ECF-200PO1-18-0010
Revision 0

Groundwater Flow And Migration Calculations to Support the Assessment of the NRDWL Groundwater Monitoring Network

Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management

Contractor for the U.S. Department of Energy
under Contract DE-AC06-08RL14788

CH2MHILL
Plateau Remediation Company

P.O. Box 1600
Richland, Washington 99352

Approved for Public Release;
Further Dissemination Unlimited

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ENVIRONMENTAL CALCULATION COVER PAGE (Continued)

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Contents

1 Purpose 1-1

2 Background 2-1

2.1 NRDWL 2-1
2.2 Use of Groundwater Models 2-3
2.3 Groundwater Elevation Analysis for NRDWL 2-4

3 Calculation Methods 3-1

3.1 Groundwater Elevation Mapping 3-1
3.1.1 Mapped Events 3-1
3.1.2 Mapping Method 3-1
3.1.3 Conceptual Model and Specific Trend Terms 3-2
3.1.4 Semi-Variogram Parameters 3-4
3.2 Particle Tracking 3-4
3.2.1 Advection-Only Particle Tracking 3-4
3.2.2 Advective-Dispersive Particle Tracking 3-4

4 Assumptions and Inputs 4-1

4.1 Assumptions 4-1
4.1.1 Groundwater Elevation Mapping 4-1
4.1.2 Particle Tracking 4-1
4.2 Input Data 4-1
4.2.1 Water-Level Mapping Input 4-2
4.2.2 Particle Starting Locations 4-2

5 Software Applications, Descriptions, Installation and Checkout, and Statements of Validity 5-1

5.1 Approved Software 5-1
5.2 Software Description 5-1
5.3 Support Software 5-1
5.4 Software Installation and Checkout 5-2
5.4.1 Statement of Valid Software Application 5-2

6 Calculation Steps and Output 6-1

6.1 Water-Level Mapping 6-1
6.2 Particle Tracking 6-1
6.3 Particle Counts 6-2

7 Results 7-1

7.1 Particle Tracking 7-9
7.2 Particle Counts 7-9

7.2.1 Relative Particle Counts at Interim Status Groundwater Monitoring Wells 7-9
7.2.2 Relative Arrival Times at Interim Status Groundwater Monitoring Wells 7-18
7.2.3 Particle Count Maps 7-23
7.3 Vertical Migration Potential 7-28
7.3.1 Drawdown Due to Pumping 7-28
7.3.2 Accrual of Recharge at the Water Table 7-29
7.3.3 Example Calculations 7-30
8 References 8-1

Appendix

A Tables of Inputs to Groundwater Level Analysis ..... A-i

Figures

Figure 1-1. Location of NRDWL with Respect to the 200 East Area 1-2
Figure 2-1. Locations of Interim Status Groundwater Monitoring Wells at NRDWL 2-2
Figure 3-1. Line Drift Points Used to Represent the Columbia River 3-3
Figure 3-2. Uniform Calculational Grid at NRDWL 3-6
Figure 4-1. Particle Release Locations at NRDWL 4-3
Figure 7-1. Water Elevation Map for NRDWL, 2013 7-2
Figure 7-2. Water Elevation Map for NRDWL, 2014 7-3
Figure 7-3. Water Elevation Map for NRDWL, 2015 7-4
Figure 7-4. Water Elevation Map for NRDWL, 2016 7-5
Figure 7-5. Local-Scale Particle Paths, Advection and Dispersion – NRDWL, 2013 7-10
Figure 7-6. Local-Scale Particle Paths, Advection and Dispersion – NRDWL, 2014 7-11
Figure 7-7. Local-Scale Particle Paths, Advection and Dispersion – NRDWL, 2015 7-12
Figure 7-8. Local-Scale Particle Paths, Advection and Dispersion – NRDWL, 2016 7-13
Figure 7-9. Particle Breakthrough Curves at Monitoring Well 699-25-34B 7-19
Figure 7-10. Particle Breakthrough Curves at Monitoring Well 699-25-34D 7-20
Figure 7-11. Particle Breakthrough Curves at Monitoring Well 699-25-34F 7-21
Figure 7-12. Particle Breakthrough Curves at Monitoring Well 699-26-33A 7-22
Figure 7-13. Particle Breakthrough Curves at Monitoring Well 699-26-34B 7-23
Figure 7-14. Particle Count Map – NRDWL, 2013 7-24
Figure 7-15. Particle Count Map – NRDWL, 2014 7-25
Figure 7-16. Particle Count Map – NRDWL, 2015 7-26
Figure 7-17. Particle Count Map – NRDWL, 2016 7-27
Figure 7-18. Comparison of Vertical Migration Evaluation Using the API Calculator and the CPGWM 7-33

Tables

Table 7-1. Mapped Water-Level Residuals....7-6
Table 7-2. Particle Density (Count) – Monitoring Well 699-25-34D....7-14
Table 7-3. Particle Density (Count) – Monitoring Well 699-26-34B....7-15
Table 7-4. Particle Density (Count) – Monitoring Well 699-26-33A....7-16
Table 7-5. Particle Density (Count) – Monitoring Well 699-25-34F....7-17
Table 7-6. Particle Density (Count) – Monitoring Well 699-25-34B....7-18
Table 7-7. Summary of Well Screen Interval Evaluation for Downgradient Wells....7-35

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Terms

API	American Petroleum Institute
ASCII	American Standard Code for Information Interchange
CERCLA	*Comprehensive Environmental Response, Compensation, and Liability Act*
CHPRC	CH2M HILL Plateau Remediation Company
CPGWM	Central Plateau Groundwater Model
DWMU	dangerous waste management unit
ECF	environmental calculation file
EPA	U.S. Environmental Protection Agency
GLS	generalized least squares
HISI	Hanford Information Systems Inventory
MEUK	multi-event universal kriging
NRDWL	Nonradioactive Dangerous Waste Landfill
P&T	pump and treat
P2R	Plateau to River
SWL	Solid Waste Landfill
TRIM	Tikhonov Regularized Inverse Methos
WMA	waste management area

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1 Purpose

This environmental calculation file (ECF) describes calculations made to evaluate the groundwater monitoring network associated with the dangerous waste management unit (DWMU) Nonradioactive Dangerous Waste Landfill (NRDWL). The interim status monitoring network that is evaluated herein is described in DOE/RL-2017-19, *Groundwater Quality Assessment Plan for the Nonradioactive Dangerous Waste Landfill, Hanford Site*. The network is designed to detect significant increases in groundwater contamination that would result from a release from the regulated unit. The calculations support evaluation of the groundwater monitoring network's suitability for detecting releases from NRDWL and help determine if additional monitoring locations are required. NRDWL is located approximately 5.6 km (3.5 mi) southeast of the 200 East Area on the Hanford Site Central Plateau (Figure 1-1).

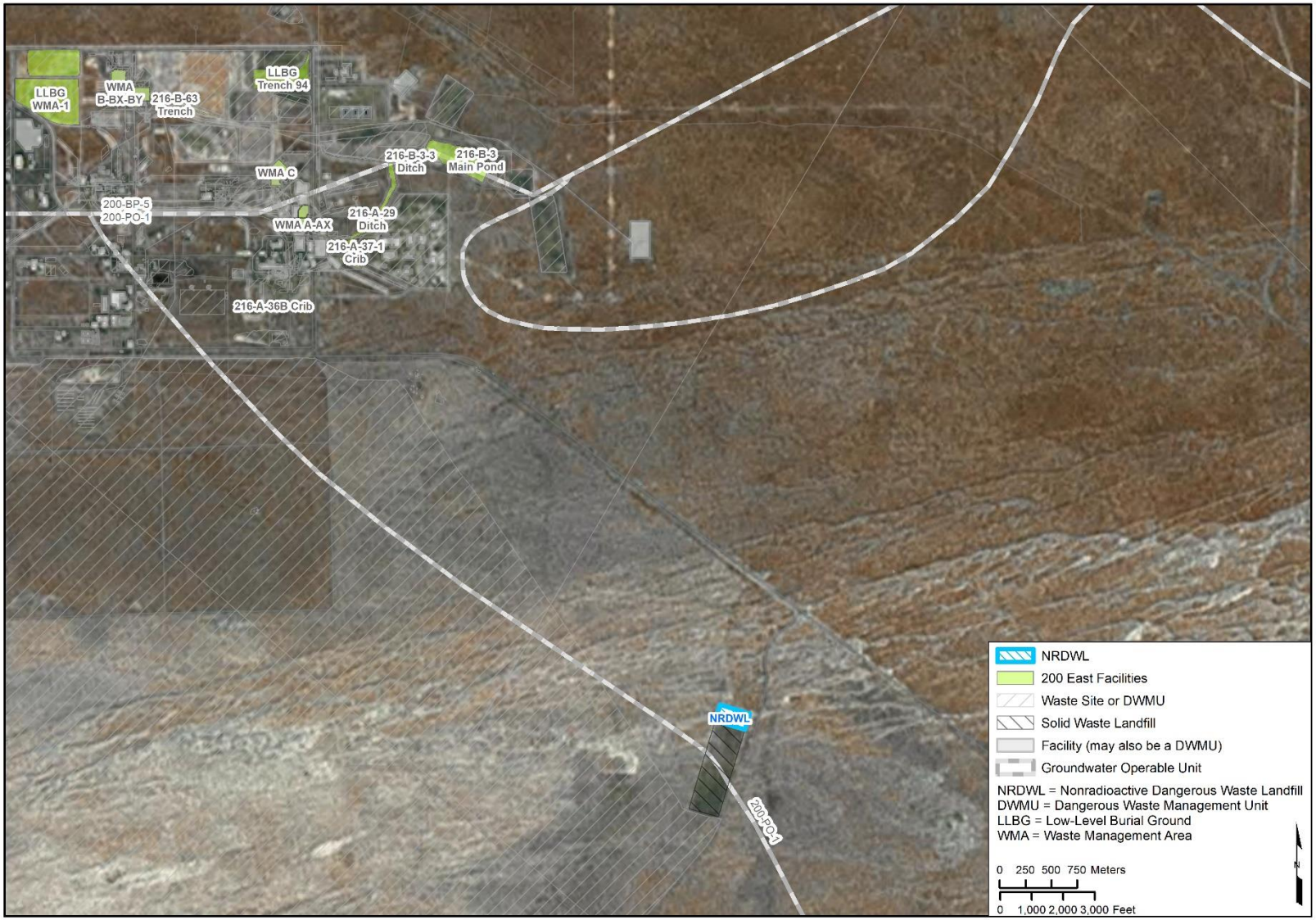

Figure 1-1. Location of NRDWL with Respect to the 200 East Area

2 Background

The history of NRDWL operations and monitoring and information about the use and applicability of different groundwater flow simulation methods in the area are discussed in the following sections.

2.1 NRDWL

NRDWL, located in the 600 Area approximately 5.6 km (3.5 mi) southeast of the 200 East Area, is a 4.0 ha (10 ac) landfill that consists of 19 trenches, 6 of which contain dangerous waste. NRDWL is immediately adjacent to the Solid Waste Landfill (SWL), and the two landfills share a perimeter fence. The trenches in NRDWL are approximately 122 m (400 ft) long, 4.9 m (16 ft) wide at their base, and 4.6 m (15 ft) deep.

NRDWL accepted dangerous waste between January 1975 and May 1985, including wastes classified as oxidizers, corrosives, and chemical wastes (Section 2.1 of DOE/RL-2017-19). The chemical wastes included nonradioactive laboratory chemicals; bulk organic waste such as solvents, paints, waste oils, and paint thinners; and metal cleaners. Most chemical waste disposed at NRDWL was contained in 208 L (55 gal) drums, and no containers holding free liquids are known to have been disposed at NRDWL. In addition to the chemical waste, nine trenches were used for asbestos disposal and one trench was used for sanitary solid waste (Section 2.3 in DOE/RL-2017-19). The last receipt of asbestos waste occurred in May 1988 (Section 2.1 of DOE/RL-2017-19).

An interim status groundwater monitoring network was established for NRDWL in 1986. Until the facility is incorporated as a final status unit into the future Revision 9 of WA7890008967, *Hanford Facility Dangerous Waste Permit*, groundwater monitoring is ongoing at the facility in accordance with interim status regulations. The monitoring well network has been revised on several occasions since the initial installation of wells, with wells added and replaced in the network. Decreasing groundwater elevations in the area (SGW-60338, *Historical Changes in Water Table Elevation and Groundwater Flow Direction at Hanford: 1944 to 2014*) have led to some monitoring wells going dry (Section 2.5 in DOE/RL-2017-19), necessitating replacement. The monitoring well network established that groundwater in the vicinity of NRDWL generally flows east-southeast, but that the gradient is small (ECF-Hanford-17-0241, *Hydraulic Gradient and Velocity Calculations for RCRA Sites in 2017*).

NRDWL is monitored under a groundwater quality assessment monitoring program. In October 2016, elevated specific conductance was identified at downgradient well 699-25-34B. Verification sampling in December 2016 confirmed the exceedance. In 2017, NRDWL entered a groundwater quality assessment monitoring program under DOE/RL-2017-19.

The interim status groundwater monitoring network comprises three upgradient wells (699-26-38, 699-26-35A, and 699-26-34A), two deep wells (699-26-35C and 699-25-33A), two crossgradient wells (699-26-34B, and 699-25-34D), and three downgradient wells (699-26-33A, 699-25-34F, and 699-25-34B) (Table 3-2 in DOE/RL-2017-19). The eight wells not designated as deep are screened at the top of the unconfined aquifer in order to detect significant increases in groundwater contamination that would result from a release that reaches the water table from within the regulated unit. The interim status monitoring network for NRDWL is shown in Figure 2-1. This ECF presents calculations that evaluate the efficacy of the groundwater monitoring network for detecting hypothetical releases from NRDWL at existing and potential new monitoring well locations.

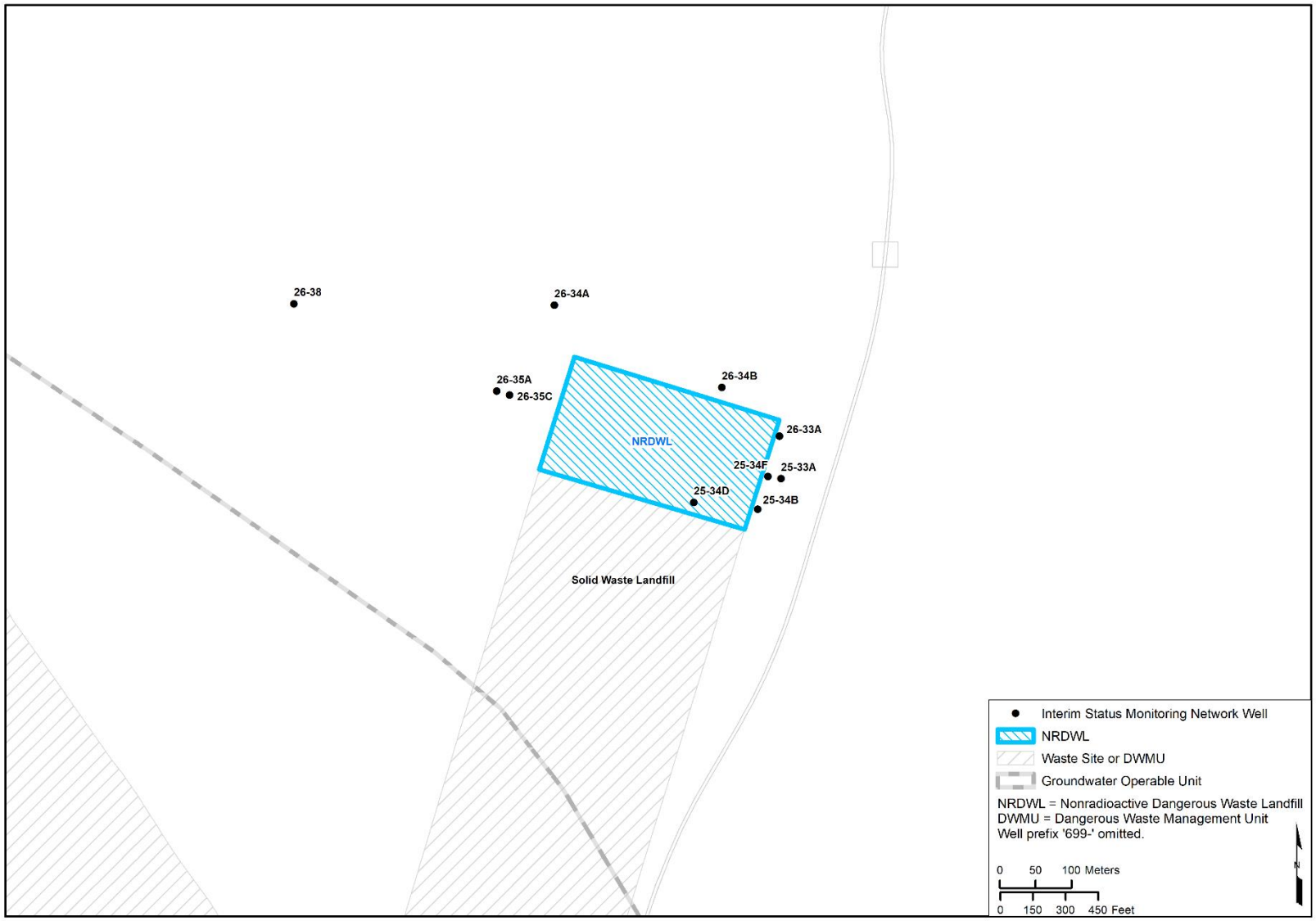

Figure 2-1. Locations of Interim Status Groundwater Monitoring Wells at NRDWL

2.2 Use of Groundwater Models

Two three-dimensional groundwater models previously were developed for fate-and-transport and remedy design purposes primarily associated with the *Comprehensive Environmental Response, Compensation, and Liability Act* (CERCLA). Together, these two models cover the entire Central Plateau: the Central Plateau Groundwater Model (CPGWM) (CP-47631, *Model Package Report: Central Plateau Groundwater Model Version 8.4.5*) and the Plateau to River (P2R) Model (CP-57037, *Model Package Report: Plateau to River Groundwater Transport Model Version 7.1*). In addition to these two models, a regularized inverse interpolation technique that is referred to as the Tikhonov Regularized Inverse Method (TRIM) was developed to obtain groundwater elevation maps to support engineering studies and evaluate DWMU monitoring networks within the 200 East Area (ECF-200E-18-0066, *Groundwater Flow and Migration Calculations to Assess Monitoring Networks in the 200 East Area Dangerous Waste Management Units*).

Although the CPGWM encompasses most of the Central Plateau, it was developed primarily to support decisions regarding the 200-ZP-1 and adjacent 200-UP-1 Groundwater Operable Unit remedies located in the 200 West Area. The CPGWM is the principal computational tool used to design and evaluate the performance of those groundwater remedies. Within the 200 West Area of the Central Plateau, the CPGWM specifically is being used to support engineering studies and reports because a predictive tool is needed to assess the impact of changing operations of the 200-ZP-1 groundwater pump and treat (P&T) system on directions and rates of groundwater flow and contaminant migration and on the efficacy of the interim status monitoring networks. In addition, the CPGWM was designed explicitly to simulate the impacts of the 200-ZP-1 P&T remedy, which will be the single greatest influence on directions and rates of groundwater flow and contaminant migration in the 200 West Area for the next 20 or more years. The CPGWM was not designed to make predictions in the region of NRDWL, which is located in the far southeast corner of the CPGWM domain.

The P2R Model, which encompasses the entire 200 East Area and extends to the Columbia River, was developed primarily to support assessments of fate and transport throughout that area and decisions made under CERCLA for the 200 East Area. The P2R model is not designed to make predictions at the scale of individual waste sites either within the 200 East Area or in the region of NRDWL. The P2R Model was developed at a large scale and using a coarse spatial discretization that are relevant to regional (i.e., far-field) rather than facility-specific (i.e., near-field) analyses. Facility-specific analyses that have previously been performed on the basis of the P2R Model were undertaken by developing local-scale facility-specific groundwater models extracted from the P2R Model using the method of telescopic mesh refinement. If the P2R Model were to be used to support analyses in the area of NRDWL, this would have to be similarly accomplished via the development of a local-scale facility specific model.

In the area near NRDWL, at the present time (2018) there is no wide-area P&T or other groundwater remedy that will affect the rates and directions of groundwater flow and contaminant migration, and none is anticipated for the foreseeable future. This eliminates the need for a predictive groundwater model that is capable of running predictive simulations representing the impacts to groundwater flow and contaminant migration from alternative potential operations of a large groundwater remedy such as the 200 West P&T.

Furthermore, the analysis of monitoring networks in the 200 East Area focuses on the uncertainty produced by the relatively low hydraulic gradients throughout the region.

While the existing large-scale groundwater models meet the objectives of their development and are suited to their purposes, on a facility-specific scale, in some parts of the 200 East Area, both the CPGWM and P2R Model do not always reflect understanding of subtle near-field groundwater conditions based on multiple lines of evidence, including the low-gradient network and independent evaluations of existing contaminant extents and migration. For this reason, within the 200 East Area, TRIM was used to develop groundwater elevation maps for the assessment of groundwater monitoring networks.

NRDWL, although located on the Central Plateau, is not part of the 200 Areas and is located beyond (downgradient of) the other Central Plateau facilities in an area of comparatively uniform (planar) groundwater flow and potential contaminant migration, that is relatively unaffected by the presence of hydrostratigraphic unit transitions and basalt or mud sub-cropping. The largely uniform gradient directions exhibited beneath NRDWL are well suited to analysis using regression-based techniques that incorporate linear trend components in the east-west and north-south directions. For these reasons and because NRDWL is in an area not anticipated to be subjected to active groundwater remediation for the foreseeable future, TRIM was not extended into this area, and the universal kriging technique embedded in multi-event universal kriging (MEUK) (Tonkin et al., 2016, “Multi-Event Universal Kriging [MEUK]”) was used that includes the necessary linear trend components.

2.3 Groundwater Elevation Analysis for NRDWL

Historically, groundwater elevations north of NRDWL near the 200 East Area varied greatly in response to discharges of site operations water to many large wastewater receiving features such as the 216-B-3 Pond. Most of those discharges had stopped by the mid-1990s, after which groundwater elevations in the 200 East Area and some surrounding areas, including NRDWL, have fallen steadily. In recent years, changes in groundwater elevations and in corresponding hydraulic gradients and flow directions have been less evident from year to year, suggesting that the groundwater elevations are asymptotically approaching a quasi-steady state condition.

Groundwater elevations in both the area near NRDWL and the 200 East Area have been evaluated recently from an area-wide perspective (e.g., ECF-Hanford-16-0013, *Hydraulic Gradients and Velocity Calculations for RCRA Sites in 2015*; SGW-60338; DOE/RL-2015-32, *Groundwater Monitoring Plan for the Nonradioactive Dangerous Waste Landfill*). None of those studies, however, produced piece-wise continuous (gridded) depictions of groundwater elevations throughout the area near NRDWL that could meet the objectives of this ECF in supporting assessment of the groundwater monitoring network associated with NRDWL. Because of this, water-level mapping was performed to produce the necessary gridded depictions of groundwater elevations throughout the area near NRDWL.

3 Calculation Methods

This chapter describes the calculation methods used to support this ECF. Simulations were conducted to evaluate the efficacy of the groundwater monitoring network for detecting significant increases in groundwater contamination that might occur from a hypothetical release at NRDWL. The wells were evaluated for their efficacy in detecting significant increases in groundwater contamination that might occur from a contaminant release that reaches the underlying water table.

The calculations include the following:

- Groundwater elevation mapping throughout the area near NRDWL for calendar years 2013, 2014, 2015, and 2016
- Particle tracking assuming advection only, to illustrate general patterns of expected groundwater flow near NRDWL
- Particle tracking assuming advection and dispersion, to illustrate general patterns of migration for a hypothetical release that reaches the underlying water table from NRDWL

3.1 Groundwater Elevation Mapping

Using the data and methods described below, groundwater elevation mapping was undertaken to produce piece-wise continuous (gridded) depictions of groundwater elevations throughout the area near NRDWL.

3.1.1 Mapped Events

Because the most comprehensive groundwater elevation datasets typically are obtained during spring (March), March is the focus period for analysis each year. Because different datasets are available for each year, however, there can be some differences in the interpretation of groundwater elevations and corresponding flow directions among years and datasets. Therefore, the four most recent comprehensive datasets (obtained for March 2013, 2014, 2015, and 2016) were evaluated for assessing the monitoring networks. The evaluation of the monitoring well network for NRDWL is based on all four of these datasets, collectively.

3.1.2 Mapping Method

Groundwater levels were mapped using the MEUK technique (Tonkin et al., 2016). MEUK is an extension of the hybrid mapping technique that combines universal kriging and analytic element method that is implemented in the water-level kriging program KT3D-H2O that is described in the technical report SGW-42305, *Collection and Mapping of Water Levels to Assist in the Evaluation of Groundwater Pump-and-Treat Remedy Performance,* and further described by Karanovic et al., 2009 ("KT3D_H20: A Program for Kriging Water-Level Data Using Hydrologic Drift Terms"). MEUK is designed to create a series of related groundwater elevation maps, each corresponding to a specific event, that can exhibit spatial relationships that persist over time. MEUK assumes that multi-event data can be described by a combination of (a) trends that vary over time, (b) trends that are invariant over time, and (c) a spatially and temporally stationary spatial correlation among the residuals from those two trends. In most applications, MEUK leads to improved trend estimates when the spatial distribution of monitoring locations varies from event to event and when there is an uncertain level of noise in the data. MEUK comprises two distinct procedures:

1. Estimation: use of a generalized least squares (GLS) regression to obtain coefficients for the defined trend terms ("calibration")

2. Prediction: solution of the MEUK system of equations using the coefficients estimated through (1) to predict water levels at intermediate locations and/or times, such as when producing a grid suitable for contouring ("mapping")

Before applying MEUK to a multi-event dataset, an underlying trend must be proposed based on independent information about the site. Components of the trend are specified as global or local: "global" trend components are assumed to apply throughout the period represented by the monitored multi-event dataset, whereas "local" trend components are assumed to apply only to individual events (or groups of events) and to change between events (or groups of events) based on internal or external stresses. Although global trends apply to the entire dataset, the effect of a global trend component may differ among events through specification of event-specific "strengths." For example, the aquifer transmissivity may be considered fairly constant over time (i.e., for all events) and is a candidate for a global trend component. However, the effect of pumping can be varied by specifying that the pumping rate differs among events. SGW-42305 presents the general form of the trend equations that are solved when constructing potentiometric surface maps using these techniques.

Using MEUK, all occasions when water levels are measured are interpolated simultaneously through the solution of a single block-diagonal "multi-event" universal kriging matrix. In doing so, water-level data from all events are evaluated simultaneously within a single operation, which enables trend coefficients and interpolated maps to be conditioned upon the entire dataset. The GLS regression enables the incorporation of physically based trend terms and the estimation and reporting of the coefficients of those trend terms. The coefficients (in particular, the estimated value for transmissivity) can be reviewed in reference to independent information. Furthermore, single-point cross-validation can be used to evaluate the role of each data point in the prediction by identifying the underlying trend when that point is excluded from the estimation. MEUK produces maps that honor measured data, and once reviewed for consistency with independent information, can be used for subsequent analyses. For this ECF, subsequent analyses include evaluating groundwater flow directions and rates and performing first-order contaminant transport analyses using advective-dispersive particle tracking without recourse to a groundwater model.

3.1.3 Conceptual Model and Specific Trend Terms

The following drift terms were used for the MEUK analysis of NRDWL elevation data:

- Unbias term (i.e., global-mean "offset") – used to allow for an area-wide adjustment in the mean evaluation of events. Allowed to vary for each event (i.e., specified as a local trend term).
- Linear drift in the east-west direction – used to represent the general underlying water level trend within the Hanford formation and Cold Creek unit sediments in the 200 East Area. Constant for all events (i.e., specified as a global trend term).
- Line drift – used to represent Columbia River, as depicted in Figure 3-1.

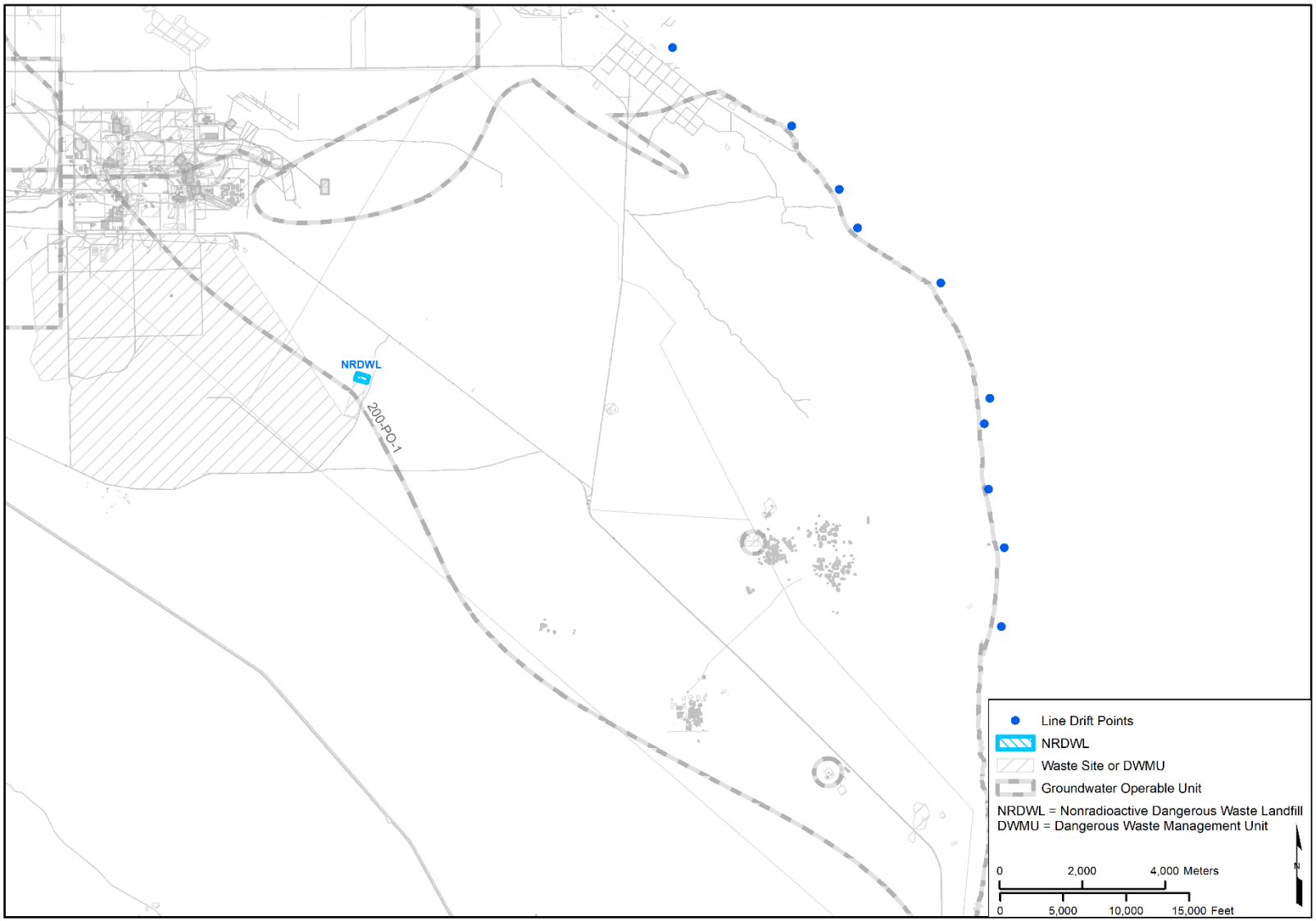

Figure 3-1. Line Drift Points Used to Represent the Columbia River

3.1.4 Semi-Variogram Parameters

Although the typical geostatistical analysis process is to compute an experimental semi-variogram and then fit a semi-variogram model, both practice and theory indicate that the procedure is not quite so clear-cut in the case of universal kriging using a nonstationary underlying trend as is the case here. This is also described in Section 4.1.5 of SGW-42305. As is the case at NRDWL, the analysis often starts with trend fitting and evaluation of the range of the variogram of the residuals; however, the final procedure generally concludes with selection of a variogram (including the nugget value) that reflects measurement errors and other sources of error, all of which are usually only qualitatively known, and provides a surface that reflects other, independent sources of information. In this context, the use of kriging is to facilitate production of a useful map, not to undertake a quantitative geostatistical analysis of groundwater level data. The variogram parameters selected for use in the groundwater elevation mapping were as follows:

- Variogram model: Exponential
- Range length: 25,000 m (82,020 ft)
- Sill: 0.01
- Nugget: 0.0005

3.2 Particle Tracking

Groundwater elevation maps depict general patterns of hydraulic gradients and groundwater flow identifying likely directions of contaminant migration from a facility in case a release reaches the water table. Particle tracking provides a method of visualizing the directions and potential paths of contaminant migration to undertake more detailed assessment of monitoring well locations. Particle tracking was performed using mod-PATH3DU (Muffels et al., 2017, *User's Guide for mod-PATH3DU, A Groundwater Path and Travel-Time Simulator*) and either considering advective only or advective and dispersive transport mechanisms. Parameters used to calculate particle tracks assume migration of a conservative (i.e., nonreactive) dissolved contaminant under representative conditions.

Calculated particle pathlines provide a way to visualize how a hypothetical release to the water table from the facility would move and spread under conditions represented in each of the four mapped years (2013, 2014, 2015, and 2016). Particle-tracking calculations specific to NRDWL and assuming advective-dispersive transport produced both particle pathlines and particle counts.

3.2.1 Advection-Only Particle Tracking

Advection-only particle tracking based on water-level mapping was performed to provide general patterns of groundwater flow near NRDWL under conditions represented by each of the four mapped events (calendar years 2013, 2014, 2015, and 2016). No detailed post-processing of the advection-only particle traces was undertaken, because their intent is qualitative only.

3.2.2 Advective-Dispersive Particle Tracking

Advective-dispersive particle-tracking calculations produce many pathlines, each of which depicts the potential path of a particle of water or dissolved contaminant released at the water table beneath a facility. The particle-tracking calculations and outputs are based on simulating the one-time release of a large number of particles representing an instantaneous release to the water table. Because vadose zone travel time is ignored, the particle release year represents only the year that hypothetical contamination reaches the water table. The outputs of the calculations from the advective-dispersive particle-tracking calculations include maps of calculated particle paths for the flow conditions determined for each of the four years (2013, 2014, 2015, and 2016).

The particle paths were post-processed to provide additional depictions and calculations, including time-series plots referred to as particle breakthrough curves, tabulations of relative particle counts for each groundwater monitoring well, and maps of particle density (particle count maps) downgradient of the facility based on the flow conditions determined for each of the four years. The post-processing of the particle paths and the resulting outputs are described in more detail below.

Calculated particle counts can be used as a surrogate for contaminant concentrations to evaluate the relative efficacy of the interim status groundwater monitoring wells and the need for and suitability of any proposed groundwater monitoring wells. Relative particle counts at well locations were calculated by counting the number of particles that pass through the vicinity of an existing or potential new monitoring well location. A radius of 20 m (66 ft) around each well location was used to count the particles as they arrived and the time of arrival was recorded. The calculations produce outputs (included in the list above) used to help evaluate the groundwater monitoring network. These are as follows:

- A tabulation of particle density (counts) for each interim status groundwater monitoring well and each potential new monitoring well. This count is the total number of particles that pass through the vicinity of the well, regardless of time.
- A time-series plot of the likely arrival, peak, and decline in the (relative) concentration of particles at each well location resulting from a hypothetical instantaneous release from the associated facility. This plot is prepared by summing the particles within a small number of arrival time bins in the manner used to construct a histogram.
- Particle count maps that depict areas of relatively higher and lower potential impact from a release that reaches the water table from a given facility. Contour maps of particle counts were generated by counting the number of particles that pass through each cell of a pre-defined uniform calculational grid (Figure 3-2). The grid used to develop the relative particle density maps is defined by 20 by 20 m (66 by 66 ft) cells. The cell size is the same dimensions as the cell size of the calculation grid used to prepare the groundwater elevation maps. The grid is oriented to be parallel to the predominant groundwater flow direction at NRDWL.

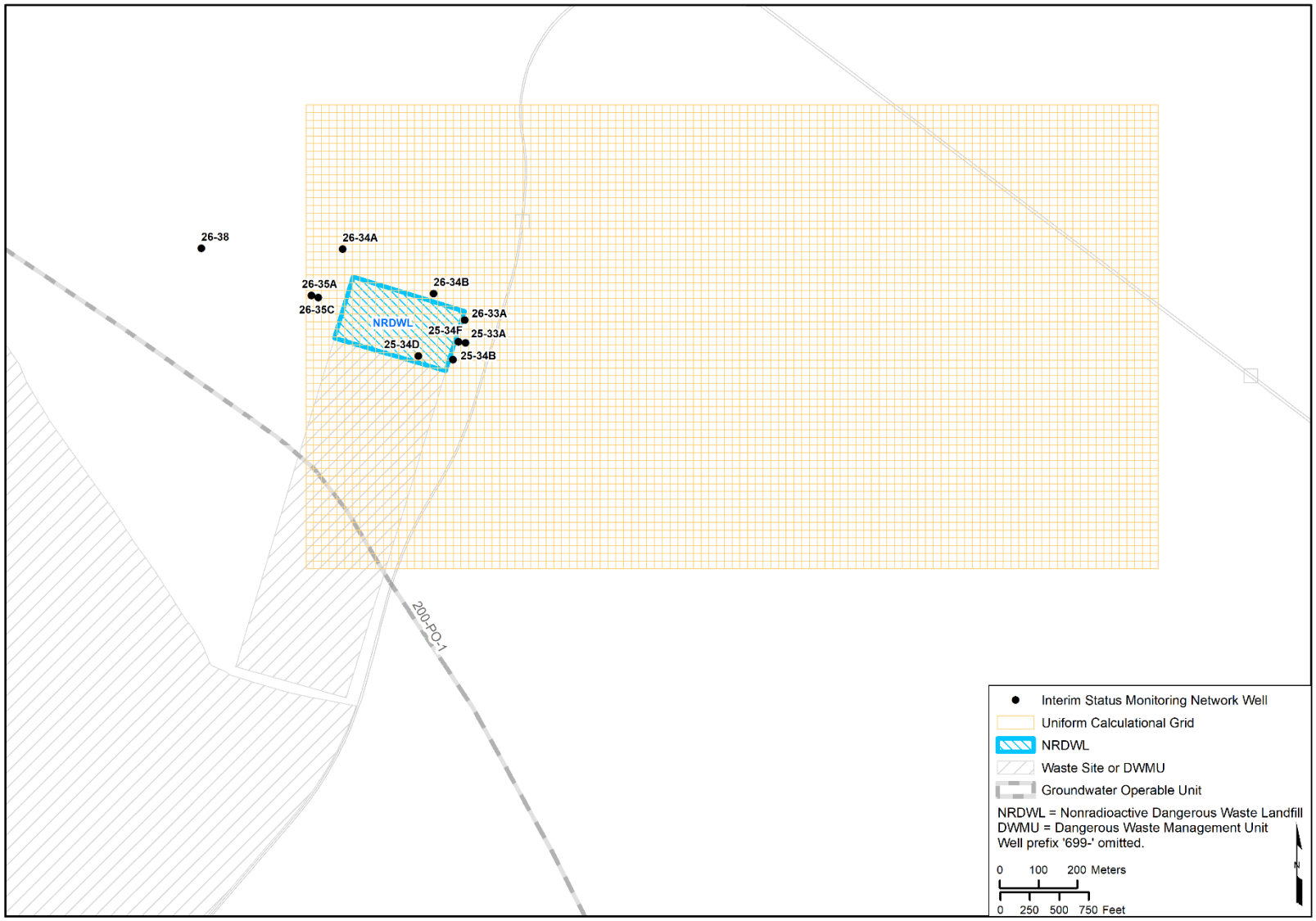

Figure 3-2. Uniform Calculational Grid at NRDWL

4 Assumptions and Inputs

Assumptions and inputs that underlie the calculations presented in this ECF are discussed in this chapter.

4.1 Assumptions

Assumptions used for groundwater elevation mapping and particle tracking are discussed in the following sections.

4.1.1 Groundwater Elevation Mapping

Water-level contour maps were constructed using a technique that incorporates the effects of certain hydrologic features such as the Columbia River (SGW-42305). While accounting for the values of water levels measured at each well, the resulting contour maps provide a plausible interpretation of groundwater levels and hydraulic gradients between measured locations. The accuracy of the contours is influenced, however, by various factors, including the following:

- The degree of adherence to, or violation of, assumptions that underlie the mapping method (as outlined in SGW-42305)
- The accuracy of the measured or recorded water levels
- The number, distribution, and location of monitoring wells
- The relationship between the vertical open interval(s) of the monitoring wells and those of any extraction and injection wells
- The presence, of large hydrologic features such as the Columbia River and connection of the river with groundwater

These potential sources of error mean that the interpolated maps only approximate actual conditions. The water-level and particle path maps are considered reasonable approximations that provide value when interpreting the likely directions and rates of groundwater movement. The maps also help identify areas downgradient of NRDWL that likely would be impacted by a release that reached the underlying water table. The use of multiple groundwater elevation events in the analysis helps in developing a reasonable estimate of potential migration pathways.

4.1.2 Particle Tracking

Particle tracking relies upon the outputs (i.e., mapped groundwater elevations) computed using MEUK. As a result, the assumptions and limitations that underlie the preparation of those maps using MEUK are implicit in any subsequent particle tracking.

Particle tracking that considers advection only relies upon the assumption that the values of the hydraulic conductivity and mobile (effective) porosity of the aquifer, which are represented as single best-estimate values, are representative of the bulk conservative transport of water and dissolved constituents.

Particle tracking that considers advection and dispersion relies upon the assumption that the values of the dispersion coefficients in the two principal directions (longitudinal and transverse) are representative of physical processes that act to disperse dissolved constituents in groundwater at the scale of the calculations.

4.2 Input Data

This section summarizes the general input requirements for the calculations described in this ECF.

4.2.1 Water-Level Mapping Input

Appendix A to this ECF provides tables of the following inputs to the groundwater-level mapping:

1. Measured water levels
2. Line drift representing Columbia River data points

4.2.1.1 Migration Parameters for Water-Level Mapping

Only a small number of parameters are required for the migration calculations performed using the groundwater elevation maps and particle-tracking method. The dispersivity parameters used in this evaluation were set at the values used for this area within the CPGWM (CP-47631). Those values were as follows:

- Longitudinal dispersivity: 3.5 m (11.5 ft)
- Transverse dispersivity: 0.7 m (2.3 ft)

The parameters used to represent dissolved contaminant migration are representative of local conditions for a conservative (i.e., nonreactive) solute dissolved within groundwater. Those parameters are as follows:

- Mobile porosity – values for mobile porosity were defined specific to NRDWL. Those values were obtained from previous work detailed in ECF-Hanford-16-0013. The mobile (effective) porosity defined for NRDWL is 0.1.

- Hydraulic conductivity – values for hydraulic conductivity were defined specific to NRDWL. Those values were obtained from previous work detailed in ECF-Hanford-16-0013. The hydraulic conductivity defined for NRDWL is 1,500 m/d (4,921 ft/d).

The primary purpose of the calculations is to estimate potential directions of migration to assess the efficacy of the geographical distribution of wells in the proposed monitoring well network. For the calculations described in this ECF, the values assigned to the hydraulic conductivity and mobile (effective) porosity do not affect the assessment of well locations. The values assigned to those parameters do, however, affect the calculations of (relative) arrival times at existing and any proposed monitoring locations.

4.2.2 Particle Starting Locations

The starting locations for the particle-tracking calculations represent the plausible release sites throughout the footprint of the facility from which a potential release would impact the underlying water table. Equally spaced release locations were specified along the six trenches that contain dangerous waste (Figure 4-1). Twenty particles were released and tracked from each release location to provide the density of particles in space and time required for the detailed facility-specific calculations, randomizing the seed values for the dispersion calculations. Thus, 2,640 (2,640 = 6 [trenches] × 22 [release locations] × 20 [releases]) particles were tracked for each of the four simulations.

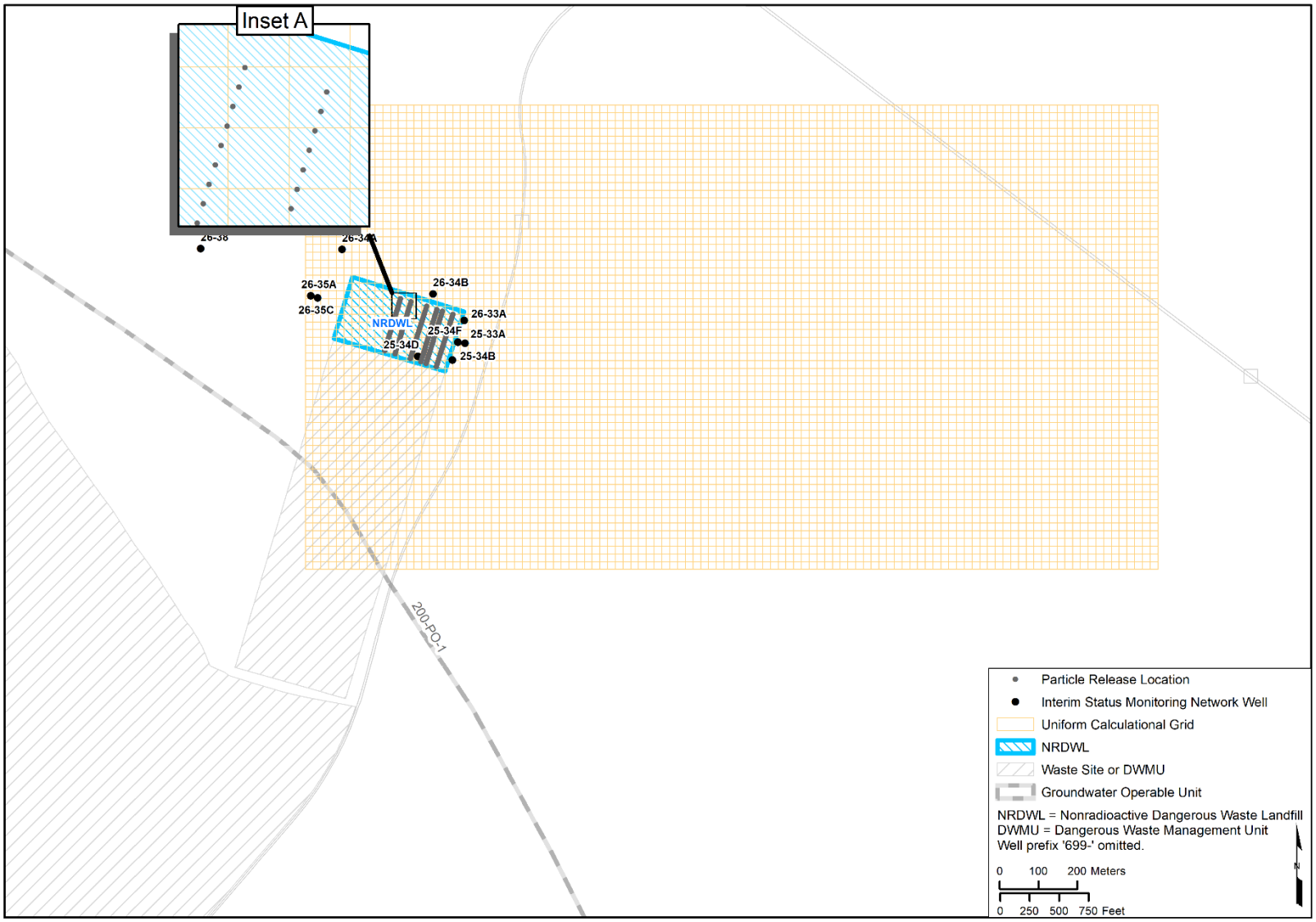

Figure 4-1. Particle Release Locations at NRDWL

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5 Software Applications, Descriptions, Installation and Checkout, and Statements of Validity

Software used to perform the calculations for this ECF was in accordance with PRC-PRO-IRM-309, *Controlled Software Management*.

5.1 Approved Software

The software used to perform the calculations for this ECF was approved and complies with PRC-PRO-IRM-309. The software is managed consistent with PRC-PRO-IRM-309 based on:

- CHPRC-02839, *KT3D_H2O and MEUK Integrated Software Management Plan: KT3D_H2O Version 3.5.1 and MEUK Version 0.2.2*

PRC-PRO-IRM-309 distinguishes between safety software and support software based on whether the software calculates reportable results or provides run support, visualization, or similar functions. Brief descriptions of the software are provided below.

5.2 Software Description

MEUK was used to perform groundwater elevation mapping using measured groundwater levels. MEUK is classified as safety software and graded level C based on responses to the Software Grading Checklist in PRC-PRO-IRM-309. Use of this software at the Hanford Site is managed under the integrated software management plan (CHPRC-02839):

- **Software title:** MEUK (S.S. Papadopulos and Associates, Inc., 2016, Version 0.2.2).
- **Software version**: CH2M HILL Plateau Remediation Company (CHPRC) Build 2 (Version 0.2.2).
- **Hanford Information Systems Inventory (HISI) identification number:** 2517 (safety software, graded level C).
- **Workstation type and property number (from which software is run):** SSPA, FE449.

MEUK is programmed in the R language (R Development Core Team, 2013, *R: A Language and Environment for Statistical Computing*) and uses the gstat package (Pebesma, 2004, "Multivariable Geostatistics in S: the gstat Package"). MEUK can be supplemented or validated using KT3D_H2O (Karanovic et al., 2009).

5.3 Support Software

The software programs discussed below are classified as support software.

- **ArcGIS®**: Visualization and post-processing tool for assessing simulated plume distributions, identifying extraction/injection well coordinates, and mapping auxiliary data (Mitchell, 1999, *The ESRI Guide to GIS Analysis, Volume 1: Geographic Patterns & Relationships*).
- **R:** The R programming environment for statistical computing and graphics (R Development Core Team, 2013; Ihaka and Gentleman, 1996, "R: A Language for Data Analysis and Graphics") was

® ArcGIS is a registered trademark of the Environmental Systems Research Institute, Inc., Redlands, California.

used to perform a variety of data processing, including post-processing calculation results and generating plots of aggregate data time series. The following R packages were also used as follows:

  - Package GSTAT provided the kriging engine for water levels.
  - Package SSPAMEUK provided functions for the generation of water level kriging drifts.
  - Package raster was used to generate water level American Standard Code for Information Interchange (ASCII) grids and raster calculations.

- **Surfer®:** Data interpolation for visualization, model implementation, and quality assurance purposes.
- **ModPath3DU**: Particle-tracking code for calculating the three-dimensional flow pathlines and travel times of solute particles.
- **Python:** The calculation and visualization of particle counts utilized Python™, an interpreted, object-oriented programming language, with scripts executed using the Anaconda® freeware Python distribution Python Version 2.7.11, distributed with Anaconda 4.1.1 (64 bit).

5.4 Software Installation and Checkout

Safety software is checked out in accordance with procedures specified in PRC-PRO-IRM-309. Executables are obtained from the CHPRC software owner (who maintains the configuration-managed copies in MKS Integrity®). Installation tests identified in CHPRC-02839 are performed on the software and successful installation confirmed. Software installation and checkout forms are required and must be approved for installations used to perform model runs. Approved users are registered in HISI for safety software.

5.4.1 Statement of Valid Software Application

The software identified above was used consistent with intended uses for CHPRC, as identified in CHPRC-02839, and is a valid use of this software for this application. The software was used within its limitations, as identified in CHPRC-02839.

® Surfer is a registered trademark of Golden Software, LLC, Golden, Colorado.

™Python is a registered trademark of Python Software Foundation, Beaverton, Oregon 97008, (www.python.org).

® Anaconda is a registered trademark of Anaconda, Inc., Austin, Texas (https://store.continuum.io/cshop/anaconda)

® MKS Integrity is a registered trademark of MKS, Inc., Needham, Massachusetts.

6 Calculation Steps and Output

This chapter describes the calculations performed to produce the results presented in this ECF, including developing the necessary input files, performing the calculations, and post-processing the outputs.

6.1 Water-Level Mapping

The following steps were taken to produce the groundwater elevation maps presented in this ECF and used in all subsequent particle-tracking calculations:

1. Input data were compiled from retrieved database sources. Measured groundwater elevations were obtained for March 2013, 2014, 2015, and 2016. Water levels for which there were multiple measurements (such as for the automated water-level network wells) were averaged so that one value was assigned to each monitoring well for each calendar year.
2. To represent a direction of regional flow and Columbia River connection to the groundwater, line drift points were created along the Columbia River. Line drift points were set constant for all events (i.e., specified as global trend terms).
3. MEUK was executed and kriging results were saved in ArcGIS ASCII (*.asc) grid format.
4. After ASCII (*.asc) grid files were imported into Surfer, water-level contours were generated in ArcGIS shapefile format.

6.2 Particle Tracking

For the particle-tracking calculations, an input file representing particle starting locations was prepared in an ArcGIS shapefile format. Particle starting locations (Figure 4-1) represent release points equally spaced along the centerline of the trenches in NRDWL.

The ArcGIS shapefile was used as input to the ModPath3DU program. A ModPath3DU particle-tracking input file that included dispersion parameters was generated to simulate dispersion. The maximum tracking time was set to 1,000 days.

Simulations of particles being released at the water table portrayed a potential water table impact for each water-level mapping event (i.e., calendar years 2013, 2014, 2015, and 2016). Particles were released and tracked from each particle starting location using a different random seed value for the dispersion calculations. Twenty particles were released from each starting location to provide the high density of particles in space and time required for these detailed facility-specific calculations. This process resulted in the simulation of a total of 2,640 (2,640 = 6 [trench] × 22 [release locations]× 20 [releases]) particles released from NRDWL.

ModPath3DU was then executed to produce a binary pathline output file. A post-processing program (writep3doutput.exe) was executed to convert the ModPath3DU binary pathline output file into both an ArcGIS shapefile format and an ASCII text file format, both of which list particle locations and times.

The resulting particle tracks were superimposed upon figures that showed monitoring well locations to determine whether monitoring locations lie in the migration pathway of the simulated releases from the facilities.

To simulate dispersion with particle tracking, the random-walk particle tracking option implemented within mod-PATH3DU was used. As described in the software documentation (CHPRC-00261, *MODFLOW and Related Codes Acceptance Test Report: CHPRC Build 7*), for consistency, this random-walk module reads and uses the same dispersion inputs as the Hanford Site version of the transport simulator MT3DMS (Modular Three-Dimensional Multispecies Transport Model for Simulation of Advection, Dispersion, and Chemical Reactions of Contaminants in Groundwater Systems).

6.3 Particle Counts

Particle counts were calculated to create maps that illustrate the relative particle density downgradient of NRDWL and to produce time-series plots, or breakthrough curves, to show the relative arrival time of particles at monitoring well locations. The steps to create this output are described below.

For the maps of particle counts:

1. An ArcGIS shapefile grid was defined having a 20 by 20 m (66 by 66 ft) cell size, large enough to envelop all pathlines generated in the previous step.
2. For each mapped event, the ArcGIS "Join" tool was used to intersect the pathlines with the regular grid and determine the count of unique pathlines intersecting each subgrid cell.
3. This grid of pathline counts was converted to an ASCII grid format and imported into ArcGIS, after which bilinear interpolation was used to develop the particle density (particle count) maps presented in Chapter 7.

Particle counts and breakthrough (arrival-time) curves for each interim groundwater monitoring well were prepared using the python script *ParticleCountCalc_v5.py* as follows:

1. The ASCII text file containing particle locations and times was read into memory.
2. The tracking times were binned by subdividing the times into regular 20-day intervals.
3. All pathlines were filtered to determine those that were first to pass within 20 m (66 ft) of each interim status monitoring well. The corresponding tracking time for each particle was recorded.
4. The total number of pathlines that met the above criteria (first to pass within 20 m [66 ft] of a specific well within a specific binned time period) was summed.
5. The results of the above calculations were tabulated and are displayed in plots presented in Chapter 7.
6. The python script *ParticleCountPlots_v6.py* was used to plot the breakthrough (arrival-time) curves, also presented in Chapter 7.

7 Results

This chapter presents results developed from the calculations described above. Figures 7-1 through 7-4 show the results of the water elevation mapping that was performed in the vicinity of NRDWL in calendar years 2013, 2014, 2015, and 2016. Water levels measured in March in calendar years 2013, 2014, 2015, and 2016 were used in this analysis because these events have a larger number of wells measured compared to other events for those calendar years. However, not all wells were measured for the March water-level measurement events. Only wells with measured water levels are shown on the water-level maps. As shown in Table 7-1, the residuals calculated as a difference between measured and mapped water levels were low with an average absolute residual value of 0.003 m, indicating excellent agreement with the measured water levels in the area. The water-level mapping forms the basis for the calculations performed for this ECF.

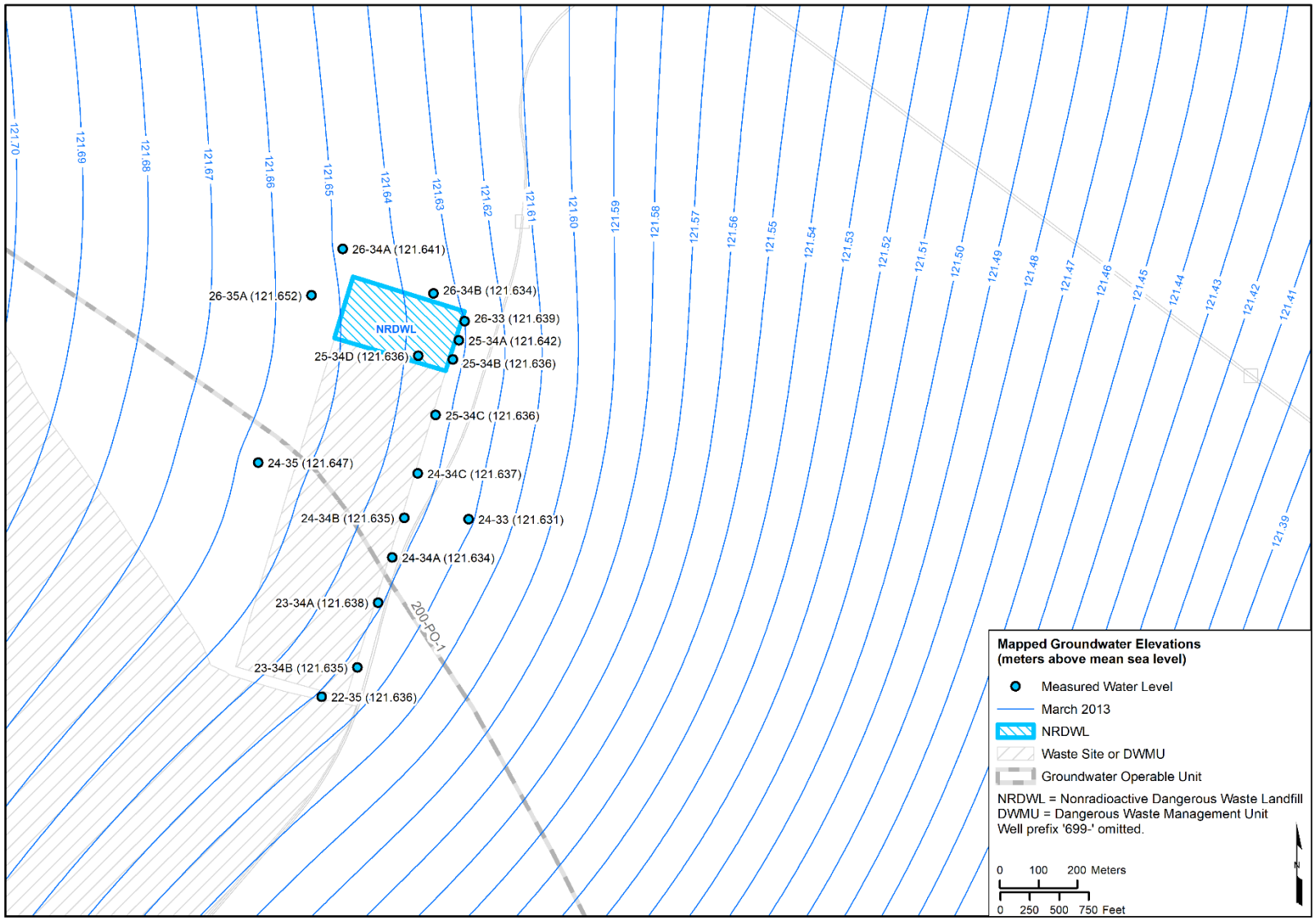

Figure 7-1. Water Elevation Map for NRDWL, 2013

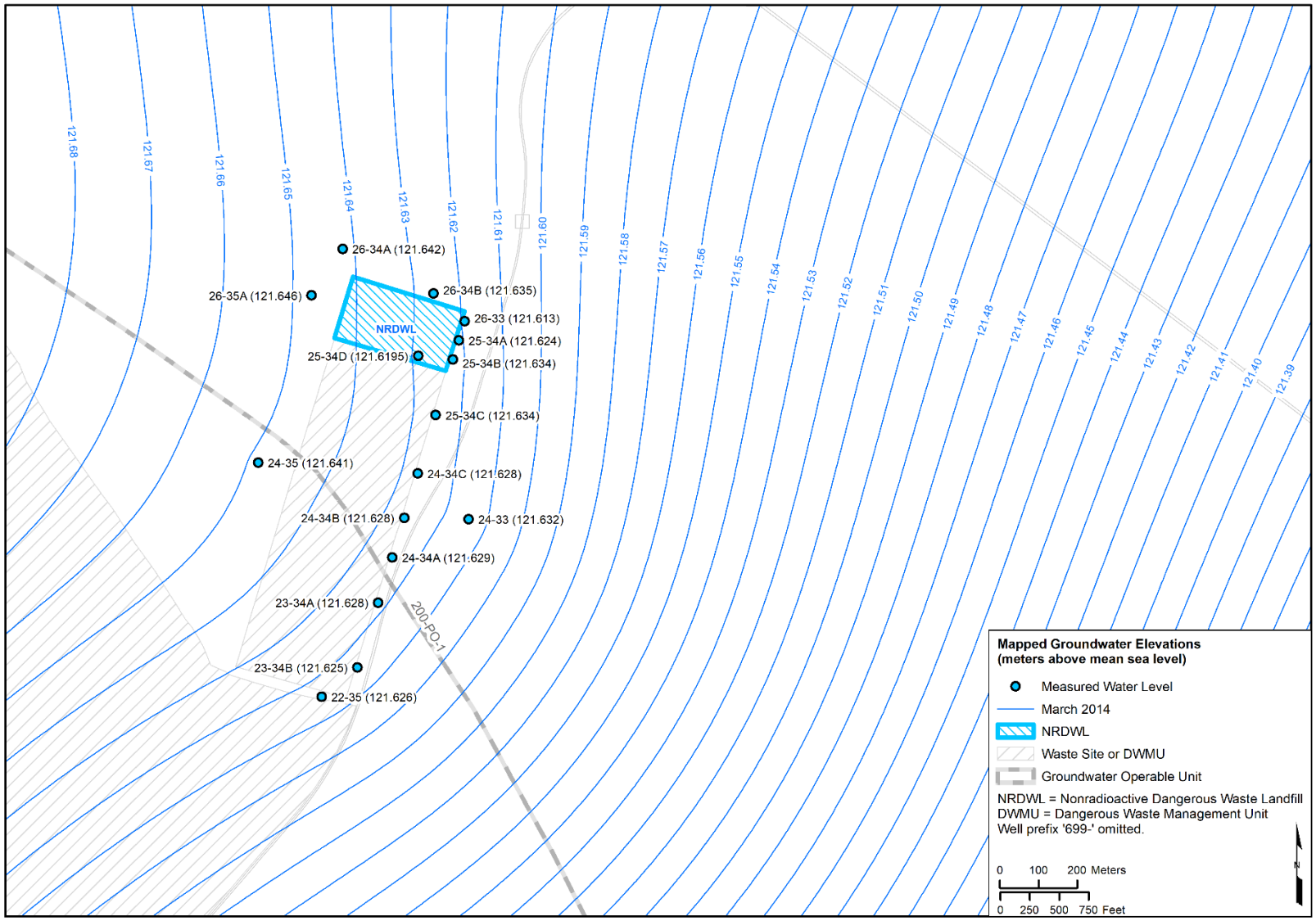

Figure 7-2. Water Elevation Map for NRDWL, 2014

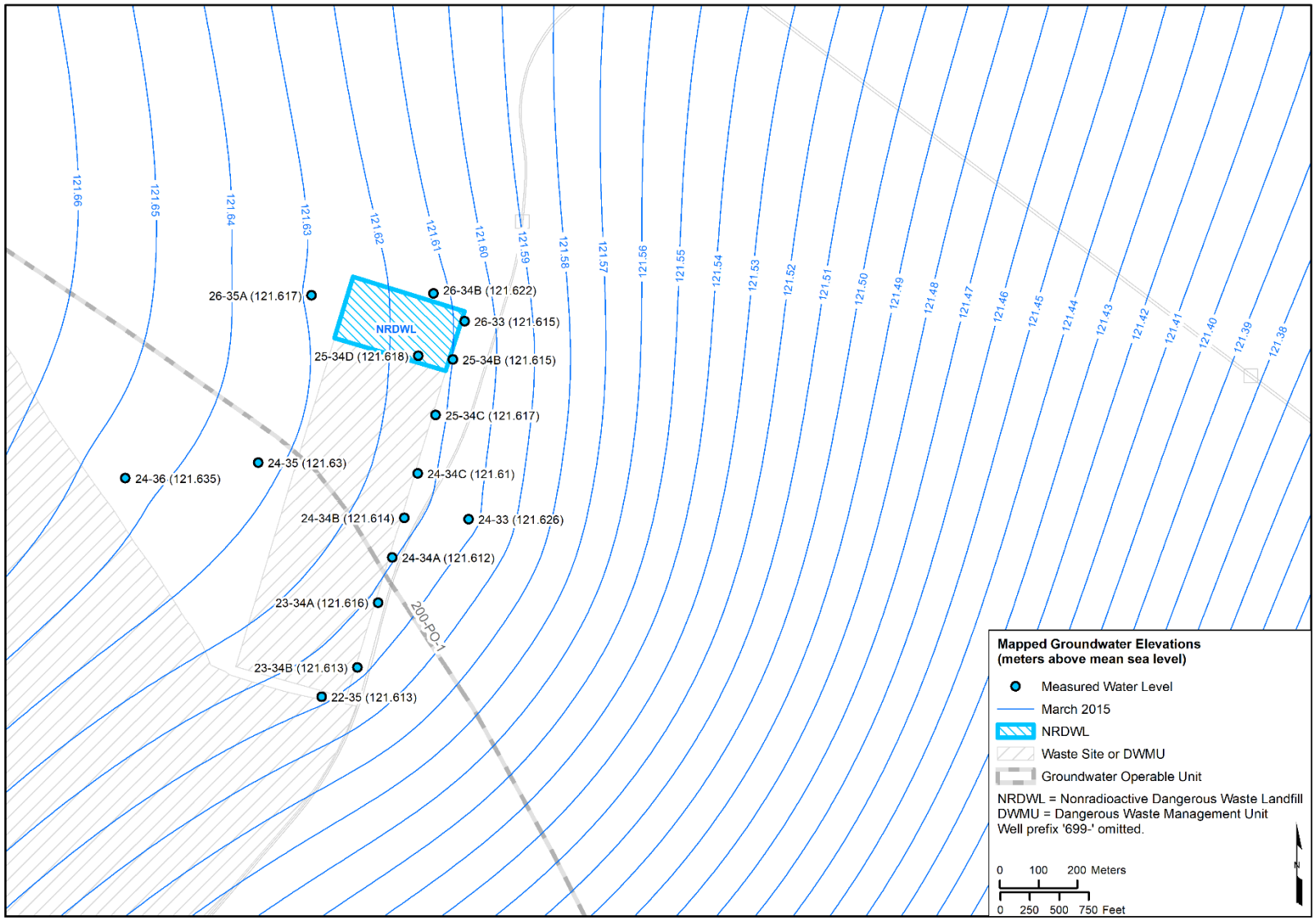

Figure 7-3. Water Elevation Map for NRDWL, 2015

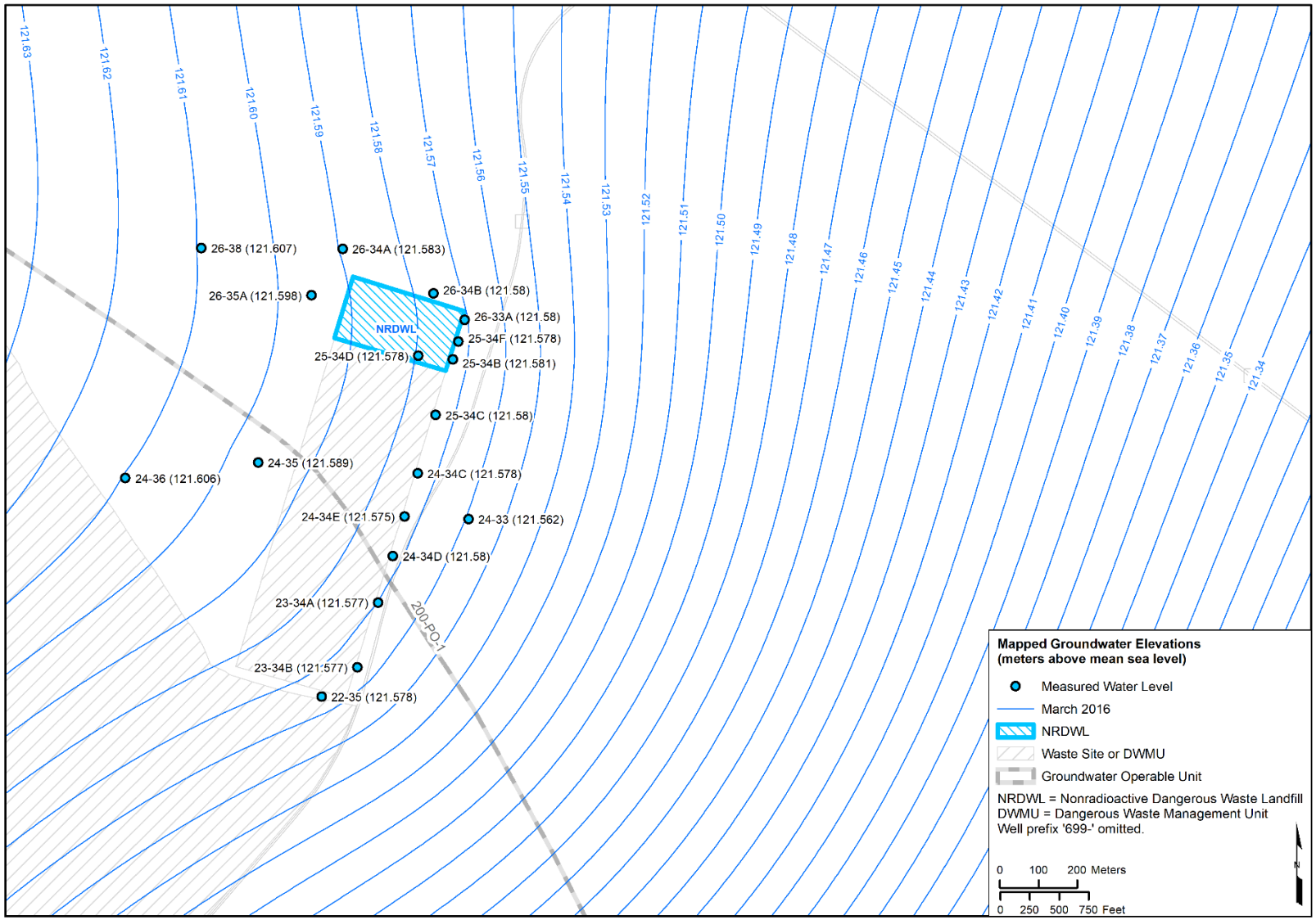

Figure 7-4. Water Elevation Map for NRDWL, 2016

Table 7-1. Mapped Water-Level Residuals

Year	Well Name	X Coordinate	Y Coordinate	Measured Water Level (m)	Mapped Water Level (m)	Residual (m)
2013	699-22-35	579341	130309	121.636	121.629	0.007
2013	699-23-34A	579486	130552	121.638	121.631	0.007
2013	699-23-34B	579433	130385	121.635	121.627	0.008
2013	699-24-33	579720	130768	121.631	121.621	0.010
2013	699-24-34A	579523	130669	121.634	121.632	0.002
2013	699-24-34B	579554	130772	121.635	121.633	0.002
2013	699-24-34C	579589	130887	121.637	121.634	0.003
2013	699-24-35	579177	130915	121.647	121.657	-0.010
2013	699-25-34A	579695	131231	121.642	121.632	0.010
2013	699-25-34B	579679	131181	121.636	121.632	0.004
2013	699-25-34C	579635	131038	121.636	121.633	0.003
2013	699-25-34D	579590	131191	121.636	121.638	-0.002
2013	699-26-33	579710	131280	121.639	121.630	0.009
2013	699-26-34A	579395	131468	121.641	121.648	-0.007
2013	699-26-34B	579629	131352	121.634	121.635	-0.001
2013	699-26-35A	579314	131347	121.652	121.654	-0.002
2014	699-22-35	579341	130309	121.626	121.616	0.010
2014	699-23-34A	579486	130552	121.628	121.622	0.006
2014	699-23-34B	579433	130385	121.625	121.616	0.009
2014	699-24-34C	579589	130887	121.628	121.627	0.001
2014	699-24-35	579177	130915	121.641	121.649	-0.008
2014	699-25-34A	579695	131231	121.624	121.621	0.003
2014	699-25-34B	579679	131181	121.634	121.623	0.011
2014	699-25-34C	579635	131038	121.634	121.626	0.008
2014	699-26-33	579710	131280	121.613	121.619	-0.006
2014	699-26-34A	579395	131468	121.642	121.642	0.000
2014	699-26-34B	579629	131352	121.635	121.626	0.009
2014	699-26-35A	579314	131347	121.646	121.647	-0.001
2015	699-22-35	579341	130309	121.613	121.602	0.011
2015	699-23-34A	579486	130552	121.616	121.608	0.008
2015	699-23-34B	579433	130385	121.613	121.602	0.011
2015	699-24-33	579720	130768	121.626	121.603	0.023

Table 7-1. Mapped Water-Level Residuals

Year	Well Name	X Coordinate	Y Coordinate	Measured Water Level (m)	Mapped Water Level (m)	Residual (m)
2015	699-24-34A	579523	130669	121.612	121.611	0.001
2015	699-24-34B	579554	130772	121.614	121.613	0.001
2015	699-24-34C	579589	130887	121.610	121.613	-0.003
2015	699-24-35	579177	130915	121.630	121.633	-0.003
2015	699-24-36	578834	130875	121.635	121.644	-0.009
2015	699-25-34B	579679	131181	121.615	121.610	0.005
2015	699-25-34C	579635	131038	121.617	121.612	0.005
2015	699-25-34D	579590	131191	121.618	121.616	0.002
2015	699-26-33	579710	131280	121.615	121.608	0.007
2015	699-26-34B	579629	131352	121.622	121.613	0.009
2015	699-26-35A	579314	131347	121.617	121.629	-0.012
2016	699-22-35	579341	130309	121.578	121.565	0.013
2016	699-23-34A	579486	130552	121.577	121.570	0.007
2016	699-23-34B	579433	130385	121.577	121.565	0.012
2016	699-24-33	579720	130768	121.562	121.559	0.003
2016	699-24-34C	579589	130887	121.578	121.574	0.004
2016	699-24-34D	579525	130673	121.580	121.572	0.008
2016	699-24-34E	579555	130775	121.575	121.573	0.002
2016	699-24-35	579177	130915	121.589	121.596	-0.007
2016	699-24-36	578834	130875	121.606	121.610	-0.004
2016	699-25-34B	579679	131181	121.581	121.573	0.008
2016	699-25-34C	579635	131038	121.580	121.574	0.006
2016	699-25-34D	579590	131191	121.578	121.579	-0.001
2016	699-25-34F	579694	131228	121.578	121.572	0.006
2016	699-26-33A	579710	131284	121.580	121.571	0.009
2016	699-26-34A	579395	131468	121.583	121.589	-0.006
2016	699-26-34B	579629	131352	121.580	121.576	0.004
2016	699-26-35A	579314	131347	121.598	121.596	0.002

Table 7-1. Mapped Water-Level Residuals

Year	Well Name	X Coordinate	Y Coordinate	Measured Water Level (m)	Mapped Water Level (m)	Residual (m)
2016	699-26-38	579030	131470	121.607	121.609	-0.002
					Correlation	0.97
					Avg Residual	0.003
					Max Residual	0.023
					Min Residual	-0.012
					SSE	0.0033
					MSE	0.000054
					RMSE	0.0074
					Obs Range	0.090
					RMSE/Obs Range	0.0817
					R^2	0.94

MSE = mean square error
Obs Range = observed range
R^2 = R-squared
RMSE = root mean square error
SSE = sum of squares error

7.1 Particle Tracking

Figures 7-5 through 7-8 depict the particle paths developed based on the groundwater elevations mapped throughout the vicinity of NRDWL. The maps were prepared based on the release of a large number of particles at the NRDWL facility. The particle paths were calculated using both advection and dispersion, depicting the patterns of spreading that might accompany the migration of contaminants near the facility for the flow conditions calculated for calendar years 2013, 2014, 2015, and 2016. Figures 7-5 through 7-8 depict the particle paths calculated after 1,000 days of travel, by which time it was determined that all particles would have arrived at or passed by the interim status groundwater monitoring wells.

Figures 7-5 through 7-8 depict an instantaneous release to the water table from all of the release locations in NRDWL to illustrate the adequacy of the well network for monitoring the entire facility.

7.2 Particle Counts

To compare the relative timing and density of the particles that pass by each monitoring well location, particle counts were calculated as described in Section 6.3. The particle counts were tabulated, particle breakthrough curves were created, and particle count maps were generated.

7.2.1 Relative Particle Counts at Interim Status Groundwater Monitoring Wells

Tables 7-2 through 7-6 present the computed particle counts over time, binned into periods of 20 days, for each of the downgradient and crossgradient interim status monitoring wells (699-26-34B, 699-25-34D, 699-25-34F, 699-25-34B, and 699-26-33A). The tables present four entries (one for each year) for each well. At the bottom of the column for each mapped event is the total number of particles that passed through the vicinity of the well, regardless of time, and the average of the totals for the four mapped years rounded to the nearest integer. Each table provides an indication of the relative timing of the expected detections at each well, and the relative potential that each well would detect a release at the facility for the flow conditions calculated for calendar years 2013, 2014, 2015, and 2016. Particles are not detected at upgradient wells 699-26-38, 699-26-35A, or 699-26-34A. Even though the released particles were tracked for 1,000 days, the tables are truncated to show sufficient number of entries to describe the relative particle breakthrough at the wells.

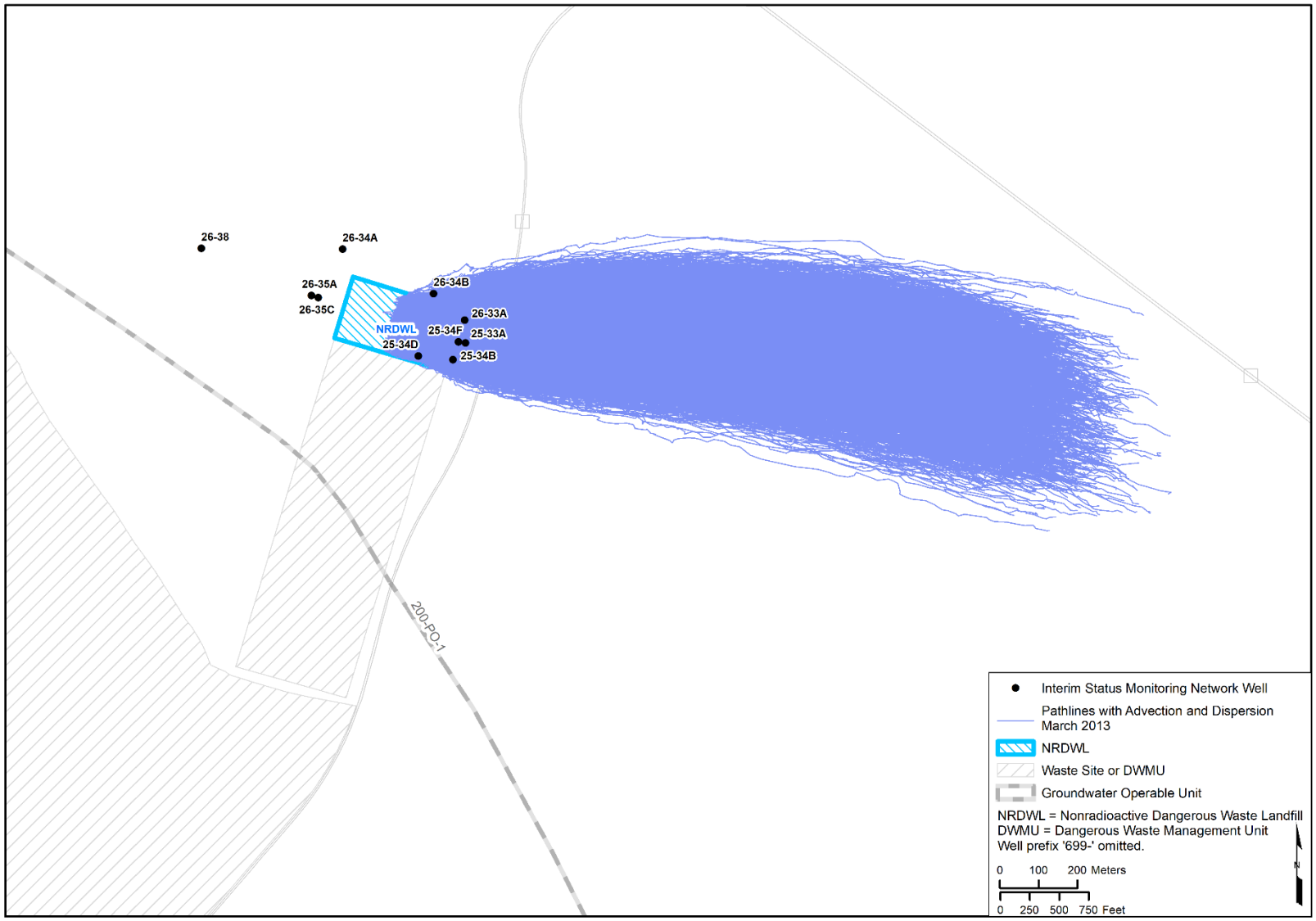

Figure 7-5. Local-Scale Particle Paths, Advection and Dispersion – NRDWL, 2013

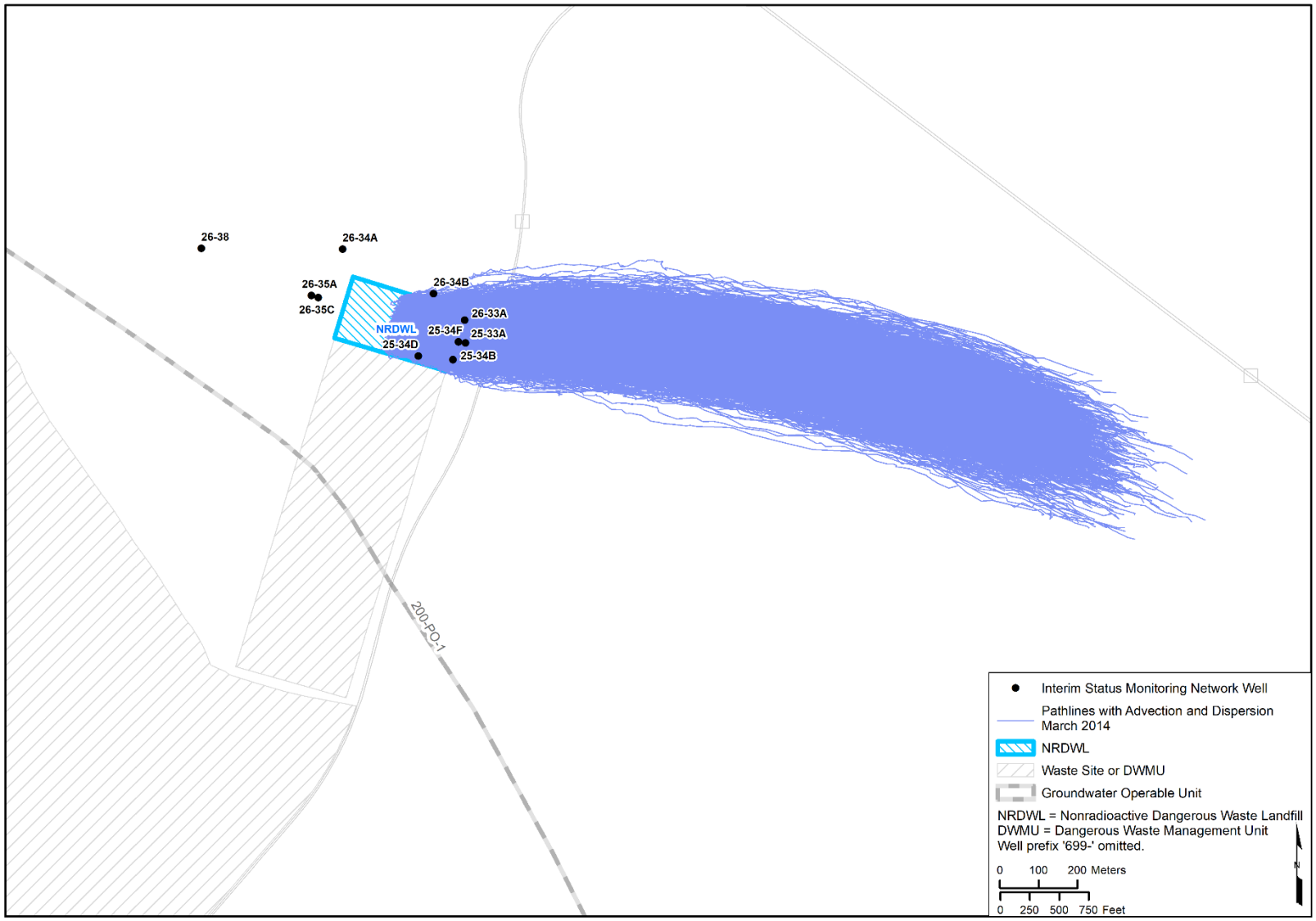

Figure 7-6. Local-Scale Particle Paths, Advection and Dispersion – NRDWL, 2014

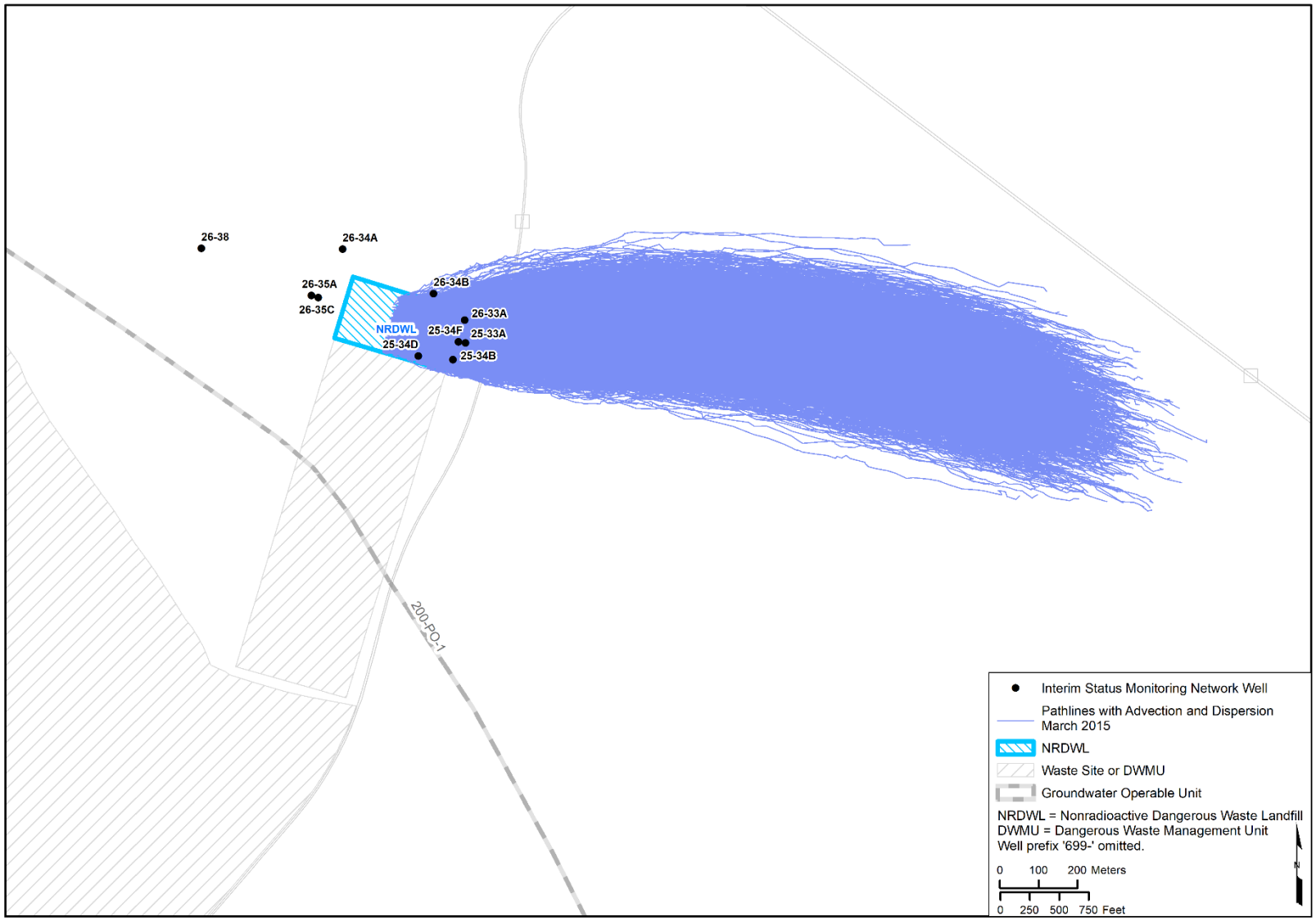

Figure 7-7. Local-Scale Particle Paths, Advection and Dispersion – NRDWL, 2015

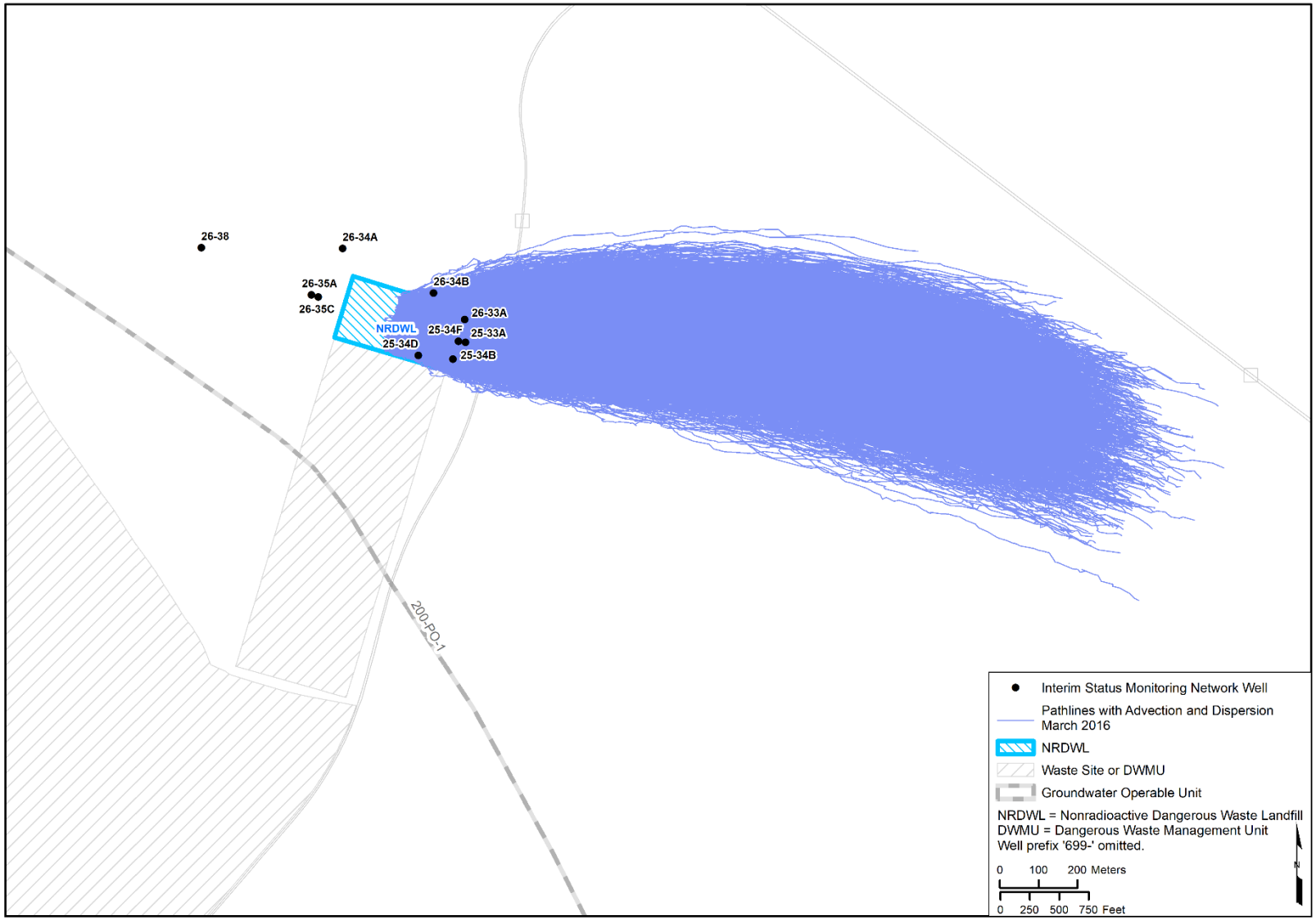

Figure 7-8. Local-Scale Particle Paths, Advection and Dispersion – NRDWL, 2016

Table 7-2. Particle Density (Count) – Monitoring Well 699-25-34D

Time Interval (days)	Relative Particle Density (Count) by Year				
	2013	2014	2015	2016	
20	185	191	186	191	
40	32	31	14	27	
60	29	39	26	54	
80	30	23	18	29	
100	25	13	15	14	
120	9	2	15	12	
140	3	3	2	3	
160	0	1	1	1	
180	0	0	2	1	
200	0	0	0	0	
220	0	0	1	0	
240	0	0	0	0	
260	0	0	0	0	**Average**
Total	**313**	**303**	**280**	**332**	**307**

Table 7-3. Particle Density (Count) – Monitoring Well 699-26-34B

Time Interval (days)	Relative Particle Density (Count) by Year				
	2013	2014	2015	2016	
20	0	0	1	1	
40	19	8	8	18	
60	28	18	13	30	
80	42	17	23	38	
100	24	13	15	29	
120	12	2	16	14	
140	7	4	5	2	
160	2	0	1	2	
180	0	0	1	2	
200	2	0	1	0	
220	0	0	0	0	
240	0	0	0	0	
260	1	0	0	0	**Average**
Total	**137**	**62**	**84**	**136**	**104.5**

Table 7-4. Particle Density (Count) – Monitoring Well 699-26-33A

Time Interval (days)	Relative Particle Density (Count) by Year				
	2013	2014	2015	2016	
20	72	91	66	76	
40	85	158	86	89	
60	92	141	90	116	
80	71	107	85	77	
100	55	85	58	53	
120	33	71	45	43	
140	35	74	47	52	
160	39	77	42	51	
180	27	36	47	30	
200	15	17	34	13	
220	18	7	22	13	
240	8	3	11	7	
260	7	3	7	6	
280	1	0	4	2	
300	4	0	1	1	
320	0	0	0	0	
340	0	0	0	1	
360	0	0	1	0	**Average**
Total	**562**	**870**	**646**	**630**	**677**

Table 7-5. Particle Density (Count) – Monitoring Well 699-25-34F

Time Interval (days)	Relative Particle Density (Count) by Year				
	2013	2014	2015	2016	
20	49	74	57	53	
40	74	102	92	89	
60	83	117	126	100	
80	74	88	96	92	
100	41	79	79	61	
120	55	66	66	47	
140	32	59	50	52	
160	64	56	57	39	
180	35	36	57	31	
200	17	25	38	24	
220	19	4	22	12	
240	12	8	21	6	
260	5	2	11	0	
280	2	0	5	3	
300	0	1	0	2	
320	0	0	0	0	
340	1	0	0	0	**Average**
Total	**563**	**717**	**777**	**611**	**667**

Table 7-6. Particle Density (Count) – Monitoring Well 699-25-34B

Time Interval (days)	Relative Particle Density (Count) by Year				
	2013	2014	2015	2016	
20	38	52	40	41	
40	93	91	84	103	
60	100	98	94	84	
80	93	70	71	96	
100	67	48	48	57	
120	50	28	34	35	
140	45	28	24	36	
160	33	18	17	41	
180	34	13	13	19	
200	21	7	12	13	
220	12	5	7	7	
240	8	3	5	3	
260	1	2	2	1	
280	0	0	2	1	
300	0	0	0	0	**Average**
Total	**595**	**463**	**453**	**537**	**512**

The average values depicted at the base of each table can be used to assess the relative potential for each well to detect a release at the facility. These averages are summarized as follows:

- 699-25-34D – Average = 307
- 699-26-34B – Average = 104.5
- 699-26-33A – Average = 677
- 699-25-34F – Average = 667
- 699-25-34B – Average = 512

7.2.2 Relative Arrival Times at Interim Status Groundwater Monitoring Wells

Figures 7-9 through 7-13 depict plots of particle counts over time (particle breakthrough curves) for each downgradient and cross-gradient well location where particles were detected. Particle breakthrough curves show the relative timing and particle density at each interim status monitoring location for the arrival, peak, and decline in particle counts resulting from the hypothetical instantaneous release at the facility. The breakthrough curves were prepared by plotting the entries in Tables 7-2 through 7-6.
The plots depict the relative potential for each well to detect a release from the facility that reaches the water table for the flow conditions calculated for calendar years 2013, 2014, 2015, and 2016. There is one figure for each well, with four lines shown on each plot (one for each year).

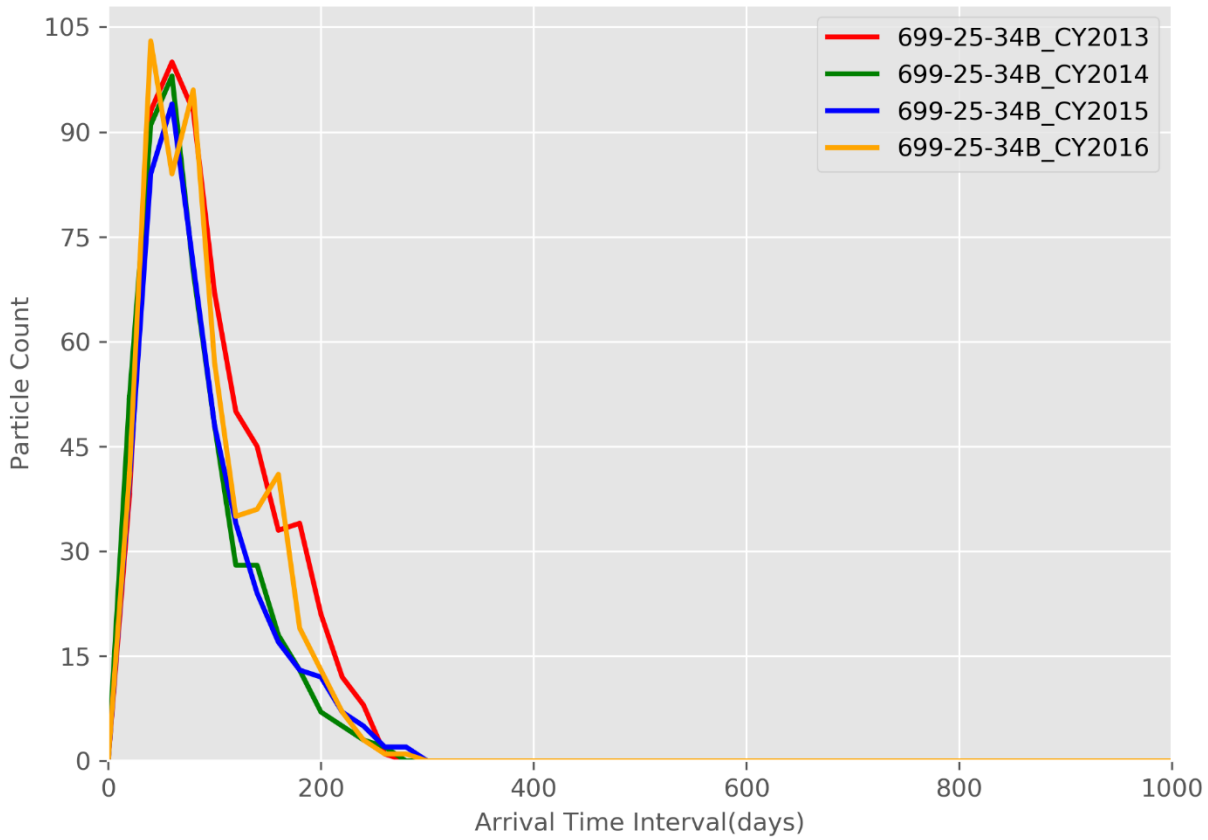

Figure 7-9. Particle Breakthrough Curves at Monitoring Well 699-25-34B

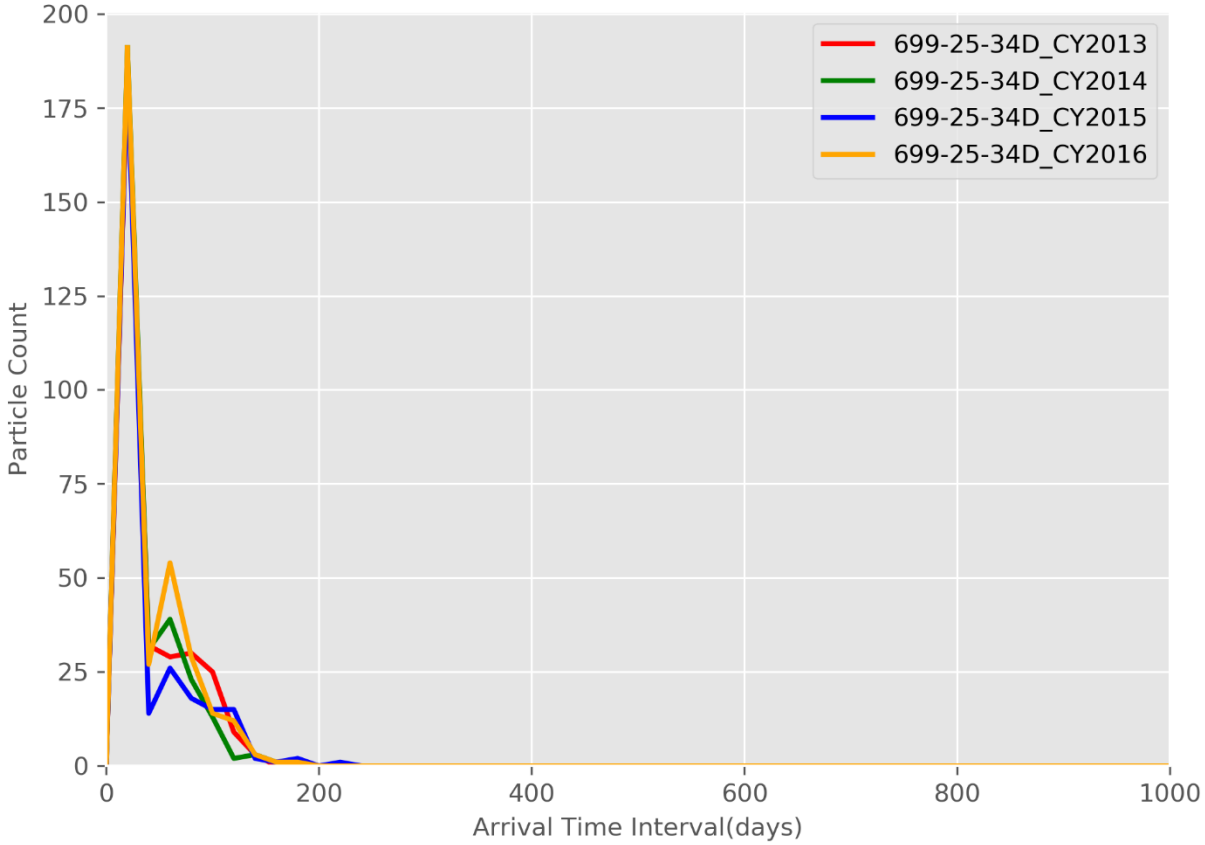

Figure 7-10. Particle Breakthrough Curves at Monitoring Well 699-25-34D

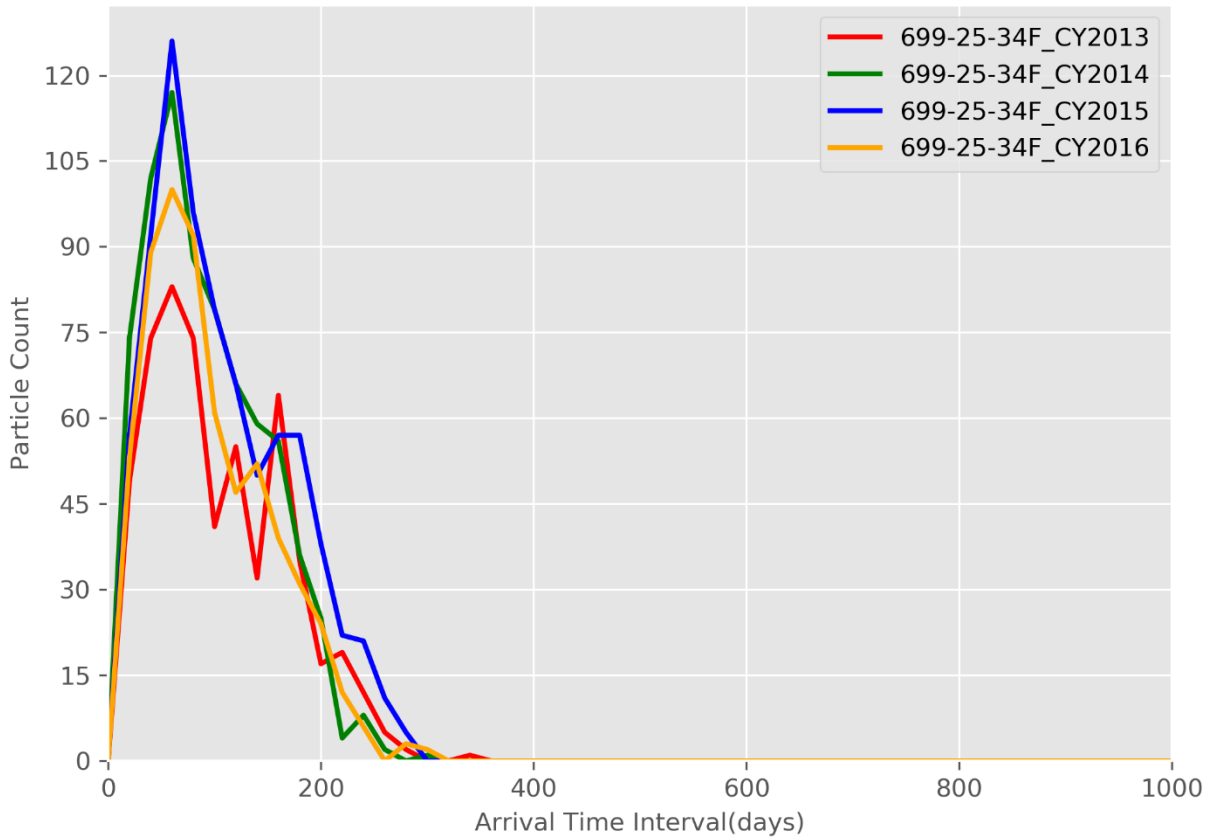

Figure 7-11. Particle Breakthrough Curves at Monitoring Well 699-25-34F

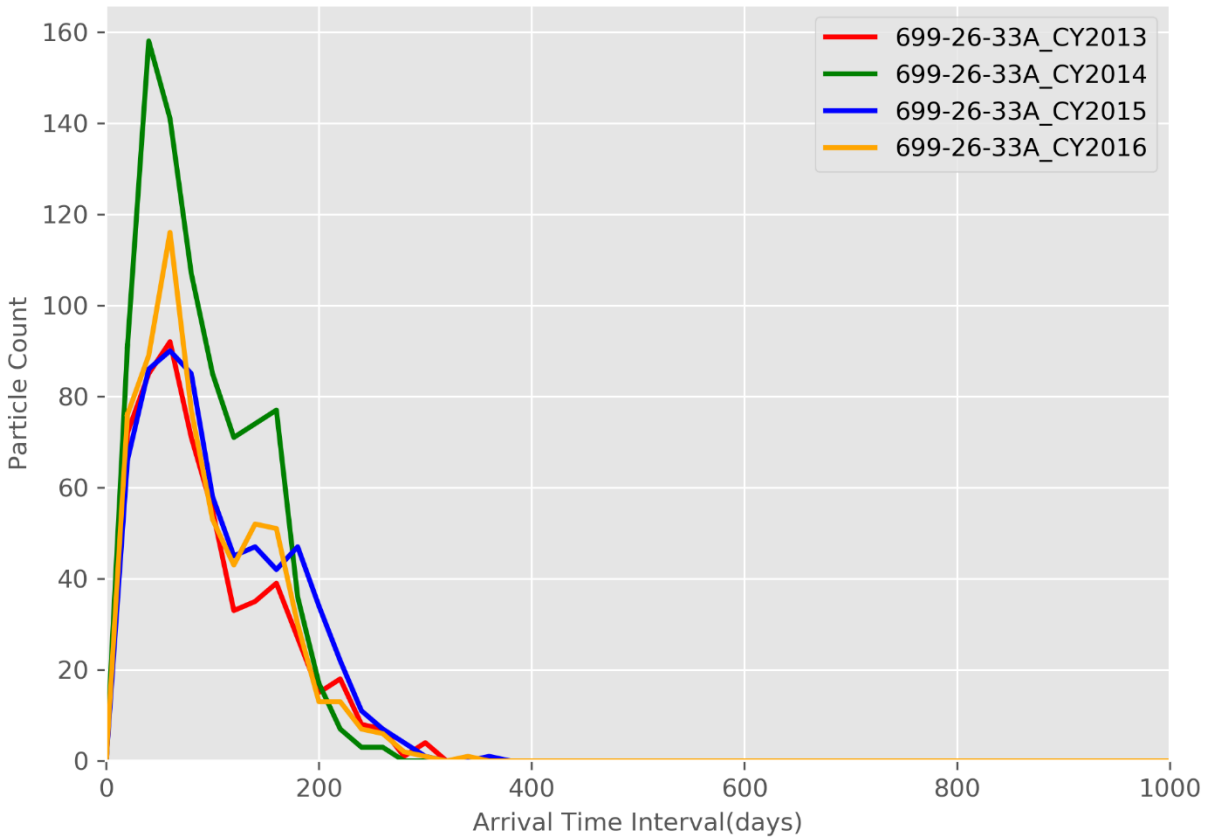

Figure 7-12. Particle Breakthrough Curves at Monitoring Well 699-26-33A

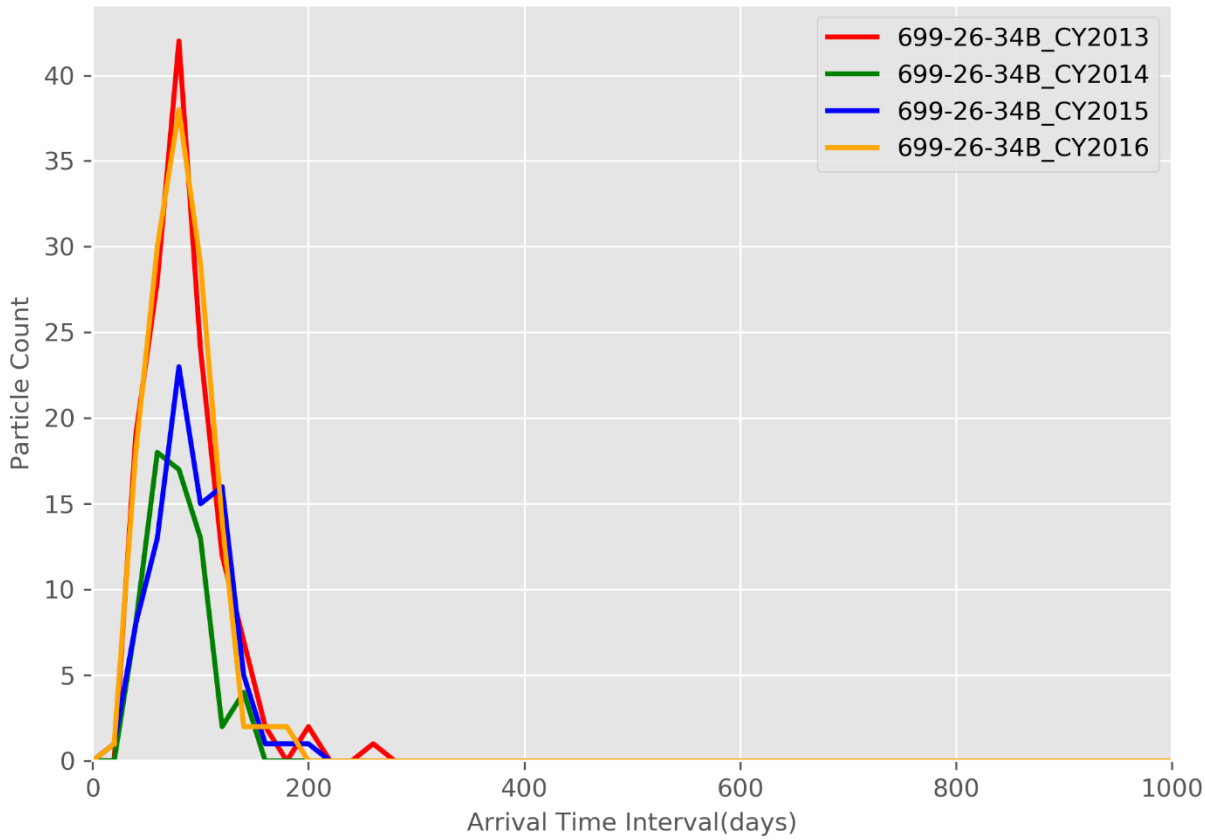

Figure 7-13. Particle Breakthrough Curves at Monitoring Well 699-26-34B

7.2.3 Particle Count Maps

Figures 7-14 through 7-17 depict the particle count maps developed based on the instantaneous release of a large number of particles at the facility. Particle movement was traced considering both advection and dispersion. The particle count maps depict areas of relatively higher and lower potential impact from a release at the facility that reaches the water table for groundwater flow conditions represented by calendar years 2013, 2014, 2015, and 2016. The particles are tracked for 1,000 days. Figures 7-14 through 7-17 depict the particle density after 1,000 days of calculated travel, by which time it was determined that all particles would have arrived at or passed by the interim status groundwater monitoring wells (see entries in Tables 7-2 through 7-6).

The goal of well placement is for the well locations to span the range of particle distribution as released from NRDWL. The particle count maps indicate well placement is suitable for detecting releases to the water table from NRDWL under the evaluated range of conditions and no additional monitoring wells are proposed.

Figure 7-14. Particle Count Map – NRDWL, 2013

Figure 7-15. Particle Count Map – NRDWL, 2014

Figure 7-16. Particle Count Map – NRDWL, 2015

Figure 7-17. Particle Count Map – NRDWL, 2016

7.3 Vertical Migration Potential

The potential effect of aquifer heterogeneity on the transport of dissolved constituents can be considered at two scales:

- At the scale of small variations in sedimentary materials (e.g., grain size variation and texture variability) that occurs within the same hydrofacies
- At the scale of lateral or vertical transitions between neighboring hydrofacies that exhibit differences in their physical or transport properties such as grain size, texture, and conductivity.

In the first instance, small-scale variations within a hydrofacies can lead to vertical movement in both directions, resulting in movement both deeper or shallower than anticipated for a homogeneous aquifer. These effects are often represented as nonsystematic or random (i.e., Fickian) by applying the theory and methods of macro-dispersion in calculations. In this case, for migration calculated using the particle tracking code mod-PATH3DU (which represents dispersion in three dimensions), particles subject to dispersion would move upward and downward compared to particles simulated without dispersion. Over sufficiently long travel paths, however, the average path of particles simulated with dispersion will closely approach that of particles simulated without dispersion.

In the second instance, as groundwater and dissolved constituents move horizontally or vertically between hydrofacies that exhibit substantially different properties (primarily hydraulic conductivity and mobile porosity), dissolved constituents may continue to migrate on the same vertical path or they may move upward or downward, depending on the differences in the properties of the two hydrofacies. If there is a single horizontal transition (or boundary) at a known location and the properties of the two hydrofacies are approximately known, then the effect of this transition can be approximated using the "plume diving" calculations described in greater detail in Section 7.3.3.1. If there is more than one horizontal transition, however, the calculations can become difficult to make using analytical techniques. The potential effects of vertical transitions between hydrofacies exhibiting different properties are best represented using a groundwater model such as the CPGWM.

Given the foregoing, if a monitoring well is located within the same hydrostratigraphic unit as the aquifer material beneath the release site, so that there are no intervening transitions between the release location and the monitoring well, then the potential effects of large-scale heterogeneity on vertical migration may be neglected and plume diving calculation methods such as described by the American Petroleum Institute (API) and presented below may be used. If this assumption is violated, however, site- or well-specific calculations should be made using a more sophisticated calculation tool, such as the following:

- Using the U.S. Environmental Protection Agency (EPA) plume diving calculator, which is described below, and which can represent lateral contrasts in aquifer hydraulic conductivity and recharge
- Representing the different strata explicitly using the CPGWM

7.3.1 Drawdown Due to Pumping

Pumping of groundwater at wells screened within an unconfined aquifer induces drawdown of the water table. This in turn can result in vertical migration of dissolved constituents that are at or close to the water table. However, the degree of vertical migration depends greatly upon the screened interval of the pumping well and the distance of the dissolved constituents from the pumping.

If the pumped well is screened throughout the full saturated thickness of the aquifer or is only screened in the upper portion of the aquifer (i.e., across the water table, with the bottom of the screen located above the aquifer base), the effect of pumping on vertical flow results from physical displacement of the water

table: groundwater flow and constituent migration remain essentially horizontal. If the well screen is fully penetrating, drawdown becomes evenly distributed throughout the entire thickness of the aquifer over time. Hantush, 1964, "Hydraulics of Wells," suggests that, for an isotropic aquifer, the drawdown will be the same across the full aquifer thickness beyond a distance of about 1.5 times the initial saturated thickness, B, of the aquifer. For an anisotropic aquifer, Hantush suggests that the same applies at a distance of about $1.5 \times B \times \sqrt{(Kh/Kv)}$ where Kh is the horizontal hydraulic conductivity and Kv is the vertical hydraulic conductivity. Although strictly developed for wells within confined aquifers, this rule-of-thumb can be reasonably applied to thick unconfined aquifers. Thus, for a fully penetrating pumping well, beyond the immediate vicinity of the well, drawdown is approximately evenly distributed throughout the full aquifer thickness and vertical gradients created by pumping dissipate both with distance from the pumping well and with elapsed time since the start of pumping.

If the pumping well is screened in the middle or lower portion of the aquifer (i.e., it is not screened across the water table, but rather the top of the screen is located some distance below the water table) then this partial penetration can lead the pumping to induce vertical gradients that move groundwater and dissolved constituents further downward than they would move absent pumping (Bair and Lahm, 1996, "Variations in Capture-Zone Geometry of a Partially Penetrating Pumping Well in an Unconfined Aquifer").
The significance of this effect depends upon the screen interval (i.e., vertical placement and degree of partial penetration), pumping rate, and distance of both the release location and the monitoring well from the pumped well.

Given the foregoing, if the monitoring well is located closer to the release location than to any groundwater extraction wells, then the potential effect of groundwater pumping on vertical migration may generally be neglected. This is particularly the case if the pumped well screen is open across the water table (i.e., the top of the pumped well screen is not located at significant depth below the water table).
If this assumption is violated, however, site- or well-specific calculations should be made using the appropriate calculation tool, most likely the CPGWM.

7.3.2 Accrual of Recharge at the Water Table

Vertical migration due to recharge accrual is often referred to as plume diving (Nichols and Roth, 2006, "Downward Solute Plume Migration: Assessment, Significance, and Implications for Characterization and Monitoring of "Diving Plumes","), although this term might be applied to all the above-mentioned conditions and factors. Plume diving due to recharge occurs when groundwater recharge has traversed the vadose zone and accrues at the top of the unconfined aquifer. Once within the aquifer, this newly accrued recharge begins to move in the direction of groundwater flow. Because the recharge water enters the aquifer from above, it can push dissolved contaminants downward. The amount that a plume "dives" due to this accrual of recharge depends on the amount of recharge water entering the system and the relative contribution this additional water makes to flow in the aquifer, which in turn depends upon the properties of the aquifer (principally, the hydraulic conductivity and the ambient horizontal hydraulic gradient).

The likely rate of vertical migration due to recharge accrual at a specific site can be estimated using a variety of methods, including analytical and numerical models. In relatively simple cases, simple analytical models can suffice to approximate the effects of recharge. In many cases, the output from these simple calculations can be compared with numerical simulations to provide confidence that they are representative, as is illustrated for this application using a series of calculations presented below. In more complex settings – such as those that exhibit lateral transitions between a small number of hydrofacies that exhibit different aquifer properties – the more sophisticated online EPA plume diving calculator (Weaver and Wilson, 2000, "Diving Plumes and Vertical Migration at Petroleum Hydrocarbon Release Sites") can approximate the vertical migration due to recharge within up to three lateral zones of different aquifer properties. In highly complex settings, where the path from the release point to the monitoring

well transitions laterally (or vertically) between several hydrofacies, the EPA calculator may not suffice, and a numerical groundwater model such as the CPGWM can be used to estimate the potential for vertical migration.

Given the foregoing, if the monitoring well is located within the same hydrostratigraphic unit as the aquifer material beneath the release site, so that there are no intervening transitions between the release location and the monitoring wells, then the potential effects of recharge on vertical migration may be estimated using the analytical techniques described by the API as presented below. If this assumption is violated, however, site- or well-specific calculations should be made using one or more appropriate calculation tools, which may include the EPA plume diving calculator or the CPGWM.

7.3.3 Example Calculations

Review of the geographic location of the Central Plateau DWMUs and the monitoring well networks under development to detect potential subsurface releases indicates that in the majority of circumstances, the existing or proposed monitoring wells are located within the same hydrostratigraphic unit as the aquifer material beneath the release site, so that there are no major transitions in the region between the release location and the monitoring wells. Furthermore, in those instances where there is groundwater pumping, primarily throughout the 200 West Area associated with the 200 West P&T remedies, the pumping wells either fully penetrate the saturated aquifer or are screened across the water table, and the monitoring wells are generally closer to the release location than to the pumped wells so that the effects of vertical gradients induced by pumping should not be significant. Under these conditions, the primary factors that may affect the vertical migration of dissolved constituents from the water table are small-scale variations within a hydrofacies that can be mimicked through dispersive mechanisms in particle-tracking calculations and accrual of recharge at the water table.

Because the effects of small-scale dispersion can be represented in mod-PATH3DU if required, a series of calculations was made to estimate the likely rate of downward vertical migration of dissolved constituents under the influence of recharge at the water table. The calculations were made using two approaches. First, analytical calculations were made using the API plume diving calculation, which is based on the ratio of the groundwater recharge rate to the groundwater discharge rate (also known as the Darcy velocity) and is the most widely used analytical calculation with the most widespread applicability. Following this, calculations were made using the CPGWM to validate the results obtained using the analytical calculation.

7.3.3.1 Analytical Calculation

The analytical calculation presented below assumes that groundwater recharge is fairly evenly distributed at the site that the subsurface in the region between the release location and the monitoring well is homogeneous and that the aquifer thickness is large relative to the rate of accumulation of recharge and the likely vertical movement of constituents. The analytical calculation provides an estimate of the rate of vertical migration (i.e., the rate of “dive”) per unit distance traveled. The calculation can be presented in many ways. Common variants, provided in Eq. 1 (modified after Nichols and Roth, 2006), are subsequently collectively referred to here as the API plume diving calculation.

$$Slope\ of\ Dive\ (S) = \frac{Accretion\ Rate\ (I)}{Seepage\ Velocity\ (V)} = \frac{Vertical\ velocity\ (v_v)}{Horizontal\ velocity\ (v_h)} = \frac{Recharge\ Rate\ (i)}{Darcy\ Flux\ (q)} \qquad \text{Eq. (1)}$$

In Eq.1, the accretion rate is equivalent to the vertical velocity which is equivalent to the recharge rate (e.g., in units of ft/yr) divided by the aquifer porosity; and the seepage velocity is equivalent to the horizontal velocity which is equivalent to the Darcy Flux (in consistent units of ft/yr: also known as the specific discharge), divided by the aquifer porosity. The calculated slope, S, can be used to estimate the

distance beneath the water table at which dissolved concentrations will be found at a specified distance from the point of release. Alternatively, the expression presented in Eq. 1 can be re-organized to estimate the potential for dissolved constituents to migrate beneath the bottom of a specific well screen that is located a known distance (x) from the point of release, as follows (Nichols and Roth, 2006):

$$i \geq \frac{qd}{x} \qquad \text{Eq. (2)}$$

Where the quantity d corresponds to the depth from the water table to the bottom of the monitoring well screen. In this relationship, if the recharge rate, *i*, exceeds the right-hand side, then the dissolved constituents may be anticipated to migrate beneath the corresponding well. For aquifers that are bounded below by an aquitard, the foregoing API plume diving calculations tend to overestimate the rate of plume dive. For this reason, its use can be conservative in that it ensures monitoring wells are not emplaced too high (i.e., too close to the water table), thereby enabling dissolved constituents to pass beneath the well screen. Furthermore, the calculations can be quickly made and tabulated to evaluate the vertical screen intervals of either existing or proposed wells for monitoring efficacy.

For demonstration purposes, the 200 West Area DMWU, Waste Management Area (WMA) T, was used as an example site. In the vicinity of the WMA T unit, the following parameters are estimated based on published values as incorporated within the CPGWM:

- Horizontal hydraulic conductivity of Ringold unit E is 5 m/d (16 ft/d)
- Horizontal hydraulic gradient is 0.008 m/m
- Mobile porosity of the Ringold unit E is 0.15
- Average groundwater recharge is 8.6 mm/yr (2 x 10^{-5} m/d, 2.8 x 10^{-2} ft/yr)

Given the above, through application of the API plume diving calculator (Eq. 1) above, the slope of dive can be determined per Eq. 3 or Eq. 4 (to about two significant digits):

$$S = \frac{v_v}{v_H} = \frac{(2\times10^{-5}\ m/d)/(0.15)}{(5\ m/d)(0.008)/(0.15)} = 5.0 \times 10^{-4} \qquad \text{Eq. (3)}$$

or

$$S = \frac{i}{q} = \frac{(2\times10^{-5}\ m/d)}{(5\ m/d)(0.008)} = 5.0 \times 10^{-4} \qquad \text{Eq. (4)}$$

The results of these calculations can also be summarized as follows: on average, within the same hydrostratigraphic unit (i.e., within the Ringold unit E), it can be anticipated that dissolved constituents will migrate vertically downward about 1 m (3 ft) for every 2,000 m (6,562 ft) of horizontal migration under the influence only of accrual of recharge at the water table. Use of full precision in these calculations results in a ratio of about 1:1690 instead of 1:2000.

7.3.3.2 Verification with the CPGWM

The foregoing results obtained from the API plume diving calculation rest upon the simplifying assumptions described previously. To test that the API plume diving calculations are reasonably representative of conditions encountered at the unit as incorporated within the CPGWM, calculations were conducted using the mod-PATH3DU postprocessor to track particles released throughout the area of the WMA T unit. The mod-PATH3DU particle-tracking code uses groundwater heads and flow fields computed by the CPGWM to migrate particles considering both advection and dispersion. Because the particle tracking calculations tend to involve the modeling of many hundreds of thousands of particles, for purposes of this verification, the following steps were taken:

1. Particle starting locations were distributed throughout the WMA T unit, and the particles were released at the water table mimicking an impact of dissolved constituents from an overlying release. In total, 4,800 particles were released and tracked for this calculation.

2. The paths of all particles were computed over time. The same longitudinal, transverse and vertical dispersivity parameters were used as for other particle tracking analyses conducted for the monitoring network evaluation performed herein.

3. At all intermediate tracking steps throughout the migration of the particles, the following were calculated for every tracked particle:

   a. The elevation of both the particle and the water table
   b. The depth below the water table of every particle
   c. The horizontal distance of the particles from their initial locations

4. Depths below the water table calculated for each particle were grouped according to horizontal distance from the starting location (for plotting purposes, they were grouped into distance intervals of 100 m [328 ft]).

5. Box-and-whisker plots were constructed of the grouped results of the "depth-below-water-table versus horizontal distance" calculations.

6. The box-and-whisker plots were then graphed together with the results of the API plume diving calculation.

Results of the comparison between particle tracking using mod-PATH3DU and the CPGWM versus the API plume diving calculations are depicted in Figure 7-19. In this figure, each set of box-and-whiskers summarizes the vertical location of *all* particles within the corresponding 100 m (328 ft) interval travel distance from their release point. The correspondence between the results obtained using the API plume diving calculator and the CPGWM is very good. In reviewing Figure 7-18, the following points are important to note:

- The figure depicts migration over a distance of 1,000 m (3,281 ft) from the hypothetical release location at WMA T. Although the monitoring wells of the WMA T unit are all located within about 200 m (656 ft) of the unit, the correspondence between the API plume diving calculator and the CPGWM extends well beyond this distance and is generally good throughout the entire 1,000 m (3,281 ft) distance.

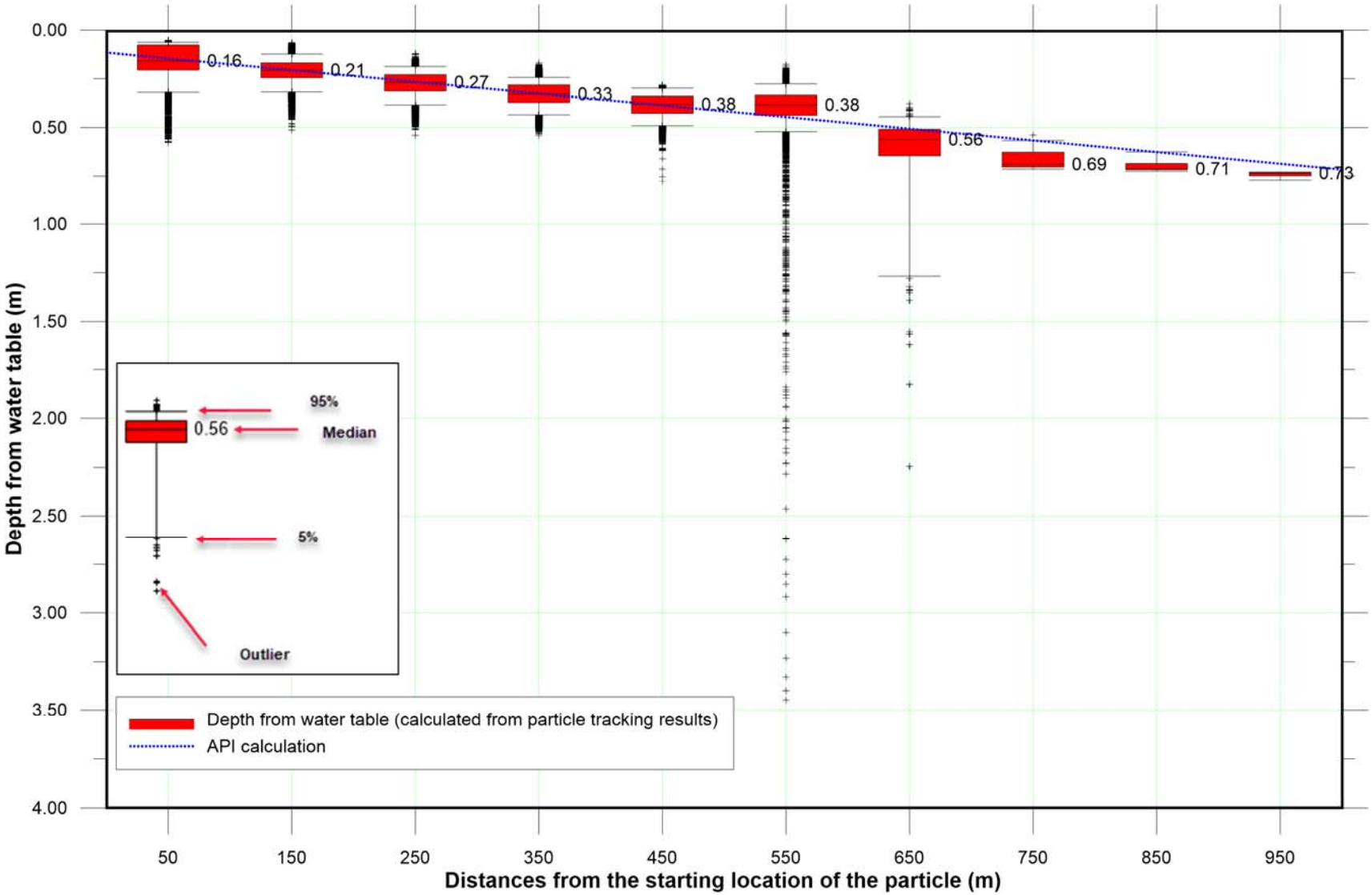

Figure 7-18. Comparison of Vertical Migration Evaluation Using the API Calculator and the CPGWM

- At a distance of about 550 m (1,804 ft) from the release location, there is evidence of greater vertical spread for some particles. This distance approximates the location of one of the 200 West P&T system extraction wells (299-W11-50). At this location, the effect of pumping appears to cause some vertical spread; however, the vertical distances between the top and bottom of the box, which represent the 25th and 75th percentiles of particle depth, respectively, and between the whiskers, which represent the 5th and 95th percentiles of particle depth, remain small and similar to the depth estimated using the API plume diving calculator.
- The comparison between the API plume diving calculator and the CPGWM is slightly less strong beyond a migration distance of about 550 m (1,804 ft) from the release point; however, this is beyond the distance of monitoring wells of interest to the WMA T unit and beyond the distance of the closest and most influential 200 West P&T system extraction well such that most particles have actually been "captured" by that well and do not migrate beyond this distance. Calculations beyond the location of the extraction well are, because of the removal of particles, based on a smaller number of particles and therefore subject to relatively more dispersive effects than the calculations upgradient of the extraction well.

The correspondence between the results obtained using the API plume diving calculator and those obtained using the CPGWM is very good. This further indicates that use of the API calculator is appropriate for estimating the potential effects of recharge on vertical migration so long as the conditions for its use, including that monitoring wells are located within the same hydrostratigraphic unit as the aquifer material beneath the release site and are closer to the release location than to any groundwater pumping wells are met.

7.3.3.3 Vertical Evaluation Summary and Applicability to NRDWL

Review of the geographic location of NRDWL and the associated monitoring well network indicates that existing or proposed monitoring wells are located within the same hydrostratigraphic unit as the aquifer material beneath the release site (so that there are no intervening transitions between the release location and the monitoring wells) (Section 2.4.2 in DOE/RL-2015-32). There are no groundwater extraction wells in the vicinity of NRDWL, and none are planned for the foreseeable future; thus, the monitoring wells are closer to the potential contaminant release location within NRDWL than to any groundwater pumping wells. Given these conditions, the API plume diving calculator provides reliable estimates of the likely average rate of vertical migration of dissolved constituents moving downgradient from their hypothetical location of release at the water table.

The API plume diving calculator can be used to evaluate the depths of the monitoring well screens in relation to the likely average rate of vertical migration of dissolved constituents moving downgradient from the location of release to the water table. Knowing the distance from the release locations to the monitoring well, Eq. 2 can be used to calculate the likely depth of the contamination at the well location and this depth can be compared to the depth of the bottom of the monitoring well screen.

The analysis above concluded that an analytical calculation, the API plume diving calculation (Nichols and Roth, 2006), could be used to estimate the likely rate of vertical migration of dissolved constituents downward under the influence of recharge at the water table. This estimated depth of the plume can be compared to the depth from the water table to the bottom of the monitoring well screen. If the depth of the plume is below the bottom of the monitoring well screen, then the dissolved constituents may be anticipated to pass beneath the well screen. If the depth of the plume falls within the interval between the top of the water table and the bottom of the well screen, then the well depth is appropriate for detecting releases at a Central Plateau facility such as NRDWL.

For each downgradient monitoring well at NRDWL, the distance used in the calculation was the distance from the centroid of the facility to each well location. The results of the API plume diving calculations for the downgradient wells for NRDWL are shown in Table 7-7.

Table 7-7. Summary of Well Screen Interval Evaluation for Downgradient Wells

Monitoring Well	Existing or Proposed Well?	Distance, D (m)[a]	Recharge, *i* (m/yr)[b]	Slope, S, of Plume Dive[c]	Estimated Depth of Plume Below Water Table (m)[d]	Depth from Water Table to Bottom of Well Screen (m)[e]	Is Plume Depth Above Bottom of the Screen? (Yes/No/N/A)
699-25-34D	Existing	61.6	8.76E-03	1.46E-04	0.0090	7.10	Yes
699-26-34B	Existing	106.4	8.76E-03	1.46E-04	0.0155	7.0	Yes
699-26-33A	Existing	121.7	8.76E-03	1.46E-04	0.0177	8.1	Yes
699-25-34F	Existing	104.5	8.76E-03	1.46E-04	0.0152	8.2	Yes
699-25-34B	Existing	112.4	8.76E-03	1.46E-04	0.0164	2.0	Yes

a. Distance of the well from the centroid of the dangerous waste management unit.

b. A representative number from the CPGWM. The recharge values, which represent fluxes from surface water discharge due to historical operations at the Hanford Site, are summarized in EMDT-BC-0002, *Vadose Zone Attenuated Recharge, Electronic Modeling Data Transmittal – Boundary Condition (Artificial Recharge)–0002*. The anthropogenic flux is added to the natural recharge component in order to establish the final total recharge flux used in the simulations. Discharges included in EMDT-BC-0002 have been attenuated to account for travel through the vadose zone.

c. Slope of the plume dive computed using the American Petroleum Institute plume diving calculation as detailed above. The migration parameters for NRDWL used in the calculation of slope are as follows:

Hydraulic conductivity: 1,500 m/d (4,921 ft/d) (a representative value from multiple sources, including the CPGWM)

Hydraulic gradient: 1.097E-04 (a representative number from the CPGWM and water-level maps)

d. Plume depth at monitoring well location computed from distance, D, times slope, S.

e. Depths obtained from Table 3-4 in DOE/RL-2017-19, *Groundwater Quality Assessment Plan for the Nonradioactive Dangerous Waste Landfill*.

CPGWM = Central Plateau Groundwater Model

N/A = not applicable

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8 References

Bair, E.S., and T.D. Lahm, 1996, "Variations in Capture-Zone Geometry of a Partially Penetrating Pumping Well in an Unconfined Aquifer," *Ground Water*, 34(5): 842–852.

CHPRC-02839, 2016, *KT3D_H2O and MEUK Integrated Software Management Plan: KT3D_H2O Version 3.5.1 and MEUK Version 0.2.2*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington.

CHPRC-00261, 2014, *MODFLOW and Related Codes Acceptance Test Report: CHPRC Build 7*, Rev. 7, CH2M HILL Plateau Remediation Company, Richland, Washington.

CP-47631, 2017, *Model Package Report: Central Plateau Groundwater Model Version 8.4.5*, Rev. 4, CH2M HILL Plateau Remediation Company, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/pdf.cfm?accession=0066449H.

CP-57037, 2015, *Model Package Report: Plateau to River Groundwater Transport Model Version 7.1*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington Available at: https://pdw.hanford.gov/arpir/pdf.cfm?accession=0080149H.

Comprehensive Environmental Response, Compensation, and Liability Act of 1980, 42 USC 9601, et seq., Pub. L. 107-377, December 31, 2002. Available at: https://www.csu.edu/cerc/researchreports/documents/CERCLASummary1980.pdf.

DOE/RL-2015-32, 2016, *Groundwater Monitoring Plan for the Nonradioactive Dangerous Waste Landfill*, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/pdf.cfm?accession=0074641H.

DOE/RL-2017-19, 2017, *Groundwater Quality Assessment Plan for the Nonradioactive Dangerous Waste Landfill, Hanford Site*, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington. Available at: http://pdw.hanford.gov/arpir/pdf.cfm?accession=0072142H.

ECF-200E-18-0066, 2018, *Groundwater Flow and Migration Calculations to Assess Monitoring Networks in the 200 East Area Dangerous Waste Management Units*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/pdf.cfm?accession=0064076H.

ECF-Hanford-16-0013, 2017, *Hydraulic Gradients and Velocity Calculations for RCRA Sites in 2015*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/pdf.cfm?accession=0075572H.

ECF-Hanford-17-0241, 2017, *Hydraulic Gradient and Velocity Calculations for RCRA Sites in 2017*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/pdf.cfm?accession=0066390H.

EMDT-BC-0002, 2009, *Vadose Zone Attenuated Recharge, Electronic Modeling Data Transmittal – Boundary Condition (Artificial Recharge)-0002*, Rev. 0, INTERA, Inc., Richland, Washington.

Hantush, M.S., 1964, "Hydraulics of Wells," *Advances in Hydroscience* 1:281-442.

Ihaka, R. and R. Gentleman, 1996, "R: A Language for Data Analysis and Graphics," *Journal of Computational and Graphical Statistics*, 5(3): 299-314. Available at: https://www.stat.auckland.ac.nz/~ihaka/downloads/R-paper.pdf.

Karanovic, M., M. Tonkin, and D. Wilson, 2009, "KT3D_H20: A Program for Kriging Water-Level Data Using Hydrologic Drift Terms," *Ground Water*, 47(4):580-586. Available at:

Mitchell, Andy, 1999, *The ESRI Guide to GIS Analysis, Volume 1: Geographic Patterns & Relationships*, First Edition, Environmental Systems Research Institute, Inc., Redlands, California.

Muffels, C., X. Wang, M. Tonkin, C. Neville, M. Ramadhan, and J.R. Craig, 2017, *User's Guide for mod-PATH3DU, A Groundwater Path and Travel-Time Simulator*, S.S. Papadopulos and Associates Inc., Bethesda, Maryland. Available at: http://mp3du.sspa.com/man/.

Nichols, E. M. and T. L Roth, 2006, "Downward Solute Plume Migration: Assessment, Significance, and Implications for Characterization and Monitoring of "Diving Plumes"," *API Soil and Groundwater Technical Task Force Bulletin 24*. Available at: https://www.api.org/~/media/files/ehs/clean_water/bulletins/24_bull.ashx.

Pebesma, E.J., 2004, "Multivariable Geostatistics in S: the gstat Package," *Computers & Geosciences* 30(7):683-691. Available at: https://www.sciencedirect.com/science/article/pii/S0098300404000676.

PRC-PRO-IRM-309, 2014, *Controlled Software Management*, Rev. 5, Change 0, CH2M HILL Plateau Remediation Company, Richland, Washington.

R Development Core Team, 2013, R: *A Language and Environment for Statistical Computing*, R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0. Available at: http://www.R-project.org/.

SGW-42305, 2009, *Collection and Mapping of Water Levels to Assist in the Evaluation of Groundwater Pump-and-Treat Remedy Performance*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington. Available at: http://pdw.hanford.gov/arpir/pdf.cfm?accession=0911170654.

SGW-60338, 2017, *Historical Changes in Water Table Elevation and Groundwater Flow Direction at Hanford: 1944 to 2014*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/pdf.cfm?accession=0072270H.

Tonkin, M.J., J. Kennel, W. Huber, and J.M. Lambie, 2016, "Multi-Event Universal Kriging (MEUK)," *Advances in Water Resources*, 87:92-105.

Weaver, J.W. and Wilson J.T., 2000, "Diving Plumes and Vertical Migration at Petroleum Hydrocarbon Release Sites," *New England Interstate Water Pollution Control Commission (NEIWPCC) LUSTLine Bulletin 36*, November. Available at: https://clu-in.org/download/contaminantfocus/mtbe/EPA-Plume-Dive-LL36DvPlm.pdf.

Appendix A

Tables of Inputs to Groundwater Level Analysis

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Tables

Table A-1. Measured Water Levels A-1
Table A-2. Coordinates of Defined Line Drift Representing Columbia River A-2

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Table A-1. Measured Water Levels

Well Name	XCOORDS	YCOORDS	March 2013	March 2014	March 2015	March 2016
299-E16-2	576129.205	135419.286	121.655	--	--	--
699-15-26	581770.33	127963.55	--	--	--	121.117
699-20-20	583518.466	129714.343	121.121	121.08	121.071	121.035
699-22-35	579340.584	130309.018	121.636	121.626	121.613	121.578
699-23-34A	579486.265	130552.382	121.638	121.628	121.616	121.577
699-23-34B	579433.025	130384.701	121.635	121.625	121.613	121.577
699-24-33	579720.068	130768.366	121.631	121.632	121.626	121.562
699-24-34A	579522.72	130669.377	121.634	121.629	121.612	--
699-24-34B	579554.117	130771.817	121.635	121.628	121.614	--
699-24-34C	579588.617	130886.874	121.637	121.628	121.61	121.578
699-24-34D	579524.7	130672.74	--	--	--	121.58
699-24-34E	579555	130775.05	--	--	--	121.575
699-24-35	579176.838	130914.962	121.647	121.641	121.63	121.589
699-24-36	578833.7	130874.73	--	--	121.635	121.606
699-25-34A	579694.867	131230.891	121.642	121.624	--	--
699-25-34B	579679.415	131181.362	121.636	121.634	121.615	121.581
699-25-34C	579635.012	131037.834	121.636	121.634	121.617	121.58
699-25-34D	579589.793	131190.9	121.636	121.6195	121.618	121.578
699-25-34F	579693.92	131227.61	--	--	--	121.578
699-26-33	579709.73	131280.289	121.639	121.613	121.615	--
699-26-33A	579709.97	131284.02	--	--	--	121.58
699-26-34A	579394.841	131467.551	121.641	121.642	--	121.583
699-26-34B	579629.347	131352.247	121.634	121.635	121.622	121.58
699-26-35A	579314.109	131347.254	121.652	121.646	121.617	121.598
699-26-38	579030.19	131469.63	--	--	--	121.607
699-28-40	577621.709	131929.765	--	--	--	121.675
699-31-31	580551.687	132794.238	121.586	121.609	121.574	121.528
699-32-43	576902.127	133278.606	121.746	121.722	121.706	121.673
699-34-39A	578013.476	133881.121	121.729	121.712	121.691	121.666
699-34-41B	577338.305	133911.728	121.751	121.729	121.699	121.684
699-37-43	576828.526	134782.511	121.757	121.745	121.723	121.709
699-8-25	582298.96	125935.61	121.022	120.962	120.936	120.8945

Table A-2. Coordinates of Defined Line Drift Representing Columbia River

X1	X2	Y1	Y2	NAME	TERM	EVENT	VAL
587054.7	589913.1	139272.9	137397.4	RIV_CP_29	29	3	1
589935.9	591065.9	137378.6	135864.1	RIV_CP_30	29	3	1
591084.8	591512.7	135840.8	134930.3	RIV_CP_31	29	3	1
591529	593523.6	134905.1	133592.2	RIV_CP_32	29	3	1
593544.9	594728.1	133571.1	130805.7	RIV_CP_33	29	3	1
594731.5	594599.4	130777	130191.7	RIV_CP_34	29	3	1
594598.4	594697.9	130161.9	128605.4	RIV_CP_35	29	3	1
594700	595078.9	128575.5	127186.5	RIV_CP_36	29	3	1
595081.7	595011.5	127156.8	125274.4	RIV_CP_37	29	3	1
595009.2	595320.8	125244.6	122623.2	RIV_CP_38	29	3	1
595322.3	594875.3	122593.4	119417.2	RIV_CP_39	29	3	1
594867.4	594444.5	119388.2	117471.5	RIV_CP_40	29	3	1