ECF-200E-19-0081
Revision 1

Groundwater Elevation Mapping for 200 East Area - Quarter 1 Calendar Year 2019

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

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ENVIRONMENTAL CALCULATION COVER PAGE (Continued)

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Terms

CCU	Cold Creek unit
CERCLA	*Comprehensive Environmental Response, Compensation, and Liability Act of 1980*
CPGWM	Central Plateau Groundwater Model
CY	calendar year
DWMU	Dangerous Waste Management Unit
ECF	environmental calculation file
HSU	hydrostratigraphic unit
LLBG	low-level burial grounds
OU	operable unit
P&T	pump and treat
RCRA	*Resource Conservation and Recovery Act of 1976*
SME	subject matter expert
TRIM	Tikhonov Regularized Inverse Method
WMA	Waste Management Area

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1 Purpose

This environmental calculation file (ECF) describes calculations made to generate water-level maps for the first quarter of calendar year (CY) 2019 in the 200 East Area at the Hanford Site Central Plateau (Figure 1-1). This ECF provides the conceptual and methodological basis for the calculations performed, details the specific methods and codes used to undertake the calculations, and presents results of calculations. These water-level maps are used in a variety of calculations and reports for the different *Resource Conservation and Recovery Act of 1976* (RCRA) Dangerous Waste Management Units (DWMUs) and *Comprehensive Environmental Response, Compensation, and Liability Act of 1980* (CERCLA) groundwater Operable Units (OUs) located within the 200 East Area. A separate ECF is being prepared to present calculations of groundwater hydraulic gradients and average linear velocities at the individual DWMUs.

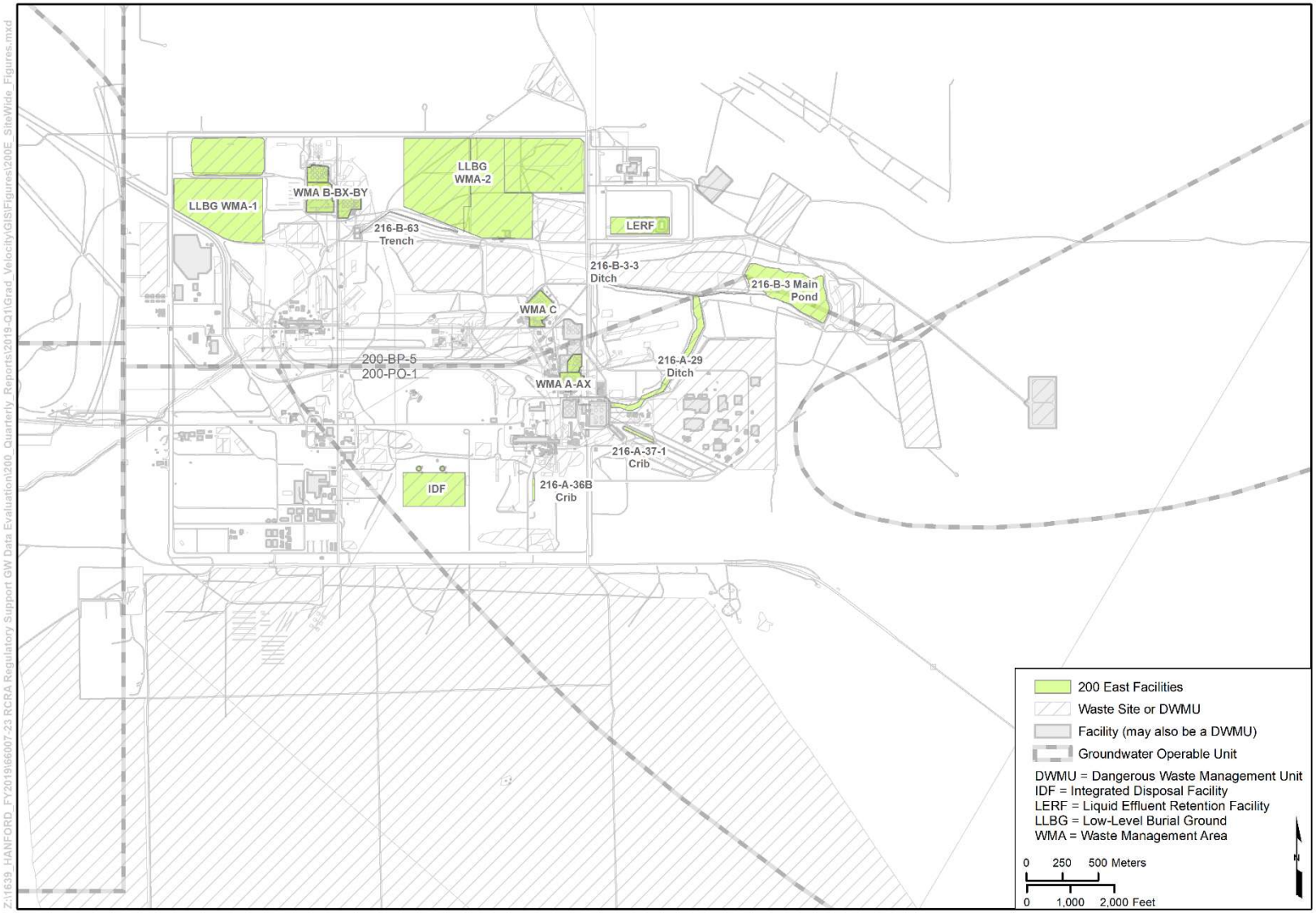

Figure 1-1. Hanford Site 200 East Area and Associated Waste Sites

2 Background

Historically, groundwater elevations in the 200 East Area varied greatly in response to discharges of water from Hanford Site operations to many large wastewater receiving features such as the 216-B-3 Pond and 216-A-25 Pond. The 200 East Area groundwater elevation also responded to historical discharges in the 200 West Area. Most of those discharges ceased by the mid-1990s, after which groundwater elevations in the 200 East Area have fallen steadily in areas where discharges formerly occurred. In recent years, changes in groundwater elevations and in corresponding hydraulic gradients and flow directions have been less evident from year-to-year, as groundwater elevations asymptotically approach a quasi-steady-state condition.

The unconfined aquifer beneath the 200 East Area of the Central Plateau occurs in a buried paleochannel consisting of highly permeable sediments of the Hanford formation and Cold Creek unit (CCU). The high permeabilities cause the water table to exhibit a very low-magnitude hydraulic gradient (i.e., the water table is flat). In 2004, the hydraulic gradient magnitude in the 200 East Area vicinity was estimated to be 1.8×10^{-5} m/m (1.8×10^{-5} ft/ft) using regional water-level measurement data (SGW-54165, *Evaluation of the Unconfined Aquifer Hydraulic Gradient Beneath the 200 East Area, Hanford Site*). At the low-level burial ground (LLBG) Waste Management Area (WMA)-1, for example, this hydraulic gradient equates to a water table elevation change of 1.6 cm (0.63 in.) across the facility. However, water-level measurements at LLBG WMA-1 typically exhibited variations of about 6 cm (2.4 in.). Thus, local variations in water-level measurements in such a low-gradient setting obscure differences in the true water table and resulting estimates of hydraulic gradients are subject to a low signal-to-noise ratio. In addition, groundwater elevations in the 200 East Area also exhibit seasonal variability in response to changes in the discharge boundary elevation at the Columbia River and periodic discharges to the Treated Effluent Disposal Facility.

To improve the accuracy of depth-to-groundwater measurements and corresponding groundwater elevation (i.e., water table) maps in the 200 East Area, a network of wells was established for which steps were taken to reduce water-level measurement error. This was first done at LLBG WMA-1 and then later at the Integrated Disposal Facility/Plutonium Uranium Extraction plant cribs area, LLBG WMA-2, and the Liquid Effluent Retention Facility. Previous work indicated that borehole deviation (i.e., non-verticality) was the most important source of error in the 200 East Area water-level measurements. To remedy this, gyroscope surveys were performed in the wells to correct for verticality error, and the tops of all the well casings were resurveyed for elevation using a highly accurate leveling technique.

The initial results at the facilities were mixed (SGW-54165), with some areas still indicating uncertain flow directions. Based on this, it was reasoned that larger study areas were needed to allow for water-level elevation differences between wells to be discerned. The well networks were expanded so that eventually a single low-gradient well network was established encompassing much of the 200 East Area. The collection of monthly water-level measurements from this network began during May 2013. The 200 East Area low-gradient network initially consisted of 56 wells and by 2018, had expanded to 70 wells.

A groundwater pump and treat (P&T) system is in place and operating within the main unconfined aquifer in the 200 East Area to address groundwater contamination at the 200-BP-5 groundwater OU. In first quarter of 2019, this groundwater P&T system consisted of a single extraction well (299-E33-360) operating at an average flow rate of 602 L/min (159 gal/min). Due to the high transmissivity of the gravel of the CCU, in which the well is installed, the effects of groundwater extraction at the well only influences hydraulic gradients and corresponding groundwater flow directions and rates measurably in the immediate vicinity of the well.

2.1 Gradient and Flow Path Interpretation Overview

The groundwater head and gradient calculation approach and tools developed for ECF-200E-18-0085, *Water Level Mapping and Hydraulic Gradient Calculations for 200 East Area RCRA Sites, 2018*, were used to meet the objectives of this ECF. The method detailed in ECF-200E-18-0085 combined a simplified groundwater flow simulator with statistical methods to obtain a best-estimate of groundwater flow patterns in the vicinity of each facility. The parameters of the underlying flow simulator were determined through a regularized inverse interpolation technique referred to as the Tikhonov Regularized Inverse Method (TRIM). The TRIM, summarized here and detailed in Chapter 3, is founded upon a formal mathematical method that seeks a tradeoff between the complexity of the method or parameterization used to interpret measured data versus the "fit" to those data that the chosen method or parameterization attains. As described by Menke, 2018, *Geophysical Data Analysis: Discrete Inverse Theory, Fourth Edition,* the calibration process is a tradeoff between method or parameter complexity and data fit – the more complex the method, or its parameterization, the more closely the outputs from that method or parameterization can be expected to fit the data. However, a better fit does not guarantee a better estimator or predictor. Particularly in cases like the 200 East Area where there is a low signal-to-noise ratio in the data, "over-fitting" can occur during which parameters respond to the noise rather than signal (Doherty, 2015, *Calibration and Uncertainty Analysis for Complex Environmental Models, PEST: Complete Theory and What it Means for Modelling the Real World*). Without constraints that recognize the presence of a low signal-to-noise ratio, overfitting can attain a good data fit by inferring high parameter or method complexity, such as exaggerated heterogeneity in a homogeneous system. In contrast, under-fitting can occur when the method or parameterization used is too simple because it does not reasonably approximate the underlying physics or reflect the dominant physical characteristics of the system. A result of under-fitting is insufficient capability to reproduce measured data. In either case of over- or under-fitting, the results often do not comport well with subject matter expert's (SME's) knowledge of the system or with independent information.

The TRIM was used to obtain a piecewise, continuous grid of groundwater elevations using a simplified groundwater flow simulator as the mechanism to interpolate between measured water levels in 2018 for ECF-200E-18-0085. This was accomplished by developing a single-layer (i.e., two-dimensional) steady-state simulation approximating dominant groundwater flow characteristics over an area encompassing the 200 East Area facilities, and then using Tikhonov regularization (Tikhonov and Arsenin, 1977, *Solutions of Ill-Posed Problems*, detailed in Chapter 3) to constrain parameter complexity and prevent over-fitting to the measured water-level data. The hydraulic conductivity field determined through TRIM analysis for ECF-200E-18-0085 was then used in the steady-state simulations to interpolate between measured water levels for the purposes of this ECF. The advantage of using a simplified groundwater flow simulator as the mechanism to interpolate between the measured water levels is that the resulting groundwater elevation grids conserve flow and are suitable for tracking particles to evaluate likely paths of groundwater.

3 Calculation Methods

Calculations were completed to develop groundwater elevation maps for the 200 East Area. This chapter describes the calculation methods used to support this ECF. Some aspects of the evaluation described here – specifically, the hydraulic conductivity field for the simplified two-dimensional groundwater flow simulator used in the TRIM analysis work – were developed for and described in ECF-200E-18-0085. The work completed herein used the underlying groundwater flow simulator documented in ECF-200E-18-0085 to create water-level maps representing the average groundwater elevation conditions for the first quarter of CY 2019.

The data, calculations, and output for water-level mapping using the TRIM for first quarter of CY 2019 are described herein. Using the data and methods described in the following sections, regularized inverse water-level mapping was performed to produce continuous gridded depictions of groundwater elevations that conserve flow throughout the 200 East Area and are consistent with measured groundwater levels.

3.1 Data Used

Maps of groundwater levels in the 200 East Area rely on measurements obtained primarily from the wells of the low-gradient network. Groundwater elevations for each well in the low-gradient network were acquired when available from the Hanford Environmental Information System database for January, February, and March 2019. The data were corrected for borehole deviation from vertical and used to prepare piecewise, continuous grids of groundwater elevations for each month of the first quarter of CY 2019. From these data, a set of averaged groundwater elevations were also calculated and used to prepare a groundwater elevation grid for the first quarter of CY 2019. Groundwater elevations from wells outside the low-gradient network are used when necessary to control contours at the boundaries or in the vicinity of the DWMUs. When used, these measurements are assigned lower weights during the calibration process due to lower confidence in the accuracy of their measurements. The process of assigning weights during calibration allows these measurements to be included where needed, but to have less influence on the overall results than the data from the low-gradient network wells.

3.2 Method Description

The method used to obtain the groundwater elevation grids (i.e., TRIM) is a formal mathematical technique that is used to trade the complexity of a method or parameterization that is being used to analyze measured data against the “fit” obtained to those data. When used with a deterministic model, Tikhonov regularization is used to constrain the parameters of the model while attempting to attain a satisfactory fit to the measured data that comports with independent SME knowledge and information.

The TRIM implements a common application of Tikhonov regularization, by supplementing the measurement dataset- in this case, water-level measurements from January to March 2019 — with other information derived from SME knowledge. This knowledge is cast as “prior information” representing an anticipated system condition (e.g., understanding of distribution and variability of hydraulic conductivity within the study area). The addition of this information results in a mathematical technique referred to as penalized-least-squares regression, because a penalty is incurred when parameters deviate from the anticipated system condition specified by the SME(s). The size of the penalty that is incurred during the regression is controlled using a weight parameter (Tikhonov and Arsenin, 1977), referred to as the global regularization weight parameter that is commonly denoted by μ (Doherty, 2015). The size of this penalty is “traded” against the degree to which the simulation matches the measurement data: to attain a better fit to the measurement data, a larger penalty is usually incurred by deviating further from the anticipated system condition.

This method of specifying the anticipated system condition can take many forms. It is commonly specified as either a "preferred-value" (e.g., it is desired that the best fit to the data be attained while attaining parameter values that are close to a value of X) or a "preferred-difference" condition (e.g., it is desired that the best fit be obtained to the data while obtaining parameter values that show minimal difference between each other). In the context of groundwater data analysis, particularly for clastic sedimentary aquifer materials such as those encountered in the unconfined aquifer of the 200 East Area, the preferred system condition that is specified is typically homogeneity, i.e., that the regression should seek as good a fit as can be obtained while keeping parameters as homogeneous as possible. This approach, also referred to as "smoothness" regularization, is used to prevent the regression from inferring parameter values that are considered by SMEs to be unlikely.

The tradeoff between the complexity of the simulator or its parameterization versus the fit obtained to the measurement data can be plotted graphically. Doing so often results in a shape similar to an upper-case letter L (i.e., concave upward to the right) and for this reason it is referred to as an L-curve (Hansen, 2000, *The L-curve and its Use in the Numerical Treatment of Inverse Problems*). L-curves are used to evaluate the relationship between two related or competing terms in many analyses, providing a graphical method to select an acceptable solution that does not over-fit nor under-fit the data. In the context of Tikhonov regularization, the L-curve depicts the tradeoff between a sum-of-squared-weighted-residuals (or "least-squares") measurement objective function, usually depicted on the X-axis, and a regularization objective function that is calculated as the sum-of-squared deviations from the preferred system condition. The manner in which this plot changes with different values of the global regularization weight parameter, μ, traces the tradeoff between these two objectives.

An example L-curve is depicted in Figure 3-1. The figure illustrates that as the value of the global regularization weight parameter increases, greater emphasis is placed on honoring the preferred system condition that keeps the regularization objective function low but results in a larger measurement objective function (penalizing the fit achieved to the measured data). Conversely, as the value of the global regularization weight parameter decreases, less emphasis is placed on honoring the preferred system condition, which results in a larger regularization objective function but provides the regression the ability to attain a better fit to the measurement data.

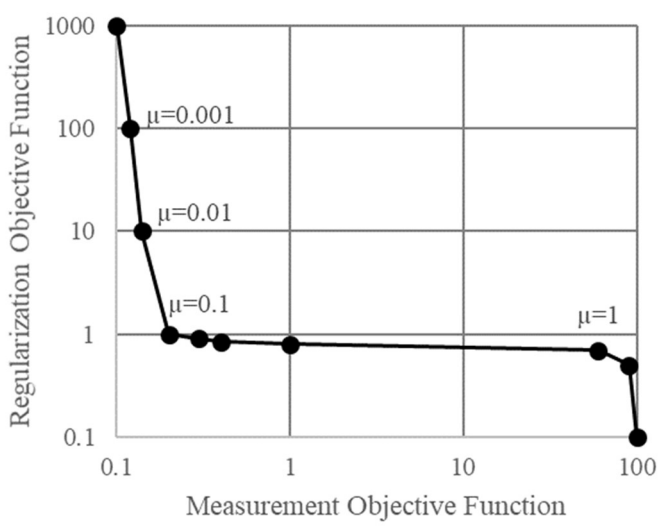

Figure 3-1. L-Curve Example (modified from Hansen, 2000)

3.3 Implementation using MODFLOW-USG and PEST

Two linked calculation tools are needed to obtain the necessary piecewise grid from the first quarter of CY 2019:

- A method for calculating groundwater elevations throughout the area
- A method for implementing the Tikhonov regularization technique to evaluate the tradeoff between complexity and data fit

The calculations described in this section were completed for and described in ECF-200E-18-0085. The underlying groundwater simulator that was developed for that work was used with the average water-level data for first quarter of CY 2019 as described in Chapter 6 to complete the calculations for this ECF.

3.3.1 Groundwater Elevations

Throughout the 200 East Area, the predominant factors that affect area-wide groundwater flow patterns are as follows:

- The high-hydraulic conductivity sediments that comprise the Hanford formation and the CCU
- The location of lower hydraulic conductivity sediments and basalts that are lateral to or a subcrop within the high-conductivity sediments
- Lateral sources and sinks (inflows and outflows) of water particularly along the northwest and southeast extents of the 200 East Area

As detailed in ECF-200E-18-0085, these predominant factors have previously been represented by developing and parameterizing a simplified single-layer (two-dimensional) steady-state simulator of groundwater flow using the unstructured grid release of the MODFLOW program, MODFLOW-USG (for UnStructured Grid) (Panday et al., 2013, *MODFLOW-USG Version 1: An Unstructured Grid Version of MODFLOW for Simulating Groundwater Flow and Tightly Coupled Processes Using a Control Volume Finite-Difference Formulation*). The MODFLOW-USG simulation code is a control-volume finite difference formulation of the commonly used finite-difference U.S. Geological Survey MODFLOW groundwater flow simulator. A disadvantage of the regular rectangular grids that result from the use of regular finite-difference methods is that when small cells are used to represent an area of interest, a very large number of cells is created throughout the domain. When used together with Tikhonov regularization, this can produce relationships between model cells that can render the problem mathematically intractable. An advantage of the unstructured grid formulation implemented in MODFLOW-USG is that it can support irregular (non-rectangular) grids. In particular, MODFLOW-USG can support a Voronoi grid, which is well suited to the purpose of this exercise because a much smaller number of cells is needed to discretize the area encompassing the 200 East Area facilities, and a correspondingly smaller number of regularization (prior information) equations is needed to specify relations between the parameter value in each cell and that of its neighbors.

As detailed in ECF-200E-18-0085, the simplified two-dimensional simulator of groundwater flow conditions was constructed as follows:

- A single-layer grid was constructed using a Voronoi mesh. The Voronoi mesh was designed using the software program AlgoMesh® (HydroAlgorithmics, 2016, *AlgoMesh User Guide*) that enables the user to adjust the number of cells, their geometry, aspect ratios, and density in focused areas of the

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domain. AlgoMesh writes a file that defines the Voronoi mesh in a format that can be read by the Groundwater Vistas program, from which the MODFLOW-USG-specific input files are generated and through which initial parameters and boundary conditions were developed.

- Lateral boundary conditions were specified using the following:
  - Specified-flux boundaries to represent the flow between 200 East Area and 200 West Area, Gable Gap to the north, the basalt to the north, and the Treated Effluent Disposal Facility to the east.
  - A specified-head boundary to represent the region to the southeast where groundwater flows eastward toward the Columbia River.
- Based on SME knowledge, the hydraulic conductivity of the sediments within which the water table resides was discretized into three hydrostratigraphic units (HSU): the Hanford formation, CCU, and Ringold Formation member of Wooded Island – unit E. Delineation of HSUs at the elevation of the water table was prepared by intersecting the Central Plateau Groundwater Model (CPGWM) water table grid with a three-dimensional geological model (ECF-HANFORD-13-0029, *Development of the Hanford South Geologic Framework Model, Hanford Site, Washington*). Within each of these delineated HSUs, the hydraulic conductivity was defined as homogeneous for purposes of defining initial parameter values (this represents the "preferred system condition" at the commencement of the Tikhonov regularization that followed).

The resulting simplified groundwater flow simulator is two-dimensional (i.e., a single layer) with the resolution of the mesh refined in areas of particular interest, such as near groups of monitoring wells. The resulting grid, boundaries, and hydraulic conductivity zones are shown in Figure 3-2.

3.3.2 Tikhonov Regularization

The method of Tikhonov regularization is implemented in several software packages and programming environments. One of these is the program PEST (Doherty, 2015), which implements Tikhonov regularization as a constrained parameter estimation or calibration procedure. PEST is used widely at the Hanford Site to assist with the calibration of groundwater models and other models, using utilities to link PEST to groundwater models and other programs, and for this reason PEST was selected for this ECF. When incorporating Tikhonov regularization in a calibration using PEST, the sum-of-squared-weighted-residuals measurement objective function that is sought to minimize during traditional parameter estimation is augmented with a second term that quantifies the degree of deviation from the preferred system condition, by calculating a sum-of-squared-weighted differences between the preferred condition and the condition that is represented by the value of the parameters (Tonkin and Doherty, 2005, "A Hybrid Regularized Inversion Methodology for Highly Parameterized Environmental Models"; Doherty, 2015; Doherty, 2016, *PEST Model-Independent Parameter Estimation User Manual Part I: PEST, SENSAN and Global Optimisers*). This sum-of-squared-weighted deviations from the preferred conditions constitutes the regularization objective function that is depicted on the L-curve figure shown in Figure 3-1.

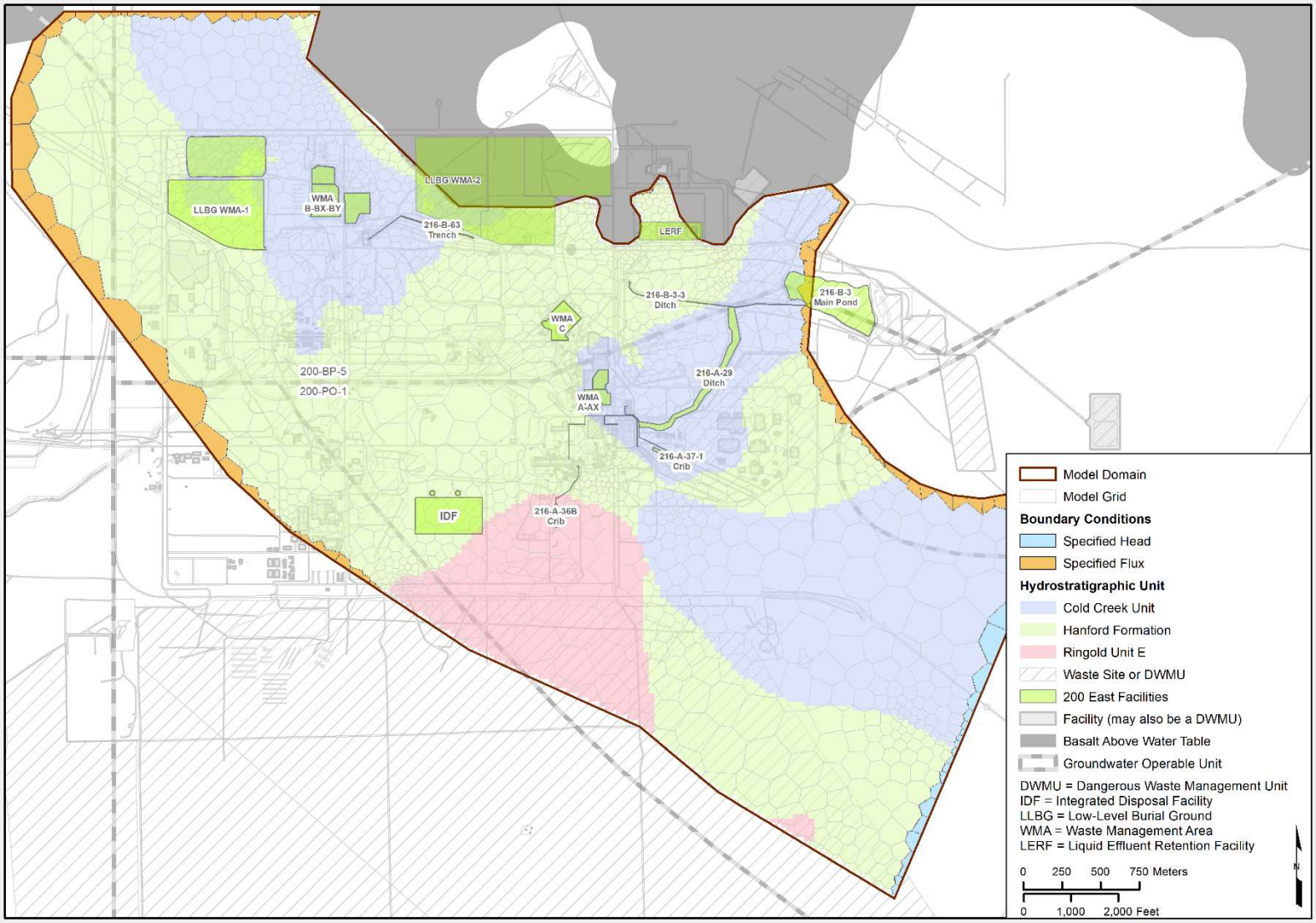

Figure 3-2. Two-Dimensional Simulator Boundary Conditions and HSUs

The PEST software can implement Tikhonov regularization in two modes of operation. When operating in the first of these modes, denoted as regularization mode, the PEST program calculates updates to the values of the parameters that provide an improved fit to the measured values and also determines a global regularization weight parameter that enables the measurement component of this composite objective function to meet a target value ascribed by the user as representing an "acceptable" fit (Doherty, 2015). When operating in the second of these modes, denoted as pareto mode, the PEST program calculates updates to the values of the parameters by conducting a form of line-search that describes a line exploring the relationship between the regularization objective function, the global regularization weight parameter, and measurement objective function in a manner that can be used to plot an L-curve such as that depicted in Figure 3-1.

3.3.3 Limitations

The simplified two-dimensional groundwater flow simulator that underlies TRIM, developed using the MODFLOW-USG code for purposes of this ECF, was implemented specifically for the purpose of providing a mechanism to interpret groundwater-level data and obtain groundwater-elevation contours depicting directions of groundwater flow and potential migration pathways based upon those measured data. The groundwater elevation contours are obtained by trading-off the complexity of the parameterization of the groundwater simulator versus the fit that is obtained to the measured groundwater elevation data, effectively using the groundwater simulator as an alternative to distance-weighted interpolation (such as kriging) to interpolate between the measured groundwater-level data. Because the resulting piecewise-continuous groundwater elevation grids depict hydraulic gradients that comport with independent SME knowledge of subsurface conditions, they are suitable for particle-tracking analyses to depict approximate rates and directions of groundwater flow and potential contaminant migration in the vicinity of the 200 East Area facilities.

The simplified two-dimensional groundwater flow simulator that underlies TRIM is not a substitute for existing three-dimensional groundwater flow and contaminant transport models at the Hanford Site, such as the CPGWM and the Plateau to River model. There are many simplifications in the underlying groundwater flow simulator developed for purposes of this ECF: these include use of a single layer representing only water table conditions; the regularization objective sought in TRIM of homogeneity without specific regard for the values or physical meaning of the resulting parameters; and the simplified representation of the lateral boundaries of the area of interest. Because of these and other simplifications and limitations, the MODFLOW-USG simulator underlying TRIM should not be used as an alternative to the existing three-dimensional groundwater flow and contaminant transport models (i.e., the CPGWM and Plateau to River model) for mass-conserved simulations of contaminant transport.

4 Assumptions and Inputs

This chapter outlines the assumptions and inputs that underlie the calculations presented in this ECF.

4.1 Assumptions

Assumptions used for the groundwater flow analysis and groundwater elevation mapping are discussed in this section. Water-level contour maps were constructed using a method that combines the use of a simplified simulator of groundwater flow together with the use of Tikhonov regularization implemented in calibration and pareto modes. The resulting contour maps provide plausible interpretations of groundwater levels and hydraulic gradients that (a) match measured water levels and monitoring wells to a degree consistent with the tradeoff between fit and complexity and (b) achieve flow conservation by using the underlying groundwater flow simulator for interpolation. The accuracy of the contours is influenced by several factors, including the following:

- 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

These potential sources of error mean that the maps are interpreted as reasonable approximations that provide useful inference in the interpretation of likely directions and rates of groundwater movement particularly in regions of low hydraulic gradients. Based on SME knowledge and understanding of the groundwater system in the 200 East Area, these estimates are assumed to be representative of observed conditions.

As discussed in Chapter 2, there is a groundwater (P&T) extraction well operating within the main unconfined aquifer in the 200 East Area to address groundwater contamination at the 200-BP-5 groundwater OU. Due to the high transmissivity of the gravel of the CCU, in which the well is installed, the effects of groundwater extraction at the well only influences hydraulic gradients and corresponding groundwater flow directions and rates measurably in the immediate vicinity of the well.

4.2 Input Data

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

Table 4-1 lists the individual average monthly water-level measurements in 68 low-gradient network monitoring wells for the first quarter of CY 2019 and the calculated average water-level elevations for that period. These data served as the inputs to the water-level mapping. Insufficient water-level measurements in February 2019 precluded the creation of a water-level map for that month. However, the data available were still used for the average water-level map for the first quarter of CY 2019. A full set of data for first quarter of CY 2019 is included in Appendix A.

Table 4-1. Water-Level Measurements

Well Name	Average Measured Water Levels (NAVD 88 meters)			Average
	Jan-2019	Feb-2019	Mar-2019	Jan-to-Mar-2019
299-E17-18	121.633	NM	121.631	121.632
299-E17-21	121.676	NM	NA	121.676
299-E17-22	121.534	NM	121.645	121.590
299-E17-23	121.631	NM	121.643	121.637
299-E17-25	121.643	NM	121.657	121.650
299-E18-2	121.683	NM	NA	121.683
299-E23-1	121.671	NM	NM	121.671
299-E24-16	121.668	NM	NM	121.668
299-E24-18	121.653	NM	NA	121.653
299-E24-21	121.638	NM	NM	121.638
299-E24-22	121.694	NM	121.861	121.778
299-E24-24	121.646	NM	121.648	121.647
299-E24-25	121.614	NM	NM	121.614
299-E24-33	121.622	NM	121.653	121.638
299-E25-19	121.646	NM	NM	121.646
299-E25-24	121.655	NM	121.640	121.648
299-E25-25	121.660	NM	NM	121.660
299-E25-32P	121.655	NM	NM	121.655
299-E25-34	121.643	NM	121.636	121.639
299-E25-35	121.639	NM	121.622	121.630
299-E25-36	NM	NM	121.322	121.322
299-E25-93	121.626	NM	121.653	121.640
299-E26-10	NM	NM	121.657	121.657
299-E26-13	121.655	NM	121.642	121.648
299-E26-14	121.768	NM	NM	121.768
299-E26-15	121.712	NM	NM	121.712
299-E26-4	121.652	NM	121.639	121.646
299-E26-79	121.694	NM	NA	121.694
299-E27-12	121.636	NM	121.901	121.769

Table 4-1. Water-Level Measurements

Well Name	Average Measured Water Levels (NAVD 88 meters)			Average
	Jan-2019	Feb-2019	Mar-2019	Jan-to-Mar-2019
299-E27-14	121.633	NM	121.673	121.653
299-E27-15	121.668	NM	121.678	121.673
299-E27-17	121.637	NM	121.632	121.635
299-E27-18	121.647	NM	121.652	121.650
299-E27-21	121.622	NM	121.638	121.630
299-E27-22	121.663	NM	121.744	121.704
299-E27-23	121.632	NM	121.662	121.647
299-E27-7	121.633	NM	121.653	121.643
299-E27-8	121.645	NM	121.646	121.646
299-E27-9	121.645	NM	121.639	121.642
299-E28-1	121.643	NM	NM	121.643
299-E28-17	121.652	NM	NM	121.652
299-E28-18	121.662	NM	NM	121.662
299-E28-27	121.675	NM	NM	121.675
299-E29-54	NM	NM	NM	--
299-E32-5	121.706	NM	NM	121.706
299-E32-6	121.682	NM	NM	121.682
299-E32-8	121.704	NM	NM	121.704
299-E33-14	121.653	NM	NM	121.653
299-E33-267	NM	NM	NM	--
299-E33-28	121.675	NM	121.651	121.663
299-E33-31	NM	121.656	NM	121.656
299-E33-32	NM	121.657	NM	121.657
299-E33-339	121.649	121.656	NM	121.653
299-E33-34	121.675	NM	NM	121.675
299-E33-342	NM	NM	NM	--
299-E33-37	121.653	NM	NM	121.653
299-E33-38	121.655	121.658	NM	121.657
299-E33-41	NM	121.650	NM	121.650

Table 4-1. Water-Level Measurements

Well Name	Average Measured Water Levels (NAVD 88 meters)			Average
	Jan-2019	Feb-2019	Mar-2019	Jan-to-Mar-2019
299-E33-42	NM	121.661	NM	121.661
299-E33-44	NM	121.650	NM	121.650
299-E34-10	121.667	NM	NM	121.667
299-E34-9	121.664	NM	121.644	121.654
699-37-43	121.615	NM	NM	121.615
699-37-47A	121.622	NM	121.621	121.622
699-49-55A	121.700	NM	121.689	121.695
699-49-57A	121.684	NM	121.667	121.676

NAV88 = North American Vertical Datum of 1988
NM = not measured
NA = data were not available at the time of data download

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 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-00257, *MODFLOW and Related Codes Functional Requirements Document*
- CHPRC-00258, *MODFLOW and Related Codes Software Management Plan*
- CHPRC-00259, *MODFLOW and Related Codes Software Test Plan*
- CHPRC-00260, *MODFLOW and Related Codes Requirements Traceability Matrix*
- CHPRC-00261, *MODFLOW and Related Codes Acceptance Test Report*

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 in Section 5.2.

5.2 Software Description

A controlled calculation software, MODFLOW-USG (Panday et al., 2013) was used for the calculations that support this ECF.

- Software title: MODFLOW-USG solves transient groundwater flow equations using the control-volume finite-difference discretization technique.
- Software version: USG-TRANSPORT VERSION 1.0.0
- Hanford Information Systems Inventory identification number: 2517
- Workstation type and property number (from which software is run): SSP&A and FE563

5.3 Support Software

The following software programs are classified as support software:

- PEST: (Doherty, 2016) Estimates parameter values that minimize the objective function(s) to calibrate models using inverse theory.
- Groundwater Vistas™: Rumbaugh and Rumbaugh, 2017, *Groundwater Vistas Version 7*. Provides graphical tools used for model quality assurance and model input/output review.
- 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*).

™ Groundwater Vistas is a trademark of Environmental Simulations, Inc., Reinholds, Pennsylvania.
® ArcGIS is a registered trademark of the Environmental Systems Research Institute, Inc., Redlands, California.

- Surfer®: Data interpolation for visualization, model implementation, and quality assurance.
- AlgoMesh®: A mesh-generating software used for creating unstructured triangular and Voronoi grids for MODFLOW-USG: AlgoMesh Version 1.2.0.37827 (64 bit) (HydroAlgorithmics, 2016).

5.4 Software Installation and Checkout

Safety software is checked out in accordance with procedures specified PRC-PRO-IRM-309. Executables are obtained from the CH2M HILL Plateau Remediation Company software owner (who maintains the configuration-managed copies in MKS Integrity®). Installation tests identified in CHPRC-00259 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, as identified in CHPRC-00257, and is a valid use of this software for this application. The software was used within its limitations, as identified in CHPRC-00257.

® Surfer is a registered trademark of Golden Software, LLC, Golden, Colorado.
® Surfer is a registered trademark of Golden Software, LLC, Golden, Colorado.
® AlgoMesh is registered trademark of HydroAlgorithmics Pty Ltd, Canberra, Australia.
® MKS Integrity is a registered trademark of MKS, Inc., Needham, Massachusetts.

6 Calculations

This chapter describes the calculations and steps performed to develop the necessary input files, perform the calculations, and post-process the outputs to produce the results presented in this ECF.

Groundwater elevation maps presented in this ECF were produced in a two-step process:

- **Data Compilation**: Input data were compiled from retrieved database sources. Outliers were flagged from constructing trend plots of all measured data and excluded from calculations. Average groundwater elevations were then calculated for first quarter of CY 2019 based on the filtered monthly measurements and used to define the targets for the calibration process.
- **Calibration**: The hydraulic conductivity field for the simplified two-dimensional groundwater flow simulator was inherited from the TRIM analysis work completed for and described in ECF-200E-18-0085. The boundary conditions described in Chapter 3 were then used as parameters for PEST in estimation mode to approximate measured groundwater levels for the first quarter of CY 2019. Targets corresponding to the north-west, north, south-east, and south of the model domain boundaries were assigned higher weights during the calibration process such that the overall average measured gradient across the 200 East Area is respected.

The calibration targets and their associated weights are listed in Table 6-1. During the calibration process, wells that were repeatedly registering high residuals were flagged and compared to adjacent measurements. Based on understandings of any nearby stresses, surrounding geology, and inferred flow directions (i.e., upgradient vs. downgradient), these wells and/or surrounding wells were assigned lower weights due to lower confidence in the accuracy of their measurements.

Table 6-1 also lists the final residuals obtained for the calibration targets. A residual, or estimated error, value for each measured point was calculated as the difference between the measured value and the value interpolated by the calculation. The target residual, that which would indicate acceptable calibration, is an absolute value of less than 0.03 m. Figure 6-1 illustrates the cumulative frequency plot of the absolute residuals obtained from the calibration. Ninety five percent of the residuals are within 3.0 cm (1.2 in.) of average measured groundwater levels for the first quarter of CY 2019. Thus, the calibration of this interpolation is deemed acceptable and the results are usable for the purposes of this evaluation.

Table 6-1. Calibration Targets for First Quarter of CY 2019

Well Name	Average Measured Water Level (m NAV88)	Grid Interpolated Water Level (m NAV88)	Residual (Estimated Error) (m)	Calibration Weight
299-E17-18	121.632	121.638	-0.006	10
299-E17-21	121.676	121.654	0.022	10
299-E17-22*	121.590	121.642	-0.052	2
299-E17-23	121.637	121.641	-0.004	10
299-E17-25	121.650	121.644	0.006	10
299-E18-2	121.683	121.684	-0.001	20
299-E23-1	121.671	121.652	0.019	10
299-E24-16*	121.668	121.643	0.025	2
299-E24-18	121.653	121.645	0.008	10
299-E24-21	121.638	121.646	-0.008	10
299-E24-22*	121.778	121.645	0.133	0
299-E24-24	121.647	121.650	-0.003	10
299-E24-25*	121.614	121.650	-0.036	2
299-E24-33	121.638	121.645	-0.007	10
299-E25-19	121.646	121.636	0.010	10
299-E25-24	121.648	121.631	0.017	10
299-E25-25*	121.660	121.632	0.028	2
299-E25-32p	121.655	121.636	0.019	10
299-E25-34	121.639	121.640	-0.001	10
299-E25-35	121.630	121.639	-0.009	10
299-E25-36*	121.322	121.640	-0.318	0
299-E25-93	121.640	121.642	-0.002	10
299-E26-10	121.657	121.677	-0.020	8
299-E26-13	121.648	121.646	0.002	10
299-E26-14	121.768	121.765	0.003	20
299-E26-15*	121.712	121.687	0.025	2
299-E26-4	121.646	121.645	0.001	10
299-E26-79	121.694	121.698	-0.004	10
299-E27-12*	121.769	121.650	0.119	2
299-E27-14	121.653	121.649	0.004	10

Table 6-1. Calibration Targets for First Quarter of CY 2019

Well Name	Average Measured Water Level (m NAV88)	Grid Interpolated Water Level (m NAV88)	Residual (Estimated Error) (m)	Calibration Weight
299-E27-15	121.673	121.651	0.022	6
299-E27-17	121.635	121.655	-0.020	10
299-E27-18	121.650	121.656	-0.006	10
299-E27-21	121.630	121.648	-0.018	10
299-E27-22*	121.704	121.651	0.053	0
299-E27-23	121.647	121.649	-0.002	10
299-E27-7	121.643	121.651	-0.008	10
299-E27-8	121.646	121.654	-0.008	10
299-E27-9	121.642	121.654	-0.012	10
299-E28-1	121.643	121.656	-0.013	10
299-E28-17	121.652	121.658	-0.006	10
299-E28-18	121.662	121.662	0.000	10
299-E28-27	121.675	121.659	0.016	10
299-E32-5*	121.706	121.673	0.033	2
299-E32-6	121.682	121.675	0.007	10
299-E32-8*	121.704	121.677	0.027	2
299-E33-14	121.653	121.658	-0.005	10
299-E33-28	121.663	121.660	0.003	10
299-E33-31	121.656	121.659	-0.003	10
299-E33-32	121.657	121.658	-0.001	10
299-E33-339	121.653	121.657	-0.004	10
299-E33-34	121.675	121.668	0.007	10
299-E33-37	121.653	121.657	-0.004	10
299-E33-38	121.657	121.659	-0.002	10
299-E33-41	121.650	121.658	-0.008	10
299-E33-42	121.661	121.658	0.003	10
299-E33-44	121.650	121.658	-0.008	10
299-E34-10	121.667	121.656	0.011	10
299-E34-9	121.654	121.657	-0.003	10
699-37-43	121.615	121.610	0.005	20

Table 6-1. Calibration Targets for First Quarter of CY 2019

Well Name	Average Measured Water Level (m NAV88)	Grid Interpolated Water Level (m NAV88)	Residual (Estimated Error) (m)	Calibration Weight
699-37-47a	121.622	121.627	-0.005	20
699-49-55a	121.695	121.687	0.008	20
699-49-57a	121.676	121.696	-0.020	10

Well assigned a low weight for PEST calibration.

NAV88 = North American Vertical Datum of 1988

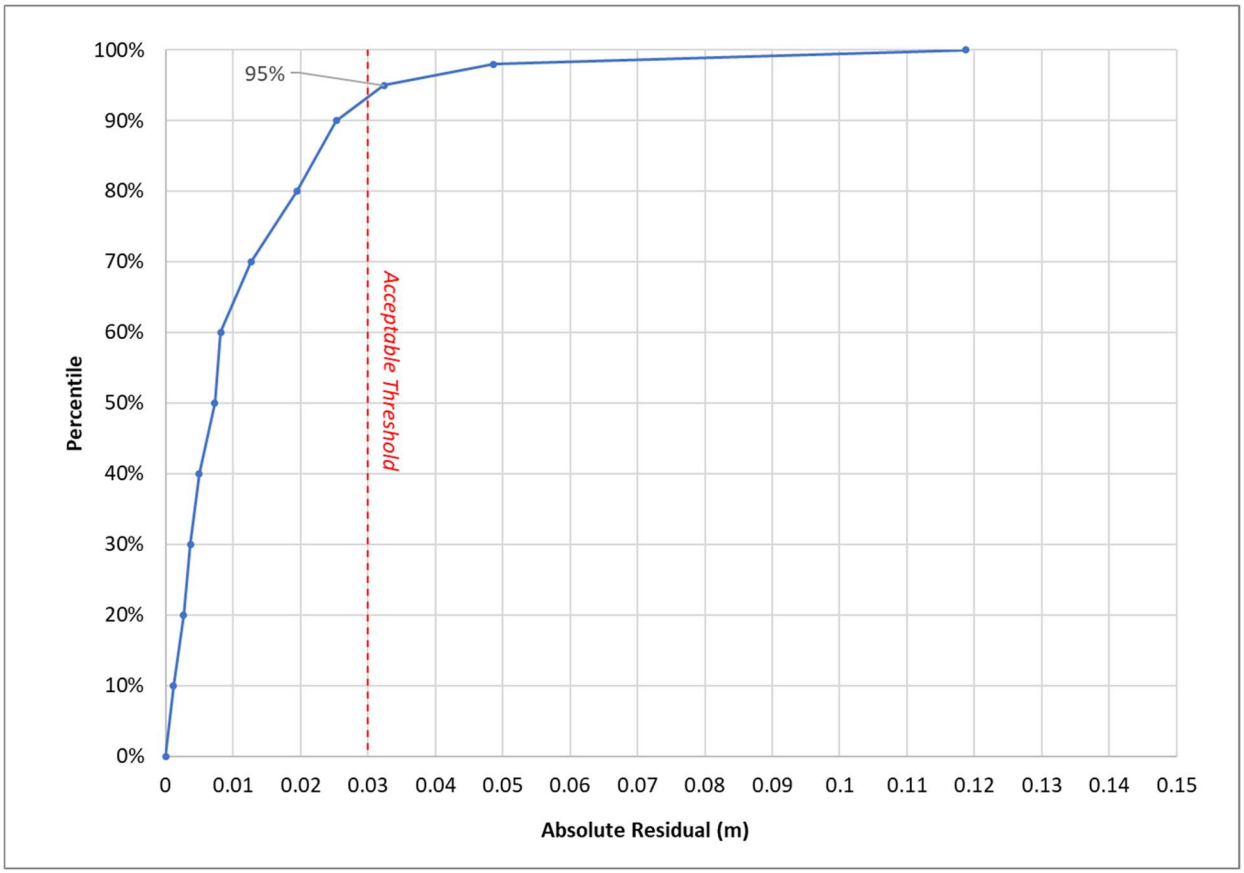

Figure 6-1. Cumulative Relative Frequency of Absolute Residuals

7 Results

This chapter presents outputs from the described calculations. These include the following:

- The 200 East Area water-level mapping results for each month in the first quarter of CY 2019. Note, a water-level map was not generated for February due to insufficient water-level measurements.
- A 200 East Area water-level map for average water levels for the first quarter of CY 2019.

After the calibration steps described in Chapter 6, scatter plots that compare the calculated groundwater elevations with the measured groundwater elevations were prepared. Figures 7-1 and 7-2 depict the monthly calibration results for January and March 2019, and Figure 7-3 shows the simulated versus the measured groundwater elevations for first quarter of CY 2019, as obtained at the conclusion of the regularized inversion steps.

Figures 7-4 and 7-5 depict the groundwater elevation contours throughout the 200 East Area for January and March respectively, and were prepared using the methods and inputs described previously. Figure 7-6 depicts the groundwater elevation contours throughout the 200 East Area that were generated using average water levels for the first quarter of CY 2019. All water-level map figures also illustrate calibration weights and calibration residuals for monitoring wells included in the calibration process.

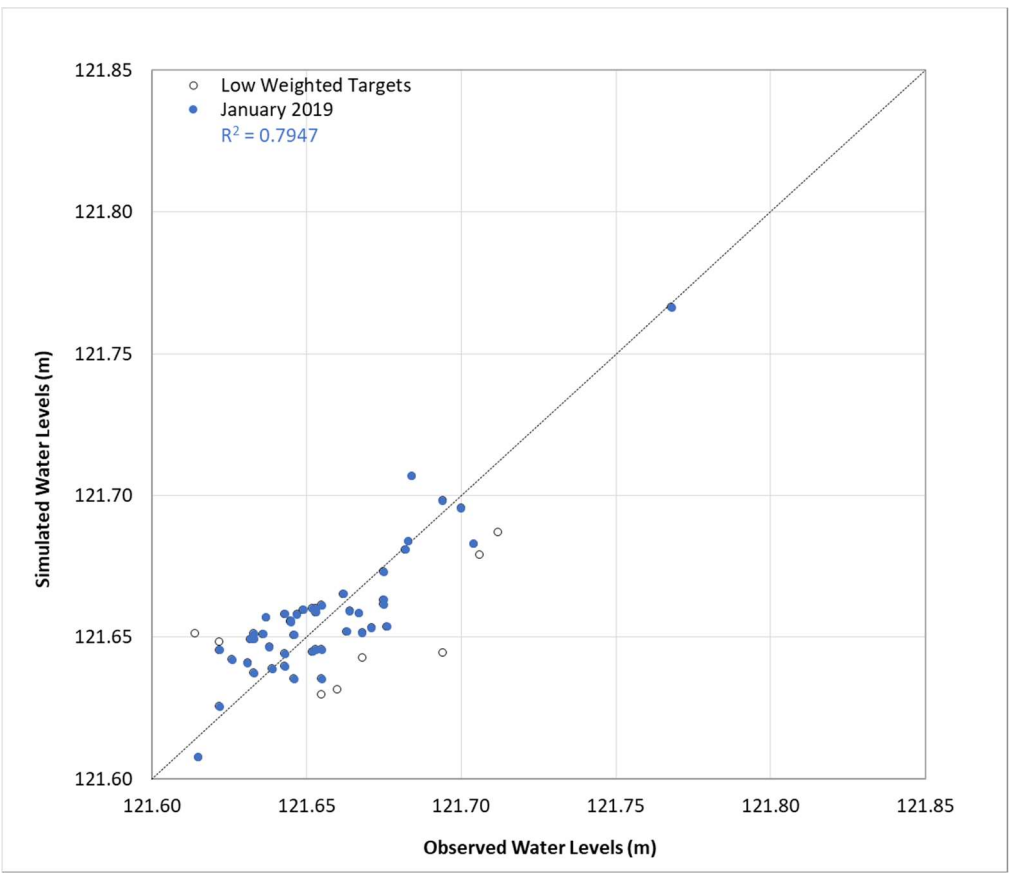

Figure 7-1. Monthly Observed vs. Simulated Calibration Plots – January 2019

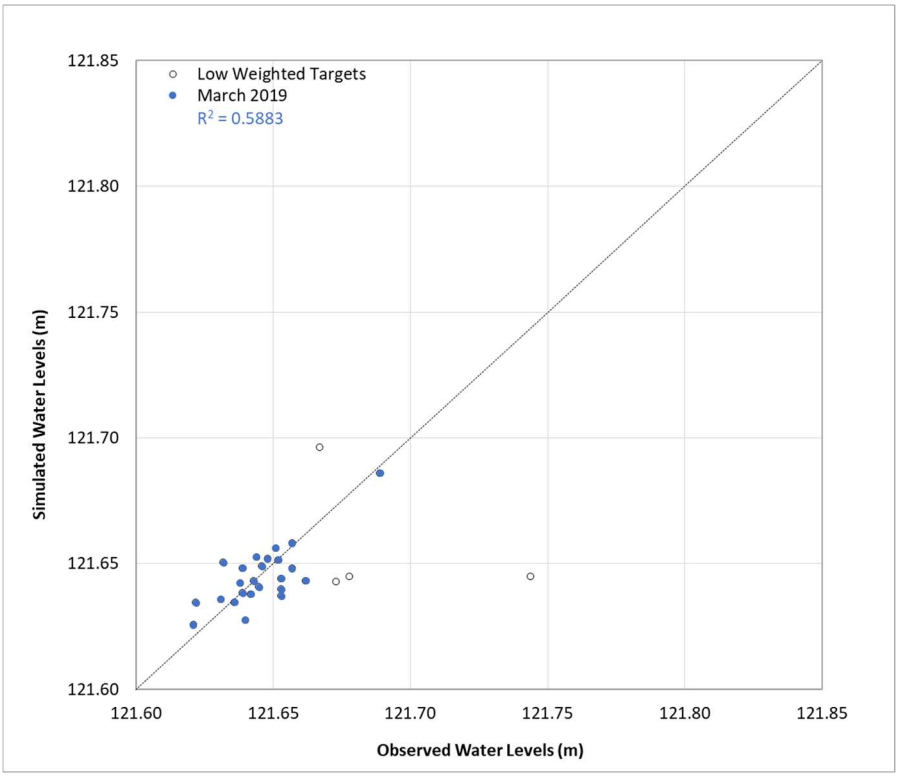

Figure 7-2. Monthly Observed vs. Simulated Calibration Plots – March 2019

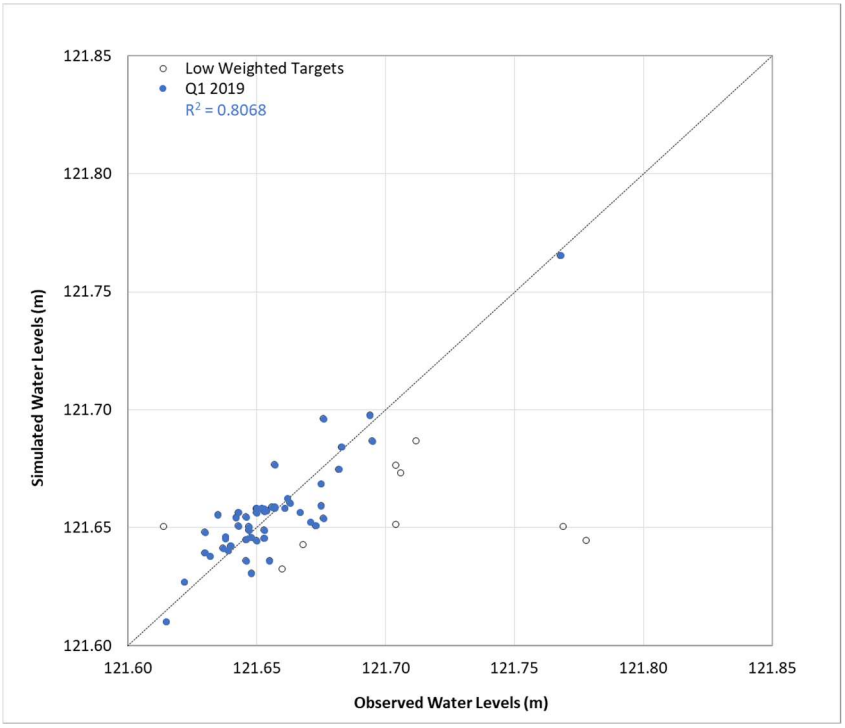

Figure 7-3. Comparison of Observed vs. Simulated Water-Levels – January Through March 2019

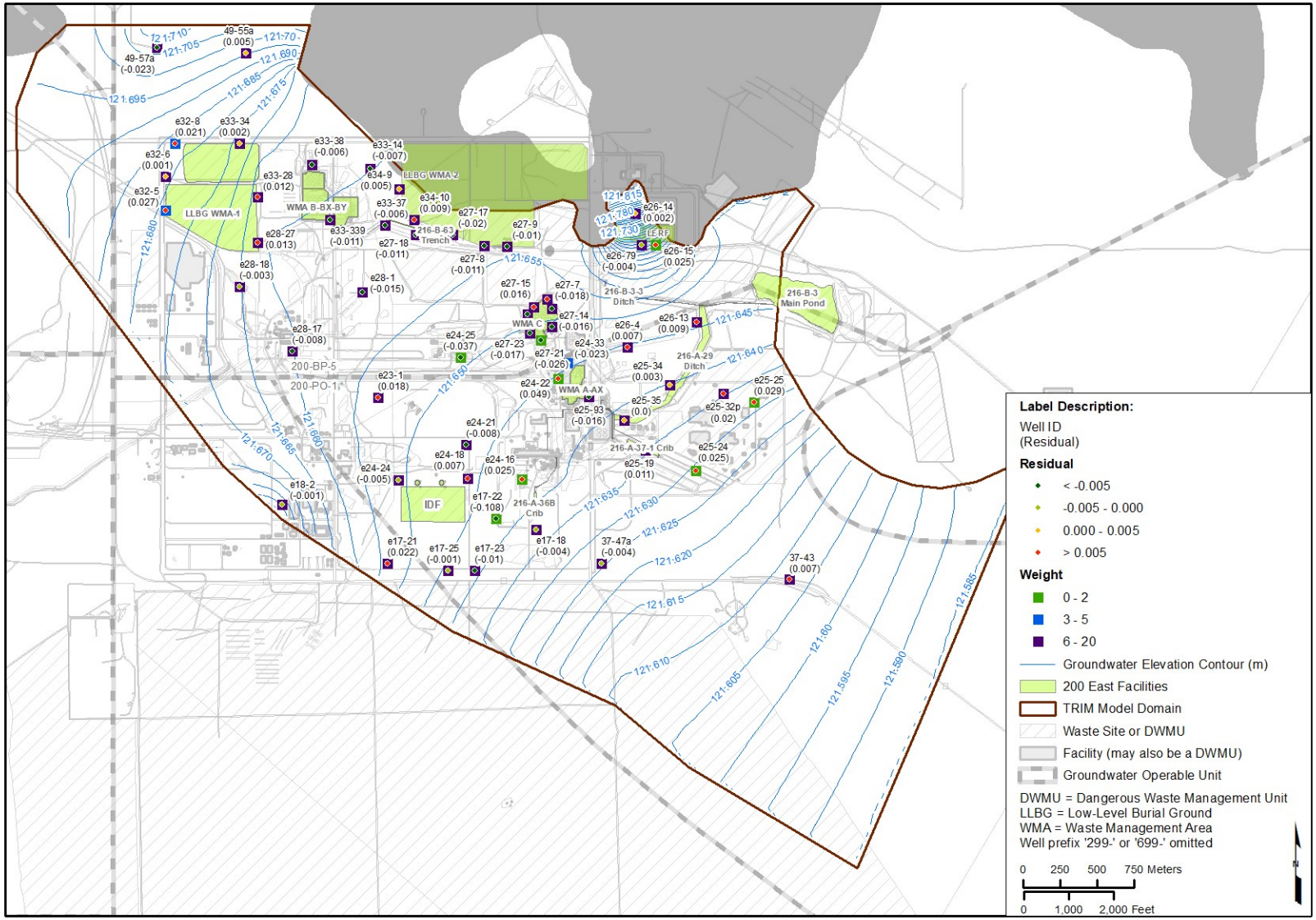

Figure 7-4. Mapped Groundwater Elevations and Calibration Residuals – January 2019

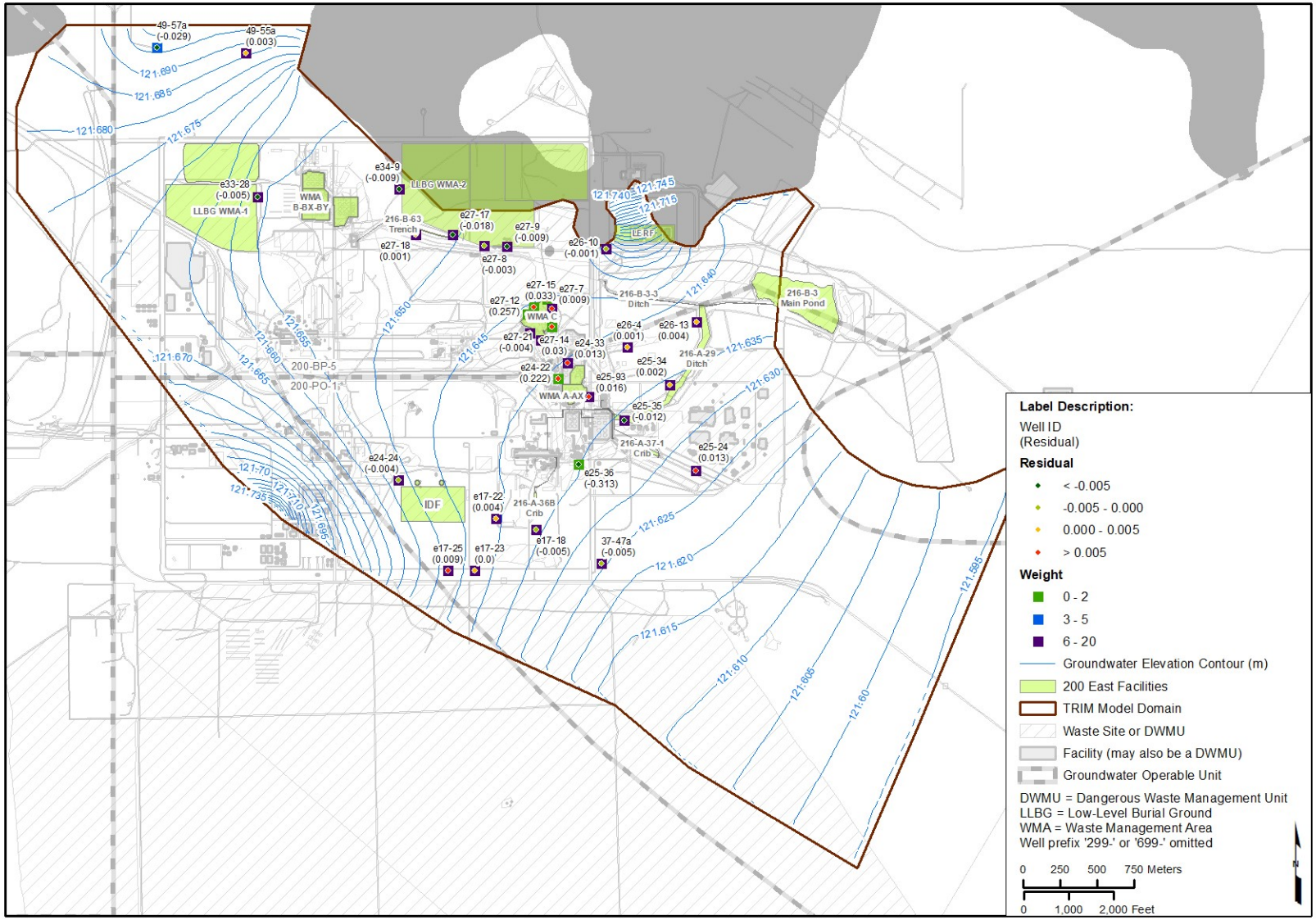

Figure 7-5. Mapped Groundwater Elevations and Calibration Residuals – March 2019

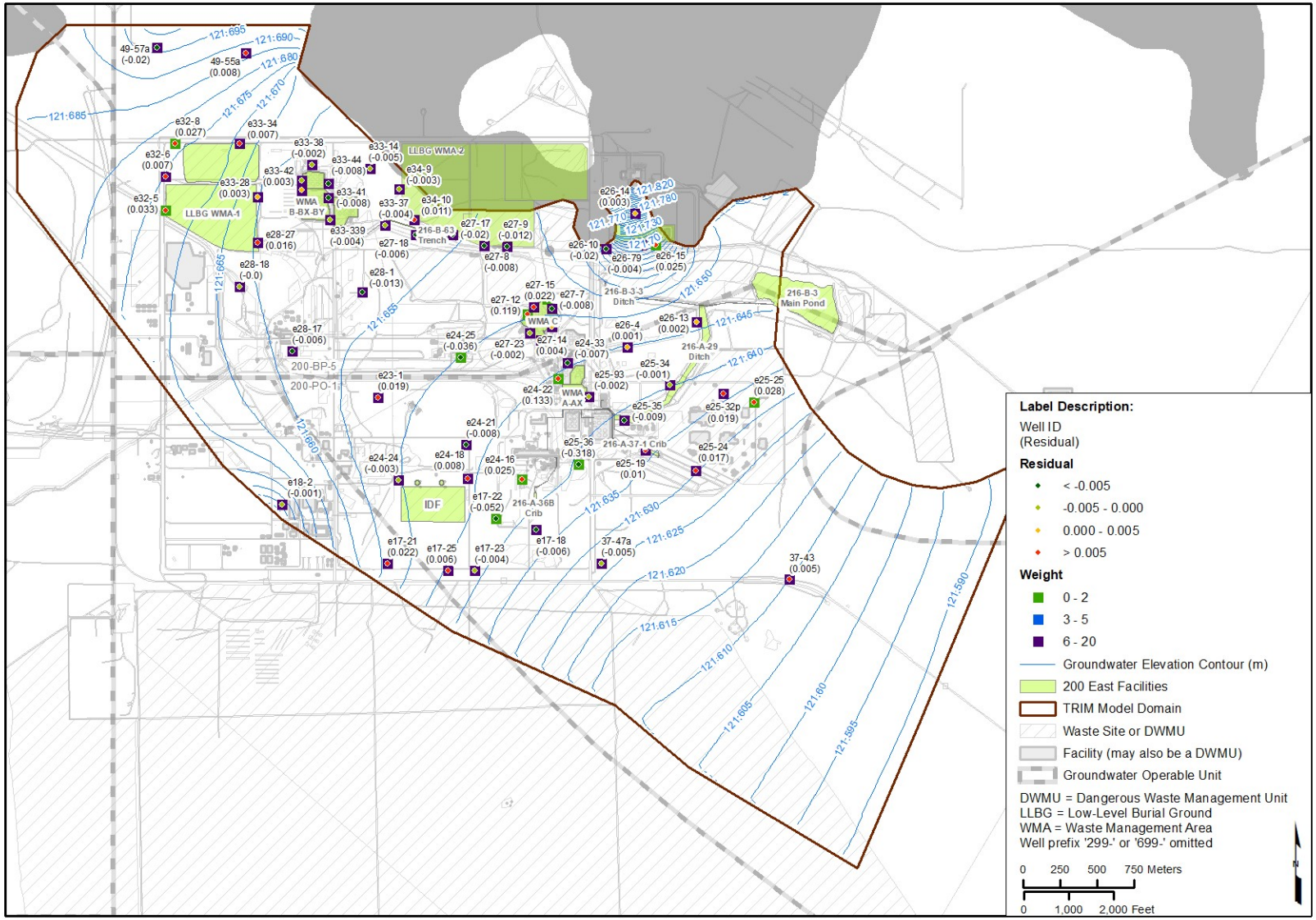

Figure 7-6. Mapped Groundwater Elevations and Calibration Residuals – Average January Through March 2019

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8 References

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Appendix A

Groundwater Elevations in Monitoring Wells

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Table A-1. Measured Groundwater Elevations Used for Water-Level Mapping: January 2019

Name	Easting	Northing	Date-Time	Measured Water Level (m NAVD88)
299-E26-14	575786	137265	1/3/19 8:09 AM	121.768
299-E26-15	575926	137051	1/3/19 9:15 AM	121.712
299-E26-79	575828	137052	1/3/19 10:02 AM	121.694
299-E28-27	573227	137070	1/7/19 9:16 AM	121.693
299-E33-28	573226	137375	1/7/19 11:29 AM	121.693
299-E23-1	574043	136017	1/8/19 11:17 AM	121.646
299-E32-5	572600	137285	1/9/19 9:20 AM	121.700
299-E32-6	572600	137515	1/9/19 11:15 AM	121.699
299-E24-21	574636	135698	1/10/19 8:46 AM	121.633
299-E24-24	574180	135459	1/10/19 9:23 AM	121.633
299-E17-25	574515	134846	1/10/19 9:55 AM	121.630
299-E25-19	575852	135659	1/10/19 10:20 AM	121.642
299-E17-23	574694	134842	1/10/19 10:27 AM	121.619
299-E25-35	575708	135865	1/11/19 9:36 AM	121.637
299-E17-22	574841	135196	1/11/19 11:27 AM	121.417*
299-E26-13	576199	136529	1/11/19 12:08 PM	121.662
299-E17-18	575112	135124	1/11/19 12:14 PM	121.644
299-E25-34	576019	136100	1/11/19 1:08 PM	121.650
299-E32-8	572663	137741	1/14/19 8:46 AM	121.695
299-E33-34	573104	137740	1/14/19 11:18 AM	121.691
299-E17-21	574107	134893	1/15/19 9:42 AM	121.690
299-E24-18	574647	135470	1/15/19 12:09 PM	121.653
699-37-43	576829	134783	1/16/19 11:21 AM	121.640
699-37-47A	575557	134893	1/24/19 9:00 AM	121.622
699-37-43	576829	134783	1/24/19 9:06 AM	121.589
299-E18-2	573392	135291	1/24/19 9:14 AM	121.683
299-E23-1	574043	136017	1/24/19 9:21 AM	121.696
299-E28-1	573933	136733	1/24/19 9:29 AM	121.643
299-E28-17	573461	136332	1/24/19 9:38 AM	121.652
299-E28-18	573104	136768	1/24/19 9:42 AM	121.662
299-E28-27	573227	137070	1/24/19 9:47 AM	121.657

Table A-1. Measured Groundwater Elevations Used for Water-Level Mapping: January 2019

Name	Easting	Northing	Date-Time	Measured Water Level (m NAVD88)
299-E32-8	572663	137741	1/24/19 9:54 AM	121.713
299-E32-6	572600	137515	1/24/19 9:59 AM	121.665
299-E32-5	572600	137285	1/24/19 10:03 AM	121.712
699-49-57A	572544	138389	1/24/19 10:52 AM	121.684
699-49-55A	573146	138352	1/24/19 11:01 AM	121.700
299-E34-10	574284	137225	1/24/19 11:10 AM	121.657
299-E34-9	574186	137430	1/24/19 11:16 AM	121.652
299-E33-34	573104	137740	1/28/19 8:07 AM	121.659
299-E33-38	573591	137594	1/28/19 8:13 AM	121.655
299-E33-339	573717	137222	1/28/19 8:18 AM	121.649
299-E27-18	574300	137119	1/28/19 8:24 AM	121.647
299-E27-17	574547	137122	1/28/19 8:29 AM	121.637
299-E27-8	574759	137044	1/28/19 8:33 AM	121.645
299-E27-9	574918	137041	1/28/19 8:38 AM	121.645
299-E27-7	575221	136619	1/28/19 8:46 AM	121.633
299-E27-22	575185	136685	1/28/19 8:51 AM	121.663
299-E27-15	575095	136630	1/28/19 8:57 AM	121.668
299-E27-12	575054	136584	1/28/19 9:09 AM	121.636
299-E27-23	575069	136452	1/28/19 9:17 AM	121.632
299-E27-14	575217	136498	1/28/19 9:23 AM	121.633
299-E33-28	573226	137375	1/28/19 9:33 AM	121.656
299-E33-37	574091	137185	1/28/19 9:41 AM	121.653
299-E33-14	573986	137567	1/28/19 9:46 AM	121.653
299-E27-21	575145	136407	1/28/19 9:55 AM	121.622
299-E24-33	575325	136251	1/28/19 10:01 AM	121.622
299-E24-22	575263	136143	1/28/19 10:08 AM	121.694
299-E25-93	575472	136022	1/28/19 10:13 AM	121.626
299-E24-25	574599	136287	1/28/19 10:53 AM	121.614
299-E26-4	575734	136361	1/28/19 11:01 AM	121.652
299-E26-13	576199	136529	1/28/19 11:05 AM	121.647
299-E25-34	576019	136100	1/28/19 11:11 AM	121.635

Table A-1. Measured Groundwater Elevations Used for Water-Level Mapping: January 2019

Name	Easting	Northing	Date-Time	Measured Water Level (m NAVD88)
299-E25-35	575708	135865	1/28/19 11:17 AM	121.640
299-E25-24	576194	135521	1/28/19 11:24 AM	121.655
299-E25-19	575852	135659	1/28/19 11:27 AM	121.649
299-E17-23	574694	134842	1/28/19 11:35 AM	121.643
299-E17-25	574515	134846	1/28/19 11:39 AM	121.655
299-E17-21	574107	134893	1/28/19 11:43 AM	121.661
299-E25-32P	576382	136044	1/30/19 8:17 AM	121.655
299-E17-18	575112	135124	1/30/19 8:35 AM	121.621
299-E17-22	574841	135196	1/30/19 8:41 AM	121.651
299-E24-21	574636	135698	1/30/19 8:52 AM	121.643
299-E24-24	574180	135459	1/30/19 8:57 AM	121.658
299-E24-16	575018	135464	1/30/19 9:09 AM	121.668
299-E25-25	576589	135984	1/30/19 10:24 AM	121.660
299-E34-10	574284	137225	1/31/19 9:20 AM	121.677
299-E34-9	574186	137430	1/31/19 9:53 AM	121.676

Reference: NAVD88, 1988, *North American Vertical Datum of 1988*.

*Represents outliers not included in the water-level mapping dataset.

Table A-2. Measured Groundwater Elevations Used for Water-Level Mapping: February 2019

Name	Easting	Northing	Date-Time	Measured Water Level (m NAVD88)
299-E33-31	573525	137491	2/7/19 8:02 AM	121.656
299-E33-339	573717	137222	2/7/19 8:37 AM	121.656
299-E33-42	573521	137424	2/7/19 8:59 AM	121.661
299-E33-41	573707	137370	2/7/19 9:12 AM	121.650
299-E33-32	573525	137354	2/7/19 9:33 AM	121.657
299-E33-44	573706	137469	2/7/19 9:43 AM	121.650
299-E33-38	573591	137594	2/7/19 11:43 AM	121.658

Reference: NAVD88, 1988, *North American Vertical Datum of 1988*.

Table A-3. Measured Groundwater Elevations Used for Water-Level Mapping: March 2019

Name	Easting	Northing	Date-Time	Measured Water Level (m NAVD88)
299-E27-21	575145	136407	3/20/19 6:57 AM	121.638
299-E24-33	575325	136251	3/20/19 7:13 AM	121.653
299-E24-22	575263	136143	3/20/19 8:15 AM	121.861*
299-E27-15	575095	136630	3/20/19 9:12 AM	121.678
299-E25-93	575472	136022	3/22/19 7:11 AM	121.653
299-E27-7	575221	136619	3/22/19 9:23 AM	121.653
299-E27-14	575217	136498	3/22/19 9:39 AM	121.673
299-E27-23	575069	136452	3/22/19 10:35 AM	121.662
299-E27-22	575185	136685	3/22/19 11:06 AM	121.744
299-E27-12	575054	136584	3/24/19 6:23 AM	121.901*
299-E33-28	573226	137375	3/27/19 11:50 AM	121.651
699-49-55A	573146	138352	3/29/19 7:16 AM	121.689
699-49-57A	572544	138389	3/29/19 7:27 AM	121.667
299-E25-36	575404	135566	3/29/19 8:00 AM	121.322
299-E34-9	574186	137430	3/29/19 8:05 AM	121.644
299-E27-18	574300	137119	3/29/19 8:17 AM	121.652
299-E27-17	574547	137122	3/29/19 8:23 AM	121.632
299-E27-8	574759	137044	3/29/19 8:30 AM	121.646
299-E27-9	574918	137041	3/29/19 8:35 AM	121.639
299-E26-10	575589	137023	3/29/19 8:40 AM	121.657
299-E26-4	575734	136361	3/29/19 8:50 AM	121.639
299-E26-13	576199	136529	3/29/19 9:08 AM	121.642
299-E25-34	576019	136100	3/29/19 9:25 AM	121.636
299-E25-35	575708	135865	3/29/19 9:38 AM	121.622
299-E25-24	576194	135521	3/29/19 9:52 AM	121.640
299-E24-24	574180	135459	3/29/19 10:18 AM	121.648
699-37-47A	575557	134893	3/29/19 10:35 AM	121.621
299-E17-18	575112	135124	3/29/19 10:58 AM	121.631
299-E17-22	574841	135196	3/29/19 11:12 AM	121.645

Table A-3. Measured Groundwater Elevations Used for Water-Level Mapping: March 2019

Name	Easting	Northing	Date-Time	Measured Water Level (m NAVD88)
299-E17-23	574694	134842	3/29/19 11:21 AM	121.643
299-E17-25	574515	134846	3/29/19 11:28 AM	121.657

Reference: NAVD88, 1988, *North American Vertical Datum of 1988*.

*Represents outliers not included in the water-level mapping dataset.

Reference

NAVD88, 1988, *North American Vertical Datum of 1988*, National Geodetic Survey, Federal Geodetic Control Committee, Silver Spring, Maryland. Available at: https://www.ngs.noaa.gov/datums/vertical/.

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