocean is included in this aquatic CSM because evidence indicates that Site contaminants came to be located in the ocean, at least in the past. For example, in 1959, sampling of river water at Vancouver, WA allowed Hanford scientists to estimate the equilibrium values for radionuclides entering the ocean. Foster and Junkins (1960) calculated equilibrium values of approximately 400 curies of phosphorus-32 and neptunium-239, approximately 7,000 curies of zinc-65, and approximately 40,000 curies of chromium-51. Tests of Pacific Coast oysters found that the level of radioactivity from zinc-65 was 46×10^{-6} microcuries per gram (μCi/g) in oysters from Willapa Bay, WA, which is near the Columbia River outlet, and approximately one-tenth that level (4.2×10^{-6} μCi/g) in oysters collected from Sequim, WA, far to the north of the Columbia River (Junkins et al., 1960, Appendix B-15). This spatial pattern suggests that radionuclides from Hanford reached the Pacific Ocean and were taken up by biological receptors (Foster and Junkins, 1960).

Biological resources of the Pacific Ocean include a wide array of salt-water dependent invertebrates and vertebrates, including oysters and other shellfish, salt-water bony fish, sharks, and large marine mammals such as seals, sea lions, dolphins, and whales.

6.6 Potential Injury Definitions

The following sections discuss potential injury definitions for these resources. As discussed in previous chapters, the potential injury definitions presented below include both injury definitions that are explicitly contained in federal regulations, as well as other potential injuries discussed during CSM planning workshops. This information is intended to assist the Trustees with assessment planning and does not represent a final or consensus list of injuries that will be assessed. Ultimate selection of injury definitions will be undertaken during development of injury assessment plans.

6.6.1 Injury definitions: Surface water resources

As described in Section 6.1, the DOI regulations define surface water resources as "the waters of the United States, including the sediments suspended in water or lying on the bank, bed, or shoreline and sediments in or transported through coastal and marine areas" [43 CFR § 11.14(pp)]. The DOI regulations present a number of definitions of injury for surface water resources, including:

- Concentrations of hazardous substances exceeding SDWA or other relevant Federal or State standards or criteria for drinking water . . . in surface water that was potable before the discharge or release [for standards] or that before the discharge or release met the criteria and is a committed use, as the phrase is used in this part, as a public water supply [43 CFR § 11.62(b)(1)(i)(ii)]
- Concentrations and duration of substances in excess of applicable water quality criteria established by Section 304(a)(1) of CWA, or by other Federal or State laws or regulations that establish such criteria . . . in surface water that before the discharge or release met the

criteria and is a committed use . . . as a habitat for aquatic life, water supply, or recreation [43 CFR § 11.62(b)(1)(iii)]

- Concentrations of substances on bed, bank, or shoreline sediments sufficient to cause the sediment to exhibit characteristics identified under or listed pursuant to Section 3001 of the SWDA [43 CFR § 11.62(b)(1)(iv)]

- Concentrations and duration of hazardous substances sufficient to have caused injury to biological resources when exposed to surface water [43 CFR § 11.62(b)(1)(v)].

A discussion of the terms "potable before the release" and "committed use" as well as the SWDA characteristics is included in the groundwater CSM (Chapter 5).

6.6.2 Injury definitions: Biological resources

Biological resources in aquatic habitats, including vegetation, invertebrates, fish, birds, amphibians, reptiles, and mammals, may have been injured by releases of hazardous substances from the Site and by stressors associated with response actions at the Site.

DOI regulations

The DOI regulations specify a number of injury tests for biological resources. Specifically, the DOI regulations state that an injury to a biological resource has resulted from the . . . release of a hazardous substance if the concentration of the substance is sufficient to:

- Cause the biological resource or its offspring to have undergone at least one of the following adverse changes in viability: death, disease, behavioral abnormalities, cancer, genetic mutations, physiological malfunctions (including malfunctions in reproduction), or physical deformations [43 CFR § 11.62(f)(1)(i)]

- Exceed action or tolerance levels established under Section 402 of the Food, Drug and Cosmetic Act, 21 USC 342, in edible portions of organisms [43 CFR § 11.62(f)(1)(ii)]

- Exceed levels for which an appropriate State health agency has issued directives to limit or ban consumption of such organism [43 CFR § 11.62(f)(1)(iii)].

The DOI regulations also state that an injury can be demonstrated if the biological response under consideration can satisfy all of the following acceptance criteria [43 CFR § 11.62(f)(2)]:

- The biological response is often the result of exposure to hazardous substances [43 CFR § 11.62(f)(2)(i)]
- Exposure to hazardous substances is known to cause this biological response in free-ranging organisms [43 CFR § 11.62(f)(2)(ii)]
- Exposure to hazardous substances is known to cause this biological response in controlled experiments [43 CFR § 11.62(f)(2)(iii)]
- The biological response measurement is practical to perform and produces scientifically valid results [43 CFR § 11.62(f)(2)(iv)].

NOAA regulations

NOAA's regulations for NRDA [15 CFR Part 990] under the Oil Pollution Act (OPA) define injury as an adverse change in a natural resource. According to the NOAA guidance (NOAA, 1996), categories of adverse changes relevant to biological organisms include:

- Survival, growth, and reproduction
- Health, physiology and biological condition
- Behavior
- Community composition
- Ecological processes and functions
- Physical and chemical habitat quality or structure
- Services to the public.

6.6.3 Other potential injury definitions

As discussed previously, Trustees are not required to use the definitions of natural resource injuries put forth in the DOI regulations [43 CFR § 11.10]. The Trustees discussed alternative injury definitions during CSM workshops; the injury definitions presented herein do not represent a consensus list of potential injuries. As stated previously, ultimate selection of injury definitions will be undertaken during development of injury assessment plans.

Other potential injury definitions that may be considered could include:

- Impairment of surface water services for any domestic, livestock, or agricultural purpose
- Unusable surface water resources because response actions such as rubble barriers or institutional controls prevent use of surface water regardless of contaminant concentrations
- Degradation of surface water quality in violation of Native American treaties
- Reduction in aquatic habitat services because of the presence of contamination, regardless of the contaminant concentrations
- Reduction in aquatic services because of the stigma of surface water contamination
- Any adverse impacts to aquatic biota, or the services provided by the biota, caused by the presence of contamination.

6.7 Services

Releases of hazardous substances from the Site may have adversely affected ecological and human services associated with aquatic resources. This section provides a brief overview of aquatic services. It is intended to be illustrative to help inform injury assessment planning. A comprehensive analysis of aquatic services and potential services losses resulting from releases of Hanford contaminants would be undertaken in the injury assessment.

The DOI regulations define services as the "physical and biological functions performed by the resource including the human uses of those functions. These services are the result of the physical, chemical, or biological quality of the resource" [43 CFR § 11.14(nn)]. The regulations further specify that "services include provision of habitat, food and other needs of biological resources, recreation, other products or services used by humans, flood control, ground water recharge, waste assimilation, and other such functions that may be provided by natural resources" [43 CFR § 11.71(e)]. All of these services are provided by aquatic resources at the Site. The provision of habitat services for spawning of fall Chinook salmon is an illustration of one of the services provided by the Hanford Reach, but many other important ecological and human services are provided as well.

Indigenous peoples are intimately connected to the aquatic food web of the Columbia River and the other aquatic resources at the Site through a range of services derived from the aquatic environment, including food, medicine, religion, recreation, education, and community. Members of the Yakama, Umatilla, Nez Perce, and Wanapum tribes rely on Columbia River fish and waterfowl for food and cultural practices (CRITFC, 1999; Anderson et al., 2002). Fish species used by the tribes most prominently include salmon (Chinook, Coho, sockeye, and chum) and trout (cutthroat and steelhead). Other species such as bass, bull trout, smelt, lamprey, suckers, whitefish, and sturgeon are also used but serve a less important role historically (Landeen and Pinkham, 1999). Recreational fishing by people of many ethnicities also connects humans to the aquatic food web. Chapter 9 provides a more comprehensive discussion of tribal and other human services.

References

Anderson, D.M., M.J. Scott, A.L. Bunn, R.A. Fowler, E.L. Prendergast, T.B. Miley, T.O. Eschbach, and J.A. Jaksch. 2002. 2001 *Columbia River Recreation Survey: Implications for the Hanford Site Integrated Assessment.* PNNL-13840. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy.

Becker, J.M., C.A. Brandt, D.D. Dauble, A.D. Maughan, and T.K. O'Neil. 1996. *Species for the Screening Assessment, Columbia River Comprehensive Impact Assessment.* DOE/RL-96-16-b. Prepared by the Pacific Northwest National Laboratory, Richland, WA. Revision 0.

Bunn, A.L., S.D. Cannon, J.P. Duncan, R.A. Fowler, B.G. Fritz, D.W. Harvey, P.L. Hendrickson, D.J. Hoitink, D.G. Horton, G.V. Last, T.M. Poston, E.L. Prendergast-Kennedy, S.P. Reidel, A.C. Rohay, M.R. Sackschewsky, M.J. Scott, and P.D. Thorne. 2005. *Hanford Site National Environmental Policy Act (NEPA) Characterization*. PNNL-6415 Rev. 17. Pacific Northwest National Laboratory. Prepared for the U.S. Department of Energy. September.

Burk, K.W., M.A. Chamness, R.A. Fowler, B.G. Fritz, P.L. Hendrickson, E.P. Kennedy, G.V. Last, T.M. Poston, M.R. Sackschewsky, M.J. Scott, S.F. Snyder, M.D. Sweeney, and P.D. Thorne. 2007. *Hanford Site National Environmental Policy Act (NEPA) Characterization.* PNNL-6415. Rev. 18. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. September.

Cowardin, L.M., V. Carter, F.C. Golet, and E.T. LaRoe. 1979. *Classification of Wetlands and Deepwater Habitats of the United States.* U.S. Fish Wildl. Serv. FWS/OBS 79/31. U.S. Government Printing Office, Washington, DC.

CRITFC. 1999. Protecting and Restoring Watersheds; A Tribal Approach to Salmon Recovery. Columbia River Inter-Tribal Fish Commission. Available: http://www.critfc.org/oldsite/handbook/TitlePage.html. Accessed 2/11/2009.

Dauble, D. 2000. Assessment of the Impacts of Development and Operation of the Columbia River Hydroelectric System on Mainstem Riverine Processes and Salmon Habitats, 1998–2000 Final Report, Project No. 199800402. Columbia River Research Laboratory, BPA Report DOE/BP-08104-1. Available: http://pisces.bpa.gov/release/documents/documentviewer.aspx?pub = H08104-1.pdf. Accessed 2/17/2009.

Dauble, D., T. Hanrahan, D. Geist, and M. Parsley. 2003a. Impacts of the Columbia River hydroelectric system on main-stem habitats of fall Chinook salmon. *North American Journal of Fisheries Management* 23:641–659.

Dauble, D.D., G.W. Patton, T.M. Poston, and R.E. Peterson. 2003b. *Evaluation of the Effects of Chromium on Fall Chinook Salmon in the Hanford Reach of the Columbia River: Integration of Recent Toxicity Test Results*. PNNL-14008. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy.

Dirkes, R.L. and R.W. Hanf (eds.). 1996. *Hanford Site Environmental Report for Calendar Year 1995.* PNNL-11139. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. June. Available: http://hanford-site.pnl.gov/envreport/. Accessed 4/1/2009.

Doctor, P.G., K.A. Gano, and J.K. Linville. 2004. *Conceptual Site Model for the 100-B/C Pilot Project Risk Assessment*. Rev. 0. BHI-01706. Prepared by Bechtel Hanford, Inc. for the U.S. Department of Energy, Richland Operations Office. March.

Downs, J.L., M.A. Simmons, J.A. Stegen, A.L. Bunn, B.L. Tiller, S.L. Thorsten, and R.K. Zufelt. 2004. *Ecological Characterization Data for the 2004 Composite Analysis.* PNNL-14884. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy.

Foster, R.F. and R.L. Junkins. 1960. Off-Project Exposure from Hanford Reactor Effluent. HW-63654. Hanford Atomic Products Operation. February 1.

Froese, R. and D. Pauly. 2009. FishBase. World Wide Web Electronic Publication. Available: http://www.fishbase.org. Accessed 4/20/2009.

Garcia Berdeal, I., B. Hickey, and M. Kawase. 2002. Influence of wind stress and ambient flow on a high discharge river plume *J. Geophys. Res.* 107(C9):3130.

Geist, D.R. 2000. Hyporheic discharge of river water into fall Chinook salmon (*Oncorhynchus tshawytscha*) spawning areas in the Hanford Reach, Columbia River. *Canadian Journal of Fisheries and Aquatic Sciences* 57:1647–1656.

Geist, D.R., J. Jones, C.J. Murray, and D.D. Dauble. 2000. Suitability criteria analyzed at the spatial scale of redd clusters improved estimates of fall Chinook salmon (*Oncorhynchus tshawytscha*) spawning habitat use in the Hanford Reach, Columbia River. *Canadian Journal of Fisheries and Aquatic Sciences* 57:1636–1646.

Gerber, M.S. 1993. History of 100-B/C Reactor Operations, Hanford Site. Westinghouse Hanford Company. Facility Operations Division. WHC-SD-EN-RPT-004. April. Available: http://b-reactor.org/hist-toc.htm. Accessed 2/11/2009.

Gerber, M.S. 1996. The Plutonium Production Story at the Hanford Site: Processes and Facilities History. Westinghouse Hanford Company, Richland, WA. Prepared for the U.S. Department of Energy. June.

Gray, R.H. and D.D. Dauble 1977. Checklist and relative abundance of fish species from the Hanford Reach of the Columbia River. *Northwest Science* 1(1):208–215.

Hartman, M.J. and W.D. Webber (eds.). 2008. *Hanford Site Groundwater Monitoring for Fiscal Year 2007*. DOE/RL-2008-1. Prepared for the U.S. Department of Energy.

Hickey, B., L. Pietrafesa, D. Jay, and W. Boicourt. 1998. The Columbia River plume study: Subtidal variability in the velocity and salinity fields. *J. Geophys. Res*. 103:10,339–10,368.

Hines, S. 2001. Columbia River Trumps Pacific Ocean When Conditions are Right. University of Washington News. Available: http://uwnews.org/article.asp?articleID = 2615. Accessed 2/20/2009.

Junkins, R.L., E.C. Watson, I.C. Nelson, and R.C. Henle. 1960. Evaluation of Radiological Conditions in the Vicinity of Hanford for 1959. HW-64371. General Electric, Hanford Atomic Products Operation, Richland, WA. May 9. Available: http://hanford-site.pnl.gov/envreport/. Accessed 4/1/2009.

Landeen, D. and A. Pinkham. 1999. *Salmon and His People: Fish & Fishing in Nez Perce Culture*. Confluence Press, Lewiston, ID.

Lower Columbia River Estuary Program. 1999. Comprehensive Conservation and Management Plan. June. Available: http://www.lcrep.org/mgmt_complete_plan.htm. Accessed 2/17/2009.

Mueller, R.P. and D.R. Geist. 1999. *Steelhead Spawning Surveys Near Locke Island, Hanford Reach of the Columbia River.* PNNL-13055. Pacific Northwest National Laboratory. Prepared for the U.S. Department of Energy. October.

Nelson, J.S., E.J. Crossman, H. Espinosa-Perez, L.T. Findley, C.R. Gilbert, R.N. Lea, and J.D. Williams. 2004. *Common and Scientific Names of Fishes from the United States, Canada, and Mexico.* 6th ed. American Fisheries Society, Bethesda, MD.

NOAA. 1996. Injury Assessment Guidance Document for Natural Resource Damage Assessment Under the Oil Pollution Act of 1990. Prepared for the Damage Assessment and Restoration Program – National Oceanic and Atmospheric Administration. August.

NOAA. 2009. Weather Observation Station Records. NOAA Satellite and Information Service – National Environmental Satellite, Data, and Information Service. National Climatic Data Center. National Oceanic and Atmospheric Administration. Station date available: http://lwf.ncdc.noaa.gov/oa/climate/stationlocator.html. Accessed 2/23/2009.

O'Connor, G. and K. Wieda. 2001. *Northwest Arid Lands: An Introduction to the Columbia Basin Shrub-Steppe*. Battelle Press, Columbus, OH.

PNNL. 1998. *Screening Assessment and Requirements for a Comprehensive Assessment: Columbia River Comprehensive Impact Assessment*. DOE/RL-96-16. Revision 1, Final. Pacific Northwest National Laboratory.

Raub, L. 2008. Lake Celilo. Entry in Lakelubbers.com. Available: http://www.lakelubbers.com/lake-celilo/424/. Accessed 2/17/2009.

Rickard, W., W. Hanson, and R. Fitzner. 1982. The non-fisheries biological resources of the Hanford reach of the Columbia River. *Northwest Science* 56:62–76.

Ridolfi. 2006. Preassessment Screen for the Hanford Facility. Public review draft. Prepared for the Confederated Tribes and Bands of the Yakama Nation. Ridolfi Inc. October 18.

Sackschewsky, M.R. and J.L. Downs. 2001. *Vascular Plants of the Hanford Site*. PNNL-13688. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. September.

Sytsma, M., J. Cordell, J. Chapman, and R. Draheim. 2004. Lower Columbia River Aquatic Nonindigenous Species Survey, 2001–2004: Final Technical Report. Prepared for the United States Coast Guard and the United States Fish and Wildlife Service. October. Available: http://www.fish.washington.edu/research/wet/publications/LCRANS_FinalRep.pdf. Accessed 2/17/2009.

Tanner, D.Q., H.M. Bragg, and M.W. Johnston. 2005. Total Dissolved Gas and Water Temperature in the Lower Columbia River, Oregon and Washington, 2005 – Quality-Assurance Data and Comparison to Water-Quality Standards. U.S. Geological Survey Data Series 148. Available: http://pubs.usgs.gov/ds/2005/148/pdf/ds148.pdf. Accessed 2/19/2009.

Topinka, L. 2008. Bonneville Reservoir. Entry in the Columbia River: A Photographic Journey. Available: http://columbiariverimages.com/Regions/Places/bonneville_reservoir.html. Accessed 2/18/2009.

Upper Columbia Salmon Recovery Board. 2007. Upper Columbia Spring Chinook, Salmon, and Steelhead Recovery Plan. Available: http://www.ucsrb.com/UCSRP%20Final%209-13-2007.pdf. Accessed 4/15/2009.

USACE. 1997. McNary Lock and Dam – Lake Wallula. U.S. Army Corps of Engineers. Available: http://www.nww.usace.army.mil/html/pub/pi/navigation/mcnary.htm. Accessed 2/15/2009.

USACE. Undated. Columbia-Snake River Inland Waterways. U.S. Army Corps of Engineers. Available: https://www.nwp.usace.army.mil/op/B/docs/brochures/Col_Snake_inland_ww_map.pdf. Accessed 2/15/2009.

U.S. DOE. 2001. *Hanford Site Biological Resources Management Plan.* Revision 0. DOE/RL 96-32. U.S. Department of Energy. August.

U.S. DOE. 2005. Aquatic and Riparian Receptor Impact Information for the 100-NR-2 Groundwater Operable Unit. Richland, WA. October 31.

U.S. DOE. 2007. *Risk Assessment Report for the 100 Area and 300 Area Component of the River Corridor Baseline Risk Assessment.* DOE/RL-2007-21. Draft A. Richland, WA.

U.S. DOE. 2008. *Remedial Investigation Work Plan for Hanford Site Releases to the Columbia River.* U.S. Department of Energy. DOE/RL-2008-11. Rev. 0. September.

U.S. EPA. 2009. Lower Columbia: From Bonneville to Pacific Ocean. Available: http://yosemite.epa.gov/r10/ECOCOMM.NSF/Columbia/Lower+Columbia. Accessed 2/17/2009.

USFWS. 2008a. Final Hanford Reach National Monument Comprehensive Conservation Plan and Environmental Impact Statement. August. Available: http://www.fws.gov/hanfordreach/planning.html. Accessed 4/13/2009.

USFWS. 2008b. Hanford Reach National Monument Final Comprehensive Conservation Plan and Environmental Impact Statement; Adams, Benton, Grant and Franklin Counties, Washington. August.

USFWS. 2009. Fish – Fact Sheet for the Hanford Reach National Monument. Available: http://www.fws.gov/hanfordreach/fish.html Accessed 4/13/2009.

USFWS. Undated. McNary National Wildlife Refuge – Concept Management Plan for Addition of Three Rivers Unit to the Existing Refuge. Available: http://ublib.buffalo.edu/libraries/e-resources/ebooks/images/edp9049.pdf. Accessed 2/17/2009.

Visser, R., D.D. Dauble, and D.R. Geist. 2002. Use of aerial photography to monitor Chinook salmon spawning in the Columbia River. *Transactions of the American Fisheries Society* 131(6):1173–1179.

WDFW. 2000. The Rattlesnake Hills (Hanford) Elk Strategic Management Plan. Washington Department of Fish and Wildlife. Available: http://wdfw.wa.gov/wlm/game/elk/hanford2.pdf. Accessed 3/19/2009.

7. Terrestrial Resources

This chapter presents a CSM for terrestrial resources potentially exposed to and/or injured by stressors in the Hanford assessment area. As discussed previously in this document, we use the term "stressors" to refer to substances or activities that may have caused injuries to natural resources for which the Trustee Council may quantify damages. Specifically, stressors may include:

- Hazardous substances as defined in Section 101(14) of CERCLA
- By-products of hazardous substances [43 CFR § 11.14(v)]
- Response actions that cause unavoidable injuries to natural resources [43 CFR § 11.15].

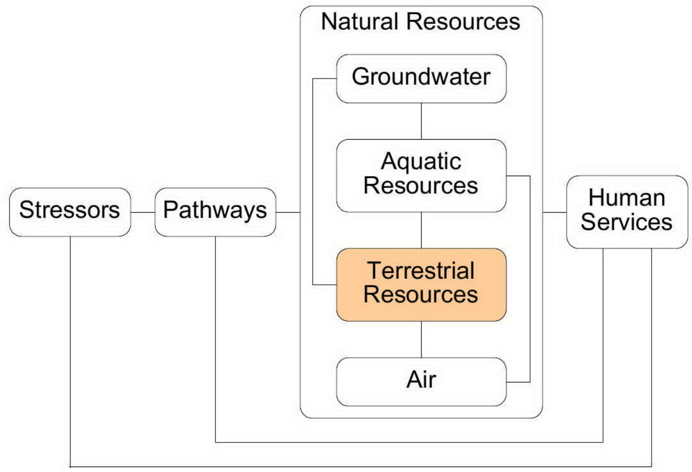


Figure 7.1. Relationship between the terrestrial resource CSM and other CSMs that together make up the NRDA CSM.

Adverse effects to terrestrial resources can occur through direct exposure to a stressor, including exposure to radionuclides or other hazardous substances released from the Site. Adverse effects to terrestrial organisms also can occur through indirect effects, such as habitat loss or degradation, a loss of prey base, changes in the food web structure, or other impacts to the organisms' physical or biological environment. Figure 7.1 illustrates the relationship between the terrestrial resource CSM and the other CSMs provided in this document.

7.1 Terrestrial Natural Resources

Terrestrial resources include biological resources and geologic resources. Biological resources are defined in the DOI regulations as ". . . fish and wildlife and other biota. Fish and wildlife include marine and freshwater aquatic and terrestrial species; game, nongame, and commercial species; and threatened, endangered, and State sensitive species" [43 CFR § 11.14(f)]. Geologic resources are "those elements of the Earth's crust such as soils, sediments, rocks, and minerals . . . that are not included in the definitions of ground and surface water resources" [43 CFR § 11.14(s)].

This terrestrial resources CSM focuses on upland resources and on the small aquatic and riparian habitats that are found within the uplands of the Hanford assessment area, including ponds, ephemeral streams, and springs. These natural resources include surface soils, vegetation, and biota, including but not limited to soil microbes, invertebrates, mammals, birds, and herpetofauna (reptiles and amphibians). Surface soils refer here to the layer of soil that is biologically active. A more specific definition of the surface soil resource could be developed during the injury assessment phase, based, for example, on zones of rooting depth or zones with a certain level of microbial activity. This terrestrial resources CSM considers soils (geologic resources) both as a potentially injured natural resource and as a pathway of contaminant transport to terrestrial biological resources and their supporting habitat. Deep soils are considered part of the vadose zone discussed in Chapter 5.

As discussed in the aquatic CSM (Chapter 6), this terrestrial CSM explicitly recognizes the many points of connection between aquatic and terrestrial resources. Riparian habitats exist at the transition between aquatic and upland habitats and are included in both the aquatic and the terrestrial CSM. Many wildlife species will include food items from a combination of aquatic, upland, and riparian habitats, with the proportion of aquatic versus terrestrial items varying seasonally and through the life-cycle of the organism (Downs et al., 2004). For example, bald eagles may include fish and small mammals as prey items and elk may forage for vegetation in upland and riparian habitat. These ecological connections between aquatic and terrestrial resources may influence pathways of contaminant transport as well as the type and degree of injury in biological resources. In addition, traditional tribal practices integrate aquatic and terrestrial resource use.

7.2 Geographic Scope

The geographic scope for the terrestrial resources CSM includes all the locations where hazardous substances and by-products of hazardous substances released from the Site have come to be located in terrestrial habitats, as well as locations of response actions that cause unavoidable injuries to terrestrial natural resources. This includes the Hanford Operations Area itself, the surrounding Hanford Reach National Monument, as well as off-site locations exposed to hazardous substances released from the Site. Off-site locations have been exposed to hazardous substances through aerial transport and deposition, deposition of contaminated surface water and sediment into riparian and floodplain habitats along the Columbia River, and potentially deposition on agricultural lands through downstream irrigation. This geographic scope has and will continue to evolve over time in response to the changing emissions of hazardous substances from the Site. For example, air emissions of radionuclides peaked in 1945. At that time, the aerial deposition of iodine-131 at concentrations greater than 0.005 nanocuries was projected to have reached Spokane (see the air resources CSM, Chapter 8). However, the radiological half life of iodine-131 is about 8 days, so all of the iodine-131 released in 1945 has now decayed. Longer-lived radionuclides also have been released into the air pathway. For example, Kr-85, with a half-life of 10.8 years, was released from the PUREX plant at Hanford between 1983 and 1992 (Patton and Cooper, 1993). Concentrations of the moderate-lived radionuclides strontium-90 and cesium-137 were measured as elevated in the plant species Carey's balsamroot and Gray's desert parsley on the Site and in offsite locations 50–70 miles from Hanford (e.g., Moses Lake, WA and Washtucna, WA) (Poston, 1995). The source of the radionuclides in the offsite locations still needs further investigation.

The Hanford Site is situated within the shrub-steppe biome of the larger Columbia Basin Province. As discussed in Chapter 2, before European settlement and extensive agricultural conversion, the Columbia Basin Province was composed primarily of shrub-steppe habitat, with a wide diversity of specific vegetation community types with different species of shrubs, grasses, forbs, and intact biological soil crusts (U.S. DOE, 2001). Today, the Columbia Basin Province includes shrub-steppe habitat, agriculture, and residential and commercial development. Because of the relative amount of available data, much of the discussion contained in the chapter of the CSM focuses on those habitats that are currently or were historically part of the Site, including the areas that are now part of the Hanford Reach National Monument (Figure 7.2). As noted above, however, the Site does not define the entire assessment area for the NRDA and the spatial focus for terrestrial resources in the injury assessment may change as more information is gained about contaminant transport and natural resource injury.

Terrestrial resources in floodplain and riparian habitats downstream of the Hanford operations area have been exposed to hazardous substances released from the Site. The extent of this exposure also has changed over time, in response to changing emissions from Hanford operations and the timing of high flows, floods, and dam construction on the Columbia River. In general, dams can trap sediment that is in the river, resulting in a potential build-up of contamination from Hanford sources behind the downstream dams on the Columbia River, including McNary, John Day, The Dalles, and Bonneville dams (Priddy et al., 2005).

7.3 Site Areas

The Site represents a unique area within the shrub-steppe zone of Washington State because of its large geographic extent and its status as one of the largest remaining contiguous tracts containing intact shrub-steppe ecosystem (Soll et al., 1999). It is located in the hottest and driest portion of the Columbia Basin Ecoregion; thus, it has some unique species assemblages and is also fragile and difficult to restore (U.S. DOE, 2001). The 586 square miles of the Site, including the Hanford Reach National Monument, have preserved unique high-quality shrub-steppe, riverine, and riparian habitats (U.S. DOE, 2001).

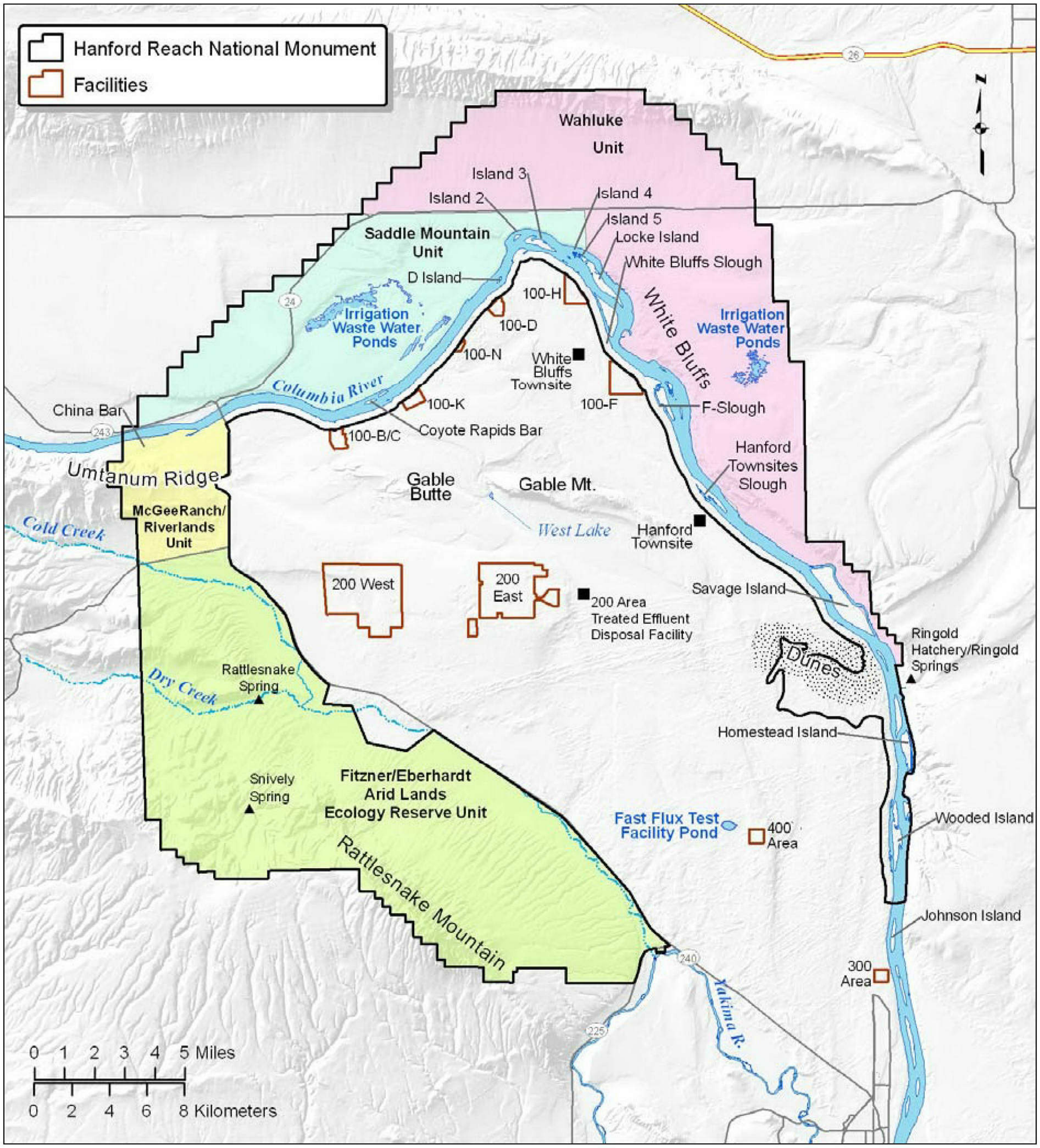


Figure 7.2. The Hanford operations area and the surrounding Hanford Reach National Monument.

Terrestrial habitats on the Site are not uniform, but vary with soil type, elevation, and distance to water. Riparian habitats associated with the Columbia River and with small surface water bodies on the Site support a high diversity and abundance of wildlife. From the viewpoint of biodiversity, the conservation values of the Site are of regional and national importance, with a large number of special status species (Soll et al., 1999). The Site and the habitats within also provide important resources and services to the members of the Yakama, Umatilla, Nez Perce, and Wanapum people.

7.3.1 Description of stressors

As described in Chapter 3, stressors include releases of hazardous substances, by-products of hazardous substances, and response actions. Releases can be classified as either primary (direct discharges) or secondary (discharges that occur through pathways from other natural resources). Terrestrial resources have been exposed to stressors, including hazardous substances such as radionuclides, organics, and metals, from sources that include:

- Air emissions during plutonium production operations
- Process and waste liquids released to soils and biological resources from surface impoundments and from unintentional leaks into the ground
- Contaminated solid wastes released to soils and biological resources from burial grounds, open pit incineration, incineration facilities, the K basins, and railroad cars used for storage
- Facilities and infrastructure associated with nuclear operation, research, and cleanup activities
- Episodic events, including overland flow, spills, leaks, and explosions, and wildfire that may have resulted in the release of hazardous substances into the environment
- Other activities at the Hanford operations area, including transportation, site maintenance, landfills, and other historic waste management facilities, and military defense facilities.

Secondary releases to terrestrial resources in the assessment area have occurred from sources that include, but are not limited to, the following:

- Aerial deposition and precipitation
- Erosion, runoff, and Aeolian transport from soils
- Movement of biotic vectors
- Discharge of contaminated groundwater into the Columbia River, with subsequent impacts on riparian habitats and biota.

Terrestrial resources have been affected by actions that result in a loss of habitat or prey base or a loss of habitat-level functions, such as contiguity of large habitat areas and connectivity between different habitat types. Relevant actions at the Hanford operations area that have been conducted after National Environmental Policy Act (NEPA) review include:

- Vegetation control measures, including mechanical, chemical, and biological methods, to control the spread of contamination through vegetation
- Response actions at the Site, including removal of contaminated soil over large areas, excavation of borrow areas to provide clean fill materials, construction of new waste treatment facilities, construction of a network of roads to link facilities to waste sites, and demolition of facilities.

7.3.2 On-site management areas

On-site management areas include the Hanford operations area, the ALE Reserve and McGee Ranch, the Hanford Reach River Corridor, and the North Slope. Each of these areas is described briefly below.

Hanford operations area

The Hanford operations area is the area that is still under active control and management of DOE. It includes the areas that are the main sources of historic and ongoing hazardous substance releases from the Hanford facility, including the 100, 200, and 300 Areas on the NPL. These areas are the focal points for response actions at the Site. The landscape of the Hanford operations area is primarily open and vegetated with shrub-steppe habitat, in varying degrees of disturbance (U.S. DOE, 2001). Operations areas were historically cleared of vegetation to prevent contamination and minimize fire risk; these areas have started to revegetate naturally but remain in a degraded condition (Doctor et al., 2004). Some waste disposal sites have been remediated and planted with non-native species, such as crested wheatgrass or Siberian wheatgrass, to stabilize the soil, control soil moisture, and prevent invasion by deep-rooted noxious weeds such as Russian thistle (Burk et al., 2007).

The Columbia River forms the northern border of the Hanford operations area. The historic reactor buildings are located close to the river shoreline, approximately 400 meters from the shoreline, in the 100 Area (Becker and McKinstry, 2004). The upland areas away from the reactors consist primarily of degraded shrub-steppe habitat (Doctor et al., 2004). The areas between the reactors and the Columbia River contained contaminated soils that have been or are likely to be impacted by response actions. There is a narrow riparian zone in this area, with steep river banks.

On the Central Plateau, including the 200 Area, there were historic waste disposal ponds, including the U, B, S, Gable, and T ponds, that have been remediated (see Chapter 3). This area also includes West Lake, which is a saline pond that increased in size during operations because liquid discharges elevated the groundwater levels (Emery and McShane, 1978). There are also waste management units in the 300 Area which are managed to exclude large wildlife from entering the area and to keep burrowing animals such as rodents and snakes from burrowing into the waste piles.

Vacant buildings, equipment, and facility structures in the Hanford operations area are used by bats and birds for roosting and nesting (Burk et al., 2007). The largest colony of roosting bats in eastern Washington was discovered in 2006 in the 183-F clearwell, which was an underground concrete structure used to store Columbia River water before the water was used in the 100-F Reactor. The clearwell provides roosting habitat for approximately 2000 bats of the species *Yuma myotis*. Originally scheduled for demolition as part of site cleanup activities, the clearwell has been preserved by DOE to protect bat habitat (Cary, 2009).

ALE Reserve and McGee Ranch

The ALE Reserve is 73,930 acres, located southwest of the Hanford operations area (Figure 7.2) and managed by the USFWS as part of the Hanford Reach National Monument. The ALE Reserve supports high-quality shrub-steppe habitat, especially at higher elevations and on north-facing aspects within the reserve. Important habitat features occurring within the ALE Reserve include two major springs, Snively Spring and Rattlesnake Spring, and Rattlesnake Mountain. The two springs provide important aquatic and riparian habitats within the otherwise dry shrub-steppe ecosystem. The crest of Rattlesnake Mountain supports high-quality soil and vegetation communities. Lower elevations contain ecologically valuable, though lower-quality shrub-steppe habitat (USFWS, 2008).

McGee Ranch is part of the McGee Ranch and Riverlands unit of the Hanford Reach National Monument, comprising approximately 9,000 acres north of the ALE Reserve (Figure 7.2) and managed by DOE. McGee Ranch provides a connection between the ALE Reserve, the Columbia River, and the Wahluke Slope (USFWS, 2008). It includes Umtanum Ridge, which runs west from the Central Plateau to the foothills of the Cascade Mountains and connects the best shrub-steppe habitat remaining in Washington (USFWS, 2008). The McGee Ranch includes a historical homestead, with some habitat disturbances associated with the historic agricultural activity.

River Corridor

The River Corridor unit of the Hanford Reach National Monument comprises 23,331 acres and includes upland, riparian, wetland, island, and sand dune habitats. The Columbia River corridor supports terrestrial biota that make use of riparian and floodplain habitats. This area also is included in the aquatic resources CSM in Chapter 6. In the Hanford Reach, riparian habitat is found along the main shoreline as well as along islands and gravel bars. The shape and width of the river canyon play a large role in determining the area suitable for riparian habitat. Where the river banks are steep, such as in the 100 Area, riparian habitat occupies a narrow zone along the river before a sharp transition to upland habitat.

The aquatic features of the river corridor are described in the aquatic CSM (Chapter 6). Important and unique terrestrial habitat features in the River Corridor include island habitats within the Columbia River, sand dune habitats associated with the river, riparian habitats, and emergent wetland habitats. Eleven islands with approximately 40 miles of shoreline are found within the Hanford Reach (Figure 7.2; Downs et al., 1993). The largest and most prominent islands are Locke Island and Wooded Island (Burk et al., 2007). Cobble shorelines on the islands and along the main shore provide some of the last fall Chinook salmon spawning habitat in the Columbia River, as well as substrate for native riparian and wetland plant species.

North Slope

The North Slope of the Columbia River includes the Saddle Mountain and Wahluke units of the Hanford Reach National Monument. Saddle Mountain is 30,981 acres and has been managed by the USFWS since 1971. The Wahluke unit is 50,034 acres and was managed for public access by WDFW from 1971 to 1999 and has been managed by the USFWS since 1999. The Wahluke Slope is characterized by a wide range of habitats and diverse plant communities. Historic land uses in these units included grazing, farming, and military training, resulting in more invasive species present in this area compared to other areas of the Hanford Reach National Monument (USFWS, 2008).

The important habitat features present on these two sites include the Wahluke Slope, the Saddle Mountains, the White Bluffs, and sand dunes. The Wahluke Slope acts as a buffer between the agricultural areas surrounding the Site and the more fragile habitats present on the White Bluffs (USFWS, 2008). The White Bluffs border the northern shore of the Columbia River and support plant communities somewhat distinct from those found throughout the Site as a whole.

7.3.3 Habitats

A number of different habitat types are found on the Site, across all the different management areas described above. The main habitat types are shrub-steppe, riparian, wetland, and aquatic (U.S. DOE, 2001), with additional smaller areas of specialized habitats, including basalt outcrops, bluffs/cliffs, and sand dunes (Downs et al., 1993). In addition, there are on-site ponds and wetlands associated with human activities, and artificial habitats that have been created through response actions.

Shrub-steppe

The primary terrestrial habitat on the Site is shrub-steppe, characterized by an overstory of arid-adapted shrubs such as sagebrush and an understory of arid-adapted grasses and forbs. Shrub-steppe uplands lack sufficient moisture to support trees, which are only found on-site in areas with an additional water source besides precipitation. Important shrubs found on the Site include big sagebrush, gray rabbitbrush, green rabbitbrush, Antelope bitterbrush, spiny hopsage, threetip sagebrush, and black greasewood (Sackschewsky and Downs, 2001). Common understory grasses include bluebunch wheatgrass, Sandberg's bluegrass, needle-and-thread grass, Indian ricegrass, Cusick's bluegrass, Idaho fescue, and an aggressively invasive species, cheatgrass (Sackschewsky and Downs, 2001). Forbs are usually found associated with the understory grasses and make up the most visible annual flowering species of the ecosystem. Common forb species found on the Site include Carey's balsamroot, long-leaved phlox, yarrow, and daisy fleabane (Sackschewsky and Downs, 2001). These shrub-grass-forb associations (sometimes called "fertile islands") are surrounded by interspaces containing cryptobiotic soil crusts, which are associations of algae, fungi, and bryophytes that transform bare soil into productive components of the ecosystem (Sackschewsky and Downs, 2001; USFWS, 2008).

A wide diversity of specific vegetation community types exist within the shrub-steppe habitat at the Site, influenced by soil-type, elevation, and local site history; these diverse habitats support a corresponding diversity of animals (Soll et al., 1999). Soils can be generally classified as sand, silt, or loam, with some areas of gravel or cobble in riparian areas (Sackschewsky and Downs, 2001; Burk et al., 2007; USFWS, 2008). The Site includes some areas with deep, sandy soil that are rare within the Columbia Basin Ecoregion (Soll et al., 1999). Precipitation increases across the Site with elevation; the crest of Rattlesnake Mountain (3,772 feet) receives approximately

12–14 inches of precipitation annually, while the annual average precipitation near the Columbia River (elevation 492 feet) is just 4.7 inches (Downs et al., 1993). One study of rare habitats and biota on the Site distinguished slope and plateau habitats because of the large influence of elevation and slope on the specific vegetation communities included within the general shrub-steppe category (Downs et al., 1993). The Biological Resources Management Plan (U.S. DOE, 2001) distinguished 48 different land-cover classes across the Site, including 12 different classes of big sagebrush habitat, depending on the understory species present (e.g., bunchgrass, bluebunch wheatgrass, Indian ricegrass).

The Site contains a large contiguous landscape connecting these different habitat types, supporting populations of plants and animals that are rare or absent in smaller preserved areas of shrub-steppe (Soll et al., 1999). Many parts of the Site are relatively free of non-native species, although in some places, especially disturbed areas, cheatgrass is common (Sackschewsky and Downs, 2001). Fire also plays an important role as a disturbance agent at the Site. After fire, habitats that were formerly a mixture of shrubs and grasses can become dominated by grasses only. Sagebrush typically does not resprout after fire but can re-establish from a seed source; therefore, natural re-establishment of big sagebrush after fire generally requires seed dispersal, germination, and regrowth from seedlings, which can take many years (Downs et al., 1993).

Until 1943, the start of nuclear production activities, European settlers living in the region used much of the Site for agriculture and grazing. The native shrub-steppe ecosystem is fragile and sensitive to disturbance, and some areas are still impacted by historic disturbances, including grazing and fire (U.S. DOE, 2001). Due in part to past disturbances such as grazing and agriculture, and more recent disturbances such as fire and site-related activities, a variety of invasive species and noxious weeds are present on the Site. Many of these species thrive in disturbed habitats, growing where native vegetation has been removed either intentionally or as a result of natural disturbance events (i.e., fire). Cheatgrass is the most widespread invasive species on the Site. It is a common invader in the western United States and is so well established at the Site that at least one study did not address it in the invasive species discussion (Evans et al., 2003). Some of the other major invasive species present include diffuse knapweed, yellow starthistle, rush skeletonweed, Russian knapweed, and whitetop (Sackschewsky and Downs, 2001; Evans et al., 2003). Even though these species are not native, areas with invasive species can provide important habitat functions for native wildlife as well as providing human services.

Riparian communities

Riparian plant communities along the Hanford Reach of the Columbia River are found at the shoreline-river interface and include species that are tolerant of fluctuating levels of surface water. Though a significant amount of riparian habitat contains non-native plant species, these areas still provide important habitat functions for wildlife. Native woody plants along the shoreline include black cottonwood and willows; exotic woody species include mulberry, Siberian elm, and Russian olive. In the understory, native riparian plants include cattails, sedges, and rushes; reed canarygrass is a common invasive species. The islands include wetland, riparian, and upland habitat features and support a range of plant communities that include the riparian vegetation discussed above as well as upland species such as cheatgrass, buckwheat, and lupine (Burk et al., 2007; USFWS, 2008).

Wetland habitats along the Hanford Reach are primarily associated with backwater sloughs and are discussed in the aquatic CSM (Chapter 6).

Natural interior streams, ponds, and wetlands

Natural aquatic habitats found within the upland areas of the Site are part of the integrated shrub-steppe ecosystem and include (1) ephemeral streams that channel overland flow after precipitation events, (2) spring-fed streams that are fed by upwelling groundwater, and (3) vernal ponds that collect water in the winter and dry up in the summer.

Ephemeral streams flow in response to snowmelt or precipitation events. At the Site, Cold Creek and its tributary Dry Creek are ephemeral streams that drain to the west, with rapid infiltration. These streams are located in the Yakima River drainage in the southwestern portion of the Site (Burk et al., 2007). Ephemeral streams generally contain fast-flowing, shallow water during the times they have surface flow.

Spring-fed streams are fed by groundwater upwelling to surface springs. These springs can flow year-round but are sensitive to groundwater levels. There are three main springs at the Site: Snively Spring, which has a perennial surface flow extending approximately 3.6 kilometers; Benson Spring, which flows for 800–900 meters; and Rattlesnake Spring, which flows for approximately 2.5 kilometers down Dry Creek. Rattlesnake Spring is the largest of the three springs, with an average discharge of 0.35 cfs (Evans et al., 2003). The riparian zones associated with Rattlesnake Spring and Snively Creek support highly diverse biological communities (Downs et al., 1993). Rattlesnake Spring has supported dense riparian vegetation that was heavily used by wildlife, such as elk, songbirds, and raptors (Evans et al., 2003; USFWS, 2008). This vegetation was impacted by the large wildfire at the Site in 2000 (Evans et al., 2003) and will take time to recover.

Vernal ponds are depressions that collect precipitation during the winter and then dry up during the summer months. At the Site, they occur in areas with a basalt surface relatively near the surface. The Site has vernal ponds in three different clusters at the Site: at the eastern end of Umtanum Ridge, in the central part of Gable Butte, and at the eastern end of Gable Mountain (see Figure 7.2). The ponds range in size from approximately 400 square feet to 15,000 square feet, depending on the size and distribution of precipitation and snowmelt events (Burk et al., 2007). Similar to ephemeral streams, vernal ponds provide important habitat for invertebrates, amphibians, reptiles, birds, and other wildlife (Vance, 2009).

Specialized habitats – basalt outcrops, bluffs/cliffs, and sand dunes

There are small areas of specialized habitats on the Site. Basalt outcrops, cliffs, and scree (loose rocks) are found along the crests and slopes of the higher elevation areas on the Site, including Rattlesnake Hills, Yakima and Umtanum Ridge, Saddle Mountains, Gable Mountain and Gable Butte. These areas can support specialized habitats and rare plant species. Scarps can support nesting sites for prairie falcons, ferruginous hawks, and other birds, as well as providing habitat for reptiles such as rattlesnakes (Downs et al., 1993).

The White Bluffs on the eastern side of the Columbia River are actively eroding into the Columbia River. The bluffs are devoid of vegetation but provide important nesting habitat for thousands of cliff swallows (Downs et al., 1993).

Sand dunes and blowouts (recently eroded areas) occur in a variety of locations around the Site. Established dunes are found south of the abandoned Hanford town site (see Figure 7.2). Various blowouts are scattered places across the Columbia River plain. These sites support specialized vegetation communities that can colonize sandy substrate (Downs et al., 1993).

Industrial ponds and wetlands

Terrestrial biota historically utilized industrial ponds at the Site. The size and number of these ponds has decreased following remediation and response actions.

During the time of active nuclear operations at the Site, there were many artificial water bodies, including ponds and ditches, that resulted from wastewater disposal at the reactor and separation facilities. For example, the unlined ponds and trenches in the 300 Area received millions of gallons of contaminated waste water between 1943 and 1994 (U.S. DOE, 2007, 2008). A study of the ecology of the waste ponds, including Gable, B, and U Ponds; West Lake; the B-3, A-29, and Z-19 ditches; and the 100-N trench found that the ponds had established diverse aquatic ecosystems, extensive riparian communities including cottonwood and willows, and were attractive to migrating birds (Emery and McShane, 1978). As part of the remedial activities, these former sites (with the exception of West Lake) have been drained, covered with overburden, and reseeded. There are still some active manmade ponds on the Site, including the 200 Area TEDF disposal ponds. These ponds receive permitted industrial wastewater and are each 0.02 square kilometers (5 acres) in size (Burk et al., 2007).

West Lake is a natural pond at the Site; it exists because of an elevated water table that intersects with the land surface in a topographically low area. Water levels of West Lake increased when wastewater discharge within the 200 Area raised the elevation of the water table. The lake has elevated dissolved solids and nitrate, which may have come from the dumping of sewage sludge in the 1940s (which has not been substantiated) or from evaporation causing natural concentration of salts found in groundwater (Burk et al., 2007). Following the decrease in groundwater discharge in the 200 Area in the early 1990s, the water level of West Lake dropped, exposing saline mud flats and salt deposits. This area provides habitat for salt-tolerant vegetation, as well as for a large population of brine flies that are consumed by bats, swallows, and migratory shorebirds (Burk et al., 2007).

Irrigation ditches and associated ponds and wetlands from irrigation runoff are other examples of human-influenced habitats at the Site. Areas to the north and east of the Site are heavily irrigated, with irrigation returns entering the Saddle Mountain and Wahluke units of the Hanford Reach National Monument. This irrigation runoff has formed large pond and wetland complexes, with cattails and other emergent aquatic vegetation surrounding open-water habitat (Burk et al., 2007). These areas also are affected by invasive species, with phragmites and Russian olive especially prevalent (Burk et al., 2007).

Irrigation ditches provide seasonal aquatic habitat, with water flowing during the times of year when irrigation is active. Studies by The Nature Conservancy (TNC) found diverse aquatic macroinvertebrates in one of the irrigation return canals near the Site (Evans et al., 2003). The irrigation ponds are used by waterfowl for nesting sites, support populations of warm-water fish, and also provide habitat for amphibians, birds, and bats (Burk et al., 2007; USFWS, 2008).

Habitats associated with response actions

Distinct habitats have been created as a result of response actions at the Site. Remediated areas, such as the liquid waste sites in the 100 B/C Area, have been revegetated with native species following soil excavation and backfill with uncontaminated soil. Species mixes designed for these remediated areas include native shrub-steppe species, but will not have the same diversity or soil types as native plant communities (Doctor et al., 2004). Other types of disturbed habitats resulting from response actions include those associated with the creation of the waste treatment facilities (see Chapter 3); the planting of exotic wheatgrass species to prevent deep-rooted vegetation from penetrating into a remediated or capped area (Burk et al., 2007); areas managed to preclude wildlife; and areas used for borrow soil, which may be in various stages of reclamation.

7.3.4 Biota

The diversity and high quality of the habitats at the Site, including rare late-successional shrub-steppe habitat, is reflected in the high diversity of terrestrial organisms found at the Site. As described in Chapter 6, Ridolfi Inc. compiled a comprehensive list of species in the Hanford area, showing the interconnected biodiversity of species that have potentially been exposed to and/or injured by stressors at the Site. In total, this list includes 269 bird species, 52 mammal species, 21 amphibian and reptile species, over 800 aquatic and terrestrial plant species, and dozens of orders, families, and genera of aquatic and terrestrial insects.

In 1994, TNC evaluated the ALE and Wahluke units at the Site to determine if there were occurrences of plant community types considered by the State of Washington's Natural Heritage Program to be an "element," defined as an entire ecological system that is a needed component of a system of natural areas. Elements are described as "storehouses of natural diversity," "examples of complex ecological systems," and "associations of abiotic and biotic components that cannot be duplicated artificially" (U.S. DOE, 2001). TNC identified 17 elements at the Site, which constitute 40% of all the terrestrial elements found in the Columbia Basin Province in Washington.

This section discusses the unique qualities of terrestrial invertebrates at the Site, presents some of the species of Conservation Concern, and then gives an overview of trophic relationships and describes species in different trophic categories. Stressors, including extensive response actions, which adversely affect terrestrial resources at the Site can affect obligate terrestrial species as well as species that utilize both terrestrial and aquatic habitats (see Chapter 6). As noted in Chapter 6, discussion of specific species is intended to be illustrative of CSM processes rather than implying that that the injury assessment need focus on these organisms.

Terrestrial invertebrates

TNC conducted intensive insect inventory work on the Hanford Site from 1994 to 1998. The result of this inventory was identification of more than 1500 separate species, including 41 species and two subspecies that were new to science and 142 species not previously known from Washington State. TNC attributed the high level of insect diversity at the Hanford Site to the size, diversity, and relatively intact condition of the native shrub-steppe habitat at the Site. This has led to the preservation of microhabitats that support a large diversity of terrestrial invertebrates (Soll et al., 1999).

Species of Conservation Concern

There are a large number of terrestrial species of special concern at the Site (Table 7.1). These species are listed not to suggest that they should necessarily be the focus for injury assessment, but instead as a further example of the high value of the habitat at the Site.

Table 7.1. Examples of special status vegetation and wildlife species occurring at the Hanford Site

Scientific name	Common name	Federal status	State status
Plants			
Castilleja exilis	Annual paintbrush		Rare/threatened
Pectocarya setosa	Bristly combseed		Watch list
Cryptantha spiculifera (C. interrupta)	Bristly cryptantha		Sensitive
Opuntia fragilis	Brittle prickly-pear		Rare/threatened
Astragalus columbianus	Columbia milkvetch		Threatened
Artemesia lindleyana	Columbia River mugwort		Watch list
Rorippa columbiae	Columbia yellowcress		Threatened
Nicotiana attenuate	Coyote tobacco		Sensitive
Astragalus succumbens	Crouching milkvetch		Watch list
Oenothera cespitosa ssp. cespitosa	Desert (Cespitose) evening primrose		Sensitive
Cryptantha scoparia	Desert cryptantha		Rare/threatened
Cuscuta denticulate	Desert dodder		Sensitive
Astragalus conjunctus var, rickardii	Dr. Bill's locoweed		Rare/threatened
Camisonia (Oenothera) pygmaea	Dwarf evening primrose		Threatened
Lindernia dubia anagallidea	False pimpernel		Unresolved taxonomic status
Penstemon eriantherus whitedii	Fuzzy beardtongue		Rare/threatened
Penstemon eriantherus	Fuzzytounge penstemon		Sensitive
Astragalus geyeri	Geyer's milkvetch		Sensitive
Cryptantha leucophaea	Gray cryptantha		Sensitive
Gilia leptomeria	Great Basin gilia		Rare/threatened
Pediocactus simpsonii var. robustior	Hedge hog cactus		Rare/threatened
Lomatium tuberosum	Hoover's desertparsley		Threatened
Loeflingia squarrosa var. squarrosa	Loeflingia		Threatened
Astragalus speirocarpus	Medic milkvetch		Watch list
Artemisia campestris ssp. borealis var. wormskioldii	Northern wormwood	Candidate	Endangered
Cirsium brevifolium	Palouse thistle		Watch list
Erigeron piperianus	Piper's daisy		Sensitive
Nama densum var. parviflorum	Purple mat		Rare/threatened
Allium robinsonii	Robinson's onion		Watch list
Balsamorhiza rosea	Rosy balsamroot		Watch list
Calyptridium roseum	Rosy calyptridium		Sensitive

Table 7.1. Examples of special status vegetation and wildlife species occurring at the Hanford Site (cont.)

Scientific name	Common name	Federal status	State status
Allium scilloides	Scilla onion		Watch list
Cyperus bipartitus (rivularis)	Shining flatsedge		Sensitive
Camissonia (Oenothera) minor	Small-flowered evening primrose		Rare/threatened
Pellaea glabella simplex	Smooth cliffbrake		Watch list
Astragalus sclerocarpus	Stalked-pod milkvetch		Watch list
Mimulus suksdorfii	Suksdorf's monkeyflower		Sensitive
Eriogonum codium	Umtanum buckwheat	Candidate	Endangered
Lesquerella tuplashensis	White bluffs bladderpod	Candidate	Endangered
Eatonella nivea	White eatonella		Threatened
Pectocarya linearis	Winged combseed		Rare/threatened
Cryptantha spiculifera	Snake River Cryptantha		Sensitive
Hypericum majus	Canadian St. John's-Wort		Sensitive
Centunculus minimus	Chaffweed		Rare/threatened
Delphinium multiplex	Kittitas larkspur		Watch list
Limosella acaulis	Southern mudwort		Watch list
Rorippa calycina	Persistent-sepal Yellowcress	Species of concern	Endangered
Terrestrial birds			
Accipter gentilis	Northern goshawk	Species of concern	Candidate/special concern
Ammodramus savannarum	Grasshopper sparrow		Watch list
Amphispiza belli	Sage sparrow		Candidate/special concern
Aquila chrysaetos	Golden eagle		Candidate/special concern
Athene cunicularia	Burrowing owl	Species of concern	Candidate/special concern
Buteo regalis	Ferruginous hawk	Species of concern	Threatened
Centrocercus urophasianus	Greater sage grouse	Candidate	Threatened
Falco columbarius	Merlin		Candidate/special concern
Falco peregrinus	Peregrine falcon	Species of concern	Sensitive
Lanius ludovicianus	Loggerhead shrike	Species of concern	Candidate/special concern
Melanerpes lewisii	Lewis' woodpecker		Candidate/special concern

Table 7.1. Special status vegetation and wildlife species occurring at the Hanford Site (cont.)

Scientific name	Common name	Federal status	State status
Oreoscoptes montanus	Sage thrasher		Candidate/special concern
Otus flammeolus	Flammulated owl		Candidate/special concern
Other terrestrial wildlife			
Lepus californicus	Black-tailed jackrabbit		Candidate/special concern
Lepus townsendii	White-tailed jackrabbit		Candidate/special concern
Masticophis taeniatus	Striped whipsnake		Candidate/special concern
Myotis ciliolabrum	Small-footed myotis	Species of concern	
Myotis volans	Long-legged myotis	Species of concern	
Sceloporus graciosus	Sagebrush lizard	Species of concern	Candidate/special concern
Sorex merriami	Merriam's shrew		Candidate/special concern
Spermophilus townsendii	Townsend's ground squirrel		Candidate/special concern
Spermophilus washingtoni	Washington ground squirrel	Species of concern	Candidate/special concern

Sources: Sackschewsky and Downs, 2001, Table 4.1; Burk et al., 2007, Table 4.5.1; USFWS, 2008, Tables 3.3 and 3.5; Soll et al., 1999.

There are more than 45 special status plant species at the Site, including four species that are listed as endangered in the State of Washington (Table 7.1). Two of these species, White Bluffs Bladderpod and Umtanum Desert Buckwheat, were discovered on the Site during The Nature Conservancy surveys and are found nowhere else in the world (USFWS, 2004).

More than 250 bird species have been noted on the Hanford Site, including 38 designated as species of Conservation Concern, which Soll et al. (1999) define as Endangered, Threatened, Candidate, Monitor, or Species of Concern according to Washington State and/or the USFWS (some of those 38 species are birds found primarily in aquatic habitats). The Hanford operations area, ALE Reserve, and North Slope each support unique fauna, including species that are only found in one of those three locations (Soll et al., 1999). Examples of birds of Conservation Concern include sage sparrow, which only nest in late-successional habitats dominated by big sagebrush; and long-billed curlew, which is common on the North Slope and the ALE Reserve; western burrowing owl, which breeds on the Hanford Site but is rarely seen; and ferruginous hawk, which breeds on the Hanford Site but is considered uncommon (Soll et al., 1999).

The Hanford Reach, including the shorelines and island areas, is used by many bird species of Conservation Concern. Bald eagle are commonly seen in the fall and winter, primarily in communal roosting and nesting areas in riparian habitat along the Hanford Reach. Other species found along the Hanford Reach include American white pelican, bank swallow, black-crowned night-heron, black-necked stilt, forster's tern, great blue heron, great egret, and osprey (Soll et al., 1999). Waterfowl are discussed primarily in the aquatic resources section, but it is worth noting that multiple species of grebe as well as the common loon are found along the Hanford Reach.

Sixteen reptile and amphibian species have been found on the Site, including three Washington State Monitor species (Woodhouse's toad, tiger salamander, and night snake), one State Candidate species (striped whipsnake), and one Federally designated Species of Concern (sagebrush lizard) (Soll et al., 1999). The large areas of contiguous habitat at the Site are particularly important for the Washington State Monitor species that are otherwise rare or have limited distributions in Washington because of losses of native shrub-steppe habitat.

Eight bat species and 14 other species of small mammals were found during surveys in 1997–1998 (Soll et al., 1999). Three species of bat were identified as species of Conservation Concern. Important habitat and/or roosting areas for bats include cliff areas, open water, White Bluffs, and several structures, including the 108-F Building, the Hanford Town Site Pump House, the 183-F clearwell, and other buildings. Small mammals are found in all the habitats across the Site, with the Great Basin pocket mouse being the most frequently captured species (Soll et al., 1999). The 1998 survey confirmed the presence of the Washington ground squirrel on-site, which is a State Candidate species (Soll et al., 1999).

Terrestrial invertebrates are highly diverse at the Hanford Site, reflecting the size, diversity, and relatively undisturbed condition of the native shrub-steppe habitat. Five years of insect inventory work found more than 1,500 insect species, including 49 butterfly species and 318 species of moths.

Forty-one species new to science were identified and described during the Hanford surveys (Soll et al., 1999). The invertebrate fauna are considered representative of the ecosystem as it existed throughout the West before European settlement (USFWS, 2008).

Large mammals such as deer and elk play an important ecological role at the Site and throughout the terrestrial assessment area. Elk inhabited the area over the past 10,000 years but appeared to have been extirpated by the mid-1800s. Rocky Mountain elk were reintroduced to Washington in the Cascade Mountains in the 1930s; these elk migrated across the state and were first seen on the Hanford Site in 1972. The core range for this elk herd (known as the "Rattlesnake Hills Elk Herd") has been the ALE area and private lands to the south and west of ALE, with peripheral use of the Hanford operations area, the Yakima Training Center, and other surrounding areas.

Starting in approximately 1975, the elk herd at Hanford began to grow at an estimated rate of 25% annually, with a population peak of more than 800 animals by 1998. This large herd size prompted multiple concerns, including impacts to habitat and agricultural lands, vehicle collisions, and increased presence of elk in the Hanford operations area where they could be exposed to contamination. In response, WDFW increased the hunting season in land surrounding the Site. USFWS, together with WDFW and DOE, also conducted two capture and relocation efforts that removed a total of 223 animals in 2000 and 2002. The elk herd was estimated at 639 animals in 2008 (USFWS, 2009).

Trophic relationships

A generalized food-web diagram for terrestrial resources in the Hanford Reach is presented in Figure 7.3. Arrows between food-web categories indicate possible pathways for contaminant transport as well as ecological relationships. For example, contaminants in air can be deposited onto soil, taken up by plants, consumed by invertebrates, consumed by birds, and then ingested by humans. Surface water and soil are direct routes of exposure for all of the categories of biota (plants, invertebrates, birds, small mammals, large omnivores/herbivores/carnivores, and humans) because of the potential for ingestion or contact. The degree of complexity of other pathways depends on the particular species involved. An example of a complex trophic relationship might be small invertebrates consumed by larger invertebrates, which in turn are consumed by small mammals, medium-sized carnivores such as raccoon, and then larger carnivores such as coyote.

At a general level, the terrestrial food-web, like the aquatic food-web, includes primary producers, primary consumers, and secondary and tertiary consumers. Primary producers provide the energetic foundation of any ecosystem, using energy from the sun to support their biological functions. Upland primary producers are diverse and prolific, including the full range of vascular plants and non-vascular, terrestrial photosynthetic organisms. Some 725 plant species have been identified on the Site (Sackschewsky and Downs, 2001). In addition to vascular plants, desert environments support biotic crust communities that include non-vascular photosynthetic organisms such as mosses, bryophytes, and algae. Biological soil crusts are extremely fragile, easily disturbed, and recover slowly from disturbances such as grazing. They are not well understood, but research indicates that they contribute nutrients such as nitrogen and phosphorous to the ecosystem. They may also be an important food source to the soil invertebrate community. Organisms that make up the biological soil crusts include lichens (e.g., *Acarospora schleircheri*, *Aspicilia* spp., *Cladonia* spp., *Collema* spp., *Peltigera* spp., *Psora Montana*, and *Trapeliopsis steppica*) and bryophytes (e.g., *Aloina bifrons*, *Bryum* spp., *Didymodon* spp., *Grimmia trichophylla*, and *Tortula brevipes*) (Evans et al., 2003).

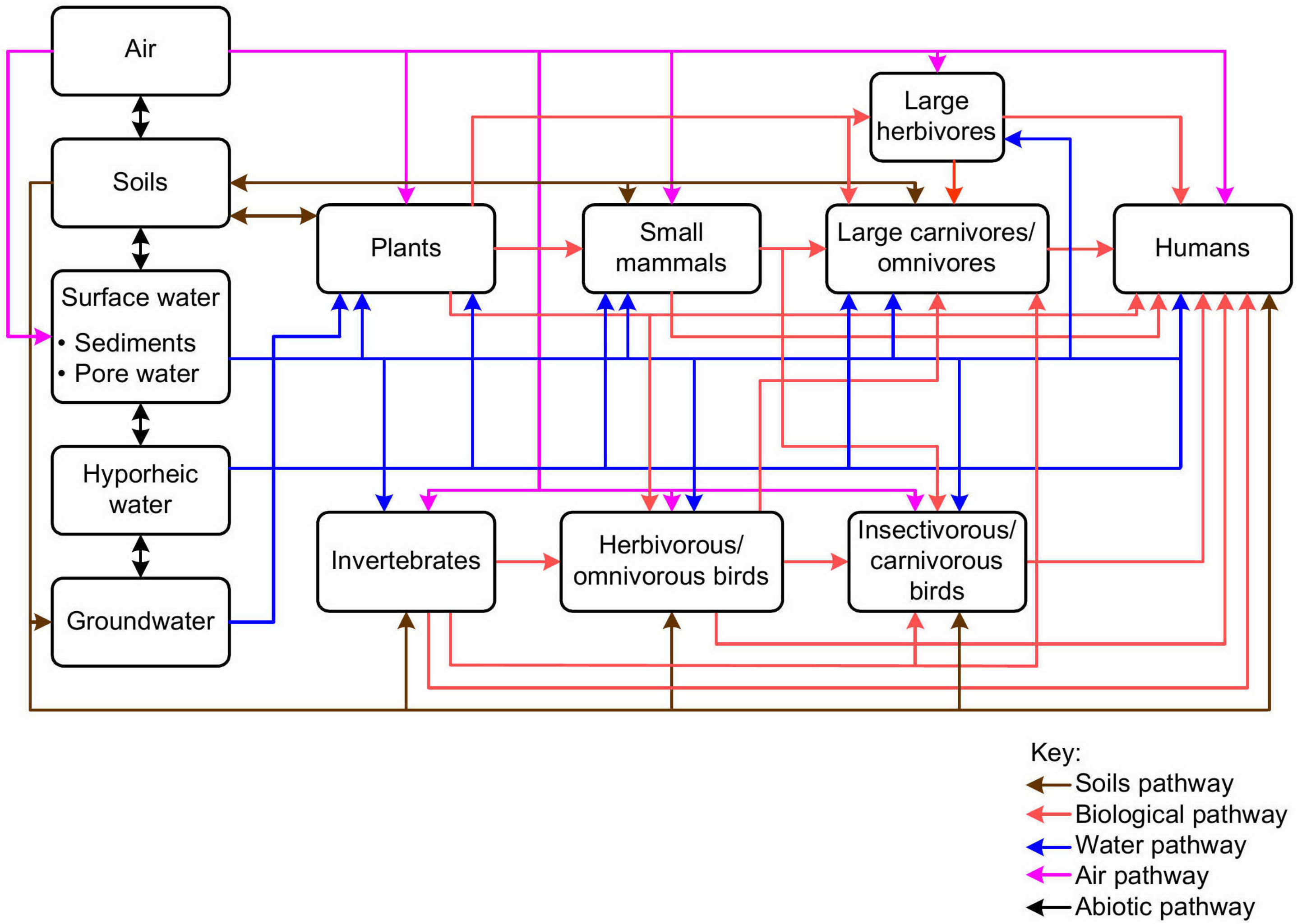


Figure 7.3. Generalized food-web diagram for terrestrial resources in the Hanford Reach.

Primary consumers in upland habitats forage on the full spectrum of vascular and non-vascular plants. The shrub-steppe ecosystem supports large grazers as well as small rodents, avian, and invertebrate herbivores. Herbivores, including humans, consume many parts of the plants, such as leaves, stalks, stems, flowers, roots, seeds, and/or fruits. Some plant species are dependent on the animals that eat them for distribution and fertilization. Examples of herbivorous invertebrates include harvester ants, darkling beetles, earwigs, grasshoppers, caddisflies, moths and butterflies, bees, and wasps (Evans et al., 2003; Doctor et al., 2004). Common native mammalian herbivores present on the Site include elk, black-tailed jackrabbit, Great Basin pocket mouse (the most abundant mammal on the Site), mule deer, sagebrush vole, and western harvest mouse (Becker et al., 1996; Downs et al., 2004; USFWS, 2008).

Secondary and tertiary consumers include insects, reptiles and amphibians, birds, and mammals, including omnivores, carnivores, predators, and/or scavengers. Some examples of carnivorous invertebrates include various species of spider, sowbugs, and scorpions (Evans et al., 2003). Carnivorous upland reptiles and amphibians are a key component of the trophic structure, including the Great Basin gopher snake, short-horned lizard, Woodhouse's toad, side-blotched lizard, and Great Basin spadefoot toad (Becker et al., 1996; Downs et al., 2004). Insectivorous and carnivorous upland bird species include golden eagle, grasshopper sparrow, gray partridge, burrowing owl, chukar, lark sparrow, long-billed curlew, prairie falcon, red-tailed hawk, rock wren, rock dove, ring-necked pheasant, sage sparrow, sage thrasher, savannah sparrow, short-eared owl, Swainson's hawk, and vesper sparrow (Downs et al., 2004). Examples of native mammalian carnivores found on the Site include badger, several species of bats, Merriam's shrew, coyote, deer mouse (Becker et al., 1996; Downs et al., 2004), and at least one recorded instance of a cougar (USFWS, 2008). Humans are the top of the food web and may hunt and consume many of the types of wildlife species present on the Site, including large game mammals and game birds, as well as consuming vegetation. Many animals and plants also serve a cultural, religious, and educational role for native communities.

7.3.5 Disturbance history

Disturbances at the Site include disturbances associated with pre-industrial activities, industrial operations and response actions, and natural disturbances such as wildfires and storms. Disturbances associated with industrial operations and response actions are included within the category of Site stressors and are described in Chapter 3.

Historic disturbances include the agricultural and homestead activities that occurred before 1943 (U.S. DOE, 2001; Burk et al., 2007). For example, in the land that is now the ALE Reserve, there was extensive winter and spring sheep grazing, as well as cattle and horse grazing, and some dryland and irrigated agriculture (USFWS, 2002). Henry Gable ran large herds of horses in the Gable Mountain area – these horses were eventually captured and removed in the early 1980s

(Dan Landeen, Nez Perce Tribe Environmental Restoration and Waste Management, personal communication to Jamie Holmes, Stratus Consulting, May 29, 2009). Livestock particularly favored the riparian area around Rattlesnake Spring. The McGee Ranch included a homestead with associated agricultural activity (USFWS, 2002).

Wildfire is an important disturbance agent at the Site. Fires are a natural part of the ecosystem and help to create a mosaic of different successional stages. However, the spread of cheatgrass has resulted in fires becoming larger and possibly spreading more widely compared to historic fire conditions. Extensive fires were documented on the ALE Reserve in 1957, 1973, 1981, and 1984, resulting in the removal of shrub cover in many areas and creating large areas of grassland (Soll et al., 1999). More recently, the "24 Command" fire in June 2000 spread across the ALE Reserve and into the Hanford operations area, mobilizing contaminants as well as removing mature sagebrush. This fire consumed over 160,000 acres, including 78,000 acres on the ALE Reserve and 60,000 acres on the Hanford operations area. The process of fire suppression, including bulldozed fire lines, flame retardant drops in waterways, and wider grading of dirt roads also impacted habitat (BAER, 2000). In the 200 West Area, the fire resulted in severe soil erosion and wind blown soils (Baker, 2000).

In 2007, there were three wildfires reported: a 25-acre grassland fire in July; an 8,000-acre fire on the ALE Reserve in August; and a larger fire in August that burned 27,000 acres on the ALE Reserve, 9,000 acres in the Hanford operations area (including vegetation planted on capped ponds), and another 8,000 acres off-site (Duncan et al., 2008).

7.4 Off-site Areas

As described previously, off-site areas exposed to stressors from the Hanford operations area include off-site habitats exposed to aerial deposition, off-site habitats associated with riparian and floodplain habitats downstream on the Columbia River, and agricultural areas and downstream irrigation ditches. The three scenarios provided below illustrate how off-site habitats have been exposed to site stressors. Further investigation of specific impacted areas and the contaminants of concern in these areas would be undertaken as part of injury assessment planning.

Off-site habitats exposed to aerial deposition

Off-site habitats exposed to aerial deposition of contaminants from the Hanford operations area include the urban and agricultural land surrounding the Site. The aerial view of surrounding areas in Figure 2.2 shows a combination of uplands, likely used for grazing, and irrigated agriculture. The natural resources associated with grazed pastures and irrigated agriculture habitat in this area have not yet been investigated. Trophic relationships in these habitats are likely to be simplified compared to trophic relationships on the Site, because of simplified and less diverse habitats. The pathways of contaminant transport and categories of potential injuries are likely to be the same, on- and off-site.

Downstream riparian and floodplain habitats

The Columbia River downstream of Hanford Reach, from Lake Wallula to the Pacific Ocean, is included within the geographic scope of the aquatic resources CSM because of evidence that contaminants from the Site have been transported downstream through the Columbia River and into the Pacific Ocean (Foster and Junkins, 1960; Junkins et al., 1960). The terrestrial resources CSM thus includes any riparian or floodplain habitat along the Columbia River that has been exposed to Hanford contaminants from surface water or sediments. Until the completion of the McNary Dam in 1956, the first dam downstream of the Hanford Reach was the Bonneville Dam. Hazardous substances released from Hanford would likely have been trapped in sediment behind the Bonneville Dam until 1956 and then behind the McNary Dam since 1956. Contaminated sediments then can potentially serve as ongoing sources of hazardous substance releases. Because dams can be effective sediment traps, there are likely to be fewer Hanford-generated hazardous substances behind The Dalles Dam or the John Day Dam, both of which were constructed after the completion of the McNary Dam.

In general, the types of trophic relationships described for riparian habitat along the Hanford Reach also apply to the downstream impoundment areas, with differences in the particular species and some of the physical parameters that affect biota. For example, riparian vegetation is restricted to shoreline areas because of a lack of island habitat. In the Lower Columbia River and Estuary, there are unique riparian and wetland habitats associated with estuarine conditions. The extent of exposure of these habitats to contaminants released from Hanford is unknown.

Downstream of the Hanford Reach, non-Hanford stressors to terrestrial resources include dam impoundments, industrial and agricultural activities, urbanization, and habitat modification. Thus, impacts to terrestrial resources in these downstream areas should distinguish the sources of stress.

Downstream lands potentially exposed through irrigation

Downstream lands may have been potentially exposed to Hanford contaminants when Columbia River water was used for irrigation. Irrigation water is drawn from the river and applied directly to agricultural fields. Contaminants present in the irrigation water may expose aquatic and terrestrial resources in irrigation ditches, as well as the irrigated soil and vegetation, wildlife that utilizes the irrigated areas, and groundwater underlying the irrigated areas.

7.5 Potential Injury Definitions

This section describes definitions of natural resource injury, including those definitions in the DOI and OPA regulations that are relevant to geologic resources and biota. It is important to remember that injuries to biological organisms and soils can occur through direct exposure to a stressor at the Site or through indirect effects if stressors from the Site result in a loss of habitat, a loss of prey base, changes in the food web structure, or other impacts to the organisms' physical or biological environment.

The following sections discuss potential injury definitions for these resources. As discussed in previous chapters, the potential injury definitions presented below include both injury definitions that are explicitly contained in federal regulations, as well as other potential injuries discussed during CSM planning workshops. This information is intended to assist the Trustees with assessment planning and does not represent a final or consensus list of injuries that will be assessed. Ultimate selection of injury definitions will be undertaken during development of injury assessment plans.

7.5.1 Injury definitions: Geologic resources

Geologic resources (soils) may have been injured from releases of hazardous substances or from response actions at the Site. Locations of potential injury include any location where contaminants were released or deposited on soils, or locations where soils have been disturbed by response actions, including areas where contaminated soils were excavated and transported to confined disposal areas.

DOI regulations

The DOI regulations for conducting NRDAs include several definitions of injury to geologic resources. These definitions are presented in Chapter 5 as part of the discussion of injury to vadose zone soils. Some injury definitions that may be most relevant to surface soils affected by Hanford stressors include:

- Concentrations of substances sufficient to cause a toxic response to soil invertebrates [43 CFR § 11.62 (e)(9)]
- Concentrations of substances sufficient to cause a phytotoxic response such as retardation of plant growth [43 CFR § 11.62 (e)(10)]
- Concentrations of substances sufficient to have caused injury to surface water, groundwater, air, or biological resources, when exposed to geologic resources [43 CFR § 11.62 (e)(11)].

NOAA regulations

The NOAA regulations under OPA [15 CFR Part 990] define injury as “an observable or measurable adverse change in a natural resource or impairment of a natural resource service. Injury may occur directly or indirectly to a natural resource and/or service. Injury incorporates the terms “destruction,” “loss,” and “loss of use” as provided in OPA.” These regulations would apply to the shoreline of a navigable waterway, including riparian soils and habitat adjacent to the Columbia River.

7.5.2 Injury definitions: Biological resources

Biological resources in terrestrial habitats, including vegetation, invertebrates, birds, reptiles, and mammals, may have been injured by releases of hazardous substances from the Site and from unavoidable response actions, including remedial activities and areas where vegetation was deliberately controlled to prevent the spread of contamination.

The DOI regulations state that an injury to a biological resource has resulted from the release of a hazardous substance if the concentration of the substance is sufficient to cause adverse changes in viability, exceed action or tolerance levels, or exceed levels for which directives are issued to limit or ban consumption. Section 6.5.2 discusses both the DOI and NOAA definitions of injury to biological resources in detail. These definitions apply to both aquatic and terrestrial biota and are not repeated here.

7.5.3 Other potential injury definitions

As discussed previously, Trustees are not required to use the definitions of natural resource injuries put forth in the DOI regulations [43 CFR § 11.10]. Alternative injury definitions for geologic or biological resources discussed in CSM planning workshops that may be considered could include:

- Impairment of geologic resource (soil) services for any domestic, livestock, or agricultural purpose
- Elimination of geologic resource services because response actions such as rubble barriers or institutional controls prevent use of soil regardless of contaminant concentrations
- Reduction in terrestrial services because of the presence of contamination, regardless of the contaminant concentrations

- Reduction in terrestrial services because of the stigma of soil contamination
- Any adverse impacts to terrestrial biota, or the services provided by the biota, caused by the presence of contamination.

7.6 Services

This section provides a brief overview of terrestrial services, to provide guidance for injury assessment planning. A comprehensive analysis of these services and potential services losses resulting from releases of Hanford contaminants would be undertaken in the injury assessment.

Site stressors may have adversely affected ecological and human services associated with terrestrial resources. Soils provide important habitat services to vegetation, invertebrates, and burrowing animals that can be impaired by the presence of hazardous substances in the soil. The diverse vegetation communities at the Site provide habitat services for a large diversity of invertebrates, birds, reptiles/amphibians, and mammals, including many species of Conservation Concern. The diversity on the Site also provides the service of a “genetic bank” for biodiversity in the Columbia Basin Ecoregion (Soll et al., 1999). Further identification and discussion of services and methods for quantification of service loss will be developed in the injury assessment plans.

Indigenous peoples are intimately connected to the terrestrial resources associated with the Hanford assessment area through a range of services they derive from the upland environment, including food, medicine, religion, recreation, education, and community. Human services also are provided from the birds and wildlife that are supported by on-site habitats and then may move to off-site locations where they are accessible to hunting or wildlife viewing. Further discussion of human services is found in Chapter 9.

References

BAER. 2000. 24 Command Fire, Benton County, Washington, June–July 2000 Burned Area Emergency Rehabilitation Plan. Prepared by Northern States Burned Area Emergency Rehabilitation Team, U.S. Department of the Interior. Available: http://www.fws.gov/fire/downloads/ES_BAR/Plan_24Command.PDF. Accessed 3/2/2009.

Baker, S. 2000. *Effects of Fire on Soil Seed Banks on the Hanford Site*. PNNL-13888. Pacific Northwest National Laboratory. Available: http://www.pnl.gov/main/publications/external/technical_reports/PNNL-13888.pdf. Accessed 3/2/2009.

Becker, J.M. and C.A. McKinstry. 2004. Response of winter birds to soil remediation along the Columbia River at the Hanford Site. *Environmental Monitoring and Assessment* 93:277–286.

Becker, J.M., C.A. Brandt, D.D. Dauble, A.D. Maughan, and T.K. O'Neil. 1996. *Species for the Screening Assessment, Columbia River Comprehensive Impact Assessment.* Revision 0. DOE/RL-96-16-b. Prepared by the Pacific Northwest National Laboratory, Richland, WA.

Burk, K.W., M.A. Chamness, R.A. Fowler, B.G. Fritz, P.L. Hendrickson, E.P. Kennedy, G.V. Last, T.M. Poston, M.R. Sackschewsky, M.J. Scott, S.F. Snyder, M.D. Sweeney, and P.D. Thorne. 2007. *Hanford Site National Environmental Policy Act (NEPA) Characterization*. Rev. 18. PNNL-6415. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. September.

Cary, A. 2009. Bats to keep Hanford home. Tri-City Herald newspaper. April 22. Available: http://www.tri-cityherald.com/kennewick_pasco_richland/story/552095.html. Accessed 6/26/2009.

Doctor, P.G., K.A. Gano, and J.K. Linville. 2004. *Conceptual Site Model for the 100-B/C Pilot Project Risk Assessment*. Rev. 0. BHI-01706. Prepared by Bechtel Hanford, Inc. for the U.S. Department of Energy, Richland Operations Office. March.

Downs, J.L., M.A. Simmons, J.A. Stegen, A.L. Bunn, B.L. Tiller, S.L. Thorsten, and R.K. Zufelt. 2004. *Ecological Characterization Data for the 2004 Composite Analysis*. PNNL-14884. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy.

Downs, J.L., W.H. Rickard, C.A. Brandet, L.L. Caldwell, C.E. Cushing, D.R. Geist, R.M. Mazaika, D.A. Neitzel, L.E. Rogers, M.R. Sackschewsky, and J.J. Nugent. 1993. *Habitat Types on the Hanford Site: Wildlife and Plant Species of Concern*. PNL-8942. Pacific Northwest Laboratory, Richland, WA. Prepared for the U.S. Department of Energy.

Duncan, J.P., T.M. Poston, and R.L. Dirkes (eds.). 2008. *Hanford Site Environmental Report for Calendar Year 2007* (Including Some Early 2008 Information). PNNL-17603. Pacific Northwest National Laboratory, Richland, WA. Prepared for U.S. Department of Energy. September.

Emery, R.M. and M.C. McShane. 1978. *Comparative Ecology of Nuclear Waste Ponds and Streams on the Hanford Site.* PNL-2499. Pacific Northwest Laboratory. Prepared for the U.S. Department of Energy.

Evans, J.R., M.P. Lih, and P.W. Dunwiddie (eds.). 2003. *Biodiversity Studies of the Hanford Site Final Report: 2002–2003.* The Nature Conservancy, Washington Field Office, Seattle, WA. August 29.

Foster, R.F. and R.L. Junkins. 1960. *Off-Project Exposure from Hanford Reactor Effluent*. HW-63654. Hanford Atomic Products Operation. February 1.

Junkins, R.L., E.C. Watson, I.C. Nelson, and R.C. Henle. 1960. *Evaluation of Radiological Conditions in the Vicinity of Hanford for 1959*. HW-64371. General Electric, Hanford Atomic Products Operation, Richland, WA. May 9. Available: http://hanford-site.pnl.gov/envreport/. Accessed 4/1/2009.

Patton, G.W. and A.T. Cooper. 1993. *Air Pathway Effects of Nuclear Material Production at the Hanford Site, 1983 to 1992*. PNL-8830. Prepared for the U.S. Department of Energy. Pacific Northwest Laboratory, Richland, WA.

Poston, T.M. 1995. *Concentrations of Radionuclides in Terrestrial Vegetation on the Hanford Site of Potential Interest to Native Americans*. PNL-10397. Prepared for the U.S. Department of Energy. Pacific Northwest Laboratory. March.

Priddy, M., G. Patton, J. Yokel, D. Delistraty, and T. Stoops. 2005. *Survey of Potential Hanford Site Contaminants in the Upper Sediment for the Reservoirs at McNary, John Day, The Dalles, and Bonneville Dams, 2003*. PNNL 14878; WDOE 04-05-016; ODOE NUC-007. Washington State Department of Health. February.

Sackschewsky, M.R. and J.L. Downs. 2001. *Vascular Plants of the Hanford Site*. PNNL-13688. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. September.

Soll, J., J.A. Hall, R. Pabst, and C. Soper (eds.). 1999. *Biodiversity Inventory and Analysis of the Hanford Site: Final Report, 1994–1999*. Prepared by the Nature Conservancy of Washington, Seattle, WA. October 15.

U.S. DOE. 2001. *Hanford Site Biological Resources Management Plan.* Revision 0. DOE/RL 96-32. U.S. Department of Energy. August.

U.S. DOE. 2007. *Risk Assessment Report for the 100 Area and 300 Area Component of the River Corridor Baseline Risk Assessment.* DOE/RL-2007-21. Draft A. Richland, WA.

U.S. DOE. 2008. *Remedial Investigation Work Plan for Hanford Site Releases to the Columbia River*. Rev. 0. DOE/RL-2008-11. September.

USFWS. 2002. Fitzner/Eberhardt Arid Lands Ecology Reserve, Hanford Reach National Monument (Fact Sheet). U.S. Fish and Wildlife Service. August.

USFWS. 2004. Planting Aids Sensitive Species at Hanford Reach National Monument. U.S. Fish and Wildlife Service Journal Entry. Region 1. April 15. Available: http://www.fws.gov/arsnew/print/print_report.cfm?arskey = 13905. Accessed 6/27/2009.

USFWS. 2008. Final Hanford Reach National Monument Comprehensive Conservation Plan and Environmental Impact Statement. U.S. Fish and Wildlife Service. August. Available: http://www.fws.gov/hanfordreach/planning.html. Accessed 2/13/2009.

USFWS. 2009. Elk, Hanford Reach National Monument. U.S. Fish and Wildlife Service. June. Available: http://www.fws.gov/hanfordreach/elk.html. Accessed 6/26/2009.

Vance, L. 2009. Geographically Isolated Wetlands and Intermittent/Ephemeral Streams in Montana: Extent, Distribution, and Function. Prepared for Montana Department of Environmental Quality and U.S. Environmental Protection Agency. Montana Natural Heritage Program. January. Available: http://mtnhp.org/reports/Isolated_Wetlands.pdf. Accessed 2/25/2009.

8. Air Resources

This chapter presents a CSM for air resources at the Site (Figure 8.1). Air is a natural resource that has been exposed to and potentially injured by stressors at the Site. It is also an important exposure pathway to other natural resources, as discussed in the pathways CSM (Chapter 4). Here we summarize information on air contamination and discuss potential injury definitions and service loss.

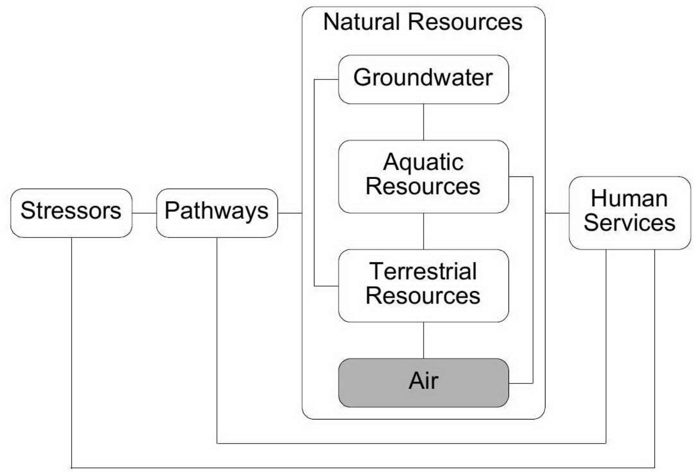


Figure 8.1. Relationship between the air resources CSM and other CSMs that together make up the NRDA CSM.

Existing CSMs for air contaminant transport at the Site are included in the Human Environmental Dose Reconstructions (HEDR) project conducted in the 1980s and 1990s, and the annual Hanford Site Environmental Reports. HEDR evaluated potential air releases from 1944 to 1971, focusing on radionuclide releases between 1945 and 1951, when the majority of iodine-131 isotopes were released. The annual environmental reports summarize air quality data collected as part of the Surface Environmental Surveillance Project (SESP).

8.1 Historical Air Releases

The vast majority of airborne radionuclides released from the Site occurred during the early years of operation (1944–1951). While the HEDR project attempted to reconstruct aerial radionuclide releases from the T Plant and B Plant, the estimates of releases are not based on environmental data. Stack emissions were not monitored with any reliability until late 1950. Instead, the estimates are based on a model with the following inputs (Napier, 1991, 2002):

- Amount of irradiated fuel being dissolved
- Irradiation history of the fuel
- Time elapsed since the fuel was removed from the reactor
- Separation process used
- Efficiency of the facility effluent controls.

The Technical Steering Panel (TSP) of the HEDR published the summary results of their work in 1994 (HEDR TSP, 1994). According to the TSP, large amounts of radioactive materials – primarily iodine-131 – were released to the atmosphere from the T and B plants during the first few years of operation, until new filter systems and stricter operating procedures were emplaced in the 1950s. The HEDR TSP (1994) estimated that 730,000 curies (2.7×10^{16} Bq, or 27 PBq) of iodine-131 were released between 1945 and 1951. The vast majority were released between 1945 and 1947 (Figure 8.2). An estimated 7,000–12,000 curies of iodine-131 were intentionally released during the Green Run in 1949 (see Chapter 3).

The HEDR TSP (1994) calculated total releases of several radionuclides comprising an estimated 99% of the total potential radiation dose from atmospheric pathways between 1944 and 1971. Of the selected radionuclides included in the HEDR TSP summary report, iodine-131 comprises 99.3% of the total releases, cerium-144 comprises 0.5% of the total, and ruthenium-103 comprises 0.15% of the total. Overall, these three radionuclides comprise nearly 99% of all radionuclides released from 1944 to 1972 (Napier, 1991; HEDR TSP, 1994).

The half life of iodine-131 is 8 days. The HEDR TSP (1994) assumes that a radionuclide has decayed to an insignificant concentration after 10 half lives, when less than 0.1% remains. Thus, the TSP estimates that an atom of iodine-131 released from the Site would no longer pose a threat of adverse effects after about 80 days. Cerium-144 has a half life of 285 days; 10 half lives of cerium-144 takes 7.8 years. Ruthenium-103 has a 40-day half life; an atom of ruthenium-103 released from the Site would be expected to disappear in about 400 days.

Significant quantities of longer-lived radionuclides have also been released to air resources from the Hanford facility, including strontium-90 (half-life of 29 years) and plutonium-239 (half life of 24,110 years). While air is a primary pathway to natural resources in terrestrial and aquatic habitats, where receptors could risk exposure to long-lived radionuclides for many years, it is not certain how long these radionuclides may remain airborne. This is discussed further in Section 8.3.

The HEDR TSP (1994) estimated that 555,000 curies of iodine-131 were released in 1945, comprising nearly 75% of all radionuclide releases that occurred between 1944 and 1971. These 1945 iodine-131 releases likely traveled the greatest distances from their source. Using a model that includes wind directions, iodine-131 transport time and decay, and other factors, the HEDR estimated iodine-131 fallout in the Pacific Northwest in 1945. Figure 8.3 presents the approximate estimate of areas where atmospheric deposition of Hanford-released iodine-131 in 1945 exceeded 0.005 nanocuries (0.185 Bq).

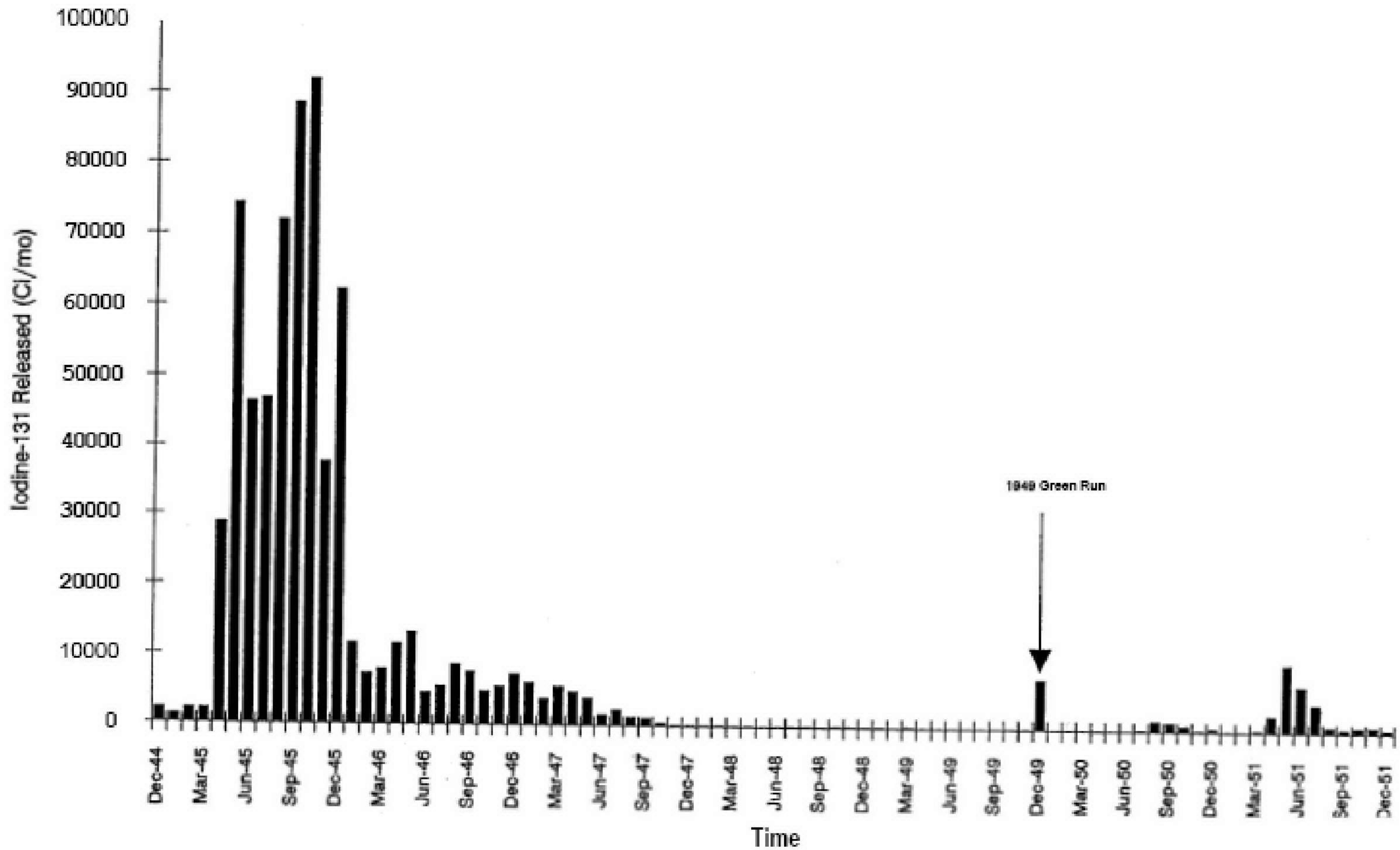


Figure 8.2. Iodine-131 releases from the Site, 1945–1951.

Source: HEDR TSP, 1994, Figure 3.

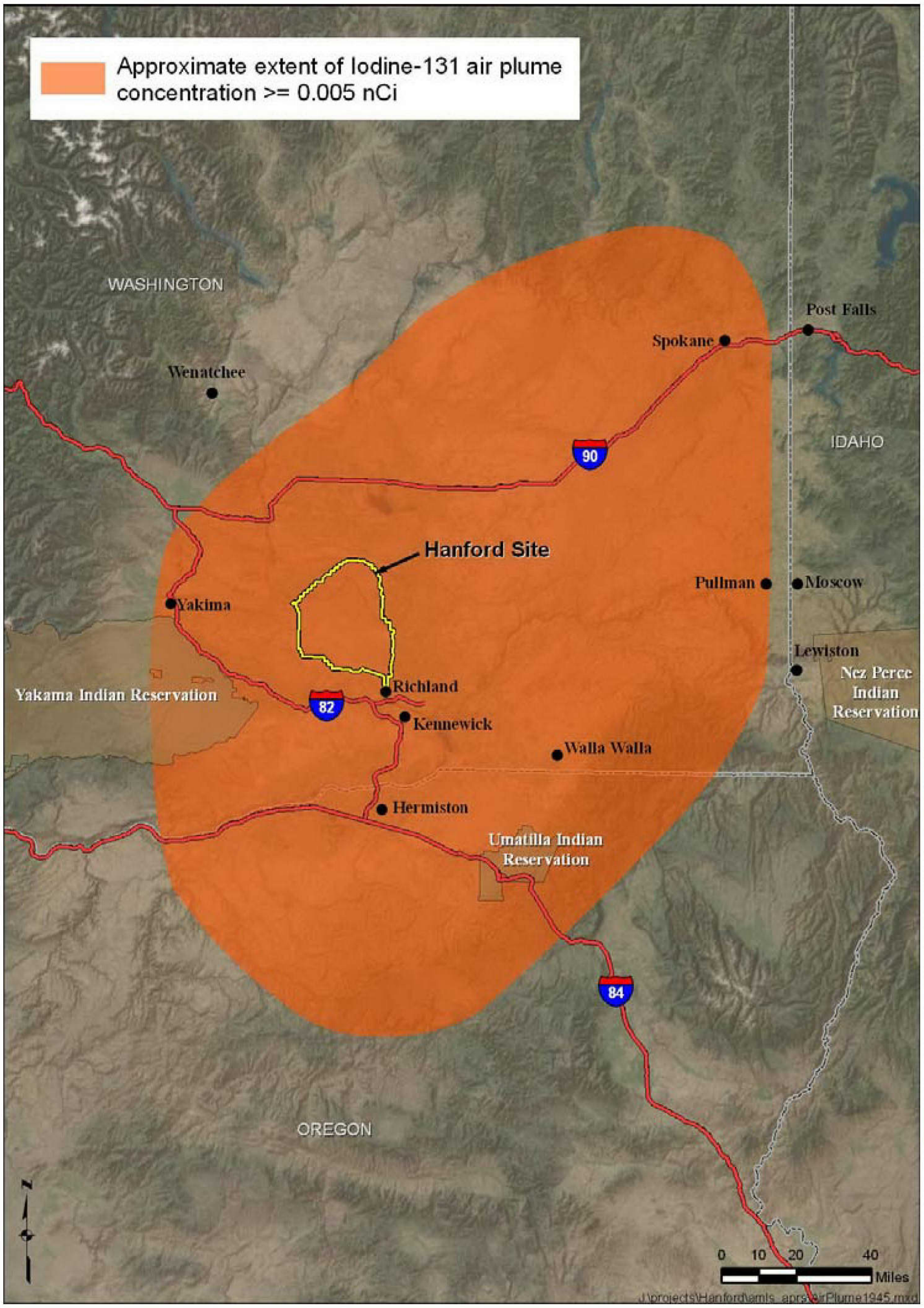


Figure 8.3. Estimated aerial deposition of iodine-131 in 1945 at concentrations exceeding 0.005 nanocuries, derived from a HEDR air dispersion model coupled with estimates of stack emissions based on production records.

Data source: Lawrence Berkeley Laboratory, 2009.

Napier (2002) subsequently revised the estimates of airborne radionuclide releases between 1950 and 1972, based on a re-evaluation of stack emissions data, calibrated with rudimentary air monitoring data from locations near the Site. The revised data found that the HEDR model may have overestimated atmospheric releases from 1950 to 1957, and underestimated releases from 1957 to 1972. Overall, though, the net change in the overall emissions estimate is only 3%, because the vast majority of iodine-131 releases occurred prior to 1950 (Napier, 2002). The Napier (2002) stack and air monitoring data show emissions of approximately 1,000 TBq (1 PBq) in 1951, declining to below 100 terabecquerel per year (TBq/yr) through the 1950s, and less than 10 TBq/yr through the first half of the 1960s.

8.2 Air Releases after 1982 Restart

Patton and Cooper (1993) summarized releases to air resources from 1983 to 1992. The PUREX plant in the 200 Area was in operation from 1983 to 1989 and was the primary source of radionuclide emissions at the Site during this period. Air monitoring stations on-site and at the downwind perimeter of the Site received elevated radionuclide concentrations compared to background (in Yakima) while PUREX was operating. Concentrations were similar to background once PUREX was decommissioned (Patton and Cooper, 1993).

The Hanford NEPA characterization summarizes current air quality at the Site (Burk et al., 2007). The NEPA document indicates no exceedences of air quality standards in the Hanford area. The calculated radionuclide dose based on airborne radionuclides from the Site is over two orders of magnitude less than the EPA and Washington State standard.

8.3 Potential Injuries and Services

The DOI regulations define air resources as those naturally occurring constituents of the atmosphere, including those gases essential for human, plant, and animal life [43 CFR § 11.14(b)]. As discussed in previous sections, the potential injury definitions presented below include both injury definitions that are explicitly contained in federal regulations, as well as other potential injuries that are not specified in the regulations. This information is intended to assist the Trustees with assessment planning and does not represent a final or consensus list of injuries that will be assessed. Ultimate selection of injury definitions will be undertaken during development of injury assessment plans.

As discussed previously, radionuclide releases to air resources include both short-lived and longer-lived radionuclides. While longer-lived radionuclides may expose natural resources for many years, it is not certain how longer radionuclides remain airborne before being deposited onto the ground. Once a contaminant is deposited, it no longer represents a potential injury to air resources. Should the Trustees pursue an injury assessment of air resources, they will need to examine both the potential for injuries from short-lived iodine-131 releases, and potential injuries from longer-lived radionuclides that would not decay while airborne, but also were released in quantities many orders of magnitude less than iodine-131.

8.3.1 Air injury

The definition of injury to air resources in the DOI regulations is:

- Concentrations of emissions in excess of standards for hazardous air pollutants established by section 112 of the Clean Air Act, 42 USC 7412, or by other Federal or State air standards established for the protection of public welfare or natural resources [43 CFR § 11.62(d)(1)].

The State of Washington also has a Clean Air Act, including criteria for radionuclide emissions [WAC 173-480]. Air resources are injured if hazardous substance concentrations exceed the criteria set forth in either the Federal or Washington Clean Air Act. However, lead is one of the few listed hazardous substance for which ambient air quality standards have been promulgated. Other substances for which criteria are promulgated include particulates, sulfur dioxide, nitrogen dioxide, carbon monoxide, ozone, and fluorides.

EPA [40 CFR § 61] and the State of Washington [WAC 173-480] have issued standards for airborne radionuclide emissions based on the dose that the maximum exposed individual (MEI) would receive. The MEI dose (10 mrem, or 100 μSv) incorporates the chemical behavior of different radionuclides. For example, between 1983 and 1989, nearly 2 million curies of krypton-85 and 400,000 curies of argon-41 were released (Patton and Cooper, 1993). However, both argon and krypton are inert gases that are not prone to incorporation into human tissues, which contrasts with iodine, which is readily incorporated into the human body. Patton and Cooper (1993) provide an example dose calculation where 0.6 curies of iodine-129 released to air resulted in a calculated dose of 0.04 μSv, four times greater than the calculated dose of 0.01 μSv from 200,000 curies of released krypton-85. Thus, the air quality standard for radionuclides is highly dependent on the behavior of the radionuclide in the human body.

The DOI regulations also include an injury definition that acknowledges the role of air resources as a secondary stressor:

- Concentrations and duration of emissions sufficient to have caused injury to surface water, ground water, geologic, or biological resources when exposed to the emissions [43 CFR § 11.62(d)(2)].

Thus, air resources meet the definition of being injured if hazardous substance concentrations are sufficient to injure another natural resource, regardless of whether those concentrations exceed a specified regulatory threshold.

8.3.2 Other potential injury definitions

Trustees are not required to use the definitions of natural resource injuries put forth in the DOI regulations [43 CFR § 11.10]. Some alternative injury definitions for air resources might include:

- Concentrations of contaminants exceeding a Federal, State, or Tribal risk-based threshold
- Reduction in air resource services because of the presence of contamination, regardless of the contaminant concentrations.

8.3.3 Services

As discussed in previous chapters, air provides the primary pathway for radionuclide dispersion from source areas to terrestrial habitat. Injured air can be a secondary stressor, causing injury to other natural resources. Air provides an essential service as the medium for gas exchange in terrestrial life. Other services that air provides are discussed in Chapter 9.

References

Burk, K.W., M.A. Chamness, R.A. Fowler, B.G. Fritz, P.L. Hendrickson, E.P. Kennedy, G.V. Last, T.M. Poston, M.R. Sackschewsky, M.J. Scott, S.F. Snyder, M.D. Sweeney, and P.D. Thorne. 2007. *Hanford Site National Environmental Policy Act (NEPA) Characterization.* PNNL-6415 Rev. 18. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. September.

HEDR TSP. 1994. Summary: Radiation Dose Estimates from Hanford Radioactive Material Releases to the Air and the Columbia River. Revision 1. Hanford Environmental Dose Reconstruction Project. April 21.

Lawrence Berkeley Laboratory. 2009. Hanford Environmental Dose Reconstruction Project. Available: http://cedrgis2.lbl.gov/Hanford/viewer.htm. Accessed 4/15/2009. Underlying GIS files provided by George Marinos, Geographic Information Science Center, University of California Berkeley, to Jamie Holmes, Stratus Consulting, 4/16/2009.

Napier, B.A. 1991. Selection of Dominant Radionuclides for Phase I of the Hanford Environmental Dose Reconstruction Project. PNL-7231 HEDR. Pacific Northwest Laboratory, Richland, WA. Prepared for the Technical Steering Panel. July.

Napier, B.A. 2002. A re-evaluation of the ^{131}I atmospheric releases from the Hanford Site. *Health Physics* 83(2):204–226.

Patton, G.W. and A.T. Cooper. 1993. *Air Pathway Effects of Nuclear Material Production at the Hanford Site, 1983 to 1992*. PNL-8830. Pacific Northwest Laboratory, Richland, WA. Prepared for the U.S. Department of Energy.

9. Human Services

This chapter presents a human services CSM to assist in evaluating of lost human services associated with injuries to natural resources in the Hanford assessment area. Figure 9.1 is a simple illustration of the relationship between the human services CSM and the other CSMs provided in this document.

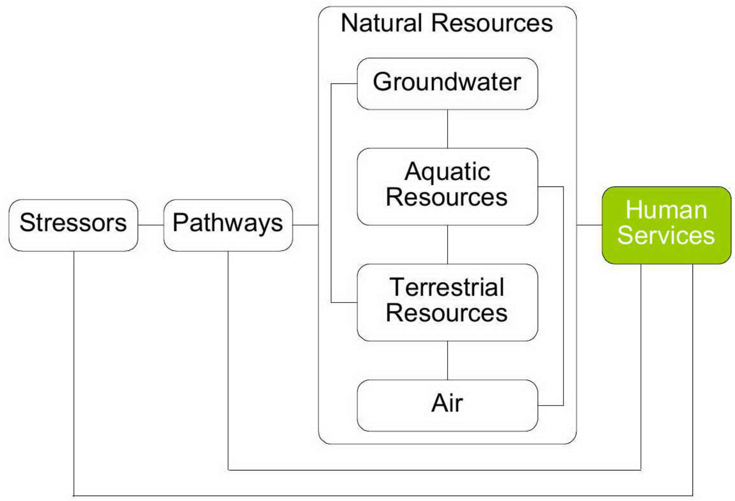


Figure 9.1. Relationship between the human services CSM and other CSMs that together make up the NRDA CSM.

As discussed in previous chapters, several potential definitions of natural resource injuries are based on concentrations of contaminants sufficient to reduce human services. The focus of this chapter is a discussion of potential relationships natural resources and services. The information presented in this chapter includes information discussed in CSM meetings and is intended to assist the Trustees with assessment planning. It does not represent a final or consensus list of human services or potential service losses that will be assessed. Ultimate selection of potential service losses resulting from Hanford stressors will be undertaken during development of injury assessment plans.

Losses of human services can occur to both Tribal members and the general public; however, the type and severity of losses may vary greatly. Impacts to human services can occur at multiple levels, from the very localized (e.g., loss of harvestable plants in one specific locations) to more fundamental changes in habitats that can alter the overall landscape and view shed.

In this chapter, "general public" refers to any non-Tribal member of the population, and "Tribes" refers to the Yakama Nation, the Nez Perce Tribe, the Wanapum, and the CTUIR, which includes the Cayuse, Walla Walla, and Umatilla Tribes. These Tribes are proximal to the Site and/or have rights to utilize natural resources potentially affected by Site stressors. The Site is approximately 20 miles east of the current Yakama Nation Reservation (Ridolfi, 2007). The CTUIR and Nez Perce reservations are located to the south and east, respectively. Wanapum members live primarily around the Wanapum Dam, upriver from the Site.

For Tribes and the general public, the services provided by uninjured natural resources as a whole are more than the sum of the enumerated services of each individual natural resource. The primary objective of the NRDA for the Tribes is full restoration of resources and services, leading to full restoration of Tribal lifeways. Natural resources are a critical component of the Tribal cultural resources of the area. While the remediation of individual resources and services is an intermediate step, anything short of a fully cleaned and restored site may leave the Tribes and general public less than whole. Although subsequent sections categorize resources for the ease of presentation, this holistic perspective is emphasized in the discussion of Tribal uses.

As mentioned in previous chapters, Ridolfi (2004) developed a comprehensive list of biota found in the assessment area, including 13 algae species, 56 fish species, 269 bird species, 52 mammal species, 21 amphibian and reptile species, over 800 aquatic and terrestrial plant species, and dozens of orders, families, and genera of aquatic and terrestrial insects. These resources, individually and as a group, provide numerous services to the Tribes and the general public, including to those who may never visit the Site.

While "services" are a useful concept for thinking about the interactions between resources and humans, it is impossible to enumerate the entire suite of services that any one resource may provide. Ridolfi (2007) provides a more detailed listing of the relationships between resources and human services (see Figure A.22 in the appendix). A general categorization of services provided by resources to humans can be categorized as follows:

- *Use services* represent those natural resource services directly used by people, such as recreational activities, subsistence fishing and gathering, research projects at the Site (including those conducted by Pacific Northwest National Laboratory), residential uses, commercial and industrial uses, or other activities that involve direct interaction with potentially affected natural resources.

- *Passive use services* (also called *nonuse services)* are those services provided that are not based on direct use or consumption of natural resources. For example, individuals may benefit from knowing the Hanford habitats exists and can be used into the future. Likewise, individuals may benefit from the preservation of historical or archaeological resources even if they never visit the assessment area to observe them.

The purpose of the human services CSM is to present a potential approach to conceptualizing the interactions among the different resources, injuries, and the resulting effect on the human services in the Hanford assessment area. While we present one approach in this chapter, there are multiple ways to develop or evaluate these interactions, and it is likely that as additional information is developed, the understanding about these interactions and the impacts of the injuries on human services will evolve.

Examples of resources and services are provided throughout this chapter. These examples are for illustrative purposes and do not represent an exhaustive list of resources or the services they provide. A more detailed discussion of human services will be part of the natural resource injury assessment.

9.1 Tribal Services

The uses and importance of resources at the Site to the Tribes are both broad and deep. These services support Tribal lifeways. Tribes have depended historically on a wide range of resources at the assessment area for sustenance as well as for cultural and religious activities (Nez Perce Tribe, 2003). Consequently, a human services conceptual model of the assessment area comprises a web of interrelated services, rather than a set of individual uses. Many authors have characterized this interdependent web as an “Ethno-Habitat” or an “Eco-Cultural System,” enforcing the concept that to Tribal members, natural resources are the “grocery store, school, church, clinic, and living room,” not simply habitat for wild game or a place for recreation. From this perspective, injuries to a single natural resource in the assessment area has cascading effects throughout this system (Hunn, 1991; Harper and Harris, 2009).

This holistic perspective reflects a high existence value for the Site and surrounding assessment area, free of contamination or adverse effects from other stressors. The provision of services between resources – aquatic, terrestrial, groundwater, and air – ensures a healthy ecosystem and persistence of the assessment area. As presented in Harper and Harris (2009), the Tribes value the option to use the natural resources in the assessment area for various activities, both for current and future generations. These passive values – existence, option, and bequest values – are included in this NRDA CSM and should be considered in the injury assessment.

While all resources in the assessment area are valuable to the Tribes, some resources are used more commonly than others. Moreover, the timing in availability of these resources dictates the extent to which they are used. Figure 9.2 illustrates the “seasonal round,” depicting the use of various resources throughout the year. The seasonal round shows how the resource base, and thus human uses, shifts depending on the time of the year. Chinook salmon, for example, serve as first foods in the early spring and then again as fall Chinook starting in September. The following sections discuss natural resources of particular Tribal importance in aquatic and terrestrial habitats. Additionally, groundwater and passive use services are discussed.

Figure 9.2. Seasonal round of tribal resources.

Source: Hunn, 1991, p. 8.

9.1.1 Tribal use services: Aquatic resources

The aquatic resources at the Hanford Reach serve many uses for the Tribes. Aquatic resources include, but are not limited to, the Columbia River, surface waters such as tributaries and on-site ponds, sediments, and associated aquatic biota. Fish constitute one of the largest portions of the Pacific Northwest Indian diet (Landeen and Crow, 1997; Landeen and Pinkham, 1999). One study estimates the Tribal consumption rate of fish at 11 times the non-Indian adult average (U.S. EPA, 2002). Aquatic species of particular importance in the Hanford assessment area, including the Columbia River downstream of the Site, include salmon (Coho, Chinook, sockeye, chum) and trout (cutthroat and steelhead). Other species consumed include bass, bull trout, smelt, lamprey, suckers, whitefish, sturgeon, clams, shellfish, birds, tule, and other riparian vegetative species.

Many aquatic species have special importance beyond their use for food. Chinook salmon are "a ceremonial resource for people of the Columbia River Basin and a focus of social, educational, ecological, linguistic, and other traditional activities" (Harris and Harper, 2000, p. 92). Salmon are a centerpiece of the entire river ecosystem (CCRH, 1974; Harper and Harris, 2009). Likewise, lamprey have significant cultural value to the Tribes, who use them in ceremonies, storytelling, and for medicinal purposes (Jackson et al., 1996; U.S. EPA, 2009).

The Tribes consider the Hanford Reach of the Columbia River to be sacred. Many areas in the Hanford Reach have been used historically for villages, fishing sites, food caches, storage areas, and cemeteries (Boyd and Hajda, 1987; Nickens et al., 1995; PNNL, 1998; Ridolfi, 2007). The water has been used for drinking, supporting traditional harvest, and as an integral part in ceremonies (CRITFC, 2000). In other words, a clean river provides a wide array of services to the Tribes that significantly shape their identity (Landeen and Crow, 1997; Landeen and Pinkham, 1999; Harris and Harper, 2000; Nez Perce Tribe, 2003).

The importance of water itself to the Tribes cannot be understated. Without clean water, Tribal lifeways are diminished, including subsistence, spiritual, and educational activities. Clean water provides nourishment and life to the entire ecosystem. Contaminated water exposes all natural resources that use the water. Thus, the quality of water is of crucial importance to the Tribes.

9.1.2 Tribal use services: Terrestrial resources

Terrestrial resources include, but are not limited to, shallow and deep soils, upland and riparian habitats, and associated biota. The Tribes have long used the Hanford assessment area as a place for hunting and gathering. Their harvest has been used for food, tools, medicine, clothing, material, and in traditional ceremonies (Hunn with Selam and family, 1990; Poston, 1995; PNNL, 1998; Harris and Harper, 2000; Sackschewsky and Downs, 2001). Species hunted in the area include deer, elk, and moose (Landeen and Pinkham, 1999; Harper and Harris, 2009). A variety of plants have been gathered in the assessment area; those most commonly harvested include wapato, balsamroot, bitterroot, brodiaea, Indian celery, biscuitroot, Indian carrot, yellow bell, huckleberries, choke cherries, camas, tule, and dogbane (CRITFC, 1999; Ridolfi, 2007).

As a whole, Tribes have used the Site and the surrounding assessment area for over 10,000 years and consider it sacred. Some of the more prominent features of the landscape have served as spiritual sites for the Tribes, including Gable Mountain, Gable Butte, the White Bluffs Trail, Rattlesnake Mountain, Goose Egg Hill, and Locke Island (U.S. DOE, 2003; Northwest Power and Conservation Council, Undated). More broadly, the Site and the assessment area include historical trails and pathways, fishing and camping sites, cemeteries, hunting grounds, plant gathering areas, landmarks, important places in Indian history, and other historical places (Bunn et al., 2004). These sites are sacred to the Tribes and their preservation is highly valued.

Landmarks throughout the assessment area may have been impacted by Hanford air releases and releases to the river.

While all species are important to Tribal members, a few select terrestrial species hold special importance. For example, coyotes, beavers, ravens, and birds of prey (e.g., eagles, hawks, and ospreys) are often used in traditional ceremonies, education, and story-telling (Landeen and Crow, 1997).

9.1.3 Tribal use services: Groundwater resources

Groundwater provides a source of water for drinking, domestic and ceremonial uses to the Tribes. Water is an important component in traditional Tribal ceremonies, such as in sweathouses (Ridolfi, 2007). This water may be obtained by the Tribes from a groundwater source, rather than the Columbia River or other surface water source.

9.1.4 Tribal passive use services

Natural resources in the Hanford assessment area have strong religious and cultural importance to the Tribes. Consequently, there are passive use values that stem from the preservation of assessment area natural resources, including existence value (the value of knowing the resources persists, even if not providing direct Tribal service), option value (the option to use the resource in the future), and bequest value (the option to pass along uncontaminated natural resources to future generations).

From a holistic perspective, all natural resources provide services to the Tribes, where uncontaminated natural resources support a healthy ecosystem and continuity of life. Natural resources are interrelated and may provide services through either direct or passive use.

9.2 Public Services

This section focuses specifically on public services that natural resources provide at the Site. It should be noted that public services may have been adversely affected throughout the Hanford assessment area. However, to outline public services for the purposes of guiding natural resource injury assessment, we have focused on services provided with the 586-acre Site. Although public access to the Site has been largely restricted for many decades, certain areas of the Site do permit access to the general public. These areas provide use services, such as recreation opportunities, as well as passive uses.

9.2.1 Public use services: Recreation

The Hanford Reach National Monument was designated in June 2000 [65 FR 37253], setting aside 165,000 acres to be managed by the USFWS and 30,000 by the DOE (Pospical, 2004; USFWS, 2008). The monument surrounds the Hanford operations area in nearly all directions, though primarily to the north and southwest (Figure 9.3). Since this area served as a buffer to the Hanford operations area for several decades, the land was protected from encroaching agricultural and urban development. Moreover, the Hanford Reach, contained within the monument, is the last unimpounded reach of the Columbia River in the United States upstream of Bonneville Dam (Pospical, 2004). For these reasons, the Site has become a popular place for recreation, supporting activities such as fishing, hunting, wildlife viewing, boating, and others. The majority of the monument still has restricted access, although three units allow for some level of access to visitors. These include the Wahluke Unit, the River Corridor Unit, and the Vernita Bridge Unit. The rest of Section 9.2.1 describes the various recreation activities mentioned above.

- **Recreational fishing**

  As the last unimpounded reach of the Columbia River upstream of Bonneville Dam, the Hanford Reach supports about 90% of the wild fall Chinook salmon that spawn in the river (Pospical, 2004). Hundreds of boats have been spotted near Vernita Bridge during the fall Chinook salmon run. In addition to salmon, other popular sport fishing species inhabiting the reach include trout (especially steelhead), whitefish, sucker, walleye, carp, bass, catfish, lamprey, and sturgeon (Mueller and Geist, 1999; WDFW, 2001). Given the opportunity to catch fish and the uninterrupted free-flowing state of the river in this area, the Hanford Reach serves as a prime recreational fishing area (Dauble and Watson, 1990; Patton et al., 2003). Boating anglers can access the river just upstream from Vernita Bridge in the Vernita Bridge Unit, at the White Bluffs boat launch in the Wahluke Unit, and at Parking Area 7 or the Ringold Fish Hatchery, both in the southern portion of the Wahluke Unit (Pospical, 2004; USFWS, 2009b).

- **Recreational hunting**

  The Hanford Reach National Monument is well-known for recreational hunting, especially for waterfowl (Anderson et al., 2002). Commonly hunted species include ducks, geese, and mule deer (Tiller et al., 1997; Anderson et al., 2002). Elk also inhabit and migrate through the Site and are hunted (WDFW, 2000). The Wahluke Unit is the primary hunting area (Pospical, 2004).

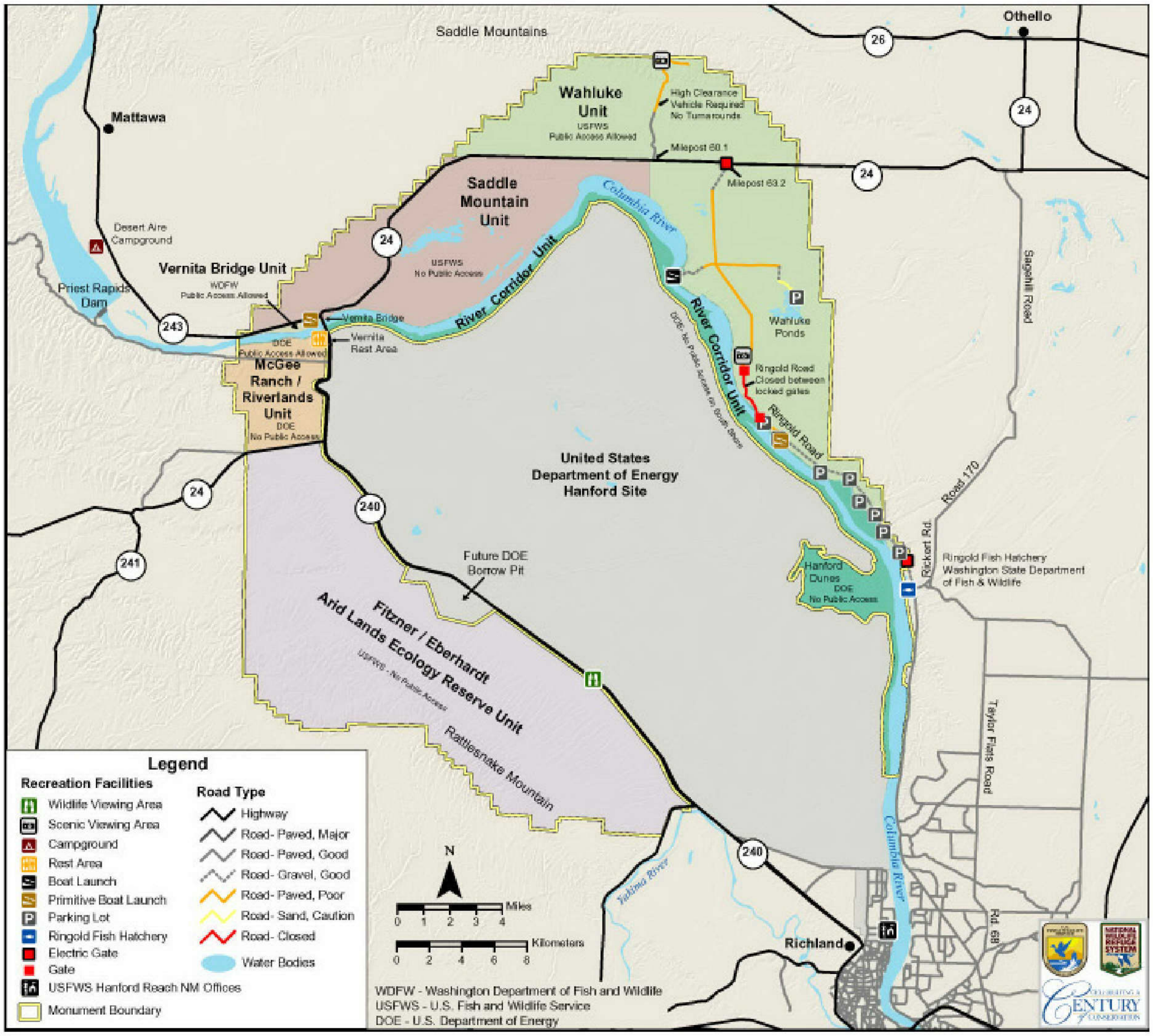


Figure 9.3. Hanford Reach National Monument.

Source: USFWS, 2009a.

- **Recreational wildlife viewing**

  Another recreation activity that takes place in the Hanford Reach National Monument is wildlife viewing. Currently, this activity takes place primarily in the Wahluke Unit and in the River Corridor Unit (Pospical, 2004). Some notable species for viewing include elk and mule deer (Tiller et al., 1997; WDFW, 2000; Harper and Harris, 2009). In addition, the National Audubon Society has recognized the Hanford Reach National Monument as a sanctuary for many bird species. The Site is both a nesting and migratory corridor for many birds, including bald eagles, bank swallows, ospreys, certain falcons, and burrowing owls.

- **Recreational bating**

  Motorized and non-motorized boating are permitted year-round with access just upstream from Vernita Bridge, at the White Bluffs boat launch, Parking Area 7, or at the Ringold Fish Hatchery (Pospical, 2004; USFWS, 2009b). In addition to angling, recreational boaters use the Hanford Reach for waterskiing and other water-based sports (Anderson et al., 2002). Moreover, the Hanford Reach was identified as one of 50 recommended paddle routes in the inland Northwest (Landers and Hansen, 1998).

- **Other recreation**

  While the aforementioned recreation categories encompass the primary uses of the Site, there are other, less-prominent recreation uses of the area, including hiking, picnicking, photography, swimming, horseback riding, windsurfing, and biking (USFWS, 1998; U.S. DOE, 2001; Anderson et al., 2002). It is possible that the Site will be used more broadly in the future for additional recreation uses.

9.2.2 Public use services: Historical and archaeological resources

The Site has a rich collection of archaeological resources, located primarily along the Columbia Reach and on adjacent plateaus and mountains (U.S. DOE, 1996, 2003; Bunn et al., 2004). In particular, the Site contains historical resources related to early Euro-American settlers and the Manhattan Project itself, including gold mining relics along the banks of the river, an historical surface irrigation canal with pump house in the 100 Area, remains of homesteads and ranches, historical Hanford buildings converted for military use (e.g., the former Hanford High School building), and even the nuclear reactors themselves (e.g., the B Reactor) (Pendergast, 2003; Bunn et al., 2004).

These resources are historically important to many descendants of Euro-American settlers. Historical buildings dating back to the days of early American settler expansion and artifacts of the Manhattan Project provide evidence of recent American history. The B Reactor, the first large scale plutonium production reactor in the world, was recently designated a National Historic Landmark.

9.2.3 Public use services: Groundwater resources

Groundwater provides a source of water for drinking, irrigation, domestic uses, surface and wetland recharge through seeps and springs, and other services (USFWS, 1998). Historically, the towns of White Bluffs and Hanford sank wells to provide domestic water. The few drinking water wells currently on site are primarily located at guard stations. Energy Northwest has a well on the Site for fire patrol. Pacific Northwest National Laboratory and the FFTF also have wells to support on-site operations.

Groundwater also provides *in situ* services. Aquifers can assimilate impurities in infiltrated water and provide clean water to downgradient rivers. The presence of groundwater also prevents subsidence. Independent of the water itself, the structure of an aquifer also serves as a valuable resource. For places prone to drought – the Hanford area averages 6.3 inches of precipitation annually – this storage function is particularly valuable (U.S. DOE, 1999). Water can be injected into an aquifer for storage and saved for later use.

9.2.4 Passive use services

The Hanford area is a unique area from which a variety of human services are derived. The Site contains one of largest contiguous shrub-steppe habitats in the Pacific Northwest, and it includes the Hanford Reach, the last free-flowing reach of the Columbia River in the U.S. upstream of Bonneville Dam. Because of access restrictions since the 1940s, much of this area has avoided the impacts of agricultural and urban development. Thus, the same passive use services described above under the discussion of Tribal services – existence, option, and bequest – are valued by the general public. The Site contains a rich diversity of species, many of which are designated as sensitive, threatened, or endangered. A 2003 report by The Nature Conservancy concluded, "Biological studies continue to confirm Hanford's national and regional importance as a refuge for both rare and common species and communities that were once far more widespread in the inland Northwest" (Evans et al., 2003, p. vi). While wildlife viewing is a recreational use at the Site (as discussed above), many people may value the existence of a biodiversity hotspot and sanctuary for rare and threatened species, separate from visiting the Site to observe such species.

Another potential passive-use service stemming from the Site to the general public is the protection of resources specifically for the Tribes. The general public may value the protection of resources for the Tribes and preservation of Tribal lifeways, even if they are not Tribal members or users of the protected resources themselves. Value is derived from knowing that Tribal members have access to their historical lands and access to resources and services in those areas.

References

Anderson, D.M., M.J. Scott, A.L. Bunn, R.A. Fowler, E.L. Prendergast, T.B. Miley, T.O. Eschbach, and J.A. Jaksch. 2002. *2001 Columbia River Recreation Survey: Implications for the Hanford Site Integrated Assessment.* PNNL-13840. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy.

Boyd, R.T. and Y.P. Hajda. 1987. Seasonal population movement along the Lower Columbia River: The social and ecological context. *American Ethnologist* 14:309–326.

Bunn, A.L., S.D. Cannon, J.P. Duncan, R.A. Fowler, B.G. Fritz, D.W. Harvey, P.L. Hendrickson, D.J. Hoitink, D.G. Horton, G.V. Last, T.M. Poston, E.L. Prendergast-Kennedy, S.P. Reidel, A.C. Rohay, M.J. Scott, and P.D. Thorne. 2004. *Hanford Site National Environmental Policy Act (NEPA) Characterization*, D.A. Neitzel (ed.). PNNL-6415 Rev. 16. Pacific Northwest National Laboratory. Prepared for the U.S. Department of Energy. September.

CCRH. 1974. Document: Boldt Decision. Center for Columbia River History website. Available: http://www.ccrh.org/comm/river/legal/boldt.htm. Accessed 3/19/2009.

CRITFC. 1999. Protecting and Restoring Watersheds: A Tribal Approach to Salmon Recovery. Columbia River Inter-Tribal Fish Commission. Available: http://www.critfc.org/oldsite/handbook/TitlePage.html. Accessed 2/11/2009.

CRITFC. 2000. Proceedings of the Columbia River Basin Tribal Water Quality Conference, November 15–16, 2000, Spokane, WA. Sponsored by the Columbia River Inter-Tribal Fish Commission.

Dauble, D.D. and D.G. Watson. 1990. *Spawning and Abundance of Fall Chinook Salmon in the Hanford Reach of the Columbia River.* PNL-7289. Pacific Northwest National Laboratory. Prepared for the U.S. Department of Energy. March.

Evans, J.R., M.P. Lih, and P.W. Dunwiddie (eds.). 2003. *Biodiversity Studies of the Hanford Site Final Report: 2002–2003.* The Nature Conservancy, Washington Field Office, Seattle, WA. August 29.

Harper, B.L. and S.G. Harris. 2009. Human Services, Risk Assessment, Lost Use & Injury. Review draft.

Harris, S.G. and B.L. Harper. 2000. Using eco-cultural dependency webs in risk assessment and characterization of risks to tribal health and cultures. *Environmental Science and Pollution Research* (Special Issue 2):91–100.

Hunn, E. 1991. The Plateau. In *The First Oregonians: An Illustrated Collection of Essays on Traditional Lifeways, Federal-Indian Relations, and the State's Native People Today,* C.M. Buan and R. Lewis (eds.). Oregon Commission for the Humanities, Portland, OR. pp. 8–14.

Hunn, E.S. with J. Selam and family. 1990. *Nch'i-Wána, "The Big River:" Mid-Columbia Indians and Their Land*. University of Washington Press, Seattle.

Jackson, A.D., P.D. Kissner, D.R. Hatch, B.L. Parker, M.S. Fitzpatrick, D.A. Close, and H. Li. 1996. Pacific Lamprey Research and Restoration Annual Report 1996. Prepared for the U.S. Department of Energy.

Landeen, D. and J. Crow. 1997. *I Am of this Land: Wetes pe m'e wes.* Western Printing, Clarkston, WA.

Landeen, D. and A. Pinkham. 1999. *Salmon and His People: Fish & Fishing in Nez Perce Culture.* Confluence Press, Lewiston, ID.

Landers, R. and D. Hansen. 1998. *Paddle Routes of the Inland Northwest, 50 Flatwater and Whitewater Trips for Canoe and Kayak.* The Mountaineers Books, Seattle, WA.

Mueller, R.P. and D.R. Geist. 1999. *Steelhead Spawning Surveys near Locke Island, Hanford Reach of the Columbia River*. PNNL-13055. Pacific Northwest National Laboratory. Prepared for the U.S. Department of Energy. October.

Nez Perce Tribe. 2003. *Treaties: Nez Perce Perspectives*. Confluence Press, Lewiston, ID.

Nickens, P.R., M.K. Wright, N.A. Cadoret, M.W. Dawson, D.W. Harvey, and E.M. Simpson. 1995. *Hanford Cultural Resources Laboratory Annual Report for Fiscal Year 1994*. PNNL-11099. Pacific Northwest National Laboratory. Prepared for the U.S. Department of Energy and the Hanford Natural Resource Trustee Council. September.

Northwest Power and Conservation Council. Undated. Hanford Reach. Available: http://www.nwcouncil.org/history/HanfordReach.asp. Accessed 2/9/2009.

Patton, G.W., B.L. Tiller, E.J. Antonio, T.M. Poston, and S.P. Van Verst. 2003. *Survey of Radiological and Chemical Contaminants in the Near-Shore Environment at the Hanford Site 300 Area*. PNNL 13693, Rev. 1. Pacific Northwest National Laboratory. Prepared for the U.S. Department of Energy. March.

Pendergast, E.L. 2003. *U.S. Department of Energy's Hanford Cultural Resources Laboratory Oral History and Ethnography Task Annual Report.* PNNL-14237. Pacific Northwest National Laboratory. Prepared for the U.S. Department of Energy. July.

PNNL. 1998. *Screening Assessment and Requirements for a Comprehensive Assessment: Columbia River Comprehensive Impact Assessment.* Revision 1, Final. DOE/RL-96-16. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy.

Pospical, A.J. 2004. *A Comparison of Eight National Monuments as Applied to the Hanford Reach National Monument*. PNNL-14801. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. August.

Poston, T.M. 1995. *Concentrations of Radionuclides in Terrestrial Vegetation on the Hanford Site of Potential Interest to Native Americans*. PNL-10397. Pacific Northwest Laboratory. Prepared for the U.S. Department of Energy. March.

Ridolfi. 2004. Draft Natural Resources Studies Matrix: Biota Studies. Prepared for the Hanford Natural Resources Trustees. Ridolfi Inc.

Ridolfi. 2007. Yakama Nation Exposure Scenario for Hanford Site Risk Assessment, Richland, Washington. Prepared for the Yakama Nation ERWM Program. Ridolfi Inc. September.

Sackschewsky, M.R. and J.L. Downs. 2001. *Vascular Plants of the Hanford Site.* PNNL-13688. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. September.

Tiller, B.L., G.E. Dagle, L.L. Cadwell, T.M. Poston, and A. Oganesian. 1997. *Investigation of Anatomical Anomalies in Hanford Site Mule Deer*. PNNL-11518. Pacific Northwest National Laboratory, Richland, WA. Prepared for the U.S. Department of Energy. March.

U.S. DOE. 1996. *Mitigation Action Plan for Liquid Waste Sites in the 100-BC-1, 100-DR-1, and 100-HR-1 Operable Units.* DOE/RL-96-19 Rev. 0. U.S. Department of Energy, Richland, WA.

U.S. DOE. 1999. *Hanford Comprehensive Land Use Plan Environmental Impact Statement.* DOE-EIS-0222-F. U.S. Department of Energy, Richland, WA.

U.S. DOE. 2001. *Hanford Site Biological Resources Management Plan*. DOE/RL 96-32. U.S. Department of Energy, Richland, WA.

U.S. DOE. 2003. *Hanford Cultural Resources Management Plan*. DOE/RL-98-10 Rev. 0. U.S. Department of Energy, Richland, WA.

U.S. EPA. 2002. *Columbia River Basin Fish Contaminant Survey:1996–1998*. EPA 910-R-02-006. U.S. Department of Environmental Protection Region 10, Seattle, WA.

U.S. EPA. 2009. *Columbia River Basin: State of the River Report for Toxics.* U.S. Department of Environmental Protection Region 10. EPA 910-R-08-004. U.S. Environmental Protection Agency, Washington, DC.

USFWS. 1998. Hanford Site 100 Area Assessment Plan Volume I: Columbia River Aquatic Resources. Prepared by U.S. Fish & Wildlife Service Upper Columbia River Basin Field Office for the Hanford Natural Resource Trustee Council. September.

USFWS. 2008. *Hanford Reach National Monument Comprehensive Conservation Plan and Environmental Impact Statement*. Richland, WA.

USFWS. 2009a. Hanford Reach National Monument. U.S. Fish & Wildlife Service. Available: http://www.fws.gov/hanfordreach/map-monument.html. Accessed 2/13/2009.

USFWS. 2009b. Hanford Reach National Monument: Boating on the Hanford Reach. U.S. Fish & Wildlife Service. Available: http://www.fws.gov/hanfordreach/boating.html. Accessed 3/6/2009.

WDFW. 2000. The Rattlesnake Hills (Hanford) Elk Strategic Management Plan. Washington Department of Fish and Wildlife. Available: http://wdfw.wa.gov/wlm/game/elk/hanford2.pdf. Accessed 3/19/2009.

WDFW. 2001. 2001 Washington Fishing Guide. Washington Department of Fish and Wildlife. Available: http://wdfw.wa.gov/outreach/fishing/wfg2001/d-f_cty.htm. Accessed 3/19/2009.