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Draft Technical Impracticability Evaluation for Iodine-129 in Groundwater at Hanford: 200-UP-1 Operable Unit

September 2018

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U.S. DEPARTMENT OF ENERGY

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

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Executive Summary

Target restoration cleanup levels for contaminated groundwater are established by applicable or relevant and appropriate requirements (ARARs) determined by federal and state drinking water quality standards. When these standards cannot be met within a reasonable timeframe due to limitations of available remediation technologies or other factors, the U.S. Environmental Protection Agency (EPA) may evaluate the technical impracticability (TI) of attaining the required groundwater cleanup levels, and establish alternative, protective remedial strategies. This report provides information relevant to consideration of a TI waiver on the current federal 1 pCi/L drinking water standard (DWS) for iodine-129 in the 200-UP-1 Groundwater Operable Unit (OU) of the Hanford Site if ongoing evaluations of treatment options do not identify a feasible treatment technology.

Groundwater in the 200-UP-1 OU is contaminated with carbon tetrachloride, uranium, nitrate, chromium (total and hexavalent), iodine-129, technetium-99, and tritium, associated with past nuclear weapons production activities at Hanford. The preferred alternative described in the 2012 Record of Decision (ROD) for the 200-UP-1 OU Interim Remedial Action includes 35 years of active remediation using a combination of groundwater pump-and treat, monitored natural attenuation (MNA) for portions of the contaminated groundwater, followed by institutional controls until cleanup levels are met for unrestricted use. As noted in the 200-UP-1 OU ROD, no treatment technology for iodine-129 had been found that could achieve the DWS of 1 pCi/L for the iodine-129 concentrations present in the 200-UP-1 OU groundwater. Therefore, the 200-UP-1 OU interim ROD specified hydraulic containment of the iodine-129 plume, update of the conceptual model for iodine-129, and further evaluation of potentially applicable iodine-129 treatment technologies. The 200-UP-1 OU ROD further stated that in the event a viable treatment technology is not available, the use of a TI waiver may need to be considered as part of the final remedy.

The 200-UP-1 OU is expected to be under institutional controls, with no withdrawals of groundwater for drinking in the foreseeable future.[1] Long-term monitoring data show that iodine-129 groundwater concentrations are declining slowly over time and the plume area is shrinking. The injection wells used for hydraulic containment appear to be effective in limiting, or eliminating, migration of the plume, although the hydraulic containment wells have only been operating since 2015 and their effects are still being evaluated. Mechanisms that may be responsible for iodine plume attenuation, including volatilization, sorption, and incorporation into carbonate or iron-oxide precipitates, have been identified in laboratory studies supporting an update of the iodine-129 plume conceptual site model. Evaluation of potential treatment technologies is also ongoing. The outcomes of these activities are relevant to considering a TI waiver and current results have been incorporated into the information presented in this report. The TI waiver process is being evaluated concurrently in case an effective treatment technology is not identified.

The information provided in this report is based on the EPA's recommended summary checklist for Superfund site groundwater TI evaluation. The checklist was developed by the EPA to assist regions in evaluating whether they have sufficient information to support a TI evaluation for the administrative record. Categories of information in the checklist include (1) the specific ARARs or media cleanup

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[1] USDOE. 2013. *Hanford Site Cleanup Completion Framework*. DOE/RL-2009-10, Rev. 1, U.S. Department of Energy, Richland Operations Office, Richland, Washington.

standards that are being addressed, (2) the spatial extent of TI decisions, (3) the development and purpose of the site conceptual model, (4) evaluation of restoration potential, (5) cost estimates, (6) alternative remedial strategies, and (7) additional remedy selection considerations. The EPA checklist is included as an appendix with linked references to specific locations in this document where supporting information can be found. Supporting information includes a summary of site hydrogeology, time-histories of measured iodine-129 concentrations in groundwater, and the changes in plume area over time. Subsurface flow and transport model projections are also presented to illustrate the effects of the current pump-and-treat system and hydraulic containment wells on iodine-129 plume dynamics.

Although the iodine-129 plume footprint is shrinking over time, model projections suggest that iodine-129 concentrations will remain above the DWS beyond the hydraulic containment specified in the ROD as an interim remedial action. Hence, to achieve site closure, a TI waiver may be necessary for recalcitrant regions of the plume that remain above the DWS within this timeframe. Natural attenuation mechanisms, or targeted remedies currently being evaluated in ongoing laboratory studies, can reduce concentrations below the DWS in the more distal regions of the plume. The information provided in this report addresses the technical basis needed for a TI waiver for iodine-129 that will also address protectiveness of human health and the environment.

Acknowledgments

This document was prepared by the Deep Vadose Zone − Applied Field Research Initiative at Pacific Northwest National Laboratory. Funding for this work was provided by the U.S. Department of Energy (DOE) Richland Operations Office. We thank Mary Hartman and Margo Aye of CH2M Hill Plateau Remediation Company (CHPRC) for their assistance in providing the most current information regarding iodine-129 contamination in the 200-UP-1 Operable Unit. We also extend our appreciation to Art Lee and Sally Simmons (CHPRC) for providing operational and monitoring data for the 200 West Area pump-and-treat system.

Acronyms and Abbreviations

ARAR	applicable or relevant and appropriate requirement
CCU	Cold Creek Unit
CERCLA	*Comprehensive Environmental Response, Compensation, and Liability Act*
CHPRC	CH2M Hill Plateau Remediation Company
CPVZ GFM	Central Plateau Vadose Zone Geologic Framework Model
DOC	dissolved organic carbon
DOE	U.S. Department of Energy
DWS	drinking water standard
EPA	U.S. Environmental Protection Agency
ERDF	Environmental Restoration Disposal Facility
FIO	For Information Only
GFM	Geologic Framework Model
GIS	geographic information system
HF	Hanford formation
HSU	hydrostratigraphic units
K_d	distribution coefficient
LOWESS	locally-weighted regression
MCL	maximum contaminant level
MNA	monitored natural attenuation
Organo-I	organo-iodine
OU	operable unit
P&T	pump-and treat
RAWP	Remedial Action Work Plan
RCRA	Resource Conservation and Recovery Act
REDOX	reduction oxidation
RI/FS	remedial investigation/feasibility study
Rlm	Ringold Formation Lower Mud
ROD	record of decision
Rtf	Ringold Formation Taylor Flats Unit
Rwia	Ringold Formation Wooded Island Unit A
Rwie	Ringold Formation Wooded Island Unit E
SOM	soil organic matter
STOMP	Subsurface Transport Over Multiple Phase
TI	technical impracticability
WMA	Waste Management Area

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1.0 Introduction

The 200-UP-1 Groundwater Operable Unit (OU), located on the U.S. Department of Energy (DOE) Hanford Site in southeastern Washington State, consists of the groundwater beneath the southern portion of the 200 West Area within the Central Plateau, as shown in Figure 1.1. Groundwater in the 200-UP-1 OU is contaminated with carbon tetrachloride, uranium, nitrate, chromium (total and hexavalent), iodine-129, technetium-99, and tritium. The DOE Richland Operations Office is the lead agency for remediation of the 200-UP-1 OU and the U.S. Environmental Protection Agency (EPA) is the lead regulatory agency, as identified in Section 5.6 and Appendix C of the Tri-Party Agreement.[1] In accordance with the Tri-Party Agreement, Article XIV, Paragraph 54, DOE developed and proposed remedial action for the 200-UP-1 OU through completion and approval of a remedial investigation/feasibility study (RI/FS) (DOE/RL-2009-122, *Remedial Investigation/Feasibility Study for the 200-UP-1 Groundwater Operable Unit*). The *Record of Decision for Interim Remedial Action, Hanford 200 Area Superfund Site, 200-UP-1 Operable Unit* (hereafter referred to as the 200-UP-1 OU ROD) (USEPA et al. 2012) was signed by EPA, DOE, and the Washington State Department of Ecology on September 27, 2012. The selected interim remedy was chosen in accordance with the *Comprehensive Environmental Response, Compensation, and Liability Act* (CERCLA), as amended by the *Superfund Amendments and Reauthorization Act of 1986*, the Tri-Party Agreement, and, to the extent practicable, the National Contingency Plan (40 CFR 300). This decision is based on the Administrative Record file for the 200-UP-1 OU.

The preferred alternative described in the 200-UP-1 OU ROD includes 35 years active remediation using a combination of groundwater pump-and treat (P&T), monitored natural attenuation (MNA) for portions of the contaminated groundwater, followed by institutional controls until cleanup levels are met for unrestricted use (USEPA et al. 2012; USDOE 2012c). The selected interim remedy stipulates groundwater P&T for parts of the carbon tetrachloride plume, technetium-99 plumes, uranium plume, high-concentration nitrate plume area, and chromium (total and hexavalent) plumes, remedy performance monitoring for all plumes, followed by institutional controls. However, as noted in the 200-UP-1 OU ROD, no current treatment technology for iodine-129 exists that can achieve the federal drinking water standard (DWS) of 1 pCi/L for the iodine-129 concentrations present in the 200-UP-1 OU groundwater. The 200-UP-1 OU interim ROD specified hydraulic containment of the iodine-129 plume and further evaluation of potentially applicable iodine-129 treatment technologies. The 200-UP-1 OU ROD further stated that the interim remedial action:

> "is only a part of the expected total remedial action for the 200-UP-1 OU, that will attain or otherwise waive the ARAR for iodine-129 upon completion of remedial action, as required by CERCLA Section 121(d)(4), "Cleanup Standards," "Degree of Cleanup. A subsequent ROD will be needed to complete the total remedial action for the 200-UP-1 OU. In the event a viable treatment technology is not available, the use of a technical impracticable waiver under 40 CFR 300.430(f)(l)(ii)(c) may need to be considered as part of the final remedy."

This document provides information relevant to future consideration of a technical impracticability (TI) waiver for iodine-129 in the 200-UP-1 OU if the evaluation of potential treatment options does not

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[1] Hanford Federal Facility Agreement and Consent Order by Washington State Department of Ecology, United States Environmental Protection Agency, United States Department of Energy, as Amended Through March 28, 2018, 89-10 Rev. 8.

identify feasible remediation technologies. The technology evaluation plan for iodine-129 specified in the interim ROD has been prepared, and updates to the conceptual model for the plume, reviews of current literature, and a feasibility analysis of potential treatment options have been published (USDOE 2017a; Truex et al. 2017). In situ technologies that are currently being evaluated include contaminant sequestration via co-precipitation and enhanced sorption processes, and treatments that would enhance iodine mobility for capture in the pump-and-treat facility. Efficient materials for ex situ removal of iodine from groundwater are also under current evaluation.

This report is organized as follows. The remainder of Section 1 provides background information on the Hanford 200 West Area and the 200-UP-1 OU. Section 2 provides information on the distribution and extent of the iodine-129 plume. Section 3 describes the components considered in the conceptual model for iodine-129 including the waste disposal history for 200-UP-1 OU, hydrogeological features affecting iodine-129 distribution and movement, and the biogeochemical processes affecting fate and transport of iodine-129. Implementation of hydraulic containment as the interim remedy for iodine-129 is described in Section 4, along with brief descriptions of alternative iodine-129 remedy technologies that are being considered.

1.1 Background

The iodine-129 plume lies within the 200-UP-1 OU, which addresses the groundwater contaminant plumes beneath the southern portion of the 200 West Area and adjacent portions of the surrounding 600 Area (Figure 1.1) (USDOE 2017b). The 200 West Area is approximately 8 km^2 (3 mi^2) in size and is located near the middle of the Hanford Site on an elevated, flat area that is often referred to as the Central Plateau. The Central Plateau contains no perennial streams, wetlands, or floodplains (USDOE 2013a). The 200-UP-1 OU is bounded on the eastern side by the 200-PO-1 Groundwater OU and to the north by the 200-ZP-1 Groundwater OU. The 200-UP-1 OU lies about 8 km (5 mi) from the Columbia River and 11.3 km (7 mi) from the nearest Hanford Site boundary (Figure 1.1) (USDOE 2013a).

Contamination of groundwater in the 200-UP-1 OU has resulted primarily from historical operations and disposal of liquid wastes associated with uranium and plutonium recovery processes. Bulk liquid waste discharges contributing the majority of contamination to the subsurface occurred from 1944 to the early 1990s. No liquid waste discharges currently occur to the ground above the OU (with the exception of septic drain fields) (USDOE 2013a). The extent of the iodine-129 plume is shown in context with the other contaminant plumes in 200-UP-1 groundwater in Figure 1.2.

The remedies selected in the interim ROD for 200-UP-1 contaminants are outlined in the remedial action work plan for the 200-UP-1 OU (USDOE 2013a). P&T remedies combined with MNA are expected to achieve cleanup levels for technetium-99 within 15 years, for uranium within 25 years, for chromium (total and hexavalent) within 25 years, and for nitrate within 35 years. MNA is the selected remedy for the tritium plume, which is expected to achieve cleanup levels within 25 years. Active restoration and MNA are anticipated to take approximately 125 years to reach the cleanup level for carbon tetrachloride, which is consistent with the time frame for cleanup of carbon tetrachloride in the adjacent 200-ZP-1 OU. Institutional controls will be implemented to prevent exposure and groundwater use until cleanup levels are achieved for these contaminants.

The RI/FS determined that mature, demonstrated, ex situ treatment processes were not available at that time to achieve the federal drinking water standard (DWS) of 1 pCi/L for iodine-129 in the groundwater in 200-UP-1 OU. Therefore, the 200-UP-1 interim ROD (USEPA et al. 2012) specified that hydraulic containment of the iodine-129 plume would be implemented until a subsequent remedial decision is made regarding the iodine-129 plume. In addition, the interim ROD specified a technology evaluation plan for iodine-129 be prepared to provide an update to the conceptual model for the plume, a review of current literature, and a feasibility analysis of potential treatment options (USDOE 2017a). That report fulfilled the associated Tri-Party Agreement milestone, M-016-192, "Submit I-129 Technology Evaluation Plan Draft A to EPA as defined in the 200-UP-1 RD/RA WP."

Remediating the iodine-129 plume in the 200-UP-1 OU is technically challenging. The plume is large, but dilute. However, the DWS is also very low. Iodine is typically very mobile in the environment, but its mobility varies with environmental conditions. Various forms are soluble in water and/or volatile, and iodine speciation affects the mobility, phase partitioning, and reactivity. Minerals such as iron and manganese may mediate iodine transformation processes, either directly or coupled with microbial processes. Iodine may also interact with organic materials in the subsurface to form (1) immobile, sediment-associated organo-iodine (Organo-I) compounds, (2) mobile soluble Organo-I compounds, or (3) volatile Organo-I compounds. Organic materials can also affect iodine fate and transport through microbially-mediated reduction reactions that directly or indirectly affect iodine speciation or by providing adsorption capacity for iodine species.

Another key challenge in remediating the iodine-129 is that naturally occurring, stable iodine-127 also exists in the plume and is present at much greater concentrations than iodine-129. In order for most strong sorbents to work effectively to lower iodine-129 concentrations, they would also have to lower natural iodine concentrations by about two orders of magnitude (Kaplan et al. 2012). As natural stable iodine concentrations in groundwater are decreased by treatment, Hanford sediments could potentially release additional iodine in response to the altered adsorption/desorption and solubility equilibrium in the subsurface system. Together, the large size of the iodine-129 plume, the very low target concentration, and the presence of relatively high concentrations of the stable iodine isotope significantly limit practical remediation options for iodine-129.

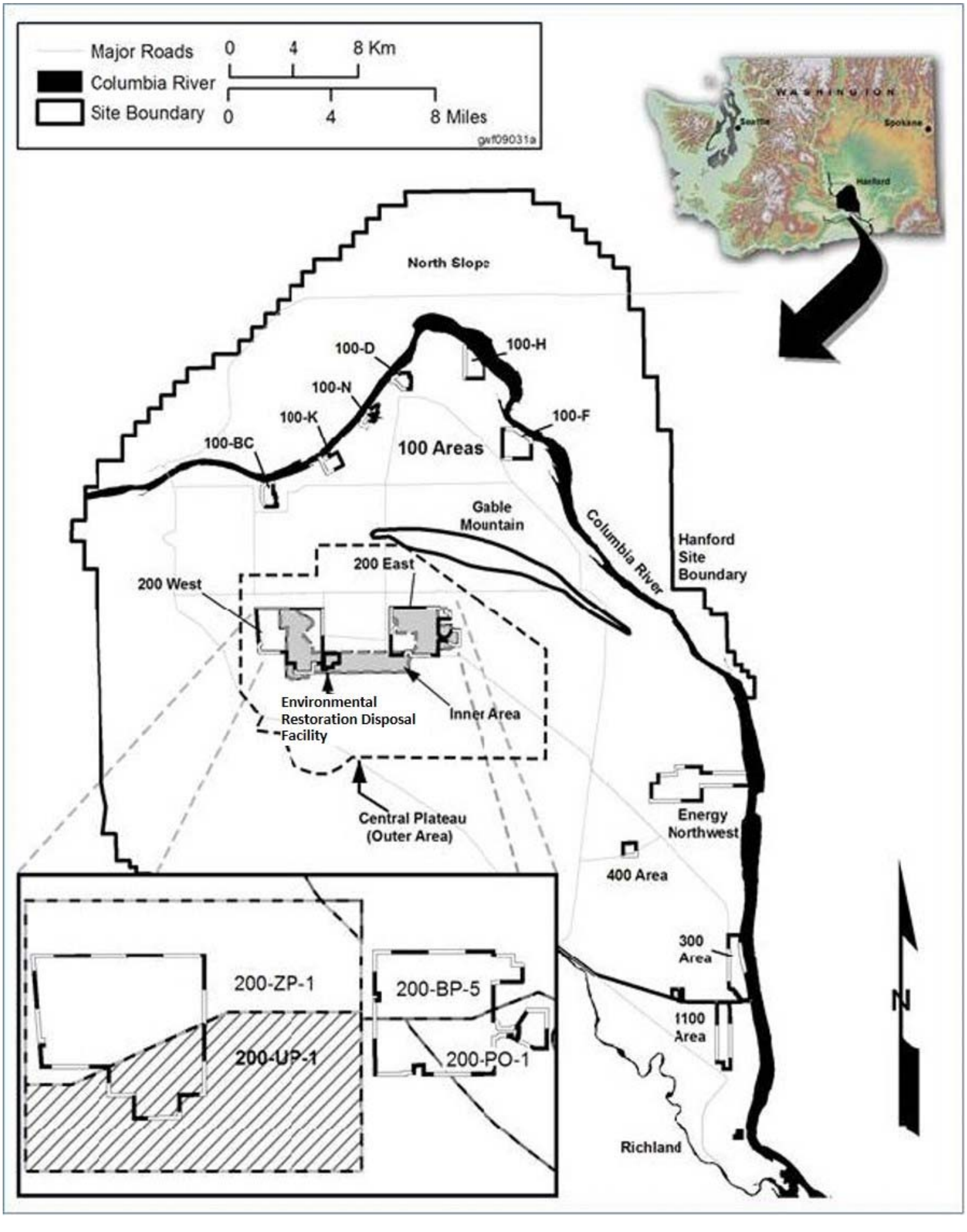

Figure 1.1. Location of 200-UP-1 Operable Unit on the Central Plateau at the Hanford Site (from USDOE 2013a)

Potential remediation options for iodine-129 are being evaluated as specified in the 200-UP-1 ROD (USDOE 2017a). The remediation technology evaluation will compile sufficient information about the technology options to demonstrate whether they are viable with respect to meeting the 200-UP-1 OU remedial action objectives for iodine-129. Based on the technology evaluation results, the OU can either pursue a technical impracticability or other applicable or relevant and appropriate requirements (ARAR) waiver, or conduct a focused feasibility study to select an iodine-129 remedy other than the hydraulic control remedy identified in the 200-UP-1 OU ROD.

In addition to the iodine-129 plume in 200-UP-1, the contaminant plumes and sources within the 200-UP-1 OU include the following (Figure 1.2):

- A uranium plume originating from the U Plant cribs
- A widespread nitrate plume originating from U Plant and S Plant cribs and Waste Management Area (WMA) S-SX
- A chromium (total and hexavalent) plume associated with WMA S-SX, and a dispersed chromium (total and hexavalent) plume in the southeast corner of the OU that originated from an S Plant crib
- Four separate technetium-99 plumes associated with WMA U, U Plant cribs, and WMA S-SX
- A widespread tritium plume originating from S Plant cribs
- In addition to the plumes that formed within the 200-UP-1 OU, a widespread carbon tetrachloride plume exists over a large portion of the 200 West Area. This plume originated from operation of the Plutonium Finishing Plant (Z Plant) facilities and has spread south and east from the 200-ZP-1 OU and into the 200-UP-1 OU.

Some of these contaminant plumes overlap portions of the iodine-129 plume, as shown in Figure 1.2, but are not explicitly considered in this evaluation of the TI for remediating iodine. Any remedy applied to address iodine-129 will need to consider the effects of the remedy on other contaminants within the 200-UP-1. The nitrate plume currently has the largest overlap with the iodine-129 plume in the 200-UP-1. Ongoing laboratory experiments are currently evaluating in situ and ex situ treatment technologies for I-129. Their potential impact on nitrate and any other contaminants present within the treatment area will need to be considered.

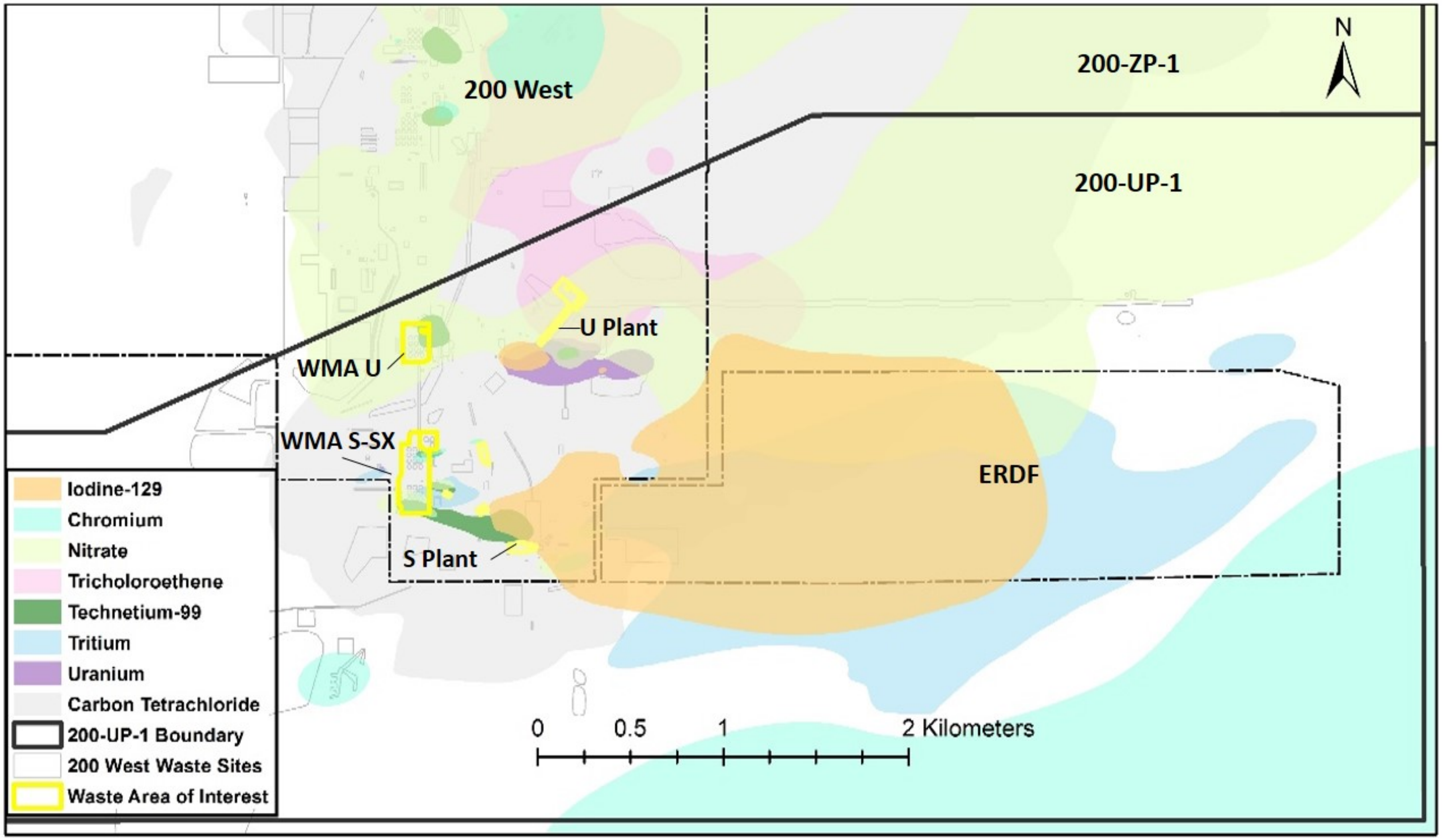

Figure 1.2. Groundwater Contaminant Plumes in 200-UP-1 Operable Unit. (USDOE 2018a). For Information Only.

2.0 Status of Iodine-129 in the 200-UP-1 Operable Unit

The sources of contaminants currently observed in groundwater at 200-UP-1 were primarily planned releases of the process liquid wastes and wastewater to the soil via discharge to engineered structures (cribs, trenches, ditches, ponds, leach fields, or injection wells). Releases to these engineered structures occurred during the 1940s through the 1990s, and there are no current liquid discharges within the OU. The iodine-129 groundwater contaminant plume resulting from the historical discharge is well defined, occurring within the unconfined aquifer beneath, and east of, the 200 West Area (USDOE 2012a). The 200-UP-1 iodine-129 plume extends less than 5 km to the east of the originating waste sources and does not interact with any surface waters within or adjacent to its boundaries.

Withdrawal of groundwater from 200-UP-1 OU is prohibited by institutional controls placed on groundwater use by DOE. The existing institutional controls (specifically, prohibitions against use of groundwater for a source of drinking water) prevent human exposure. The plume currently does not extend past the OU boundary and does not extend to the groundwater discharge areas along the Columbia River to the east; thus, no ecological receptors are exposed. Estimates of groundwater travel times indicate that the current institutional controls should remain effective at preventing exposure to human and ecological receptors for the foreseeable future. Current land use on the Central Plateau is industrial, and public access to the site is restricted. The OU is anticipated to continue as an industrial area under institutional control for ongoing waste disposal operations and infrastructure services (USDOE 2013b).

All iodine-129 concentrations measured in monitoring wells within the 200-UP-1 plume boundaries are less than 50 pCi/L, with most measured concentrations less than 10 pCi/L, but above the DWS of 1 pCi/L. The maximum concentration in the iodine-129 plume during 2017 was 22.8 pCi/L in well 299-W21-3. Among the other 11 wells sampled for iodine-129 in 2017, the cleanup level of 1 pCi/L was exceeded in 8 wells, with concentrations ranging from 1.08 to 11.7 pCi/L. The highest concentrations measured within the current plume boundary occur at locations downgradient from their original source areas (the REDOX and U Plant cribs). This is consistent with the cessation of waste/wastewater releases within 200-UP-1 almost half century ago and suggests that secondary sources in the vadose zone sources are diminished. Natural stable iodine (iodine-127) is also present in the aquifer at much greater concentrations than iodine-129. The presence of iodine-127 in groundwater is important because most remediation technologies are not specific for a particular iodine isotope (e.g., Truex et al. 2017; USDOE 2017a).

2.1 Sources of I-129

The main waste sites that contributed to iodine-129 contamination in groundwater within the 200-UP-1 OU included ponds, cribs, and trenches receiving liquid waste from the 202-S Reduction Oxidation (REDOX) Facility (S Plant) and U Plant operations, and unplanned releases from WMA S-SX (USDOE 2012a). The REDOX Plant conducted plutonium separations from 1952 through 1967; U Plant conducted uranium recovery from 1952 through 1957. Unplanned releases resulted from inadvertent releases of the same or similar waste materials from tanks, pipelines, or other waste storage or conveyance components. Most of the liquid waste and wastewater migrated downward through the soil column by gravity to reach the underlying groundwater. Downward flux through the vadose zone may continue to contribute contaminants to the groundwater at a low rate, but most groundwater monitoring well data suggest that there are no significant, ongoing sources of iodine-129 to the water table.

As described in the 2016 Hanford Groundwater Monitoring Report (USDOE 2017b), the iodine-129 groundwater plume in 200-UP-1 OU emanates primarily from disposal cribs located near U Plant and S Plant (Figure 2.1). The waste sites believed to be the most important contributors to the plume are 216-S-1&2, 216-S-7, and 216-U-1&2 (Truex et al. 2017). Other sites such as 216-A-10 and 216-S-9 had either very dilute iodine-129 solutions or much smaller total iodine-129 mass disposed in them.

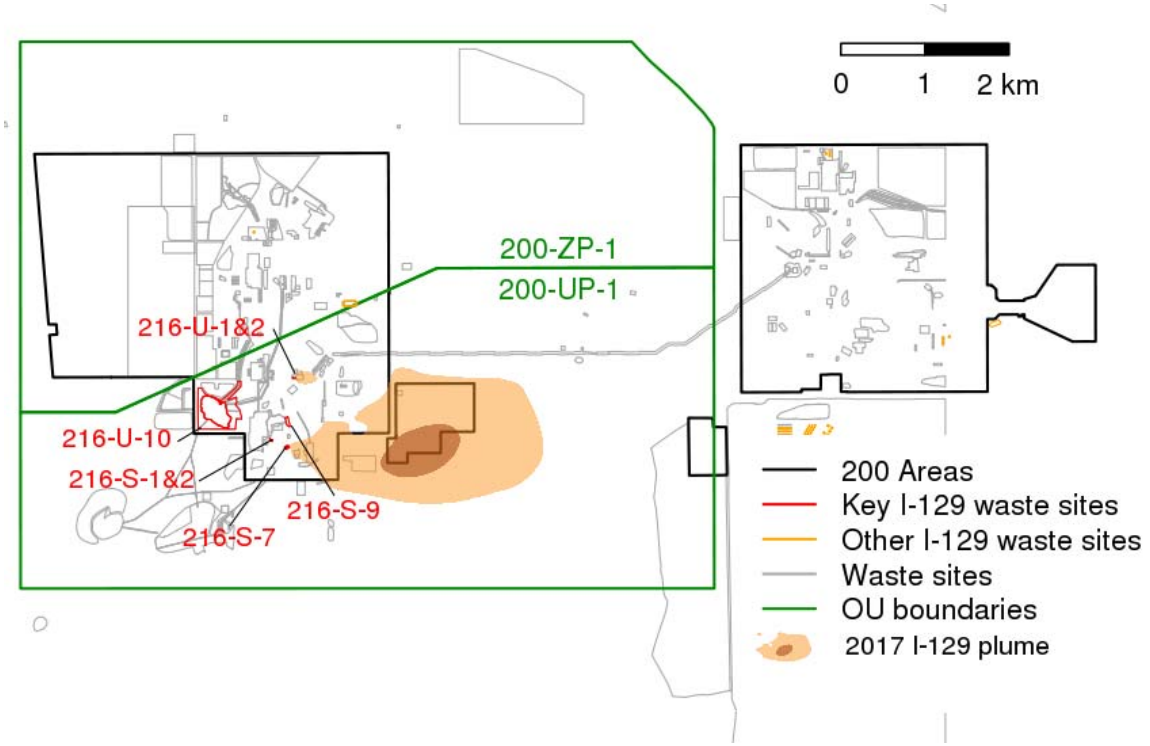

Figure 2.1. Map of Key Iodine-129 Source Areas within 200-UP-1 OU in Relation to the 2017 Iodine-129 Plume. The light and dark plume colors denote 1 and 10 pCi/L contour levels, respectively. For Information Only.

The highest iodine-129 concentrations in 200-UP, greater than 10 times the 1 pCi/L cleanup level, probably originated from the 216-S waste sites, but the 216-U-1&2 cribs also produced a plume that was locally significant in the past. East of the 200 West Area, the plumes merged, forming a larger comingled plume extending across the OU, which generally follows the same groundwater flow path across the OU as tritium. Additional information on releases and volumes of iodine-129 and water is discussed in Section 3.3.

2.2 Areal Extent of Iodine-129 Groundwater Plume

Plume locations and extents are inferred from the well sample data collected by the Hanford Groundwater Monitoring Program and reported annually (USDOE 2017b). The areal extent of the iodine-129 plume estimated in 2017 from groundwater concentrations in the 200-UP-1 OU (as defined by the 1 pCi/L contour) is approximately 3.4 km^2. The plume extends approximately 3 km (1.9 mi) east from the REDOX Plant waste sites into the 600 Area (Figure 2.2). In 2016, the estimated areal extent of the plume was 4.2 km^2 (USDOE 2017b). The largest iodine-129 concentrations are greater than 10 times the 1 pCi/L cleanup level.

Figure 2.3 and Figure 2.4 depict the plume extent over the past several decades based on well sample data. These show that plume has oscillated, but declined, in areal extent. The most recent plume estimations indicate that the interior plume area above 10 pCi/L may also be declining, The maximum distance between 1 pCi/L plume centers is about 760 m (between years 1994 and 2006), and location of the 2017 plume center is only about 55 m from the 1993 location.

Changes in the inferred plume shape and boundary are due in part to changes in well status and sampling variability in time. Iodine-129 was previously found to occur beneath the SX Tank Farm (WMA S-SX) at concentrations slightly above the 1 pCi/L cleanup level, and the estimated areal extent of the plume before 2014 reflects that. The iodine-129 concentration was 2.0 pCi/L in a December 2011 sample from well 299-W23-19, located within the SX Tank Farm (as indicated on Figure 2.2). Concentrations in the WMA S-SX area have declined since startup of groundwater extraction in the area during July 2012. In June 2015, the iodine-129 concentration in well 299-W23-19 was 1.6 pCi/L. During 2016, no sample results from wells in the WMA S-SX area exceeded the 1 pCi/L cleanup level. Iodine-129 was detected above the cleanup level at 299-W22-26 (downgradient from the S Tank Farm) before this well became dry (2.8 pCi/L in 2011), but the source was considered to be the 216-S-9 Crib. Iodine concentrations measured in two new wells drilled in 2016 to replace wells that had gone dry also influence the current plume extent. Well 299-W21-3 replaced dry well 699-35-70, and well 299-W22-114 replaced dry well 299-W22-9. Before the new wells were drilled and sampled, 2005 groundwater sampling continued to be used for plume. Data from the new wells showed a decrease in the plume area greater than 10 pCi/L compared to previous years. Plume size overall generally has decreased over time as shown in Figure 2.5.

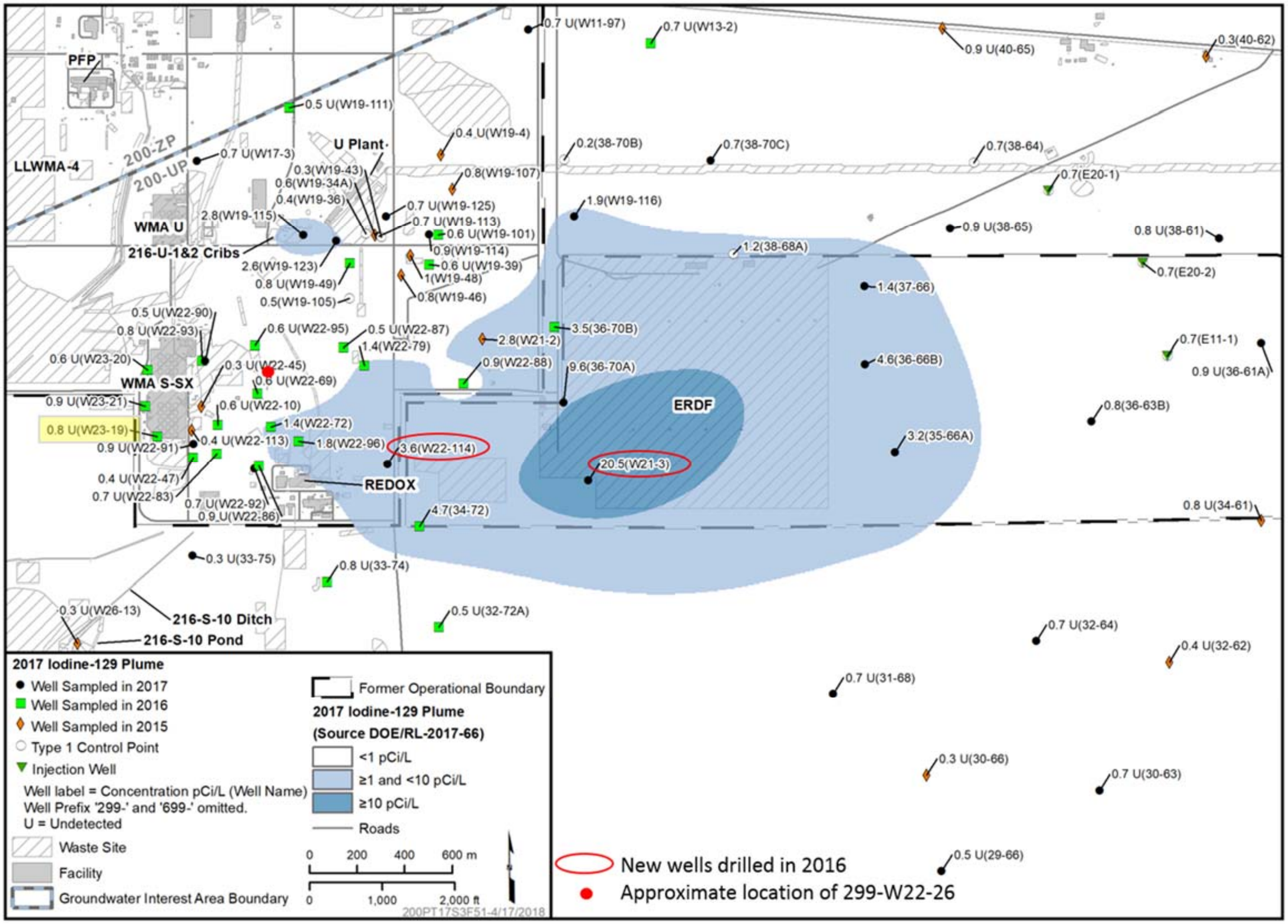

Figure 2.2. Detailed Map of Iodine-129 Plume from Hanford Site Groundwater Monitoring Report for 2017, DOE/RL-2017-66 (USDOE 2018a). (Groundwater monitoring wells are shown with iodine-129 concentration data (pCi/L) as of publication of that report, followed by the well identifier).

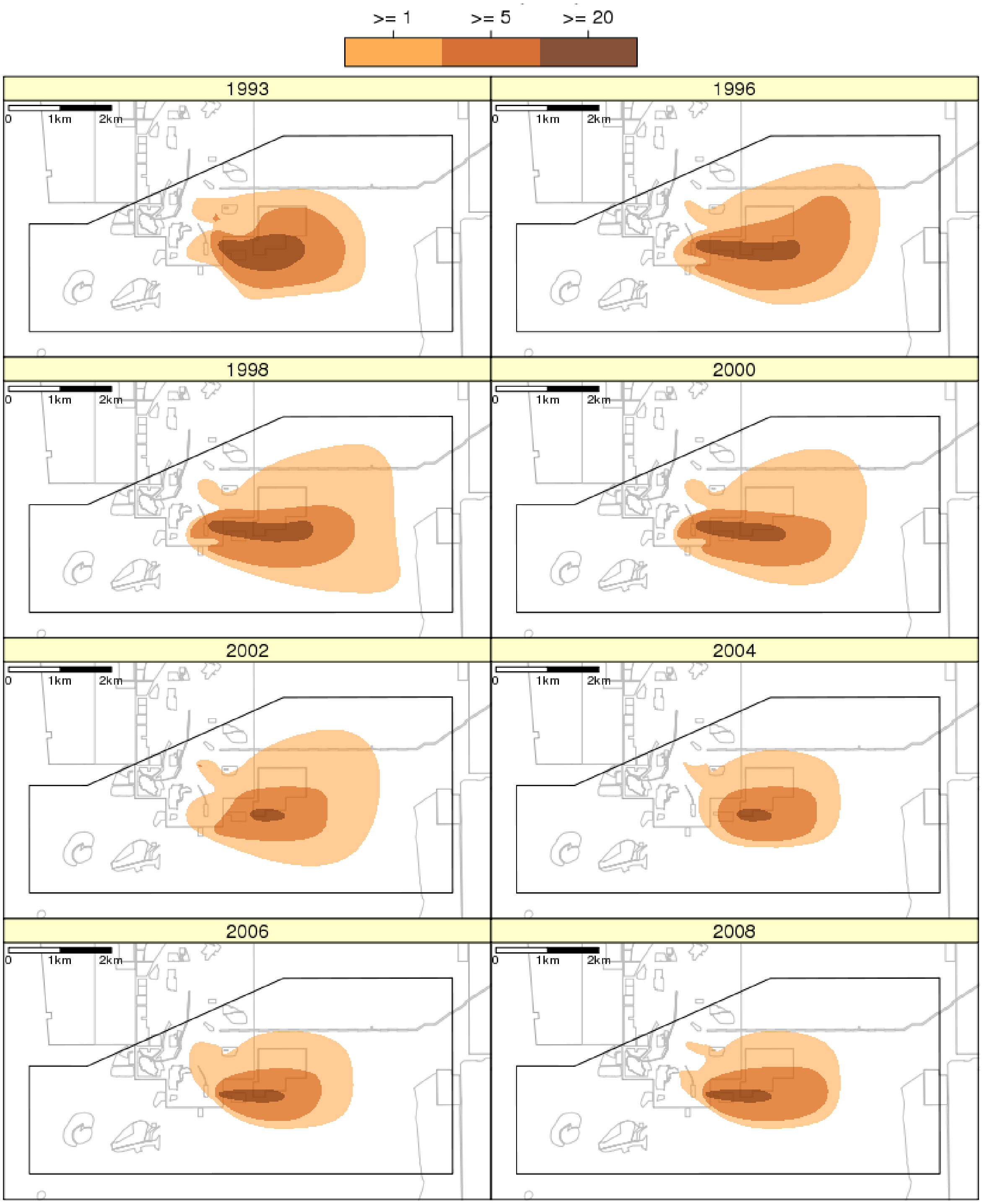

Figure 2.3. Estimated Extent of the 200-UP-1 OU Iodine-129 Plume for 1993 to 2008 with 1, 5, and 20 pCi/L contours. For Information Only.

Since 2008, efforts to estimate the 5 and 20 pCi/L contour levels have been discontinued; instead, a 10 pCi/L countour level is calculated and reported by the Hanford Groundwater Monitoring Program as shown in Figure 2.4.

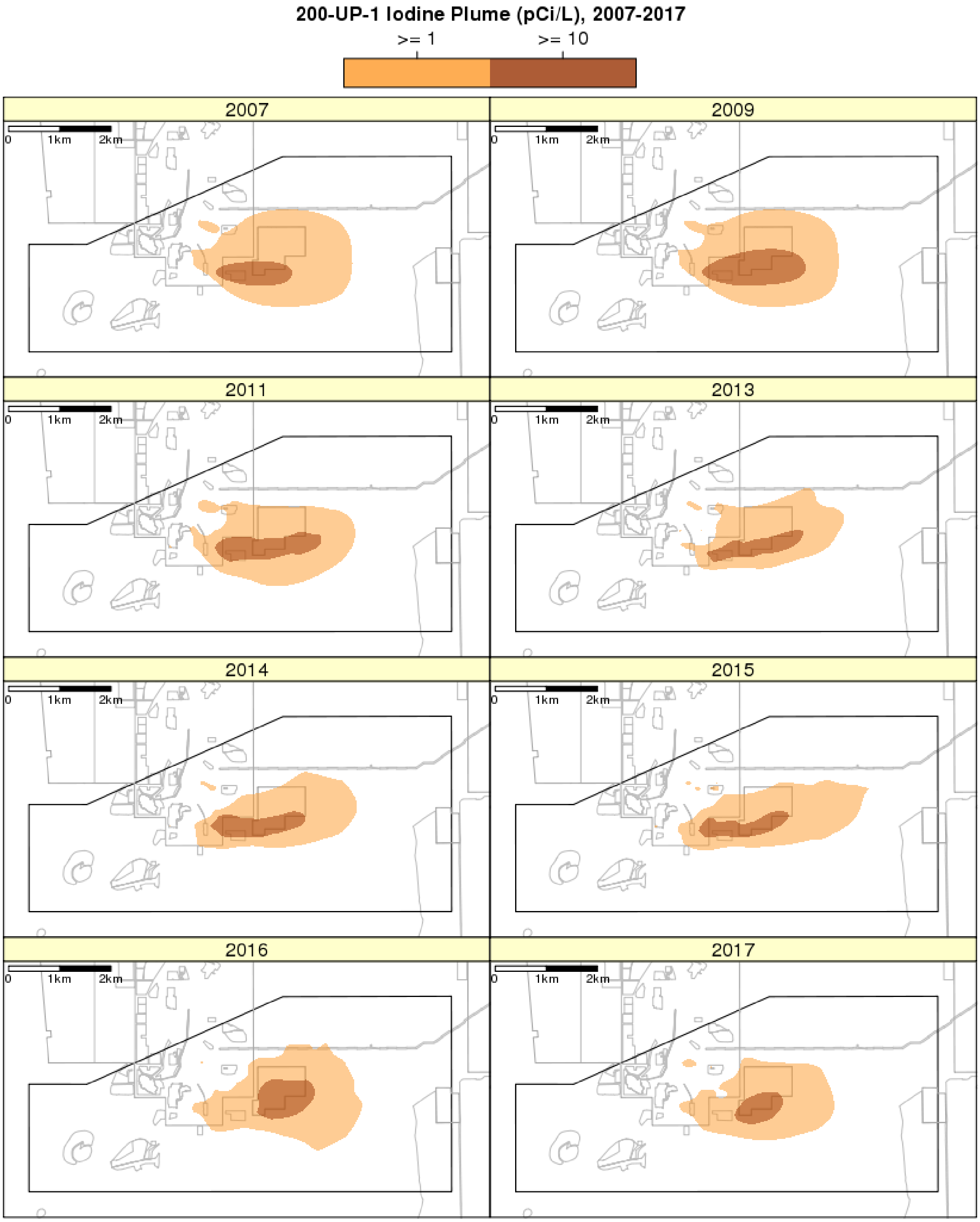

Figure 2.4. Estimated Extent of the 200-UP-1 OU Iodine-129 Plume for the Period from 2007 through 2017 for the 1 and 10 pCi/L Contour Levels. For Information Only.

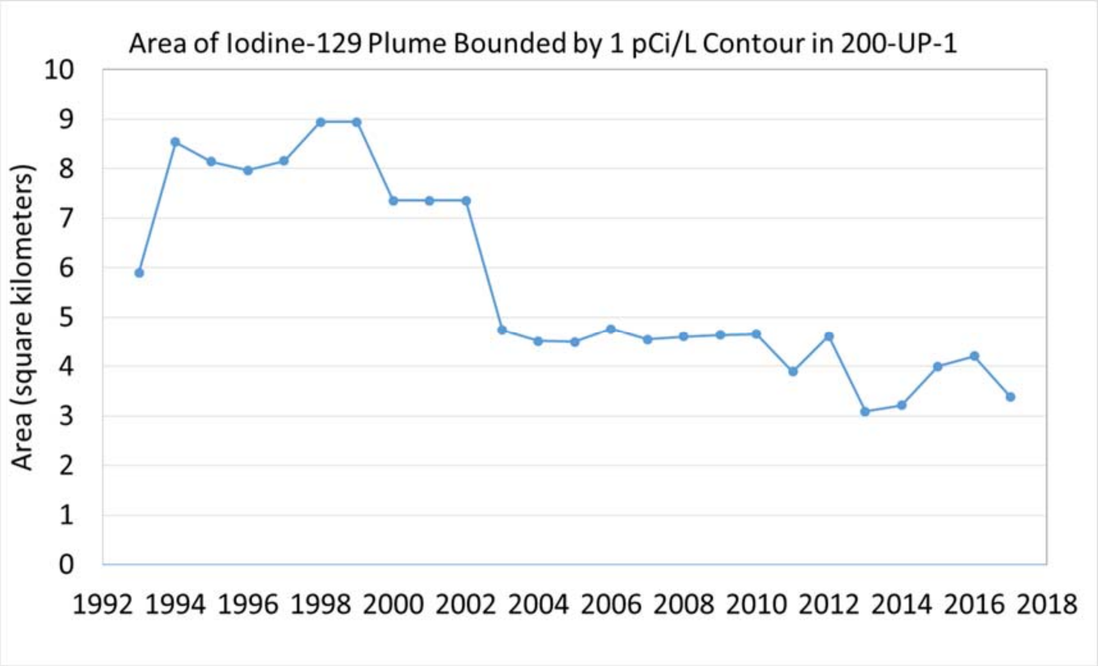

Figure 2.5. Trend in Estimated Areal Extent of the Iodine-129 Plume in 200-UP-1 Operable Unit. For Information Only.

2.3 Vertical Extent of I-129 Plume

The known vertical extent of the iodine-129 plume is limited to the unconfined aquifer above the Ringold Lower Mud formation. Depending on location within the plume, the portion of the unconfined aquifer contaminated at the 1pCi/L level ranges from just the upper part of the aquifer to the full thickness. Depth-discrete profiles of iodine-129 measured in five wells drilled in 2016 are shown in Table 2.1 and the well locations are shown in Figure 2.2 and Figure 2.9. At well 299-W22-114, the maximum concentration observed during drilling was 4.03 pCi/L in the uppermost sample collected 3.4 m (11 ft) below the water table.

Two conceptual cross sections were made along transect lines A-A’ and F-F’ in Figure 2.6 as part of the Remedial Action Work Plan (RAWP) for 200-UP-1 (USDOE 2013a), based on data collected through 2011. The iodine-129 conceptual cross section for each of these locations, including depth-specific concentration data and an interpretation of the vertical extent of iodine-129 at 1 pCi/L or above, are shown in Figure 2.7 and Figure 2.8. The cross section along A-A’ (Figure 2.7) indicates that the extent of the iodine-129 plume remains localized downgradient of 216-U-1&2, and the depth-discrete data indicate that the I-129 contamination is limited to the upper portion of the unconfined aquifer. The A-A’ cross section is now located on the edge of the most recent (2017) mapping of the plume, which is consistent with a continued interpretation that the plume is shallow in that area.

Cross section F-F’ (Figure 2.8) extends from a location up-gradient of the S Plant sources, downgradient approximately along the center of the current plume, to near the eastern boundary of 200-UP-1. This figure illustrates two separate plumes: (1) a small emerging plume beneath the WMA S-SX (which is coincident with the WMA technetium-99, nitrate, and chromium plumes from that source); and (2) the much larger iodine-129 plume that forms from multiple smaller plumes merging downgradient from the 216-S-1&2, 216-S-7, and 216-S-9 crib sources. Figure 2.8 interprets the iodine-129 contamination as extending through the total thickness of the unconfined aquifer below the area where concentrations exceed 10 pCi/L. This is a conservative interpretation because there are no depth-discrete data available in this area to validate the vertical extent of the iodine-129.

The plume is interpreted to occur at a shallow depth near the source to well 299-W19-116 but deepens farther eastward. The plume is fully mixed vertically at well 699-38-70C, 1.8 km (1.1 mi) east of the cribs—this well is screened just above the Ringold Lower Mud unit and had a concentration of 1.51 pCi/L during 2016 (USDOE 2017b). However, iodine-129 has not been measured in wells that are only screened below the Ringold Lower Mud, which indicates that only the upper unconfined aquifer has been contaminated above the 1 pCi/L level. Concentrations above 1 pCi/L occur in approximately the upper 20 m (70 ft) of the aquifer at well 299-W22-114 (USDOE 2017b). Data for well 299-W21-3, drilled in 2016, indicate that iodine-129 occurs above the 1 pCi/L cleanup level throughout the aquifer thickness (Table 2.1)

Table 2.1. Iodine-129 Sample Results by Depth for New Wells Drilled in 2016 in 200-UP-1 (Data for Well 299-W21-3, Well 299-W22-114, Well 699-36-63B, Well 299-W19-115, and Well 299-W19-116 as reported in tables 11.2 through 11.6 in USDOE 2017b; *Hanford Site Groundwater Monitoring Report for 2016*)

Well 299-W21-3			Well 299-W22-114			Well 699-36-63B			Well 299-W19-115			Well 299-W19-116		
Depth Below Water Table (m)	Depth Below Water Table (ft)	I-129 (pCi/L)	Depth Below Water Table (m)	Depth Below Water Table (ft)	I-129 (pCi/L)	Depth Below Water Table (m)	Depth Below Water Table (ft)	I-129 (pCi/L)	Depth Below Water Table (m)	Depth Below Water Table (ft)	I-129 (pCi/L)	Depth Below Water Table (m)	Depth Below Water Table (ft)	I-129 (pCi/L)
1.5	4.8	14.1	3.2	10.6	4.01	2.3	7.4	0.678	4.3	14.2	0.93	2.8	9.1	2.75
14.9	48.9	38.9	10.4	34.1	1.73	5.2	17.2	<0.695	10.3	33.9	<0.834	11.9	39.3	2.25
21.2	69.6	7.14	20.5	67.4	1.49	11.5	37.6	0.848	15.7	51.6	0.642	21.3	69.9	<0.63
30.4	99.9	14.5	29.8	97.7	<0.663	17.6	57.6	<0.53	21.7	71.5	<0.616	30.1	98.8	<0.928
39.2	128.7	3.70	39.8	127.6	<0.763	23.7	77.8	<0.867	27.7	90.8	<0.511	36.3	119.0	<0.542
45.4	149.0	2.31	54.1	177.6	<0.613							45.3	148.6	<0.609
			60.1	197.3	<0.422							50.2	164.7	<0.789

Well 299-W21-3: screened interval depth from 11.6 to 17.7 m (38.1 to 58.1) ft below the water table

Well 299-W22-114: screened interval depth from 0.04 to 10.7 m (0.13 to 35.1 ft) below the water table

Well 299-699-36-63B: screened interval depth from 0 to 20.9 m (0 to 68.7 ft) below the water table

Well 299-W19-115: screened interval depth from 1.6 to 12.2 m (5.1 to 40.1 ft) below the water table

Well 299-W19-116 screened interval depth from 0 to 9.7 m (0 to 31.7 ft) below the water table

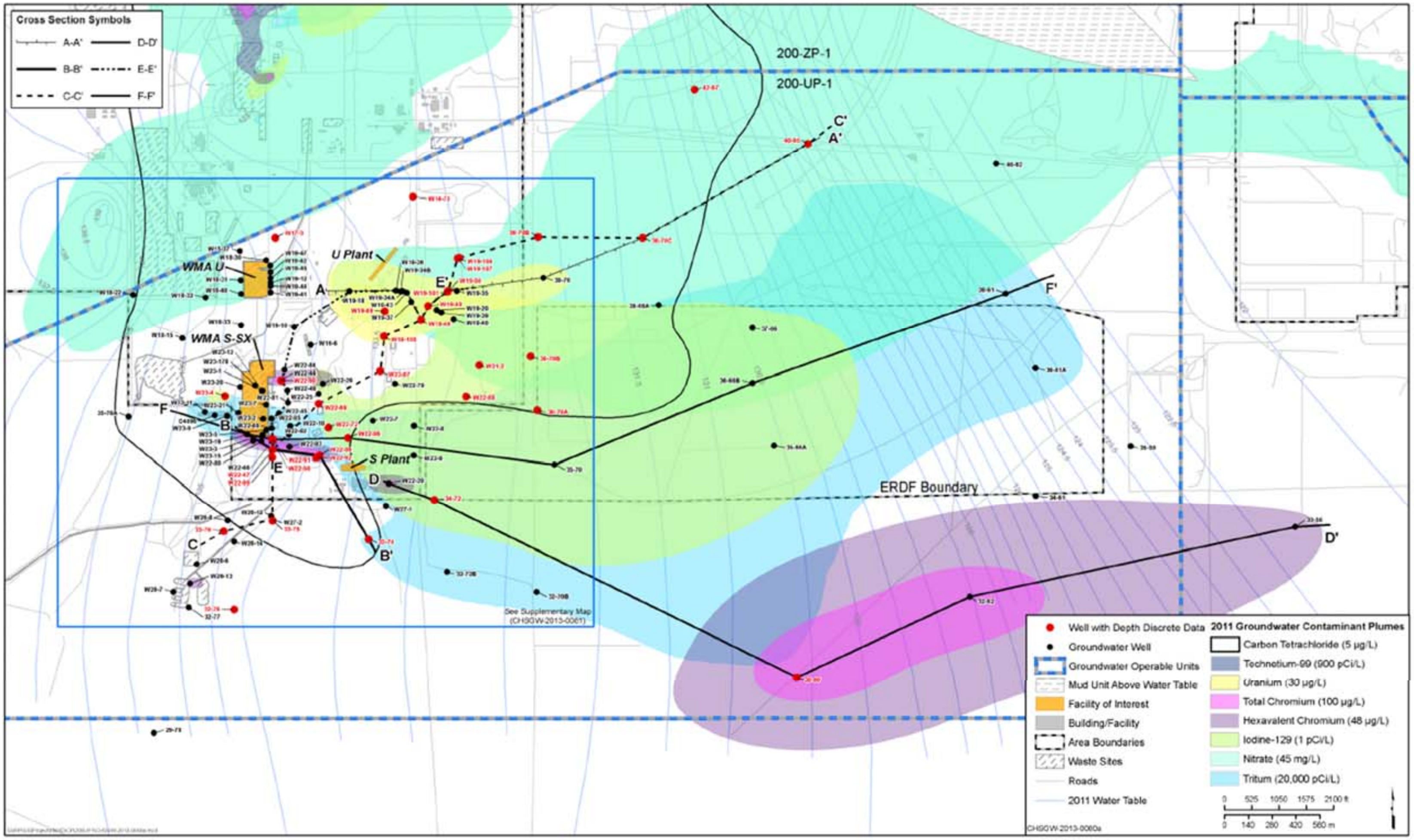

Figure 2.6. Location Map Showing Groundwater Plumes and Conception Cross Section Orientations within 200-UP-1 (Figure A-1 from USDOE 2013a). Cross sections corresponding to lines A-A’ and F-F’ are shown in Figures 2.7 and 2.8.

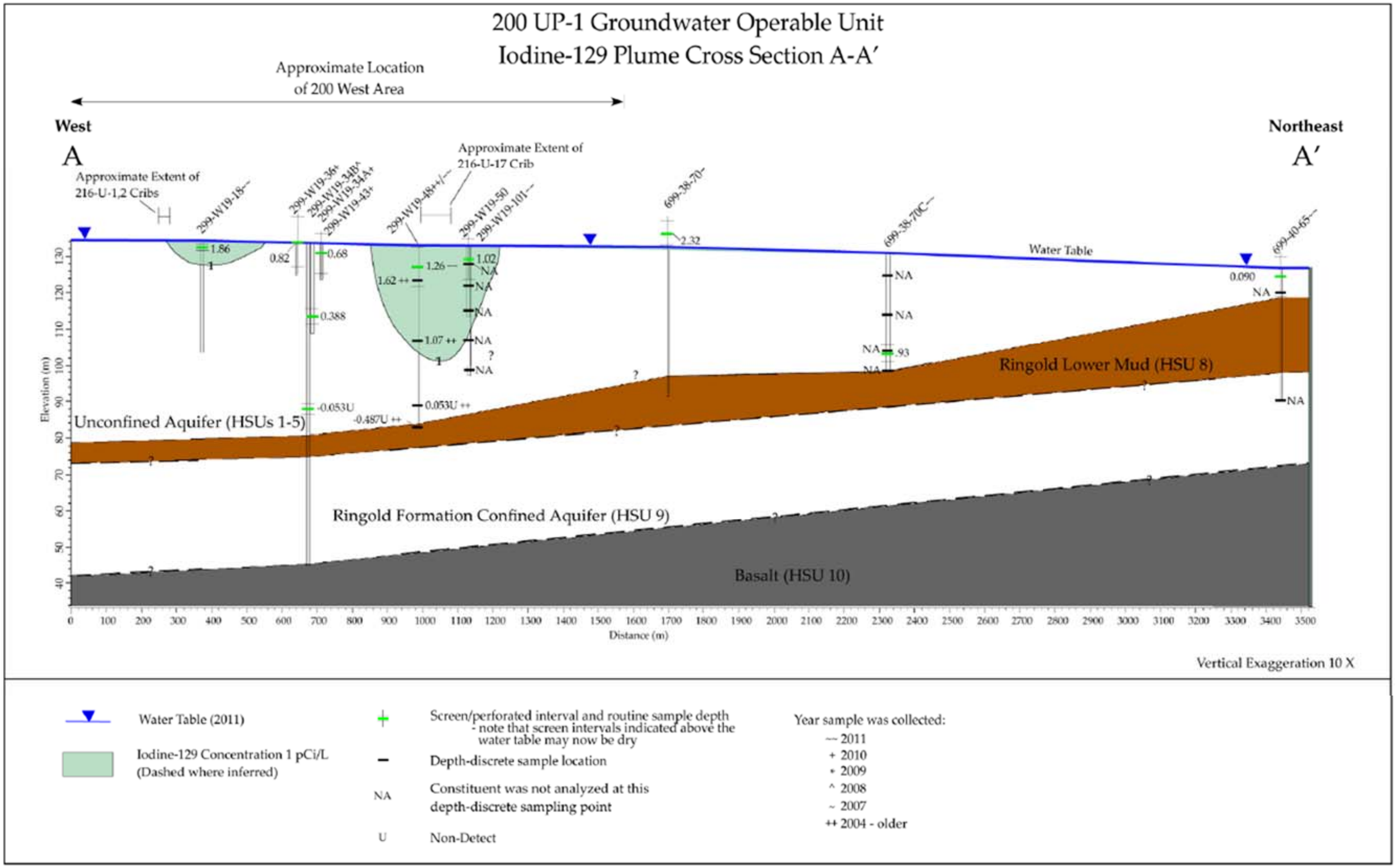

Figure 2.7. Iodine-129 Conceptual Cross Section A-A'. (Figure A-6 in USDOE 2013a.)

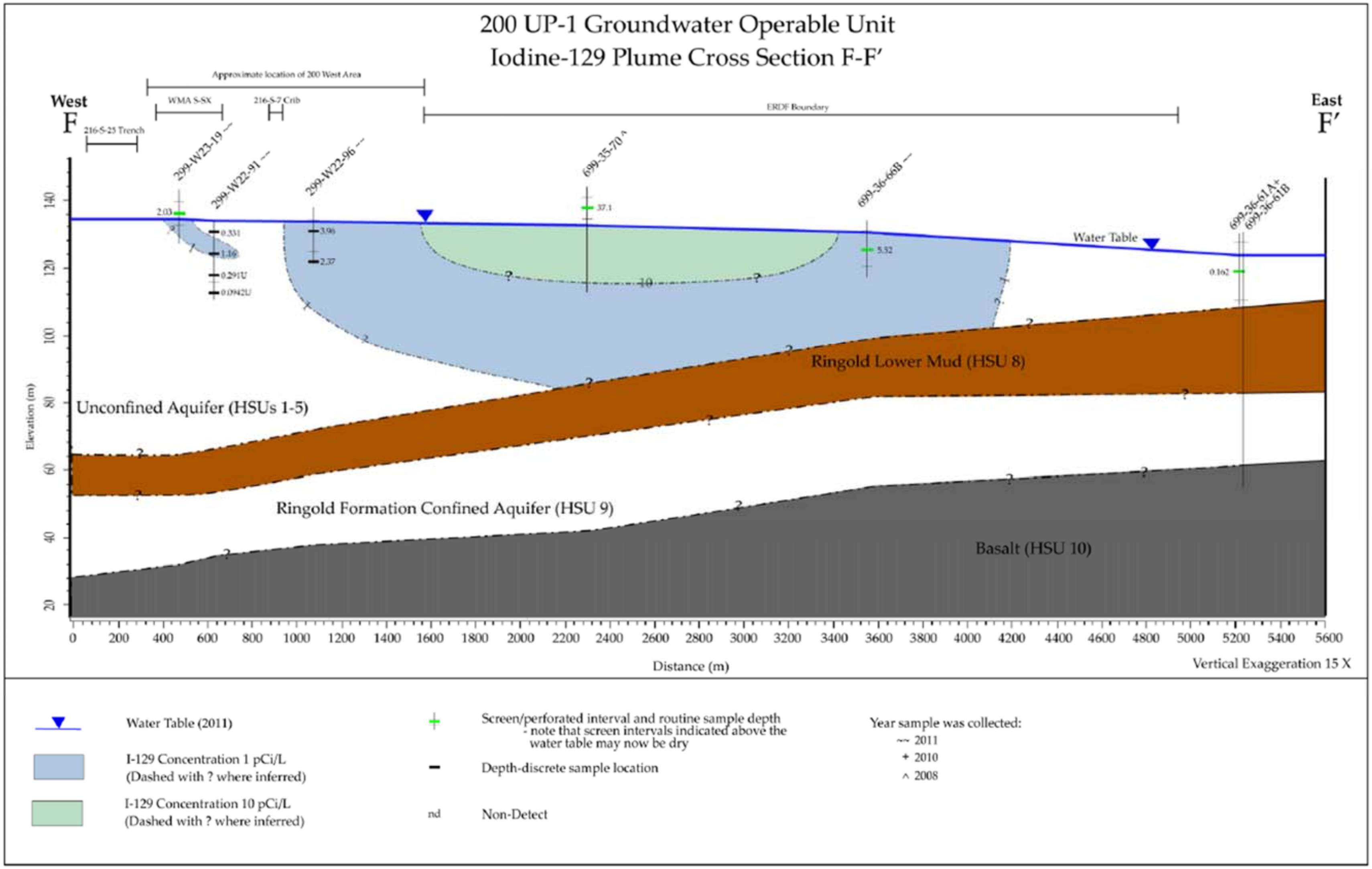

Figure 2.8. Iodine-129 Conceptual Cross Section F-F'. (Figure A-7 in USDOE 2013a.)

2.4 I-129 Trends in Monitoring Wells

Iodine-129 concentrations in most of the groundwater wells sampled around the iodine-129 plume are stable and/or decreasing. The locations of 36 representative wells are shown with the estimated boundaries for the 2017 plume data in Figure 2.9 with color coding indicating the maximum concentration measured over the lifetime of each well. These data provide further indication that the plume has declined in size and that lateral movement of the plume has not been significant. Time-series concentration data for 12 of these wells are shown in Figure 2.10 and Figure 2.11. Most of the wells exhibit declining trends, and none of the wells exhibit large increases compared to the recent past.

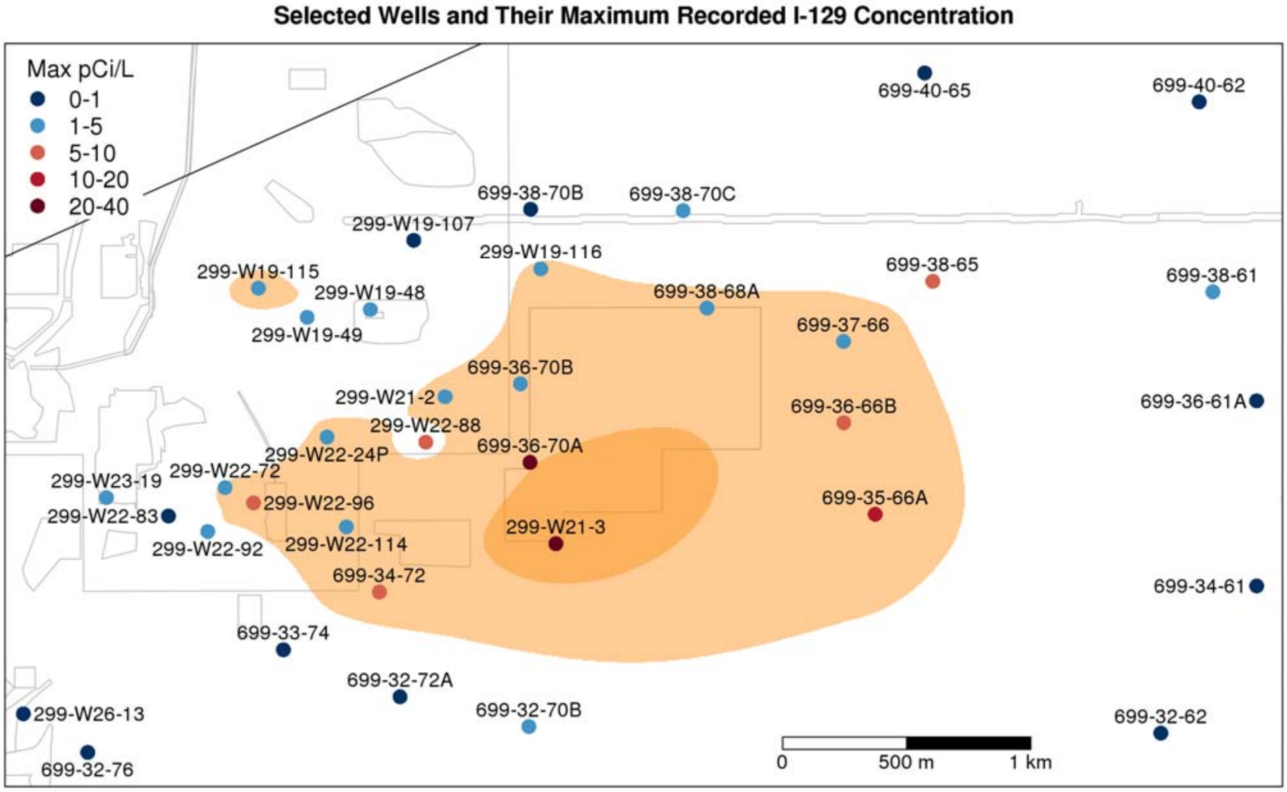

Figure 2.9. Iodine-129 Plume for 2017 (Hanford Site Groundwater Monitoring Program) and Selected Wells, Color-Coded by Their Maximum Lifetime Iodine-129 Concentration Value (pCi/L). For Information Only.

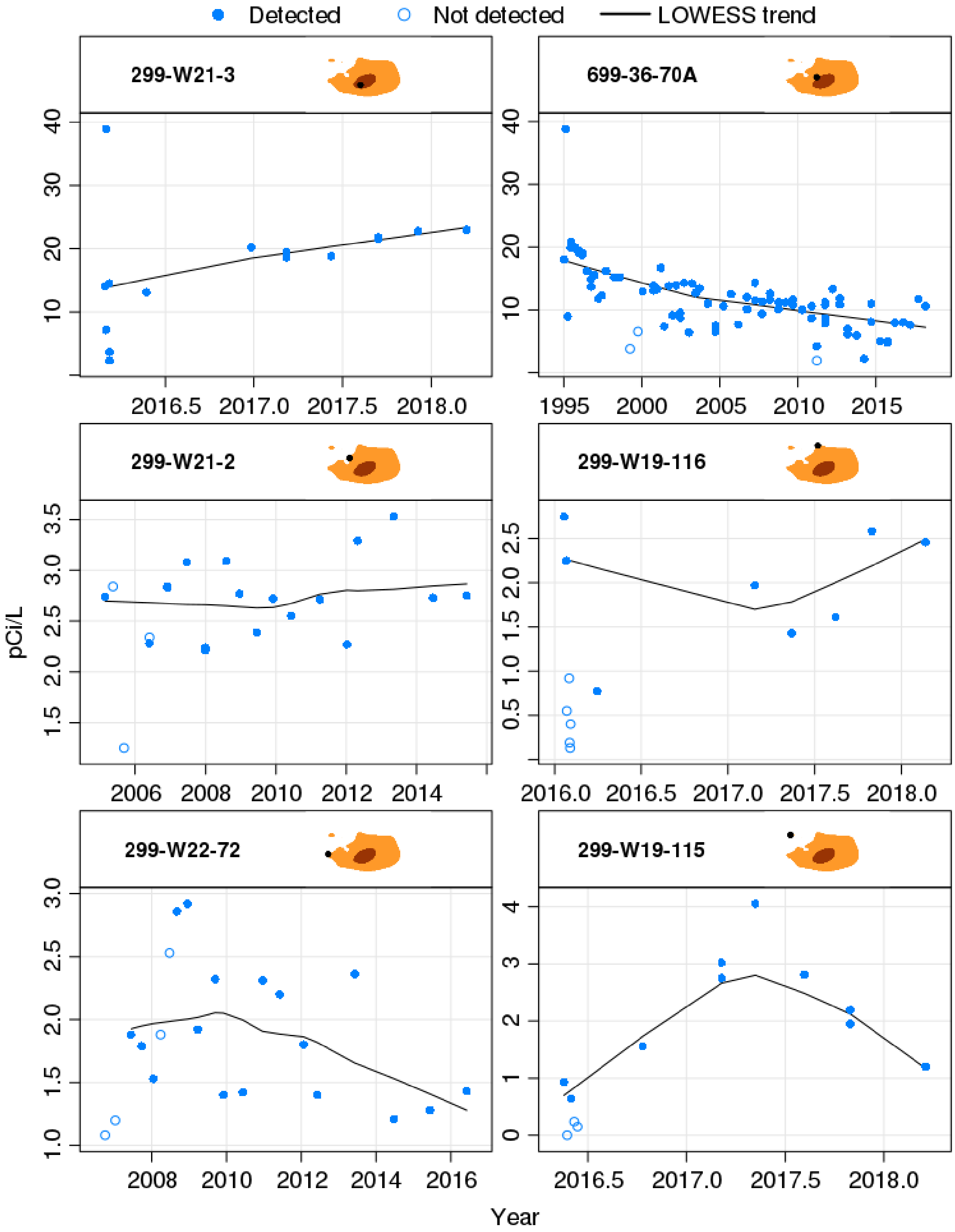

Figure 2.10. Iodine-129 Concentration versus Time at Selected Wells—Set 1. Solid blue dots represent measured values and open circles represent non-detects (which are reported with a value). The locally-weighted regression (LOWESS) line (black) suggests the approximate trend over time (fit excludes non-detects). The well location in relation to the 2017 plume is shown as a black dot in the panel strip. Wells are arranged in order of decreasing value of the most recent point in time of the trend line. For Information Only.

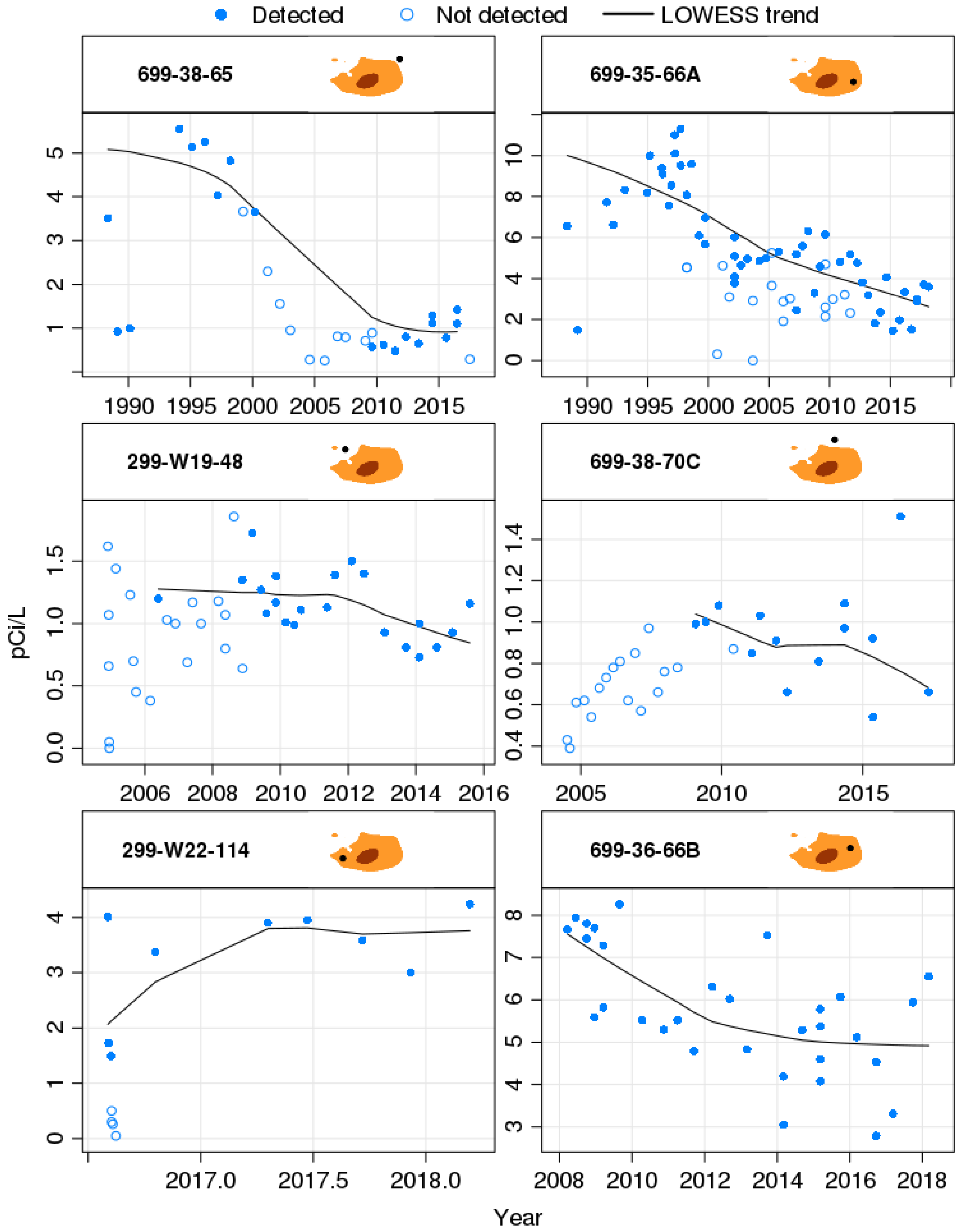

Figure 2.11. Iodine-129 Concentration versus Time at Selected Wells—Set 2. Solid blue dots are measured values, open circles are non-detects (which are reported with a value). Black line is a locally-weighted regression (LOWESS) line to suggest an approximate trend over time (fit excludes non-detects). Well location in relation to the 2017 plume is shown as a black dot in the panel strip. Wells are arranged in order of decreasing value of the most recent point in time of the trend line, continuing from set 1 wells in Figure 2.10. FIO.

3.0 Site Conceptual Model

The conceptual model for 200-UP-1 OU is being developed to describe the nature and extent of subsurface iodine-129 contamination, evaluate processes that control behavior of the iodine-129 plume, and identify factors relevant to potential remediation processes in the 200-UP-1 OU. Iodine-129 is an uncommon contaminant, and relevant remediation experience and scientific literature are limited. Different iodine species exhibit unique transport behavior with respect to solid phase and aqueous phase interactions. Plume behavior and iodine transport are influenced by subsurface geology, hydrology, redox minerals, organic material, carbonate, and microorganisms. Water chemistry components such as dissolved organic matter and pH can affect transformation reactions and transport. In addition, co-contaminants, such as nitrate or other compounds that participate in redox reactions, may influence iodine transformation reactions and sorption (Truex et al. 2017). The conceptual model for iodine transport and fate in the 200-UP-1 OU considers the factors affecting plume behavior and remediation, including the following:

- Hydrogeology affecting water movement and iodine transport in the subsurface (Section 3.1)
- Geochemical and biological processes that can influence iodine reactions and iodine-129 transport (Section 3.2)
- Iodine-129 sources and estimated release volumes in 200-UP-1 OU (Section 3.3)
- Prediction of the distribution, transport and fate of iodine-129 in 200-UP-1 (Section 3.4)

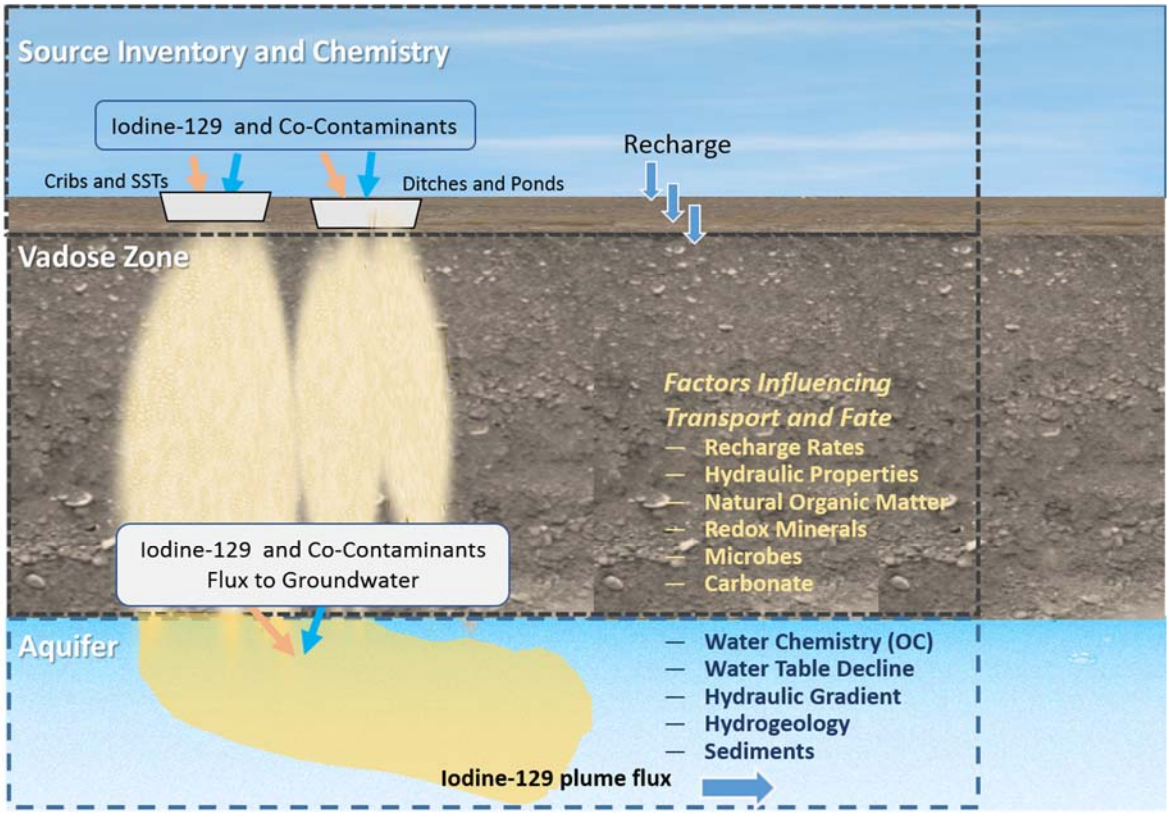

Figure 3.1. System-Level Depiction of Elements Affecting Iodine Fate and Transport.

To the extent possible, all components of the conceptual model are based on measured data. A numerical flow and transport model, based on the conceptual model, is also used to infer behavior for regions or features where measured data are not available, such as in the vadose zone. Some results shown in subsequent sections are from the numerical model. All model results are considered to be preliminary and For Information Only (FIO), since the model is still under development and is being updated as new data become available. Consequently, all figures and tables depicting model results are qualified as FIO.

3.1 Geologic and Hydrologic Features of 200-UP-1 OU

The Hanford Site lies within the semiarid Pasco Basin of the Columbia Plateau in southeastern Washington State (see Figure 1.1). Structural basins within the Yakima Fold Belt, including the Pasco Basin, are filled with sedimentary sequences from ancestral river systems, cataclysmic Ice Age floods, and localized deposits of colluvium and loess. The 200 Areas are located on a broad, relatively flat area that constitutes a local topographic high near the center of the Hanford Site—designated as the Central Plateau. The 200-UP-1 OU underlies the southern portion of the 200-West Area, which is on the western side of the Central Plateau. Surface elevations above the OU range from approximately 183 m (600 ft) to more than 213 m (700 ft) above mean sea level. Basalt of the Columbia River Basalt Group and a sequence of overlying sediments comprise the local geology. The overlying sediments are approximately 169 m (555 ft) thick and primarily consist of the Ringold Formation and Hanford formation, which are composed primarily of sand and gravel, with some silt layers. The unconfined aquifer is within the Ringold Formation and the depth to water table is approximately 85 m.

The sedimentary layers and underlying basalt are divided into primary geologic units that are laterally continuous across the majority of the OU (Figure 3.2). In some Hanford reports, these layers are parsed into hydrostratigraphic units (HSUs), but the original geologic names are primarily used in this document. From top to bottom, these units are as follows:

- Hanford formation (HF, HSU1) – unconsolidated sand and gravel
- Cold Creek unit (CCU, HSU 3) – silt, sand, gravel
- Ringold Formation Taylor Flats unit (Rtf, HSU4) – semi-consolidated silt, sand, and gravel
- Ringold Formation Wooded Island Unit E (Rwie, HSU5) – semi-consolidated gravel and sand
- Ringold Formation Lower Mud (Rlm, HSU8) – silt and clay
- Ringold Formation Wooded Island Unit A (Rwia, HSU9) – semi-consolidated sand and gravel
- Columbia River Basalt (Basalt, HSU5) – flood basalt lava flows and interbedded sediments

All of these units are illustrated with more detail in the stratigraphic column of Figure 3.2.

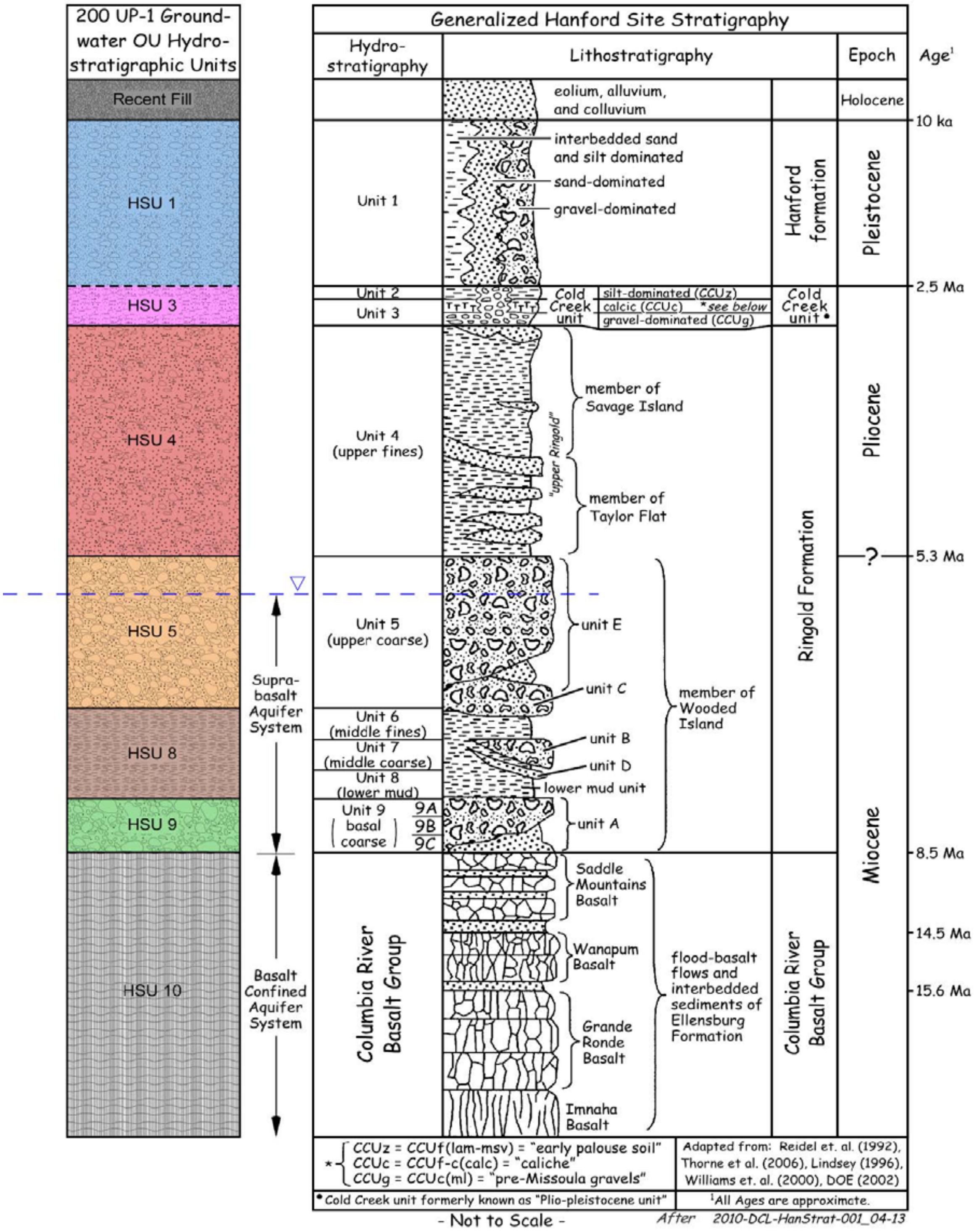

Figure 3.2. Hydrostratigraphic Units and Generalized Hanford Site Stratigraphy for 200-UP-1 Groundwater OU (Hammond and Lupton 2015)

Geologic data indicate the Rlm is continuous beneath most of 200-UP-1, but is absent in the northeast quarter of the 200 West Area (Hammond and Lupton 2015). Groundwater in the unconfined aquifer flows from areas where the water table is higher (west of the Hanford Site) to areas where it is lower (the

Columbia River). In general, groundwater flow through the Central Plateau occurs in a predominantly easterly direction from the 200 West Area to the 200 East Area (Figure 3.3 through 3.6). In addition to the upper, unconfined aquifer, where the iodine-129 contamination exists, groundwater is also found deeper in a mostly confined condition in the Rwia (HSU 9) (and the basalt).

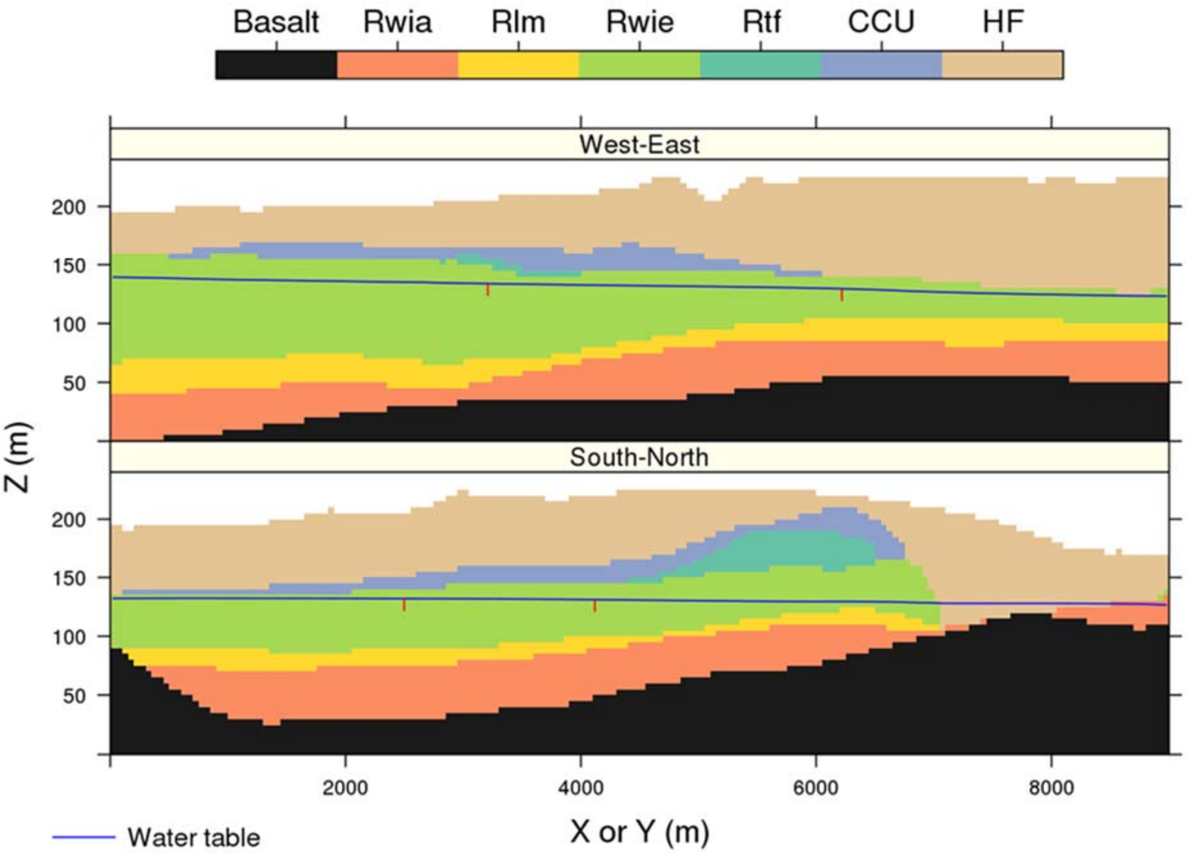

Figure 3.3. Cross Sections of Geologic Framework Model (GFM), West to East (left to right) and South to North through the 1 pCi/L Plume Center of the 2017 Iodine-129. Red ticks under the blue water table line mark the lateral extent of the plume. The extent of GFM and its discretization shown here are for the eSTOMP model domain. Grid blocks are 50 m in x- and y-directions and 5 m in the z-direction. Vertical exaggeration of the figure is 10x. FIO.

The Rwie unit contains the unconfined aquifer in Central Plateau and the Rlm unit is the primary confining unit that limits downward migration of groundwater and contaminants. The thickness of the unconfined aquifer varies substantially within the Central Plateau, from over 200 m (656 ft) southeast of the 200 East Area to zero where the aquifer pinches out against mud units and basalt above the water table. The water table is as deep as 106 m (348 ft) below ground surface beneath the Central Plateau. The conceptual west-to-east cross section in Figure 3.3 shows the relationship between waste sites, vadose zone, water table, and geologic units in the Central Plateau.

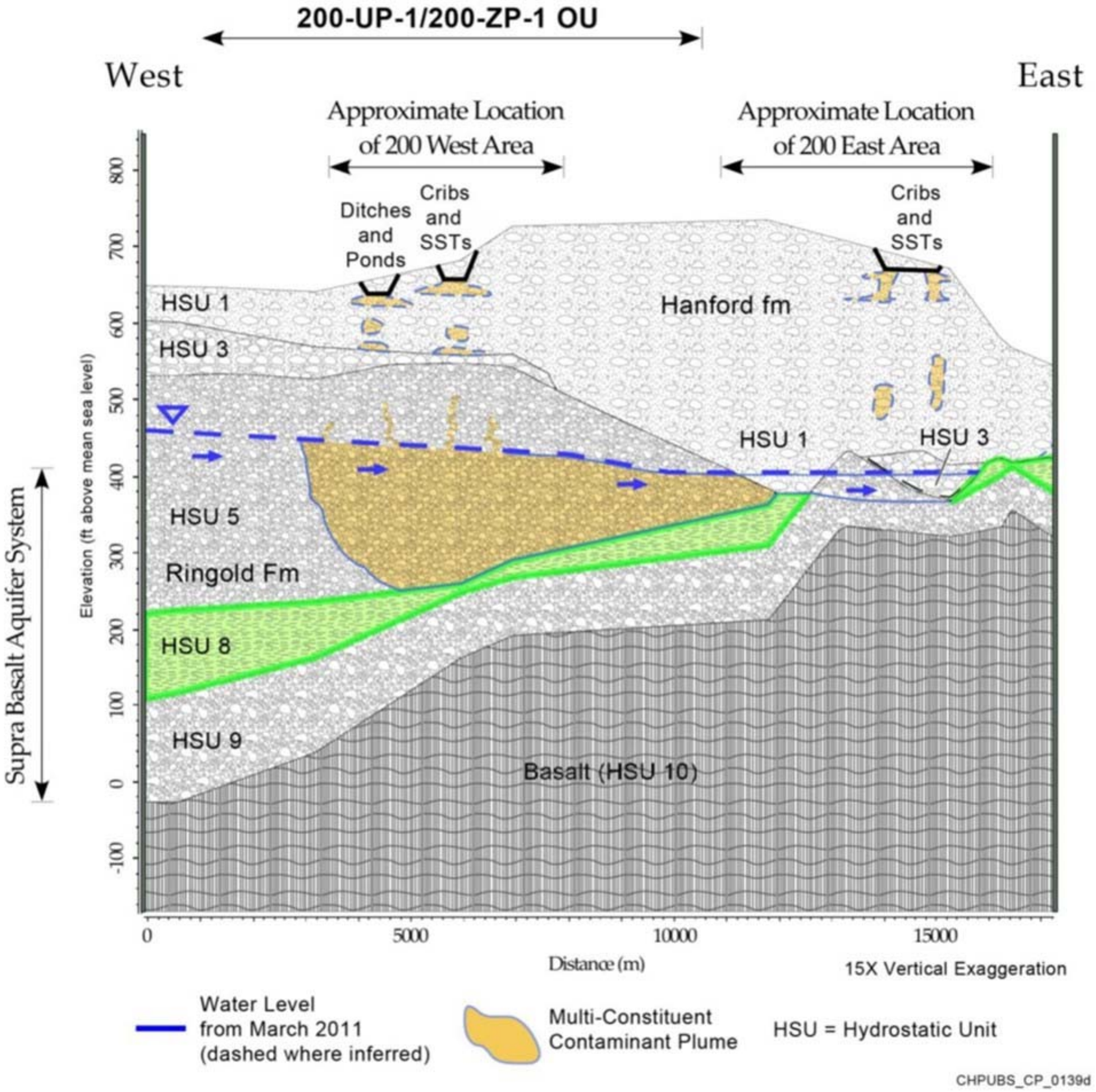

Figure 3.4. Conceptual Vertical Cross Section Showing the Extent of Contaminant Plumes with Respect to Hydrostratigraphic Units (from USDOE 2013a).

3.1.1 Physical and Hydraulic Properties of Subsurface Materials

Physical and hydraulic properties for Hanford sediments have been determined using a variety of laboratory and field methods. Physical and hydraulic properties for Hanford saturated zone materials (aquifer sediments) have been documented in various reports (Spane et al. 2001a,b, 2002, 2003; Spane and Newcomer 2010a,b). Thorne and Newcomer (2002) initiated the development of a database for saturated zone hydraulic properties, but this database has not been updated since the early 2000s. Saturated zone modeling efforts that have used facies-based or other representations of the unconfined aquifer materials for which hydraulic parameters have been calibrated include Thorne et al. (2006), Williams et al. (2006), and McDonald (2018). Vadose zone physical and hydraulic properties, including parameters describing water retention and hydraulic conductivity, have also been documented in various reports (Bergeron et al. 1987; Bjornstad, 1990; Connelly et al. 1992a,b; Rockhold et al. 1993, 2015, 2018; Khaleel and Freeman 1995; Last et al. 2006, 2009).

3.1.2 Depth to Groundwater

The water table is relatively deep within the 200-UP-1 OU. Data from 2018 indicate water levels range from 59 to 97 m below ground surface for the 36 wells shown in Figure 2.9, with a mean of 78 m. The eSTOMP model indicates that in the region bounded by the 2017 1 pCi/L plume, the saturated thickness of the unconfined aquifer is entirely within the Rwie (Figure 3.2), and ranges from approximately 20 to 65 m, with an average of 41 m.

3.1.3 Hydraulic Gradients (Horizontal and Vertical)

Groundwater beneath the Central Plateau flows generally from west to east, although the 200 West P&T system disrupts this pattern locally. Natural recharge to the unconfined aquifer comes from Cold Creek Valley, Dry Creek Valley, Rattlesnake Hills, and infiltrating precipitation. The hydraulic gradient within the 2017 plume area has a northeasterly direction and a magnitude of approximately 8.7e-4 (calculated from Figure 3.6). Directly east and northeast of the plume, the hydraulic gradient steepens markedly to approximately 3.9e-3. This is caused in part by a decrease in the aquifer saturated thickness and transmissivity. The hydraulic conductivity of the aquifer sediments may also decrease toward the east, which would contribute to the larger hydraulic gradient. Groundwater velocity in the Central Plateau generally ranges from a few millimeters to tenths of a meter per day. Vertical gradients within the saturated zone are small in comparison and flow is primarily lateral. Geologic structure under 200-UP-1 is low-angle layered stratigraphy, and vertical lithologic features that could provide preferential pathways are unknown.

Current treatment of iodine-129 at the 200-UP-1 OU within the Central Plateau at the Hanford Site is accomplished by hydraulic containment of the iodine-129 groundwater plume using injection wells placed at the leading edges of the plume (Figure 3.6). Groundwater flow is also locally influenced by the 200-ZP-1 OU final remedy P&T system north of the plume and the WMA S-SX interim remedial measure extraction system west of the plume. The effects of pumping and injection on the water table are shown in Figure 3.5 (DOE/RL-2017-68, Draft Rev. 0; USDOE 2018b).

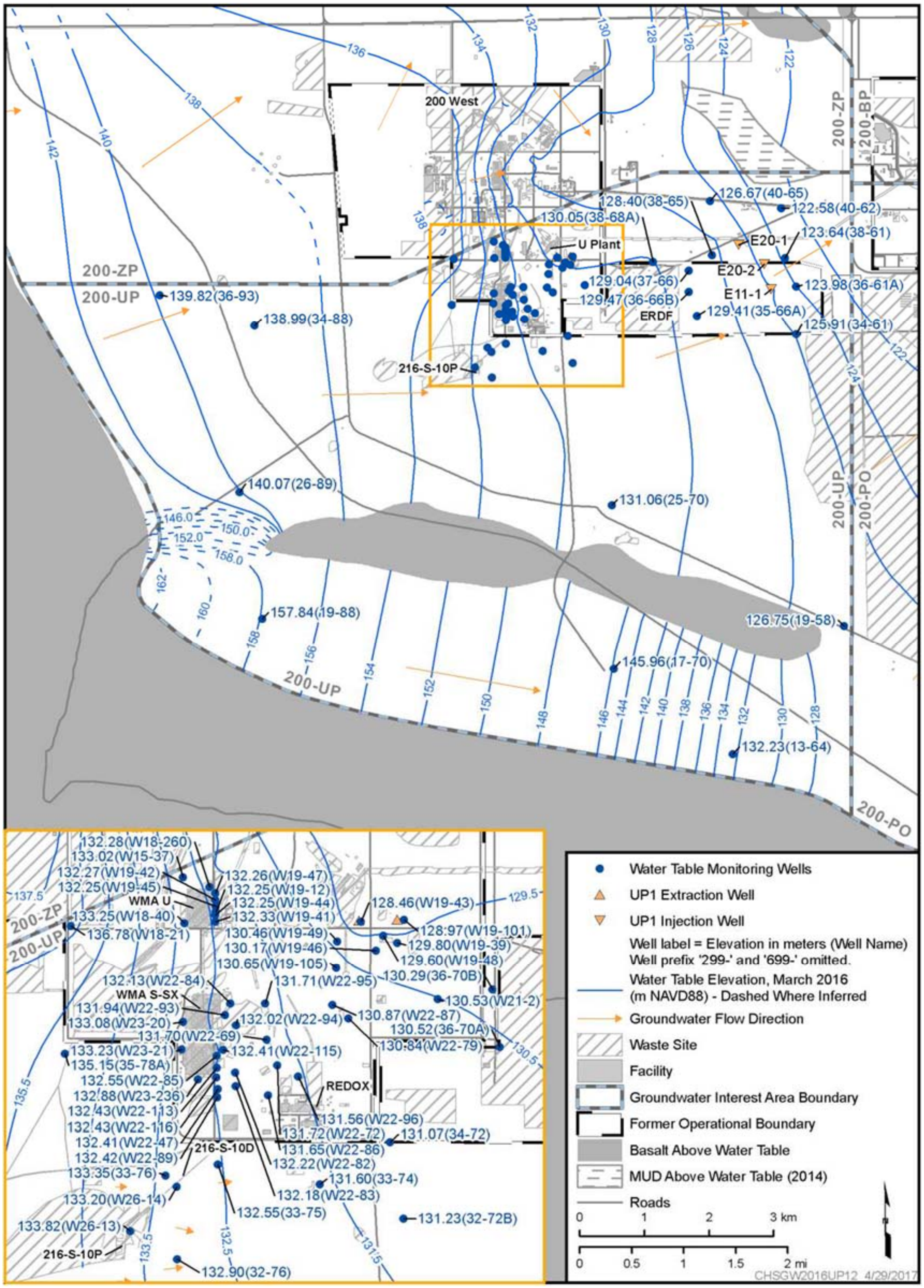

Figure 3.5. Water Table Elevation in 200-UP Interest Area from March 2016. (Figure 11-2 from USDOE 2017b.)

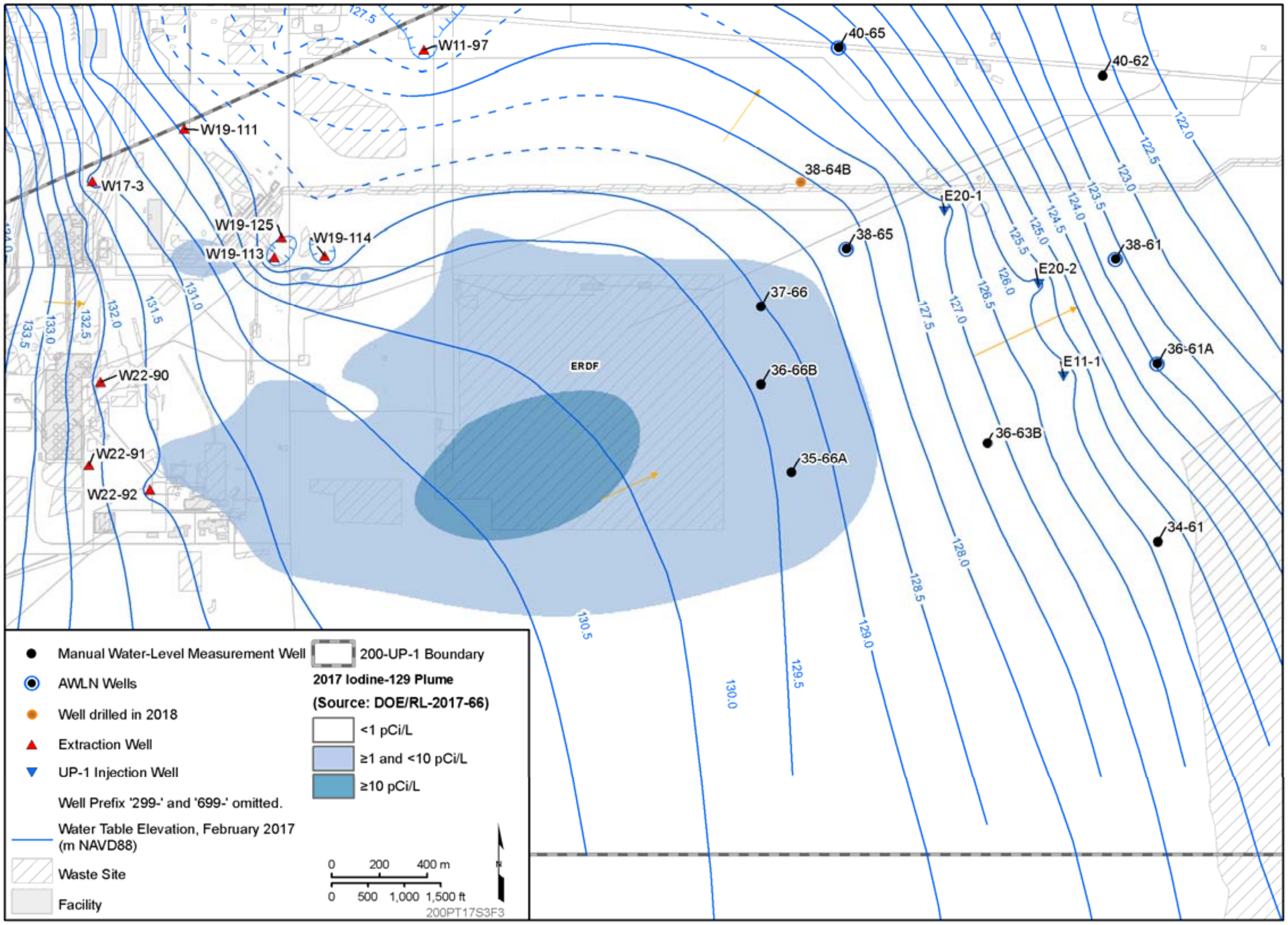

Figure 3.6. Water Level Monitoring Network and Water Table Elevations as Influenced by Iodine-129 Plume Hydraulic Containment Remedy as of December 2017 (DOE/RL-2017-68, Draft Rev. 0; USDOE 2018b.)

3.1.4 Temporal Variability in Hydrologic Conditions and Contaminant Concentrations

Historical liquid waste discharges to the ground (e.g., cooling water and process wastewater) during the 1940s through the 1990s significantly altered the groundwater flow regime, especially around the 216-U-10 Pond in the 200 West Area, which created a large water table mound that deflected the groundwater flow to the northeast. As drainage from these discharges has ceased, the water table has been declining, and groundwater flow direction is returning to a more easterly direction through the Central Plateau. There are currently no liquid waste discharges to the ground in 200-UP-1 (with the exception of sanitary drain fields). The 200-UP-1 P&T system has altered the hydraulic gradients locally since operation began in 2012 (Figure 3.5). The historical rise and fall of water levels at selected wells in the vicinity of the I-129 plume is shown in Figure 3.7.

3.1.5 Groundwater Recharge and Discharge Information

Recharge is defined here as the flux of water from meteoric sources (i.e., rainfall and snowmelt) that infiltrates through the vadose zone and reaches the water table. Direct measurement of recharge at the water table is usually impractical on the Hanford Site Central Plateau due to inaccessibility; the water table is commonly located at depths of 80 m or more below ground surface, and access is influenced by historical and current Hanford operations (Fayer and Keller 2007). Instead, measurements in the shallow portion of the vadose zone and numerical and tracer analyses have been used to estimate the deep drainage flux, that is, water leaving the evapotranspiration zone and ostensibly traveling to the water table (Fayer and Walters 1995; Last et al. 2006; Fayer and Keller 2007; Rockhold et al. 2009; Fayer et al. 2010).

Recharge is the primary mechanism for ongoing transport of contaminants from the vadose zone to groundwater. Long-term average recharge rates at the Hanford Site can range from near zero to more than 100 mm/yr depending on local climate, vegetation cover, soil hydraulic properties, land use, and topography (Fayer and Walters 1995; Fayer et al. 2010). Fayer and Keller (2007) reported long-term recharge rates ranging from <0.1 for vegetated soils to 92 mm/yr for disturbed soils with graveled surface (Table 3.1). For Hanford soils or gravel surfaces without vegetation (such as the surfaces maintained above waste sites), the long-term drainage estimates range from 8.6 to 92 mm/yr.

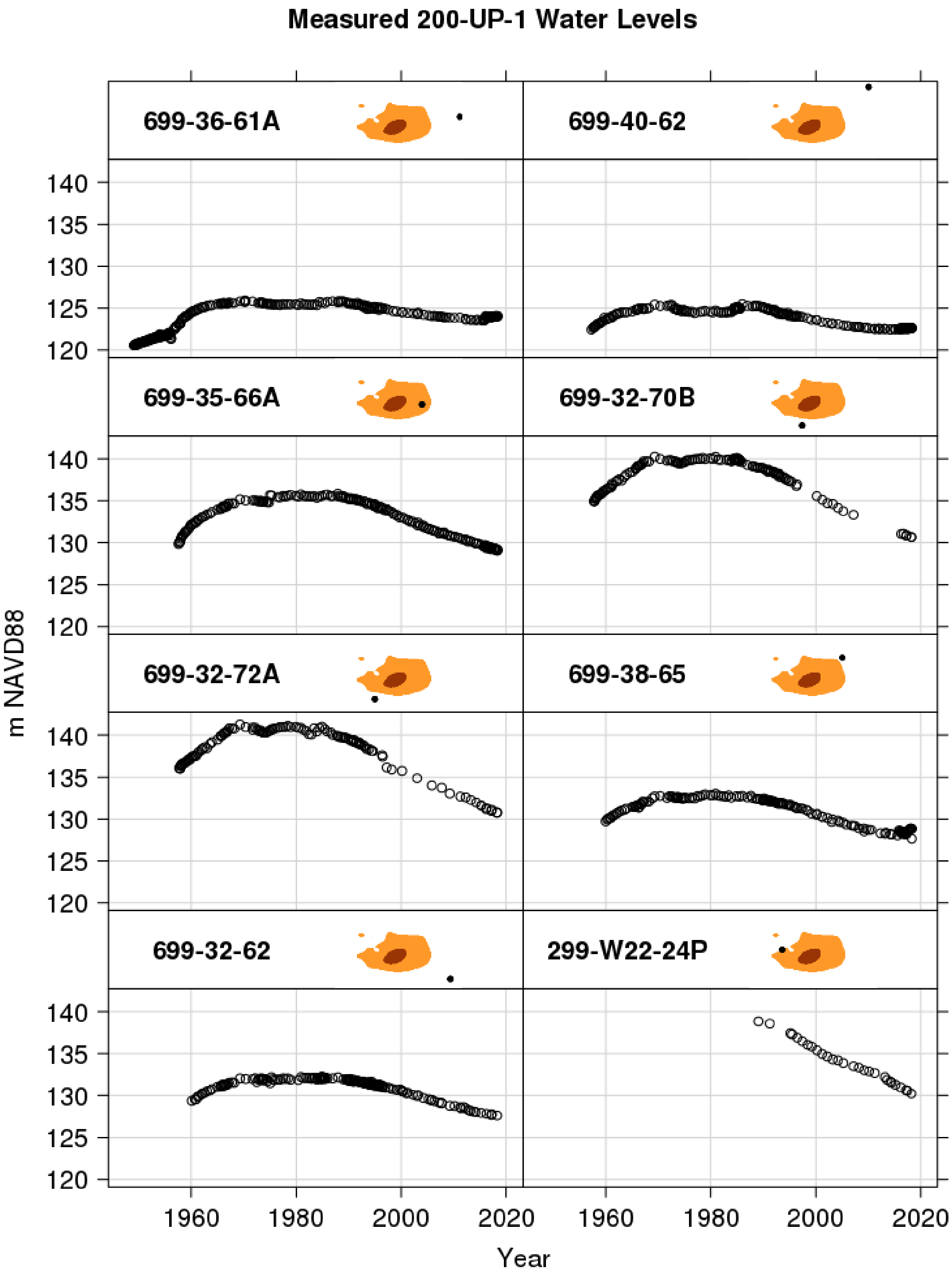

Figure 3.7. Measured Water Table Elevations Over Time at Selected Wells. Water level data are from the Hanford Environmental Information System. The well location in relation to the 2017 plume is shown as a black dot in the panel strip. This figure is FIO.

Table 3.1. Estimated Long-Term Recharge Rates for Use in Hanford Assessments (Table 6.1 from Fayer and Keller 2007)

Soil Type	Estimated Long-Term Drainage Rates (mm/yr)	
	Shrub	No Plants
Rupert sand (near U.S. Ecology)	5.0	30
Rupert sand (200 East Area)	0.9	45
Rupert sand (elsewhere on Central Plateau)	1.7	45
Burbank loamy sand	1.9	53
Ephrata sandy loam	2.8	23
Hezel sand	<0.1	8.7
Esquatzel silt loam	<0.1	8.6
Hanford formation sand	Np	62
Graveled surface	Np	92
Modified RCRA C barrier	0.1	0.1
Gravel side slope on surface barrier	1.9	33[(a)]

Np = Not provided by Last et al. (2006) or Fayer and Keller (2007); RCRA = *Resource Conservation and Recovery Act*.

(a) Tentative estimate because of concerns regarding presence of some plants, road, and small section of vegetated silt-loam within the drainage collection zone.

Performance assessment calculations for Hanford waste sites usually use a combination of recharge rates to represent different areas and time periods, including pre-Hanford, operational, and post-closure periods. During the pre-Hanford period, recharge rates are usually relatively low and are assumed to be representative of undisturbed soil conditions with native shrub-steppe vegetation. Higher recharge rates are typically applied during the operational period to account for disturbance of soils for emplacement of waste storage tanks, placement of gravel over the tank farms, and maintaining the gravel-covered surfaces free of vegetation. Post-closure conditions are usually assumed to include reduced infiltration rates to account for infiltration barriers over waste sites, followed by a change in recharge rates back to assumed pre-Hanford-type conditions.

3.1.6 Groundwater Withdrawal and Potential Receptors

Based on the anticipated yield and natural water quality, the State of Washington has determined that the aquifer setting for the 200-UP-1 OU meets the WAC 173-340-720 definition for potable groundwater, which is the highest recognized beneficial use. EPA generally defers to state definitions of groundwater classification provided under EPA-endorsed Comprehensive State Groundwater Protection Programs (USEPA 1988). Under EPA's groundwater classification program, 200-UP-1 OU groundwater would be designated Class II-B, which is groundwater that is not a current source of drinking water but is a potential future source (USDOE 2017a).

Withdrawal of groundwater from 200-UP-1 OU for beneficial uses is currently prohibited by institutional controls placed on groundwater by DOE. There are no drinking water supply wells and no wellhead protection areas. The existing institutional controls (specifically, prohibitions against use of groundwater for a source of drinking water) prevent human exposure. Current land use on the Central Plateau is industrial, and public access to the site is restricted.

Land use in the 200 West and 200 East Areas is anticipated to remain industrial for the foreseeable future and the areas will be used for ongoing waste disposal operations and infrastructure services.[1] The iodine-129 contaminant plume in 200-UP-1 OU extends less than 5 km to the east of the originating waste sources and does not interact with any surface waters within or adjacent to its boundaries. There are no wetlands, perennial streams, or floodplains present. The plume currently does not extend past the OU boundary and does not extend to the groundwater discharge areas along the Columbia River to the east; thus, no ecological receptors are currently exposed to 200-UP-1 OU contaminants of concern or contaminants of potential concern.

Previous investigations simulating iodine-129 transport in the OU using MODFLOW-2000 and MT3DMS indicated that iodine-129 is not expected to leave the Central Plateau within a 1000-year timeframe and would not interact with any surface waters within that period (USDOE 2012b). That previous modeling indicates that iodine-129 contamination in the 200-UP-1 OU will move beyond the OU boundary at concentrations above the DWS in the absence of further remediation.

In summary, under the current withdrawal and use restrictions, there are no direct pathways for human exposures, and no ecological exposure pathways to iodine-129 contamination in the 200-UP-1 OU because the groundwater is not used for agriculture or human consumption, and does not discharge to surface water or reach the Columbia River at levels above the DWS (USDOE 2017b). Due to institutional controls, groundwater within this OU is not expected to become a future source of drinking water until drinking water standards are achieved. Based on the current selected remedy, which is a combination of P&T, hydraulic containment, and MNA, it is expected that it will take 125 years for contaminants other than iodine-129 to be cleaned up to drinking water standards.

3.2 Geochemical and Biological Processes Affecting Iodine-129 in Soils and Groundwater

The behavior of iodine in the environment is complicated by its multiple physical states, multiple redox states, interactions with organic matter, and microbial transformations (Truex et al. 2017). A conceptual overview showing known subsurface biogeochemical processes that affect the fate and transport of iodine at Hanford is shown in Figure 3.8. It is important to note that stable iodine-127 is found at much higher concentrations in the groundwater under 200-UP-1 OU ($^{127}IO_3^-$ / $^{129}IO_3^-$ ratios ranging from 100 to 300) (Truex et al. 2017). It exhibits the same chemical behavior in the subsurface as iodine-129, and thus, the presence of iodine-127, and influences the biogeochemical processes for iodine-129. Most remediation technologies are not specific for a particular iodine isotope (Kaplan et al. 2012; Truex et al. 2017), and both iodine-129 and iodine-127 should be considered when evaluating contaminant transport and fate. Although the source of iodine-127 is uncertain, iodine is known to be a trace constituent of nitric acid, and enormous volumes of nitric acid were used during Hanford operations. This is considered the most likely source for the iodine-127 in Hanford groundwater.

This section summarizes information on the subsurface properties that influence reactive transport including iodine speciation and adsorption, precipitation, transformations between iodine species, and microbially mediated interactions.

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[1] USDOE. 2013. *Hanford Site Cleanup Completion Framework*. DOE/RL-2009-10, Rev. 1, U.S. Department of Energy, Richland Operations Office, Richland, Washington.

Detailed discussions of the site-specific geochemical and biological processes affecting fate and transport of iodine-129 in the 200-UP-1 OU and updates to the conceptual model for iodine-129 are presented in Truex et al. (2017).

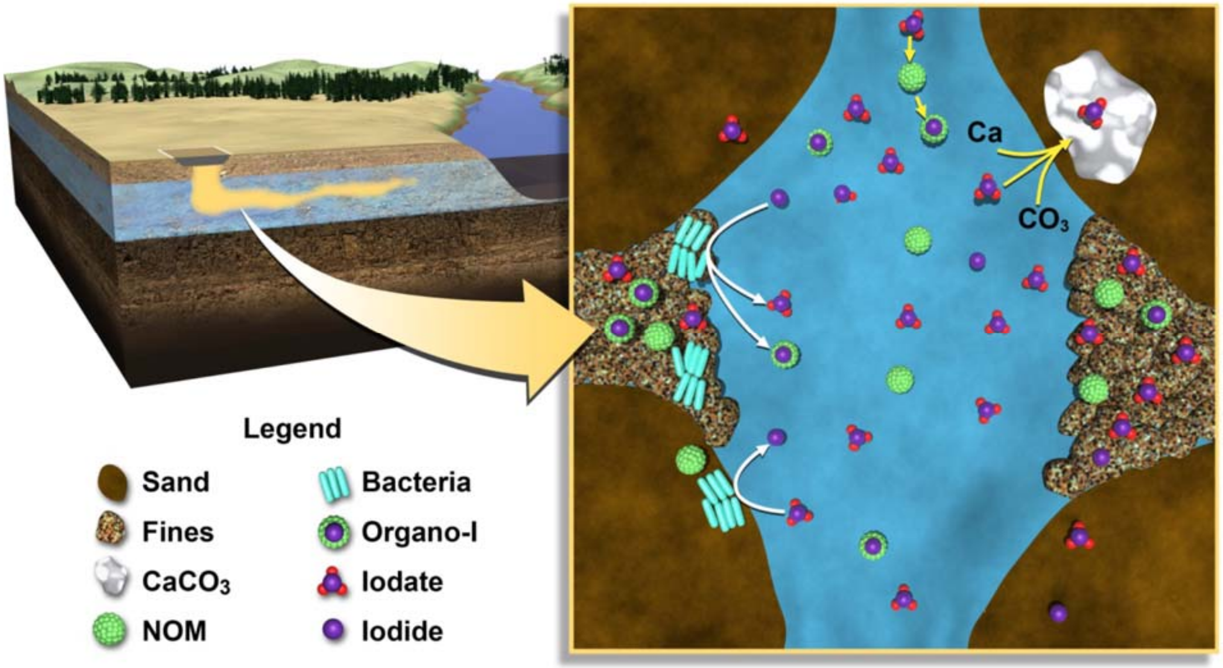

Figure 3.8. Conceptual Overview of Subsurface Biogeochemical Processes Affecting Iodine Fate and Transport (from Truex et al. 2017). Processes include biotic (bacteria) transformations between iodine species and potential transformations to other iodine species. Iodate reduction may also occur abiotically (e.g., by reactions with sediment-associated iron/manganese at the Hanford Site). Iodine species adsorb to sediment surfaces (e.g., on iron oxide deposits or phyllosilicates), with greater adsorption expected in fine-textured sediment zones (Fines). Natural organic matter may facilitate sorption and accumulation of iodine or, as a dissolved organic carbon (DOC), may form mobile Organo-I. Iodate may co-precipitate with calcium carbonate. The figure does not distinguish between iodine-129 and iodine-127 because the processes are the same for both isotopes.

3.2.1 Iodine Speciation

The three primary aqueous iodine species are iodate (IO_3^-), iodide (I^-), and Organo-I. Iodine can form hypodiodous acid in water, and both of these species can react with natural organic matter to form Organo-I compounds (Luther 2011). The relative quantity of these three primary iodine chemical species present in the groundwater is important to predicting iodine plume behavior because each chemical species has different transport characteristics and may be subject to transformation reactions.

Iodide originally was assumed to be the dominant iodine species in Hanford groundwater. However, measurements of speciation of iodine-127 in groundwater in the 200 West Area show a mixture of iodine species (Zhang et al. 2013). Results from seven samples (two from the 200-UP-1 OU and five from the 200-ZP-1 OU) characterized in the work by Zhang et al. are presented in Table 3.2.

Table 3.2. Chemistry and Iodine-127 Speciation in Filtered Hanford Site Groundwater Samples (from Zhang et al. 2013)

Well	pH	Eh (mV)	DOC (µM)	Ca (mg/L)	Si (mg/L)	Iodide (µg/L)	Iodate (µg/L)	Organo I (µg/L)	Total I (µg/L)	Iodide (%)	Iodate (%)	Organo-I (%)
299-W14-11	7.7	250	50.2	59.4	7.5	0.35	59.50	15.18	75.03	0.5	79.3	20.2
299-W14-13	7.7	249	63.0	81.9	7.4	0.33	42.72	17.01	60.05	0.6	71.1	28.3
299-W14-15	7.9	220	25.5	35.4	5.6	0.43	32.63	5.66	38.72	1.1	84.3	14.6
299-W11-43	7.6	150	37.2	78.8	7.0	0.36	6.66	2.76	9.78	3.7	68.1	28.3
299-W11-88	7.8	321	15.6	22.1	15.0	0.17	7.08	2.08	9.33	1.8	75.9	22.3
699-36-70B	7.8	334	35.3	19.4	10.7	0.23	5.87	2.28	8.38	2.8	70.0	27.2
699-38-70B	7.8	125	21.5	29.7	8.9	1.38	4.18	3.68	9.24	15.0	45.2	39.8
Average	7.8	236	35.5	49.5	8.9	0.46	22.66	6.95	30.08	3.6	70.6	25.8

The premise that iodate was the dominant iodine species disposed to the vadose zone at Hanford also is supported by Sakurai et al. (1989). They measured iodine speciation in spent fuel solutions and their results showed that more than 90% of the added iodine volatilized to I^2 (g) and the remaining iodine in solution was present as iodate (47.6%), iodide (3.2%), molecular iodine (17.3%), organic iodine (6.1%), and colloidal iodine (12.4%). The average ratio of iodate to iodide in those solutions was 19.5, which agrees with that measured in Hanford groundwater (19.6) by Zhang et al. (2013). Zhang et al. (2013) demonstrated that Hanford groundwater samples contained, on average, about 70% iodate, about 26% Organo-I, and a small amount (about 4%) of iodide. Their data also indicate that iodine-127 concentrations were much greater near source terms (e.g., wells 299-W14-11, -13, and -15 in Table 3.2) than further from the source terms. There did not appear to be trends in the observed speciation with respect to either distance from the sources or whether the groundwater sample was collected from the high- or low-concentration portions of the plume, although only a limited number of samples were collected. The fact that iodine-127 exists predominantly as iodate suggests that there are natural biogeochemical drivers promoting the existence of iodine in the oxidized state. The presence of iodine in multiple oxidation states and species within a given aqueous sample is consistent with previous reports of radioiodine and stable iodine speciation measurements at other DOE sites (Kaplan et al. 2014; Otosaka et al. 2011; Truex et al. 2017).

More recent sampling of groundwater wells in 200-UP-1 within the iodine-129 plume extent also shows that iodate is the prevalent species present in the groundwater. Table 3.3 shows iodine speciation data for samples collected at depth-discrete locations below the water table in well 299-W22-114. Iodate was the only iodine-127 species present in samples except for the shallowest sample depth (257.5 ft below ground surface; 7.6 ft below water table). Radioactive iodine-129 was present above drinking water standards in samples taken between 7.6 and 67.3 ft below the water table.

Table 3.3. Iodine Speciation in Groundwater Samples During Drilling Monitoring Well 299-W22-114 (August 2016) (from Truex et al. 2017)

Depth (ft bls)[a]	Depth (ft bwt)[b]	Iodine-129 (pCi/L)	Iodine-127 (µg/L)	Iodate (µg/L)	Iodide (µg/L)	Nitrate (mg/L)
257.5	7.6	4.0	6.2	2.8	3.6	79.7
284.0	34.1	1.7	13.6	17.8	ND	5.3
317.2	67.3	1.5	11.0	14.5	ND	4.4
347.6	97.7	0.3	13.0	17.1	ND	3.5
377.6	127.7	0.5	13.2	17.6	ND	3.9
427.5	177.6	0.3	16.1	21.8	ND	6.2
447.2	197.3	0.05	17.1	22.4	ND	7.5

(a) ft bls =feet below ground surface
(b) ft bwt = feet below water table
ND = non-detect; detection limits: I-127 1.26 µg/L, iodate 0.81 µg/L, iodide 1.23 µg/L
I-129 and NO_3 data were received from CH2M HILL Plateau Remediation Company (CHPRC).

Groundwater samples from three existing monitoring wells located in the plume along with an additional sample from 299-W22-114 also were analyzed to determine possible changes in speciation across the length of the iodine plume. Table 3.4 indicates that iodate was the only species present in the iodine-129 plume.

Table 3.4. Iodine Speciation in Groundwater Samples Collected Over the Length of the 200-UP-1 Plume (from Truex et al. 2017)

Well ID	Depth (ft bwt)[a]	Iodine-129 (pCi/L)	Iodine-127 (µg/L)	Iodate (µg/L)	Iodide (µg/L)	NO_3 (mg/L)
299-W22-114[b]	7.6	4.0	NA	NA	NA	84.1
699-36-70A	34.1	8.0	10.1	13.0	ND	16.8
699-35-66A	67.3	1.5	11.0	13.0	ND	24.3
699-36-66B	97.7	2.8	12.7	17.1	ND	53.1

(a) ft bwt = feet below water table
(b) Samples from 299-W22-114 were collected in June 2017 and were not analyzed for iodine-127 or to determine speciation
NA= Not available
ND = non-detect; detection limits: I-127 1.26 µg/L, iodate 1.62 µg/L, iodide 2.46 µg/L
I-129 and NO_3 data were received from CHPRC.

3.2.2 Iodine Sorption

Sorption is used to describe aqueous iodine partitioning to a solid phase, and may include adsorption, absorption, complexation, precipitation, co-precipitation, and ionization with organic carbon. Kaplan et al. (2014) summarized sorption behavior of the different iodine species in Hanford groundwater as follows:

> “Iodine sorption is mostly reversible, but a small fraction is not. Consequently, measured (ad)sorption Kd values are less than desorption Kd values. Adsorption and interaction with OM are the dominant attenuation mechanisms for iodine-129 in groundwater. Iodate

> is typically adsorbed more strongly than iodide; adsorption is inversely related to pH. Sediment OM generally decreases iodine mobility, especially when bound to larger organic moieties. To a lesser extent, organo-iodine complexes may increase mobility, especially when iodine is bound to smaller organic moieties. Radioiodine speciation has been measured at the SRS and Hanford Site contaminant plumes. In both cases, iodide was not the dominant species and iodate and organo-iodine aqueous species were also present. This speciation distribution is not predicted by thermodynamic considerations."

Iodine and organic carbon form extremely strong covalent bonds, so the presence of small concentrations of dissolved organic carbon can have significant effects on iodine sorption. Organic materials in the subsurface may interact with iodine and affect its fate and transport through (1) formation of immobile sediment-associated Organo-I compounds, (2) formation of mobile soluble Organo-I compounds, (3) formation of volatile Organo-I compounds, (4) providing electron donors for microbially mediated reduction reactions that directly or indirectly affect iodine speciation, and (5) providing adsorption capacity for iodine species.

Low concentrations of Organo-I (and iodate) previously have been detected in Hanford groundwater (Santschi et al. 2012). More recent studies have detected a broad range of organic compounds in the 200-UP-1 OU aquifer groundwater (Truex et al. 2017), including lipid-like, aliphatic, olefinic, and aromatic compounds. Preliminary assessments could not confidently identify specific Organo-I complexation structures in the 200-UP-1 site at Hanford, but the results suggested that these compounds exist at Hanford. Differences in organic matter composition suggest that pore water samples have a higher abundance of aromatic compounds, which are a better target for iodine complexation (Truex et al. 2017).

Studies of sorption in shallow soils indicate that the organic matter also is a primary control on iodine sorption to sediments (Assemi and Erten 1994; Bird and Schwartz 1997; Emerson et al. 2014; Fukui et al. 1996; Kaplan 2003; Neal and Truesdale 1976; Sheppard and Thibault 1991; Whitehead 1974; Yoshida et al. 1992; Yu et al. 1996). Iodine association with natural organic matter is important in sediments, even when organic carbon concentrations are very low (e.g., <0.2% at the Hanford Site) (Santschi et al. 2017; Xu et al. 2015; Zhang et al. 2013). Xu et al. (2015) performed sequential extractions on Hanford sediment samples and showed that a substantial fraction of sediment-associated iodine was more strongly bound to sediments than expected. They noted that the iodine incorporated into calcite accounted for 2.9% to 39.4% of the total sedimentary iodine. Organic carbon appeared to control iodine binding to the sediments and was assumed to be responsible for incorporation of residual iodine (57.1% to 90.6%). Xu et al. (2015) showed that the greater the organic carbon concentrations in the sediments, the greater the values of uptake distribution coefficient (K_d), desorption K_d, and the greater residual iodine concentrations (non-exchangeable, non-calcite-incorporated and not associated with Mn or Fe-oxide).

Metal oxides and hydroxides (e.g. Fe $(OH)_3$, $Al(OH)_3$, $MnIVO_2$) may play an important role in controlling iodine behavior in soils, through both adsorption of inorganic iodine and oxidation of iodide (Shetaya et al. 2012). Ferric and aluminum oxides adsorb iodate more strongly than iodide (e.g., Whitehead 1984; Kodama et al. 2006).

Iodate can co-precipitate with calcium carbonate (Zhang et al. 2013; Podder et al. 2017), which may have important implications related to iodine partitioning near the source terms, where extreme chemical conditions may promote calcite dissolution and re-precipitation. This would facilitate co-precipitation of $iodate_-$ and incorporation into the newly formed calcium carbonate. Iodate removal from the mobile aqueous phase through incorporation into $CaCO_3$ crystal lattice was previously demonstrated under field conditions at the Hanford Site (Xu et al. 2015, Zhang et al. 2013. Results of these experiments demonstrate that iodate- precipitation more easily occurs concurrently with calcite precipitation and that the water chemistry affects this process. Recent results suggest that iodate incorporation in precipitates occurred during the calcite precipitation process and that removal of iodate was also by adsorption (Truex et al. 2017). Co-precipitation of iodate with calcium carbonate may be important to the long-term fate of iodine in the far field, where natural calcium carbonate dissolution and precipitation cycling may occur.

Early studies of iodide sorption reported K_d with values in the range of 0 to 2 mL/g (Kaplan et al. 2000). More recently, studies in Hanford sediments have identified species-specific iodate sorption as 0.3 to 1.2 mL/g (retardation factor of 2.4 to 6.2), and iodide sorption as 0.07 to 0.1 mL/g (retardation factor 1.3 to 1.5) (Truex et al. 2017; Szecsody et al. 2017). Using subsurface sediments, desorption K_d values were much higher than the iodine adsorption K_d values, indicating that sorption was only partially reversible (Xu et al. 2015). In these studies, similar trends were noted for I^- and IO_3^-, but results indicated that iodate sorption to Hanford Site sediments was greater than iodide sorption (Truex et al. 2017).

3.2.3 Iodine Transformation Processes

Transformation reactions can change the relative quantity of chemical species, result in accumulation as a solid phase, or promote volatilization of iodine (Truex et al. 2017). As shown in Figure 3.3, transformation of iodine between species is a key factor in understanding iodine fate and transport. Minerals that participate in redox reactions (e.g., iron and manganese) may mediate iodine transformation processes, either directly or coupled with microbial processes. Microorganisms and/or their cell exudates can mediate many important processes associated with iodine transformations between species, associations with organic compounds, and adsorption. Biotransformation of iodine species includes oxidation of iodide to iodine and then spontaneous formation of more oxidized species, and reduction of iodate to iodide. Iodate reduction appears to be caused by a combination of abiotic phases (e.g., ferrous iron surface phases) and microbial reduction, and the functional capacity for these abiotic and biotic processes may depend on mass of abiotic phases and available substrate for microbial processes.

Reduction of iodate in Hanford Site sediments was observed as part of partitioning experiments (Xu et al. 2015) and may have been driven by sediment-associated ferrous iron or microbial reactions. Data from the 200 Area suggest that Fe(II) concentrations in Ringold Formation sediments could be on the order of 3.4 to 6.9 wt% (MinChem Database [Mackley et al. 2010] – unpublished). Thus, ferrous iron incorporated in minerals may be a reactive facies (as iron sulfide, if present, or other ferrous minerals) that needs to be considered relative to iodine fate and transport.

Sediments from locations within the Hanford Site 200-ZP-1 OU iodine plume with background, low, and high levels of iodine-129 were determined to contain microbial taxa (Lee et al. 2015) that have shown the ability to both oxidize I^- and reduce IO_3^-. Microbes enriched from sediments obtained from iodine-contaminated portions of the Hanford 200 West Area have demonstrated the potential for both iodide oxidation and iodate reduction (Lee et al. 2018).

Oxidation of iodide can also lead to the generation of more complex organic iodine compounds, including iodinated soil organic matter (SOM). This process may occur in Hanford groundwater since iodide- oxidation was demonstrated by Hanford bacterial isolates. Understanding this process will be important since Organo-I comprises approximately 25% of the iodine species in Hanford groundwater.

Bacteria can use iodate as an alternate electron acceptor for growth; it is converted to iodide under anaerobic or microaerobic conditions. To date, nitrate-reducing, iron-reducing, and sulfate-reducing bacteria have been found to reduce iodate. Sediments from traps incubated in iodine-contaminated groundwater at the Hanford Site have yielded a number of bacterial isolates that can oxidize or reduce different iodine species (Truex et al. 2017), and experiments were performed to determine the ability of various Hanford isolates to reduce iodate in the presence of nitrate, a common co-contaminant in the 200-UP-1 groundwater. Results for one isolate related to *Agrobacterium tumefaciens* indicated that iodate reduction occurred under both anaerobic and micro-aerobic conditions.

Methyl iodide, CH_3I, is a volatile iodine compound that plays a large role in carrying iodine from terrestrial and marine environments to the atmosphere. Recent research has shown that a variety of terrestrial bacteria volatilize iodine through the methylation of iodide (Amachi et al. 2001, 2003), and iodine-volatilizing bacteria are ubiquitous in the soil environment. Volatilization of iodine has been shown to be linked to iodide-oxidation, and this process may occur in Hanford groundwater since iodide-oxidation was demonstrated by Hanford bacterial isolates. Formation of volatile Organo-I species during the I-oxidation process is currently being tested in the laboratory. Work by Keppler et al. (2000) has shown also that halide ions can be alkylated during oxidation of organic matter by electron acceptors such as Fe(III), and sunlight or microbial mediation are not required. They suggest that such abiotic processes could make a significant contribution to the budget of the atmospheric compounds CH_3Cl, CH_3Br, and CH_3I. This mechanism for volatilization of iodine has not been previously considered for Hanford.

3.3 Iodine-129 Source and Release Information

As described in Section 2 of this report, iodine-129 in the 200-UP-1 OU originated from the 216 U 1 and 216 U 2 Cribs near U Plant and from the REDOX Plant waste sites in the southern portion of the 200 West Area. A summary of estimated total iodine-129 activities and liquid effluent volumes and calculated mean concentrations that were released to the most significant of the 200-UP-1 waste sites is presented in Table 3.5. The REDOX Plant cribs (216-S-1/2, 216-S-7, and 216-S-9) were the primary sources with the largest discharge volumes and highest iodine-129 concentrations in 200 UP-1; greater than 100 times the 1 pCi/L cleanup level.

Table 3.5. Primary Waste Sites with Highest Iodine-129 Activity and Liquid Effluent Releases in 200-UP-1 (Eslinger et al. 2006a,b). This table is FIO.

Site	Total Activity (Ci)	Liquid Effluent Volume (m^3)	Mean Concentration (pCi/L)
216-S-1/2	1.37E-01	160,426	855
216-S-7	3.55E-01	389,901	911
216-U-1/2	2.27E-06	15,929	0.14
216-S-9	2.98E-02	49,580	601
216-U-10	2.14E-01	159,859,379	1.34

Concentration trends of iodine-129 in groundwater show no clear evidence of a continuing source of iodine-129 from the vadose zone to the groundwater aquifer at concentrations above 1 pCi/L. (Truex et al 2017). Supporting model calculations (Section 3.4) suggest that iodine-129 from the original releases does remain in the vadose zone and will continue to migrate into the underlying groundwater. However, concentrations of residual iodine-129 left in the vadose zone are lower than what was released during the peak discharge periods, and natural groundwater recharge rates are low, so the continuing flux of iodine-129 from the vadose zone to groundwater may be low enough that groundwater concentrations below the vadose zone source areas will remain below the DWS.

The 200-UP-1 RAWP (USDOE 2013a) estimated a total mass of 0.1 Ci for iodine-129 (Table 3.6) based on data from the 2011 Hanford Groundwater Monitoring report (USDOE 2012b). Given the general lack of depth-discrete groundwater monitoring data, and the paucity of data for vadose zone pore water samples, any further insights into the spatial distribution of iodine-129 in the aquifer and vadose zone, and potential future transport and fate, will require the use of numerical models. The total release of iodine-129 from the five sites listed in Table 3.5 was 0.73 Ci, suggesting that most of the iodine-129 activity may remain in the vadose zone and not within the groundwater plume.

Table 3.6. Characteristics of the Iodine-129 Plume Within 200-UP-1 (from 200-UP-1 RAWP; USDOE 2013a)

Porosity[(a)]	Iodine-129 Plume Area ha (ac)[(b)]	Iodine-129 Estimated Average Plume Thickness, m (ft)[(b)]	Iodine-129 Plume Pore Volume, Billion L (gal)	90th Percentile Concentration[(b)]	Estimated Iodine-129 Mass (Ci)
0.2	383 (948)	30 (100)	23 (6.2)	3.5 pCi/L	0.1

(a) Source: Record of Decision for Interim Remedial Action, Hanford 200 Area Superfund Site, 200-UP-1 Operable Unit (USEPA et al., 2012) Information was generated in 2009 as part of the RI/FS Report (DOE/RL-2009-122, Remedial Investigation/Feasibility Study for the 200-UP-1 Groundwater Operable Unit).

(b) Based on Hanford Site Groundwater Monitoring for 2011 (DOE/RL-2011-118; USDOE 2012b).

3.4 Simulation of Iodine-129 Transport and Fate

Groundwater monitoring data indicate that the size of the iodine-129 plume appears to be decreasing (Section 2). However, the size and depth of the affected area and nature of the subsurface make characterization and monitoring challenging. Available observations are also relatively sparse in space and time. In this section, results of a numerical flow and transport model implemented using the eSTOMP simulator (Fang et al. 2018) are used along with information from the Hanford Groundwater Monitoring Program to infer the movement of iodine-129 from locations and times of release through migration out of 200-UP-1 in the absence of long-term containment. The field-measured results are augmented with depictions from the integrated vadose zone-aquifer system model that is being developed specifically for investigating iodine-129 fate and transport in the 200-UP-1 OU (Rockhold et al. 2017).

3.4.1 Movement of Iodine through the Vadose Zone and Aquifer

The distribution and history of iodine-129 in the unconfined aquifer system has been described using measured values from well sampling (see Section 2). The distribution of iodine-129 in the vadose zone is more difficult to determine because core sampling is very sparse. A model of the combined 200-UP-1 and 200-ZP-1 OUs was developed with eSTOMP (Fang et al. 2018), a parallel version of the STOMP simulator (White et al. 2018; White and Oostrom, 2006), to help evaluate the potential transport, fate, and distribution of iodine-129 in both the vadose zone and aquifer. Although model development is not yet complete, predictions are useful for providing an approximate, integrated view of the combined vadose-groundwater system and the potential iodine-129 movement within it.

The model domain (Figure 3.9) is 9 km on a side and includes 200-ZP-1 OU because movement of the iodine-129 plume is affected by a groundwater P&T system that was first constructed in 200-ZP-1. That system was later expanded to include injection and extraction wells located within the 200-UP-1 OU, including the three hydraulic containment wells located downgradient of the iodine-129 plume. The preferred alternative in the interim ROD (USEPA et al. 2012) for groundwater cleanup in the 200 West Area of Hanford included 35 years of operation of the P&T system, which spans the time frame from 2012 to 2047. That pumping schedule is included in the model, which assumes removal of ambient iodine-129 dissolved in groundwater, and injection of clean water devoid of iodine-129.

The eSTOMP flow and transport model uses a geologic framework model for the Central Plateau (Hammond and Lupton 2015) and records of water and iodine-129 releases and water table boundary conditions to represent the period from 1944 to 2018, with continuation of current water table boundary conditions to the year 3000. Source terms used in the model to specify internal additions and withdrawals of water and iodine-129 are based on best estimates of liquid effluent discharges and iodine-129 releases from Corbin et al. (2005) and Eslinger et al (2006a,b) for primary 200-UP-1 OU waste sites identified by Truex et al. (2015), as well as P&T records provided by CHPRC (email from Art Lee (CHPRC) to Catherine Yonkofski (PNNL), 09-Aug-2017, Re: P&T injection/extraction rates). Note that the estimated iodine-129 discharged to the 216-U-10 site (U pond) was not included in the current model because this produced a much larger (albeit dilute) groundwater iodine-129 plume than has been observed in the field (Rockhold et al. 2017). Future model updates will use recently released revised inventory estimates (Zaher and Agnew 2018). A K_d approach is used in the current model due to a lack of data to elucidate dominant mechanisms for iodine-129 sorption and other attenuation processes. Laboratory investigations are ongoing. Results will be used to update model descriptions of sorption and/or other reaction processes that affect iodine-129 attenuation in the field.

Figure 3.10 and Figure 3.11 show the plan-view extents of the iodine-129 plume at different times based on maps produced by the Groundwater Monitoring Program (contour lines), and simulated plumes (filled contours) generated using a linear equilibrium isotherm model with $K_d = 0$ mL/g. Figure 3.12 and Figure 3.13 show similar results generated using a linear equilibrium adsorption model with $K_d = 0.02$ mL/g. The simulated plumes for both cases are smaller and narrower than the inferred plume maps based on groundwater sampling data. The differences in plume size may be a result of inaccuracies in the source terms used in the model, and/or in the features or hydraulic properties assigned to both the vadose zone and aquifer materials. The model was based on the Hanford South Geologic Framework Model (Hammond and Lupton 2015), which does not consider sublayers of the Hanford formation or Cold Creek Unit. Consideration of these sublayers could result in predicting more lateral spreading of water and contaminants in the vadose zone, creating a wider, more dispersed plume in the underlying aquifer.

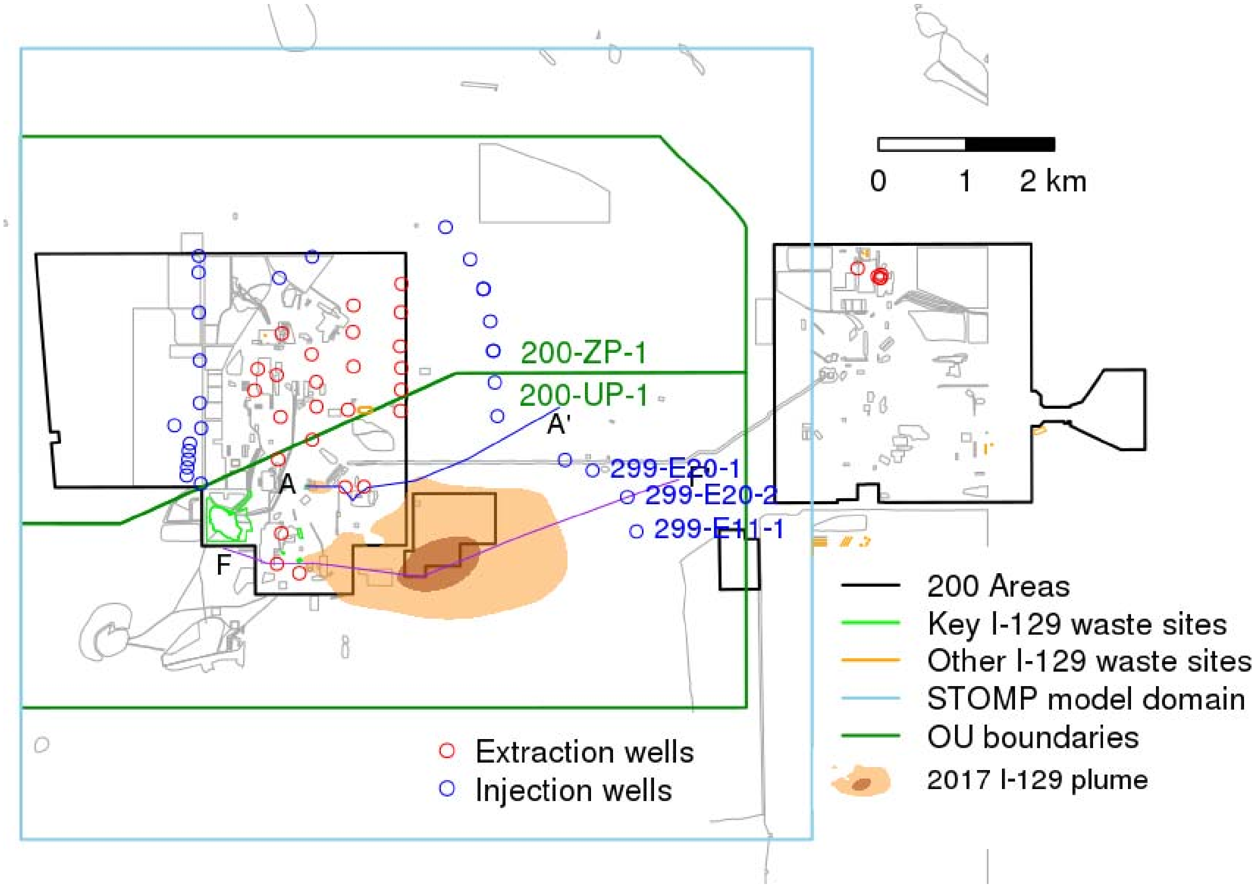

Figure 3.9. Reference Map Showing eSTOMP Model Domain. Transect lines A-A' and F-F' are same as those in Figure 2.6. This figure is FIO.

Figure 3.12 and Figure 3.13 also show that the simulated plume for the K_d = 0 mL/g case appears to move faster than the actual plume, while the simulated plume with K_d = 0.02 mL/g appears to move at similar rate to the actual plume. The simulated plume areas also increase over time while the observed plume areas slowly decrease. This difference is presumably due to physical or biogeochemical processes that are not currently represented in the model (e.g., volatilization, kinetic adsorption, or other reactions). Representations of these processes will be incorporated in the next model iteration based on updates to the iodine conceptual model. Updated estimates of radionuclide inventory of direct liquid discharges to soils in the Hanford 200 Areas have also recently been generated (Zaher and Agnew 2018). A new Central Plateau Vadose Zone Geologic Framework Model has also recently become available (Springer 2018). These recently released data will be incorporated into the next iteration of the model.

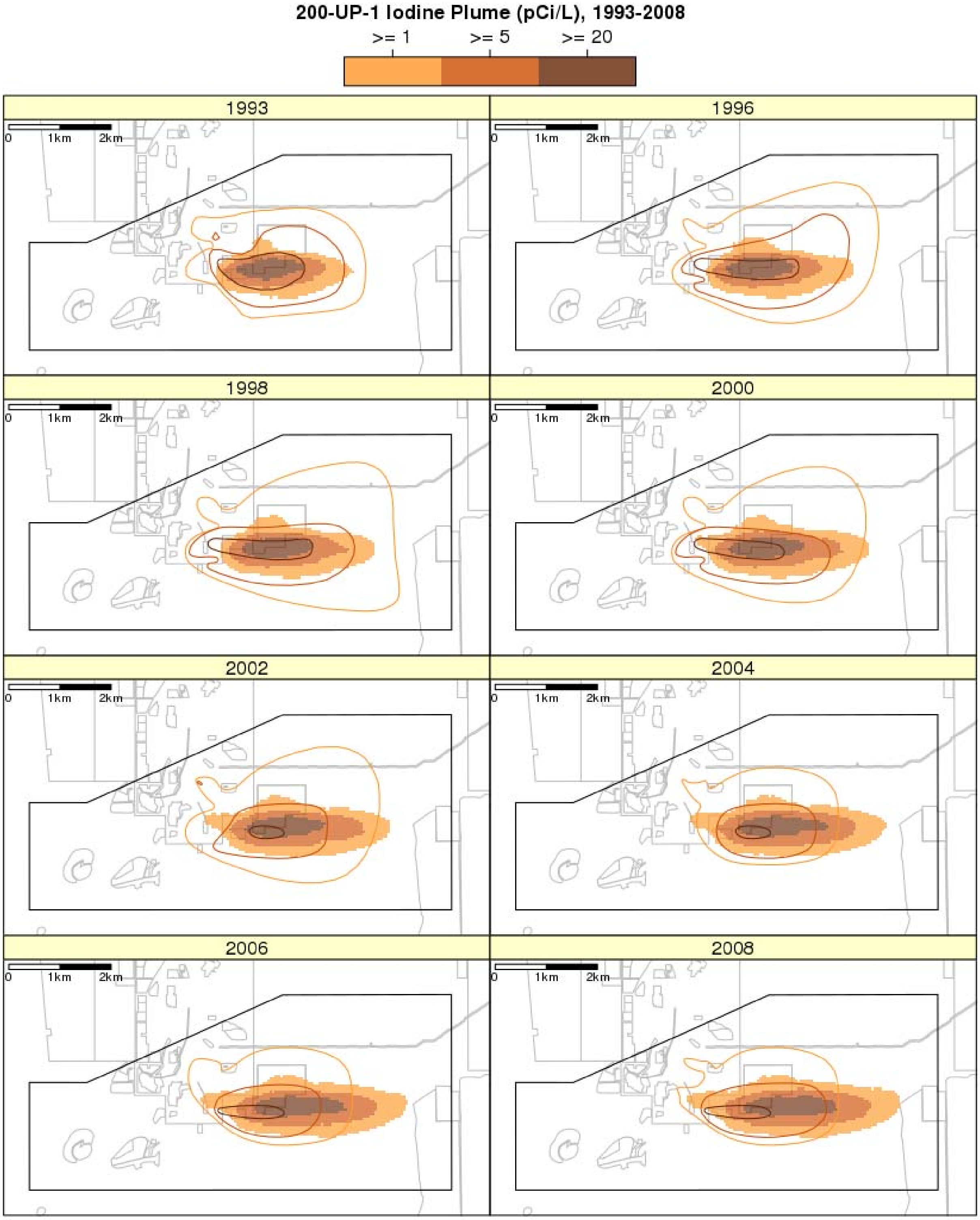

Figure 3.10. eSTOMP Simulation Results (filled contours) Using a Linear Adsorption Isotherm Model with K_d = 0 mL/g, and Geographic Information System (GIS) Maps of Field Data (contour lines) for Years 1993-2008. This figure is FIO.

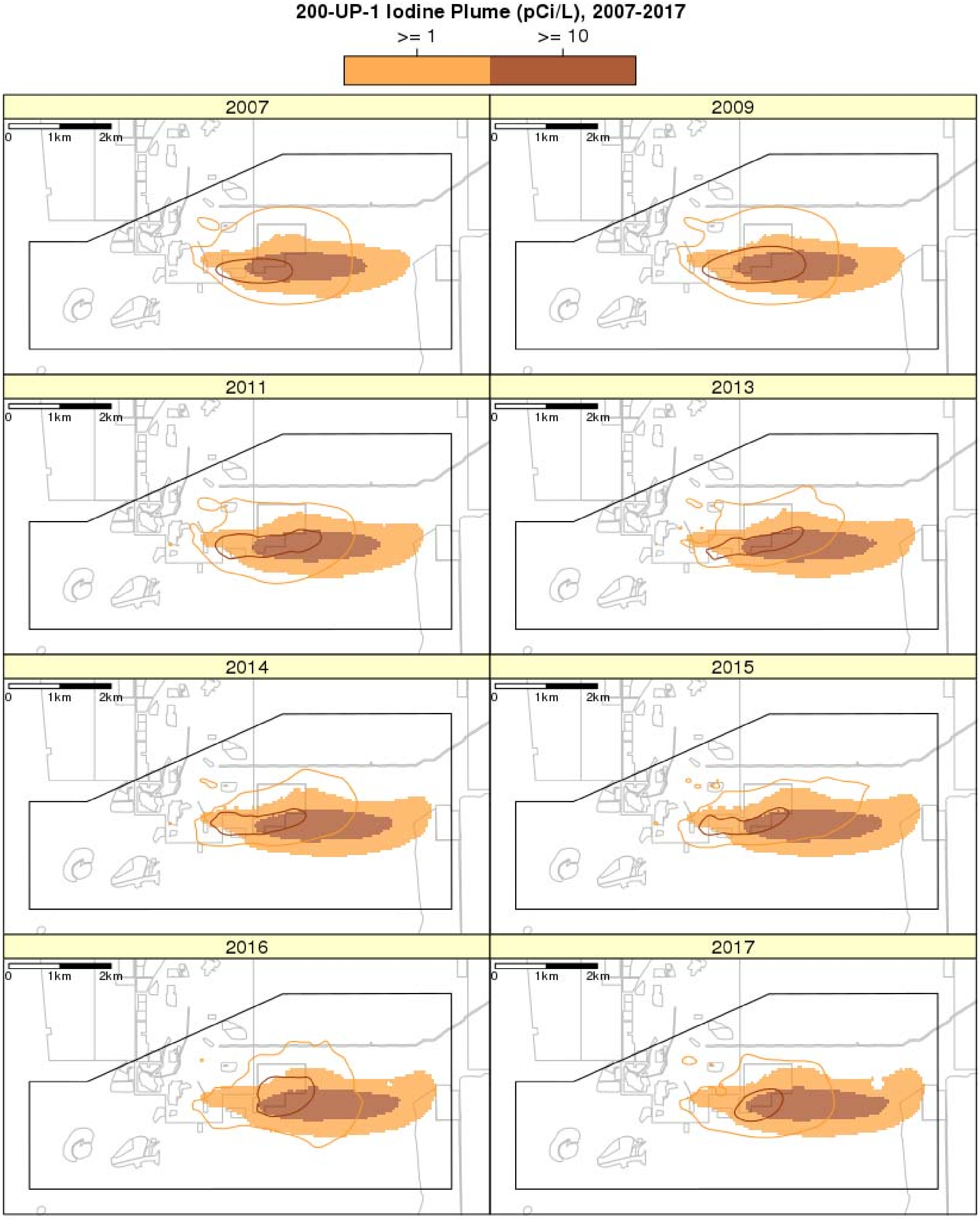

Figure 3.11. eSTOMP Simulation Results (filled contours) Using a Linear Adsorption Isotherm Model with K_d = 0 mL/g, and GIS Maps of Field Data (contour lines) for Years 2007-2017. This figure is FIO.

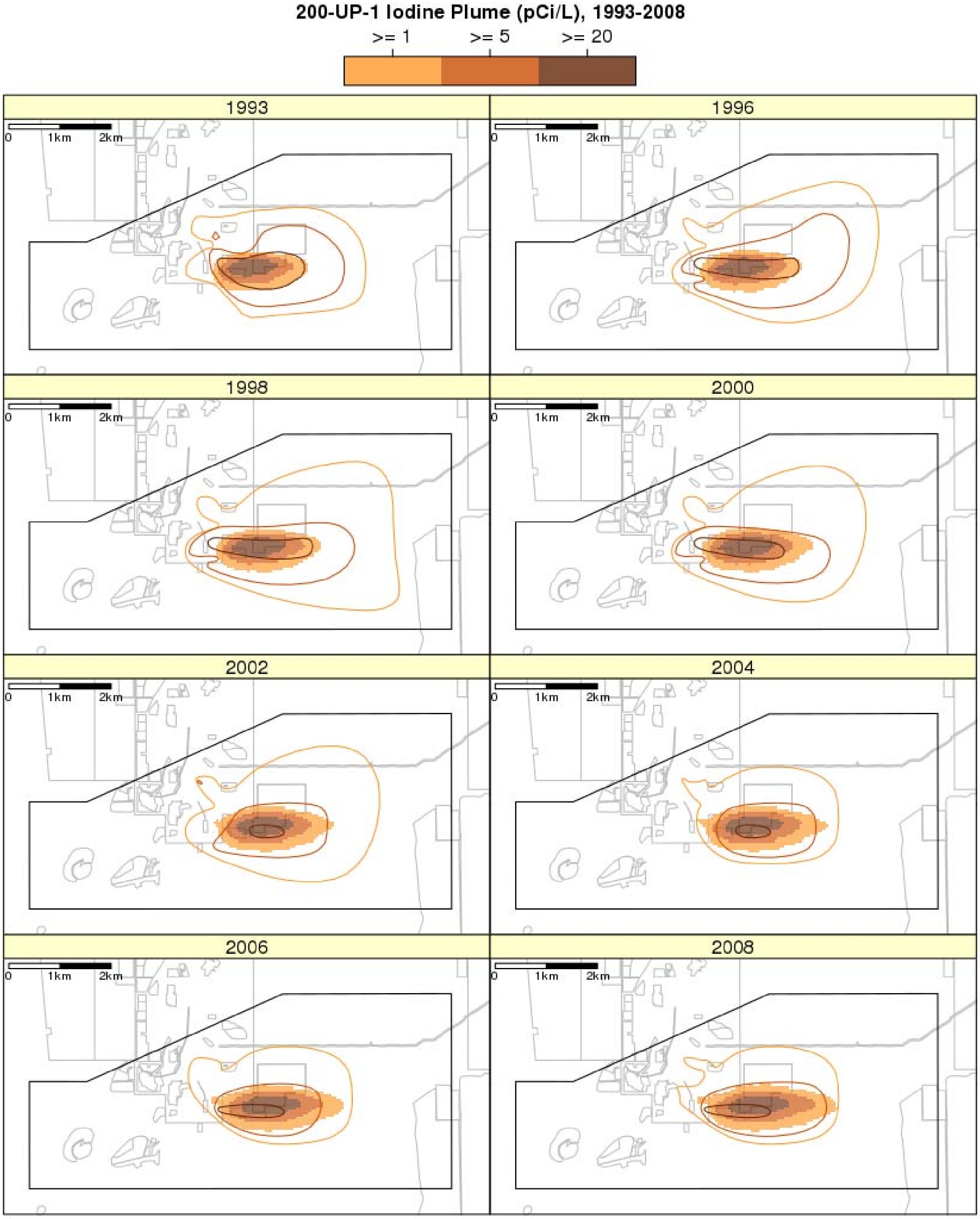

Figure 3.12. eSTOMP Simulation Results (filled contours) Using a Linear Adsorption Isotherm Model with K_d = 0.02 mL/g, and GIS Maps of Field Data (contour lines) for Years 1993-2008. This figure is FIO.

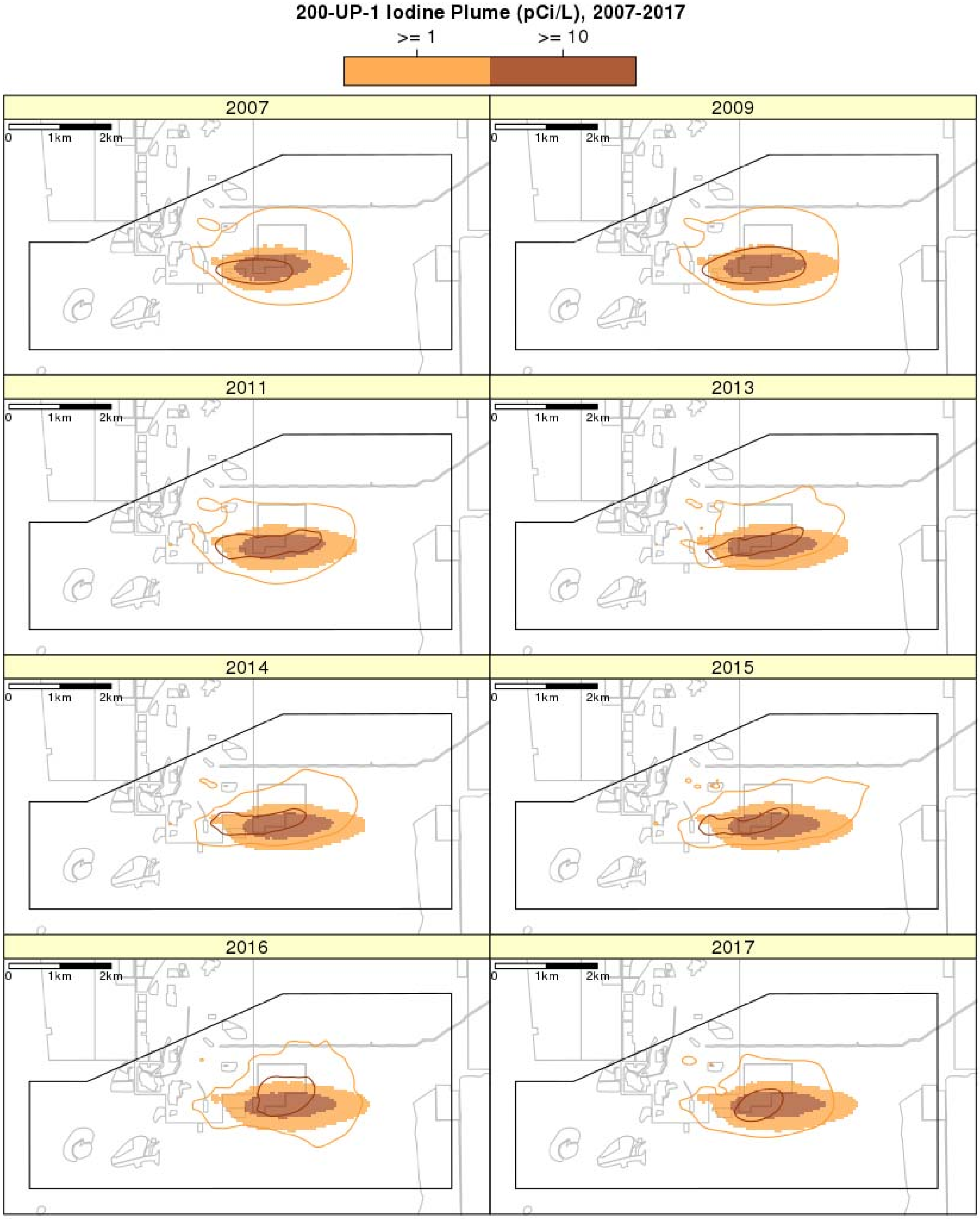

Figure 3.13. eSTOMP Simulation Results (filled contours) Using a Linear Adsorption Isotherm Model with K_d = 0.02 mL/g, and GIS Maps of Field Data (contour lines) for Years 2007-2017. This figure is FIO.

The plume maps produced by the Hanford Groundwater Monitoring Program represent interpolated results based on sparse well data while the model results represent a horizontal slice through the modeled domain. The lack of well monitoring results is due in part to the fact that the core of the iodine-129 groundwater plume is located immediately below the Environmental Restoration Disposal Facility (ERDF). Restrictions on drilling new wells through an active waste disposal facility impose some limitations on how well the plume is defined in the field. Model results are also based on historical records of liquid waste and iodine-129 released from the major iodine-129 release site in the 200-UP-1, which are uncertain. Therefore, some degree of mismatch between field observations and modeling results is expected. The match between simulated and GIS maps is anticipated to improve, however, after a planned recalibration of the eSTOMP model after incorporation of revised hydrostratigraphy for the vadose zone (Springer 2018), new inventory estimates (Zaher and Agnew 2018) and an improved representation of biogeochemical behavior of iodine in the subsurface.

The current 200 West Area P&T system began operation in 2012. The injection wells being used for hydraulic containment of the iodine-129 plume in the 200-UP-1 began pumping in 2015. Both of the simulation cases were run out into the future with the P&T system operating until 2047 (35 years after the start of the P&T system). At that point the source terms used to represent all extraction and injection wells were turned off. Simulation results for the $K_d = 0.02$ case are shown in map view and cross section for years 2018 and 2047 in Figures 3.14 and 3.15, respectively. The effects of the hydraulic containment wells can be seen in the distortion and change in orientation of the simulated plumes between years 2018 and 2047. At later times (not shown), the simulated plumes drift to the east-northeast and appear to have left the simulated domain before year 2400 for both K_d cases. Accurately assessing plume behavior at later times will require the use of model with a larger domain.

The two cross-sections shown in Figures 3.14 and 3.15 depict total (sorbed plus aqueous phase) iodine activity and activity in the aqueous phase only, respectively. The cross-section locations along the north-south direction correspond to the center of mass for the vadose and groundwater iodine in each of the years. Also shown are the travel paths for the center of mass since the onset of iodine contamination. The separation between the vadose and groundwater travel paths and between the transect locations may suggest a decoupling of the vadose zone iodine and the groundwater plume. In 2018, the groundwater plume is east of the source area but still connected to it via a zone created by advection, dispersion, and the water table drop. In 2047, at the end of P&T operations, the center of the groundwater plume appears to have detached from the vadose source.

The preliminary eSTOMP model developed for this work incorporates primary processes for the fate and transport of iodine-129, namely, downward movement of water and iodine from waste disposal sites in the vadose zone, retention of waste solutions in the vadose zone (unsaturated zone above the water table), lateral movement in groundwater, and linear equilibrium sorption throughout the subsurface (when K_d is non-zero). The very large thickness of the vadose zone in the Central Plateau, and the decline of the water table after large liquid discharges ended, results in a large amount of simulated iodine being located above the water table. Based on model results in a 10 km^2 area near the plume and primary iodine waste sites, the mean water table rose from a historical background elevation of approximately 129.6 m to a high of about 143 m in 1979, followed by a decline to 133.6 m in 2018. The water table would need to decline another 4 m to reach the historical background level. The modeled retention of iodine in the vadose zone, and the very low amount of natural recharge at the ground surface and resulting slow movement of iodine in the vadose zone, implies that a significant amount of iodine will remain below the waste sites in the vadose zone into the foreseeable future, even as the iodine in the groundwater plume migrates away in regional groundwater flow.

The modeled iodine-129 activity above and below the water table through time is shown in Figure 3.. Most of the simulated iodine remains sorbed to sediment above the water table, with a lesser amount held in solution above the water table. The 200-UP-1 RAWP (USDOE 2013a) estimated 0.1 Ci of iodine-129 in the unconfined aquifer, based on measured concentrations/activities for monitoring well samples and assumptions about the porosity and thickness of the aquifer. Slightly higher estimates (0.11 to 0.12 Ci in aqueous phase below the water table) are indicated by Figure 3., based on the simulation results that used liquid discharges and iodine-129 release estimates for the primary waste sites in the 200-UP-1 OU.

The movement of the groundwater plume according to calculations based on the Groundwater Monitoring Program GIS maps and the model results are shown in Table 3.7. Movement was calculated from the change in location of the center of mass positions in both the GIS maps and the modeled results. The GIS-mapped plume appears to have moved north then south, directions that are transverse to the hydraulic gradient. This apparent movement is primarily a result of changing map-making methods and assumptions. The simulated plume, in contrast, moves consistently in a downgradient direction, east-northeast. During the 2018-2047 period, which is assumed to have a P&T system operating at constant rates, the simulated plume moves 20 m/yr. After pumping ends in 2047, the migration rate of the simulated plume increases (results not shown). Note that field water level data currently indicate an overall eastward gradient (Figure 3.5), which is consistent with model predictions.

The EPA checklist (Appendix A) requires defining the area for which a TI waiver is being sought. That area was originally defined for this report as the 200-UP-1 OU boundary. The eastern border of the model was located accordingly. However, simulation results suggest that the plume will exit the eastern boundary of the domain of the current model at concentrations exceeding the DWS. This leaves open the question of how large an area would need to be considered before natural plume attenuation processes would reduce iodine-129 concentrations below the current MCL, if in situ or ex situ treatment technologies are not applied.

Table 3.7. Estimated and Modeled Migration of Iodine-129 Groundwater Plume. Movement of the plume as documented by the Groundwater Monitoring Program (USDOE 2018a) is calculated from the centroids of the GIS polygons representing the 1 pCi/L plume. Movement of the STOMP model plume is calculated from the center of mass for dissolved iodine-129 in the z = 115-125 m horizon. This table is FIO.

Time Period	Groundwater Monitoring GIS		eSTOMP Model	
	Distance and Direction	Rate (m/yr)	Distance and Direction	Rate (m/yr)
1993-2008	99 m N	6.6	420 m E	28
2008-2017	68 m S	7.6	292 m E	33
2008-2018	N/A	N/A	312 m E	31
2018-2047	N/A	N/A	566 m E	20

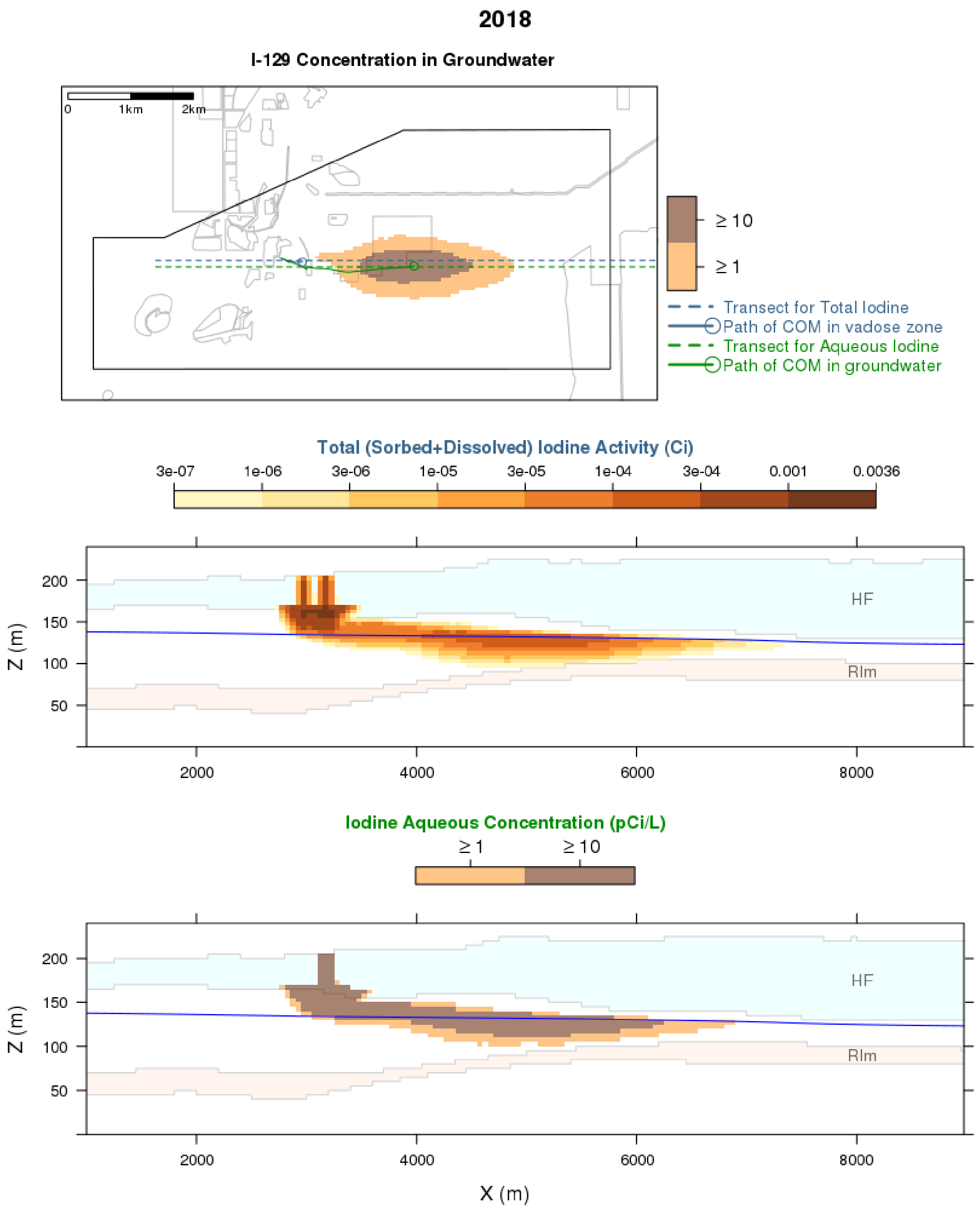

Figure 3.14. Simulated Iodine-129 Activity at Year 2018 for K_d = 0.02 mL/g. Top graphic is map of groundwater plume in 200-UP-1 and shows locations of cross sections and path-lines taken by center of mass for total iodine above the water table, and dissolved iodine in groundwater, respectively. Bottom two graphics show the respective variables in cross section. This figure is FIO.

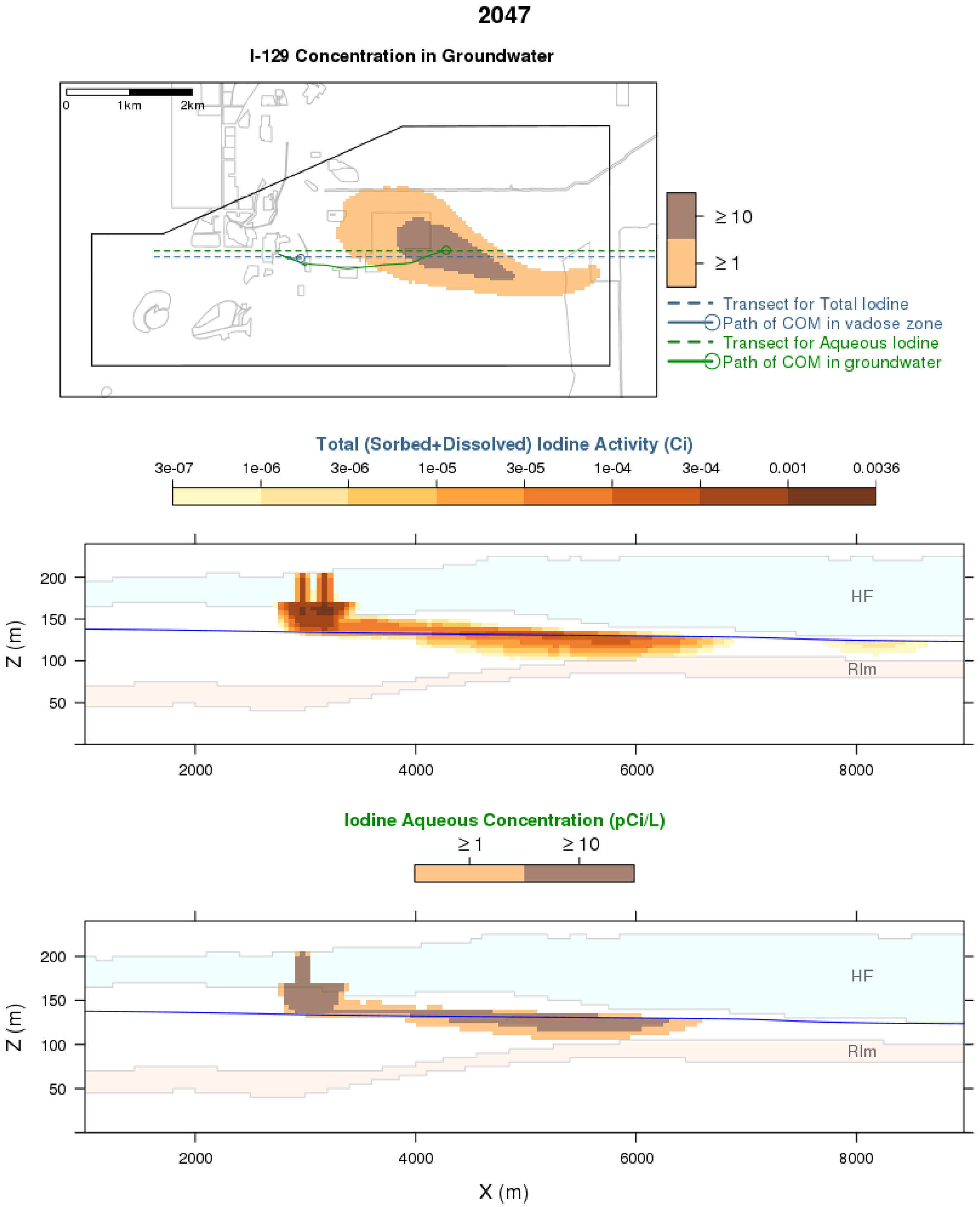

Figure 3.15. Simulated Iodine-129 Activity at Year 2047 for $K_d = 0.02$ mL/g. Top graphic is map of groundwater plume in 200-UP-1 and shows locations of cross sections and path-lines taken by center of mass for total iodine above the water table, and dissolved iodine in groundwater, respectively. Bottom two graphics show the respective variables in cross section. This figure is FIO.

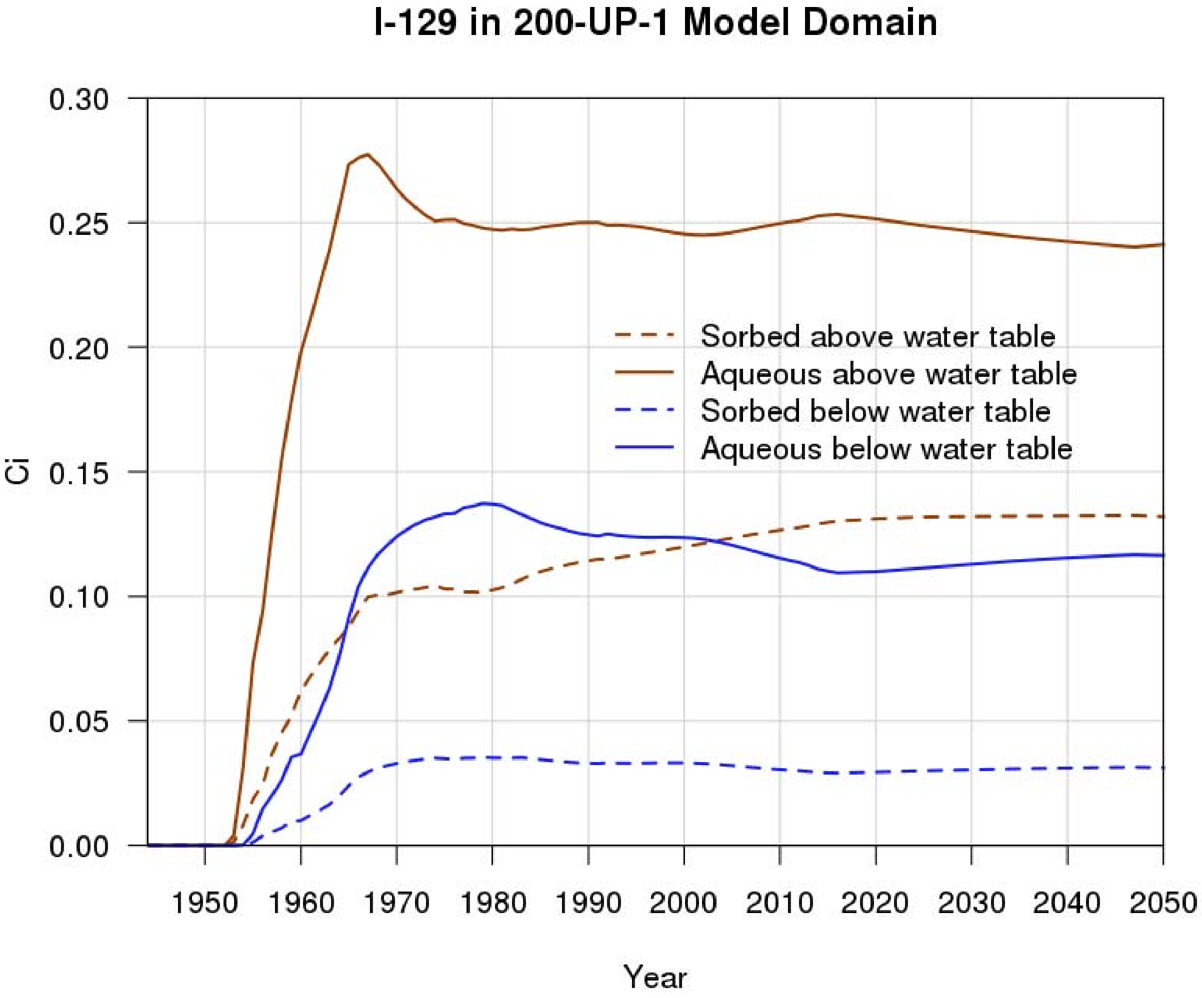

Figure 3.16. Simulated Iodine-129 Activity within Different Parts of the eSTOMP Model Domain through Time for the K_d = 0.02 mL/g Case. This figure is FIO.

4.0 Evaluation of Restoration Potential

Restoration options for remediation of the iodine-129 contamination beneath the 200-UP-1 OU currently are limited by the size of the plume, the biogeochemistry of iodine-129 and natural stable iodine-127, and tested, viable treatment technologies. Although demonstrated remediation technologies are not yet available to treat or remove iodine-129 contamination from the groundwater, a number of alternative treatment technologies have been identified and are being evaluated at the laboratory scale. The potential remediation technologies identified can be categorized into three classes: in situ groundwater remediation, ex situ groundwater remediation, and vadose zone remediation. Until viable treatment technologies are demonstrated, the interim remedy of hydraulic containment of the iodine-129 plume, which was implemented in 2015, will continue.

As described in Sections 2.1 and 3.2 of this document, discharge of waste waters to the cribs, ponds, and ditches that were the original sources of iodine-129 in 200-UP-1 groundwater have been discontinued. There are no current discharges of waste water containing iodine-129 to the ground surface. Continued downward flux of iodine-129 through the vadose zone may continue to contribute contamination to the groundwater at a very low rate, but most groundwater monitoring well data suggest that no significant, ongoing sources of iodine-129 exist within the OU. More accurately stated, the concentrations and fluxes of iodine-129 moving from the vadose zone into the groundwater may be low enough that when sampled over a 5-m well screen, the sampled iodine-129 concentrations may be below the maximum contaminant level (MCL).

Section 4.1 provides relevant information on operation of the injection wells installed to provide hydraulic containment of the iodine-129 plume and suitability and performance of the groundwater monitoring program for 200-UP-1 OU. Section 4.2 provides context regarding the current state of knowledge on restoration, and the potential timeframe for restoration. The ongoing evaluations of remediation technologies identified as potentially viable treatments for iodine-129 in groundwater are discussed in Section 4.3.

4.1 Remedial Action Performance Analysis

The 200 West P&T system operates the injection wells for hydraulic containment of the iodine-129 plume. Section 4.1.1 describes implementation of the hydraulic containment remedy. Section 4.1.2 presents additional data indicating that iodine-129 concentrations in groundwater are decreasing.

In addition to the iodine-129 plume, technetium-99, uranium, tritium, nitrate, chromium, and carbon tetrachloride also form groundwater plumes in the OU. During 2016, the 200 West P&T system treated a total volume of 3038.7 million L (802.2 million gal), removing 1721 kg of carbon tetrachloride, 330,877 kg of nitrate, 69.7 kg of chromium (total and hexavalent), 8.6 kg of trichloroethene, and 147 g (2.52 Ci) of technetium-99 (USDOE 2017c). Iodine-129 removal was negligible, as the influent and effluent concentrations throughout 2016 were less than the detection limit of 0.6 pCi/L.

An extensive groundwater monitoring program is operated across the Hanford Site (USDOE 2017b,c) and contaminant concentrations were monitored in 1,053 wells across the site in FY 2016. Within the 200 UP-1, groundwater monitoring is conducted under CERCLA for the 200-UP-1 OU and ERDF, and under RCRA for WMA S-SX, WMA U, and the 216 S-10 pond and ditch. More than 1400 groundwater samples collected from more than 80 wells located in 200-UP-1 have been analyzed for iodine-129 during monitoring since 2003. As described in Section 2 of this document, concentrations of iodine-129 are decreasing in most of the monitored wells within the OU. Comparisons of inferred plume contours from 1993 to 2017 also indicate that the plume areal extent is shrinking (Figure 2.3, Figure 2.4, and Figure 2.5).

4.1.1 Hydraulic Containment Remedy for Iodine-129

The iodine-129 plume remedy is implemented as part of the 200 West P&T design, which includes a total of 26 extraction and 27 injection wells, with an installed capacity to treat up to 9464 L/min (2500 gpm) of extracted groundwater. At the end of 2016, three active remedies were operating in 200 UP-1: WMA S-SX groundwater extraction system, U Plant area P&T system, and the hydraulic containment system for the iodine-129 plume. The U Plant area P&T and the iodine-129 plume hydraulic containment system began operating in 2015 as part of the 200-UP-1 remedy (USDOE 2017c).

The iodine-129 plume hydraulic containment system consists of three hydraulic control wells for injecting treated water from the 200 West P&T system to the east of the iodine-129 plume boundary (between the 200 West and 200 East Areas). Operation of these wells provides a degree of hydraulic containment by increasing the water table elevation downgradient of the plume to slow its eastward migration while treatment technologies are further evaluated. The three injection wells (299-E11-1, 299-E20-1, and 299-E20-2) were established approximately 375 to 550 m east (downgradient) of the leading edge of the plume. Previous numerical modeling indicated that three wells located downgradient of the plume with injection rates of 189 to 379 L/min (50 to 100 gpm) per well would be sufficient for hydraulic containment. The injected water is post-treatment effluent from the treatment system, and average concentrations in the treated water meet all of the cleanup levels specified in the 200-UP-1 ROD (USEPA et al. 2012; USDOE 2017c). In 2017, the total average flow rate for all three wells was 777 L/min (205 gal/min), or 136% of the minimum nominal flow rate. The total volume of water injected into the aquifer during 2017 was 404 million L (106.7 million gal), and the total volume of water injected since system startup was 742 million L (196.0 million gal) (USDOE 2018b; DOE/RL-2017-68).

Operation of the hydraulic containment injection wells began on October 28, 2015. Monthly water level measurements began in September 2015 from a network of monitoring wells near the injection wells. Potentiometric surface maps prepared using multi-event universal kriging from the water level measurements taken in 2017 show small groundwater mounds around the injection wells, but injection has only been operated for 2 years. The groundwater flow direction is toward the east-northeast, and the magnitude of the hydraulic gradient is large, as shown by the close spacing of the water table contours to the east of the injection wells (Figure 4.1). The increased magnitude in the hydraulic gradient is caused, at least in part, by a decrease in aquifer thickness to the east, and a resulting decrease in transmissivity (USDOE 2017c). The Rlm unit, which forms the base of the unconfined aquifer, increases in elevation toward the east, resulting in a thinner aquifer. The hydraulic conductivity of the aquifer sediments may also decrease toward the east, which would also contribute to the reduced transmissivity and larger hydraulic gradient.

The 2017 Hanford Groundwater Pump and Treat (USDOE 2018b) report presents an evaluation of the hydraulic control remedy by considering the development of reduced hydraulic gradients to the east-northeast of the plume with baseline water table compared with pre-injection conditions. Their analysis shows a decrease in the magnitude of the hydraulic gradient around the injection wells, and a reduction in the gradient magnitude (based on larger spacing between water contour levels for 2017 compared to pre-injection conditions). These data suggest that the migration rate of the iodine-129 plume has been reduced.

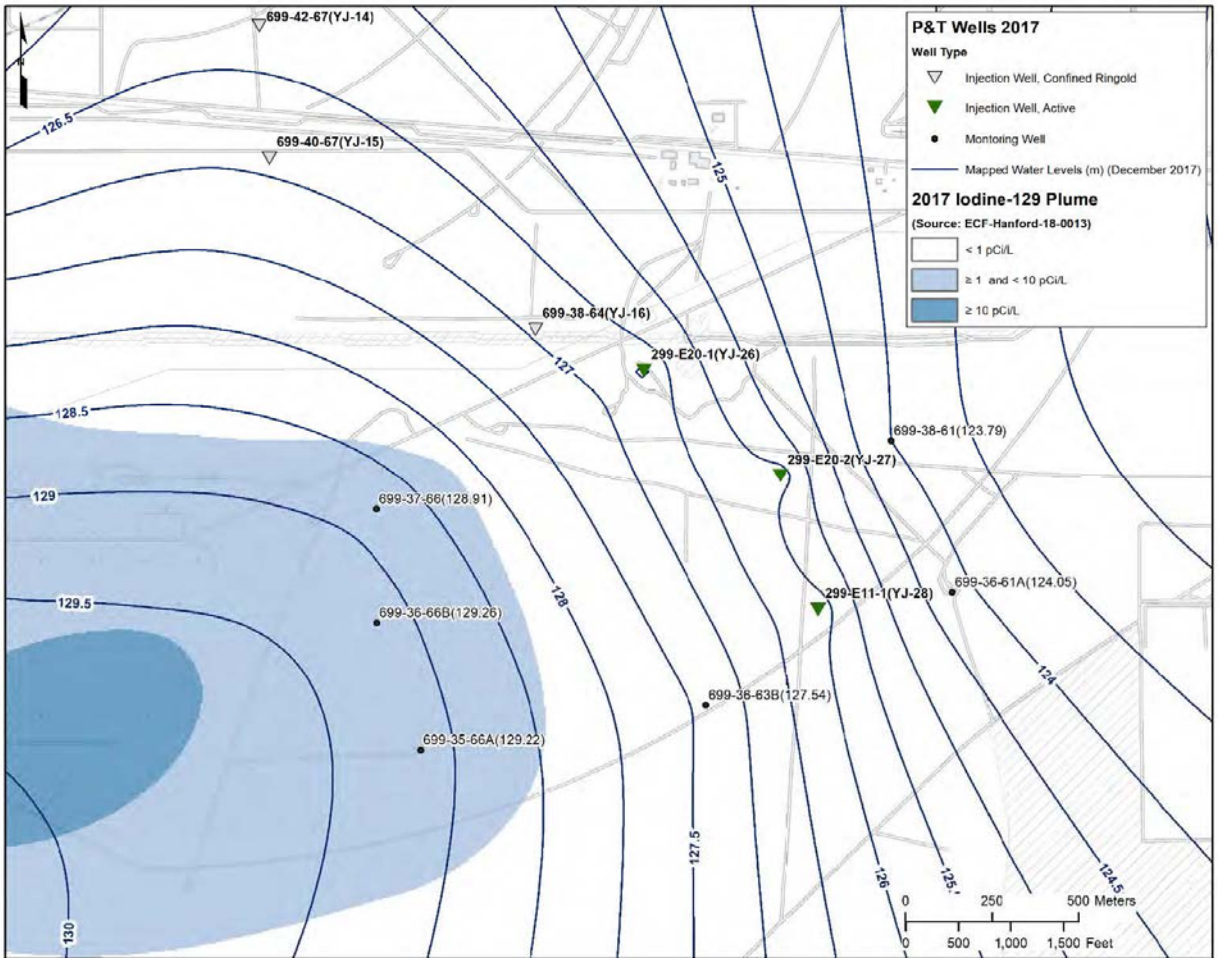

Figure 4.1. Water Table for the Iodine 129 Plume Hydraulic Containment Remedy, December 2017 (from USDOE 2018b)

4.1.2 Trends in Subsurface Iodine-129 Concentrations

As illustrated in Section 2, the areal extent of the iodine-129 plume has contracted since initial estimation of plume boundaries in 1993. In addition, concentrations of iodine-129 show a downward trend in most wells that are sampled. Maps illustrating the iodine-129 plume extent over a 20-year period beginning in 1993 shown in Truex et al. (2017) and Section 2.2 of this document indicate that plume has oscillated, but declined overall, in areal extent. Well data, in conjunction with the plume maps, are consistent with influences from (1) historical pulses of iodine into the groundwater that have now diminished in magnitude and (2) declining hydraulic gradients from dissipation of the historical 200 West Area groundwater mound created during processing operations. The data imply that the current plume was generated from a historical source that has diminished, and that a discrete plume is now migrating in the aquifer.

The overall decline in plume area and concentration are consistent with natural attenuation processes affecting the plume. Increases in concentrations for discrete locations in the central portion of the plume are consistent with movement of a higher concentration core along a flow path. A higher concentration core may still be attenuating, but temporal data at individual wells may be showing the progression of a plume core past the location of the well. In addition, iodine-129 currently in the vadose zone may still be a future source for groundwater contamination, even though the existing plume appears to be in a stable-to-declining condition (Truex et al. 2015). The water table and inferred groundwater movement as shown in Figure 4.1 indicates a strong overall gradient to the east. The effect of the hydraulic containment wells appears to be localized, but the wells have only been operating since 2015, so their full effect is still under evaluation. Predictive modeling results suggest that the hydraulic containment wells are effective in slowing plume migration.

4.2 Restoration Timeframe Analysis

The half-life of iodine-129 is 15.7 million years. MNA is generally not a viable remedy for such a long-lived radionuclide unless the hydraulic regime, transport distance, and/or other attenuation processes are such that mixing, dispersion, sorption, and/or reactions can be shown to reduce groundwater concentrations to less than the MCL in a reasonable timeframe. The model results shown in the previous section, generated using an integrated model of the combined vadose zone-aquifer system with a linear equilibrium sorption isotherm (or K_d) model, suggest that under current and expected future conditions, plume concentrations will remain above the MCL for the next 300-400 years. After this period, model simulations suggest that the iodine-129 plume will have moved to the east, outside of the 200-UP-1 OU boundaries. While the preliminary model results are mostly consistent with monitoring data, the monitoring data suggest that additional processes other than simple sorption, which are not currently considered in the model, are affecting the plume behavior. Other potential plume attenuation mechanisms, including volatilization and slow, kinetic adsorption/reaction processes, are currently being evaluated in ongoing laboratory studies. The model simulations also do not account for application of any additional remediation technologies that might be applied in the future. Other mechanisms responsible for plume attenuation, and the potential effects of additional remediation technologies on plume behavior, will be evaluated using the model when more information from laboratory investigations becomes available. Thus, MNA may be a potential remedy, but future work is needed to estimate of the timeframe needed for iodine-129 to drop below the MCL.

4.3 Other Applicable Technologies

As noted in the 200-UP-1 Evaluation Plan (USDOE 2017a), field-tested, mature remediation technologies are not readily available to use in remediating the iodine-129 plume in 200-UP-1 OU. However, investigations have been conducted to identify potential remediation technologies, prioritize research needs, and begin bench-scale testing. Potentially applicable remediation technologies for iodine-129 remediation were evaluated as part of the remedy specified in the interim 200-UP-1 ROD (USDOE 2017a). That literature review and analysis provided a starting point for further screening and identification of promising remediation technologies for iodine in the 200-UP-1 OU (Strickland et al. 2017a). The remediation technologies identified as potentially feasible can be categorized into three classes: *in situ groundwater remediation*, *ex situ groundwater remediation*, and *vadose zone remediation*.

Current studies are focused on those remediation technologies that were identified as high or medium priorities for in situ and ex situ groundwater remediation.

Ongoing work is described in a series of reports by the Deep Vadose Zone Initiative that will be published concurrently with this report. These and other recent laboratory experimental results will form the basis for updating and refining the descriptions of attenuation processes in the integrated model of the combined vadose zone-aquifer system for the 200-UP-1 OU. The updated model will be used to assess the potential effectiveness of alternative treatment technologies in the field.

5.0 Summary and Conclusions

The preferred alternative described in the 2012 ROD for the 200-UP-1 OU Interim Remedial Action includes active remediation using a combination of (1) groundwater P&T and (2) MNA for portions of the contaminated groundwater, followed by institutional controls until cleanup levels are met for unrestricted use. As noted in the 200-UP-1 OU ROD, no treatment technology for iodine-129 had been found that could achieve the DWS of 1 pCi/L for the iodine-129 concentrations present in the 200-UP-1 OU groundwater. Therefore, the 200-UP-1 OU interim ROD specified hydraulic containment of the iodine-129 plume, update of the conceptual model for iodine-129, and further evaluation of potentially applicable iodine-129 treatment technologies. The 200-UP-1 OU ROD further stated that in the event a viable treatment technology is not available, the use of a TI waiver be considered as part of the final remedy.

Although the plume can be hydraulically contained, this action will not reduce iodine-129 concentrations to below the DWS. Naturally occurring attenuation mechanisms, however, can reduce the plume concentrations, as evidenced by field data that show a shrinking iodine-129 plume footprint over time. This means that a TI waiver may only be appropriate for the more recalcitrant regions of the 200-UP-1 plume, as natural attenuation mechanisms and targeted remedies (that are still under evaluation) may reduce the more distal regions of the iodine-129 plume to below the DWS.

Risk analyses are planned for the next update of the model to assure protectiveness of human health and the environment under either monitored natural attenuation or active remediation scenarios. At that time, incorporation of appropriate attenuation mechanisms represented at the field scale will be assessed (e.g., volatilization, kinetic sorption, and incorporation into carbonate or iron-oxide precipitates [Truex et. al 2017]). In this way, the model can be used to evaluate different remediation approaches, as well provide the technical basis for safely achieving site closure.

6.0 Quality Assurance

The results presented in this report originate from work performed by the Pacific Northwest National Laboratory under a Nuclear Quality Assurance Program (NQAP). The NQAP implements the requirements of U.S. Department of Energy Order 414.1D, *Quality Assurance*, and 10 CFR 830 Subpart A, *Quality Assurance Requirements*. The NQAP uses ASME NQA-1-2012, *Quality Assurance Requirements for Nuclear Facility Applications*, as its consensus standard and NQA-1-2012 Subpart 4.2.1 as the basis for its graded approach to quality.

Two quality grading levels are defined by the NQAP:

Basic Research - The required degree of formality and level of work control is limited. However, sufficient documentation is retained to allow the research to be performed again without recourse to the original researcher(s). The documentation is also reviewed by a technically competent individual other than the originator.

Not Basic Research - The level of work control is greater than basic research. Approved plans and procedures govern the research, software is qualified, calculations are documented and reviewed, externally sourced data is evaluated, and measuring instrumentation is calibrated. Sufficient documentation is retained to allow the research to be performed again without recourse to the original researcher(s). The documentation is also reviewed by a technically competent individual other than the originator.

The work supporting the results presented in this report was performed in accordance with *Not Basic Research* grading level controls. Results presented here are considered to be preliminary and for information only.

7.0 References

Amachi S, M Kasahara, S Hanada, Y Kamagata, H Shinoyama, T Fujii, and Y Muramatsu. 2003. "Microbial participation in iodine volatilization from soils." *Environmental Science & Technology* 37(17):3885-3890.

Amachi S, Y Kamagata, T Kanagawa, and Y Muramatsu. 2001. "Bacteria Mediate Methylation of Iodine in Marine and Terrestrial Environments." *Applied and Environmental Microbiology* 67(6):2718-2722.

Ashworth DJ and G Shaw. 2006. "Effects of Moisture Content and Redox Potential on In Situ K_d Values for Radioiodine in Soil." *Science of the Total Environment* 359(1-3):244-254.

Ashworth DJ, G Shaw, AP Butler, and L Ciciani. 2003. "Soil Transport and Plant Uptake of Radio-Iodine from Near-Surface Groundwater." *Journal of Environmental Radioactivity* 70(1-2):99-114.

Assemi S and HN Erten. 1994. "Sorption of Radioiodine on Organic Rich Soil, Clay Minerals, and Alumina." *Journal of Radioanalytical and Nuclear Chemistry* 178:193-204.

Bergeron MP, GV Last, AE Reisenauer. 1987. *Geohydrology of a Commercial Low-Level Radioactive Waste Disposal Facility near Richland, Washington.* Prepared for US Ecology, Inc., Louisville, Kentucky under Contract 2311207358, by Battelle – Pacific Northwest National Laboratory, Richland, Washington.

Bird GA and W Schwartz. 1997. "Distribution Coefficients, Kds, for Iodide in Canadian Shield Lake Sediments under Oxic and Anoxic Conditions." *Journal of Environmental Radioactivity* 35(3):261-279.

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

Campayo, L, A Grandjean, A Coulon, R Delorme, D Vantelon, and D Laurencin. 2011. "Incorporation of iodates into hydroxyapatite: a new approach for the confinement of radioactive iodine." *Journal of Materials Chemistry* 2011, 21, 17609.

Claret F, C Lerouge, T Laurioux, M Bizi, T Conte, et al. 2010. "Natural iodine in a clay formation: Implication for iodine fate in geological disposals." *Geochimica et Cosmochimica Acta* 74:16-29. doi: 10.1016/j/gca.2009.09.030.

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

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

Corbin RA, BC Simpson, MJ Anderson, WF Danielson III, JG Field, TE Jones, and CT Kincaid. 2005. *Hanford Soil Inventory Rev. 1*. RPP-26744, Rev. 0, CH2M Hill Hanford Group, Inc. Richland, Washington.

Emerson HP, C Xu, Y Feng, M Lilley, DI Kaplan, PH Santschi, and BA Powell. 2014. “Geochemical Controls of Iodine Transport in Savannah River Site Subsurface Sediments.” *Chemical Geology* 45:105-113.

Eslinger PW, CT Kincaid, WE Nichols, and SK Wurstner. 2006a. *A Demonstration of the System Assessment Capability (SAC) Rev. 1 Software for the Hanford Remediation Assessment Project*. PNNL-16209, Pacific Northwest National Laboratory, Richland, Washington.

Eslinger PW, DW Engel, LH Gerhardstein, CA Lopresti, TB Miley, WE Nichols, DL Strenge, and SK Wurstner. 2006b. *Updated User Instructions for the Systems Assessment Capability, Rev. 1, Computer Codes – Volume 1: Inventory, Release, and Transport Modules*. PNNL-16115, Volume 1, Pacific Northwest National Laboratory, Richland, Washington.

Fang Y, D Appriou, DH Bacon, V Freedman, ML Rockhold, C Ruprecht, G Tartakovsky, MD White, SK White, and F Zhang. 2015. *eSTOMP Online User Guide*. Accessed on September 15, 2018 at http://stomp.pnnl.gov/estomp_guide/eSTOMP_guide.stm (last update March 2015).

Fayer MJ and JM Keller. 2007. *Recharge Data package for Hanford Single-Shell Tank Waste Management Areas*. PNNL-16688, Pacific Northwest National Laboratory, Richland, Washington.

Fayer MJ, DL Saunders, RS Herrington, and D Felmy. 2010. *Soil Water Balance and Recharge Monitoring for the Hanford Site – FY 2010 Status Report*. PNNL-19945, Pacific Northwest National Laboratory, Richland, Washington.

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

Fukui M, Y Fujikawa, and N Satta. 1996. “Factors Affecting Interaction of Radioiodide and Iodate Species with Soil.” *Journal of Environmental Radioactivity* 31(2):199-216.

Hammond TB and D Lupton. 2015. *Development of the Hanford South Geologic Framework Model, Hanford Site, Washington*. ECF-HANFORD-13-0029, Rev. 2, CH2M Hill Plateau Remediation Company, Richland, Washington.

Kaplan DI. 2003. “Influence of Surface Charge of an Fe-Oxide and an Organic Matter Dominated Soil on Iodide and Pertechnetate Sorption.” *Radiochimica Acta* 91(3):173-178.

Kaplan DI, ME Denham, S Zhang, C Yeager, C Xu, KA Schwehr, H-P Li, YF Ho, D Wellman, and PH Santschi. 2014. “Radioiodine biogeochemistry and prevalence in groundwater.” *Crit. Rev. Environ. Sci. Technol*. 44(20:2287-2335. doi: 10.1080/10643389.2013.828273.

Kaplan DI, RJ Serne, KE Parker, and IV Kutnyakov. 2000. “Iodide sorption to subsurface sediments and illitic minerals.” *Environ. Sci. Technol*. 34(3): 399-405, doi:10.1021/es990220g.

Kaplan DI, C Yeager, ME Denham, S Zhang, C Xu, KA Schwehr, H-P Li, R Brinkmeyer, and PH Santschi. 2012. *Biogeochemical Considerations Related to the Remediation of ^{129}I Plumes*. SRNL-STI-2012-00425, Rev. 0 (RPT-DVZ-AFRI-002), Savannah River National Laboratory, Aiken, South Carolina.

Keppler F, R Eiden, V Niedan, J Pracht, and HF Schöler. 2000. “Halocarbons produced by natural oxidation processes during degradation of organic matter.” *Nature* 403(6767):298-301.

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

Kodama S, Y Takahashi, K Okumura, and T Uruga. 2006. “Speciation of iodine in solid environmental samples by iodine K-edge XANES: application to soils and ferromanganese oxides.” *Sci. Total Environ*. 363(1-3):275-284.

Last GV, ML Rockhold, CJ Murray, and KJ Cantrell. 2009. *Selection and Traceability of Parameters to Support Hanford-Specific RESRAD Analyses – Fiscal Year 2008 Status Report.* PNNL-18564, Pacific Northwest National Laboratory, Richland, Washington.

Last GV, EJ Freedman, KJ Cantrell, MJ Fayer, GW Gee, WE Nichols, BN Bjornstad, DG Horton. 2006. *Vadose Zone Hydrogeology Data Package for the 2004 Composite Analysis*. PNNL-14702, Rev. 1, Pacific Northwest National Laboratory, Richland, Washington.

Lee BD, JT Ellis, A Dodwell, EER. Eisenhauer, DL Saunders, and MH Lee. 2018. “Iodate and Nitrate Transformation by Agrobacterium/Rhizobium Related Strain Dvz35 Isolated from Contaminated Hanford Groundwater.” Journal of Hazardous Materials 350:19-26. doi:https://doi.org/10.1016/j.jhazmat.2018.02.006.

Lerouge C, F Claret, MA Denecke, G Wille, G Falkenberg, C Romboz, C Bény, E Giffaut, T Schäfer, and EC Gaucher. 2010. “Comparative EPMA and u-XRF methods for mapping micro-scale distribution of iodine in biocarbonates of the Callovian-Oxfordian clayey formation at Bure, Eastern part of the Paris Basin.” In *12th International Conference on the Chemistry and Migration Behavior of Actinides and Fission Products in the Geosphere* (Migration ’09), Sept. 2009, Kennewick, Washington. RSC 35(6-8), pp. 271-277, doi:10.1016/j.pce.2010.04.003.

Lu Z, HC Jenkyns, and EM Rickaby. 2010. “Iodine to calcium ratios in marine carbonate as a paleo-redox proxy during oceanic anoxic events.” *Geology* 38:1107-1110.

Luther GW III. 2011. “Thermodynamic redox calculations for one and two electron transfer steps: implications for halide oxidation and halogen environmental cycling.” In Tratnyek P, T Grundl, and SB Haderlein. (eds.) Aquatic redox chemistry, vol. 1071. Washington, D.C: American Chemical Society, pp. 15-35.

Maillant S, MI Sheppard, G Echevarria, S Denys, G Villemin, P Tekely, E Leclerc-Cessac, and JL Morel. 2007. “Aged Anthropogenic Iodine in a Boreal Peat Bog.” *Applied Geochemistry* 22(5):873-887.

McDonald JP. 2018. *Capture –Zone and Particle-Tracking Analysis for the WMA S-SX Pump and Treat System Using a Sub Model from the 2017 Updated Central Plateau Model*. ECF-200W-17-0045, Rev. 0. CH2M Plateau Remediation Company, Richland, Washington.

Neal C and VW Truesdale. 1976. “Sorption of Iodate and Iodide by Riverine Sediments – Its Implications to Dilution Gauging and Hydrochemistry of Iodine.” *Journal of Hydrology* 31(3-4):281-291.

Otosaka S, KA Schwehr, DI Kaplan, KA Roberts, S Zhang, C Xu, H Li, Y Ho, R Brinkmeyer, CM Yeager, PM Santschi. 2011. "Factors controlling mobility of ^{127}I and ^{129}I species in an acidic groundwater plume at the Savannah River Site." *Sci. Total Environ.* 409(10):3857-3865.

Podder J, J Line, W Sun, Y Pan, SM Botis, J Tse, N Chen, Y Hu, D Li, and J Seaman. 2015. "Uptake and speciation of iodine in calcium carbonate." In Proceedings of the 35th Annual Canadian Nuclear Society (CNS) Conference, Saint John, NB, Canada, May 31- June 3 2015.

Rockhold ML, MJ Fayer, and PR Heller. 1993. *Physical and Hydraulic Properties of Sediments and Engineered Materials Associated with Grouted Double-Shell Tanks Waste Disposal at Hanford*. PNL-8813, Pacific Northwest Laboratory, Richland, Washington.

Rockhold ML, DL Saunders, CE Strickland, SR Waichler, RE Clayton. 2009. *Soil Water Balance and Recharge Monitoring at the Hanford Site – FY09 Status Report.* PNNL-18807, Pacific Northwest National Laboratory, Richland, Washington.

Rockhold ML, FA Spane, TW Wietsma, DR Newcomer, RE Clayton, I Demirkanli, DL Saunders, MJ Truex, MM Valenta-Snyder, and CJ Thompson. 2018. *Physical and Hydraulic Properties of Sediments from the 200-DV-1 Operable Unit.* PNNL-27846, RPT-DVZ-CHPRC 0005, Rev 0, Pacific Northwest National Laboratory, Richland, Washington.

Rockhold ML, CMR Yonkofski, VL Freedman, and SR Waichler. 2017. *Technical Basis for Remediation Endpoints: Status Report on the Development of the Iodine Technical Impracticability Waiver Request.* PNNL-26925, Pacific Northwest National Laboratory, Richland, Washington.

Rockhold ML, ZF Zhang, PD Meyer, and JN Thomle. 2015. *Physical, Hydraulic, and Transport Properties of Sediments and Engineered Materials Associated with Hanford Immobilized Low-Activity Waste*. PNNL-23711, RPT-IGTP-004, Rev. 0, Pacific Northwest National Laboratory, Richland, Washington.

Sakurai T, A Takahashi, N Ishikawa, and Y Komaki. 1989. "The Behavior of Iodine in a Simulated Spent-Fuel Solution." *Nuclear Technology* 85:206-212.

Santschi PH, C Xu, S Zhang, KA Schwehr, R Grandbois, DI Kaplan, and CM Yeager. 2017. "Iodine and plutonium association with natural organic matter: A review of recent advances." *Applied Geochemistry* 85:121-127.

Santschi PH, C Xu, S Zhang, Y –F Ho, H P Li, KA Schwehr, and DI Kaplan. 2012. *Laboratory Report on Iodine 129I and 127I) Speciation, Transformation, and Mobility in Hanford Groundwater, Suspended Particle, and Sediments*. SRNL-STI-2012-00592, Rev. 0., Savannah River National Laboratory, Aiken, South Carolina.

Sheppard MI and JL Hawkins. 1995. "Iodine and microbial interactions in an organic soil." *Radioactivity* 29:91-109.

Sheppard MI and DH Thibault. 1991. "A 4-Year Mobility Study of Selected Trace-Elements and Heavy-Metals." *Journal of Environmental Quality* 20(1):101-114.

Shetaya WH, SD Young, MJ Watts, EL Ander, and EH Bailey. 2012. “Iodine dynamics in soils.” *Geochimica et Cosmochimica Acta* 77:457-473.

Spane FA and DR Newcomer. 2010a. *Slug Test Characterization Results for Multi-Test/Depth Intervals Conducted During the Drilling of CERCLA Operable Unit OU UP-1 Wells 299-W19-48, 699-30-66, and 699-36-70B*. PNNL-19482, Pacific Northwest National Laboratory, Richland, Washington.

Spane FA and DR Newcomer. 2010b. *Slug Test Characterization Results for Multi-Test/Depth Intervals Conducted During the Drilling of CERCLA Operable Unit OU ZP-1 Wells 299-W11-43, 299-W15-50, and 299-W18-16*. PNNL-19491, Pacific Northwest National Laboratory, Richland, Washington.

Spane FA, Jr., PD Thorne, and DR Newcomer. 2001a. *Results of Detailed Hydrologic Characterization Tests – Fiscal Year 1999*. PNNL-13378, Pacific Northwest National Laboratory, Richland, Washington.

Spane FA, Jr., PD Thorne, and DR Newcomer. 2001b. *Results of Detailed Hydrologic Characterization Tests – Fiscal Year 2000*. PNNL-13514, Pacific Northwest National Laboratory, Richland, Washington.

Spane FA, Jr., PD Thorne, and DR Newcomer. 2002. Results of Detailed Hydrologic Characterization Tests – Fiscal Year 2001. PNNL-14113, Pacific Northwest National Laboratory, Richland, Washington.

Spane FA, Jr., PD Thorne, and DR Newcomer. 2003. Results of Detailed Hydrologic Characterization Tests – Fiscal Year 2002. PNNL-14186, Pacific Northwest National Laboratory, Richland, Washington.

Springer SD. 2018. *Model Package Report: Central Plateau Vadose Zone Geoframework, Version 1.0*. CP-60925, Revision 0. CH2MHill Plateau Remediation Company, Richland Washington.

Strickland CE, CD Johnson, BD Lee, N Qafoku, JE Szecsody, MJ Truex, and VR Vermeul. 2017a. *Identification of Promising Remediation Technologies for Iodine in the UP-1 Operable Unit*. PNNL-26934, Pacific Northwest National Laboratory, Richland, Washington.

Strickland CE, AR Lawter, NP Qafoku, JE Szecsody, MJ Truex, and G Wang. 2017b. *Evaluation of Iodine Remediation Technologies in Subsurface Sediments: Interim Status Report.* PNNL-26957; RPT-DVZ-AFRI-051, Pacific Northwest National Laboratory, Richland, Washington.

Szecsody JE, BD Lee, AR Lawter, NP Qafoku, CT Resch, SR Baum, II Leavy, VL Freedman. 2017. *Effect of Co-Contaminants Uranium and Nitrate on Iodine Remediation.* PNNL-26955, RPT-DVZ-AFRI-048, Rev. 0.0, Pacific Northwest National Laboratory, Richland, Washington.

Szecsody JE, RC Moore, MJ Rigali, VR Vermeul, and J Luellen. 2016. *Use of a Ca-Citrate-Phosphate Solution to Form Hydroxyapatite for Uranium Stabilization of Rifle Sediments: Laboratory Proof of Principal Studies*. PNNL-25303, Pacific Northwest National Laboratory, Richland, Washington.

Szecsody JE, ML Rockhold, M Oostrom, RC Moore, CA Burns, MD Williams, L Zhong, JS Fruchter, JP McKinley, VR Vermeul, MA Covert, TW Wietsma, AT Breshears, and BJ Garcia. 2009. *Sequestration of Sr-90 Subsurface Contamination in the Hanford 100-N Area by Surface Infiltration of a Ca-Citrate-PO_4 Solution*. PNNL-18303, Pacific Northwest National Laboratory, Richland, Washington.

Szecsody JE, VR Vermeul, JS Fruchter, MD Williams, ML Rockhold, N Qafoku, and JL Phillips. 2010. *Hanford 100-N Area In Situ Apatite and Phosphate Emplacement by Groundwater and Jet Injection: Geochemical and Physical Core Analysis*. PNNL-19524, Pacific Northwest National Laboratory, Richland, Washington.

Thorne PD and DR Newcomer. 2002. P*rototype Database and User's Guide of Saturated Zone Hydraulic Properties for the Hanford Site*. PNNL-14058, Pacific Northwest National Laboratory, Richland, Washington.

Thorne PD, MP Bergeron, MD Williams, and VL Freedman. 2006. *Groundwater Data Package for Hanford Assessments*. PNNL-14753, Rev. 1, Pacific Northwest National Laboratory, Richland, Washington.

Truex MJ, GB Chronister, CE Strickland, CD Johnson, GD Tartakovsky, M Oostrom, RE Clayton, TC Johnson, VL Freedman, ML Rockhold, WJ Greenwood, JE Peterson, SS Hubbard, and Al Ward. 2018. *Deep Vadoze Zone Treatability Test of Soil Dessication for the Hanford Central Plateau*. PNNL-26902, Pacific Northwest National Laboratory, Richland, Washington.

Truex MJ, BD Lee, CD Johnson, NP Qafoku, JE Szecsody, JE Kyle, M Tfaily, MMV Snyder, KJ Cantrell, DL Saunders, AR Lawter, M Oostrom, G Tartakovsky, II Leavy, EM Mcelroy, D Appriou, R Sahajpal, MM Carroll, RK Chu, EA Cordova, GV Last, MH Lee, DI Kaplan, W Garcia, S Kerisit, O Qafoku, M Bowden, F Smith, JG Toyoda, and AE Plymale. 2017. *Conceptual Model of Iodine Behavior in the Subsurface at the Hanford Site*. PNNL-24709, Rev. 2, Pacific Northwest National Laboratory, Richland, Washington.

Truex MJ, VR Vermeul, D Adamson, M Oostrom, L Zhang, RD Mackley, BG Fritz, JA Horner, TC Johnson, JN Thomle, DR Newcomer, CD Johnson, M Rysz, TW Wietsma, and CJ Newell. 2015. "Field Test of Enhanced Remedial Amendment Delivery Using a Shear-Thinning Fluid." *Ground Water Monitoring and Remediation* 35(3):34-45.

USDOE. 2012a. *Remedial Investigation/Feasibility Study for the 200-UP-1 Groundwater Operable Unit.* DOE/RL-2009-122, U.S. Department of Energy, Richland Operations Office, Richland, Washington.

USDOE. 2012b. *Hanford Site Groundwater Monitoring for 2011.* DOE/RL-2011-118, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington.

USDOE. 2012c. *Proposed Plan for Remediation of the 200-UP-1 Groundwater Operable Unit*. DOE/RL-2010-05, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington.

USDOE. 2013a. *200-UP-1 Groundwater Operable Unit Remedial Design/Remedial Action Work Plan.* DOE/RL-2013-07, Rev. 0, CH2M Hill Plateau Remediation Company, U.S. Department of Energy, Richland, Washington.

USDOE. 2013b. *Hanford Site Cleanup Completion Framework.* DOE/RL-2009-10, Rev. 1, U.S. Department of Energy, Richland Operations Office, Richland, Washington.

USDOE. 2017a. *UP-1 Evaluation Plan for Iodine.* DOE/RL-2015-69, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington.

USDOE. 2017b. *Hanford Site Groundwater Monitoring Report for 2016.* DOE/RL-2016-67, Rev. 0, CH2M Hill Plateau Remediation Company, U.S. Department of Energy, Richland, Washington.

USDOE. 2017c. *Calendar Year 2016 Annual Summary Report for the 200-ZP-1 and 200-UP-1 Operable Unit Pump-and-Treat Operations.* DOE/RL-2016-69, Rev. 0, CH2M Hill Plateau Remediation Company, U.S. Department of Energy, Richland, Washington.

USDOE. 2018a. *Hanford Site Groundwater Monitoring Report for 2017.* DOE/RL-2017-66, Rev. 0, CH2M Hill Plateau Remediation Company, U.S. Department of Energy, Richland, Washington.

USDOE. 2018b. *Calendar Year 2017 Annual Summary Report for the 200-ZP-1 and 200-UP-1 Operable Unit Pump-and-Treat Operations.* DOE/RL-2017-68, Draft Rev. 0, CH2M Hill Plateau Remediation Company, U.S. Department of Energy, Richland, Washington.

USEPA. 1988. *Guidelines for Ground-Water Classification Under the EPA Ground-Water Protection Strategy*. U. S. Environmental Protection Agency, Office of Ground-water Protection, Washington DC.

USEPA, Washington State Department of Ecology, and USDOE. 2012. *Record of Decision for Interim Remedial Action Hanford 200 Area Superfijnd Site 200-up-1 Operable Unit.* U.S. Environmental Protection Agency, Washington State Department of Ecology, and U.S. Department of Energy, Olympia, Washington.

Vermeul VR, BN Bjornstad, BG Fritz, JS Fruchter, RD Mackley, DR Newcomer, DP Mendoza, ML Rockhold, DM Wellman, and MD Williams. 2009. *300 Area Uranium Stabilization through Polyphosphate Injection: Final Report*. PNNL-18529, Pacific Northwest National Laboratory, Richland, Washington.

Vermeul VR, JE Szecsody, BG Fritz, MD Williams, RC Moore, and JS Fruchter. 2014. "An Injectable Apatite Permeable Reactive Barrier for In Situ ^{90}Sr Immobilization." *Ground Water Monitoring and Remediation* 34(2):28-41.

White MD and M Oostrom. 2006. *STOMP – Subsurface Transport Over Multiple Phases, Version 4.0, User's Guide*. PNNL-15782, Pacific Northwest National Laboratory, Richland, Washington.

White MD, D Appriou, DH Bacon, Y Fang, V Freedman, ML Rockhold, C Ruprecht, G Tartakovsky, SK White, and F Zhang. 2015. *STOMP Online User Guide*. Accessed on September 15, 2018 at http://stomp.pnnl.gov/user_guide/STOMP_guide.stm (last update March 2015).

Whitehead DC. 1974. "The Sorption of Iodide by Soil Components." *Journal of the Science of Food and Agriculture* 25:73-79.

Whitehead D. 1984. "The Distribution and Transformations of Iodine in the Environment." *Environment International* 10(4):321-339.

Williams MD, PD Thorne, MP Bergeron, and DL Ward. 2006. *Transient Inverse Calibration of a Facies-Based Groundwater Flow and Transport Model using Contaminant Concentration and Hydraulic Head Data*. PNNL-16425 (Limited Distribution), Pacific Northwest National Laboratory, Richland, Washington

Xu C, D Kaplan, S Zhang, M Athon, Y Ho, H Li, C Yeager, K Schwehr, R Grandbois, D Wellman, and P Santschi. 2015. “Radioiodine sorption/desorption and speciation transformation by subsurface sediments from the Hanford Site.” *Journal of Environmental Radioactivity* 139:43-55.

Yoshida S, Y Muramatsu, and S Uchida. 1992. “Studies on the Sorption of I- (iodide) and IO3- (iodate) onto Andosols.” *Water Air and Soil Pollution* 63(3-4):321-329.

Yu Z, JA Warner, RA Dahlgren, and WH Casey. 1996. “Reactivity of Iodine in Volcanic Soils and Noncrystalline Soil Constituents.” *Geochimica et Cosmochimica Acta* 60:4945-4956.

Zaher U, and S Agnew. 2018. *Hanford Soil Inventory Model (SIM-v2) Calculated Radionuclide Inventory of Direct Liquid Discharges to Soil in the Hanford Site’s 200 Areas*. ECF-HANFORD-17-0079, Rev. 0. CH2M Plateau Remdiation Company, Richland, Washington.

Zhang S, C Xu, D Creeley, Y -F Ho, H -P Li, R Grandbois, K A Schwehr, DI Kaplan, CM Yeager, D Wellman, and PH Santschi. 2013. “Iodine-129 and Iodine-127 Speciation in Groundwater at the Hanford Site, U.S.: Iodate Incorporation into Calcite.” *Environmental Science & Technology* 47(17):9635-9642. https://doi.org/10.1021/es401816e

Zhang ZF, CE Strickland, JG Field, and DL Parker. 2011. *T-TY Tank Farm Interim Surface Barrier Demonstration – Vadose Zone Monitoring FY10 Report*. PNNL-20144, Pacific Northwest National Laboratory, Richland, Washington.

Zhang ZF, CE Strickland, and LO Link. 2017. “Design and performance evaluation of a 1000-year evapotranspiration-capillary surface barrier.” *Journal of Environmental Management* 187:31-42. doi:10.1016/j.jenvman.2016.11.007.

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Appendix A

Summary Checklist for Groundwater Technical Impracticability Evaluation

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Summary Checklist for Groundwater Technical Impracticability Evaluation

The U.S. EPA Checklist for evaluating a Superfund site for consideration of a groundwater technical impracticability waiver is provided in this Appendix for convenience. For each applicable section of the EPA Checklist, the relevant sections of this document that address the checklist issue are identified.

RECOMMENDED SUMMARY CHECKLIST FOR A SUPERFUND GROUNDWATER TECHNICAL IMPRACTICABILITY EVALUATION

Regions should consider the recommended checklist below when evaluating whether they have sufficient information to support a TI evaluation for the administrative record. [EPA 1993, 4.4]:

A. Specific ARARs or Media Cleanup Standards [EPA 1993, 4.4.1]

- ☐ Identifies the specific ARARs for which the TI waiver is sought (see Section 1.0)
- ☐ Identifies the technical feasibility of restoring some of the groundwater contaminants (see Section 1.1)
- ☐ Identifies potential benefits of attaining ARARs for some of the specific COCs (see Section 1.1)

B. Spatial Extent of TI Decisions [EPA 1993, 4.4.2]

- ☐ Specifies the spatial distribution (vertical and horizontal) of subsurface contaminants in the unsaturated and saturated zones where the TI is sought (see Section 2.2 and 2.3)
- ☐ Identifies the spatial extent of the TI zone as small as possible (see Section 2.2 and 2.3)
- ☐ Identifies the vertical limit of the TI zone in either absolute (e.g., mean sea level) or relative (e.g., aquifer system) terms (see Section 2.3)

C. Development and Purpose of the Site Conceptual Model [EPA 1993, 4.4.3, Figure 4]

1. Background Information [EPA 1993, 4.4.3]

- ☐ Groundwater classification (see Section 3.1.6)
- ☐ Location of potential environmental receptors (see Section 3.1.6)
- ☐ Nearby wellhead protection areas or sole-source aquifers (see Section 3.1.6)
- ☐ Location of water supply wells (see Section 3.1.6)

2. Geologic and Hydrologic Information [EPA 1993, 4.4.3]

- ☐ Detailed description of regional and site geology (see Section 3.1)
- ☐ Physical properties of subsurface materials (see Section 3.1.1)
- ☐ Stratigraphy, including thickness, lateral extent, continuity of units, and presence of depositional features, such as channel deposits, that may provide preferential pathways for, or barriers to, contaminant transport (see Section 3.1)
- ☐ Hydraulic gradients (horizontal and vertical) (see Section 3.1.3)
- ☐ Geologic structures or other subsurface features that may form preferential pathways for NAPL migration or zones of accumulation (see Section 3.1.3)
- ☐ Hydraulic properties of subsurface materials (see Section 3.1.1)
- ☐ Temporal variability in hydrologic conditions (see Section 3.1.4)
- ☐ Groundwater recharge and discharge information (see Section 3.1.5)
- ☐ Groundwater/surface water interactions (see Section 3.1.6)
- ☐ Characterization of secondary porosity features (e.g., fractures, karst features) to the extent practicable (Not applicable)
- ☐ Depth to groundwater (see Section 3.1.2)

3. Contaminant Source and Release Information [EPA 1993, 4.4.3]

- ☐ Location, nature, and history of previous contaminant releases or sources (see Sections 2.1 and 3.3)
- ☐ Locations and characterizations of continuing releases or sources (see Section 2.1)
- ☐ Locations of subsurface sources (e.g., NAPLs) (see Sections 2.1 and 3.3)

4. Contaminant Distribution, Transport, and Fate Parameters [EPA 1993, 4.4.3]

- ☐ Temporal trends in contaminant concentrations in each phase (see Sections 2.4 and 4.1.2)
- ☐ Estimates of subsurface contaminant mass (see Section 3.3)
- ☐ Phase distribution of each contaminant in the unsaturated and saturated zones (e.g., gaseous, aqueous, sorbed, free-phase NAPL, or residual NAPL) (see Section 3.4.1)
- ☐ Spatial distribution of subsurface contaminants in each phase in the unsaturated and saturated zones (see Section 3.4.1)
- ☐ Sorption information, including contaminant retardation factors (see Section 3.2.2)
- ☐ Contaminant transformation processes and rate estimates (see Section 3.2.3)
- ☐ Contaminant migration rates (see Section 3.4.1)
- ☐ Assessment of facilitated transport mechanisms (e.g., colloidal transport) (see Section 3.2)
- ☐ Properties of NAPLs that affect transport (e.g., composition, effective solubility, density, viscosity) (Not applicable)
- ☐ Geochemical characteristics of subsurface media that affect contaminant transport and fate (see Section 3.2)
- ☐ Other characteristics that affect distribution, transport, and fate (e.g., vapor transport properties) (see Section 3.2)

D. Evaluation of Restoration Potential [EPA 1993, 4.4.4]

1. Source Control Measures [EPA 1993. 4.4.4.1]

- ☐ Demonstrates that contamination sources have been located and will employ removal, migration control or containment, or treatment, to the extent practicable (see Sections 2.1, 3.3 and 4.1)

2. Remedial Action Performance Analysis [EPA 1993. 4.4.4.2]

☐ Demonstrates that the groundwater monitoring program within and outside the aqueous contaminant plume is of sufficient quality and detail to fully evaluate remedial action performance (e.g., to analyze plume migration or containment and identify concentration trends within the remediation zone) (see Section 4.1)

☐ Demonstrates that the existing remedy has been effectively operated and adequately maintained (see Section 4.1.1)

☐ Describes and evaluates the effectiveness of any remedy modifications (whether variations in operation, physical changes, or augmentations to the system) designed to enhance its performance (see Section 4.1.1)

☐ Evaluates trends in subsurface contaminant concentrations. Consider such factors as whether the aqueous plume has been contained, whether the areal extent of the plume is being reduced, and the rates of contaminant concentration decline and contaminant mass removal. Further considerations include whether aqueous-phase concentrations rebound when the system is discontinued, whether dilution or other natural attenuation processes are responsible for observed trends, and whether contaminated soils on site are contaminating groundwater (see Section 4.1.2)

☐ Analyzes performance of any ongoing or completed remedial actions, including:
  - ☐ Operational information (see Section 4.1.1)
  - ☐ Enhancements to original remedy (including optimization efforts) (Not applicable)

3. Restoration Timeframe Analysis [EPA 1993. 4.4.4.3]

☐ Estimates timeframe for groundwater restoration (see Section 4.2)

☐ Documents predictive analyses of the timeframes to attain required cleanup levels as part of the overall demonstration using available technologies and approaches laying out the associated modeling inputs and uncertainties (see Section 3.4)

4. Other Applicable technologies [EPA 1993. 4.4.4.4]

☐ Conducted and documented a literature search to determine what cleanup approaches are possible based on the contaminants and geology at the site (see Section 4.3)

☐ Lists technologies and approaches that were evaluated (Ongoing research—not summarized here)

☐ Analyzed chemical and hydrogeologic data to support any technology capable of achieving cleanup levels (Ongoing—not summarized here)

☐ Evaluated treatability study data (bench, pilot or full-scale) (Ongoing research—not summarized here)
  - ☐ Provide study objectives (Ongoing research—not summarized here)
  - ☐ Provide study results (Ongoing research—not summarized here)

☐ Demonstrates that no other remedial technologies (conventional or innovative) could reliably, logically, or feasibly attain the cleanup levels at the site within a reasonable timeframe (Ongoing research—not summarized here)

5. **Cost Estimates [EPA 1993, 4.4.5]**
   - ☐ Provides cost estimates for the potentially viable remedial alternatives included in the Evaluation of Restoration Potential, including construction, operation and maintenance costs (Not yet available)
   - ☐ Provides cost estimates of selected remedy(s) for continued operation of existing remedy including operation and maintenance costs (if a remedy has been implemented) (Not yet available)
   - ☐ Provides cost estimates for the proposed Alternative Remedial Strategy (ARS) (Not yet available)

6. **Alternate Remedial Strategies (ARS) [EPA 1993, 5.0]**
   - ☐ Selects and summarizes an ARS that is technically practicable, protective of human health and the environment, and satisfies Superfund statutory and regulatory requirements [EPA 1993, 5.1] (Not yet available)
   - ☐ Demonstrates that the ARS addresses exposure prevention [EPA 1993, 5.1.1] (Not yet available)
   - ☐ Demonstrates that the ARS addresses source control and remediation [EPA 1993, 5.1.2] (Not yet available)
   - ☐ Demonstrates that the ARS addresses aqueous plume remediation [EPA 1993, 5.1.3] (Not yet available)

7. **Additional Remedy Selection Considerations [EPA 1993, 5.2.3]**
   - ☐ Aggressive action for shorter timeframes than other options (Not available)
   - ☐ Shorter timeframe to reduce potential human exposures (Not available)
   - ☐ Shorter timeframe to reduce impacts to environmental receptors (Not available)

Other

☐ Discusses additional information or analyses considered for the TI evaluation (summarized below, with page numbers if applicable).

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