ECF-Hanford-16-0013
Revision 0

Hydraulic Gradients and Velocity Calculations for RCRA Sites in 2015

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

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Richland, Washington 99352

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APPROVED
By Julia Raymer at 7:54 am, Jul 20, 2016

Release Approval   Date

ENVIRONMENTAL CALCULATION COVER PAGE

Section 1: Completed by the Responsible Manager

Project: Soil & Groundwater Remediation

Date: 6/28/16

Calculation Title & Description: Hydraulic Gradients and Velocity Calculations for RCRA Sites in 2015

RELEASE / ISSUE

DATE: Jul 20, 2016 — HANFORD RELEASE

Section 2: Completed by Preparer

Calculation No.: ECF-Hanford-16-0013 **Revision No.:** 0

Revision History

Revision No.	Description	Date	Affected Pages
0 RS	Initial release		
			☒

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

Section 4: Document Review & Approval

Role	Name / Position	Signature	Date
Preparer:	M.J. Hartman/Senior Scientist	Mary J Hartman	29 June 2016
Checker:	J.M. Lynn/Scientist	[signature]	29 June 2016
Senior Reviewer:	J.P. McDonald/Senior Scientist	[signature]	6/29/2016
Responsible Manager:	W.R. Faught/Manager	[signature]	7-19-16

Section 5: Applicable if calculation is a risk assessment or uses an environmental model

PRIOR TO INITIATING MODELING:

Required training for modelers completed:

Role	Name / Position	Signature	Date
Integration Lead	N/A		

Safety Software Approved:

Role	Name / Position	Signature	Date
Integration Lead	N/A		

CALCULATION APPROVED:

Role	Name / Position	Signature	Date
Risk/Modeling Integration Manager:	N/A		

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Terms

ANOVA	analysis of variance
m/d	meters per day
IDF	Integrated Disposal Facility
LLWMA	Low-Level Waste Management Area
NAVD88	North American Vertical Datum of 1988
NRDWL	Nonradioactive Dangerous Waste Landfill
PUREX	Plutonium Uranium Extraction Plant
RCRA	*Resource Conservation and Recovery Act of 1976*
WMA	Waste Management Area

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1 Purpose

The purpose of these environmental calculations is to estimate hydraulic gradients and groundwater flow velocities at selected Hanford Site *Resource Conservation and Recovery Act* (RCRA) facilities in 2015.

2 Methodology

In most cases, gradients were estimated by using least squares-regression analysis of water-level data. A Microsoft Excel 2007®[1] spreadsheet was used to calculate hydraulic gradients and groundwater velocity based on water-level data from monitoring wells.

Water-level data were analyzed by trend-surface analysis calculations in a Microsoft Excel 2007 spreadsheet created by J.P. McDonald. The method was described by Davis (2002, *Statistics and Data Analysis in Geology*). A first-order, linear trend surface (i.e., a plane) was fitted to the water-level elevation data by using least squares regression. The slope of the fitted surface represented the hydraulic gradient magnitude, and the dip direction represented the hydraulic gradient direction. To determine if the fitted planes were valid for determining the hydraulic gradient, statistical tests were used to evaluate the goodness of fit of the planes to the water-level data. Sections 2.1 and 2.2, written by J.P. McDonald, describe the trend-surface analysis and statistical test. Section 2.3 describes calculation of average linear velocity.

For some sites, gradients were estimated by using a digital grid. The water table in the 200 East Area is very flat (i.e., a low hydraulic gradient magnitude), and water-level measurements typically exhibit a variability that is larger than the local change in the water table elevation (i.e., a low signal to noise ratio). Thus, it is difficult to use water-level measurements in the local vicinity of a 200 East Area RCRA site to determine the gradient. Groundwater flow directions in the 200 East Area were determined by preparing a digital grid of the water table across most of the 200 East Area by using annual average water-level measurements. In some cases, the grid nodes from the local area around a RCRA site were then extracted from the larger grid and a trend surface was fitted to the grid node values to determine the gradient. In other cases, the contoured grid (i.e. the water table map) was used to estimate the gradient magnitude and direction at a RCRA site by inspection. The use of the digital grid to determine hydraulic gradients is described in Section 2.4.

2.1 Trend-Surface Analysis

The following linear regression equation was used for the trend-surface analysis (from Davis [2002]):

$$z = b_0 + b_1 x + b_2 y \qquad \text{Equation 1}$$

where, z is the predicted water-level elevation (meters North American Vertical Datum of 1988 [NAVD88]) at a location x,y, in which x is the easting geographic coordinate (meters) and y is the northing geographic coordinate (meters), b_0 is the offset (meters), b_1 is the slope in the x-direction (meter/meter), and b_2 is the slope in the y-direction (meter/meter). Equation 1 can be rearranged as follows:

$$b_1 x + b_2 y - z + b_0 = 0 \qquad \text{Equation 2}$$

This equation has the same form as

[1] Microsoft Excel is a registered product of the Microsoft Corporation.

$$ax + by + cz + d = 0 \qquad \text{Equation 3}$$

which is the familiar equation of a plane in standard form.

The least squares regression was performed by solving the following matrix equation for the regression coefficients, b_0, b_1, and b_2 (from Davis [2002]):

$$\begin{bmatrix} k & \sum_{j=1}^{k} x_j & \sum_{j=1}^{k} y_j \\ \sum_{j=1}^{k} x_j & \sum_{j=1}^{k} x_j^2 & \sum_{j=1}^{k} x_j y_j \\ \sum_{j=1}^{k} y_j & \sum_{j=1}^{k} x_j y_j & \sum_{j=1}^{k} y_j^2 \end{bmatrix} \cdot \begin{bmatrix} b_0 \\ b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} \sum_{j=1}^{k} z_j \\ \sum_{j=1}^{k} x_j z_j \\ \sum_{j=1}^{k} y_j z_j \end{bmatrix} \qquad \text{Equation 4}$$

where k is the number of wells, x_j is the easting geographic coordinate of the j^{th} well, y_j is the northing geographic coordinate of the j^{th} well, and z_j is the measured water-level elevation in the j^{th} well. Equation 4 was solved in a spreadsheet modeled after the spreadsheet of Devlin (2003, *A Spreadsheet Method of Estimating Best-Fit Hydraulic Gradients Using Head Data from Multiple Wells*).

The hydraulic gradient magnitude is represented by the slope of the fitted plane. It follows from mathematics that vector $<a,b,c>$ is a normal vector to the plane (i.e., a vector perpendicular to the plane) in Equation 3, and therefore, vector $<b_1,b_2,-1>$ is a normal vector to the plane represented in Equation 2. The slope of the fitted plane, which is the gradient magnitude, was calculated from the deviation of vector $<b_1,b_2,-1>$ from the vertical (i.e., its “tilt”) by using the Pythagorean theorem as follows:

$$i = \left(b_1^2 + b_2^2\right)^{1/2} \qquad \text{Equation 5}$$

Vector $<b_1,b_2,-1>$ begins at the origin of the coordinate system and points in the negative z direction (i.e., downward), because c = -1. Thus, the vector $<-b_1,-b_2,1>$ is also a normal vector to the fitted plane pointing in the positive z direction (i.e., upward). This vector can be projected onto the x,y plane by setting c = 0, and the direction of the resulting vector, $<-b_1,-b_2,0>$, is the direction of the hydraulic gradient. This direction was calculated from $-b_1$ and $-b_2$ by using trigonometric functions.

2.2 Statistical Test

It is possible to use the equations in Section 2.1 to fit a plane to any set of x_j,y_j,z_j data, even random data, and calculate the slope and dip direction of the fitted plane. When applying these equations to water-level measurements, how can it be known that the results are due to the hydraulic gradient and not due to random error? In other words, how can it be known that the hydraulic gradient has been measured successfully? This question was answered by performing a statistical test.

In a statistical test, a null hypothesis and alternative hypothesis are established such that if the null hypothesis is false, then the alternative hypothesis will be true (Davis, 2002; Ott and Mendenhall, 1985, *Understanding Statistics*). The test is designed such that the null hypothesis will only be rejected if the probability of obtaining the observed result, or a result more contradictory to the null hypothesis, assuming the null hypothesis is true, is below some threshold value. In statistical testing, there is always a chance that the decision to reject or not reject the null hypothesis will be incorrect. A Type I error occurs when the null hypothesis is rejected when it is true, and a Type II error occurs when the null hypothesis is not rejected when it is false. The acceptable probability of committing a Type I error is denoted by α

(alpha), and the probability of committing a Type II error is denoted by β (beta). The threshold value for rejecting or not rejecting the null hypothesis is α, and the probability of obtaining the observed result or a result more contradictory to the null hypothesis, assuming the null hypothesis is true, is referred to as the level of significance (denoted as the *p*-value). Thus, if the *p*-value is less than or equal to α, the null hypothesis will be rejected and the alternative hypothesis will be accepted. However, if the *p*-value is greater than α, it does not mean that the null hypothesis is true. Instead, it means there is insufficient justification to reject the null hypothesis. To emphasize, a statistical test does not choose between the null and alternative hypotheses. Rather, it tests whether or not there is sufficient justification to accept the alternative hypothesis.

The statistical test used for these analyses is known as an analysis of variance (ANOVA). In this test, the variance (i.e., the variability) of the set of deviations of each measurement from a horizontal plane centered on the mean of the measurements is compared to the variance of the set of deviations of each measurement from the fitted plane. If the deviations from the fitted plane are much smaller than the deviations from the horizontal plane, it can be concluded that there is a linear trend in the data not attributed to random error. Thus, the fitted plane would be deemed statistically significant.

For the ANOVA analysis, the specific null hypothesis was both b_1 and b_2 in Equation 1 were equal to zero (i.e., the best fit plane is horizontal). The alternative hypothesis was that either b_1 was not equal to zero, b_2 was not equal to zero, or both b_1 and b_2 were not equal to zero (i.e., the best fit plane is distinguishable from a horizontal plane). To evaluate the null hypothesis, the ratio of the variance about the horizontal plane to the variance about the fitted plane was computed (this value is known as the test statistic), and then the probability of obtaining that ratio or a larger ratio (i.e., the *p*-value[2]) was determined by using the *f* probability distribution[3]. The acceptable probability of committing a Type I error (α) was chosen, *a priori*, to be 0.05 for this study. Thus, when the *p*-value for a given trend-surface analysis was less than or equal to 0.05, the null hypothesis (both coefficients are equal to zero) was rejected and the alternative hypothesis (one or both coefficients are nonzero) was accepted, and there was a 95% chance that this decision was correct. In other words, if the probability of obtaining the observed deviations about the fitted plane (or a set of smaller deviations) from a random sampling of deviations about a horizontal plane was less than or equal to 0.05, then there was high confidence that a spatial trend exists in the water-level measurements and that the hydraulic gradient was measured successfully.

The goodness of fit coefficient (R^2) was another statistic used in this study to ascertain whether or not the water-level measurements fit a plane. This statistic is the ratio of the sum of squares due to the regression (SS_R) to the total sum of squares (SS_T), as follows (Davis 2002):

$$R^2 = \frac{SS_R}{SS_T} \qquad \text{Equation 6}$$

where the sum of squares due to the regression is given by:

$$SS_R = \sum_{j=1}^{k} (\hat{z}_j - Z)^2 \qquad \text{Equation 7}$$

and the total sum of squares is given by:

[2] P values calculated via a function of Microsoft Excel.

[3] The *f* probability distribution is "…the theoretical distribution of values that would be expected by randomly sampling from a normal population and calculating, for all possible pairs of sample variances, the ratios" of those variances (Davis, 2002).

$$SS_T = \sum_{j=1}^{k} (z_j - Z)^2 \qquad \text{Equation 8}$$

in which z_j is the measured water-level elevation in the j^{th} well, Z is the average water-level elevation in all k wells, and $\hat{z}_j$ is the predicted water-level elevation for the j^{th} well from the trend-surface regression equation. If the measurements fit a plane closely, SS_R and SS_T will be approximately equal and their ratio, R^2, will be approximately 1. If the measurements do not fit a plane very well, the best fit plane will be nearly horizontal. In this case, SS_R will be small compared to SS_T and their ratio will be near zero. Thus, the more closely an R^2 value is to unity, the better the measurements fit a plane.

2.3 Average Linear Velocity

The average linear velocity of groundwater can be calculated by using a form of the Darcy equation (Freeze and Cherry, 1979):

$$\bar{v} = \frac{Ki}{n_e} \qquad \text{Equation 9}$$

in which $\bar{v}$ is average linear velocity, K is hydraulic conductivity, i is hydraulic gradient, and n_e is effective porosity.

However, Equation 9 does not account for dispersion *factors*, such as preferential flow pathways, which will influence the average linear velocity. As presented, Equation 9 provides an estimation of the average linear velocity based on measured or estimated variables.

2.4 Digital Grid Method

In the 200 East Area, the magnitude of the hydraulic gradient is very low (i.e., the water table is very flat). The flat water table is a consequence of the very high hydraulic conductivity sediments that comprise the unconfined aquifer. This makes it difficult to determine gradients at local areas because the variability in the water-level measurements is larger than the local change in the water table elevation (i.e., a low signal to noise ratio). The sources of this variability include uncertainties in casing elevation surveys, deviations of the boreholes from vertical, and barometric pressure fluctuations.

Beginning in 2005, measures were taken to improve the accuracy of water-level measurements at selected 200 East Area RCRA sites. Those measures included resurveys of casing elevations by using a highly accurate leveling method, gyroscope surveys to control for borehole deviation error, and an assessment of barometric pressure effects. This was referred to as the low gradient evaluation study, but this effort, reported in SGW-54165, *Evaluation of the Unconfined Aquifer Hydraulic Gradient Beneath the 200 East Area, Hanford Site*, was only partly successful. At some RCRA sites, the water table was simply too flat to determine the hydraulic gradient by using local water-level measurements.

Beginning in 2013, a new approach was employed to determine gradients in the 200 East Area. The network of wells used in the low gradient evaluation study was expanded to cover much of the 200 East Area. It was reasoned that if the water table could be mapped regionally across the 200 East Area, the map could be used to infer gradients at local areas, such as the RCRA sites. The network consists of 56 wells in which water levels are measured monthly. All of the wells have been resurveyed for casing elevation and all have been gyroscopically surveyed to control for deviation error. The water table was mapped by preparing digital grids by using annual average water-level elevations in the wells to control for barometric pressure fluctuations. The results are documented in SGW-58828, *Water Table Maps for the Hanford Site 200 East Area, 2013 and 2014*.

The 2015 200 East Area water table grid was used to determine gradients at many of the 200 East Area RCRA sites. Preparation of this digital grid is documented in ECF-200E-16-0093, *Preparation of the 200 East Area Water Table Map for Calendar Year 2015*. The grid was prepared by using the inverse distance to a power method with the gridding options set to emphasize spatial averaging of the data. The details are explained in ECF-200E-16-0093.

To determine the gradient at some of the 200 East Area RCRA sites, selected grid nodes in the vicinity the site were extracted from the 2015 water table grid and a trend surface was fitted to the grid node values as described in Sections 2.1 and 2.2. This was done for the 216-A-29 Ditch, 216-A-36B Crib, 216-A-37-1 Crib, the Integrated Disposal Facility (IDF), and Low-Level Waste Management Area 1 (LLWMA-1). The grid nodes and the associated hydraulic head values extracted for each site are listed on the associated calculation spreadsheet. In some instances, the interpreted flow direction is based on plume distributions and local hydrogeologic conditions rather than the trend surface results from the digital grid. These are noted in Section 6. The gradients for the other 200 East Area RCRA sites (LLWMA-2 and 216-B-63 Trench combined, Waste Management Area (WMA) A-AX, WMA C, and WMA B-BX-BY), were estimated by using contours on the 200 East Area water table map for 2015 which was prepared from the grid and is shown in Figure 1.

3 Assumptions and Inputs

For the conventional calculations (i.e., all except the low gradient sites in 200 East Area), water-level data were retrieved from the "Environmental Monitoring" module of the Hanford Site's Virtual Library for wells screened across the water table near RCRA WMAs. Calculations were performed for March 2015 and, in some cases, for additional time periods. The data are provided in the associated calculation spreadsheets.

Well coordinates (northing and easting) were retrieved from the Hanford Site "Environmental Dashboard Application" (http://environet.rl.gov/EDA), rounded to the nearest hundredth of a meter. Coordinates are included in the calculation spreadsheets.

For the 200 East Area sites the gradient was determined by using the digital grid, which is based on annual average water-level elevations for all of 2015 (ECF-200E-16-0093).

The hydraulic gradient calculation assumes that the water table is planar. This is of course a simplification, because water table contours form a varied "topography." Thus, the hydraulic gradient calculation provides an average hydraulic gradient result.

As applied here, the Darcy equation assumes that flow is horizontal (vertical gradients are insignificant) and the aquifer is homogeneous and isotropic. Hydraulic parameters and their sources are listed in Table 2.

4 Software Applications

A Microsoft Excel 2013® spreadsheet was used to perform calculations described in Sections 2.1 and 2.2, by using the default calculation formulae available in that software. The hydraulic gradient spreadsheet previously was validated by comparison of results with a commercial software (personal communication, e-mail from Dennis Weier, Pacific Northwest National laboratory, to John McDonald, Fluor Hanford, Inc., "Spreadsheet verification," April 7, 2008).

5 Calculations

To illustrate the calculations, Table 1 shows an example spreadsheet with formulae visible to illustrate the calculations. On sheet 1, from left to right, the user entered well names, easting, northing, hydraulic head, and measurement dates with consistent units (meters) into the blue-shaded cells (B9 through F15). The spreadsheet calculations fit a plane through the data and compute what the head "should" be at each well based on that approximation.

Sheet 1 of Table 1 also shows computed data with formulae for predicted hydraulic head, and the predicted difference from mean and residuals, in cells G9 through I20. The magnitude and direction of the hydraulic gradient are displayed in cells L10 and L11. Statistical formulae are in L15 through L19. The statistical indicators for goodness of fit (L15) and correlation coefficient (L16) should be very close to 1.0. The level of significance is set at 0.05. If the P-value (L18) is less than the level of significance, there is a statistically significant trend (L19). Additional intermediate calculations such as number of observations and sum of easting and sum of northing are displayed in columns K and L below the statistical formulae. Columns N through S, rows 13 through 17, display an ANOVA table on Sheet 1 of Table 2.

On sheet 2 of Table 1, computed data formulae continue in cells G21 through I28 and in columns K through O. To calculate the groundwater velocity, hydraulic conductivity (K) and effective porosity (n_e) are entered into cells C35 through F35. The spreadsheet is designed so that minima and maxima can be input to calculate a range of velocities. In the example (Table 1), a single value was input for K (9,000 meters per day [m/d]) in cells C35 and D35 and for n_e (0.17) in E35 and F35. Cell B35 repeats the computed hydraulic gradient from cell L10. The formulae in cells G35 and H35 compute velocity.

Cells K38 through M77 (sheets 2 and 3 of Table 1), contain normal vector to the fitted plane formulae, gradient magnitude and gradient direction formulae.

6 Results

Table 2 and the following paragraphs summarize results of the hydraulic gradient and velocity calculations.

6.1 1301-N Liquid Waste Disposal Facility

This facility is located near the Columbia River in 100-N Area. Groundwater typically flows to the northwest toward the river. However, river stage was relatively high in February and early March 2015, which affected the gradient. In March 2015 the gradient was 3.5×10^{-4} m/m and dipped to the north-northeast (33 degrees east of north). Statistical tests indicated a moderately good fit but the P value was 0.075, which is above the 0.05 level of significance. A bend in the water table contour indicates the March 2015 water table cannot be approximated by a single plane. However, results are generally consistent with the interpreted water table map for the inland region, directly beneath the facility. Estimated groundwater flow rates ranged from 0.01 to 0.13 m/d.

Data from September 2015, when river stage was low, were also evaluated. The gradient had a magnitude of 2.4×10^{-3} m/m and dipped to the north-northwest. The P value is 0.10, which is above the 0.05 level of significance. Results are considered generally representative.

6.2 1324-N Surface Impoundment and 1324-NA Percolation Pond

The 1324-N Surface Impoundment and 1324-NA Percolation Pond (1324-N/NA Facilities) are located in southern 100-N Area. The KX pump and treat system includes injection wells located approximately 200 to 300 meters west and south of 1324-N/NA. No water-level data are available between these injection wells and the 1324-N/NA monitoring network, and it is likely that the water table beneath 1324-N/NA is not truly planar. Thus the gradient estimated by trend-surface analysis has more uncertainty here than at other locations.

Based on March 2015 water-level data, the gradient was 9.8×10^{-4} m/m, and dipping toward the northeast (53 degrees). Goodness of fit and correlation coefficients were near 1.0 but the P-value was 0.18. The direction and magnitude appear reasonable compared to the water table map. Estimated groundwater flow rates ranged from 0.02 to 0.36 m/d.

Results for September 2015 were similar to March: 9.6×10^{-4} m/m, and dipping toward the north-northeast (14 degrees). Statistical parameters show a good fit and acceptably low P-value.

6.3 1325-N Liquid Waste Disposal Facility

This facility is located in the 100-N Area and is farther from the river than the 1301-N facility. The gradient in March 2015 was 5.1×10^{-4} m/m and dipping to the north-northwest (350 degrees). This gradient is lower than typically observed at this site because of the effects of high river stage in February and March 2015. Statistical tests indicated a good fit. Estimated groundwater flow rates ranged from 0.01 to 0.19 m/d.

In September 2015 (low river stage) the water-level measurement from upgradient well 199-N-74 was excluded because it was out of trend. The gradient was 1.4×10^{-3} m/m, dipping to the north-northeast (25 degrees). Statistical tests indicated a fairly good fit, though the P value was 0.08, which is above the 0.05 level of significance. Estimated groundwater flow rates ranged from 0.03 to 0.52 m/d.

6.4 183-H Basins

This unit is located in 100-H Area. The HX pump and treat system affects groundwater flow in this region with extraction wells located north and east of 183-H, and injection wells located to the west. In March 2015 the gradient was 1.2×10^{-3} m/m, dipping to the east (80 degrees). Statistical tests indicated a good fit. Estimated groundwater flow rates ranged from 0.06 to 1.6 m/d.

6.5 216-A-29 Ditch

This unit is located east of the 200 East Area. The hydraulic gradient was determined by extracting head values from the 200 East Area water table digital grid for calendar year 2015 and performing a trend-surface analysis, as described in Section 2.4. The calculated gradient magnitude was 5.8×10^{-6} m/m, with a direction of 205 degrees (south-southwest). However, plume distributions and local hydrogeology suggest a flow direction toward the south-southeast. The estimated groundwater flow rate is 0.001 m/d.

6.6 216-A-36B Crib

This crib is located in the southeast part of the 200 East Area south of the Plutonium-Uranium Extraction (PUREX) Plant. The hydraulic gradient was determined by extracting head values from the 200 East Area water table digital grid for calendar year 2015 and performing a trend-surface analysis, as described in Section 2.4. The calculated gradient was 4.4×10^{-6} m/m, dipping to the east-southeast (114 degrees). Estimated groundwater flow rates ranged from 0.0008 to 0.13 m/d.

6.7 216-A-37-1 Crib

This crib is located east of the southern part of the 200 East Area. The hydraulic gradient was determined by extracting head values from the 200 East Area water table digital grid for calendar year 2015 and performing a trend-surface analysis, as described in Section 2.4. The calculated gradient magnitude was 3.2×10^{-6} m/m, with a direction of 245 degrees (west-southwest). However, plume distributions and local hydrogeology suggest a flow direction is toward the south-southeast. Estimated groundwater flow rates range from 0.0002 to 0.01 m/d.

6.8 216-B-3 Pond

This pond is located east of the 200 East Area. The hydraulic gradient was determined by using water-level measurements collected during January, March, and July 2015, with consistent results for the three periods. The calculated gradient was 1.35×10^{-3} m/m, dipping to the southwest (227 degrees). Statistical indicators showed a good fit. The estimated groundwater flow rate is 0.0054 m/d.

6.9 216-B-63 Trench

This facility is located in the northern part of the 200 East Area and is adjacent to LLWMA 2. The hydraulic gradient was estimated to be 6.5×10^{-6} m/m toward the southeast based on the 200 East Area water table map contours for 2015. The flow rate is estimated at 0.0045 m/d.

6.10 216-S-10 Pond and Ditch

This unit is located in southern 200 West Area. Gradients were calculated for 3 data sets from March, May, and November 2015. The November data had a high P-value and was excluded from averages. The average gradient was 2.7×10^{-3} m/m dipping to the east-southeast (106 degrees). Statistical indicators showed a good fit. Groundwater flow velocity estimates ranged from 0.027 to 1.2 m/d.

6.11 300 Area Process Trenches

This unit is located near the Columbia River in the 300 Area. The gradient in March 2015 was 3.0×10^{-4} m/m dipping to the south-southeast (162 degrees). Statistical indicators showed a good fit. Groundwater flow velocity was estimated at 16 m/d.

Results for June 2015 were similar, with a magnitude of 3.5×10^{-4} m/m dipping to the south (180 degrees). Statistical indicators showed a good fit. Groundwater flow velocity was estimated at 18 m/d.

6.12 IDF

This facility is located in the southeast part of the 200 East Area. The hydraulic gradient was determined by extracting head values from the 200 East Area water table digital grid for calendar year 2015 and performing a trend-surface analysis, as described in Section 2.4. The calculated gradient magnitude was 3.9×10^{-6} m/m, with a direction of 144 degrees (southeast). The interpreted flow direction is toward the east-southeast based on plume distributions and local hydrogeology. The estimated groundwater flow rate is 0.003 m/d.

6.13 Liquid Effluent Retention Facility

This facility is located just outside the northeast corner of the 200 East Area. The hydraulic gradient was determined by trend-surface analysis of monthly water-level measurements between January and November 2015. Due to the low gradient magnitude in this area, all wells used have been resurveyed for casing elevation and have had gyroscope surveys performed to control for deviation error. The average hydraulic gradient was 2.5×10^{-4} m/m toward the south (184 degrees) and the estimated groundwater flow rate is 0.10 m/d.

6.14 Low-Level Waste Management Area (LLWMA) 1

This unit is located in the northwest corner of the 200 East Area. The hydraulic gradient was determined by extracting head values from the 200 East Area water table digital grid for calendar year 2015 and performing a trend-surface analysis, as described in Section 2.4. The calculated gradient was 4.8×10^{-6} m/m, dipping to the southeast (125 degrees) and the estimated groundwater flow rate is 0.41 m/d.

6.15 LLMWA 2

This unit is located in the northern part of the 200 East Area and is adjacent to the 216-B-63 Trench. The hydraulic gradient was estimated to be 6.5×10^{-6} m/m toward the southeast and south based on the 200 East Area water table map contours for 2015. On the west side of the LLWMA, groundwater flows to the southeast at 0.0059 m/d. On the east side of the LLWMA the flow rate is 0.05 m/d.

6.16 LLWMA 3

This unit is located in the northern 200 West Area. Two injection wells for the 200 West Pump and Treat (P&T) system are located within the boundaries of LLMWA-3 and the water table cannot be approximated by a single plane. Therefore, flow calculations are based on data from wells east of the injection wells. In March 2015 the hydraulic gradient was 7.3×10^{-3} m/m dipping toward the east (98 degrees). Statistical indicators showed a good fit but large residuals. Groundwater velocity was estimated to range from 0.18 to 0.73 m/d.

6.17 LLWMA 4

This unit is located in southwestern 200 West Area where the natural direction of groundwater flow is to the east. Injection wells for the 200 West P&T system are located west of LLWMA 4, creating a groundwater mound. In March 2015 the gradient was 4.0×10^{-3} m/m dipping to the east (95 degrees). Statistical tests indicated a good fit. Groundwater velocity was estimated to range from 0.10 to 0.40 m/d.

6.18 Nonradioactive Dangerous Waste Landfill

This landfill is located southeast of the 200 East Area. The hydraulic gradient was determined by using water-level measurements collected during March and October 2015. Due to the low gradient magnitude in this area, all wells used have been resurveyed for casing elevation and have had gyroscope surveys performed to control for deviation error, and all water levels were normalized to a constant barometric pressure. The calculated average gradient was 2.4×10^{-5} m/m, dipping to the southeast (119 degrees). Statistical indicators showed a good fit. Average groundwater flow rates were between 0.12 and 0.37 m/d.

6.19 WMA A-AX

These tank farms are located in the eastern part of the 200 East Area south of WMA C. The hydraulic gradient was determined by extracting head values from the 200 East Area water table digital grid for calendar year 2015 and performing a trend-surface analysis, as described in Section 2.4. The calculated gradient was 4.8×10^{-6} m/m, dipping to the southeast (152 degrees). The interpreted flow direction is south-southeast based on this calculated gradient as well as plume movement. The groundwater flow rate is estimated to be 0.096 m/d.

6.20 WMA B-BX-BY

These tank farms are located in the northwestern part of the 200 East Area east of LLWMA 1. The hydraulic gradient was estimated to be 4.2×10^{-6} m/m toward the southeast based on the 200 East Area water table map contours for 2015. The flow rate is estimated at 0.39 m/d.

6.21 WMA C

This tank farm is located in the eastern part of the 200 East Area north of WMA A-AX. The hydraulic gradient was estimated to be 3.0×10^{-6} m/m toward the southeast based on the 200 East Area water table map contours for 2015. The flow rate is estimated at 0.26 m/d.

6.22 WMA S-SX

These tank farms are located in the southern 200 West Area. Two extraction wells for the 200 West P&T system operate immediately east of the WMA. Gradients were calculated for 8 data sets collected at various times in 2015. The average gradient was 3.3×10^{-3} m/m dipping toward the east (88 degrees). Statistical indicators showed a good fit. Groundwater flow velocity estimates ranged from 0.020 to 0.52 m/d.

6.23 WMA T

This tank farm is located in northern 200 West Area. An extraction well for the 200 West P&T is located east of the site. Using March 2015 data from seven monitoring wells, fit statistics and P-value were acceptable, but some of the wells had high residual values (observed minus predicted head). The gradient was re-calculated without the 2 highest residual wells. The gradient was 6.0×10^{-3} m/m dipping toward the southeast (125 degrees). Statistical indicators showed a good fit. Estimated groundwater velocity ranged from 0.37 to 0.59 m/d.

6.24 WMA TX-TY

These tank farms are located in central 200 West Area. An extraction well for the 200 West P&T system is located immediately east of the site and the water table converges on that well. Consequently, gradients were calculated separately for the north and south parts of the WMA.

Based on three wells in the north, the gradient was 1.2×10^{-2} m/m dipping slightly south of the east (100 degrees). Fit statistics are not meaningful because there were only three wells.

The gradient in the south, based on four wells, was 3.6×10^{-3} m/m dipping toward the northeast (50 degrees). R squared and R values were 0.89 and 0.94 respectively, and the P-value was 0.34. Thus this estimate is less robust than others. It is considered generally representative.

Groundwater flow rates are estimated to range from 0.0045 to 1.28 m/d in the north and from 0.0014 to 0.40 m/d in the south.

6.25 WMA U

The tank farm is located in southern 200 West Area. Gradients were calculated for 4 data sets collected at various times in 2015. The average gradient was 5.2×10^{-3} m/m dipping slightly north of east (81 degrees). Statistical tests indicate a good fit. Groundwater velocity estimates ranged from 0.04 to 0.50 m/d.

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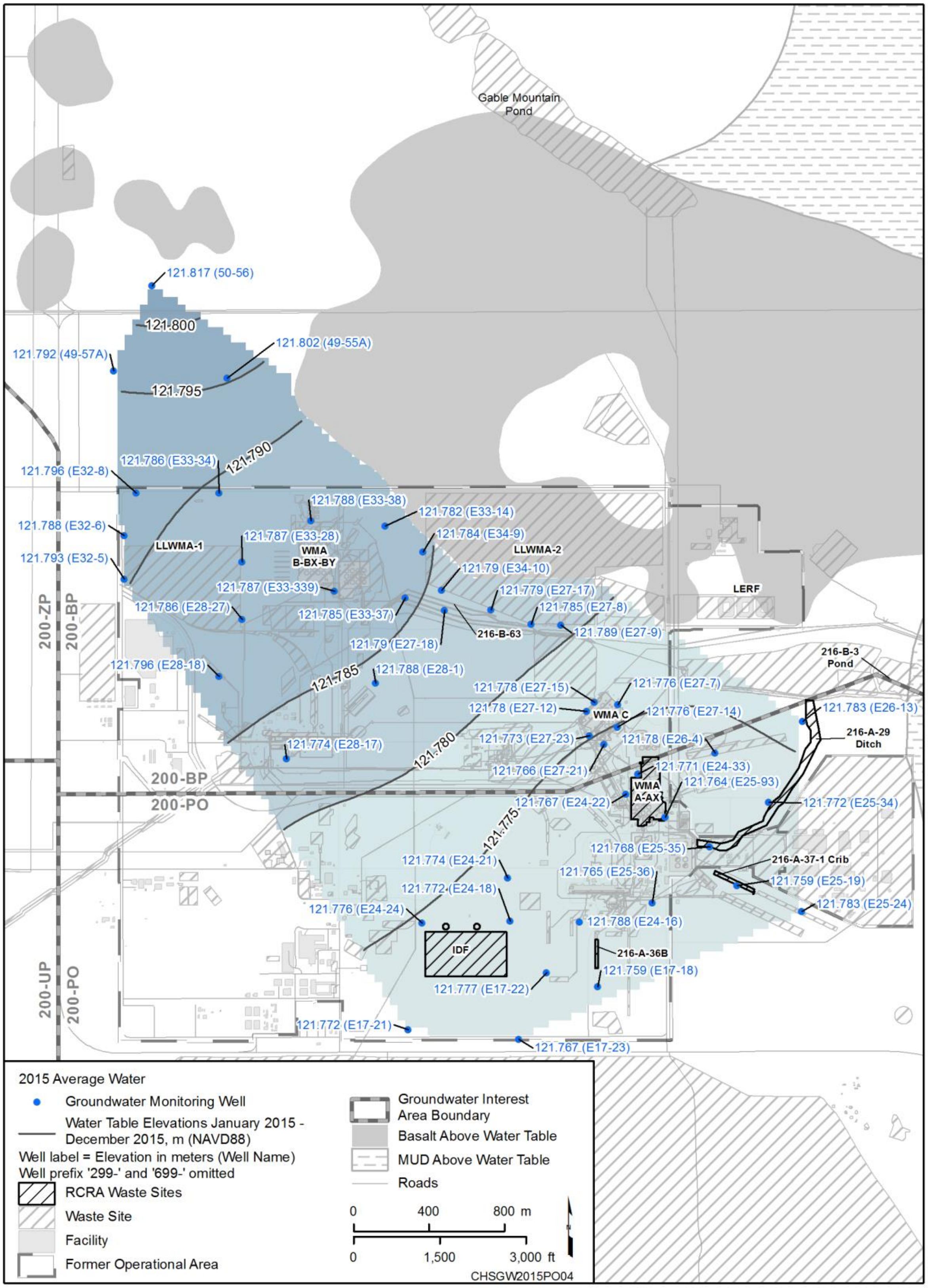

Figure 1. 200 East Area Water Table Map for 2015 Generated from the Water Table Digital Grid

Table 1. Gradient Calculation Spreadsheet with March 2015 Data for 1301-N (3 sheets)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	Trend-Surface Analysis of Hydraulic Gradient																		
2	(Least Squares Regression of a Plane to Points in 3-D Space)																		
3	Reference: Davis, J. C. 2002. Statistics and Data Analysis in Geology, John Wiley & Sons																		
4	Prepared by JP McDonald																		
5																			
6																			
7		Input Data					Computed Data												
8		Well Name	Easting (x-coord)	Northing (y-coord)	Observed Hydraulic Head (z-coord)	Date	Predicted Hydraulic Head	Predicted Diff from Mean	Residuals (Observed - Predicted)		**Hydraulic Gradient**								
9		199-N-105A	571602.30	150024.96	118.953	3/3/2015	=IF(ISBLANK(E9),,$L$52+$L$53*C9+$L$54*D9)	=IF(G9=0,0,G9-SUM($G$9:$G$28)/$L$23)	=IF(ISBLANK(E9),,G9-E9)										
10		199-N-2	571476.21	149859.43	119.002	3/3/2015	=IF(ISBLANK(E10),,$L$52+$L$53*C10+$L$54*D10)	=IF(G10=0,0,G10-SUM($G$9:$G$28)/$L$23)	=IF(ISBLANK(E10),,G10-E10)		**Gradient Magnitude:**	=L64							
11		199-N-3	571317.38	149794.61	119.04	3/3/2015	=IF(ISBLANK(E11),,$L$52+$L$53*C11+$L$54*D11)	=IF(G11=0,0,G11-SUM($G$9:$G$28)/$L$23)	=IF(ISBLANK(E11),,G11-E11)		**Gradient Direction (azimuth):**	=INDEX(M69:M77,MATCH("Yes",L69:L77,0))							
12		199-N-57	571413.17	149542.05	119.138	3/3/2015	=IF(ISBLANK(E12),,$L$52+$L$53*C12+$L$54*D12)	=IF(G12=0,0,G12-SUM($G$9:$G$28)/$L$23)	=IF(ISBLANK(E12),,G12-E12)										
13		199-N-34	571737.41	149653.89	119.005	3/3/2015	=IF(ISBLANK(E13),,$L$52+$L$53*C13+$L$54*D13)	=IF(G13=0,0,G13-SUM($G$9:$G$28)/$L$23)	=IF(ISBLANK(E13),,G13-E13)		**Statistics**			**ANOVA**					
14							=IF(ISBLANK(E14),,$L$52+$L$53*C14+$L$54*D14)	=IF(G14=0,0,G14-SUM($G$9:$G$28)/$L$23)	=IF(ISBLANK(E14),,G14-E14)					Var Source	Sum of Squares	Df	Mean Squares	F-Test	P-Value
15							=IF(ISBLANK(E15),,$L$52+$L$53*C15+$L$54*D15)	=IF(G15=0,0,G15-SUM($G$9:$G$28)/$L$23)	=IF(ISBLANK(E15),,G15-E15)		Goodness of Fit (R^2):	=L36/L35		Regression	=SUM(H9:H28*H9:H28)	2	=O15/P15	=Q15/Q16	=FDIST(R15,P15,P16)
16		8					=IF(ISBLANK(E16),,$L$52+$L$53*C16+$L$54*D16)	=IF(G16=0,0,G16-SUM($G$9:$G$28)/$L$23)	=IF(ISBLANK(E16),,G16-E16)		Correlation Coefficient (R):	=SQRT(L15)		Deviation	=SUM(I9:I28*I9:I28)	=L23-3	=O16/P16		
17		9					=IF(ISBLANK(E17),,$L$52+$L$53*C17+$L$54*D17)	=IF(G17=0,0,G17-SUM($G$9:$G$28)/$L$23)	=IF(ISBLANK(E17),,G17-E17)		Level of Significance:	0.05		Total	=O15+O16	=L23-1			
18		10					=IF(ISBLANK(E18),,$L$52+$L$53*C18+$L$54*D18)	=IF(G18=0,0,G18-SUM($G$9:$G$28)/$L$23)	=IF(ISBLANK(E18),,G18-E18)		P-Value:	=ROUND(S15,4)							
19		11					=IF(ISBLANK(E19),,$L$52+$L$53*C19+$L$54*D19)	=IF(G19=0,0,G19-SUM($G$9:$G$28)/$L$23)	=IF(ISBLANK(E19),,E19-G19)		Statistically Significant Trend?:	=IF(L23=3,"N/A - 3 pts",IF(L18<=L17,"Yes","No"))							
20		12					=IF(ISBLANK(E20),,$L$52+$L$53*C20+$L$54*D20)	=IF(G20=0,0,G20-SUM($G$9:$G$28)/$L$23)	=IF(ISBLANK(E20),,E20-G20)										

Table 1. Gradient Calculation Spreadsheet with March 2015 Data for 1301-N (3 sheets)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
21		13					=IF(ISBLANK(E21),,$L$52+$L$53*C21+$L$54*D21)	=IF(G21=0,0,G21-SUM($G$9:$G$28)/$L$23)	=IF(ISBLANK(E21),,E21-G21)		**Intermediate Computations**								
22		14					=IF(ISBLANK(E22),,$L$52+$L$53*C22+$L$54*D22)	=IF(G22=0,0,G22-SUM($G$9:$G$28)/$L$23)	=IF(ISBLANK(E22),,E22-G22)										
23		15					=IF(ISBLANK(E23),,$L$52+$L$53*C23+$L$54*D23)	=IF(G23=0,0,G23-SUM($G$9:$G$28)/$L$23)	=IF(ISBLANK(E23),,E23-G23)		# of Observations:	=COUNT(C9:C28)							
24		16					=IF(ISBLANK(E24),,$L$52+$L$53*C24+$L$54*D24)	=IF(G24=0,0,G24-SUM($G$9:$G$28)/$L$23)	=IF(ISBLANK(E24),,E24-G24)		Sum of Easting:	=SUM(C9:C28)							
25		17					=IF(ISBLANK(E25),,$L$52+$L$53*C25+$L$54*D25)	=IF(G25=0,0,G25-SUM($G$9:$G$28)/$L$23)	=IF(ISBLANK(E25),,E25-G25)		Sum of Northing:	=SUM(D9:D28)							
26		18					=IF(ISBLANK(E26),,$L$52+$L$53*C26+$L$54*D26)	=IF(G26=0,0,G26-SUM($G$9:$G$28)/$L$23)	=IF(ISBLANK(E26),,E26-G26)		Sum of Easting*Northing:	=SUM(C9:C28*D9:D28)							
27		19					=IF(ISBLANK(E27),,$L$52+$L$53*C27+$L$54*D27)	=IF(G27=0,0,G27-SUM($G$9:$G$28)/$L$23)	=IF(ISBLANK(E27),,E27-G27)		Sum of Easting^2:	=SUM(C9:C28^2)							
28		20					=IF(ISBLANK(E28),,$L$52+$L$53*C28+$L$54*D28)	=IF(G28=0,0,G28-SUM($G$9:$G$28)/$L$23)	=IF(ISBLANK(E28),,E28-G28)		Sum of Northing^2:	=SUM(D9:D28^2)							
29											Sum of Observed Heads:	=SUM(E9:E28)							
30											Sum of Easting*Observed Heads:	=SUM(C9:C28*E9:E28)							
31											Sum of Northing*Observed Heads:	=SUM(D9:D28*E9:E28)							
32		Darcy velocity - input K and N									Sum of Observed Heads^2:	=SUM(E9:E28^2)							
33		Gradient	K min	K max	n min	n max	v min	v max			Sum of Predicted Heads:	=SUM(G9:G28)							
34			m/d	m/d			m/d	m/d			Sum of Predicted Heads^2:	=SUM(G9:G28^2)							
35		=L10	9000	9000	0.17	0.17	=+C35*(B35)/F35	=+D35*B35/E35			SSt:	=L32-(L29^2)/L23							
36											SSr:	=L34-(L33^2)/L23							
37																			
38											Matrix equation (Equation 5.86 in Davis, 2002)								
39																			
40											=L23	=L24	=L25	b0	=L29				
41											=L24	=L27	=L26	b1	=L30				
42											=L25	=L26	=L28	b2	=L31				
43																			

Table 1. Gradient Calculation Spreadsheet with March 2015 Data for 1301-N (3 sheets)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
44											Inverse Matrix								
45																			
46											=MINVERSE(K40:M42)	=MINVERSE(K40:M42)	=MINVERSE(K40:M42)						
47											=MINVERSE(K40:M42)	=MINVERSE(K40:M42)	=MINVERSE(K40:M42)						
48											=MINVERSE(K40:M42)	=MINVERSE(K40:M42)	=MINVERSE(K40:M42)						
49																			
50											Coefficients of the Fitted Plane (z = b0 + b1x + b2y)								
51																			
52											b0=	=MMULT(K46:M48,O40:O42)							
53											b1=	=MMULT(K46:M48,O40:O42)							
54											b2=	=MMULT(K46:M48,O40:O42)							
55																			
56											Normal Vector to the Fitted Plane (<a,b,c> where a = -b1, b = -b2, c = 1)								
57																			
58											a:	=$L$53*(-1)							
59											b:	=$L$54*(-1)							
60											c:	1							
61																			
62											**Gradient Magnitude**								
63																			
64												=SQRT(L58^2+L59^2)							
65																			
66											**Gradient Direction**								
67																			
68													Azimuth:						
69											Horizontal Plane?:	=IF(AND($L$58=0,$L$59=0),"Yes","No")	n/a						
70											Due North?:	=IF(AND($L$58=0,$L$59>0),"Yes","No")	=IF(L70="Yes",0,"n/a")						
71											Due East?:	=IF(AND($L$58>0,$L$59=0),"Yes","No")	=IF(L71="Yes",90,"n/a")						
72											Due South?:	=IF(AND($L$58=0,$L$59<0),"Yes","No")	=IF(L72="Yes",180,"n/a")						
73											Due West?:	=IF(AND($L$58<0,$L$59=0),"Yes","No")	=IF(L73="Yes",270,"n/a")						
74											First Quadrant?:	=IF(AND($L$58>0,$L$59>0),"Yes","No")	=IF(L74="Yes",ATAN($L$58/$L$59)*180/PI(),"n/a")						
75											Second Quadrant?:	=IF(AND($L$58>0,$L$59<0),"Yes","No")	=IF(L75="Yes",90+ATAN(ABS($L$59)/$L$58)*180/PI(),"n/a")						
76											Third Quadrant?:	=IF(AND($L$58<0,$L$59<0),"Yes","No")	=IF(L76="Yes",180+ATAN($L$58/$L$59)*180/PI(),"n/a")						
77											Fourth Quadrant?:	=IF(AND($L$58<0,$L$59>0),"Yes","No")	=IF(L77="Yes",270+ATAN($L$59/ABS($L$58))*180/PI(),"n/a")						

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Table 2. Results of Gradient and Velocity Calculations

WMA	Date	v min (m/d)	v max (m/d)	Gradient (m/m)	Direction (degrees east of north)	Goodness of Fit (R^2)	Correlation Coefficient (R):	P-Value	Hydrologic Properties (references)	Comments
Gradients Estimated from Measured Data										
1301-N	3/3/2015	0.0072	0.13	3.5E-04	33	0.92	0.96	0.075	K = 6.1 to 37 m/d (PNL-8335); ne = 0.10 to 0.30	Relatively high river stage. Water table not planar; estimate generally valid for inland region.
	9/14/2015	0.049	0.89	2.4E-03	332	0.99	0.99	0.102		Low river stage.
1324-N/NA	3/3/2015	0.020	0.36	9.8E-04	53	0.97	0.98	0.181	K = 6.1 to 37 m/d (PNL-8335); ne = 0.10 to 0.30	Influenced by 100-K injection wells to south; water table likely not planar. Results considered generally representative.
	9/16/2015	0.020	0.36	9.6E-04	14	0.97	0.98	0.034		
1325-N	3/3/2015	0.010	0.19	5.1E-04	350	0.99	1.00	0.000	K = 6.1 to 37 m/d (PNL-8335); ne = 0.10 to 0.30	Relatively high river stage flattened water table
	9/14/2015	0.029	0.52	1.4E-03	25	0.92	0.96	0.082		Low river stage
183-H	3/4/2015	0.058	1.6	1.2E-03	80	0.96	0.98	0.037	K = 15 to 140 m/d (PNL-6728); ne = 0.10 to 0.30	Extraction wells to east and injection wells to west
216-B-3	Jan, Mar, Jul	0.0054	0.0054	1.4E-03	227	0.97	0.99	0.027	K = 1 m/d (WHC-SD-EN-EV-002; PNNL-10195); ne = 0.25 (assumed)	Average of 3 months*

Table 2. Results of Gradient and Velocity Calculations

WMA	Date	v min (m/d)	v max (m/d)	Gradient (m/m)	Direction (degrees east of north)	Goodness of Fit (R^2)	Correlation Coefficient (R):	P-Value	Hydrologic Properties (references)	Comments
216-S-10	Mar, May	0.027	1.2	2.7E-03	106	0.96	0.98	0.040	K = 2 to 42.7 m/d (PNL-8337); ne = 0.1 to 0.2 (assumed)	Average of 2 months*
300 APT	3/9/2015	16	16	3.0E-04	162	0.94	0.97	0.000	K = 9,000 m/d; ne = 0.17 (PNL-17708)	Relatively high river stage
300 APT	6/7/2015	18	18	3.5E-04	180	0.93	0.96	0.001	K = 9,000 m/d; ne = 0.17 (PNL-17708)	River stage lower than normal for June
LERF	Jan-Nov	0.10	0.10	2.5E-04	184	0.99	1.00	0.085	K = 39.5 m/d (DOE/RL-2013-46); ne =0.1 (assumed)	Average of 11 months*
LLWMA-3	3/13/2015	0.18	0.73	7.3E-03	98	0.98	0.99	0.001	K= 2.5 to 10 m/d; ne = 0.10 (PNNL-14753)	200 West P&T injection wells in WMA. Gradient calculated east of injection wells
LLWMA-4	3/13/2015	0.10	0.40	4.0E-03	95	0.99	0.99	0.011	K= 2.5 to 10 m/d; ne = 0.10 (PNNL-14753)	P&T injection wells west of WMA
NRDWL	Mar, Oct	0.12	0.37	2.4E-05	119	0.48	0.69	0.039	K = 518 to 1,524 (WHC-EP-0021); ne = 0.1 (assumed)	Average of 2 months*
WMA S-SX	Mar; Jun-Dec	0.020	0.52	3.3E-03	88	0.95	0.97	0.000	K = 1.33 to 14.4 m/d (PNNL 14113 and PNNL-14186); ne = 0.09 to 0.2 (assumed)	Average of 8 months*

Table 2. Results of Gradient and Velocity Calculations

WMA	Date	v min (m/d)	v max (m/d)	Gradient (m/m)	Direction (degrees east of north)	Goodness of Fit (R^2)	Correlation Coefficient (R):	P-Value	Hydrologic Properties (references)	Comments
WMA T	3/13/2015	0.37	0.59	6.0E-03	125	1.00	1.00	0.004	K = 6.11 to 9.69 m/d; ne = 0.10 (PNNL-17732)	P&T extraction well east of WMA. Excluded 2 wells with large residuals
WMA TX-TY (north)	3/13/2015	0.0045	1.3	1.2E-02	100	N/A	N/A	N/A	K= 0.07 to 19.9 (PNNL-18279); ne = 0.18 (DOE/RL- 2009-38)	General direction based on 3 wells in north part of WMA
WMA TX-TY (south)	3/13/2015	0.0014	0.40	3.6E-03	50	0.89	0.94	0.337	K= 0.07 to 19.9 m/d (PNNL-18279); ne = 0.18 (DOE/RL- 2009-38)	General direction based on 4 wells in north part of WMA
WMA U	Mar, Jun, Sep and Dec	0.044	0.50	5.2E-03	81	1.00	1.00	0.000	K = 1.69 to 9.5 m/d (PNNL-13378); ne = 0.1 to 0.2 (assumed)	Average of 4 months*
Gradients Estimated from Digital Grid or Water Table Map for 2015 Low Gradient										
216-A-29	2015	0.0010	0.0010	5.8E-06	205	0.97	0.99	0.000	K = 18 m/d (WHC-SD-EN-DP-047); ne = 0.1 (assumed)	Based on digital grid
216-A-36B	2015	0.00080	0.13	4.4E-06	114	0.95	0.98	0.000	K = 18 to 3,000 m/d (PNNL-11523); ne = 0.1 (assumed)	Based on digital grid
216-A-37-1	2015	0.0002	0.0095	3.2E-06	245	0.80	0.90	0.000	K = 18 to 300 m/d (PNNL-11523); ne n = 0.1 to 0.3 (assumed)	Based on digital grid

Table 2. Results of Gradient and Velocity Calculations

WMA	Date	v min (m/d)	v max (m/d)	Gradient (m/m)	Direction (degrees east of north)	Goodness of Fit (R^2)	Correlation Coefficient (R):	P-Value	Hydrologic Properties (references)	Comments
216-B-63	2015	0.0045	0.0045	6.5E-06	South-east	--	--	--	K = 139 m/d (SGW-44329); ne = 0.2 (assumed)	Gradient from water table map
WMA A-AX	2015	0.096	0.096	4.8E-06	152	0.93	0.97	0.000	K = 1,981 m/d (PNNL-8337, WHC-SD-EN-TI-019); ne = 0.1 (assumed)	Based on digital grid
IDF	2015	0.0026	0.0029	3.9E-06	144	0.97	0.99	0.000	K = 68 to 75 m/d (PNNL-13652, PNNL-11957); ne = 0.1 (assumed)	Based on digital grid
LLWMA-1	2015	0.41	0.41	4.8E-06	125	0.98	0.99	0.000	K = 17,000 m/d (CP-57037); ne = 0.2 (assumed)	Based on digital grid
LLWMA-2 (west)	2015	0.0059	0.0059	6.5E-06	South-east	--	--	--	K = 180 m/d (SGW 44329); ne = 0.2 (assumed)	Gradient from water table map
LLWMA-2 (east)	2015	0.049	0.049	6.5E-06	South	--	--	--	K = 1,500 m/d (PNL-6820); ne = 0.2 (assumed)	Gradient from water table map
WMA B-BX-BY	2015	0.39	0.39	4.2E-06	South-east	--	--	--	K = 18,800 m/d (200-BP-5 treatability test results, and CP-57037); ne = 0.2 (assumed)	Gradient from water table map
WMA C	2015	0.26	0.26	3.0E-06	South-east	--	--	--	K = 17,000 m/d (CP-57037); ne = 0.2 (assumed)	Gradient from water table map

Table 2. Results of Gradient and Velocity Calculations

WMA	Date	v min (m/d)	v max (m/d)	Gradient (m/m)	Direction (degrees east of north)	Goodness of Fit (R^2)	Correlation Coefficient (R):	P-Value	Hydrologic Properties (references)	Comments

*For units listing average velocity and gradient, statistical values are given for the March 2015 calculation.

IDF = Integrated Disposal Facility

LERF = Liquid Effluent Retention Facility

LLWMA = low-level waste management area

K = horizontal hydraulic conductivity

N/A = not applicable

NRDWL= Nonradioactive Dangerous Waste Landfill

WMA = waste management area

n_e = effective porosity

P&T = pump and treat

v = average linear velocity

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