ECF-100BC5-15-0121
Revision 0

# HYDRAULIC GRADIENTS IN 100-BC-5 OPERABLE UNIT 2010 THROUGH 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

P.O. Box 1600
Richland, Washington 99352

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ch2m

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APPROVED
By Julia Raymer at 8:37 am, Apr 27, 2016

Release Approval                Date

# ENVIRONMENTAL CALCULATION COVER PAGE

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# Contents



# Figures

# Tables

# Terms

| | |
|---|---|
| AWLN | automated water level network |
| ANOVA | Analysis of Variance |

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# 1 Purpose

This calculation evaluates groundwater levels in 100-BC Area for use in the Remedial Investigation and other reports. It includes the following elements:

- Water table maps for time periods representative of low and high river stage, with a contour interval finer than usually employed for annual groundwater reports
- Potentiometric surface map based on data from wells screened in the lower part of the unconfined aquifer
- Magnitude and direction of horizontal hydraulic gradients in the upper part of the unconfined aquifer for various time periods in 2010 through 2015
- Magnitude and direction of horizontal hydraulic gradients in the lower part of the unconfined aquifer in 2014 and 2015
- Magnitude and direction of vertical hydraulic gradients based on automated and manual water level data

# 2 Methodology

This section describes methods for creating contour maps of water level data, calculating horizontal hydraulic gradients, and calculating vertical hydraulic gradients.

## 2.1 Water Table and Potentiometric Surface Maps

Figure 1 illustrates river stage with dates of water level measurements in shallow and deep wells. June 2014 and September 2015 were selected to represent high and low river stage, respectively, for the water table maps. A consistent data set for deep wells was limited to a single period, September 2015.

Maps were manually contoured, using linear interpolation between data points.

## 2.2 Horizontal Hydraulic Gradients

Magnitude and direction of horizontal gradients were calculated using least squares regression of a plane to points in space. Water-level data (primarily manually measured data) were analyzed by trend-surface analysis calculations in a Microsoft Excel® spreadsheet created by J.P. McDonald.[1] 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 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 of ECF-HANFORD-12-0048 describe the methodology in detail.

## 2.3 Vertical Hydraulic Gradients

Magnitude and direction of vertical gradients were calculated in an Excel® spreadsheet by subtracting water levels in shallow wells from water levels in adjacent, deep wells and dividing by the vertical distance between screen bottoms. Vertical hydraulic gradient calculations were made primarily from

[1] Microsoft Excel® is a registered trademark of the Microsoft Corporation in the United States.

# 3 Assumptions and Inputs

Manually-measured water-level data were retrieved from the “Environmental Monitoring” module of the Hanford Site’s Virtual Library for wells in and near 100-BC Area for various time periods between 2010 and 2015. Table 1 lists data for wells screened at the water table and Table 2 lists data for wells screened in the lower part of the unconfined aquifer. Well coordinates (northing and easting) were retrieved from the Hanford Site “Environmental Dashboard Application” (http://environet.hanford.gov/EDA/), rounded to the nearest hundredth of a meter. In some cases, data from the automated water-level network were used to supplement the manual data set (noted in Table 1).

The hydraulic gradient calculation assumes that the water table (or potentiometric surface) is planar. This is of course a simplification, because water table contours form a varied “topography.” In the 100-BC Area the water table in the south is nearly horizontal, while the water table in the north slopes toward the river. Accordingly, separate calculations were done for each of these areas for each time period with sufficient data, except for June 2014. A water table map for June 2014 showed that the gradient could be approximated by a plane representing the entire 100-BC Area. Tables 1 and 2 include notation of which wells were considered for each region, and which data were excluded in order to improve the fit of the plane.

The potentiometric surface of the lower part of the unconfined aquifer can be approximated by a single plane for the entire 100-BC Area.

AWLN data from shallow/deep well pairs were derived from the Virtual Library. In some cases, comparison to manual water level measurements indicated transducer drift. Affected data were corrected to match the manual measurements, where necessary. The AWLN data and corrections are included in Excel spreadsheets associated with this document.

Well pair 199-B5-1 and 199-B5-13 is equipped with an AWLN station but irregularities in the data prevented their use in these calculations.

Data files are provided with this calculation as the following Microsoft Excel 2013® spreadsheets:

- 100-BC Gradients_2010-2015.xlsx
- 100-BC Gradients_2014-2015_DEEP.xlsx
- 100-BC_Vertical_Gradients.xlsx

# 4 Software Applications

A Microsoft Excel 2013® spreadsheet was used to perform calculations described in Section 2, 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 Calculation

## 5.1 Horizontal Gradients

To illustrate the calculations, Table 3 shows the June 2015 spreadsheet for the northern 100-BC Area, with formulae visible to illustrate the calculations. On Sheets 1 and 2, from left to right, the user enters well names, easting, northing, hydraulic head, and measurement dates with consistent units (meters) into the blue-shaded cells (B9 through F28). The spreadsheet calculations fit a plane through the data and compute what the head "should" be at each well based on that approximation.

Table 3 also shows computed data with formulae for predicted hydraulic head, and the predicted difference from mean and residuals, in cells G9 through I28. 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 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. Columns N through S, rows 13 through 17, display an Analysis of Variance (ANOVA) table. On sheet 2 of Table 2, computed data formulae continue in cells G26 through I28 and in columns K through O. On sheet 3 of Table 3, normal vector to the fitted plane, gradient magnitude and gradient direction formulae are in columns K, L, M.

Data sets were assigned to categories of low, moderate, or high river stage (Tables 1 and 2). These determinations were based on daily average river stage below Priest Rapids Dam for 2010 through 2015. Figure 1 illustrates river stage with dates of water level measurements. River stage less than the 33$^{rd}$ percentile was considered "low," between 33 and 67 percentiles considered "moderate," and greater than 67$^{th}$ percentile considered "high." One exception was made for the water table data set: the daily average river stage on June 2014 was slightly below the 67$^{th}$ percentile, but river stage had recently dropped from the high range so the time period was categorized as high river stage. Three exceptions were made for the data set for the lower part of the unconfined aquifer; the daily average river stage was barely in the "high" range in March 2014, January 2015, and April 2015, but the river had just risen from the moderate range and the data sets were categorized as moderate.

Not all of the available data were necessarily used in each calculation. Some data points were excluded to improve fit. Notes to that effect are provided in the worksheets of the data files *100-BC Gradients_2010-2015.xlsx* and *100-BC Gradients_2014-2015_DEEP.xlsx.*

## 5.2 Vertical Gradients

A simple Excel formula calculated the difference in head in shallow and deep wells for each concurrent measurement. These values were divided by the vertical distance between the bottoms of the screened intervals to derive vertical gradients (*100-BC_Vertical_Gradients*).

# 6 Results

## 6.1 Contour Maps

Figures 2 and 3 are water table maps for September 2015 and June 2014, respectively. Figure 4 is a potentiometric surface for the lower part of the unconfined aquifer in September 2015.

## 6.2 Horizontal Gradient in Upper Part of Unconfined Aquifer

Tables 4 and 5 summarize results of gradient calculations for the water table. Figure 5 shows flow vectors for low, moderate, and high river stage periods in northern and southern 100-BC.

**Northern 100-BC.** During low and moderate river stage periods, groundwater flow was within 7º east or west of north, with an average gradient of $1.9 \times 10^{-3}$ m/m. The strongest gradients were observed during low river stage. A reversed gradient was observed during high river stage in June 2011. Other high river stage periods showed weak gradients toward the northeast.

**Southern 100-BC.** The horizontal hydraulic gradient in southern 100-BC was more than an order of magnitude lower than northern 100-BC, averaging $6.3 \times 10^{-5}$ m/m. The direction of groundwater flow varied from north (during low river stage) to northeast and east (during high or moderate river stage). The average direction of flow is northeast (41º east of north). Migration of a hexavalent chromium plume in this region also indicates overall flow to the northeast.

## 6.3 Horizontal Gradient in Lower Part of Unconfined Aquifer

Eight wells are screened in the lower part of the unconfined aquifer (Table 2). Seven data sets from 2014 and 2015 were evaluated. The most robust data sets, with data from all eight wells, were for March 2014 and September 2015. Table 6 and Figure 6 summarize results.

The horizontal hydraulic gradient in the lower part of the aquifer slopes 8º west of north at an average of $1.2 \times 10^{-3}$ m/m.

## 6.4 Vertical Gradient

Table 7 summarizes vertical hydraulic gradients based on AWLN data sets in three well pairs and manual measurements in three well pairs.

Figure 7 illustrates water levels and vertical gradients in wells 199-B3-47 and 199-B3-51 in northern 100-BC, adjacent to the Columbia River. Water levels in deep well 199-B3-51 fluctuate above and below those in the shallow well and the vertical gradient varies from upward to downward over periods of hours, as river stage rises and falls. The gradient averaged upward over the period evaluated, as expected near a groundwater discharge area. The data set in this well pair was limited to January through October 2015 because prior to that time the transducer in one of the wells was not deep enough to be under water during periods of low water levels.

Figure 8 illustrates water levels and vertical gradients in wells 199-B4-14 and 199-B5-6 from 2011 through October 2015. The well pair is located in southern 100-BC and the direction of the vertical gradient varies seasonally in this region. The gradient is downward when water levels are low or declining, and is upward when water levels are rising. The gradient was downward 81% of the time period evaluated, with an average magnitude of $-3.3\times10^{-3}$ m/m, which is notably stronger than the horizontal hydraulic gradient in southern 100-BC.

Figure 9 illustrates water levels and vertical gradients in another well pair in southern 100-BC, 199-B4-7 and 199-B4-18. The data set is limited to a rising limb in early 2014 and a nearly complete set for December 2014 through October 2015. Results were consistent with those observed over a longer time period in 199-B4-14 and 199-B5-6.

Figures 10 and 11 illustrate manual water level measurements from two well pairs in southern 100-BC that are not equipped with AWLN stations. Results are generally consistent with those from the AWLN well pairs: downward gradients during periods of low and declining water levels, and upward gradients during periods of rising water levels.

Figure 12 illustrates manual water level measurements in 199-B5-1 and 199-B5-13, located in the inland portion of northern 100-BC. The gradient was consistently downward with an average magnitude of $-1.9 \times 10^{-2}$ m/m. The strongly downward gradient may be related to leakage of water from the 182-B Reservoir, located nearby.

# 7 References

Davis, J. C., 2002, *Statistics and Data Analysis in Geology*, 3rd Edition, John Wiley & Sons, New York.

ECF-HANFORD-12-0048, 2012, *Hydraulic Gradients and Velocity Calculations for RCRA Sites in 2011*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington.

Weier, Dennis, April 7, 2008, "Spreadsheet verification," Pacific Northwest National Laboratory, Richland, Washington. Personal communication via e-mail to John McDonald, Fluor Hanford, Inc., Richland, Washington.

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**Table 1. Water Level Elevations (m NAVD88) in Wells Screened at the Water Table for Selected Time Periods, 2010 through 2015**

| Region | Well Name | Easting (m) | Northing (m) | Feb. 26, 2010 (L) | May 10-11, 2010 (M) | July 27-28, 2010 (M) | Sep 2-7 2010 (L) | Mar. 4, 2011 (H) | June 28-29, 2011 (H) | Mar. 1, 2012 (L) | Feb. 27, 2013 (L) | Oct. 23-24, 2013 (L) | Feb. 28, 2014 (L) | June 10-12, 2014 (H) | Jun 16, 2014 (H) | Oct 10-16, 2014 (L) | Mar. 3, 2015 (M) | June 3-5, 2015 (M) | Sep. 15, 2015 (L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| N | 199-B2-13 | 564086.52 | 145264.56 | 120.62 | 120.85 | 121.24 | 120.73 | 121.58 | | 120.91 | 121.21 | 120.91 | 120.93 | | | 120.82 | 121.73 | | 120.87 |
| N | 199-B2-14 | 565095.99 | 145232.26 | | 120.68 | 120.62 | 119.74 | | 122.65* | 120.20 | 120.39 | 119.85* | 119.12 Y | | 121.39 | 120.05 | 121.38 | 120.98 | 120.06 |
| N | 199-B3-1 | 565561.46 | 145342.08 | 119.95 | 120.53 | 120.70 | 119.69 | 121.20 | | 120.16 | 120.40 | 120.15 | 120.04 | 122.02 | | 120.04 | 121.33 | 120.88 | 120.02 |
| N | 199-B3-46 | 565899.57 | 145369.04 | 119.92 | 120.51 | 120.70 | 119.81 | 121.13 | | 120.17 | 120.39 | 120.15 | 120.06 | 121.94 | | 120.05 | 121.29 | 120.84 | 120.04 |
| N | 199-B3-47 | 565388.66 | 145368.95 | 119.86 | 120.55 | 120.52 | 119.47 | 121.20 | 122.87 | 120.02 | 120.21 | 120.02* | 119.93 | 122.04* | 121.25 Y | 119.82 | 121.25 | 120.58* | 119.83 |
| N | 199-B3-50 | 566028.90 | 145058.21 | | 120.82 | 121.51 | 120.92 (9/2/2010) | | 122.55 | 121.17 (3/12/12) | 121.35 | 121.17 | 120.89 | 121.92 | 121.84 | 121.09 | 121.64 | 121.47 | 121.01 |
| N | 199-B4-1 | 565289.81 | 144791.53 | 121.16 | 121.23 | | | 121.59 | | 121.55 | 121.86 | | 121.44 | | 122.12 | 121.69 | 121.91 | | 121.61 |
| S | 199-B4-14 | 564969.25 | 144313.98 | | | | | 121.69 | 122.63 | 121.71 | 122.00 | 121.82* | 121.60 | 122.18 | 122.21 | 121.86 | 121.98* | 121.95 | 121.77 |
| S | 199-B4-16 | 566132.01 | 144479.91 | | | | | | | | | | | | | 121.88 | 121.93* | 121.93* | 121.76 |
| S | 199-B4-4 | 565377.08 | 144479.71 | 121.33 | 121.26 | 121.82 | 121.69 | 121.68 | | 121.70 | 121.97 | 121.85 | 121.59 | | | 121.88 | 121.95 | | 121.75 |
| S | 199-B4-7 | 565398.86 | 144382.85 | 121.34 | | | | 121.69 | | 121.73 | 121.99 | 121.86 | 121.62 | | | 121.89 | 121.97 | | 121.77 |
| N | 199-B4-8 | 565578.45 | 144653.79 | | 121.22 | 121.79 | 121.68 (9/2/2010) | | | | | 121.81 | 121.57 | 122.12 | 122.13 | 121.84 | 121.92 | 121.90 | 121.72 |
| N | 199-B5-1 | 564878.15 | 144764.90 | 121.12 | 121.14 | 121.75 | 121.48 | 121.66 | | 121.54 | 121.83 | | 121.40 | 122.21 | | 121.67 | 121.93 | | 121.57 |
| S | 199-B5-10 | 564812.14 | 144250.15 | | | | | | | | | | | | | 121.80 | | | 121.71 |
| S | 199-B5-12 | 565178.86 | 144241.26 | | | | | | | | | | | | | 121.90 | | | 121.78 |
| S | 199-B5-14 | 564170.23 | 144520.06 | | | | | | | | | | | | | 121.82 | | | 121.77 |
| N | 199-B5-2 | 565405.43 | 144939.70 | | 121.03 | 121.66 | | | | | | 121.55 | 121.33 | 122.13 | 122.10 | 121.65 | 121.88 | 121.82 | 121.51 |
| S | 199-B5-8 | 566014.00 | 143587.69 | | | | | | 122.52* | 121.73 | 121.99 | 121.87 | 121.62 | 122.11* | 122.16 | 121.90 | 121.95 | 121.93 | 121.76** |
| S | 199-B8-6 | 564498.83 | 144157.79 | 121.34 | 121.28 | 121.92 | 121.72 | 121.74* | 122.69* | 121.73 | 122.01 | 121.84 | 121.62 | 122.25 | 122.23* | 121.84 | 122.02 | 121.97 | 122.77* |
| S | 199-B8-7 | 564760.86 | 144045.17 | 121.34 | | | | | | | | | | | | | | | |
| S | 199-B8-8 | 565006.14 | 144001.01 | 121.35 | | | | | | | | | | | | | | | |
| S | 199-B8-9 | 565276.43 | 144054.45 | | | | | | 122.59 | 121.74 | 122.01 | | 121.62 | | 122.19 | 121.87 | 121.97 | 121.95 | 121.79 |
| S | 199-B9-2 | 565534.79 | 144078.08 | | 121.27 | | | | | | | 121.86 | | | | 121.85 | | | |
| S | 199-B9-3 | 565667.36 | 144046.72 | 121.34 | 121.26 | 121.84 | 121.71 | 121.66 | | 121.73 | 121.99 | 121.86 | 121.62 | 122.15 | | 121.85 | 121.96 | 121.94 (6/10/2015) | 121.77 |
| S | 699-65-83 | 564590.47 | 143249.09 | 121.36 | 121.32 (5/17/10) | 121.84 (8/2/2010) | 121.75 | | | 121.75 | 122.01 | 121.87 | 121.63 | | | 121.93 (10/7/13) | 121.99 | | 121.78 |

**Table 1. Water Level Elevations (m NAVD88) in Wells Screened at the Water Table for Selected Time Periods, 2010 through 2015**

| Region | Well Name | Easting (m) | Northing (m) | Feb. 26, 2010 (L) | May 10-11, 2010 (M) | July 27-28, 2010 (M) | Sep 2-7 2010 (L) | Mar. 4, 2011 (H) | June 28-29, 2011 (H) | Mar. 1, 2012 (L) | Feb. 27, 2013 (L) | Oct. 23-24, 2013 (L) | Feb. 28, 2014 (L) | June 10-12, 2014 (H) | Jun 16, 2014 (H) | Oct 10-16, 2014 (L) | Mar. 3, 2015 (M) | June 3-5, 2015 (M) | Sep. 15, 2015 (L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S | 699-67-86 | 563661.65 | 143873.05 | 121.34 | 121.37 (5/18/10) | 121.78 (8/2/2010) | 121.78 | | | 121.72 (3/12/12) | 122.04 | | 121.62 | | 122.44 | 121.61 (10/7/14) | 122.13 | 122.04 | 121.68 (9/29/15) |
| N | 699-71-77 | 566401.95 | 145098.61 | 120.82 | 121.02 (5/17/10) | 121.07 (8/2/2010) | 121.01 | 121.43 | | 121.18 | 121.44 | | 121.09 | | | 121.12 (10/27/14) | 121.66 | | 121.16 |

H = high river stage

L = moderate river stage

M = low river stage

N = northern 100-BC region (from well 199-B4-8 northward)

S = southern 100-BC region (south of well 199-B4-8)

Y = suspect data; not used

*Automated water level network (noon reading). Other data are manual measurements from the dates in the headers, unless other dates indicated.

**No manual or AWLN data available. Used assumed value equal to that in 199-B4-16, based on previous trends in the two wells.

Shaded cells indicate data excluded from the analysis to improve fit (see spreadsheet notes)

**Table 2. Water Level Elevations (m NAVD88) in Wells Screened in Lower Part of Unconfined Aquifer for Selected Time Periods, 2014-2015**

| Region | Well Name | Easting (m) | Northing (m) | Mar 24, 2014 (M) | Jul 8, 2014 (H) | Oct 10-16, 2014 (L) | Jan 16, 2015 (M) | Apr 10, 2015 (M) | Jul 15-16, 2015 (M) | Sep 15, 2015 (L) |
|---|---|---|---|---|---|---|---|---|---|---|
| N | 199-B2-16 | 564915.00 | 145190.68 | | | 120.42 | | | | 120.42 |
| N | 199-B3-51 | 565379.25 | 145362.36 | 121.21* | 121.83* | 120.03 | 121.19* | 120.08* | 119.73 | 120.11 |
| N | 199-B5-13 | 564893.41 | 144764.86 | | | 121.10 | | | 121.32 | 121.10 |
| N | 199-B5-5 | 564721.99 | 144955.49 | | | 120.74 | | | | 120.88 |
| S | 199-B4-18 | 565401.02 | 144392.22 | 121.61 | 122.28 | 121.78 | 121.76 | 122.02 | 121.78 | 121.68 |
| S | 199-B5-11 | 565188.90 | 144241.27 | 121.67 | 122.34 | 121.75 | 121.79 | 122.05 | 121.81 | 121.70 |
| S | 199-B5-6 | 564967.70 | 144316.44 | 121.49* | 122.32 | 121.56* | 121.74 | 121.99 (4/13/15) | 121.74 | 121.63 |
| S | 199-B5-9 | 564821.98 | 144250.05 | 121.64 | 122.33 | 121.75 | 121.75 | 122.02 (4/13/15) | 121.79 | 121.66 |

H = high river stage

L = moderate river stage

M = low river stage

N = northern 100-BC region (from well 199-B4-8 northward)

S = southern 100-BC region (south of well 199-B4-8)

*Automated water level network (noon reading). Other data are manual measurements from the dates in the headers, unless other dates indicated.

Shaded cell indicates data excluded from the analysis to improve fit (see spreadsheet notes)

**Table 3. Hydraulic Gradient Calculation Spreadsheet with Data for June 2015, Northern 100-BC Area (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-B2-14 | 565095.99 | 145232.26 | 120.977 | 6/3/2015 | =IF(ISBLANK(E9),,$L$52+$L$53*C9+$L$54*D9) | =IF(G9=0,0,G9-SUM($G$9:$G$28)/$L$23) | =IF(ISBLANK(E9),,G9-E9) | | | | | | | | | | |
| 10 | | 199-B3-1 | 565561.455 | 145342.08 | 120.879 | 6/5/2015 | =IF(ISBLANK(E10),,$L$52+$L$53*C10+$L$54*D10) | =IF(G10=0,0,G10-SUM($G$9:$G$28)/$L$23) | =IF(ISBLANK(E10),,G10-E10) | | **Gradient Magnitude:** | =L64 | | | | | | | |
| 11 | | 199-B3-46 | 565899.57 | 145369.04 | 120.844 | 6/5/2015 | =IF(ISBLANK(E11),,$L$52+$L$53*C11+$L$54*D11) | =IF(G11=0,0,G11-SUM($G$9:$G$28)/$L$23) | =IF(ISBLANK(E11),,G11-E11) | | **Gradient Direction (azimuth):** | =INDEX(M69:M77,MATCH("Yes",L69:L77,0)) | | | | | | | |
| 12 | | 199-B3-47 | 565388.66 | 145368.95 | 120.954 | 6/10/2015 | =IF(ISBLANK(E12),,$L$52+$L$53*C12+$L$54*D12) | =IF(G12=0,0,G12-SUM($G$9:$G$28)/$L$23) | =IF(ISBLANK(E12),,G12-E12) | | | | | | | | | | |
| 13 | | 199-B3-50 | 566028.9 | 145058.21 | 121.473 | 6/5/2015 | =IF(ISBLANK(E13),,$L$52+$L$53*C13+$L$54*D13) | =IF(G13=0,0,G13-SUM($G$9:$G$28)/$L$23) | =IF(ISBLANK(E13),,G13-E13) | | **Statistics** | | | **ANOVA** | | | | | |
| 14 | | 199-B4-8 | 565578.45 | 144653.79 | 121.896 | 6/3/2015 | =IF(ISBLANK(E14),,$L$52+$L$53*C14+$L$54*D14) | =IF(G14=0,0,G14-SUM($G$9:$G$28)/$L$23) | =IF(ISBLANK(E14),,G14-E14) | | | | | **Var Source** | Sum of Squares | Df | Mean Squares | F-Test | P-Value |
| 15 | | 199-B5-2 | 565405.427 | 144939.695 | 121.815 | 6/3/2015 | =IF(ISBLANK(E15),,$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$23) | =IF(ISBLANK(E20),,E20-G20) | | | | | | | | | | |
| 21 | | 13 | | | | | =IF(ISBLANK(E21),,$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) | | | | | | | |

**Table 3. Hydraulic Gradient Calculation Spreadsheet with Data for June 2015, Northern 100-BC Area (3 sheets)**

| | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R | S |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 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 | | | | | | | | | | | **Sum of Observed Heads^2:** | =SUM(E9:E28^2) | | | | | | | |
| 33 | | | | | | | | | | | **Sum of Predicted Heads:** | =SUM(G9:G28) | | | | | | | |
| 34 | | | | | | | | | | | **Sum of Predicted Heads^2:** | =SUM(G9:G28^2) | | | | | | | |
| 35 | | | | | | | | | | | **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 | | | | | | | | | | | | | | | | | | | |
| 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 | | | | | | | | | | | | | | | | | | | |

**Table 3. Hydraulic Gradient Calculation Spreadsheet with Data for June 2015, Northern 100-BC Area (3 sheets)**

| | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R | S |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 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 4. Horizontal Water Table Gradients in Northern 100-BC**

| Date | River Stage | Degrees East of North | Magnitude (m/m) | $R^2$ | Correlation Coefficient | P Value | Statistically Significant* Trend? | Comment |
|---|---|---|---|---|---|---|---|---|
| 2/26/2010 | Low | 2 | 2.0E-03 | 0.87 | 0.93 | 0.017 | Yes | |
| 5/11/2010 | Moderate | 6 | 1.0E-03 | 0.97 | 0.98 | 0.000 | Yes | |
| 7/27/2010 | Moderate | 3 | 1.8E-03 | 0.83 | 0.91 | 0.005 | Yes | |
| 9/7/2010 | Low | -9 | 3.3E-03 | 0.97 | 0.99 | 0.000 | Yes | |
| 3/4/2011 | High | 21 | 6.1E-04 | 0.99 | 1.00 | 0.000 | Yes | |
| 6/28/2011 | High | -173 | 1.5E-03 | N/A | N/A | N/A | N/A | Only 3 points; no statistics. Reversed gradient |
| 3/1/2012 | Low | 3 | 2.4E-03 | 0.87 | 0.93 | 0.006 | Yes | |
| 2/27/2013 | Low | -6 | 2.9E-03 | 1.00 | 1.00 | 0.000 | Yes | |
| 10/23/2013 | Low | 5.1 | 2.6E-03 | 0.92 | 0.96 | 0.006 | Yes | |
| 2/28/2014 | Low | -3 | 2.4E-03 | 0.99 | 0.99 | 0.000 | Yes | |
| 6/12/2014 | High | 51 | 1.8E-04 | 0.95 | 0.97 | 0.000 | Yes | Combined for north and south regions |
| 10/10/2014 | Low | -4 | 2.9E-03 | 0.98 | 0.99 | 0.000 | Yes | |
| 3/3/2015 | Moderate | -3 | 1.1E-03 | 0.94 | 0.97 | 0.000 | Yes | |
| 6/5/2015 | Moderate | -5 | 1.8E-03 | 0.91 | 0.95 | 0.009 | Yes | |
| 9/15/2015 | Low | -5 | 3.0E-03 | 1.00 | 1.00 | 0.000 | Yes | |
| **AVERAGE** | | **-8** | **1.9E-03** | | | | | |
| Minimum | | -173 | 1.8E-04 | | | | | |
| Maximum | | 51 | 3.3E-03 | | | | | |

*At 0.05 level of significance

**Table 5. Horizontal Water Table Gradients in Southern 100-BC**

| Date | River Stage | Degrees East of North | Magnitude (m/m) | $R^2$ | Correlation Coefficient | P Value | Statistically Significant* Trend? | Comment |
|---|---|---|---|---|---|---|---|---|
| 2/26/2010 | Low | -4 | 2.0E-05 | 0.85 | 0.92 | 0.009 | Yes | |
| 5/11/2010 | Moderate | 60 | 5.3E-05 | 0.88 | 0.94 | 0.042 | Yes | |
| 7/27/2010 | Moderate | 38 | 1.3E-04 | N/A | N/A | N/A | N/A | Only 3 points; no statistics. |
| 9/7/2010 | Low | 18 | 4.1E-05 | 0.98 | 0.99 | 0.132 | No | Results uncertain |
| 3/4/2011 | High | 93 | 6.1E-05 | 0.88 | 0.94 | 0.113 | No | Results uncertain |
| 6/28/2011 | High | 74 | 1.3E-04 | 1.00 | 1.00 | 0.064 | No | |
| 3/1/2012 | Low | 7 | 2.5E-05 | 0.52 | 0.72 | 0.163 | No | Results uncertain |
| 2/27/2013 | Low | 57 | 2.6E-05 | 0.77 | 0.87 | 0.013 | Yes | |
| 10/23/2013 | Low | -29 | 2.2E-05 | 0.78 | 0.88 | 0.047 | Yes | |
| 2/28/2014 | Low | 0 | 1.8E-05 | 0.51 | 0.71 | 0.119 | No | Results uncertain |
| 6/12/2014 | High | 51 | 1.8E-04 | 0.95 | 0.97 | 0.000 | Yes | Combined for north and south regions |
| 10/15/2014 | Low | -6 | 1.1E-04 | 0.91 | 0.95 | 0.008 | Yes | Results uncertain; sensitive to choice of wells |
| 3/3/2015 | Moderate | 90 | 6.9E-05 | 0.82 | 0.91 | 0.002 | Yes | |
| 6/3/2015 | Moderate | 73 | 4.3E-05 | 0.90 | 0.95 | 0.010 | Yes | |
| 9/15/2015 | Low | 96 | 1.1E-05 | 0.55 | 0.74 | 0.134 | No | Results uncertain |
| **AVERAGE** | | **41** | **6.3E-05** | | | | | |
| Minimum | | -29 | 1.8E-05 | | | | | |
| Maximum | | 96 | 1.8E-04 | | | | | |

*At 0.05 level of significance

**Table 6. Horizontal Hydraulic Gradients for the Lower Part of the Unconfined Aquifer**

| Date | River Stage | Degrees East of North | Magnitude (m/m) | Goodness of Fit ($R^2$) | Correlation Coefficient (R): | P-Value | Statistically Significant* Trend? | Comment |
|---|---|---|---|---|---|---|---|---|
| 3/24/2014 | Moderate | -20 | 4.4E-04 | 0.92 | 0.96 | 0.078 | No | |
| 7/8/2014 | High | -3 | 4.7E-04 | 1.00 | 1.00 | 0.001 | Yes | |
| 10/13/2014 | Low | 3 | 1.5E-03 | 0.98 | 0.99 | 0.001 | Yes | Robust data set |
| 1/16/2015 | Moderate | -14 | 5.8E-04 | 1.00 | 1.00 | 0.002 | Yes | |
| 4/10/2015 | Moderate | -11 | 1.9E-03 | 0.99 | 1.00 | 0.007 | Yes | |
| 7/15/2015 | Moderate | -10 | 2.0E-03 | 0.99 | 1.00 | 0.007 | Yes | |
| 9/15/2015 | Low | 2 | 1.4E-03 | 0.98 | 0.99 | 0.000 | Yes | Robust data set |
| AVERAGE | | -8 | 1.2E-03 | | | | | |
| *At 0.05 level of significance | | | | | | | | |

**Table 7. Vertical Hydraulic Gradients**

| | 199-B3-47 and 199-B3-51 (AWLN) | 199-B4-14 and 199-B5-6 (AWLN) | 199-B4-7 and 199-B4-18 (AWLN) | 199-B5-1 and 199-B5-13 (Manual) | 199-B5-10 and 199-B5-9 (Manual) | 199-B5-12 and 199-B5-11 (Manual) |
|---|---|---|---|---|---|---|
| **Elev. Bottom of Shallow Well Screen** | 115.8 | 116.9 | 117.7 | 108.7 | 116.5 | 116.7 |
| **Elev. Bottom of Deep Well Screen** | 88.6 | 87.1 | 88.0 | 87.7 | 88.7 | 86.1 |
| **Vertical Distance (m)[a]** | 27.2 | 29.8 | 29.7 | 21.1 | 27.8 | 30.6 |
| **Minimum Gradient (m/m)** | -2.7E-02 | -1.2E-02 | -4.1E-03 | -2.72E-02 | -3.24E-03 | -4.84E-03 |
| **Maximum Gradient (m/m)** | 3.5E-02 | 8.1E-03 | 1.6E-03 | -1.85E-02 | 2.91E-03 | 1.08E-03 |
| **Average Gradient (m/m)** | 3.9E-03 | -3.3E-03 | -1.2E-03 | -2.26E-02 | -2.52E-04 | -1.28E-03 |
| **Count if upward[b]** | 2,216 (63%) | 5,984 (19%) | 993 (14%) | 0 (0%) | 5 (45%) | 4 (36%) |
| **Count if downward[c]** | 1,282 (37%) | 26,345 (81%) | 5,904 (86%) | 6 (100%) | 6 (55%) | 7 (64%) |

Note: Upward gradient is positive and downward gradient is negative

a. Elevation difference between bottoms of well screens

b. Number of paired measurements showing upward (positive) gradient

c. Number of paired measurements showing downward (negative) gradient

AWLN = automated water level network

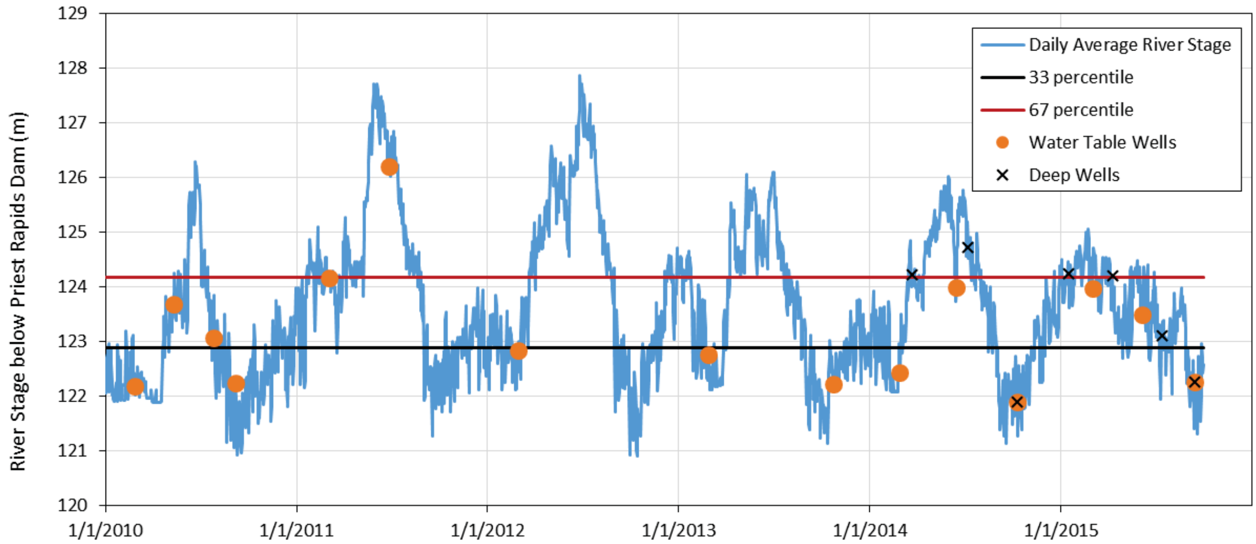



**Figure 1. Water Level Measurement Dates in Relation to Columbia River Stage**

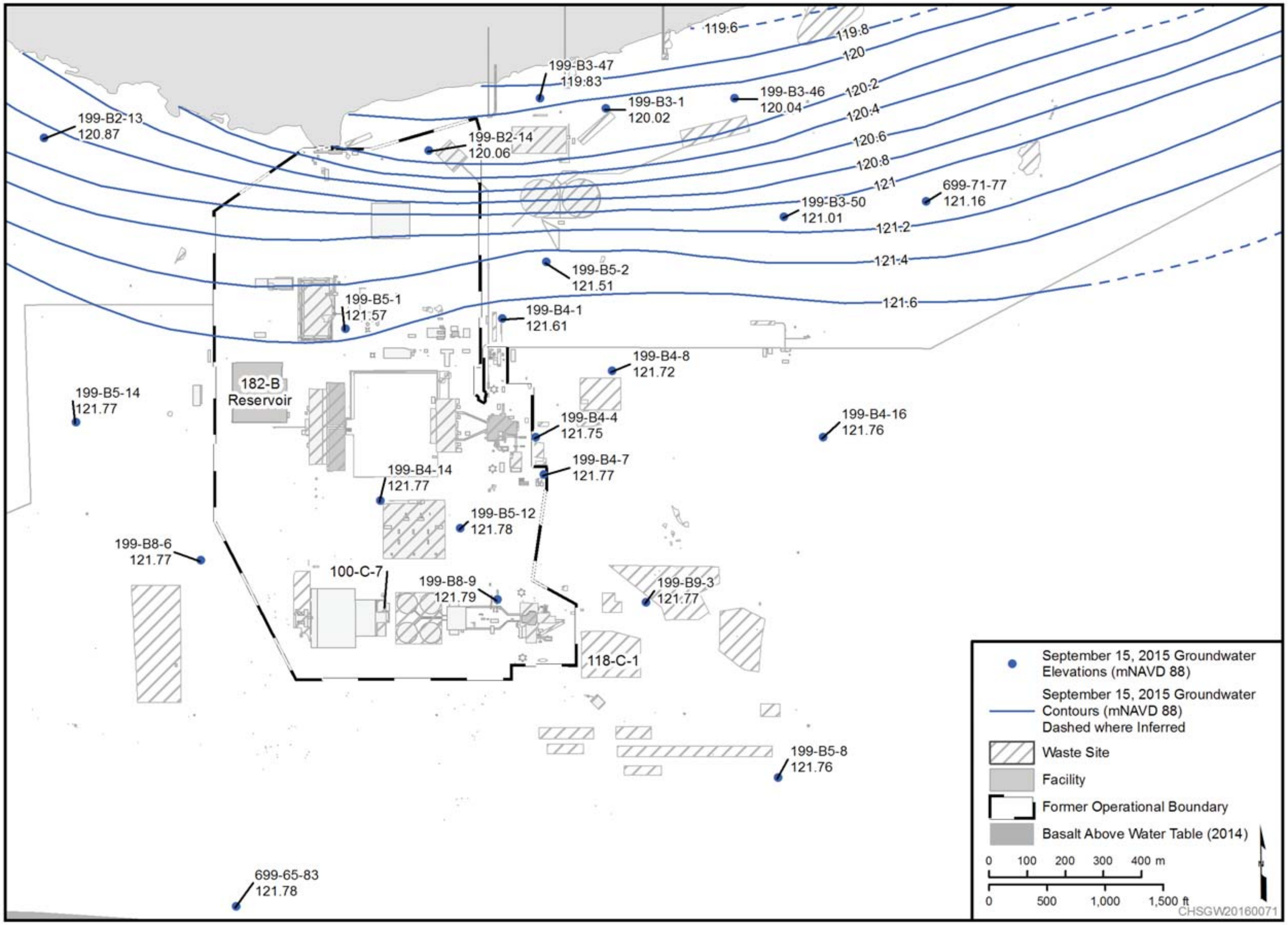



**Figure 2. September 2015 Water Table in 100-BC**

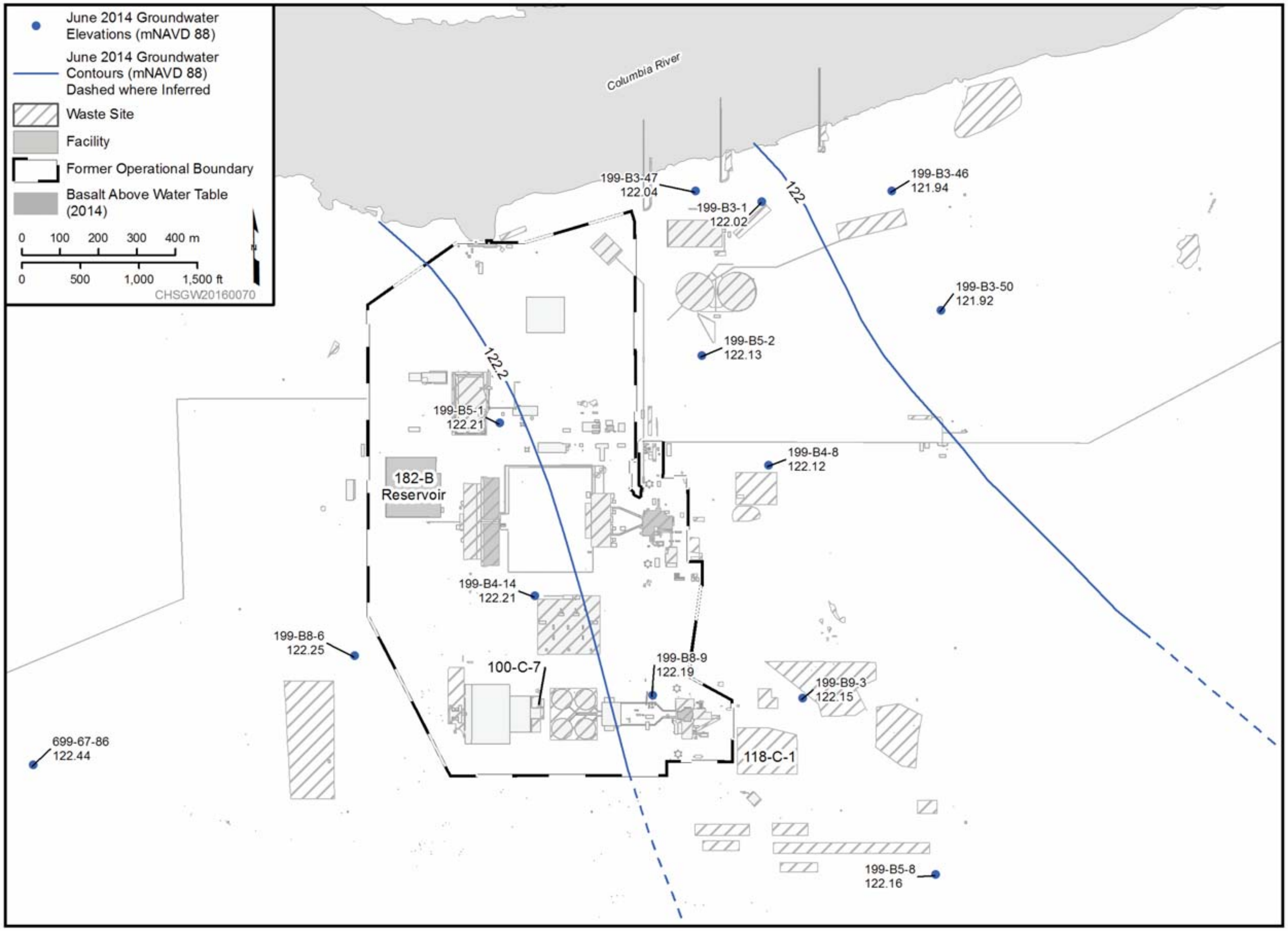



Figure 3. June 2014 Water Table in 100-BC

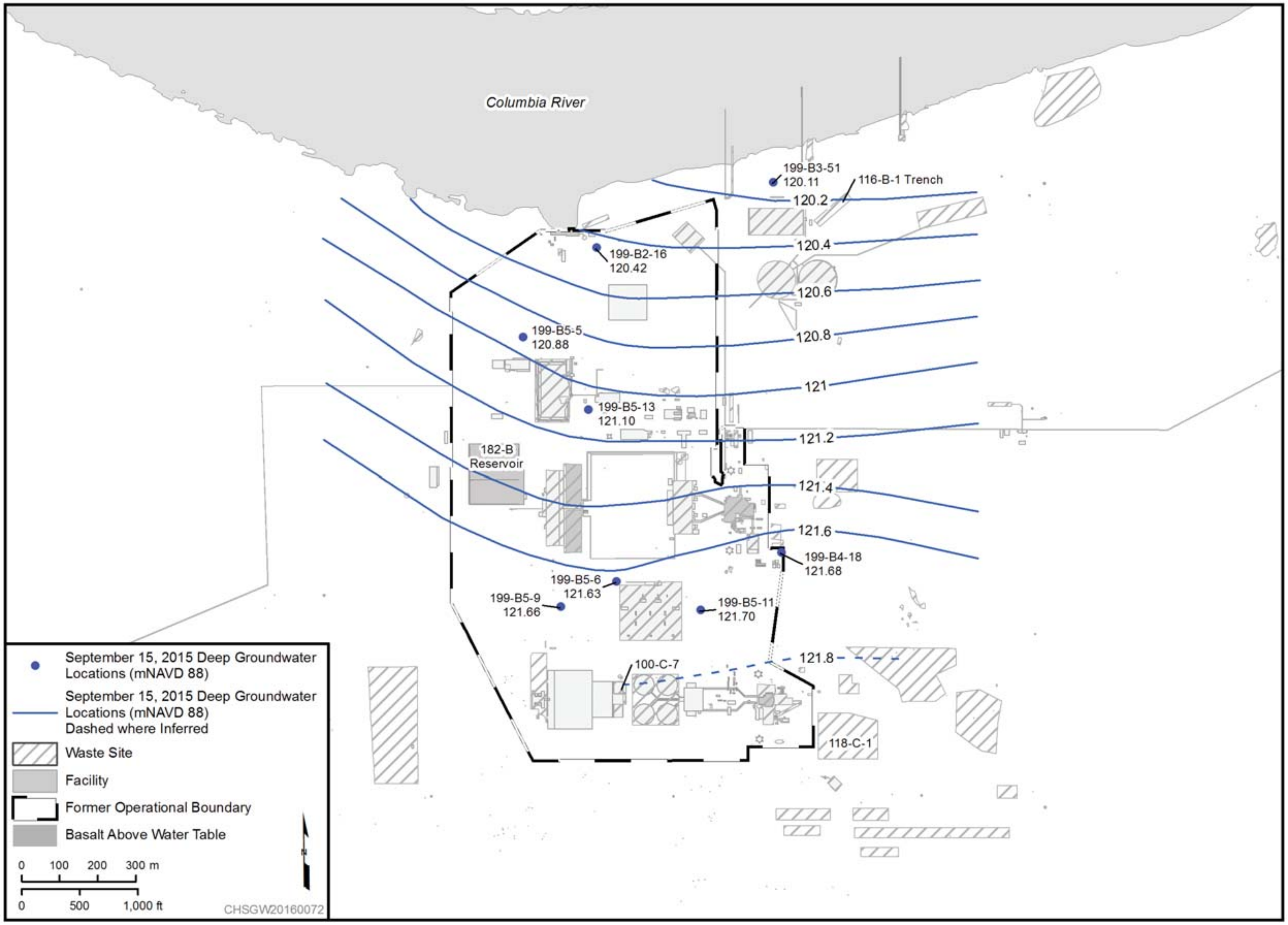



**Figure 4. September 2015 Potentiometric Surface, Lower Part of Unconfined Aquifer**

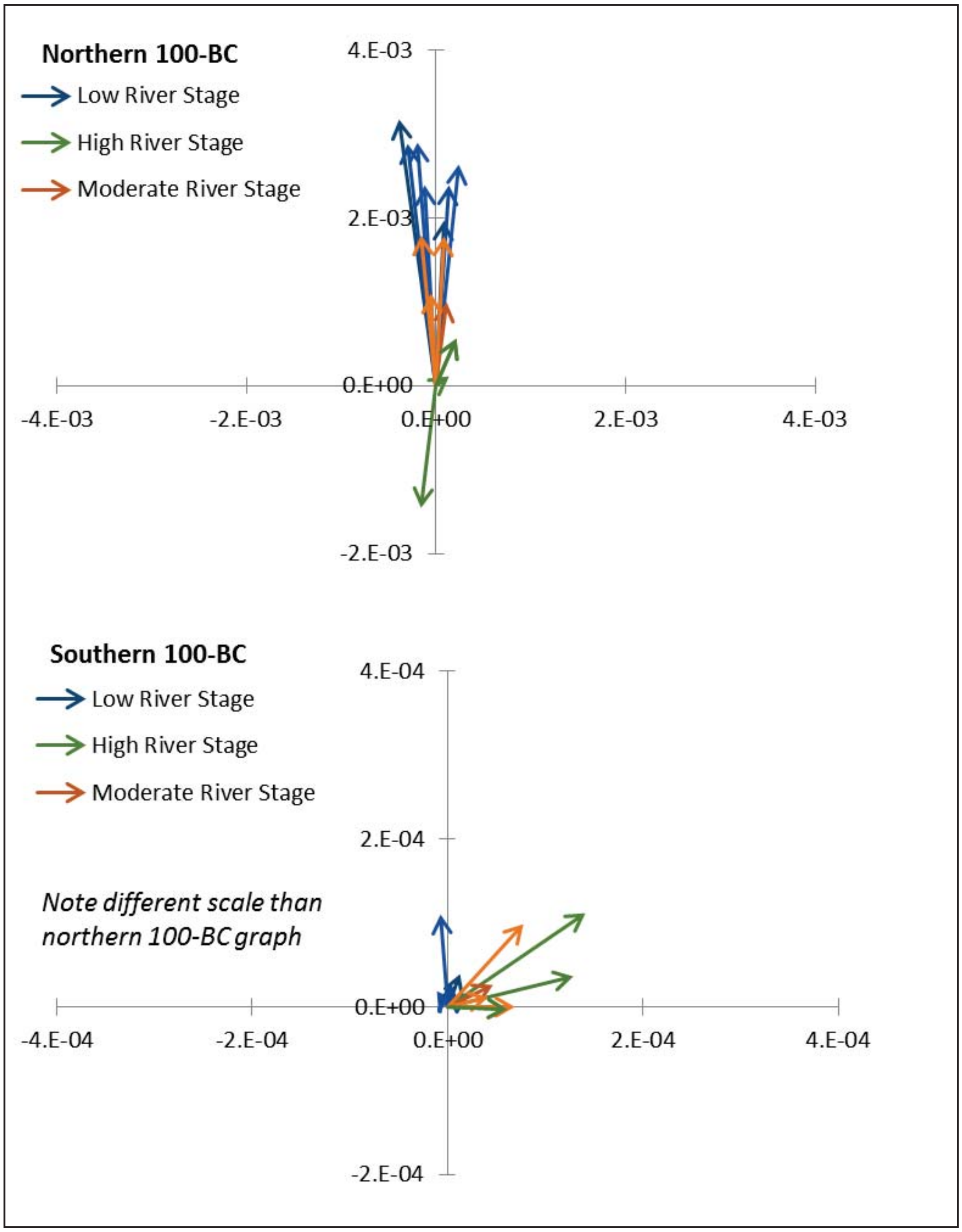



**Figure 5 Gradient Vectors for Water Table**

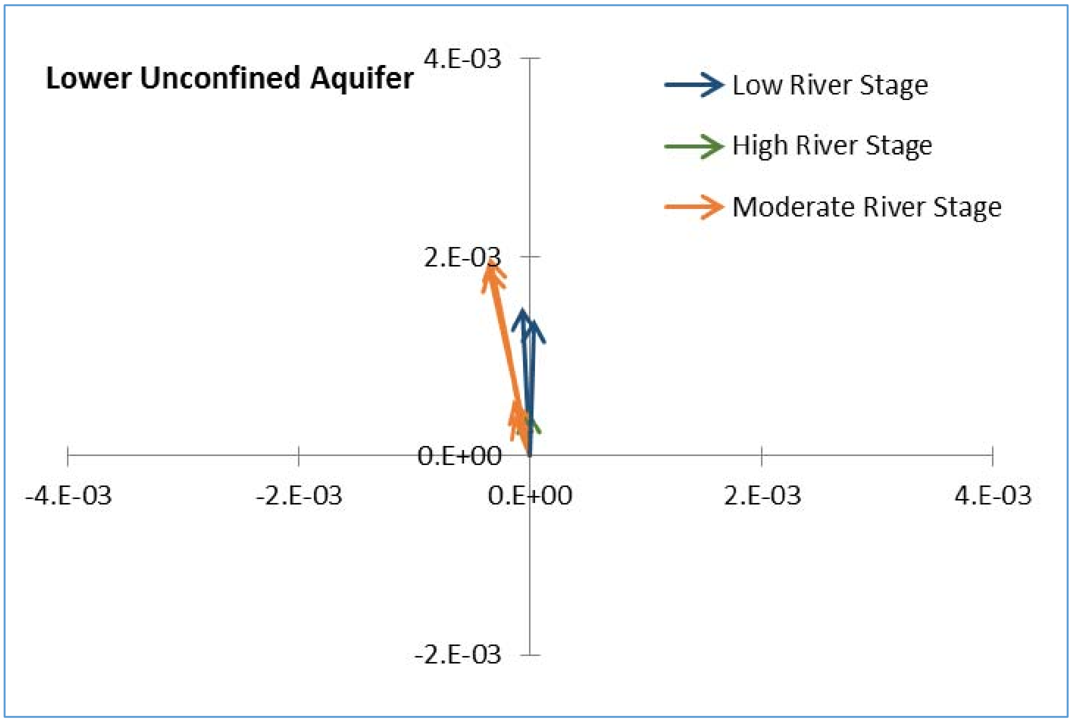



**Figure 6. Gradient Vectors for Lower Part of Unconfined Aquifer**

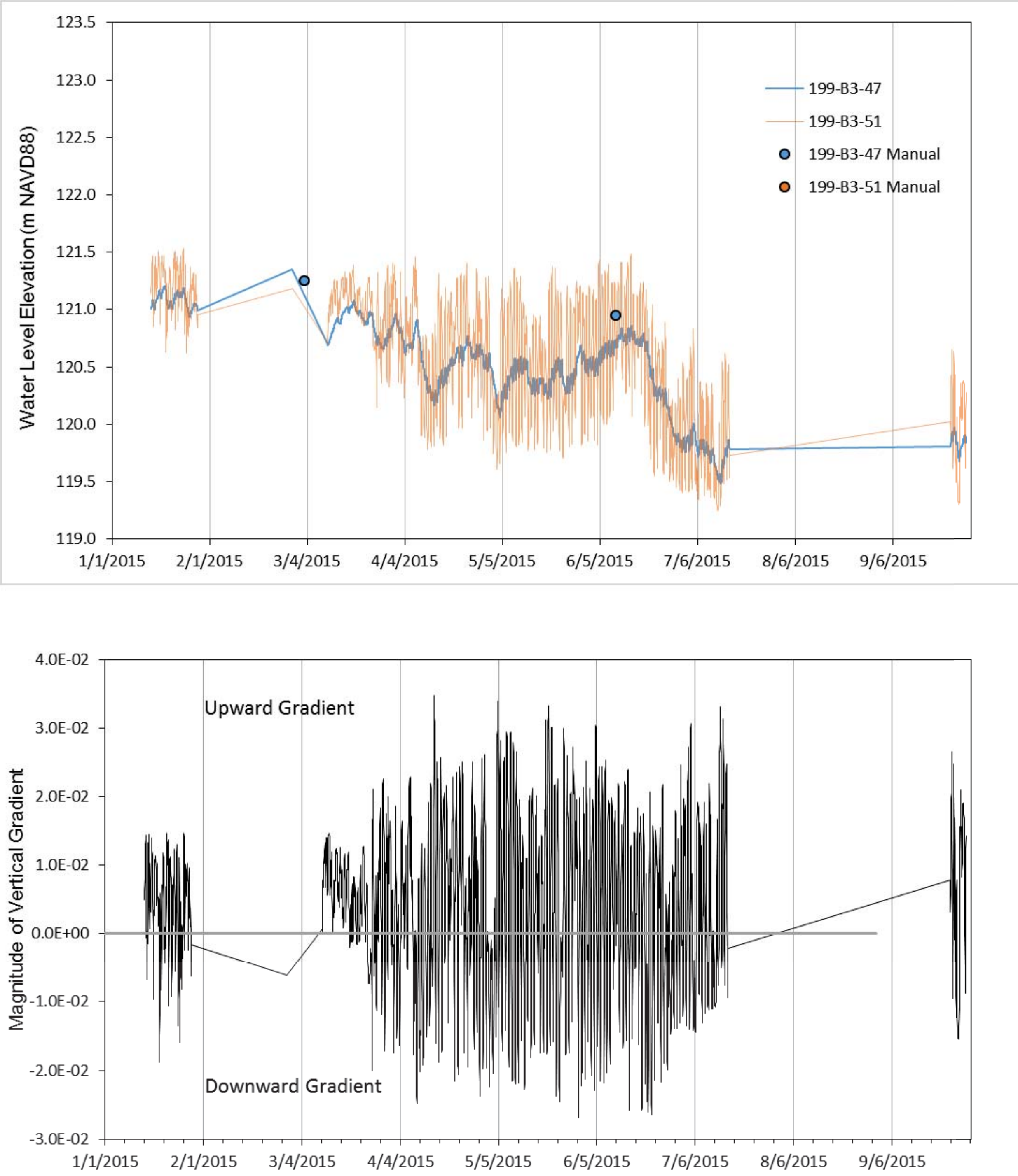
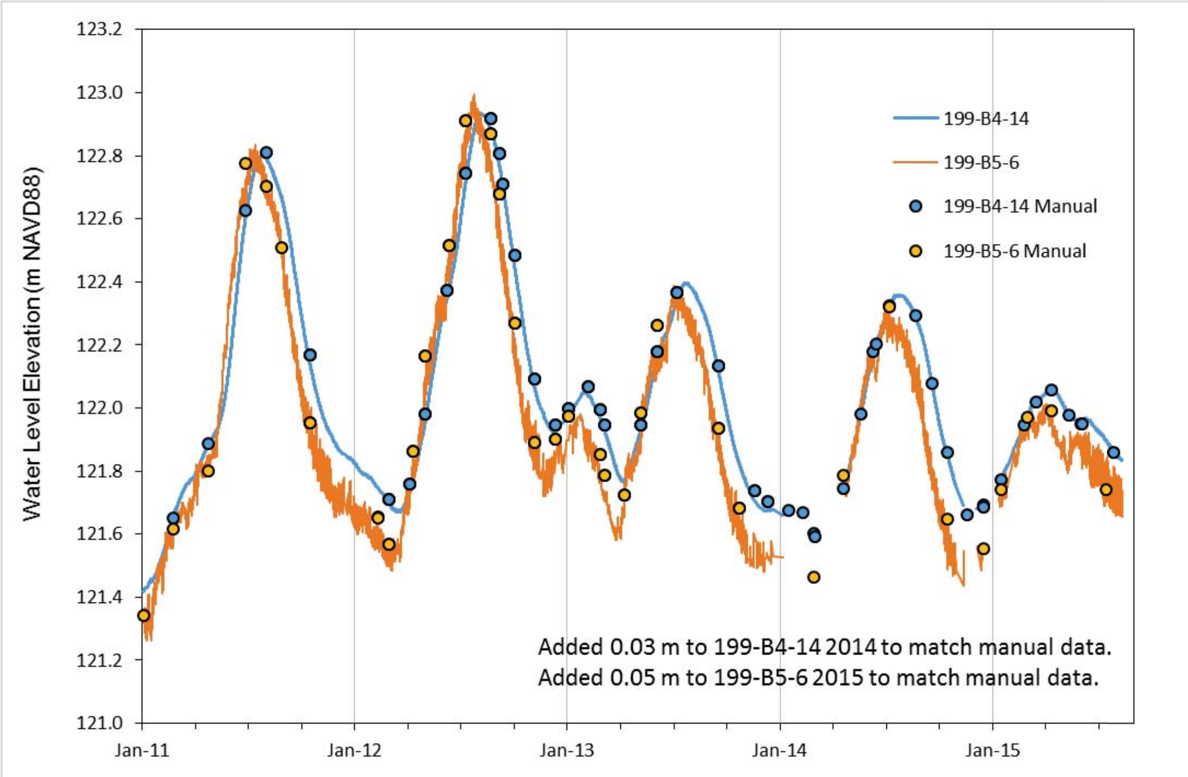



**Figure 7. Water Levels and Vertical Gradient for 199-B3-47 (Water Table) and 199-B3-51 (Bottom of Unconfined Aquifer)**



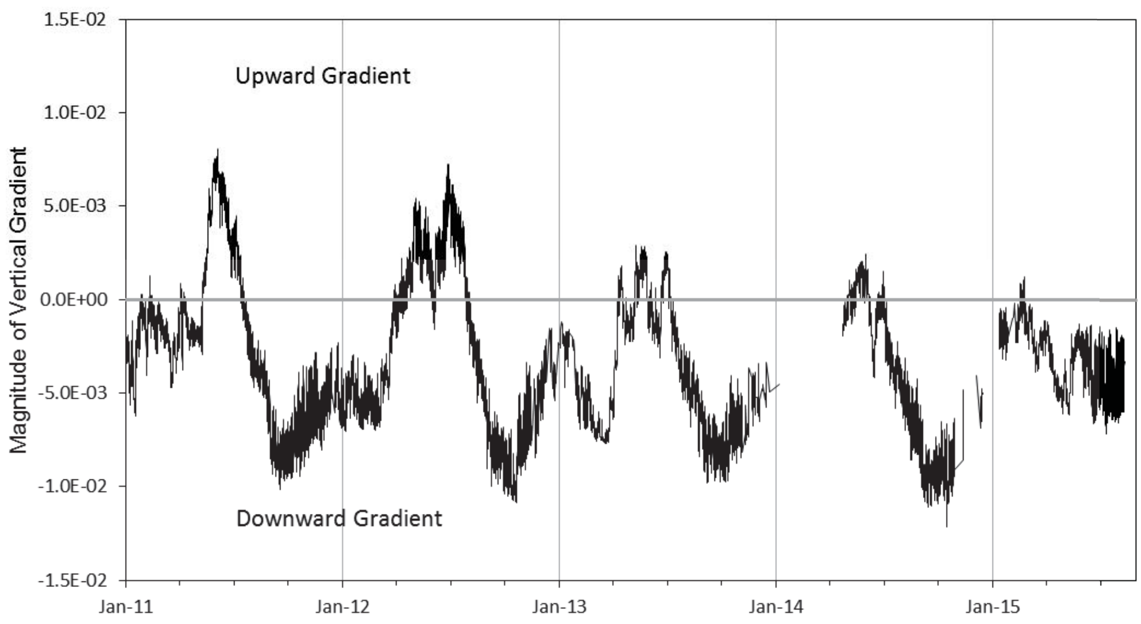
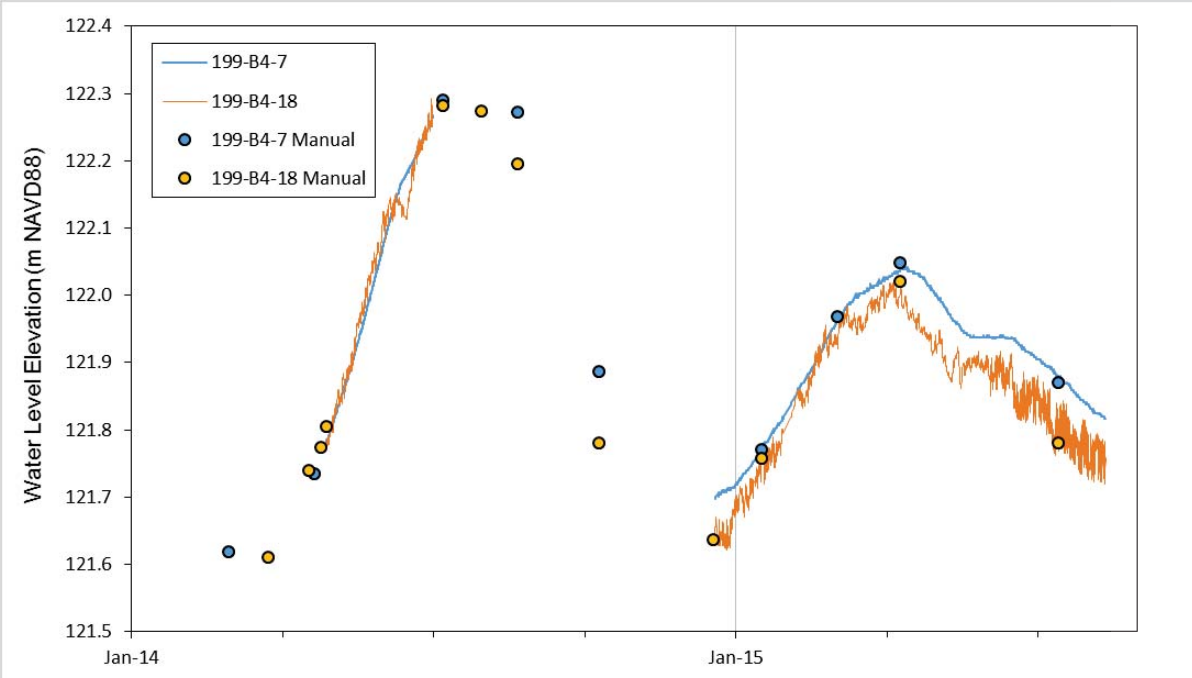




**Figure 8. Water Levels and Vertical Gradient for 199-B4-14 (Water Table) and 199-B5-6 (Bottom of Unconfined Aquifer)**



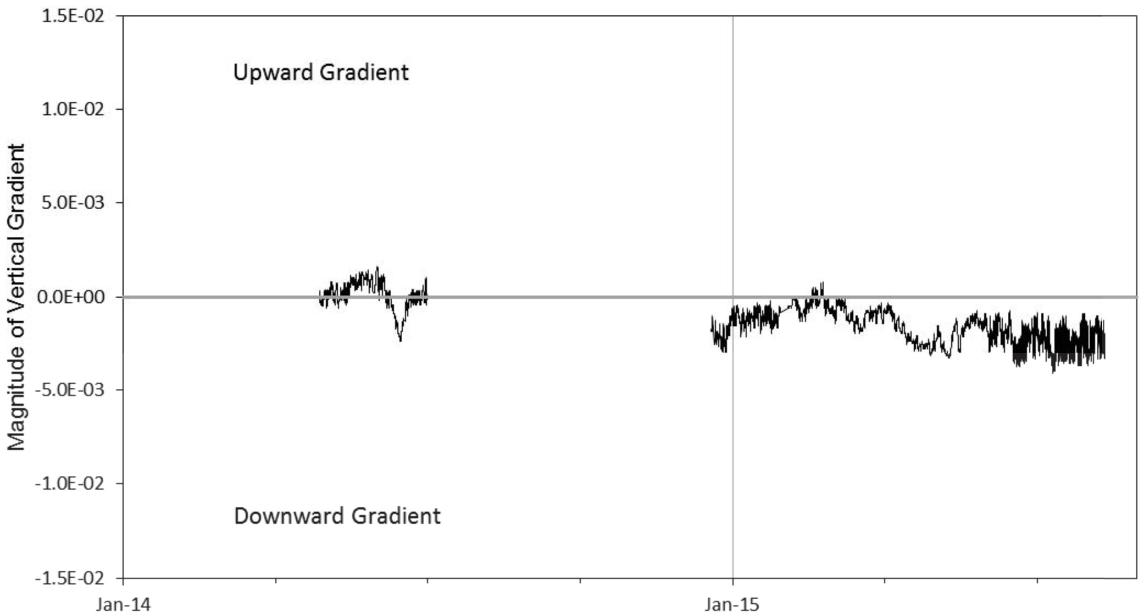




**Figure 9. Water Levels and Vertical Gradient for 199-B4-7 (Water Table) and 199-B5-18 (Bottom of Unconfined Aquifer)**

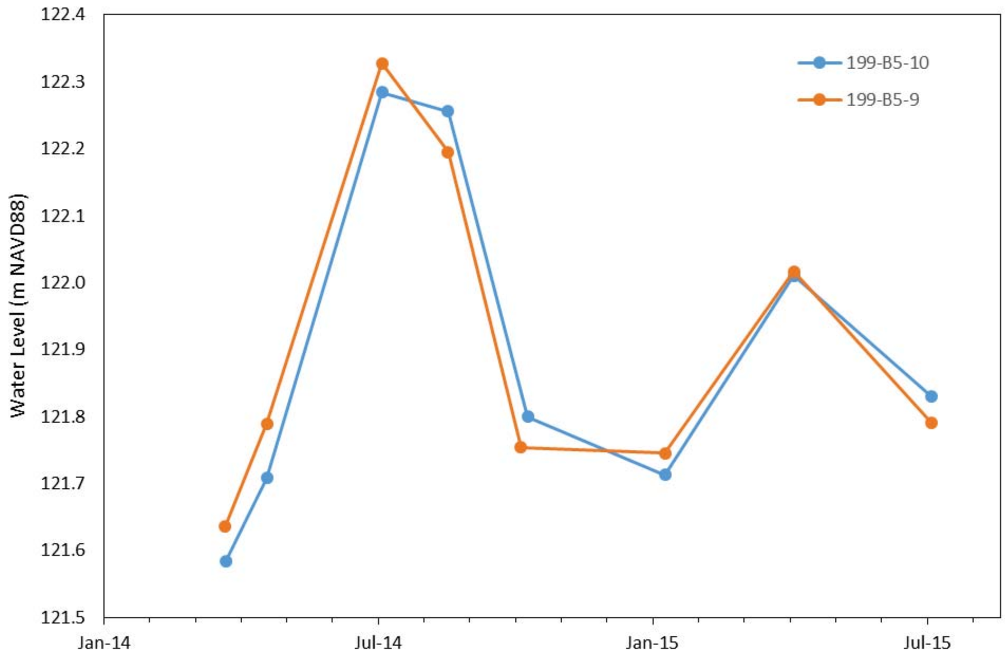



**Figure 10. Manually Measured Water Levels in 199-B5-10 (Water Table) and 199-B5-9 (Bottom of Unconfined Aquifer)**

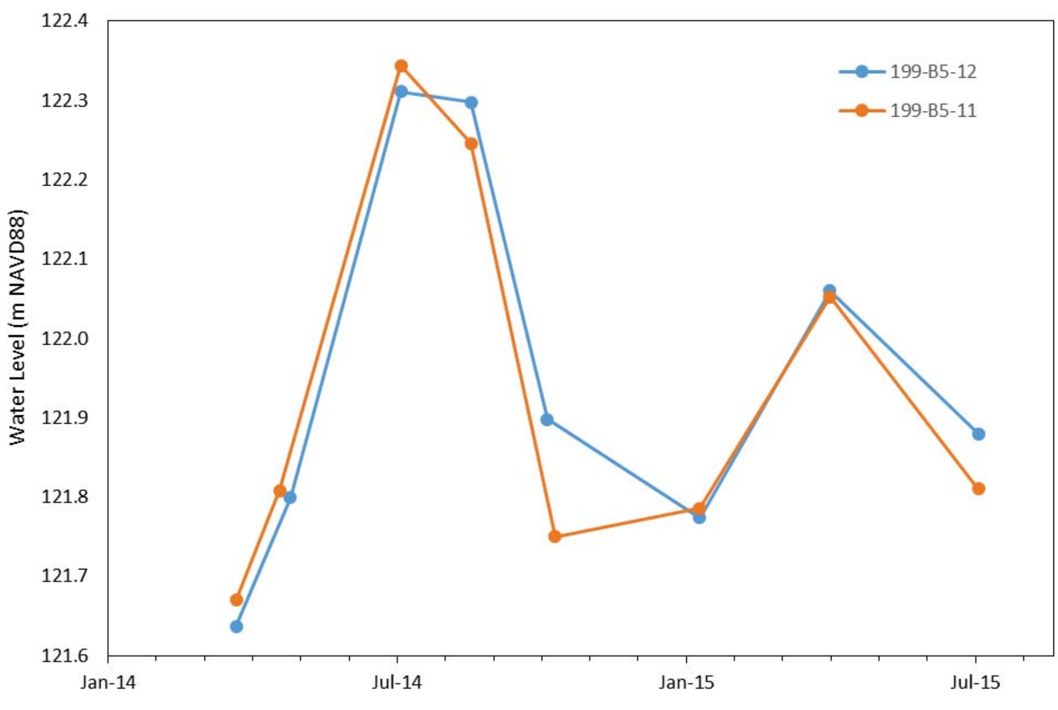



**Figure 11 Manually Measured Water Levels in 199-B5-12 (Water Table) and 199-B5-11 (Bottom of Unconfined Aquifer)**

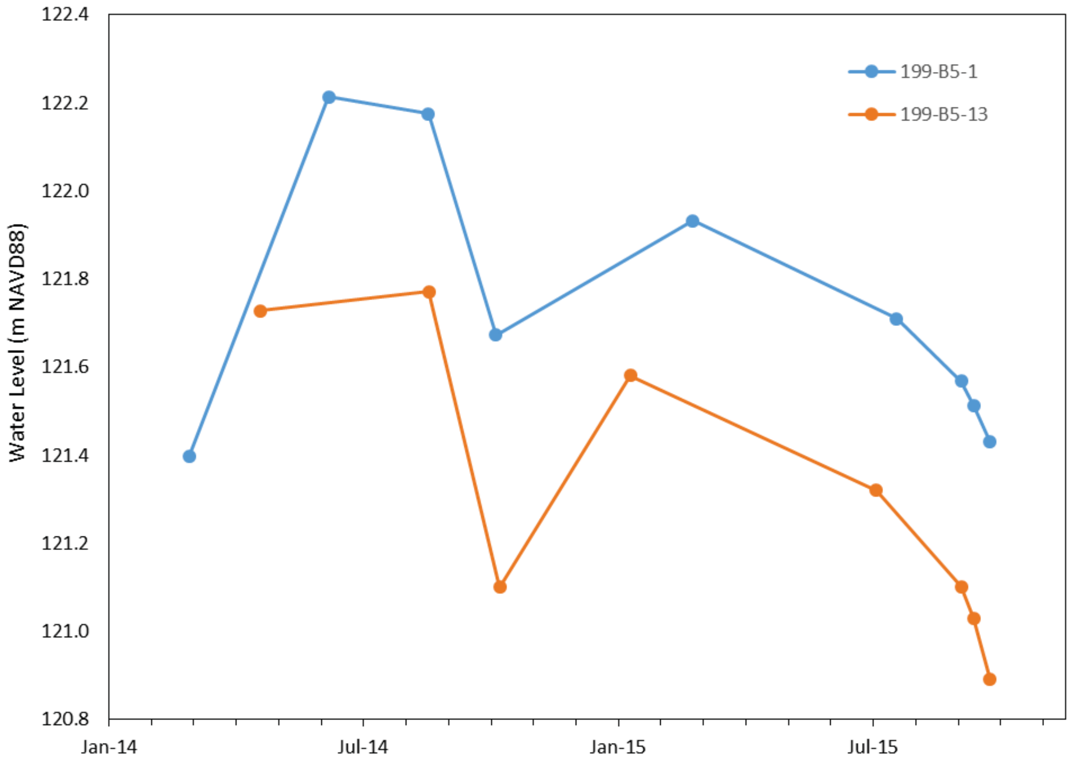



**Figure 12. Manually Measured Water Levels in 199-B5-1 (Water Table) and 199-B5-13 (Bottom of Unconfined Aquifer)**