ECF-200E-18-0085
Revision 0

WATER LEVEL MAPPING AND HYDRAULIC GRADIENT CALCULATIONS FOR 200 EAST AREA RCRA SITES, 2018

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

SECTION 1 - Completed by the Responsible Manager

Project:
Soil & Groundwater Remediation

Date:

Calculation Title and Description:
Water Level Mapping and Hydraulic Gradient Calculations for 200 East Area RCRA Sites, 2018

RELEASE / ISSUE

DATE:
May 22, 2019
HANFORD RELEASE

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ENVIRONMENTAL CALCULATION COVER PAGE (Continued)

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Calculation Number: ECF-200E-18-0085 | Revision Number: 0

Revision History

Revision No.	Description	Date	Affected Pages

SECTION 3 - Completed by the Responsible Manager

Document Control:

Is the document intended to be controlled within the Document Management Control System (DMCS)? ◉ Yes ○ No

Does document contain scientific and technical information intended for public use? ◉ Yes ○ No

Does document contain controlled-use information? ○ Yes ◉ No

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ENVIRONMENTAL CALCULATION COVER PAGE (Continued)

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Terms

CHPRC	CH2M HILL Plateau Remediation Company
CPGWM	Central Plateau Groundwater Model
ECF	environmental calculation file
FY	fiscal year
HISI	Hanford Information Systems Inventory
HSU	Hydrostratigraphic Unit
IDF	Integrated Disposal Facility
LERF	Liquid Effluent Retention Facility
LLBG	Low-Level Burial Grounds
RCRA	*Resource Conservation and Recovery Act*
SME	subject-matter expert
SST	single-shell tank
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 fiscal year (FY) 2018 and the use of these estimated water levels to calculate hydraulic gradients at Hanford Site *Resource Conservation and Recovery Act of 1976* (RCRA) facilities in 2018. Gradient calculations were made for the RCRA Facilities listed below and depicted in Figure 1-1:

- 216-A-29 Ditch
- 216-A-36B Crib
- 216-A-37-1 Crib
- 216-B-3 Pond
- 216-B-63 Trench
- Integrated Disposal Facility (IDF)
- Liquid Effluent Retention Facility (LERF)
- Low-Level Burial Grounds (LLBG) Waste Management Area (WMA)-1
- LLBG WMA-2
- Single-Shell Tank (SST) WMA A-AX
- SST WMA B-BX-BY
- SST WMA C

This ECF provides the conceptual basis for the calculations that were performed, details the specific methods and codes used to undertake the calculations, and presents results of calculations that are applicable to the 200 East Area generally and to each specific 200 East RCRA Facility.

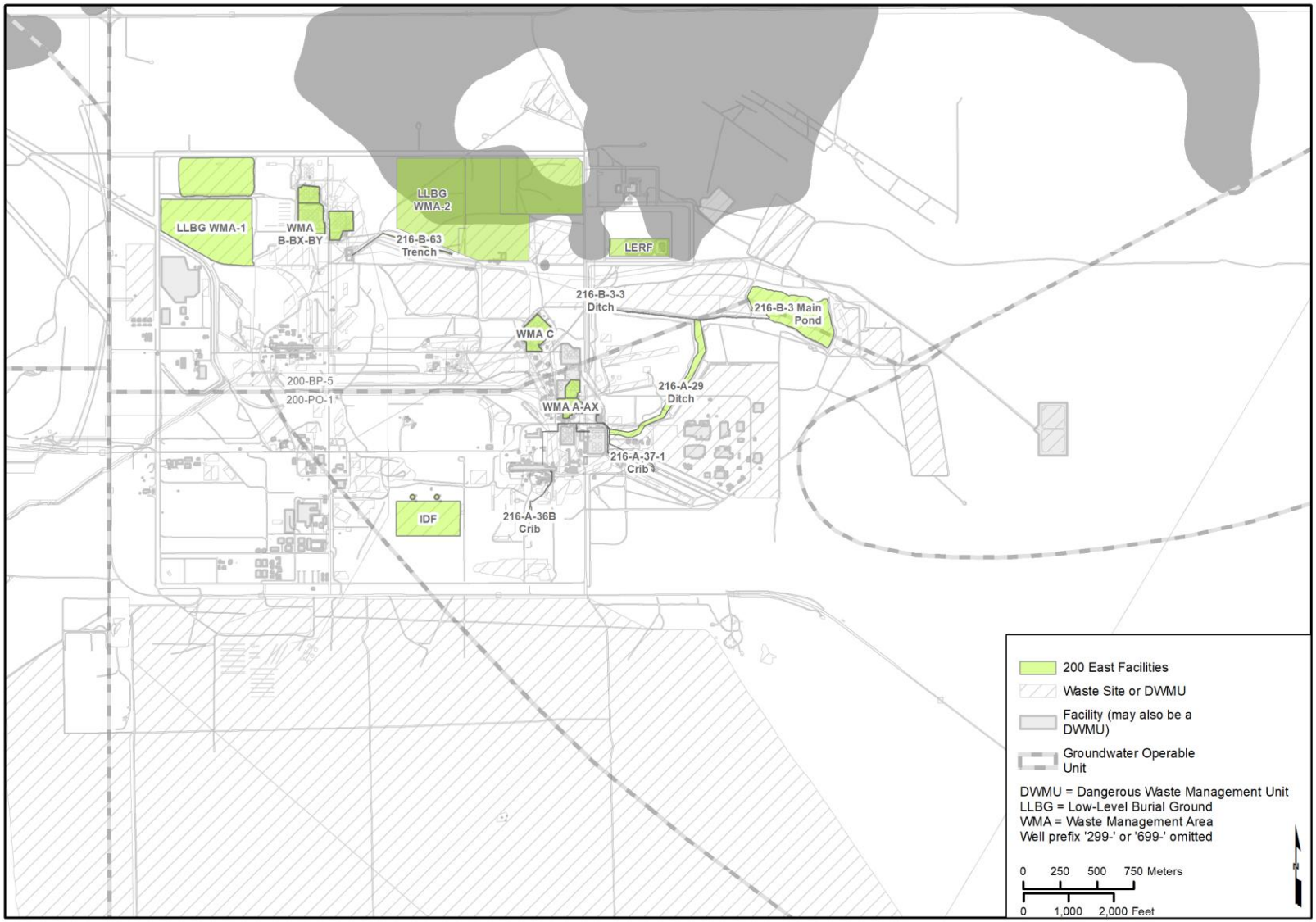

Figure 1-1. 200 East RCRA Facilities Evaluated in this ECF

2 Background

Historically, groundwater elevations in the 200 East Area varied greatly in response to discharges of water from site operations to many large wastewater receiving features such as 216-B-3 Pond. 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 occurs in a buried paleochannel consisting of highly permeable sediments of the Hanford formation and Cold Creek unit. As a result, the water table exhibits a low-magnitude hydraulic gradient (i.e., a flat water table). In 2004, the hydraulic gradient magnitude in the 200 East Area vicinity was estimated using regional water-level measurement data to be 1.8×10^{-5} m/m (1.8×10^{-5} ft/ft) (SGW-54165, *Evaluation of the Unconfined Aquifer Hydraulic Gradient Beneath the 200 East Area, Hanford Site*). At LLBG WMA-1, for example, this equates to a water table elevation change of 1.6 cm (0.63 in.) across the site. However, water-level measurements at LLBG WMA-1 typically exhibited a range of 6 cm (2.4 in.). As a result, estimates of hydraulic gradients for the water table are subject to a low signal-to-noise ratio (i.e., noise in the data can obscure small differences in the true water table making the determination of hydraulic gradients difficult).

To improve the accuracy of depth-to-groundwater measurements and corresponding 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 LERF. Previous work indicated that borehole deviation 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 more easily 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 was expanded to 62 wells in 2015.

The foregoing studies provided insight into the difficulties encountered estimating hydraulic gradients and established a monitoring network for such analyses. However, these studies did not produce groundwater elevation depictions and resulting piecewise, continuous groundwater elevation grids throughout the 200 East Facilities suitable to meet the objectives of this ECF.

To meet the objectives of this ECF, the method used in ECF-200E-18-0066, *Groundwater Flow and Migration Calculations to Assess Monitoring Networks in the 200 East Area Dangerous Waste Management Units*, to obtain groundwater elevation maps was used. The method is a regularized inverse interpolation technique that is 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*, and others, 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 suitable constraints that recognize the presence of a low signal-to-noise ratio, overfitting can attain a very good data fit by inferring high parameter or method complexity which manifests as a high parameter variance, 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, and as a result has insufficient capability (degrees-of-freedom) to reproduce the measured data. In either case of over- or under-fitting, the results often do not comport well with subject matter expert (SME) knowledge of the system or with independent sources of information.

For the purposes of this ECF, the TRIM is used to obtain piecewise, continuous grids of groundwater elevations using a simplified groundwater flow simulator as the underlying mechanism to interpolate between measured water levels. This is 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 Facilities, and then using Tikhonov regularization (Tikhonov and Arsenin, 1977, *Solutions of Ill-Posed Problems*, detailed in Chapter 3) to constrain parameter complexity in the simulation to prevent over-fitting to the measured water-level data. The advantage of using a simplified groundwater flow simulation as the underlying 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 the likely paths of groundwater.

3 Calculation Methods

This chapter describes the calculation methods used to support this ECF.

3.1 Water-Level Mapping Using the Tikhonov Regularized Inverse Method

Using the data and methods described in the following sections, regularized inverse mapping was performed to produce continuous gridded depictions of groundwater elevations encompassing the 200 East RCRA Facilities to represent groundwater elevations throughout the 200 East Area.

3.1.1 Data Used

Maps of groundwater levels in the 200 East Area rely primarily on measurements obtained from the wells of the low-gradient network, supplemented with data from other wells when necessary. For each well, monthly depth-to-water measurements are obtained and used to estimate water levels in 200 East Area:

- Monthly values of the measured depth-to-water were obtained from all monitoring wells during FY 2018 representing the period from October 2017 through September 2018. Two sets of averaged groundwater elevations were then calculated.
- The first set, representing annual average values of the corresponding groundwater elevations, were calculated for FY 2018 representing the period from October 2017 through September 2018.
- The second set, calculated using average water levels obtained over the period May – September 2018, was prepared as a result of notable variability in the water levels over the year including increases in groundwater levels in the Fall of 2017. The second set of averaged elevations is used to recalibrate parameters of the TRIM as explained in subsequent sections.

3.1.2 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 measured data that also comports with independent or SME knowledge and information.

The TRIM implements a common application of Tikhonov regularization, by supplementing the measurement dataset - in this case, averaged water-level measurements from May through September 2018 - with other information derived from SME knowledge. This knowledge is cast as “prior information” representing an anticipated system condition. The addition of this information results in a mathematical technique often referred to as penalized-least-squares regression, because a penalty is incurred when the parameters deviate too far 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 global weighting 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, although it is most 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 often referred to as "smoothness" regularization, is used to prevent the regression from inferring parameter values that are considered by SMEs to be unlikely given their knowledge.

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 different analyses, providing a graphical means to identify an acceptable solution that does not either over-fit or 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 objective functions.

An example L-curve is depicted in Figure 3-1 (after Hansen, 2000). The figure illustrates that as the value of the global regularization weight parameter increases, greater emphasis is placed on honoring the preferred system condition which keeps the regularization objective function low but results in a larger measurement objective function (effectively 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 that results in a larger regularization objective function but provides the regression the flexibility to deviate from the preferred condition and attain a better fit to the measurement data.

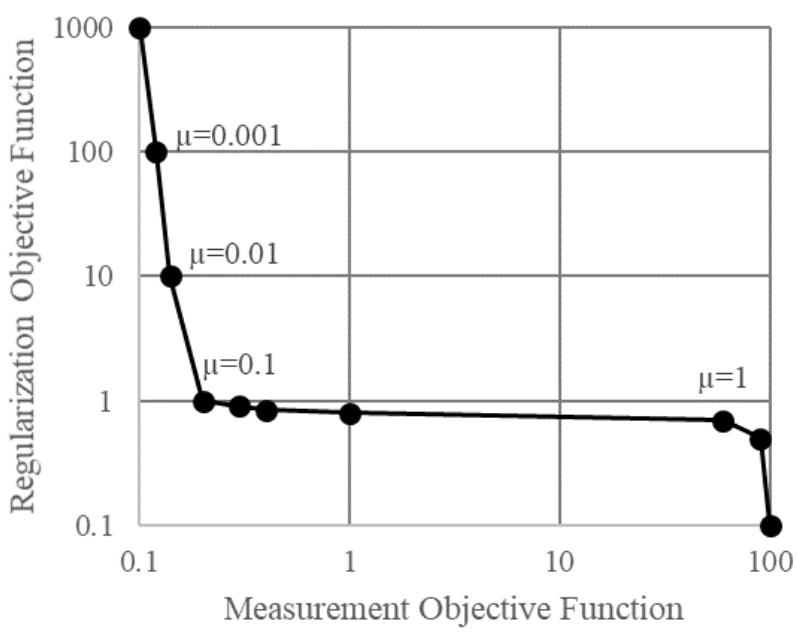

Figure 3-1. L-Curve Example

3.1.3 Implementation using MODFLOW-USG and PEST

Two linked calculation tools are needed to obtain the necessary piecewise grid from 2018:

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

3.1.3.1 Groundwater Elevations

Throughout the 200 East Area the predominant factors that affect area-wide groundwater flow patterns are (1) the high-hydraulic conductivity sediments that comprise the Hanford formation and the Cold Creek unit, (2) the location of lower hydraulic conductivity sediments and basalts that are lateral to or subcrop within the high-conductivity sediments, and (3) lateral sources and sinks (inflows and outflows) of water particularly along the northwest and southeast extents of the 200 East Area. For purposes of this ECF, these predominant factors are represented by developing and parameterizing a simplified single-layer (two-dimensional) steady-state simulation of groundwater flow using the unstructured grid release of the MODFLOW program, MODFLOW-USG.

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 when calculating groundwater levels 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 a number of relationships between parameters 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) a much smaller number of cells is needed to discretize the area encompassing the 200 East Facilities, and (b) 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 nearest neighbors.

The simplified two-dimensional simulator of groundwater flow conditions was constructed as follows:

1. 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 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.
2. Lateral boundary conditions were specified using (a) 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; and (b) a specified-head boundary to represent the region to the southeast where groundwater flows eastward toward the Columbia River.
3. Based on SME knowledge, the hydraulic conductivity of the sediments within which the water table resides was discretized into three hydrostratigraphic unit (HSU) zones, representing the

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Hanford formation, Cold Creek unit, 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 HSU zones, 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 boundary conditions and initial parameter values were defined in text files in a format that can be read by the MODFLOW-USG program. The resulting simplified groundwater flow simulator is two-dimensional (i.e., a single layer) and is composed of 1,811 active cells 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.

3.1.3.2 Tikhonov Regularization

The method of Tikhonov regularization is implemented in several commonly used software packages and programming environments. One of these is the parameter estimation and uncertainty analysis 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 a suite of utilities to link it to groundwater models and other programs, and for this reason was selected for use for purposes of this ECF. When incorporating Tikhonov regularization in a calibration using PEST, the sum-of-squared-weighted-residuals measurement objective function that PEST seeks to minimize during traditional parameter estimation is augmented with a second term that quantifies in a similar manner the degree of deviation from the preferred system condition, by calculating a sum-of-squared-weighted differences between the preferred condition and the actual 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). This sum-of-squared-weighted deviations from the preferred condition constitutes the regularization objective function that is depicted on the L-curve figure shown in Figure 3-1.

The PEST software can implement Tikhonov regularization in two specific 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. Both modes of operation were used for purposes of this ECF, as detailed in Chapter 6.

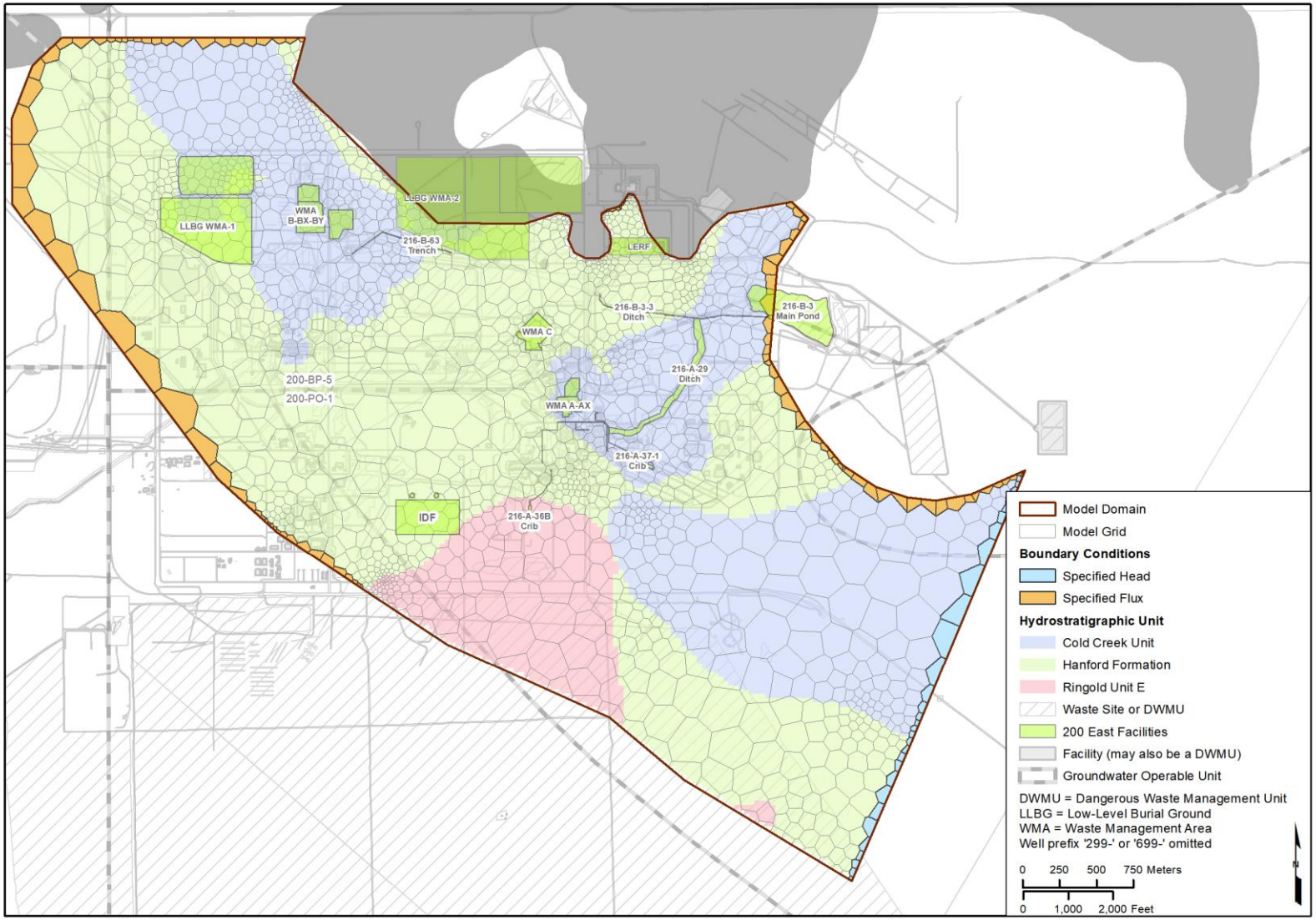

Figure 3-2. Two-Dimensional Simulator Boundary Conditions and HSU Zones

3.1.3.3 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 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 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.

3.2 Gradient Calculation Using Particle Tracking

The groundwater elevation maps produced using TRIM depict general patterns of hydraulic gradients and groundwater flow direction. Particle tracking provides a method of visualizing and estimating these directions under conditions represented in FY 2018. After the grids of groundwater elevations were created using TRIM, they were used as the base for particle tracking. Particle tracking was performed using mod-PATH3DU considering only advective transport (Muffels et al., 2018, *User's Guide for mod-PATH3DU: A Groundwater Path and Travel-Time Simulator*). Gradients specific to each facility were calculated using particle tracking by integrating the calculated movement of particles between two points along the pathlines. Points along the pathlines were extracted using a specified time interval. Each point is represented by x and y coordinates and estimated water elevation. The magnitude of the gradients (***i***) and the azimuth were calculated for each pair of points along the pathline then summarized in the table in Section 7.

$$i = \frac{dH}{L} \qquad \textbf{(Eq. 1)}$$

Where: *dH* is the estimated water level difference (meters) and L is a horizontal distance in meters between two particle points.

The azimuth is calculated as the horizontal angle in degrees between North and a vector represented by two pathline points, in a clockwise direction.

4 Assumptions and Inputs

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

4.1 Assumptions

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

4.1.1 Tikhonov Regularized Inverse Method of Water-Level Analysis

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 both calibration and Pareto-front analysis modes. The resulting groundwater elevation contour maps provide plausible interpretations of groundwater levels and hydraulic gradients between measured locations that match measured water levels and monitoring wells to a degree consistent with the tradeoff between that fit and parameter complexity and that achieve flow conservation through the use of the underlying groundwater flow simulator as the interpolation mechanism between measurement locations.
The accuracy of the contours, however, 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 only approximate actual conditions. The water-level and particle pathline maps are considered reasonable approximations that provide useful inference in the interpretation of likely directions and rates of groundwater movement particularly in regions of low hydraulic gradients.

4.1.2 Particle Tracking

Particle tracking based upon water-level mapping relies upon outputs (i.e., grids of mapped groundwater elevations) computed using TRIM. As a result, the assumptions and limitations that underlie the preparation of those maps are implied in any subsequent particle tracking.

Particle tracking that considers advection only as a transport mechanism relies upon:

- The assumptions in the underlying tracking scheme
- The interpolation method it employs
- Limitations in the groundwater flow model, including discretization and boundary effects

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

Table 4-1 lists the individual monthly water level measurements for FY 2018 and average water-level elevations calculated (a) for the period from October 2017 to September 2018 and (b) for the period from May 2018 to September 2018, which are inputs to the water-level mapping.

Table 4-1. Water Level Measurements

Well Name	Measured Water Levels (NAVD 88 meters)												Average	
	Oct-2017	Nov-2017	Dec-2017	Jan-2018	Feb-2018	Mar-2018	Apr-2018	May-2018	Jun-2018	Jul-2018	Aug-2018	Sep-2018	Oct-2017 to Sep-2018	May-2018 to Sep-2018
299-e17-18	121.703	121.686	121.675	NM	121.661	121.662	121.632	121.664	121.675	121.682	121.655	121.653	121.668	121.666
299-e17-21	NM	121.724	121.722	121.649	121.688	121.654	NM	121.710	121.711	121.724	121.705	121.685	121.697	121.707
299-e17-22	121.740	NM	121.714	NM	121.679	121.684	121.676	121.687	121.696	121.703	121.683	121.666	121.693	121.687
299-e17-23	121.708	121.705	121.713	NM	121.684	121.684	121.647	121.682	121.697	121.702	121.704	121.669	121.691	121.691
299-e17-25	121.733	NM	121.708	NM	121.696	121.698	121.661	121.691	121.707	121.714	121.692	121.677	121.698	121.696
299-e18-2	121.756	121.788	121.737	121.740	121.732	121.739	NM	121.753	121.737	121.766	121.755	121.727	121.748	121.748
299-e23-1	121.768	121.724	121.741	121.669	121.677	121.680	121.650	121.676	121.679	121.698	121.680	121.661	121.692	121.679
299-e24-16	121.762	121.739	121.734	121.704	121.698	121.705	121.682	121.708	121.701	121.721	121.700	121.725	121.715	121.711
299-e24-18	NM	NM	121.688	NM	121.672	121.666	121.656	121.674	121.687	121.692	121.666	121.662	121.674	121.676
299-e24-21	121.728	121.669	121.701	NM	121.682	121.681	121.668	121.684	121.693	NM	121.683	121.669	121.686	121.682
299-e24-22	121.712	121.679	121.652	121.723	121.672	NM	NM	121.679	121.679	NM	121.674	121.662	121.681	121.674
299-e24-24	121.750	121.710	121.722	NM	121.686	121.691	121.668	121.688	121.691	NM	121.687	121.677	121.697	121.686
299-e24-25	121.714	121.693	121.687	121.683	121.664	121.658	121.636	121.683	121.665	121.651	121.677	121.657	121.672	121.667
299-e24-33	121.720	121.682	121.654	121.727	121.676	121.674	NM	121.686	121.690	NM	121.678	121.668	121.686	121.681
299-e25-19	121.793	121.703	121.664	121.723	121.684	121.682	121.667	121.666	121.691	121.684	121.677	121.685	121.693	121.681
299-e25-24	121.781	NM	121.694	121.719	121.686	121.691	121.669	121.676	121.685	121.686	121.674	121.687	121.695	121.682
299-e25-25	NM	NM	121.699	NM	NM	NM	121.681	NM	NM	NM	NM	NM	121.690	NM
299-e25-34	121.748	121.689	121.708	121.693	121.668	121.675	121.672	121.675	121.685	121.677	121.690	121.676	121.688	121.681

Table 4-1. Water Level Measurements

Well Name	Measured Water Levels (NAVD 88 meters)												Average	
	Oct-2017	Nov-2017	Dec-2017	Jan-2018	Feb-2018	Mar-2018	Apr-2018	May-2018	Jun-2018	Jul-2018	Aug-2018	Sep-2018	Oct-2017 to Sep-2018	May-2018 to Sep-2018
299-e25-35	121.760	121.680	121.669	121.711	121.672	121.673	NM	121.681	121.679	121.674	121.671	NM	121.687	121.676
299-e25-93	121.724	121.689	121.680	121.700	121.669	121.668	NM	121.684	121.681	NM	121.675	121.666	121.684	121.677
299-e26-10	121.772	121.731	121.735	121.722	121.697	121.704	121.717	121.702	121.731	121.708	NM	NM	121.722	121.714
299-e26-13	121.750	121.716	121.722	121.701	121.676	121.690	121.689	121.686	121.703	121.683	121.699	121.684	121.700	121.691
299-e26-14	121.820	121.807	121.811	121.799	121.778	121.782	121.772	121.789	121.797	121.799	NM	NM	121.795	121.793
299-e26-15	NM	NM	NM	121.730	NM	121.710	NM	121.679	NM	NM	NM	121.706	121.706	121.693
299-e26-4	121.713	121.700	121.716	NM	NM	121.673	121.687	121.682	121.696	121.678	121.691	121.682	121.692	121.686
299-e26-79	121.765	121.747	121.742	121.733	121.721	121.721	121.714	121.723	121.741	NM	NM	NM	121.734	121.732
299-e27-12	121.733	121.703	121.683	121.706	121.679	121.683	NM	121.674	121.687	121.674	121.683	121.678	121.689	121.679
299-e27-14	NM	121.695	121.683	121.711	121.676	121.678	121.669	121.687	121.685	121.679	121.680	121.673	121.683	121.681
299-e27-15	121.736	121.703	121.695	121.705	121.681	121.680	121.669	121.675	121.688	121.682	121.685	121.676	121.690	121.681
299-e27-17	121.714	121.697	121.681	121.715	121.692	121.677	121.675	121.668	121.694	121.694	121.687	121.685	121.690	121.686
299-e27-18	121.742	121.718	121.713	121.716	121.693	121.690	121.676	121.754	121.697	121.693	121.703	121.693	121.707	121.708
299-e27-21	121.716	121.684	NM	121.707	121.676	121.664	121.658	NM	121.677	121.675	121.663	121.657	121.678	121.668
299-e27-22	NM	121.729	121.722	121.730	121.709	121.706	121.691	121.692	121.716	121.711	121.712	121.703	121.711	121.707
299-e27-23	121.724	121.690	121.668	121.712	121.674	121.677	121.658	121.679	121.684	121.678	NM	121.665	121.683	121.677
299-e27-7	121.723	121.691	121.661	121.722	121.684	121.682	121.670	NM	121.687	121.683	121.678	NM	121.688	121.683
299-e27-8	121.725	121.709	121.704	121.717	121.682	121.688	121.671	121.677	121.695	121.690	121.699	121.693	121.696	121.691

Table 4-1. Water Level Measurements

Well Name	Measured Water Levels (NAVD 88 meters)												Average	
	Oct-2017	Nov-2017	Dec-2017	Jan-2018	Feb-2018	Mar-2018	Apr-2018	May-2018	Jun-2018	Jul-2018	Aug-2018	Sep-2018	Oct-2017 to Sep-2018	May-2018 to Sep-2018
299-e27-9	121.716	121.705	121.696	121.713	121.682	121.688	121.673	121.701	NM	121.691	121.695	NM	121.696	121.696
299-e28-1	121.727	121.745	121.761	121.691	121.695	121.702	121.666	121.703	121.686	NM	121.735	121.682	121.709	121.702
299-e28-17	121.692	121.726	121.731	121.689	121.679	121.686	121.654	121.689	121.693	121.698	121.705	121.684	121.694	121.694
299-e28-18	NM	NM	121.738	121.713	121.702	121.708	121.676	121.711	121.707	121.719	NM	121.700	121.708	121.709
299-e28-27	121.742	121.736	121.737	121.708	121.691	121.696	121.669	121.706	121.700	NM	121.701	121.696	121.708	121.701
299-e29-54	NM	121.721	121.708	NM	121.680	121.685	121.652	NM	NM	NM	NM	NM	121.689	NM
299-e32-5	121.752	121.750	121.726	121.718	121.692	121.707	121.676	121.714	121.698	NM	121.713	121.710	121.714	121.709
299-e32-6	121.754	121.747	121.733	121.724	121.697	121.705	121.680	121.716	121.702	121.720	121.715	121.714	121.717	121.713
299-e32-8	121.761	121.756	121.736	121.731	121.703	121.712	121.688	121.719	121.707	121.726	121.722	121.719	121.723	121.719
299-e33-14	121.735	121.745	121.736	121.714	121.690	121.698	121.671	121.681	121.688	121.708	121.700	121.692	121.705	121.694
299-e33-267	121.720	121.746	121.744	NM	121.693	NM	121.676	121.688	121.689	121.716	NM	NM	121.709	121.698
299-e33-28	NM	121.741	121.723	121.701	121.691	121.697	121.678	121.694	121.700	121.710	121.708	121.698	121.704	121.702
299-e33-31	NM	121.751	121.750	121.705	121.698	121.674	121.676	121.675	121.688	121.709	NM	NM	121.703	121.691
299-e33-32	121.749	121.737	121.723	121.707	121.691	121.687	121.670	121.685	121.687	121.706	NM	NM	121.704	121.693
299-e33-339	121.753	121.736	121.719	121.709	121.687	121.686	121.669	121.686	121.690	121.708	121.699	121.683	121.702	121.693
299-e33-34	121.757	121.756	121.739	121.720	121.701	121.709	121.684	121.697	121.702	121.719	121.717	121.704	121.717	121.708
299-e33-342	121.757	NM	121.733	121.712	121.688	121.692	121.658	121.687	121.692	121.709	NM	NM	121.703	121.696
299-e33-37	121.753	121.722	121.735	121.719	121.695	121.689	121.679	121.694	121.698	121.692	121.706	121.676	121.705	121.693

Table 4-1. Water Level Measurements

Well Name	Measured Water Levels (NAVD 88 meters)												Average	
	Oct-2017	Nov-2017	Dec-2017	Jan-2018	Feb-2018	Mar-2018	Apr-2018	May-2018	Jun-2018	Jul-2018	Aug-2018	Sep-2018	Oct-2017 to Sep-2018	May-2018 to Sep-2018
299-e33-38	121.767	121.743	121.727	121.715	121.693	121.695	121.679	121.692	121.700	121.712	121.705	121.700	121.711	121.702
299-e33-41	121.750	121.732	121.722	121.704	121.684	121.684	121.666	121.684	121.688	121.702	NM	NM	121.702	121.691
299-e33-42	121.683	121.737	121.731	121.709	121.692	121.686	121.684	121.685	121.690	121.709	NM	NM	121.701	121.695
299-e33-44	121.750	121.755	NM	121.726	121.689	121.704	NM	121.672	121.695	121.710	NM	NM	121.713	121.692
299-e34-10	121.749	121.721	121.741	121.722	121.691	121.693	121.680	121.690	121.695	121.695	121.706	121.695	121.707	121.696
299-e34-9	121.740	121.714	121.741	121.717	121.687	121.693	121.680	121.685	121.691	121.695	121.704	121.692	121.703	121.693
699-37-43	121.696	121.657	121.711	121.674	121.638	121.645	121.635	121.627	121.650	121.642	121.642	121.637	121.655	121.640
699-37-47a	121.730	NM	121.707	121.672	121.658	121.662	121.640	121.679	121.677	121.694	121.671	121.652	121.677	121.675
699-49-55a	121.765	121.770	121.762	121.745	121.715	121.732	121.703	121.729	121.738	121.748	121.734	121.740	121.740	121.738
699-49-57a	121.778	121.768	121.762	121.733	121.708	121.718	121.694	121.732	121.732	121.738	121.738	121.738	121.737	121.736

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

Notes:

Well 699-49-55a: Since water level value was not measured in Jun 2018, water level was calculated as an average value of measured water levels in May and July 2018.

Well 699-49-57a: Since water level value was not measured in Jun 2018, used average measured water level from May.

Well 699-49-57a: Since water level value was not measured in July 2018, used average measured water level from August.

NM = not measured

4.2.1.1 Migration Parameters for Particle Tracking

The primary purpose of the assessment presented in this ECF is to estimate flow direction and hydraulic gradients, therefore the particle tracking input parameters that describe mobility - mobile porosity and hydraulic conductivity - were set to values necessary to obtain site specific pathlines long enough to exit the site boundary in a downgradient direction and cross at least two water level contours with an interval of 0.005 m.

4.2.2 Particle Starting Locations

To reduce uncertainty related to the assumptions previously listed, each facility used a minimum of three particle starting locations set along a line perpendicular to the general flow direction and located at either the edge or in the middle of the facility. One particle was then released and tracked from each of the three starting locations. The starting locations for these calculations for each facility are shown in Figure 4-1.

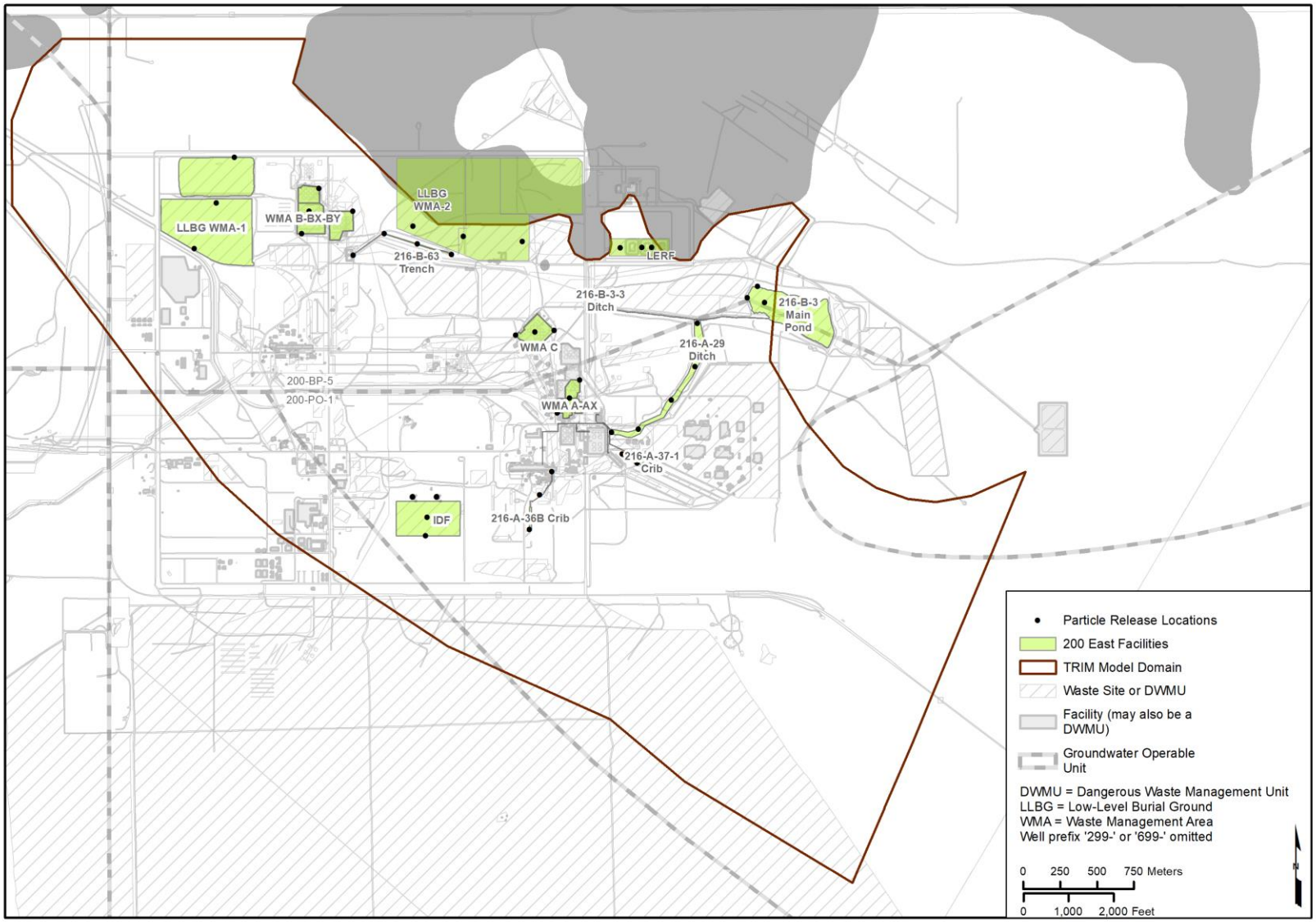

Figure 4-1. Release Locations at 200 East Area Facilities

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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 for this ECF was approved and complies with PRC-PRO-IRM-309. The software is managed under the following documents consistent with PRC-PRO-IRM-309:

- 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 upon 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, "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"), 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 (HISI) identification number**: **2517**
- **Workstation type and property number (from which software is run)**: S.S. Papadopulos and Assoc., Inc., FE563.

5.3 Support Software

The following software programs are classified as support software.

- **PEST**: (Doherty, 2015) 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*. Provided graphical tools used for model quality assurance and model input/output review.

™ Groundwater Vistas is a trademark of Environmental Simulations, Inc., Reinholds, Pennsylvania.

- **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*).
- **Surfer®**: Data interpolation for visualization, model implementation, and quality assurance.
- **mod-PATH3DU**: 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 Version 2.7.11 distributed with Anaconda 4.1.1 (64 bit).
- **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 (CHPRC) 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 for CHPRC, 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.

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

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

™Python is a registered trademark of Python Software Foundation, Beaverton, Oregon (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 Calculations

This chapter describes the calculations performed to examine all 200 East Facilities. The following steps were taken to develop the necessary input files, perform the calculations, and post-process the outputs to produce the results presented in this ECF.

6.1 Water-Level Analysis Using the Tikhonov Regularized Inverse Method

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

1. **Data Compilation**: Input data were compiled from the retrieved database sources. Average groundwater elevations were calculated for the period from May to September 2018 and used to define calibration targets for TRIM. These summer months were selected for calibration because the annual average (October 2017 – September 2018) water levels exhibited notable regional rebound in water elevations in fall of 2017 that were determined to have resulted from discharges to groundwater at the Treated Effluent Disposal Facility. Figure 6-1 shows an example of historical water levels.

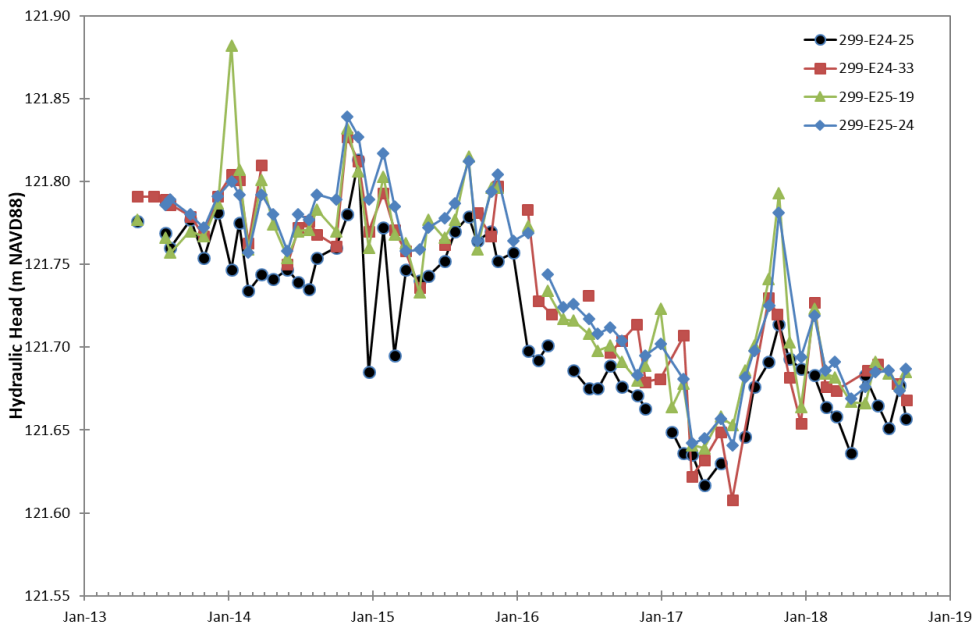

Figure 6-1. Water Level Hydrographs

2. **Tikhonov Regularized Inversion**: Values for the parameters of the simplified two-dimensional groundwater flow simulator were iteratively updated using the Tikhonov regularization method implemented in PEST by obtaining successive improvements in the fit between the calculated and measured groundwater levels in the calibration data set. This process occurred in two substeps:

   a. First, an initial calibration was undertaken to produce a groundwater elevation map that approximated the measured groundwater levels but resulted in minimal deviation from the preferred system condition of homogeneity. This provided initial estimates for (a) the (relative) flow rates at each of the specified flux boundaries, (b) the hydraulic head at the specified head boundary, and (c) the (relative) hydraulic conductivity in each of the three HSU zones.

b. Second, a series of iterations of Tikhonov regularized inversion was executed using PEST in the regularization mode, during which the effect on patterns of groundwater flow and hydraulic gradients of trading off the variance of the simulator parameters against the fit to the measured data was explored. For this second step, the value of the (relative) hydraulic conductivity for all cells were estimated via the regularized inversion. A preferred difference (i.e., smoothness) Tikhonov regularization scheme was defined within each of these three HSU zones by specifying prior information equations that penalized the (square of the) difference in the value of the hydraulic conductivity between neighboring cells. During the second step of the regularized inversion it was observed that a small number of monitoring wells consistently accounted for a significant proportion of the measurement objective function (i.e., the misfit). The measurements associated with these wells were consequently ascribed a low-valued or zero-valued weight in the regression. The full set of calibration targets, measured and estimated water levels, and their associated weights, is listed in Table 6-1.

3. **Formal Pareto Analysis**: In the third step of the process, the PEST program was executed using Pareto mode incorporating the Tikhonov regularization results obtained in Step 2. The purpose of this step of the analysis was to produce the Pareto-front or L-curve to depict the tradeoff between the measurement objective function (i.e., fit to the water-level data) and the regularization objective function (i.e., the correspondence with the preferred state of parameter smoothness) (Doherty, 2015). The parameter value estimates that were obtained from the previously regularized inversion step were used as initial parameter values for the Pareto analysis. The PEST program was then executed to complete 10 iterations within which the global regularization weight parameter applied to the regularization objective function was raised geometrically from 0.01 (1×10^{-2}) to 0.2 (2×10^{-1}). The outputs from these Pareto calculations were then used to plot the L-curve depicted in Figure 6-2.

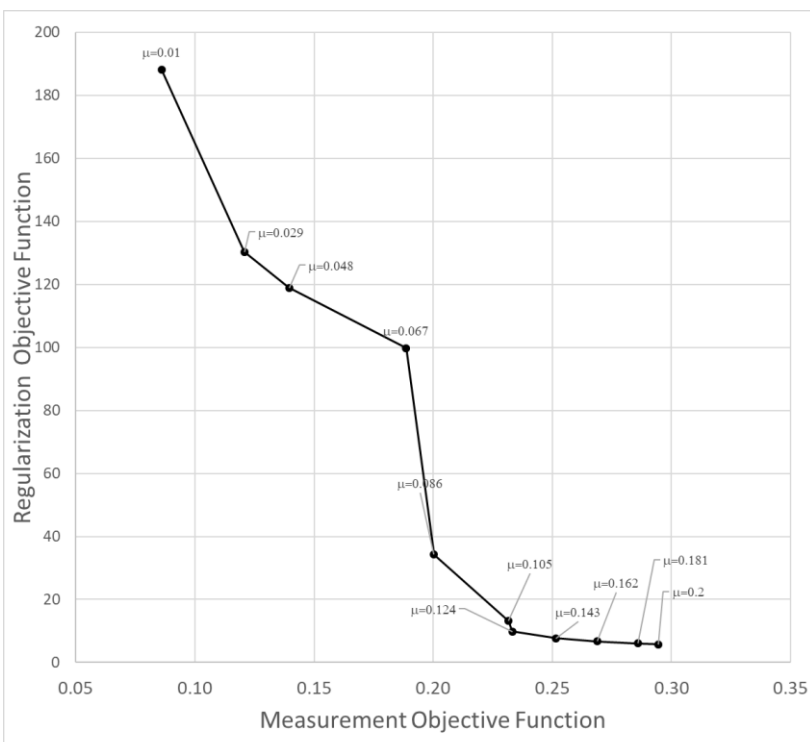

Figure 6-2. Calculated L-Curve

At the conclusion of the Pareto analysis, a combined review was completed by SMEs of both the resulting L-Curve and the individual groundwater elevation contour maps produced using the global regularization weight parameters. From this review, the outputs produced by the Pareto iteration using a global regularization weight parameter of 0.124 were considered to represent a reasonable correspondence between the calculated and measured groundwater elevations, and this global regularization weight parameter was selected for purposes of subsequent assessments. This result was selected based on a weight-of-evidence approach as it (a) provided acceptable correspondence between calculated and measured groundwater elevations given estimated measurement errors, (b) produces groundwater elevation contours and hydraulic gradients that comport with each SME's independent understanding of groundwater elevations and gradients at each of the 200 East Facilities, and (c) results in calculated flow paths that comport with each SME's independent understanding of likely migration patterns downgradient of each of the 200 East Facilities.

To verify the Tikhonov Regularized Inversion approach, using already calibrated hydraulic parameters based of calibration targets derived on average May 2018 – September 2018 water levels, a second water-level map was generated using the annual average (October 2017 – September 2018) data set. In this case PEST is used to calibrate only boundary conditions with some weight adjustments to calibration targets.

A scatter plot of calibration results of the simulated versus the measured groundwater elevations for both data sets is provided in Figure 6-3. Maps of the simulated groundwater levels together with the water-level residuals and target weights are presented in Chapter 7.

Similarly, to annual average, monthly water-level maps were also prepared calibrating only boundary conditions. Monthly water-level maps and calibration scatter plots are presented in Chapter 7.

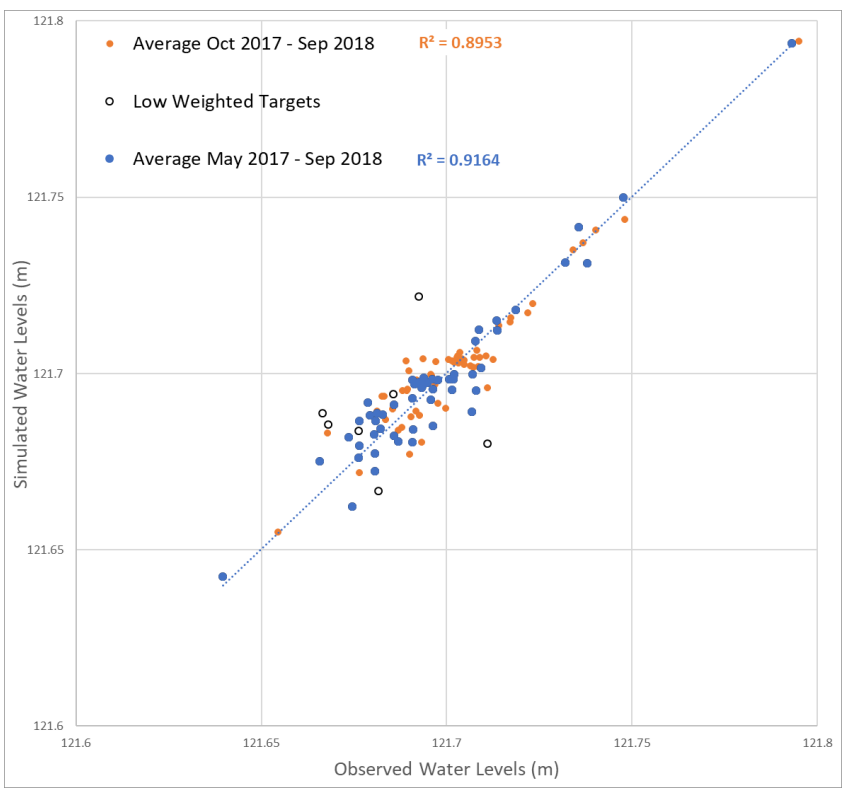

Figure 6-3. Comparison of Observed Versus Simulated Water Levels after Pareto Analysis

Table 6-1. Calibration Targets for Period May – September 2018

Well Name	Average Measured Water Level (m NAVD88)	Estimated Water Level (m NAVD88)	Residual (Estimated Error) (m NAVD88)	Calibration Weight
299-e17-18	121.666	121.675	-0.009	10
299-e17-21	121.707	121.698	0.009	10
299-e17-22	121.687	121.680	0.007	10
299-e17-23	121.691	121.680	0.011	10
299-e17-25	121.696	121.684	0.012	10
299-e18-2	121.748	121.744	0.003	10
299-e23-1	121.679	121.691	-0.013	10
299-e24-16 [a]	121.711	121.680	0.031	2
299-e24-18 [a]	121.676	121.683	-0.007	1
299-e24-21	121.682	121.684	-0.002	10
299-e24-22	121.674	121.682	-0.008	10
299-e24-24	121.686	121.690	-0.005	10
299-e24-25 [a]	121.667	121.689	-0.022	1
299-e24-33	121.681	121.682	-0.002	10
299-e25-19	121.681	121.672	0.009	10
299-e25-24 [b]	121.682	121.666	0.016	0
299-e25-25 [b]	NM	121.668	-121.668	0
299-e25-34	121.681	121.677	0.004	10
299-e25-35	121.676	121.676	0.001	10
299-e25-93	121.677	121.679	-0.003	10
299-e26-10	121.714	121.712	0.002	10
299-e26-13	121.691	121.684	0.007	10
299-e26-14	121.793	121.793	0.000	20
299-e26-15 [b]	121.693	121.722	-0.029	0
299-e26-4	121.686	121.682	0.004	10
299-e26-79	121.732	121.731	0.001	10
299-e27-12	121.679	121.688	-0.009	10
299-e27-14	121.681	121.686	-0.005	10

Table 6-1. Calibration Targets for Period May – September 2018

Well Name	Average Measured Water Level (m NAVD88)	Estimated Water Level (m NAVD88)	Residual (Estimated Error) (m NAVD88)	Calibration Weight
299-e27-15	121.681	121.689	-0.007	10
299-e27-17 [a]	121.686	121.694	-0.009	1
299-e27-18	121.708	121.695	0.013	10
299-e27-21 [a]	121.668	121.685	-0.017	1
299-e27-22	121.707	121.689	0.018	10
299-e27-23	121.677	121.686	-0.010	10
299-e27-7	121.683	121.688	-0.005	10
299-e27-8	121.691	121.693	-0.002	10
299-e27-9	121.696	121.693	0.003	10
299-e28-1	121.702	121.696	0.006	10
299-e28-17	121.694	121.698	-0.004	10
299-e28-18	121.709	121.701	0.008	10
299-e28-27	121.701	121.698	0.002	10
299-e29-54 [b]	NM	121.698	-121.698	0
299-e32-5	121.709	121.710	-0.001	10
299-e32-6	121.713	121.712	0.002	10
299-e32-8	121.719	121.715	0.003	10
299-e33-14	121.694	121.698	-0.004	10
299-e33-267	121.698	121.698	-0.001	10
299-e33-28	121.702	121.700	0.002	10
299-e33-31	121.691	121.698	-0.008	10
299-e33-32	121.693	121.698	-0.005	10
299-e33-339	121.693	121.697	-0.004	10
299-e33-34	121.708	121.709	-0.001	10
299-e33-342	121.696	121.699	-0.003	10
299-e33-37	121.693	121.696	-0.003	10
299-e33-38	121.702	121.699	0.003	10
299-e33-41	121.691	121.697	-0.006	10

Table 6-1. Calibration Targets for Period May – September 2018

Well Name	Average Measured Water Level (m NAVD88)	Estimated Water Level (m NAVD88)	Residual (Estimated Error) (m NAVD88)	Calibration Weight
299-e33-42	121.695	121.698	-0.003	10
299-e33-44	121.692	121.698	-0.005	10
299-e34-10	121.696	121.696	0.001	10
299-e34-9	121.693	121.697	-0.003	10
699-37-43	121.640	121.642	-0.002	20
699-37-47a	121.675	121.662	0.013	10
699-49-55a	121.738	121.737	0.001	20
699-49-57a	121.736	121.733	0.002	20

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

a. Well assigned a low weight for PEST calibration

b. Well excluded from calibration

NM = not measured

6.2 Particle Tracking

After the grids of groundwater elevations were created using TRIM, they were used as the base for particle tracking. Gradients specific to each facility were calculated using particle tracking by integrating calculated gradients for each particle tracking time step. Particle tracking input files were prepared using following steps:

1. The groundwater elevations calculated throughout the domain using TRIM with the average May – September 2018 data set were imported into the Groundwater Vistas Graphical User Interface software and then exported as a regular grid using the Surfer grid format for use as an input to the particle-tracking calculations.

2. The mod-PATH3DU input file representing particle starting locations (release points) was prepared in an ArcGIS shapefile format. For each facility, a minimum of three particles was released at locations that are perpendicular to the general flow direction and located at the edge and in the middle of the facility. One particle was released and tracked from each particle starting location. The starting locations for the particle calculations for each facility are shown in Figure 4-1.

3. A mod-PATH3DU particle-tracking input file was generated using the following inputs:

    a. A maximum tracking time was set for each facility that allowed the vast majority of the particles released to migrate beyond the locations of the facility's boundary during the calculations.

b. Particles were released and tracked using only advective transport.

Mod-PATH3DU was executed to make the particle-tracking calculations and produce a binary pathline output file containing the pathline for each tracked particle.

A post-processing program (writep3doutput.exe) was executed to convert the mod-PATH3DU binary pathline output file into ArcGIS shapefile format which list particle locations and travel time. An output point shapefile was imported in ArcMap. Then, using ArcGIS "Spatial Analyst" tool, water elevation values from TRIM groundwater water-level map were linearly interpolated to each point in a shapefile.

Data from the shapefile containing particle coordinates and water table elevations was then imported into Excel® where the gradient magnitude and azimuth were calculated per each pathline segment. Calculated gradient statistic for magnitude and azimuth including minimum, maximum, average and median values are presented in Chapter 7.

® Excel is a registered trademark of Microsoft Corporation in the United States and other countries.

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7 Results

This chapter presents outputs from the previously described calculations. The results presented include the following:

- The water-level mapping results from the application of the TRIM.
- A map of calculated particle paths used for calculations of hydraulic gradients.
- A table of hydraulic gradients calculated at each facility.

7.1 200 East Area Groundwater Elevation Maps

Figure 7-1 depicts the groundwater elevation contours throughout the 200 East Area that were prepared using the methods and inputs described previously. The figure depicts general groundwater elevations for conditions represented by average water levels for the period from May through September 2018.

Figure 7-2 depicts the groundwater elevation contours throughout the 200 East Area that were generated using average water levels for the period from October 2017 through September 2018.

Figure 7-3 to 7-14 depicts the monthly groundwater elevation contours throughout the 200 East Area that were generated using monthly water levels for the period from October 2017 through September 2018.

All water level map figures also illustrate calibration weights and calibration residuals for monitoring wells included in the calibration process.

Figure 7-15 depicts a scatter plot of monthly calibration results of the simulated versus the measured groundwater elevations.

7.2 Gradients

Figure 7-16 depicts the map of particle pathlines that were calculated using the May – September 2018 mapped groundwater elevations throughout the 200 East Area illustrating groundwater flow direction in the vicinity of each RCRA Facility.

The estimated hydraulic gradients at each RCRA Facility are included in Table 7-1 and depicted in Figure 7-17.

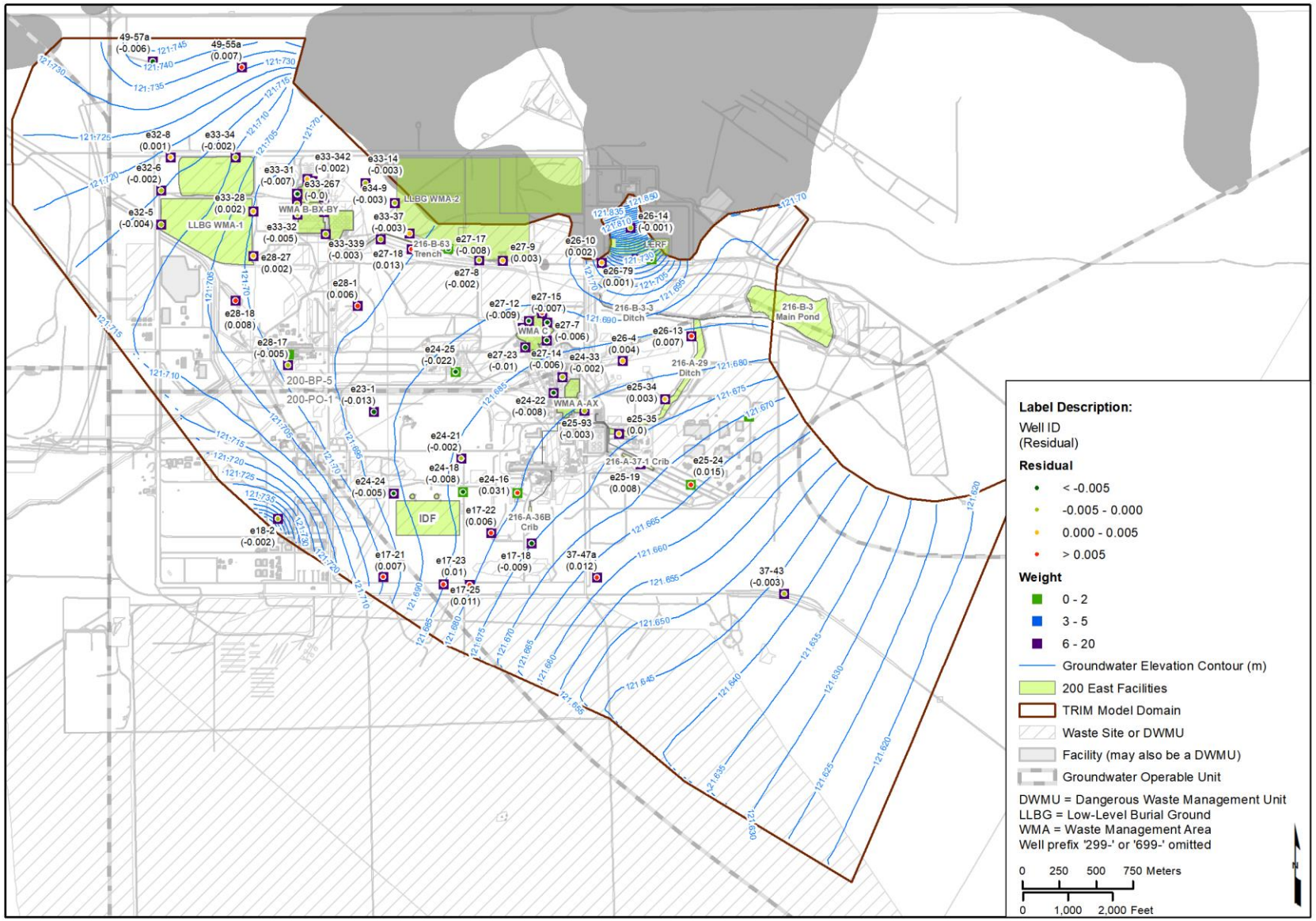

Figure 7-1. Mapped Groundwater Elevations and Calibration Residuals: Average May – September 2018

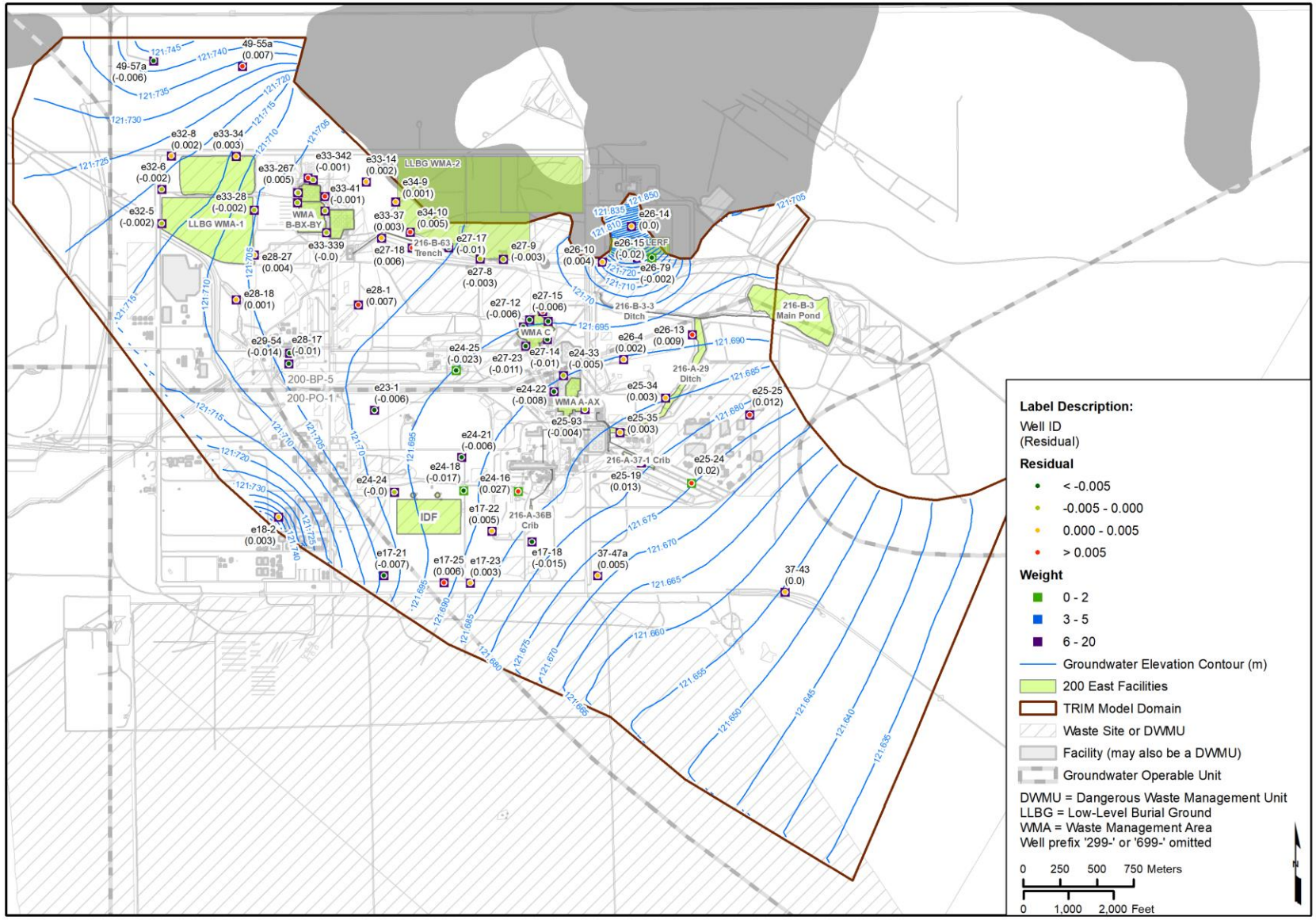

Figure 7-2. Mapped Groundwater Elevations and Calibration Residuals: Average October 2017 – September 2018

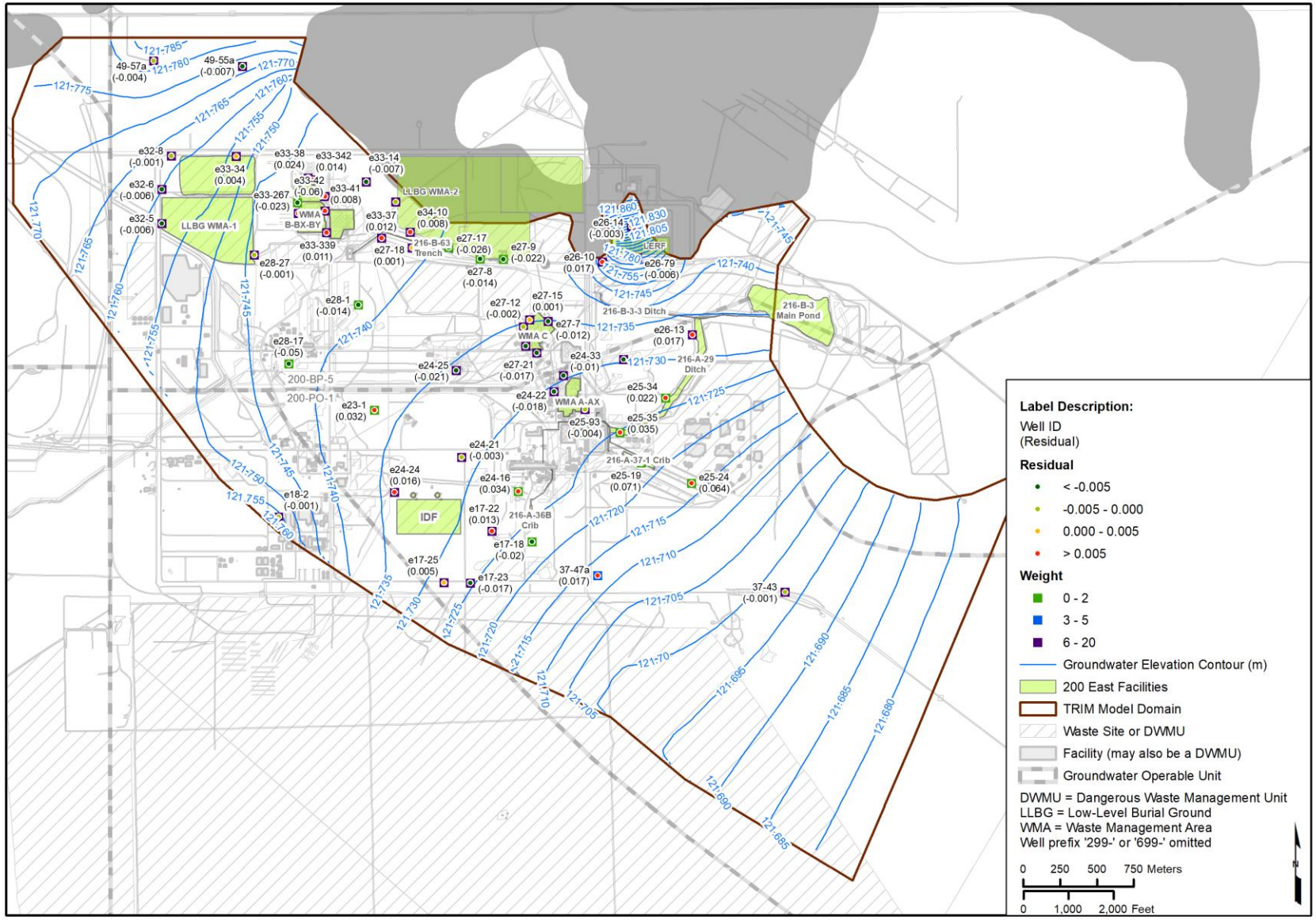

Figure 7-3. Mapped Groundwater Elevations and Calibration Residuals: October 2017

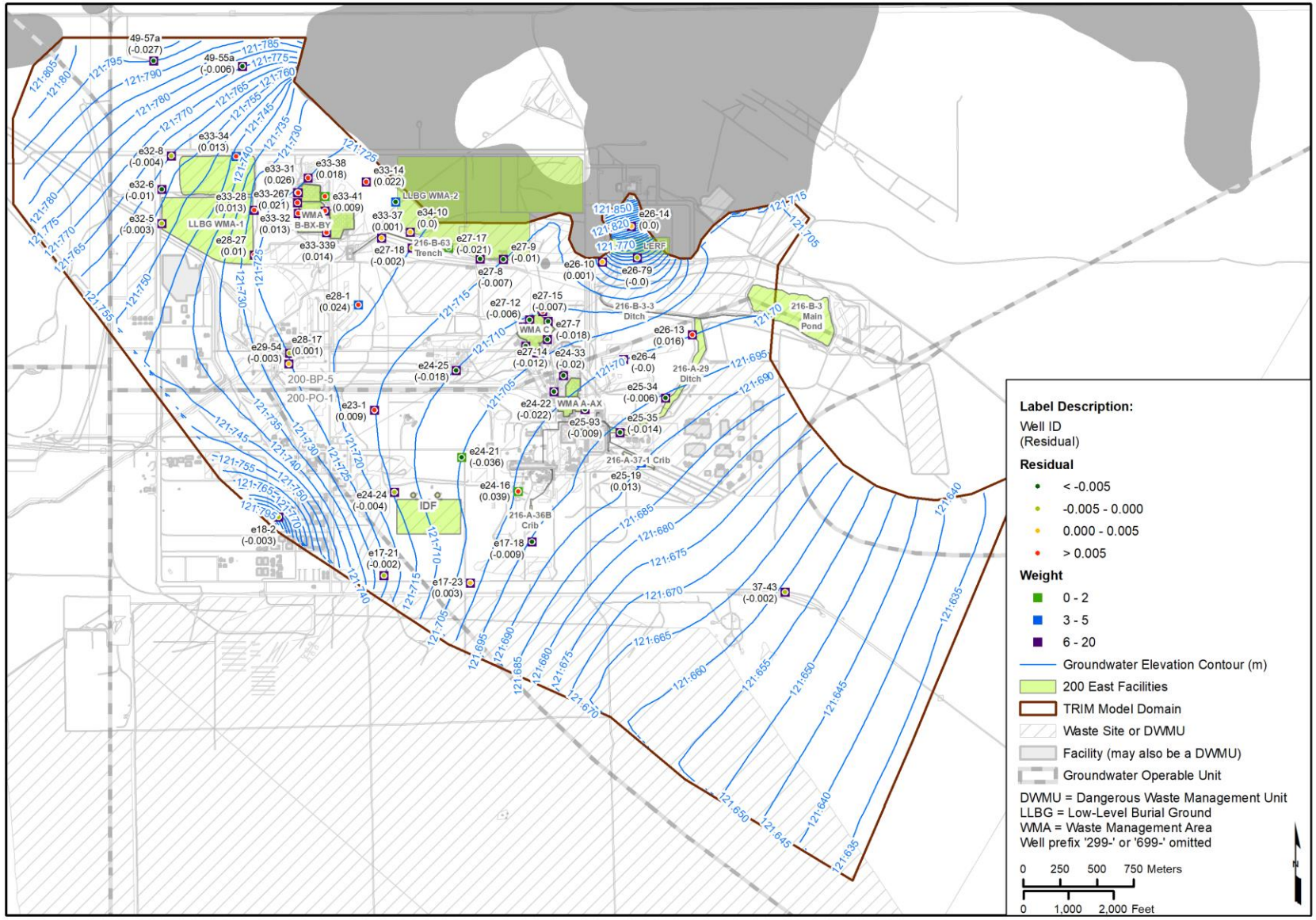

Figure 7-4. Mapped Groundwater Elevations and Calibration Residuals: November 2017

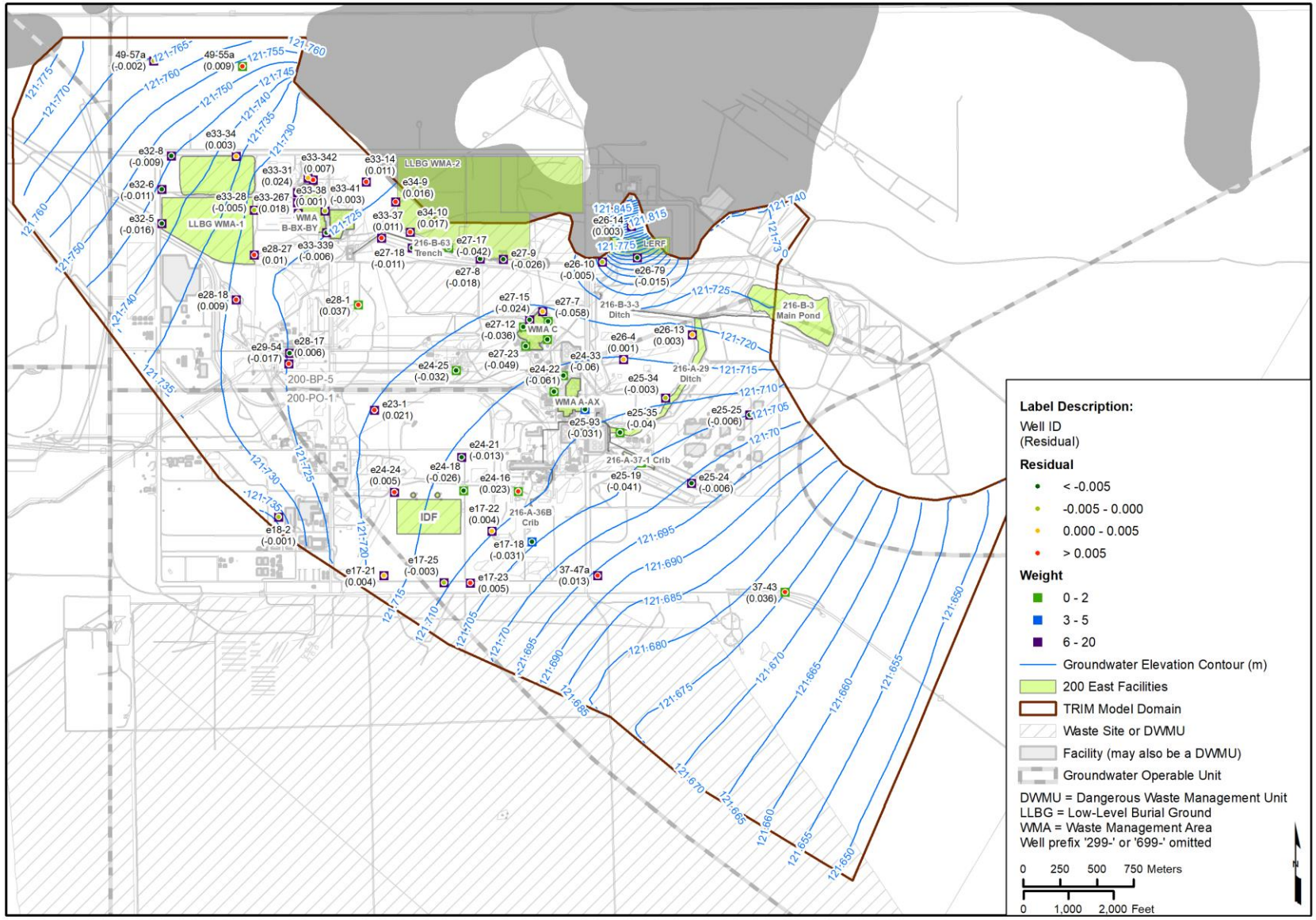

Figure 7-5. Mapped Groundwater Elevations and Calibration Residuals: December 2017

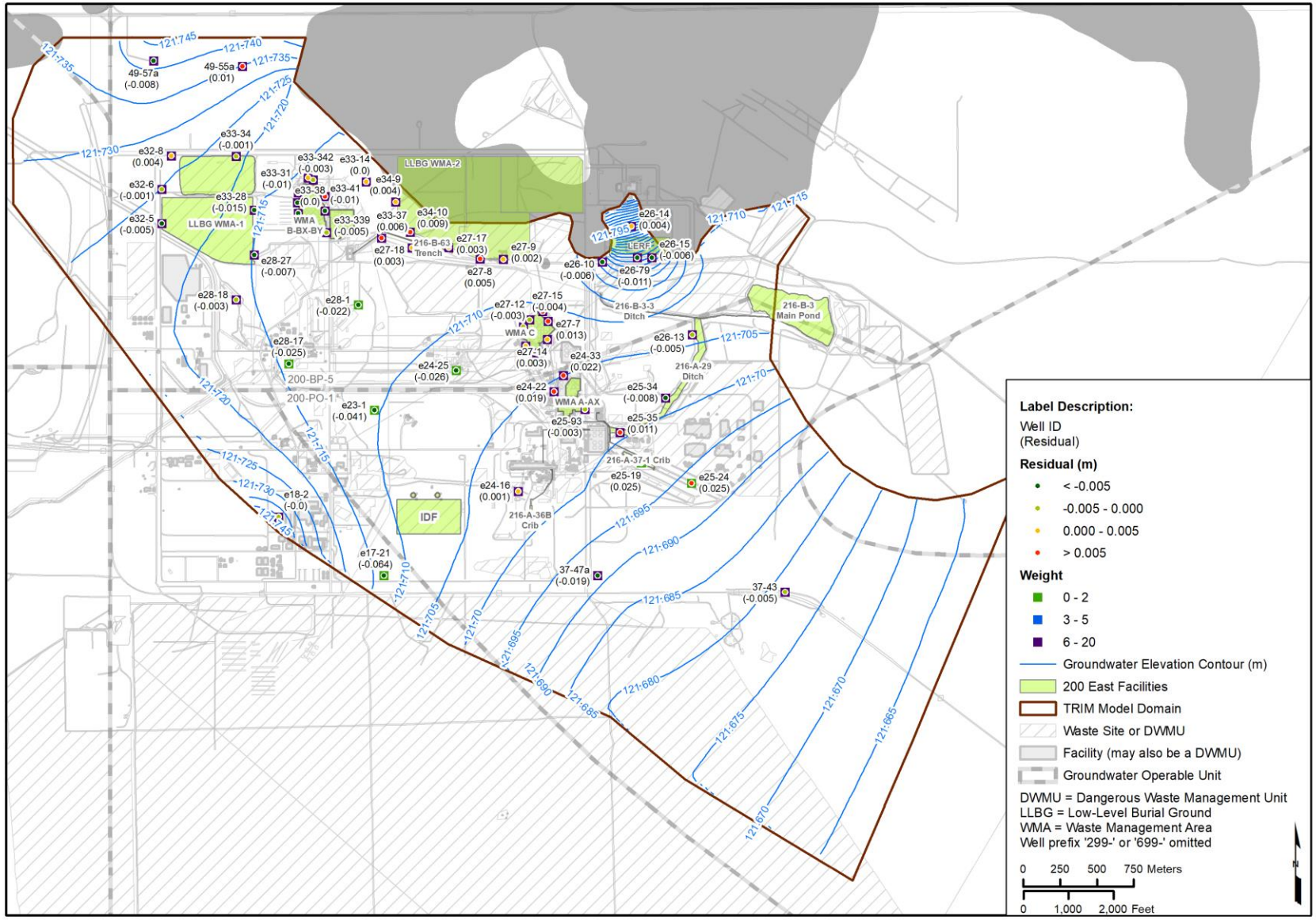

Figure 7-6. Mapped Groundwater Elevations and Calibration Residuals: January 2018

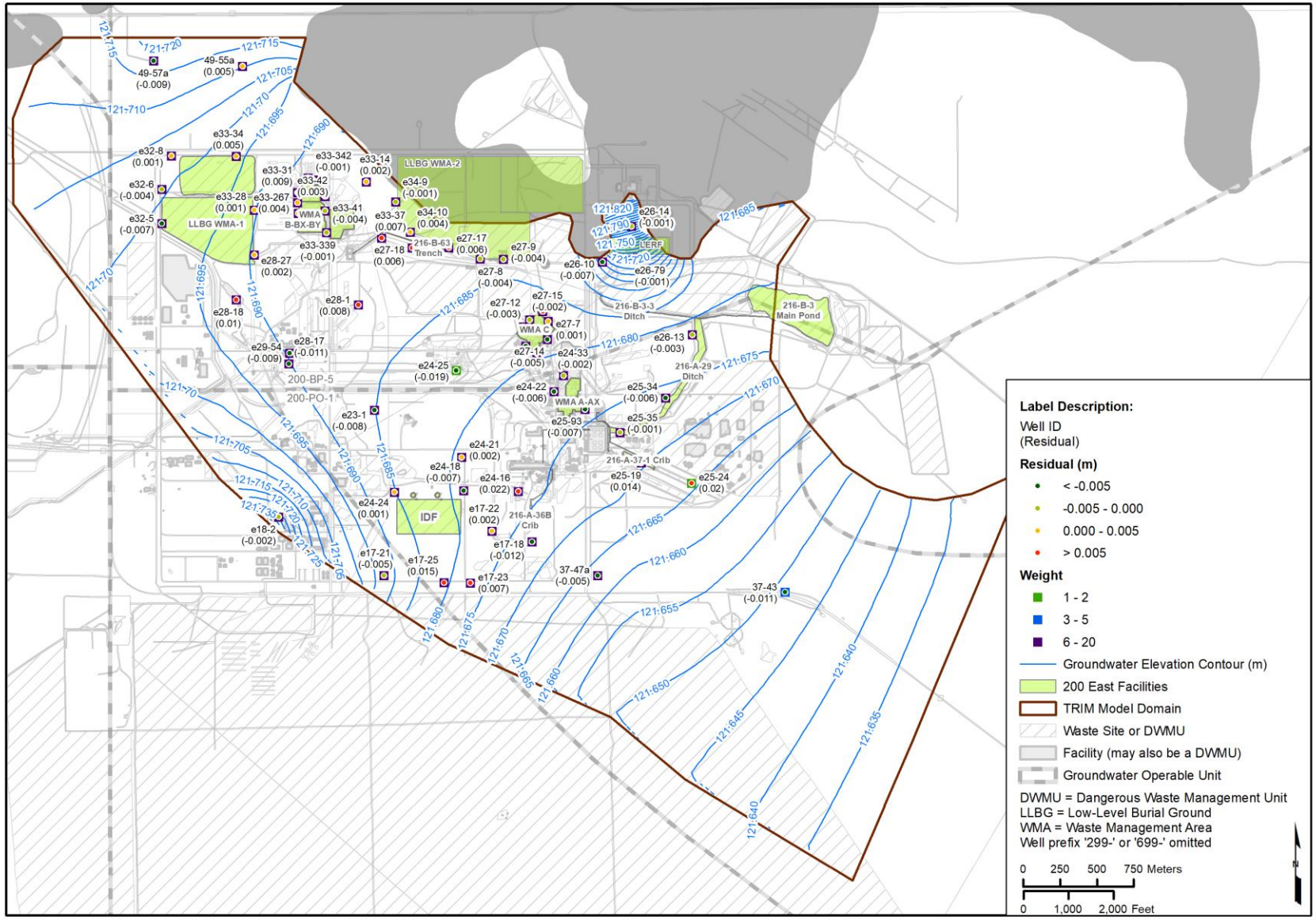

Figure 7-7. Mapped Groundwater Elevations and Calibration Residuals: February 2018

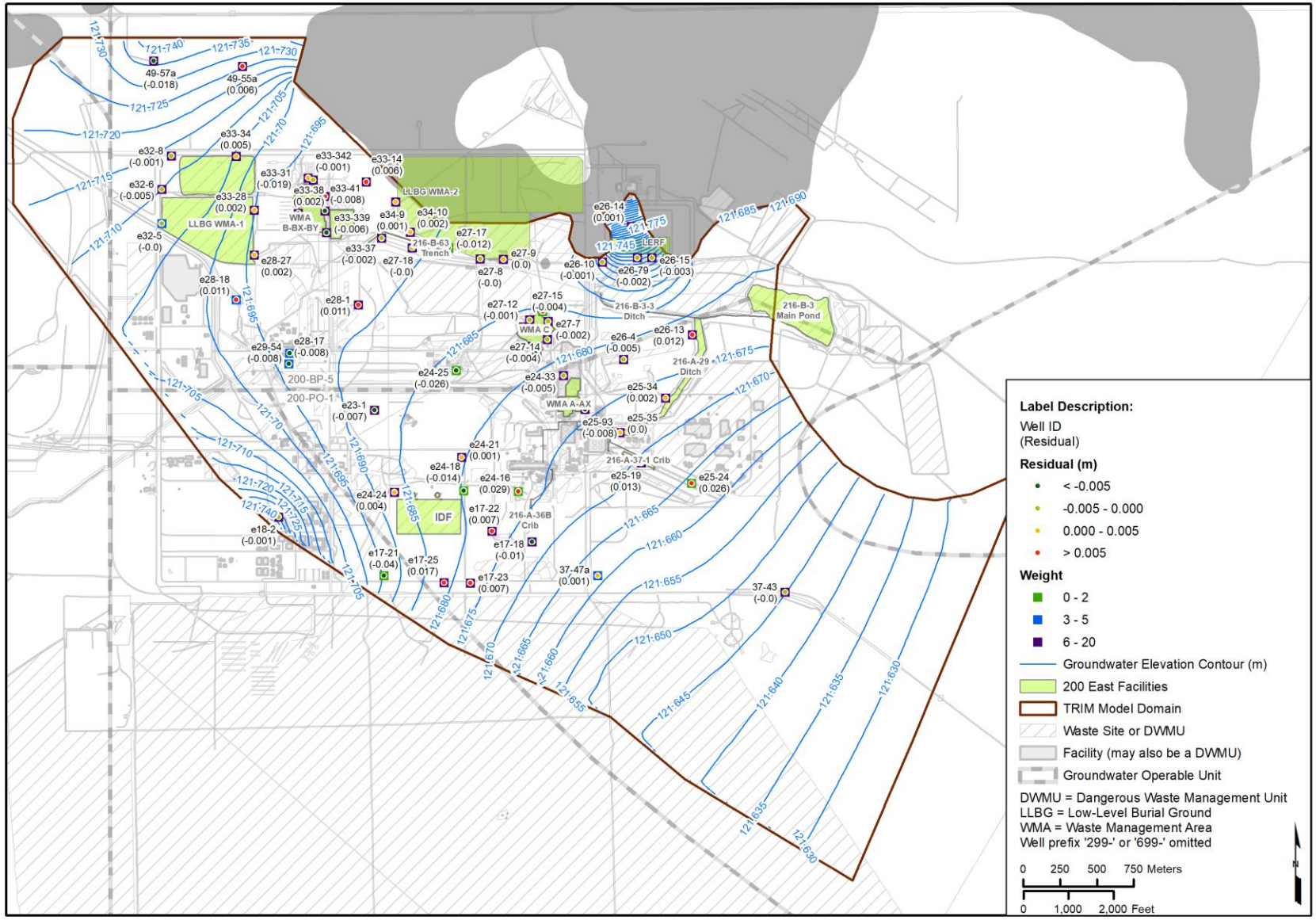

Figure 7-8. Mapped Groundwater Elevations and Calibration Residuals: March 2018

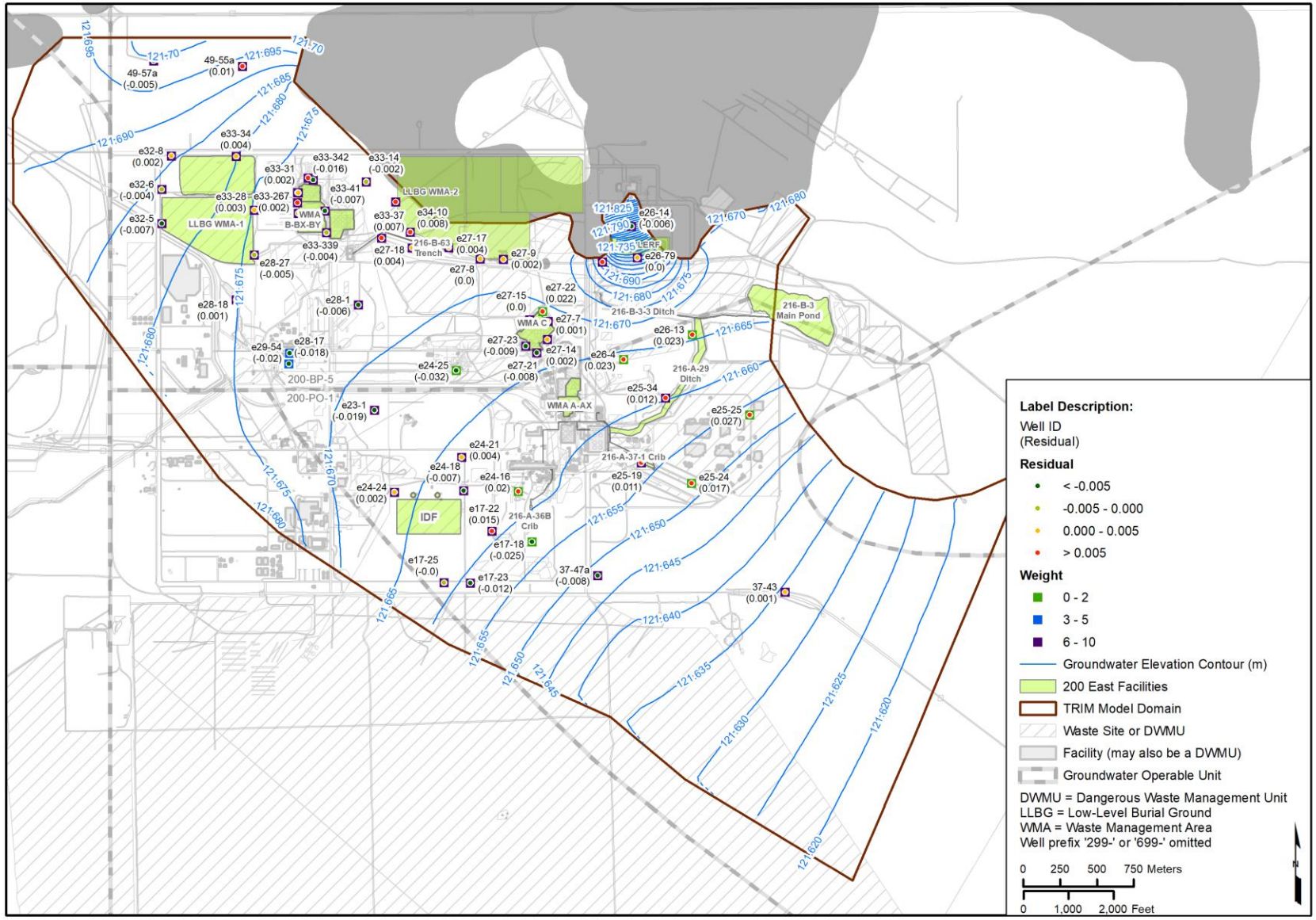

Figure 7-9. Mapped Groundwater Elevations and Calibration Residuals: April 2018

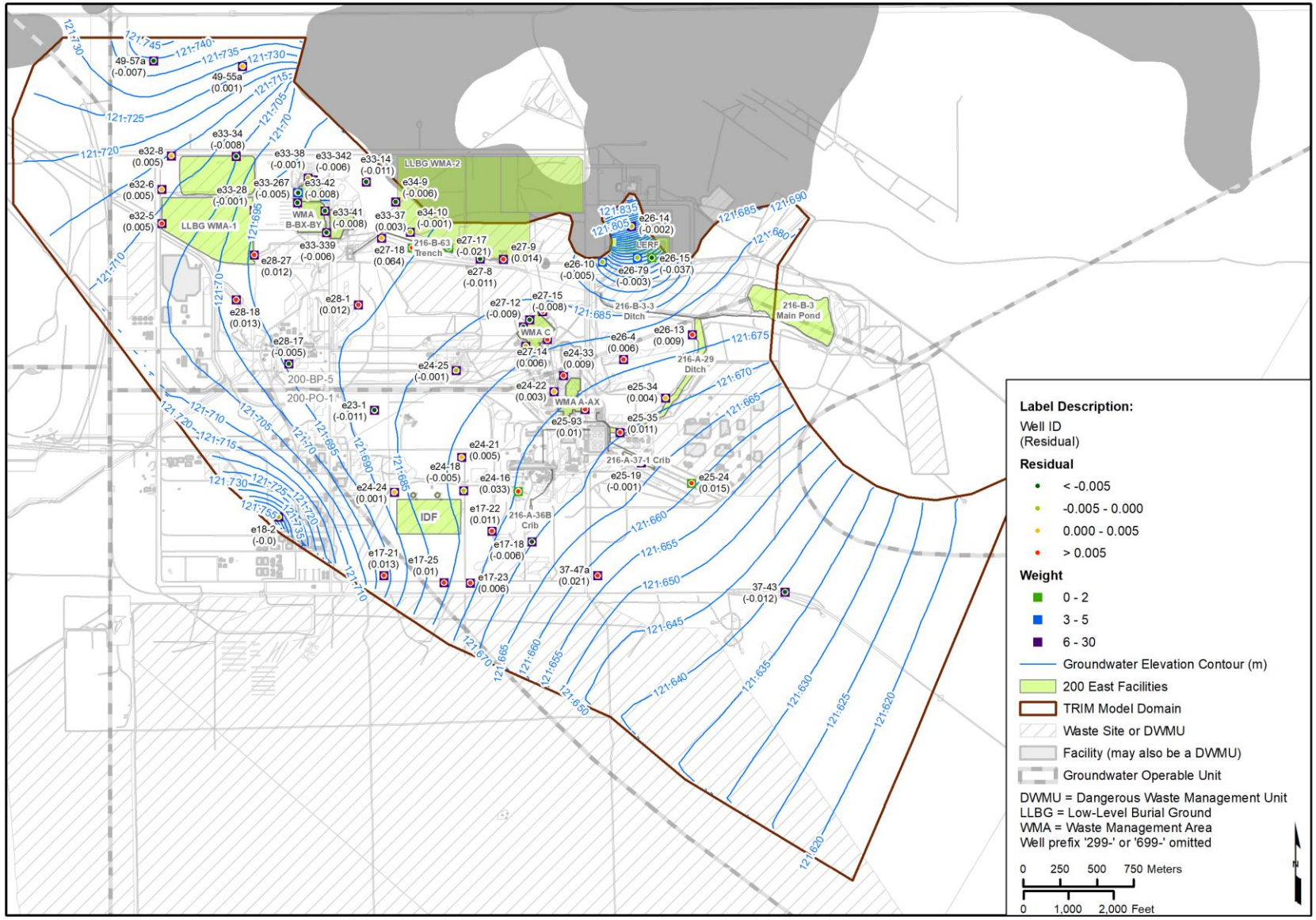

Figure 7-10. Mapped Groundwater Elevations and Calibration Residuals: May 2018

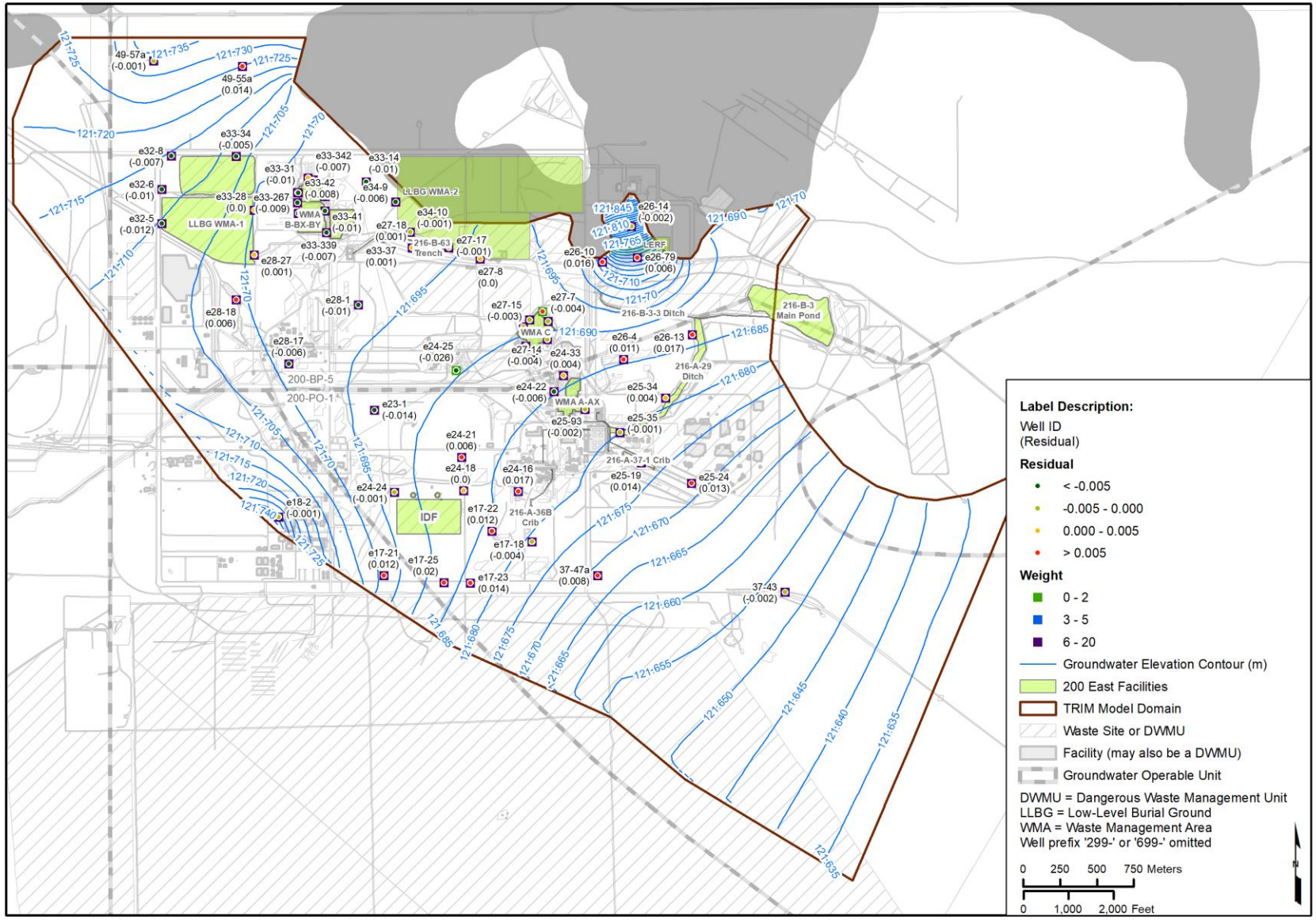

Figure 7-11. Mapped Groundwater Elevations and Calibration Residuals: Jun 2018

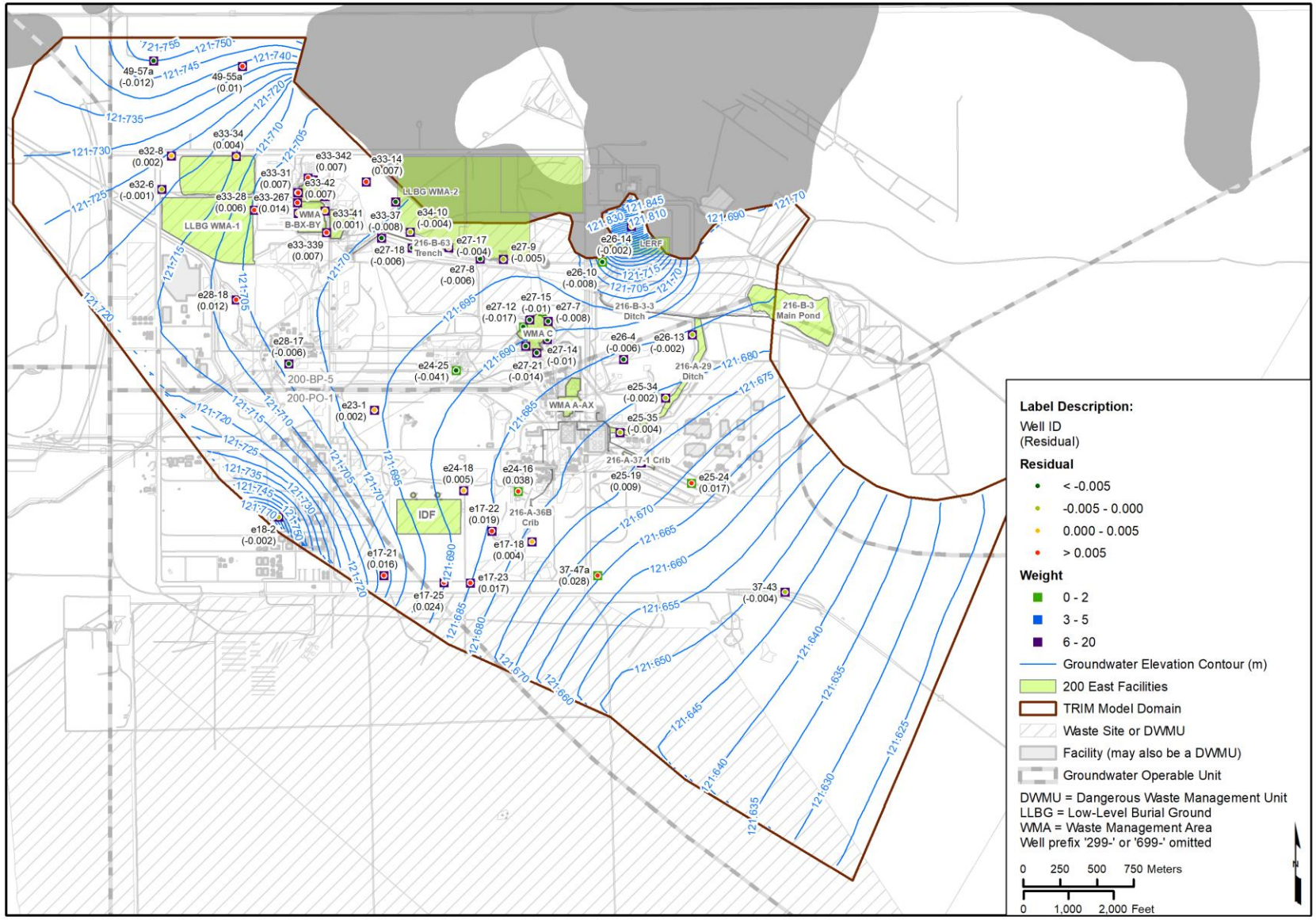

Figure 7-12. Mapped Groundwater Elevations and Calibration Residuals: July 2018

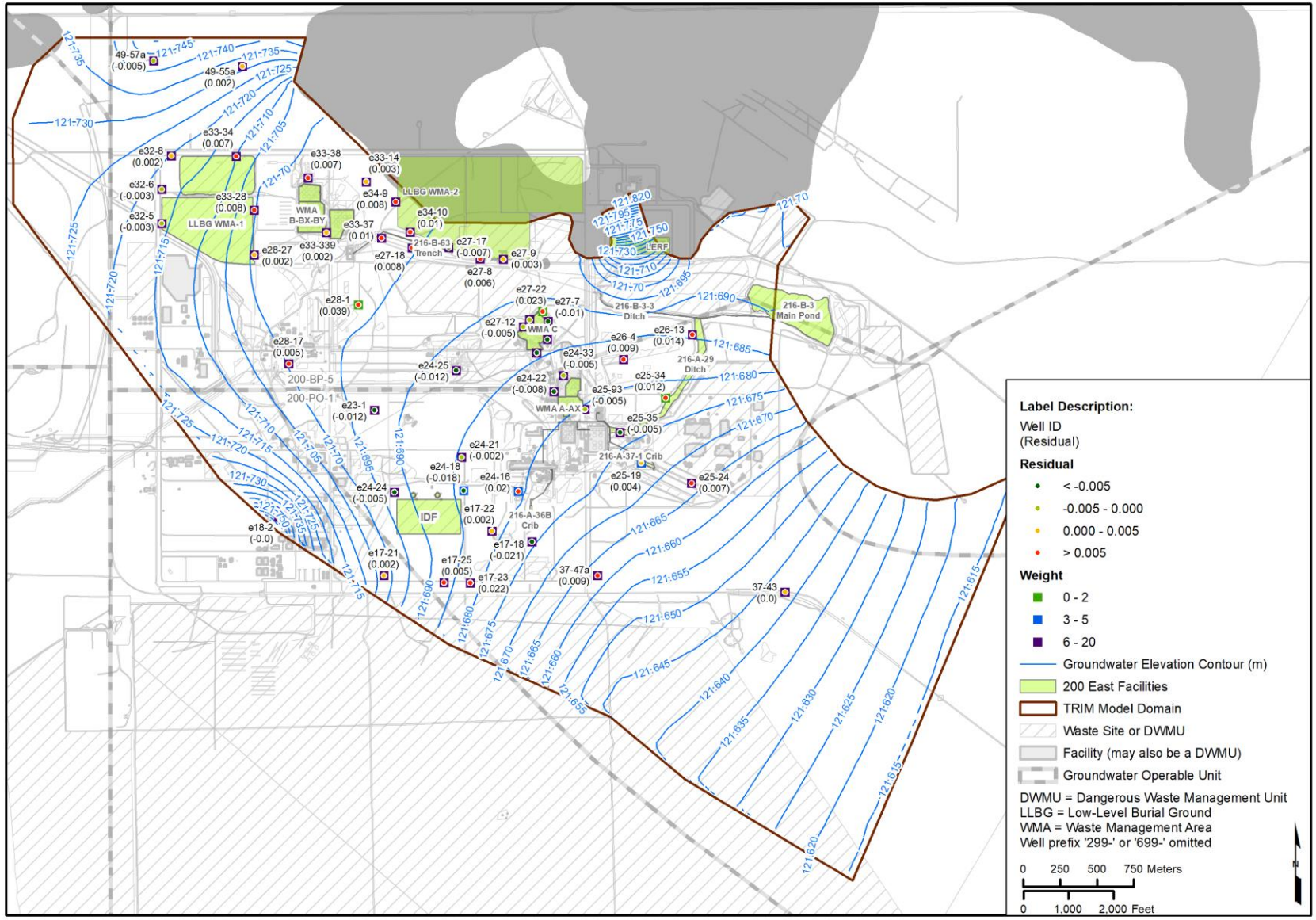

Figure 7-13. Mapped Groundwater Elevations and Calibration Residuals: August 2018

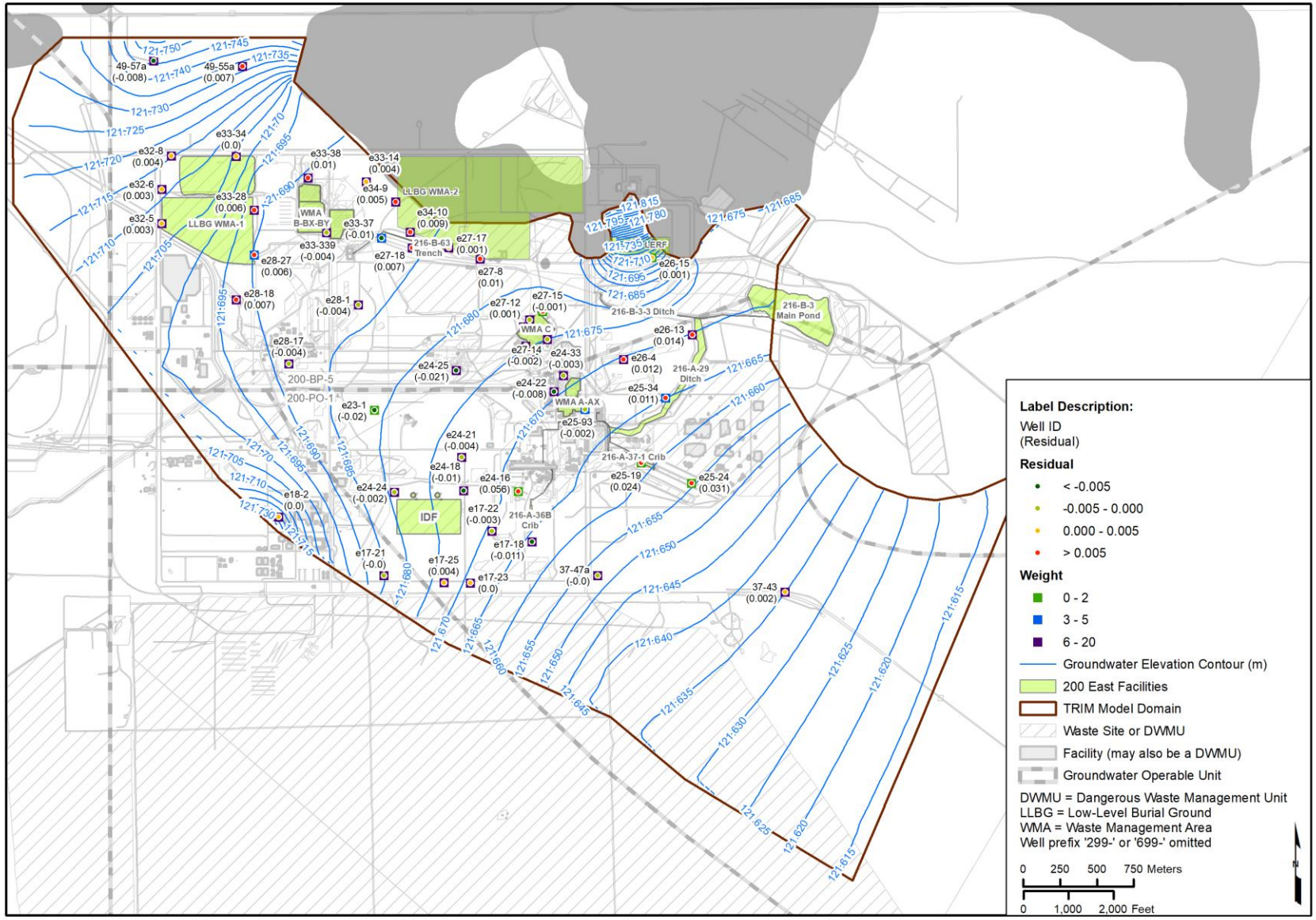

Figure 7-14. Mapped Groundwater Elevations and Calibration Residuals: September 2018

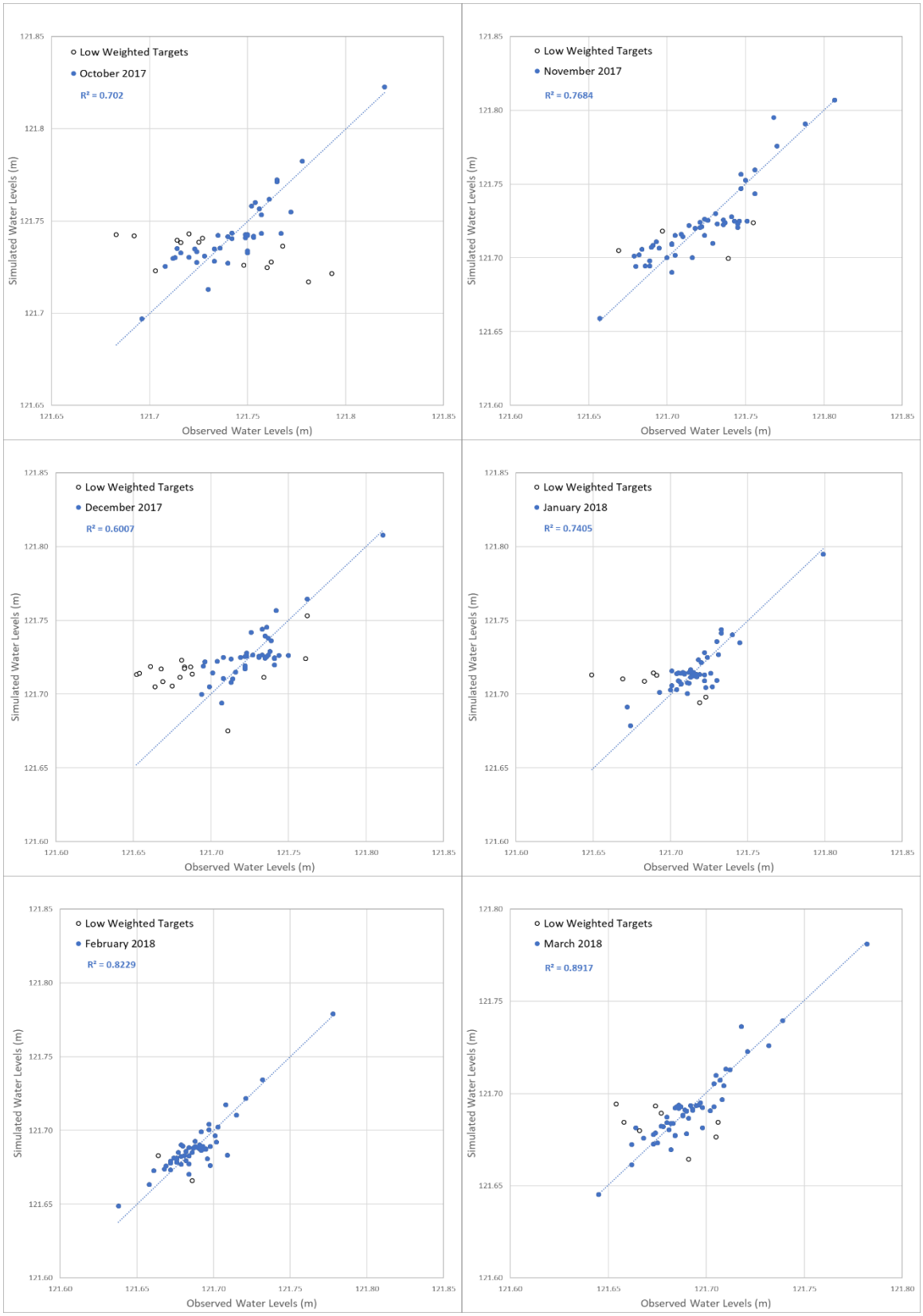

Figure 7-15. Observed vs. Simulated Calibration Plots (Page 1 of 2)

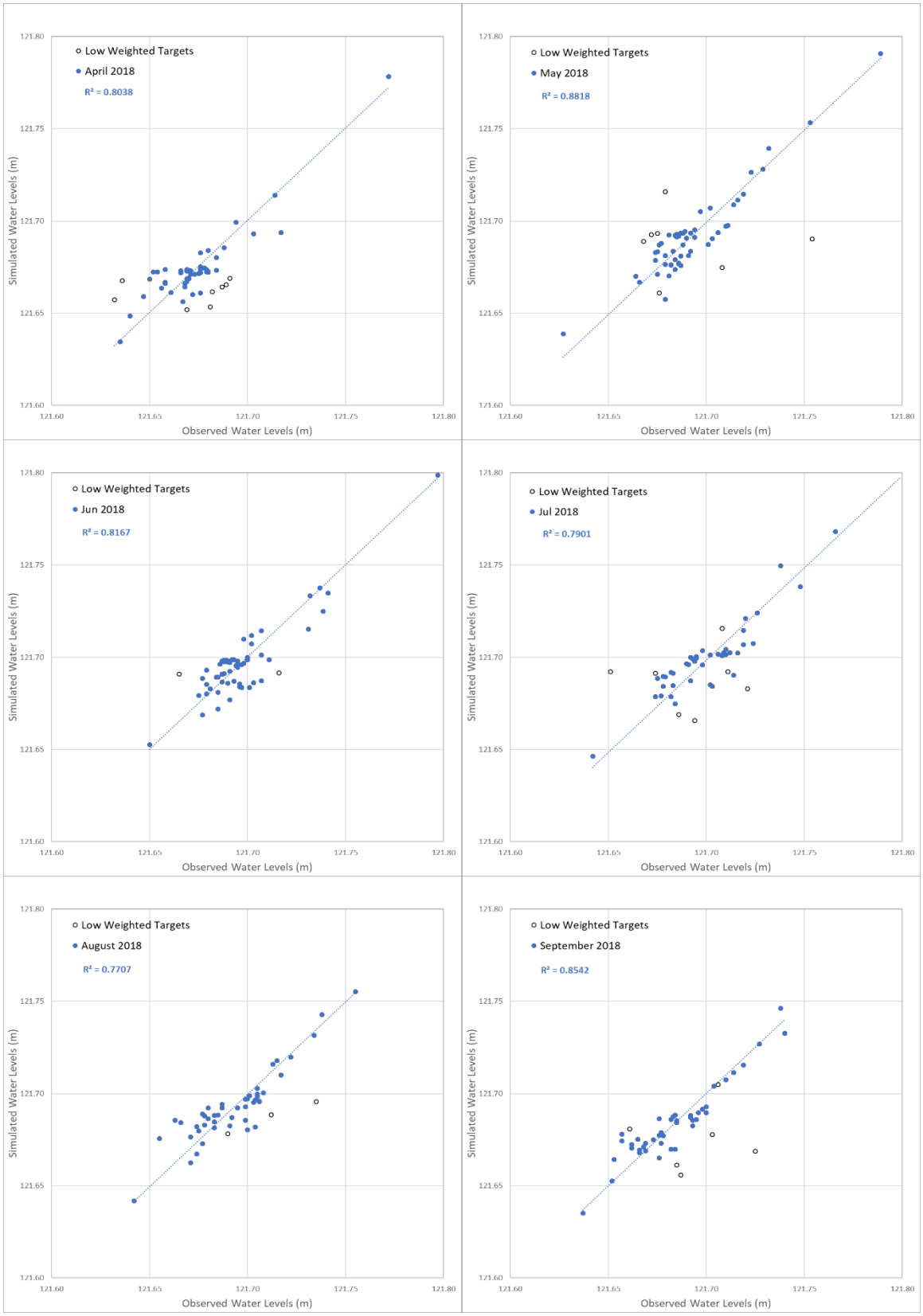

Figure 7-15. Observed vs. Simulated Calibration Plots (Page 2 of 2)

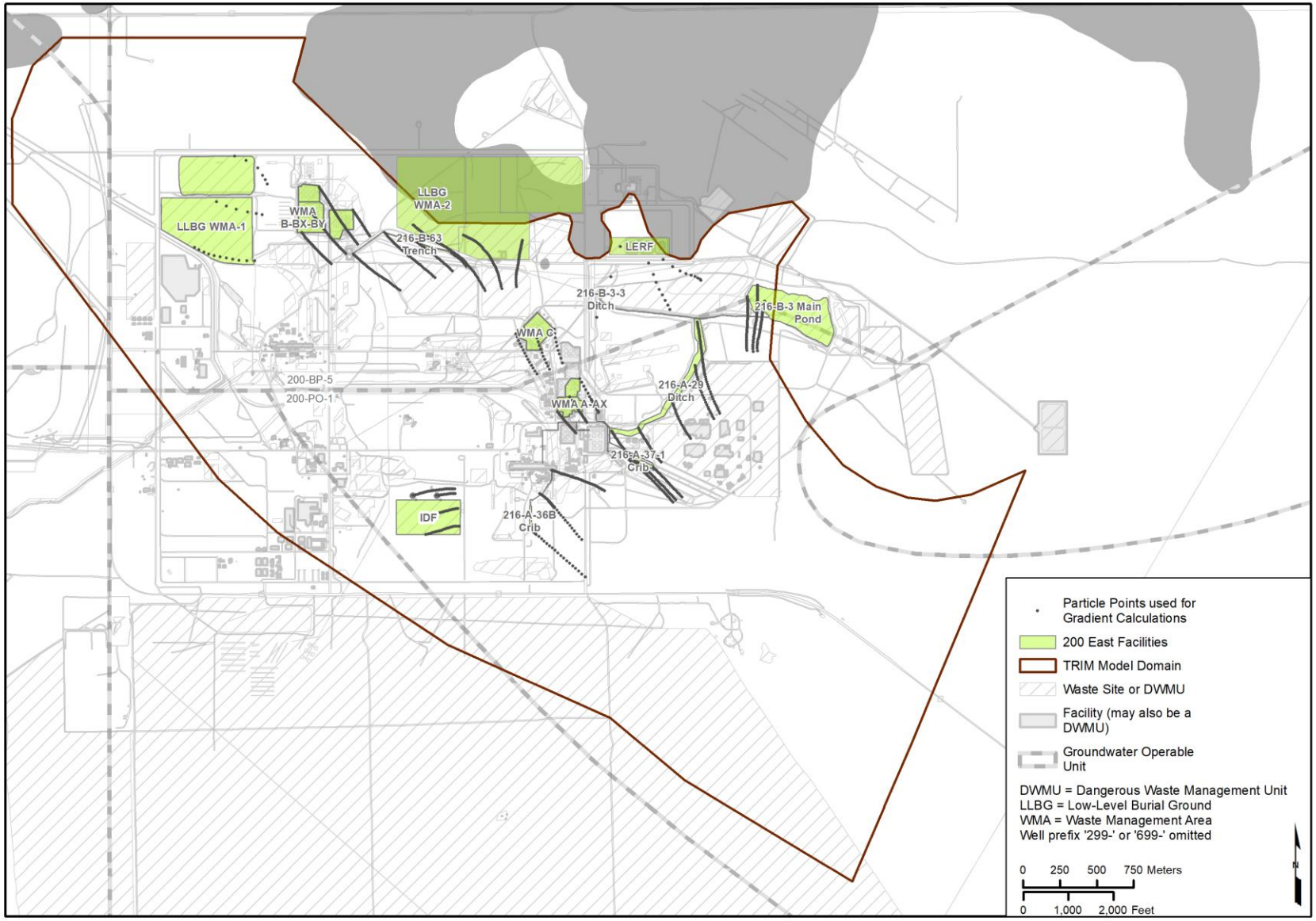

Figure 7-16. Estimated Particle Pathlines

Table 7-1. Estimated Hydraulic Gradients at 200 East RCRA Facilities

Site	Magnitude				Azimuth (degrees from North)			
	Min	Max	Ave	Median	Min	Max	Ave	Median
216-A-29	1.39E-05	2.64E-05	1.91E-05	1.78E-05	130.5	173.3	154.3	154.6
216-A-36B	1.08E-05	2.96E-05	1.97E-05	2.17E-05	105.0	140.8	125.4	130.9
216-A-37-1	1.37E-05	2.32E-05	1.86E-05	1.85E-05	128.8	139.3	134.7	135.0
216-B-3	1.09E-05	2.86E-05	1.50E-05	1.42E-05	175.2	194.5	184.1	183.4
216-B-63	2.75E-06	7.88E-06	4.65E-06	4.59E-06	119.5	140.5	129.9	130.0
IDF	1.13E-05	1.99E-05	1.50E-05	1.49E-05	70.6	90.2	79.4	78.3
LERF	1.63E-05	1.95E-04	8.11E-05	6.93E-05	107.0	205.5	148.7	152.7
WMA-1	1.27E-05	4.13E-05	2.54E-05	2.30E-05	89.3	152.1	112.3	108.2
WMA-2	3.10E-06	8.95E-06	5.41E-06	5.37E-06	115.6	198.0	149.9	140.2
WMA-A-AX	1.11E-05	1.28E-05	1.16E-05	1.15E-05	137.6	153.4	144.7	145.5
WMA-B-BX	2.42E-06	4.56E-06	3.01E-06	2.99E-06	131.7	149.9	141.9	143.0
WMA-C	1.23E-05	1.60E-05	1.37E-05	1.32E-05	147.1	173.8	158.1	157.0

IDF = Integrated Disposal Facility
LERF = Liquid Effluent Retention Facility
RCRA = *Resource Conservation and Recovery Act*
WMA = waste management area

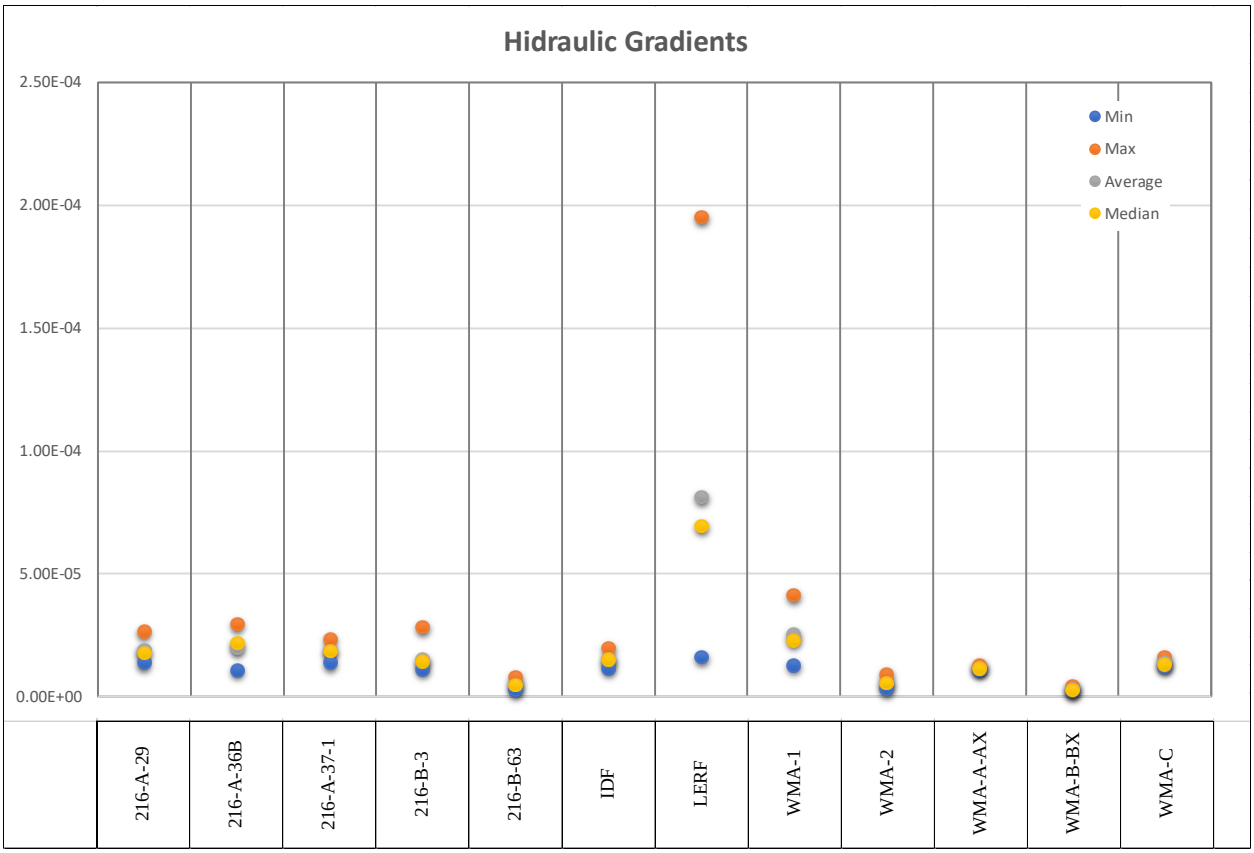

Figure 7-17. Estimated Hydraulic Gradient Magnitudes at 200 East RCRA Facilities

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