APPENDIX 3E
Hydrogeologic Data Interpretation

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APPENDIX 3E
HYDROGEOLOGIC DATA INTERPRETATION

This appendix provides additional detail on Area of Investigation (AOI) hydrogeology and is intended to compliment Section 3.2.5 (Hydrogeology) of the remedial investigation (RI) report, focusing on hydrogeologic processes that influence the distribution, fate and transport of contaminants. Hydrogeologic information is presented as follows:

- Section 1.0 of this appendix summarizes hydrogeologic investigations in the AOI;
- Section 2.0 presents hydrostratigraphy and groundwater movement within the hydrostratigraphic units;
- Section 3.0 discusses groundwater levels including the influence of lake level and precipitation on water levels;
- Section 4.0 discusses horizontal and vertical groundwater gradients;
- Section 5.0 summarizes the results of hydraulic conductivity testing;
- Section 6.0 summarizes the water balance calculation, additional details of which are presented in Appendix 3F; and
- Section 7.0 summarizes the current understanding of groundwater flow.

1.0 HYDROGEOLOGIC INVESTIGATIONS

Environmental assessments related to the upland portion of the AOI began in the early 1970s during planning and development of Gas Works Park. Investigations from this time through the mid-1980s included the installation and sampling of monitoring wells. Hydrogeologic investigations including aquifer testing and evaluation of groundwater flow (e.g., modeling) were performed in the late 1980s by Tetra Tech (1987a, 1987b) and HDR (1988, 1989) in support of the City of Seattle's (City's)management of upland contamination. The next phase of hydrogeologic investigation was performed under the 1997 Agreed Order (Ecology 1997) by the City of Seattle and Puget Sound Energy (PSE) to identify remedial alternatives for the focused feasibility study (FFS). Work included evaluation of the fate and transport of polycyclic aromatic hydrocarbons (PAHs) and benzene culminating in the selection of monitored natural attenuation and air sparging/soil vapor extraction in the Cleanup Action Plan (CAP) for the AOI upland.

Additional hydrogeologic investigations were performed under Agreed Order DE 2008 (Ecology 2005) between Ecology, PSE, and the City, as amended (Ecology 2013). In 2010, GeoEngineers and Aspect Consulting (GeoEngineers 2010) installed six wells in the park and collected additional hydrogeologic data in support of developing a site-wide, three-dimensional (3D) numerical groundwater flow model. It was this study that resulted in a reinterpretation of the geologic and hydrogeologic conceptual site model (CSM), as discussed in Section 3 of the RI. Additional hydrogeological field investigations were conducted during the 2013 Supplemental Investigation (SI) to supplement previous hydrogeologic investigations in the AOI upland. The 2013 field activities included the installation of shallow and deep well pairs in key areas along the shoreline, slug testing of select new shallow- and deep-screened wells, and groundwater monitoring of more than 60 wells (including wells monitored by others at the Metro site) during two groundwater monitoring events (one in April [68 wells] and one in October 2013 [69 wells]. An additional seventeen shallow and deep monitoring wells were installed in 2017 within and around the Play Area. Groundwater elevation data are compiled in Appendix 3J and groundwater elevations for April 2016 and September 2017 are shown on Figures 3E-1 and 3E-2. Table 3J-1 of Appendix 3J is a comprehensive presentation of available well construction information for the AOI. Additional information related to previous hydrogeologic investigations in the AOI is presented in Appendices 2A and 2D.

2.0 HYDROSTRATIGRAPHY

Four major hydrostratigraphic units have been identified in the AOI. A hydrostratigraphic unit consists of one or more geologic units grouped by location and similar hydraulic (i.e., groundwater flow) properties. Hydrostratigraphic units have been defined using data generated during hydrogeologic investigations.

The AOI hydrostratigraphic units are presented in the Revised Hydrogeology CSM (GWSA Technical Team 2011a), which was in turn based on findings presented in the Revised Geology CSM (Appendix 3B, Attachment 3B-1). These units were used for the creation of the 2012 groundwater flow model for the AOI (Aspect Consulting, et al. 2012) and the 2018 revised groundwater flow model for the AOI (Appendix 3F). The four hydrostratigraphic units in the AOI are described below, from youngest to oldest.

2.1. Fill

Fill is one of the units in the AOI upland in which the water table occurs. Fill is generally thin and unsaturated in the northern portion of the upland and becomes thicker and water-bearing in the central and shoreline areas. The fill is heterogeneous, and boring logs reveal occasional perching of shallow groundwater in some areas of the upland (e.g., MW-09). The 2017 Play Area investigation and well installation found further evidence of perching in the fill (e.g., wells MW-41S and MW-42S, Figure 3E-2). The fill, which extends across most of the upland and offshore, is the primary geologic unit present in the upland in direct contact with Lake Union.

2.2. Lake Sediment (includes Ql and Qvrl)

Recent lacustrine deposits (Ql) are present in most of the sediment portion of the AOI; they are absent in Lakeshore and upper Lake Slope zones (Appendix 3B, Figure 3B-2)[1]. Vashon recessional glaciolacustrine deposits (Qvrl) are present off the western shore of the upland and in small pockets in the upland. The lake sediment hydrostratigraphic unit is saturated and extends to an unknown depth. Some component of deep groundwater moving within the till beneath the upland is assumed to discharge into the lake sediment offshore (Appendix 3F).

2.3. Glacial Outwash Deposits

Glacial outwash deposits generally make up a large portion of the upper water-bearing zone (i.e., above the till) in the western, southwestern, and eastern portions of the upland. Outwash deposits are absent in the northern and the southeast portion of the AOI upland (beneath and east of the Cracking Towers) along the crest of the till ridge. The majority of outwash deposits occur at an elevation lower than Lake Union water level (i.e., below 20 feet U.S. Army Corps of Engineers [USACE] datum). Two different glacial outwash units (Vashon recessional outwash [Qvr] and Vashon advance outwash [Qva]), and one recent beach and shallow shelf deposits unit (Qb) present in the AOI (as described on Table 3B-1 of Appendix 3B) were considered similar enough in occurrence and hydraulic properties to be classified a single hydrostratigraphic unit (collectively lumped as glacial outwash deposits).

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[1] Recent deposits exist in the Lakeshore and upper Lake Slope zones in a dredged area off the southwest corner of the prow.

2.4. Glacial Till

The till is the dominant hydrostratigraphic unit in that it limits recharge to the water-bearing zone from upslope and controls vertical and horizontal groundwater flow in the AOI upland (directly where the water table is within the till and indirectly where the water table is above the till). Recharge from precipitation percolates through the fill where impermeable surfaces are absent and either discharges through the fill along the shoreline or flows predominantly near the top of the till and into outwash deposits draped along the flanks of the till core. From these outwash deposits, groundwater eventually discharges to Lake Union relatively close to the shoreline.

3.0 WATER LEVELS

Most monitoring wells are installed in shoreline areas to monitor potential contaminant migration from the upland toward sediment and Lake Union. Groundwater levels in the upland away from the shoreline are primarily controlled by recharge from precipitation. Groundwater levels near the shoreline are less influenced by precipitation; the surface water levels in Lake Union are the primary factor controlling groundwater levels near the shoreline.

Review of available water level data indicates that groundwater levels near the shoreline are generally constrained within or slightly above the controlled range for Lake Union (20- to 22-foot USACE average)[2], and water levels in most shoreline wells have been observed to mimic the level of Lake Union. A composite hydrograph (Figure 3E-3) shows water levels for two shoreline wells (TSW-2 and TDW-2) plotted with Lake Union elevation for the year between May 2010 and April 2011. During this period, it is evident that water levels in these two wells located near the shoreline (TSW-2 and TDW-2; located within 35 feet of Lake Union) followed the same general pattern as the lake; they appear to be closely tied to the level of Lake Union, thus indicating the lake controls shoreline well water levels.

Well MW-03, located in the northern portion of the upland away from the lake, appears to respond primarily to precipitation (Figure 3E-4) and not to changes in lake level, thus indicating that precipitation is likely the primary factor influencing water levels in the upland. High-resolution transducer data collected in upland monitoring well MW-27 between October 16 and November 5, 2010, appear to support these observations; water levels at MW-27 responded to two >1-inch precipitation events, while water levels at MW-28 (near shoreline) did not show significant response to these same events (Aspect Consulting, et al. 2012). Water levels in deep monitoring well MW-03D do not appear to respond as readily to precipitation, likely because the well is screened deep within the till and the till inhibits vertical infiltration from precipitation. Other upland wells screened shallower in the till (MW-27, MW-29, MW-30) appear to respond to precipitation events. These relationships imply short-term precipitation events exhibit a greater degree of control on shallow groundwater flow in the upland than on deeper groundwater flow, and that deeper groundwater in MW-03D is likely representative of water entering the AOI as through-flow from the north.

Figures 3E-1 and 3E-2 present groundwater elevations and contours for April 2016 and September 2017, respectively, for a comparison of groundwater elevations and flow conditions during high water table conditions (i.e., spring) and low water table conditions (i.e., late summer or fall). Water levels in upland

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[2] Precipitation recharge to Lake Union from large rain events may result in lake levels above 22 feet USACE for short periods of time.

wells were 1 to 3 feet higher in April 2016 than in September 2017 due to recharge from increased precipitation and higher water table conditions typical of spring months. The exception to this trend is deep till well MW-03D, which as discussed above is not controlled by precipitation, where water levels were only 0.55 feet higher in April 2016 than September 2017.

In April 2016, groundwater elevations for both shallow and deep wells located along the shoreline were higher than the lake level elevation (0.39 to 0.88 feet higher; Figure 3E-1), which indicates a hydraulic gradient toward Lake Union. Shoreline groundwater levels in September 2017 varied relative to the lake level; groundwater elevations in the eastern and far western portions of the AOI upland were higher than the lake level during the September 2017 groundwater monitoring event (0.05 feet to 0.14 feet higher) (Figure 3E-2). However, groundwater levels in the central portion of the shoreline near the Prow and Kite Hill were slightly lower than lake level (between 0.14 feet to 0.09 feet lower), indicating the hydraulic gradient was inland at those locations. The presence of substantial fill associated with Kite Hill and the concrete wall along the Prow may be affecting shoreline water levels in these areas at times, as discussed below, and causing temporary inland hydraulic gradients near the shoreline.

4.0 GROUNDWATER GRADIENTS

Horizontal groundwater gradients are influenced by seasonal recharge to groundwater and variation in water levels. Groundwater levels in the upland (upgradient of the shoreline) are primarily controlled by precipitation, with high groundwater levels occurring in the wet seasons (winter and spring) and lower groundwater levels occurring in the drier seasons (summer and fall). This seasonal variation results in higher hydraulic gradients (steeper water table) in the upland during the wet seasons because of localized recharge, and lower hydraulic gradients in the drier seasons because of less recharge. Groundwater levels near the shoreline are primarily controlled by the level of Lake Union, which is in turn controlled by the Ballard Locks. Water levels and hydraulic gradients are discussed further below.

Groundwater flowing through the AOI upland results primarily from precipitation recharge within or close to the park boundaries (Appendix 3F). Recharge from precipitation is estimated to account for approximately 98 percent of groundwater entering the AOI upland, while lesser amounts (an estimated 2 percent of total flow) enters the AOI upland from lateral subsurface flow (through-flow) from the till unit north of Gas Works Park (see Figure 3E-5). In general, precipitation recharge is believed to percolate through the three relatively permeable near-surface units (i.e., fill, Qvr, Qva), with a lesser degree of infiltration into the lower-permeability till (Qpgt). Consequently, the direction and gradient of groundwater flow across the AOI upland is a strong function of the topography of the till, particularly in the northern part of the AOI upland where the till is close to the ground surface.

4.1. Horizontal Gradients

Horizontal groundwater gradients can be deduced from the groundwater elevation figures for April 2016 and September 2017 (Figures 3E-1 and 3E-2). Shallow-screened (water table) wells were used to create the contours, which represent the slope of the water table. Water levels from deeper (non-water table) wells are also shown, but deeper monitoring wells were not used in creation of the groundwater contours as indicated in the figures.

The following three variables control groundwater gradients, as explained below: depth of groundwater, proximity to the shoreline, and seasonality. Shallow groundwater gradients are steeper than deep groundwater gradients, with a greater change in the shallow water table elevation from upland areas to Lake level than that of deeper groundwater. In general, shallow groundwater gradients are higher in upland areas away from the shoreline and lower near the shoreline. Groundwater flow directions do not appear to vary significantly by season, as observed from the April 2016 and September 2017 contour maps. However, changing water table conditions do appear to affect the horizontal gradient in some areas, as discussed below.

The direction of horizontal flow in the western half of the AOI upland (generally between Harbor Patrol and the Cracking Towers) is to the southwest, with gradients decreasing from upland to lakeshore areas. Deep groundwater gradients (measured using non-water table wells MW-31 and TDW-1) in the upland portion of this area are steeper in September (0.018 feet per foot [feet/foot]) when lake levels are lower, and flatter in April (0.013 feet/foot) when lake levels are higher. Groundwater horizontal gradients near the lakeshore (between MW-19 and CMP-1) are flatter though still seasonally variable (0.0031 feet/foot in September vs. 0.0043 feet/foot in April).

Groundwater gradients in the area around Kite Hill are relatively flat and do not vary as significantly between April and October as those observed in upland wells. The relatively flat water table may be due to the greater transmissivity in this area due to the combination of historical shoreline filling with relatively coarse fill material and a thicker section of outwash.

In the eastern half of the AOI upland (generally between the Cracking Towers and the northeast corner), groundwater flow is eastward, with gradients decreasing toward the shoreline. Near-shoreline deep groundwater gradients in the northeastern corner (between deep wells MW-26 and MW-39D) are relatively stable, varying from 0.015 feet/foot in April to 0.012 feet/foot in September. Deep groundwater gradients west and south of the Play Barn, in the vicinity of MW-09 and the glacial till “trough,” were 0.019 feet/foot in April and 0.013 feet/foot in September when measured between wells MW-27 and MW-36D.

Shallow groundwater flowing along the MW-27 and MW-36D alignment is influenced by the till ridge to the south, which is located approximately 150 feet east of the Cracking Towers, and localized perching (e.g., wells MW-41S and MW-42S, Figure 3E-2). The till ridge forms a localized topographic high point that intersects the water table. The low permeability of the till effectively creates a hydrologic divide; recharge from precipitation on the till ridge is slower and water table is higher, thereby causing the majority of groundwater flowing from upslope to be diverted around the till ridge. As shown in Figures 3E-1 and 3E-2, most groundwater originating from the northeastern portion of the AOI upland flows east toward the Play Area or south toward the Cracking Towers, as indicated by the groundwater flow direction arrows on each figure. As a result of the presence of the till ridge in combination with the sea wall (Prow) to the south, less groundwater is expected to flow through the area including the Cracking Towers and the adjacent area to the east, with more groundwater discharging to the southwest and east.

4.2. Vertical Gradients

Well completion information and measured head elevations for 10 paired well sets, consisting of 128 individual head measurements, were evaluated to identify significant vertical hydraulic gradients that may exist. Most paired well sets are located near the shoreline and are completed within the two shallowest hydrostratigraphic units (i.e., fill, glacial outwash deposits). The only paired well set completed entirely in the till unit is well pair MW-03/MW-03D, which is also the only well pair not located at the shoreline.

Average vertical gradients are presented in Table 3E-1, with upward gradients represented by negative values and downward gradients represented by positive values. Vertical groundwater gradients can only be determined for well pairs, which are two monitoring wells situated side-by-side or in very close proximity with screens extending to different depths below ground. Head measurements for well pairs were used in this analysis only if both wells in a pair had been measured on the same date. Dates of head measurements range from 1986 to 2013, and the number of measurement events ranges from 2 (i.e., MW-39S/MW-39D) to 34 (i.e., MW-25/MW-23). Calculated vertical gradients for the 10 well pairs ranged from a maximum upward gradient of -0.0059 feet/foot at well pair MW-25/MW-23 to a maximum downward gradient of 0.17 feet/foot at well pair MW-03/MW-03D.

Several well pairs are shown to have significant vertical gradients both upward and downward. Those well pairs showing significant downward gradients may be located in areas where recharge is concentrated close to the well pair (e.g., low-lying areas that receive runoff from impermeable surfaces or areas that receive runoff from Kite Hill).

The largest vertical gradient measured (0.17 feet/foot in well pair MW-03/MW-03D) is more than 10 times the average wet season horizontal gradient (0.016 feet/foot). Both wells of this well pair are completed in the till unit. The relatively large downward gradient measured at well pair MW-03/MW-03D might indicate the presence of a significant recharge zone if the wells were screened in the same water-bearing zone. However, the hydraulic connection between these wells is limited due to the relatively low vertical hydraulic conductivity of the till resulting in low recharge rates from precipitation and a high degree of hydraulic separation between shallow and deeper portions of the till screened by the two wells.

In general, well pairs with upward gradients are not unexpected near the shoreline near where groundwater discharges upward into Lake Union. The upward vertical gradient (-0.0059 feet/foot) apparent at well pair MW-25/MW-23 may be related to the concrete seawall barrier (the Prow), which likely impedes horizontal water flow to Lake Union and results in upwelling water. Upward vertical gradients in this vicinity and south of Kite Hill may also be affected by historically placed fill materials, finer grained fill material at the mudline, or rise in the till surface near the shoreline (see Figure 3B-10 in Appendix 3B). Another possible cause of the upward vertical gradients observed in this area could be related to the presence of the Kite Hill Outfall drainage pipe (see Figure 3-21 of the RI), which may be locally affecting water levels in MW-32S.

5.0 HYDRAULIC CONDUCTIVITY TESTING

Hydraulic conductivity testing has yielded a range of hydraulic conductivity values for some of the upland geologic units. These values have been estimated through slug testing and three pumping tests performed at the Site. Pumping tests provide an estimate of hydraulic conditions applicable to a broader area than slug tests because a larger volume of the aquifer is tested and monitored during pumping; slug tests, on the other hand, are single-well tests that that provide a measurement of localized near-well aquifer conditions. Organized by hydrogeologic unit, results of hydraulic testing are discussed below[3]. Hydraulic conductivity values are presented in Table 3E-2.

3 Hydraulic testing not discussed includes older hydraulic testing performed at 13 wells by TetraTech in 1987 (Tetra Tech 1987a) and at three wells by HDR in 1988 (HDR 1988): these single-well “aquifer pump tests” were conducted using methodologies that are not clearly explained in the investigation reports. This section focuses on more recent (post-1990) hydraulic testing.

5.1. Fill

The geometric mean hydraulic conductivity for the fill unit determined by slug testing is 1.9E-02 centimeters per second (cm/sec) and 54 feet per day (feet/day), which is consistent with literature values for fine to coarse sand (Driscoll 1986). In 2007, slug testing was completed on wells screened in the fill (TSW-1, TSW-2 and TSW-3; Appendix 3J). The average hydraulic conductivity for the three wells was 3.3E-02 cm/sec. Average hydraulic conductivity derived from slug tests performed on wells MW-32S, MW-33S, MW-36S, and MW-39S for the 2013 SI was similar, at 2.0E-02 cm/sec (56 feet/day).

The field measured values suggest the fill unit has the highest hydraulic conductivity for all units in the AOI. However, all slug tests were performed at shoreline wells where the fill is coarser and not necessarily representative of site-wide conditions. Therefore, the mean hydraulic conductivity value calculated from slug tests within the fill unit may be biased. This is evident when comparing the field calculated hydraulic conductivity value to the calibrated results for the groundwater flow model presented in Appendix 3F, which calculated a lower hydraulic conductivity value for the fill unit of 8.11E-04 cm/sec (2.3 feet/day) (Table 3F-1). This suggests the fill may have a lower hydraulic conductivity away from the shoreline which is consistent with geologic observations that the fill is finer grained farther into the upland.

5.2. Lake Sediment

The hydraulic conductivity of the lake sediment hydrostratigraphic unit estimated for the 2016 groundwater flow model is 4.0E-04 cm/sec (1.1 feet/day), which is consistent with literature values for fine sand and silt (Driscoll 1986).

In 2018, GeoEngineers evaluated the hydraulic conductivity value used in the 2016 model using an empirical formula, the Kozeny-Carmen equation, which calculates a hydraulic conductivity value based on estimated void ratio and grain-size distribution for a particular soil. The Kozeny-Carmen equation has been used for reliable estimated of hydraulic conductivity for all soil types (Hussain and Nabi 2016). The hydraulic conductivity value calculated using the Kozeny-Carmen equation was 0.9 feet/day, which is generally consistent with the hydraulic conductivity value used for the groundwater flow model (Appendix 3F).

5.3. Glacial Outwash

The geometric mean hydraulic conductivity for the glacial outwash deposits is 2.0E-03 cm/sec (5.7 feet/day). This field-measured value is consistent with average literature values for fine sand and silt (Driscoll 1986).

A 50-hour pumping test was conducted on well RW-1 using piezometers PZ-2, PZ-9, and PZ-10 as observation wells (Appendix 2C, Attachment 2C-1). All of the wells used for the test are screened in the Qvr unit. A pumping rate of 0.25 gallon per minute (gpm) was maintained for the duration of the test. Multiple analytical methods were used to calculate the average hydraulic conductivity values, which ranged from 5.6E-04 to 3.5E-03 cm/sec (1.5 to 9.9 feet/day). The upper end of this range is close to the calibrated value for the groundwater flow model of 4.69E-03 cm/sec (13.3 feet/day) (Table 3F-1).

Slug testing was completed in several wells installed as part of the 2013 SI (see Appendix 2A). Slug testing was performed in the following wells screened within the glacial outwash: MW-32D (Qva), MW-36D (Qvr), and MW-39D (Qvr). Average hydraulic conductivity values derived from slug tests performed during the 2013 SI are on the lower end of the range of values determined from the pumping test at RW-1, with an average from all outwash-screened wells tested of 5.0E-04 cm/sec (1.4 feet/day). As discussed above, pumping tests are a better measure of aquifer conditions than slug tests and provide a more reliable estimate of aquifer hydraulic parameters.

5.4. Glacial Till

The till has the lowest hydraulic conductivity, with a geometric mean hydraulic conductivity value of 2.4E-04 cm/sec (0.69 feet/day). This field-measured value is consistent with upper-end literature values for glacial till (Driscoll 1986).

Two short-duration pumping tests were completed on wells MW-03D and MW-30 using MW-03, MW-10, and MW-29 as observation wells (Aspect Consulting 2012). All wells used for the test were screened in the pre-Fraser till (Qpgt) with the exception of MW-10, which was screened in the fill (Af). MW-03D, screened between -15.7 and -18.7 feet (USACE datum), was pumped at a rate of 0.1 gpm for 300 minutes, with 7.6 feet of total drawdown. No response to pumping was observed in paired well MW-03, which is screened between 37.1 and 28.1 feet (USACE). This lack of response occurred because either the duration of pumping was not adequate to measure hydraulic response between the wells or the wells are not in hydraulic continuity. From multiple analytical methods, the averaged hydraulic conductivity value calculated from MW-03D pumping test data was 5E-05 cm/sec (0.14 feet/day).

Well MW-30, screened between 19.9 and 9.9 feet (USACE) was pumped at a rate of 0.48 gpm for 327 minutes, with 1.9 feet of total drawdown. This well was screened more shallowly in the till and had a higher yield than MW-03D. Multiple analytical methods were used to calculate the hydraulic conductivity, which was 6E-04 cm/sec (1.7 feet/day).

Hydraulic conductivity values were about an order of magnitude lower in the well screened deeper (MW-03D). Slug tests conducted on wells MW-26 through MW-31, MW-03, and MW-03D, all of which are screened in pre-Fraser till, had average conductivity values between 1E-05 and 7E-04 cm/sec (0.028 and 1.98 feet/day), which generally corroborated the pumping test results. The results of these investigations are presented in Attachment 3E-1.

6.0 WATER BALANCE CALCULATION

As discussed previously, groundwater in the AOI upland is derived primarily from on-site and nearby surface precipitation recharge and subsequent percolation. A small component of groundwater entering the upland (i.e., 15 to 48 cubic feet [ft^3]/day) is estimated to result from subsurface horizontal flow from upland till deposits to the north underlying Wallingford Hill, as shown by groundwater flow model. Additional details regarding water balance are discussed in Appendix 3F.

Expected inflows/outflows have been estimated in prior studies:

- Tetra Tech (1987a, b) estimated inflows/outflows ranging from 11.6 to 14.5 gallons per minute (gal/min) (i.e., 2,230 to 2,790 ft^3/day).
- The U.S. Geological Service (Sabol et al. 1988) estimated the maximum theoretical recharge from precipitation to be 1,045,000 cubic feet per year (ft^3/yr) (i.e., 2,863 ft^3/day). This value was considered a maximum possible value because of its assumption of zero runoff.

- Parametrix and Key Environmental (1998) estimated that the "groundwater flow from the shallow groundwater system at the Park to Lake Union is 11.9 gal/min" (i.e., 2,290 ft^3/day).
- Aspect Consulting et al. (2012), as part of an overall numerical simulation of AOI groundwater flow, concluded that total groundwater discharge for May 2011 and January 2011 was 1,100 and 1,920 ft^3/day, respectively.

The total groundwater discharge is estimated to be to be between 2,085 and 2,118 ft^3/day based on the numerical simulation of groundwater flow (Appendix 3F).

7.0 CURRENT UNDERSTANDING OF GROUNDWATER FLOW

The hydrogeologic CSM for the AOI has evolved over time as more site-specific data have become available; the geologic sequences and associated geologic CSM have become better defined; and additional hydrogeologic studies have been undertaken. Prior to a substantial revision to the hydrogeologic CSM in spring 2011, it was assumed that "two laterally continuous, site-wide aquifers" existed in the AOI. The upper aquifer was considered to be a "shallow unconfined aquifer within the fill and Recessional Stratified Drift (RSD)." The lower aquifer was thought to exist within the "Advanced Stratified Drift (ASD)" and thought to be "confined below a layer of glacial till" (Sabol et al. 1988). In spring of 2011, the hydrogeologic CSM was substantially revised (GWSA Technical Team 2011a), based on additional well installations; the updated CSM noted the following:

> *"…the revised hydrogeologic CSM includes no aquifer units in the uplands or GWSA. Rather, the primary hydrostratigraphic unit across the uplands is low permeability till, with the only presence of higher permeability Glacial outwash deposits found draped along the eastern and western shorelines areas. Because the nearshore outwash deposits receive groundwater discharge from the till, the hydraulic parameters of the till unit primarily control the rate of groundwater flow across the uplands to the GWSA. Because the low permeability till unit is the primary control on upland groundwater flow, groundwater fluxes from the uplands to the GWSA are lower than assumed in the prior hydrogeologic CSM…"*

This interpretation of the hydrogeologic CSM was further refined during calibration of groundwater flow models. The initial model was completed in spring of 2012 (Aspect Consulting et al. 2012). The groundwater flow model was subsequently reconstructed to incorporate supplemental investigation results. Key results from modeling studies include the following:

- Till is the dominant hydrostratigraphic unit and is the only unit contributing upgradient groundwater into the Gas Works Park Site (GWPS), which eventually exits the till and discharges radially to one of the overlying units.
- Upland recharge derived from precipitation and perhaps irrigation is the dominant source of groundwater, contributing about 98 percent of total groundwater flow.
- Upland groundwater originates primarily from upland recharge and, to a much lesser degree, through-flow from Wallingford Hill. Groundwater flows downward within the till from recharge areas, flows laterally toward the shoreline, and finally upward to the mudline and discharges to Lake Union.

The most recent modeling effort in 2018 by GeoEngineers incorporated the results of supplemental investigations conducted in 2013, 2014, and 2016 to reflect the updated geologic and hydrogeologic CSM and refined the understanding of the groundwater flow system. In particular, the model refined the understanding of groundwater discharge (volumetric flow rate also called flux) at the shoreline and into Lake Union. Additional detail on groundwater discharge at the shoreline and mudline, including variations in the magnitude of groundwater discharge along the shoreline and with distance from the shoreline and shoreline location, is presented in Appendix 3F.

The current understanding of the groundwater flow system is that the primary source of groundwater is derived from precipitation in upland areas, and the flow of groundwater is controlled in large part by the low-permeability glacial till unit. Based on the 2018 groundwater model, more than 98 percent of groundwater discharging to Lake Union originates as recharge at the park, while approximately 2 percent of discharge originates as regional through-flow (Figure 3E-5).

Subsequent to recharge, upland groundwater flow is primarily subhorizontal through fill and outwash deposits with a small amount flowing into the till. Most of the groundwater in the fill and outwash flows along the top of the till downslope to the shoreline—due to low conductivity (*K*) values in the till, ultimately discharging directly to Lake Union. The estimated shoreline groundwater discharge calculated by the 2018 model, presented as volumetric flow rate (discharge per unit area), is depicted in Appendix 3F, Figure 3F-16. Calculated groundwater volumetric flow rate at the shoreline is generally less than 0.005 feet/day through the till, while the volumetric flow rate through the fill ranges from about 0.005 to 0.1 feet/day and from about 0.02 to greater than 0.1 feet/day through the outwash (Figure 3F-16).

As groundwater approaches Lake Union through these units, flow changes from sub-horizontal and downward to upward prior to discharge to the lake at the mudline (Figures 3F-14 and 3F-15). The majority of groundwater discharge to Lake Union occurs relatively close to the shoreline, predominantly through the fill unit (Appendix 3F). Based on the 2018 model, near-shore discharge (depicted as red to dark blue areas in Figure 3F-17) accounts for 92 percent of total mudline discharge to the Lake while discharge in areas further from shore (Figure 3F-17, unshaded areas) accounts for only 2 percent of the total discharge at the mudline. The near-shore discharge area, defined as the "groundwater discharge zone," encompasses the area where groundwater flowing through the fill and the outwash at the shoreline discharges. Groundwater movement is slow, even in the higher discharge areas. Groundwater velocity was calculated at about 2 inches per day for high flux areas (Figure 3F-17, red shaded areas) whereas it would take more than a year to travel 1 inch in areas farther from shore (Figure 3F-17, unshaded areas)[4].

[4] Calculations assume a discharge of 0.05 feet/day and an effective porosity of 30 percent (corresponding to the fill) in nearshore higher discharge areas and a discharge of 0.0001 foot/day and an effective porosity of 45 percent (corresponding the recent deposit) in lower discharge areas farther offshore. The effective porosity value of 30 percent for the fill is considered a conservative estimate based on the range of laboratory measured total porosity values for the fill of 34 to 69 percent (see Appendix 5F). The effective porosity value of 45 percent is half the estimated total porosity of 90 percent for the recent deposits (see Appendix 3F).

8.0 REFERENCES

Aspect Consulting, LLC, GeoEngineers Inc., Anchor QEA LLC, and Floyd|Snider. 2012. Groundwater Flow Model Memorandum, Draft Groundwater Flow Model Construction and Calibration, Gas Works Sediment Area, Seattle, Washington.

Driscoll, Fletcher G. 1986. Groundwater and Wells. Johnson Division, St. Paul, Minnesota.

Electric Power Research Institute (EPRI) and Puget Sound Energy (PSE). 1998. Fate and Transport Assessment of Polycyclic Aromatic Hydrocarbons from Tar. Gas Works Park MGP Site.

GWSA Technical Team. 2011. Preliminary Revised Hydrogeologic Conceptual Site Model. April 18.

HDR. 1988. Focused Field Investigation and Irrigation Feasibility Study, Gas Works Park, Seattle, Washington.

HDR. 1989. Groundwater Contaminant Migration Control System Conceptual Dosing Report, Gas Works Park. June 1989.

Hussain, F. and G. Nabi. 2016. Empirical Formulae Evaluation for Hydraulic Conductivity Determination Based on Grain Size Analysis. Center of Excellence in Water Resources Engineering, UET, Lahore, Pakistan. February 22.

McWhorter, David B, and Daniel K Sunada. 1977. Ground-water Hydrology and Hydraulics.

Parametrix, Inc., and Key Environmental. 1998. Draft Gas Works Park Environmental Cleanup, Focused Feasibility Study Report Volumes 1 and 2.

Sabol, MA, GL Turney, and GN Ryals. 1988. Evaluation of Available Data on the Geohydrology, Soil Chemistry, and Ground-Water Chemistry of Gas Works Park and Surrounding Region, Seattle, Washington. Prepared in cooperation with the WA Department of Ecology.

Tetra Tech. 1987a. Gas Works Park Groundwater Investigation and Site Evaluation.

Tetra Tech. 1987b. Supplemental Data Report, Gas Works Park, Groundwater Investigation and Site Evaluation.

Washington Department of Ecology. 2005. Agreed Order DE 2008—Gas Works Park Sediment Site issued to the City of Seattle and Puget Sound Energy. State of Washington Superior Court.

Washington Department of Ecology. 2013. Approval of Request to Amend Agreed Order DE 2008--Gas Works Park Sediment Site.

Table 3E-1

Average Vertical Hydraulic Gradients for Select Monitoring Wells

Gas Works Park Site
Seattle, Washington

Well Pairs (Shallow/Deep)	Total Number of Data Points	Vertical Gradient (ft/ft)	Screened Hydrogeologic Unit for Well Pair (Shallow/Deep)
MW-24/MW-22	16	-0.0013	Qvr/Qva
MW-25/MW-23	34	-0.0059	Qvr/Qpgt
MW-32S/MW-32D	3	-0.012	Fill/Qva
MW-36S/MW-36D	3	0.0039	Fill/Qvr
MW-39S/MW-39D	2	-0.00049	Fill/Qva-Qpgt
MW-03/MW-03D	13	0.17	Qpgt/Qpgt
PZ-8/DW-5	33	0.0076	Qvr/Qva
TSW-1/TDW-1	14	0.0063	Fill/Qva
TSW-2/TDW-2	14	0.0017	Fill/Qva
TSW-3/TDW-3	14	-0.0084	Fill/Qva

Notes:

ft/ft = feet per foot

Qpgt = Pre-Fraser glacial till

Qva = Advance outwash

Qvr = Recessional outwash

Negative values indicate upward vertical gradient, positive values indicate downward vertical gradient.

Vertical gradient calculated at well screen mid-point for water levels measured between 1998 and 2013. For water table wells, only the submerged screen length was used for calculation.

Table 3E-2

Estimated Hydraulic Conductivity by Hydrostratigraphic Unit for Selected Monitoring Wells

Gas Works Park Site
Seattle, Washington

Well	Hydraulic Conductivity (K, cm/sec)	Hydraulic Conductivity (K, ft/day)	Well Screened Interval at Time of Installation (ft bgs)	Well Screened Interval (USACE elevation in feet)	Screened Hydrogeologic Unit [a]	Screened Interval Soil Type
Wells Screened in Till and Till-like Deposits [f]						
MW-03 [b]	2.00E-04	5.67E-01	1.6 - 10.6	37.1 - 28.1	Qpgt	SP-GP
MW-3D [b]	9.00E-05	2.60E-01	54.6 - 57.6	-15.7 - 18.7	Qpgt	SP-SM
MW-3D [d]	6.00E-04	1.70E+00	54.6 - 57.6	-15.7 - 18.7	Qpgt	SP-SM
MW-26 [b]	1.27E-04	3.60E-01	9 - 12.6	23.9 - 20.3	Qpgt	SM
MW-27 [b]	3.33E-04	8.50E-01	12 - 15	23.4 - 20.4	Qpgd	SM/ML
MW-28 [b]	4.67E-04	1.32E+00	17 - 27	20.6 - 10.6	Qpgt	SM/ML
MW-29 [b]	5.67E-04	1.61E+00	13 - 23	18.5 - 8.5	Qvr/**Qpgt**	SP/SM
MW-30 [b]	6.67E-04	1.89E+00	12 - 22	19.9 - 9.9	Qvr/**Qpgt**	SP-GW/SM
MW-30 [c]	6.00E-04	1.70E+00	12 - 22	19.9 - 9.9	Qvr/**Qpgt**	SP-GW/SM
MW-31 [b]	1.50E-05	4.25E-02	35 - 45.5	6.3 - 4.2	Qpgt	SM
Geometric Mean	**2.43E-04**	**6.84E-01**	--	--	--	--
Wells Screened in Glacial Outwash Deposits [f]						
MW-32D/GEO-1 [c]	7.00E-04	2.09E+00	42 - 46.8	-12.1 - 17.1	**Qva**/Qpgt	SP-SM/SM
MW-36D [c]	9.35E-05	2.65E-01	29.3 - 33.8	0.7 - 3.8	**Qvr**/Qpgt	SM
MW-39D [c]	7.00E-04	1.98E+00	17.1 - 21.8	10 - 5.2	Qva/Qpgt	SP-SM/SM
RW-1 [d]	2.00E-03	5.67E+00	12.5 - 22.5	24.4 - 14.4	**Qvr**/Qpgt	SP/SP-SM/SM
TDW-2 [e]	2.00E-02	5.67E+01	34.5 - 39.5	-9.7 - -14.7	**Qva**/Qpgt	SP-GP/SM
TDW-3 [e]	2.00E-02	5.67E+01	34.5 - 39.5	-7.4 - 12.4	Qvr/**Qva**/Qpgt	SP/SM/SM
TDW-1 [e]	4.00E-03	1.13E+01	37.5 - 42.5	-12.6 -17.6	Qva/Qpgt	SP/SM
Geometric Mean	**2.04E-03**	**5.82E+00**	--	--	--	--
Wells Screened in Fill [f]						
MW-32S [d]	7.15E-03	2.03E+01	16.5 - 31	13.3 - 1.2	Fill	SP/Wood/GP
MW-33S(b) [c]	1.40E-02	3.97E+01	13.1 - 22	25.7 - 16.7	**Fill**/Qvr	SP/SM/SP
MW-36S [c]	1.82E-02	5.16E+01	8 - 22.8	22.1 - 7.3	Fill	GP-SP
MW-39S [c]	2.90E-02	8.22E+01	3.9 - 14	23 - 12.8	**Fill**/Qva	SP-SM/SP
TSW-1 [e]	6.00E-02	1.70E+02	5.3 - 10.3	20.5 - 15.5	Fill	SP
TSW-2 [e]	1.00E-02	2.83E+01	7 - 12	20.5 - 15.5	Fill	SP
TSW-3 [e]	3.00E-02	8.50E+01	6 - 11	21.5 - 16.5	Fill	SP-SM
Geometric Mean	**1.92E-02**	**5.43E+01**	--	--	--	

Notes:

[a] Geologic unit(s) exposed to well screen. Where well screens span multiple geologic units, the unit with largest exposure to well screen is bolded. Where multiple units have equal exposure to well screen, none are bolded.

[b] Value presented in Aspect Consulting et al. 2012 *Hydrogeologic Testing Report, Gas Works Sediment Area (GWSA),* January 31, 2012. Hydraulic conductivity values determined by slug test.

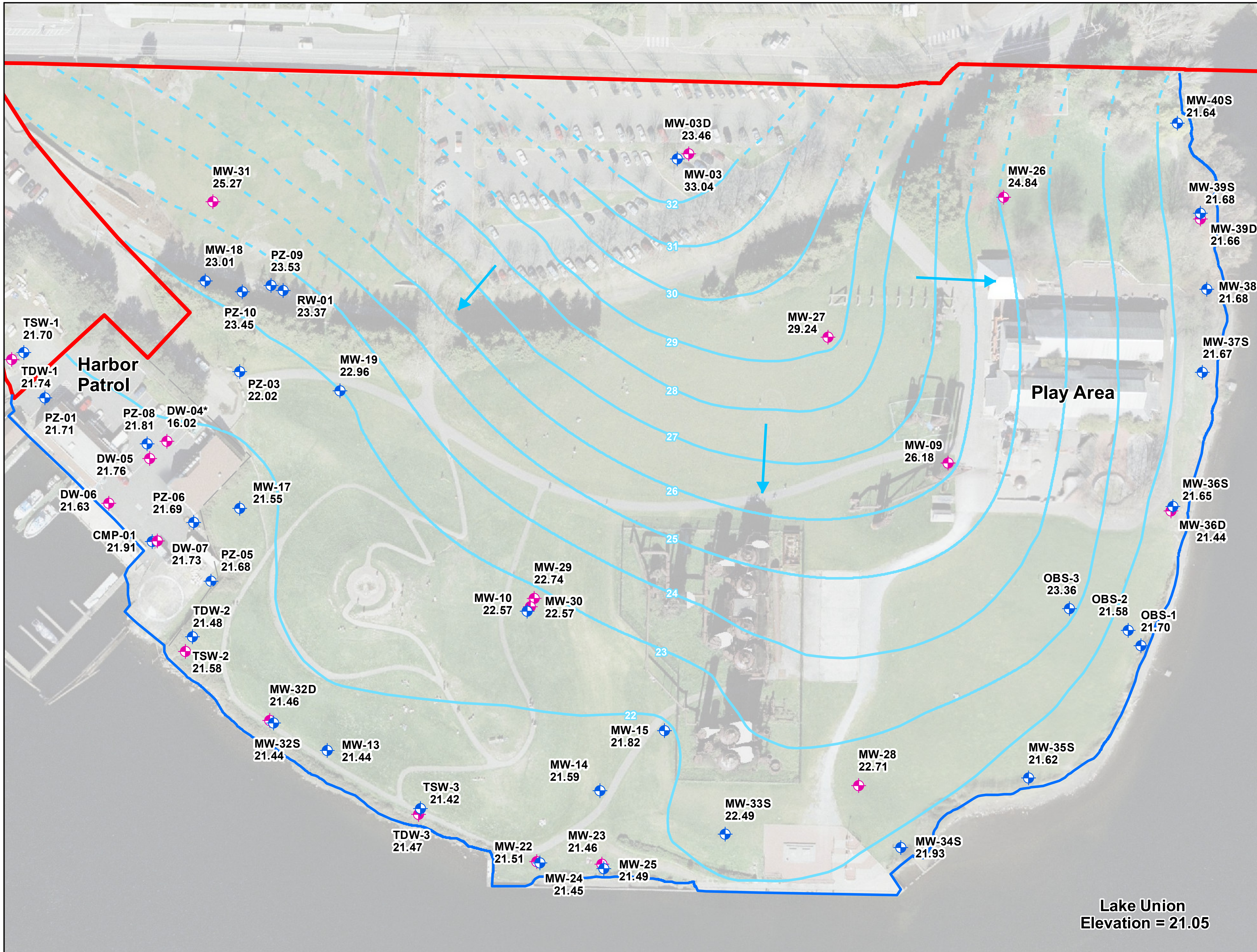
[c] Value determined during GeoEngineers 2013 Supplemental Investigation. Hydraulic conductivity was estimated by slug test using the Bouwer and Rice (1976) method or the Butler and Garnett (2000) method. Falling head data were not analyzed in wells MW-33S and MW-39S because the water table occurred within the screened interval.

[d] Value is an estimate from 50-hour pumping test by RETEC (RI Appendix 2C, Attachment 2C-1).

[e] Value determined by slug testing in WSA Shoreline Investigation Data Report (RI Appendix 2C).

[f] Hydrostratigraphic units presented in this table are based on hydrostratigraphic unit groupings presented in RI Section 3.2.5.1.

cm/sec = centimeters per second
Qpgt = Pre-Fraser Glacial Till
Qpgd = Pre-Fraser Diamict
Qvr = Vashon Recessional Outwash
Qva = Vashon Advance Outwash
GP = poorly-graded gravel
ML = silt
SM = silty sand
SP = poorly-graded sand
See text for full acronym list.
Bold type indicates the unit with largest exposure to well screen, in situations where well screen spans multiple geologic units.



Path: P:\0\0186846\GIS\MXD\Phase01\T1635\018684601_F3-15_GWContoursApril_2016R.mxd Map Revised: 11 November 2021 alarson

Legend

- Area of Investigation
- Shoreline (OHWM)
- Water Table Monitoring Well
- Deeper Monitoring Well (Not Used for Contouring)
- 22 Approximated Groundwater Elevation Contour (USACE) (Dashed Where Inferred)
- Inferred Groundwater Flow Direction
- MW-40S 21.05 Monitoring Well Identifier Measured Water Level Elevation (USACE)

Notes:

1. Groundwater elevations measured on 4/14/2016, except TSW-2, MW-34S and CMP-01 measured on 5/13/2016.
2. Lake Union elevation taken from Lake Washington Ship Canal at Locks, 08:00 a.m.on 5/13/2016. http://www.nwd-wc.usace.army.mil/dd/common/dataquery/www/?k=lake%20washington
3. Monitoring wells TSW-1, TDW-1, DW-05, DW-07, MW-18 and MW-09 contained NAPL; groundwater elevations have been corrected for LNAPL density if detected beyond trace.
4. *DW-04 well screen may be fouled by product; measurements not representative of groundwater conditions, excluded from contouring.
5. MW-09, MW-27 and MW-26 deeper monitoring wells used for contouring.
6. Basemap 2005 USGS aerial photograph. Does not show current conditions.
7. Projection: NAD 1983 StatePlane Washington North FIPS 4601 Feet

DISCLAIMER: This drawing is for information purposes. It is intended to assist in showing features discussed in an attached document. The locations of all features are approximate. GeoEngineers, Inc. cannot guarantee the accuracy and content of electronic files. The master file is stored by GeoEngineers, Inc. and will serve as the official record of this communication.

N W E S

100 0 100

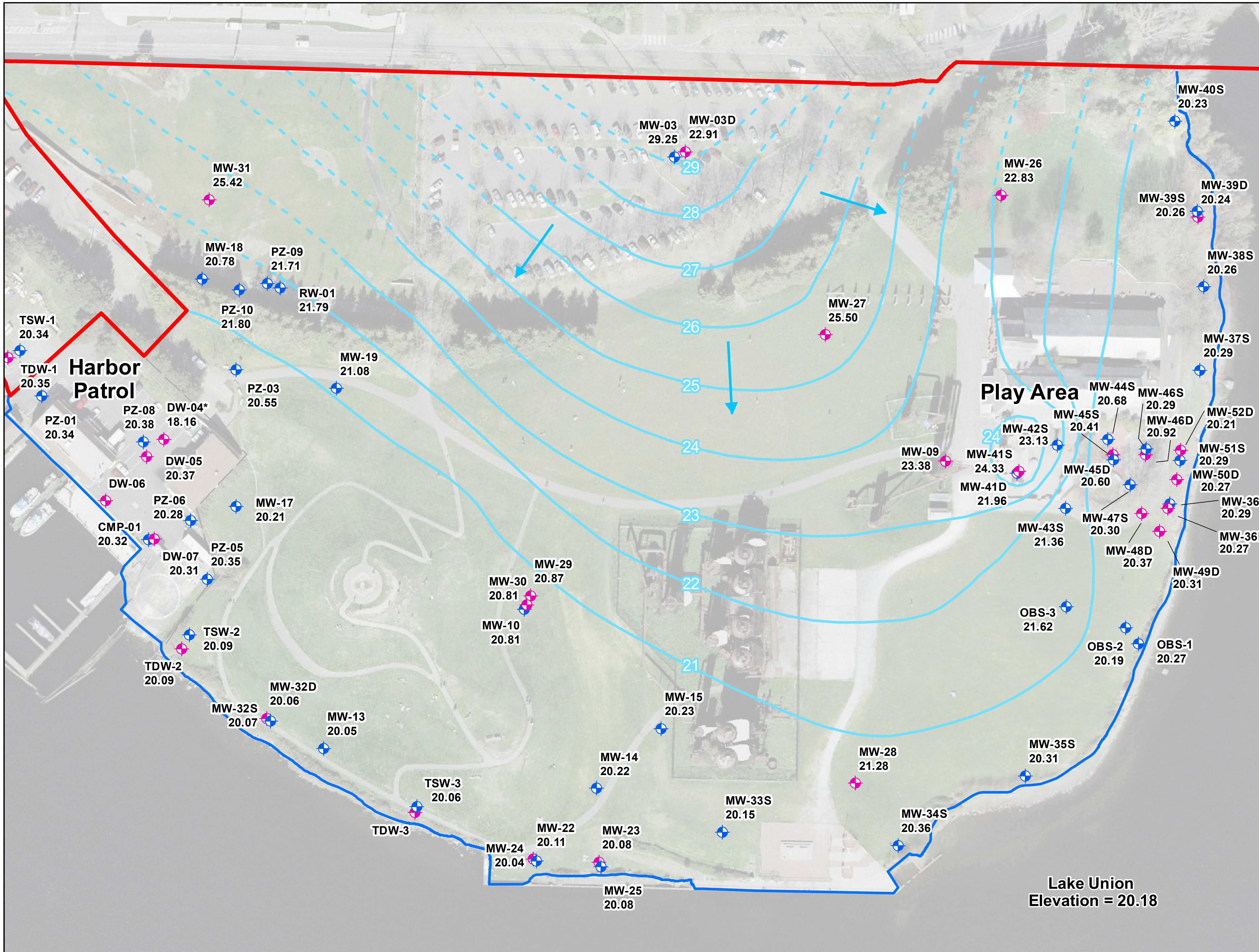
Feet

Groundwater Elevations and Water Table Contours (April 14, 2016)

Gas Works Park Site
Seattle, Washington

GeoEngineers

Figure 3E-1



Legend

- Area of Investigation
- Shoreline (OHWM)
- Water Table Monitoring Well
- Deeper Monitoring Well (Not Used for Contouring)
- 21 Approximated Groundwater Elevation Contour (USACE) (Dashed Where Inferred)
- Inferred Groundwater Flow Direction
- MW-40S 20.35 — Monitoring Well Identifier, Measured Water Level Elevation (USACE)

Notes:
1. Groundwater elevations measured on 9/18/2017.
2. Lake Union elevation taken from Lake Washington Ship Canal at Locks, 08:00 a.m. on 9/18/2017. http://www.nwd-wc.usace.army.mil/dd/common/dataquery/www/?k=lake%20washington
3. Monitoring wells MW-09, MW-44S, and MW-45S contained greater than a trace of LNAPL and groundwater elevations corrected for LNAPL.
4. *DW-04 well screen may be fouled by product; measurements not representative of groundwater conditions, excluded from contouring.
5. Basemap 2005 USGS aerial photograph. Does not show current conditions.
6. Projection: NAD 1983 StatePlane Washington North FIPS 4601 Feet

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N W E S

100 0 100
Feet

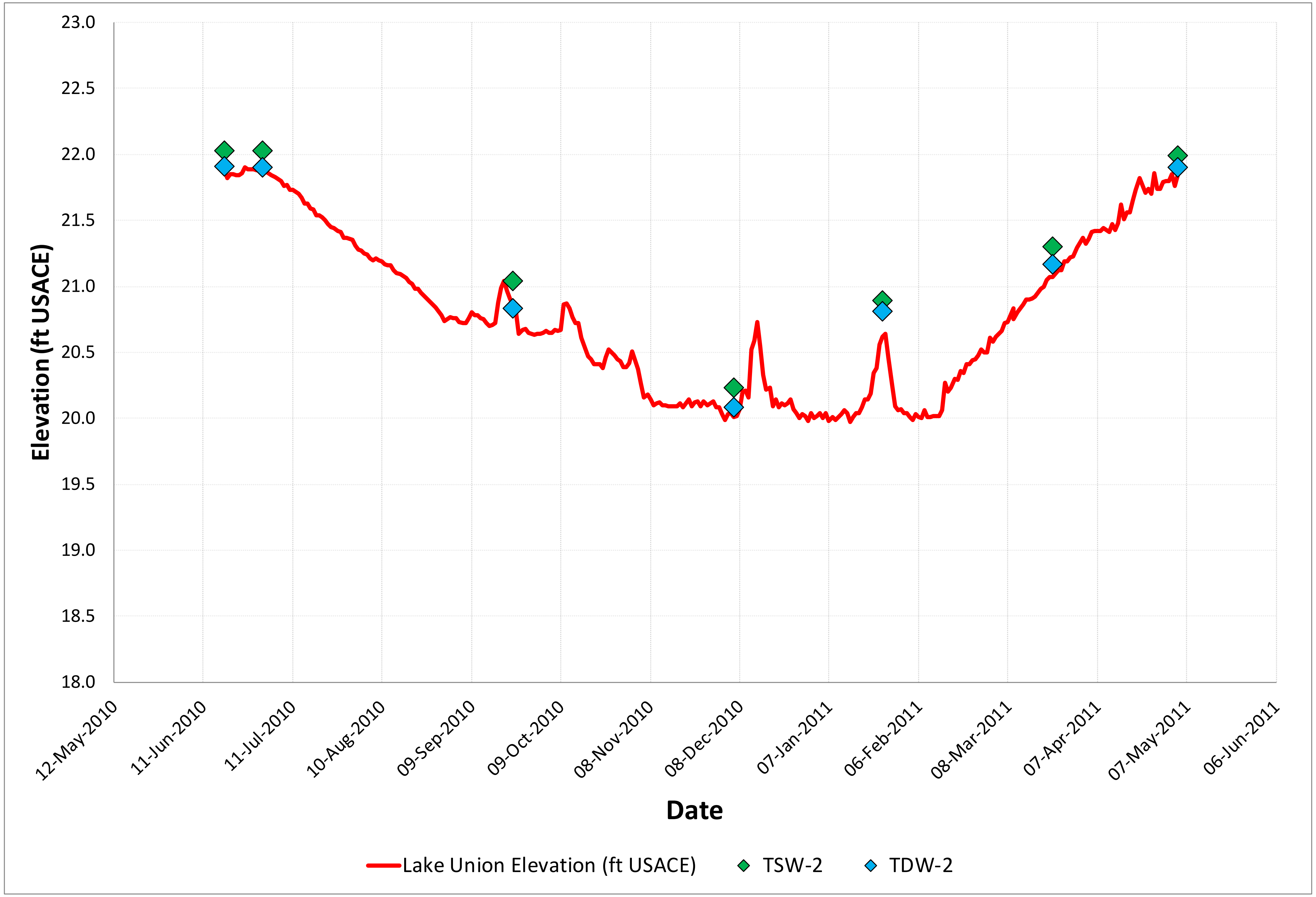
Groundwater Elevations and Water Table Contours (September 18, 2017)

Gas Works Park Site
Seattle, Washington

GeoEngineers

Figure 3E-2

Path: P:\0\0186846\GIS\MXD\Phase01\T1635\018684601_F3-16_GWContoursSept_2017R.mxd Map Revised: 11 November 2021 alarson



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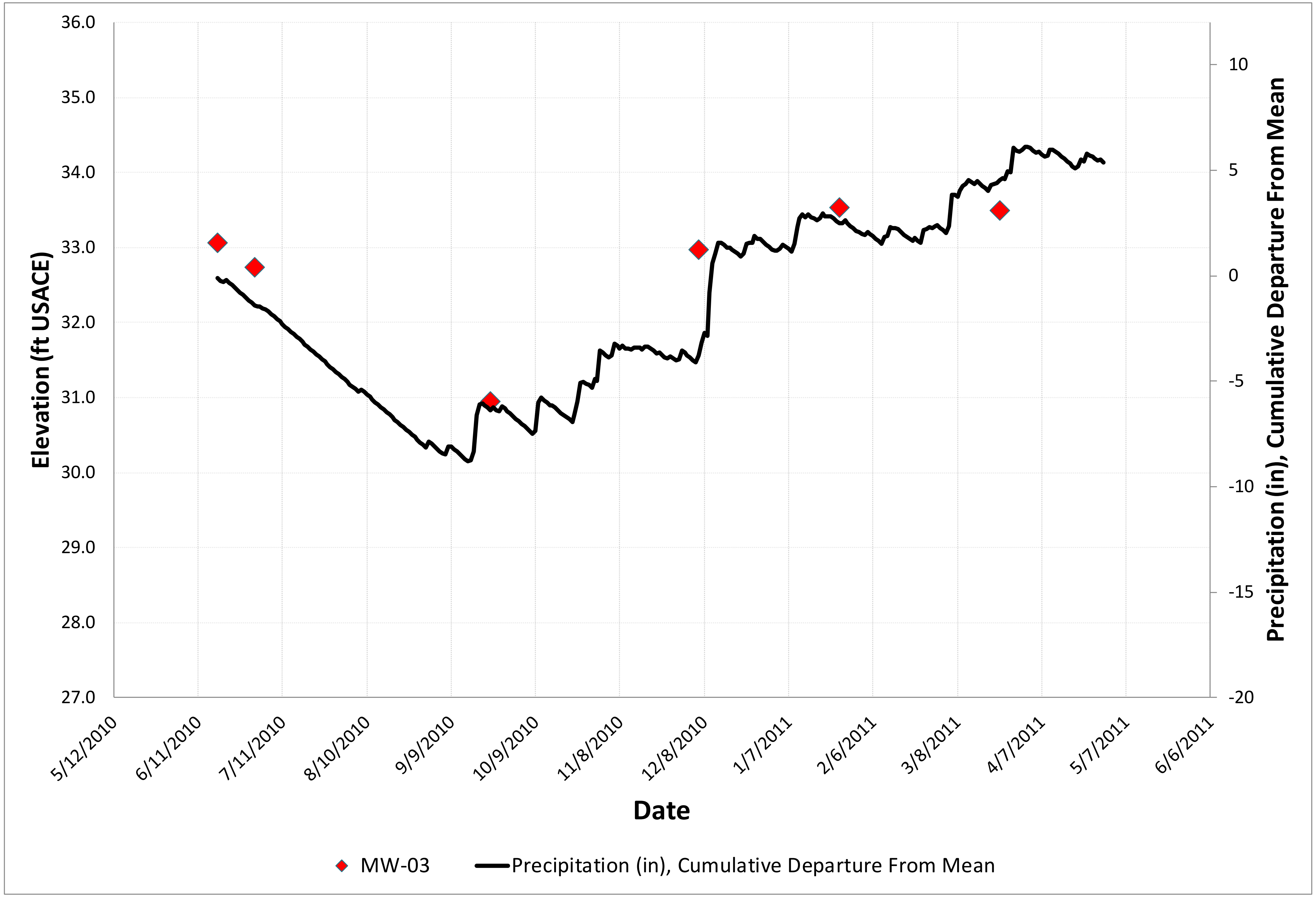
TSW-2 and TDW-2 Groundwater Elevations and Lake Levels

Gas Works Park Site
Seattle, Washington

GeoEngineers

Figure 3E-3



MW-03 Groundwater Elevation and Precipitation

Gas Works Park Site
Seattle, Washington

GeoEngineers

Figure 3E-4

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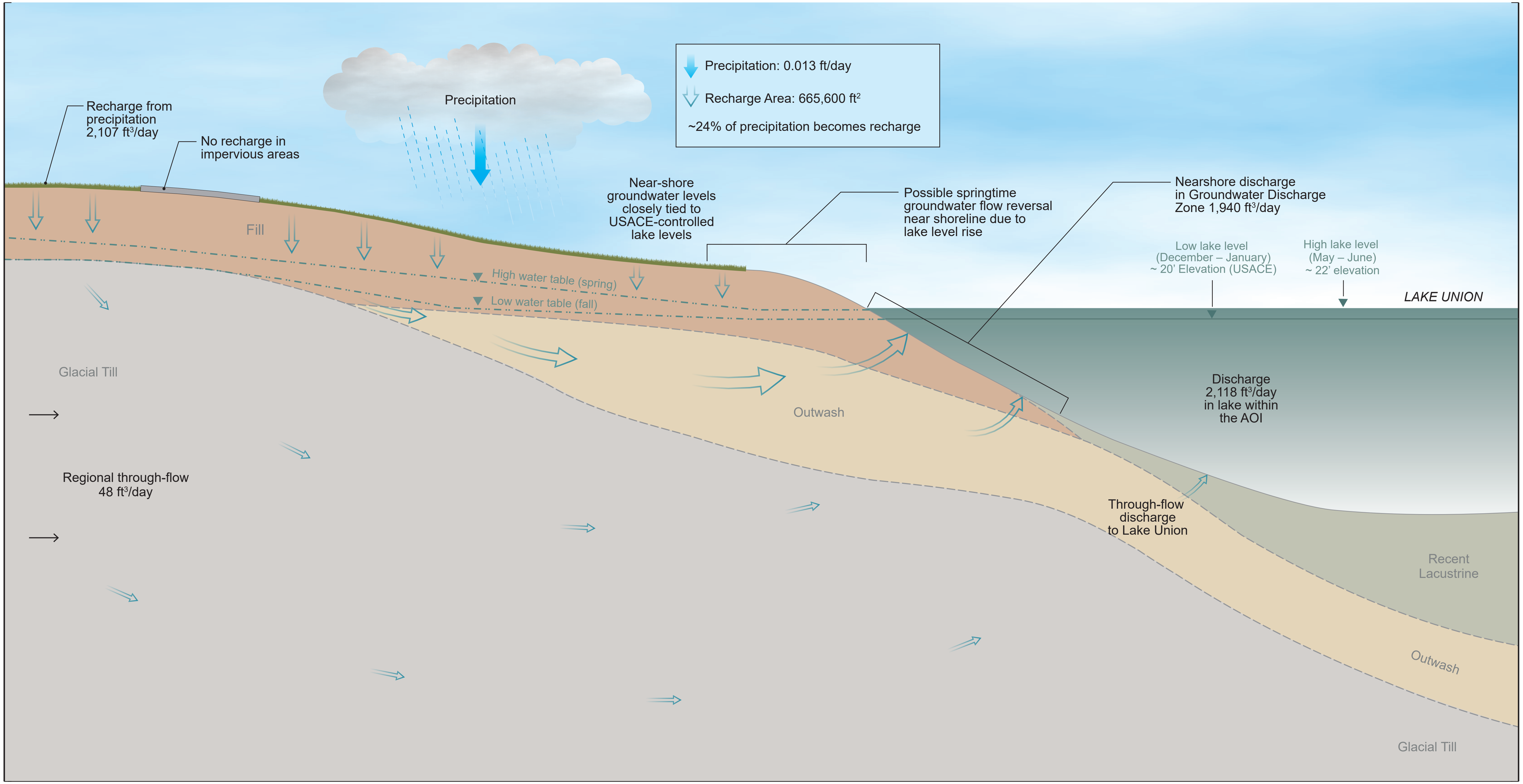

Notes:
1. An estimated 37 ft³/day flows from the AOI into the larger model domain.

Legend
- Groundwater flow
- Recharge from precipitation
- Regional through-flow

Hydrogeologic Conceptual Site Model

Gas Works Park Site
Seattle, WA

GeoEngineers

Figure 3E-5

ATTACHMENT 3E-1
Hydrogeologic Testing Report

HYDROGEOLOGIC TESTING REPORT

Gas Works Sediment Area (GWSA)

Prepared on behalf of the City of Seattle for the
GWSA Technical Team

Project No. 060102-002-02 • January 31, 2012

Aspect CONSULTING

earth + water

HYDROGEOLOGIC TESTING REPORT

Gas Works Sediment Area (GWSA)

Prepared on behalf of the City of Seattle for the
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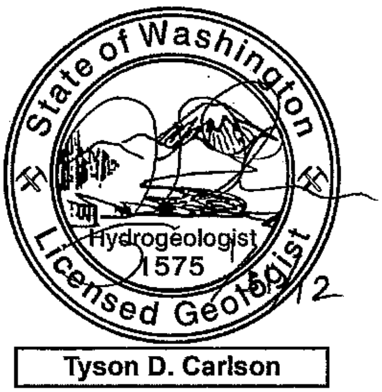
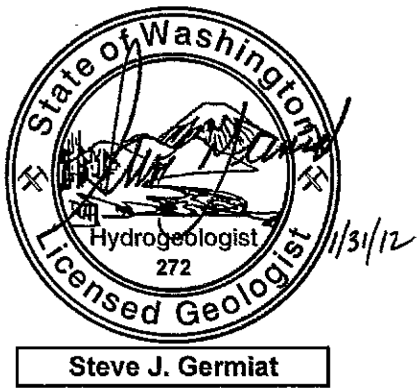
Prepared by: Aspect Consulting, LLC

Project No. 060102-002-02 • January 31, 2012





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1 Introduction

This Hydrogeologic Testing Report presents test data collected during the hydrogeologic investigation completed in the Gas Works Sediment Area (GWSA). The GWSA is located along the northern shore of Lake Union offshore of Gas Works Park in Seattle, Washington. Hydrogeologic testing occurred in wells located in the Gas Works Park uplands, upgradient of the GWSA.

The purpose of this investigation is to collect additional hydrogeologic data in support of developing a site-wide, three-dimensional numerical groundwater flow model. The model will include the entire GWSA and uplands contributing groundwater to the offshore sediment areas, including Gas Works Park and adjacent properties. The final calibrated groundwater flow model will be used as a common tool to assess potential remedial options as part the feasibility studies for the GWSA.

The hydrogeologic investigation consisted of two components: (1) monitoring well installation and development, and (2) hydraulic testing of the new and select existing wells. This Hydrogeologic Testing Report is paired with the companion *Monitoring Well Installation Report* (GeoEngineers, 2010) presented under separate cover. The *Monitoring Well Installation Report* includes a narrative summary of drilling, including a description of the materials encountered, along with boring and well construction logs.

2 Scope of Work

Hydrogeologic testing was conducted in general accordance with the Washington State Department of Ecology (Ecology)-approved *Work Plan for Hydrogeologic Investigation* (Work Plan) (Aspect, 2010). The hydrogeologic testing portion of the Work Plan consisted of the following elements:

1. Hydraulic testing of the newly installed wells and other select existing wells to refine aquifer parameter estimates. Testing consisted of pumping tests and/or slug tests;
2. Survey of all accessible groundwater monitoring wells in the Gas Works Park and neighboring properties to ensure accuracy and a common vertical datum; and
3. Collection of one year of quarterly groundwater level data from all accessible monitoring wells in Gas Works Park and the Harbor Patrol property.

Results of these elements are discussed below. Figure 1 shows the site monitoring wells, and depicts wells at which hydraulic testing was conducted in the current investigation.

3 Hydraulic Testing

Hydraulic testing proposed in the Work Plan included pumping tests at each of six new wells MW-26 through MW-31 and existing well MW-3D. However, based on the conditions observed during drilling and well development, together with pumping test results for two wells, it was determined that the wells were not suitable for full scale pumping tests due to difficulty in maintaining suitably stable pumping rates at less than a gallon per minute[1]. Therefore, it was concluded that slug testing was an appropriate test method for the materials encountered in the uplands adjacent to the GWSA. In support of this approach, the two wells where both pumping test and slug test methods were conducted showed good agreement in hydraulic conductivity (K) estimates as described below.

A summary of the hydraulic testing activities is provided below. Appendix A presents the pumping test data analysis methods. Slug testing methodology and analysis is presented in Appendix B.

3.1 Pumping Tests

Low-flow constant-rate pumping tests were completed at two wells, MW-30 and MW-3D. Prior to testing, down-hole pressure transducers were deployed in select wells to monitor baseline groundwater levels. The baseline groundwater hydrographs along with daily precipitation are provided as Figures 2 through 9.

The water generated during the pumping test program was conveyed via temporary piping or buckets to an on-site 18,000 gallon storage tank for containment. The tank was located on the large concrete pad located east of the Cracking Towers. Following completion of the testing program, all discharge water (including well development water) was transported, treated, and disposed of off-site. No discharge to the sanitary sewer occurred.

3.1.1 MW-30

The 4-inch diameter pumping well MW-30 was selected first for testing. MW-30 has one of the higher short-term yields as determined during well development (0.9 gpm) and has two adjacent observation wells, MW-29 and MW-10. Due to the low yield of MW-30 observed during development, it was not technically feasible to accurately step test the pumping well as planned; therefore, testing began on October 19th with two short constant-rate pumping tests designed to indicate a longer-term flow rate for testing. The short tests were conducted at 0.2 gpm for approximately 27 minutes and 1.0 gpm for 44 minutes, with 0.7 and 8.2 feet of observed drawdown, respectively.

The longer-term constant-rate test began at 9:19 am on October 20th with a target pumping rate of 0.5 gpm. The average flow rate for the pumping test was 0.48 gpm. No intermittent adjustments were made to the flow rate during the test. The flow rate was: (1)

[1] In accordance with the Work Plan, the ability to sustain a pumping rate of several gallons per minute (gpm) was a suitability consideration for hydraulic testing of a well. None of the wells identified for testing in the Work Plan can produce a several gpm flow rate.

measured with an inline flow meter, and (2) routinely calculated by recording the time (via stopwatch) it took to pump a defined volume, as measured by a graduated cylinder.

Pumping was ultimately terminated after 327 minutes of pumping at 3:16 pm. A brief (less than 1 minute) interruption in pumping occurred at 240 minutes when the pump's electrical cord was mistakenly unplugged by a park visitor. Total drawdown in MW-30 was 1.9 feet at cessation of pumping. Water levels in the pumping and observation wells were monitored for complete recovery.

3.1.2 MW-3D

Following redevelopment, a single low-flow constant-rate pumping test was performed in MW-3D. The 2-inch well, along with the neighboring shallower MW-3, was monitored during testing. The constant-rate pumping test was conducted at 0.1 gpm for 300 minutes with 7.6 feet of observed drawdown. Following pumping, water levels were monitored for complete recovery.

3.1.3 Pumping Test Results

Pumping test data were downloaded from the pressure transducers and hydrographs were created to compare the responses to pumping of the various monitoring points at different depths and distances from each pumping well.

Select data from each constant-rate pumping test were analyzed to provide information on hydraulic properties of the water-bearing unit adjacent the screened interval. Multiple methods of analysis using both drawdown and recovery data were used. A summary of the aquifer parameters (transmissivity, hydraulic conductivity, and storativity) estimated from the pumping test data are presented in Table 1. Table 1 also presents the average parameter values from the multiple methods of analysis for each well.

At MW-30, the measured average hydraulic conductivity and storage coefficient are 6 x 10^{-4} centimeters per second (cm/sec) and 0.02 (dimensionless), respectively. At the deeper well MW-3D, the average K and storage coefficient are 5 x 10^{-5} cm/sec and 0.03 (dimensionless), respectively.

Figures 10 through 13 illustrate the drawdown and recovery data for each of the pumping tests, displayed in arithmetic space. Appendix A presents a description of analytical methods used in data analysis, along with additional hydrographs of test data.

3.1.3.1 Water Quality

During each constant-rate pumping test, the water quality parameters temperature, specific conductance, pH, oxidation reduction potential (ORP or redox), dissolved oxygen (DO), and turbidity were monitored in the field, in accordance with the Work Plan. A YSI 556 multi-parameter water quality meter with an in-line flow cell was used to collect the field parameters. Field values were generally stable throughout testing. Field parameter measurements near the conclusion of each test are presented below.

Well	Temperature in °C	Specific Conductance (µS/cm)	pH	ORP in mV	DO in mg/L	Turbidity
MW-30	16.9	549	7.18	-40.8	1.0	Clear
MW-3D	13.6	250	9.80	-74.8	2.5	Clear

3.2 Slug Testing

Slug testing was completed in the new (MW-26 through MW-31) and select existing monitoring wells (MW-3 and MW-3D). Multiple slug tests were repeated in each of the new wells. A summary of the slug test data analysis and results are included as Table 2. Table 2 also presents the estimated average K value for wells with repeated tests.

The average K estimates for the eight wells are constrained within two orders of magnitude, ranging between 1 x 10^{-5} and 7 x 10^{-4} cm/sec. For the two wells with both pumping test and slug test data, the average K estimates between test methods agreed relatively closely (6 x 10^{-4} vs. 7 x 10^{-4} cm/sec at MW-30; 5 x 10^{-5} vs. 9 x 10^{-5} cm/sec at MW-3D; see Tables 1 and 2).

Appendix B presents a description of the testing procedure and the analytical methods used in analysis. In Appendix B, Figures B-1 through B-8, illustrate the slug test response and regression fit used in analysis.

3.3 Water Level Monitoring

As part of this hydrogeologic investigation, four rounds of concurrent groundwater level measurements will be made from accessible existing wells located in Gas Works Park and neighboring properties. The wells within Gas Works Park and Harbor Patrol property were surveyed by a City of Seattle and Washington State-licensed surveyor relative to a common horizontal (NAD83 WA State Plane North) and vertical (US Army Corps of Engineers [USACE] Chittenden Locks) datum being used for the project. Survey data also can be converted to the NAVD88 vertical datum[2] as required by Ecology. Updated well location data are presented in Table 1 of the *Monitoring Well Installation Report* (GeoEngineers, 2010).

To date, three (July, September, and December 2010) groundwater monitoring events have been completed. The March 2011 monitoring event is pending. The data collected, along with the corresponding groundwater contour maps, will be presented as part of the pending update to the conceptual site model (CSM).

[2] The USACE Locks datum is 3.25 feet below the NAVD88 datum, therefore elevations relative to the USACE datum are 3.25 feet higher than those relative to the NAVD88 datum (i.e., elevation per USACE datum = elevation per NAVD88 datum + 3.25 feet).

4 References

Aspect Consulting, LLC (Aspect), 2010, Work Plan for Hydrogeologic Investigation, Gas Works Sediment Area (GWSA), Prepared on behalf of the City of Seattle for the GWSA Technical Team. Seattle, Washington, Unpublished Work, September 13, 2010.

Boulton, N.S., 1963, Analysis of data from non-equilibrium pumping tests allowing for delayed yield from storage, Proc. Inst. Civil Eng., 26, Paper No. 6693: 469-482.

Bouwer H., and Rice, R.C., 1976, A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells, V.12 No. 3, 423-428, Water Resources Research.

Cooper, H.H., and Jacob, C.E., 1946, A generalized graphical method for evaluating formation constants and summarizing wellfield history, Transactions of the American Geophysical Union, Vol. 27, pp. 526-534.

Freeze and Cherry, 1979, Groundwater, Prentice Hall, Englewood Cliffs, NJ, 1979.

GeoEngineers, 2010, Monitoring Well Installation Report, Prepared on behalf of Puget Sound Energy for the GWSA Technical Team, December 29, 2010.

Hantush, M.S. and Jacob, C.E., 1955, Non-steady radial flow in an infinite leaky aquifer, Trans. Am. Geophys. Union, 36, No.1: 95-100.

Hunt, B., 2003, Groundwater Analysis Using Function.xls. Department of Civil Engineering, The University of Canterbury, Christchurch, New Zealand, 2003.

Kruseman, G.P. and de Ridder, N.A., 1994, Analysis and Evaluation of Pumping Test Data. ILRI Publication 47, International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands, 377 pp.

Theis, C.V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage, Transactions of the American Geophysical Union, No. 2, pp. 519-524.

Limitations

Work for this project was performed and this report prepared in accordance with generally accepted professional practices for the nature and conditions of work completed in the same or similar localities, at the time the work was performed. It is intended for the exclusive use on behalf of the City of Seattle for the GWSA Technical Team for specific application to the referenced property. This report does not represent a legal opinion. No other warranty, expressed or implied, is made.

Table 1 - Aquifer Hydraulic Conductivity Estimates from Pumping Tests

Hydrogeologic Testing Report, GWSA

Pumping Test	Pumping Rate in gpm	Observation Location	Method (Solution)	Transmissivity in ft^2/min	Hydraulic Conductivity in cm/sec	Storage Coefficient (dimensionless)
MW-30	0.48	MW-30	Time-Drawdown (Boulton)	1E-02	8E-04	0.03
		MW-10	Time-Drawdown (Boulton)	4E-03	4E-04	0.01
		MW-30	Time-Recovery (Cooper Jacob)	1E-02	5E-04	-
		MW-30, MW-29, MW-10	Distance-Drawdown (Cooper Jacob)	1E-02	6E-04	-
			Average	**9E-03**	**6E-04**	**0.02**
MW-3D	0.10	MW-3D	Time-Drawdown (Theis)	4E-04	7E-05	0.04
		MW-3D	Time-Drawdown (Boulton)	3E-04	5E-05	0.03
		MW-3D	Time-Drawdown (Hantush)	4E-04	6E-05	0.04
		MW-3D	Time-Recovery (Cooper Jacob)	5E-04	2E-05	-
		MW-3D, MW-3	Distance-Drawdown (Cooper Jacob)		NA	
			Average	**4E-04**	**5E-05**	**0.03**

Notes:
NA - Not analyzed. No discernable pumping response in monitoring well.
-' - not able to be calculated from the analysis method.

Table 2 - Aquifer Hydraulic Conductivity Estimates from Slug Tests

Hydrogeologic Testing Report, GWSA

Monitoring Well	MW-26 Test 1	MW-26 Test 2	MW-26 Test 3	MW-27 Test 1	MW-27 Test 2	MW-27 Test 3	MW-28 Test 1	MW-28 Test 2	MW-28 Test 3	MW-29 Test 1	MW-29 Test 2	MW-29 Test 3	MW-30 Test 3	MW-30 Test 4	MW-30 Test 5	MW-31 Test 1	MW-31 Test 2	MW-3D	MW-3
Well Depth in Feet	**12.5**	**12.5**	**12.5**	**14.5**	**14.5**	**14.5**	**27.0**	**27.0**	**27.0**	**23.0**	**23.0**	**23.0**	**22.0**	**22.0**	**22.0**	**45.0**	**45.0**	**57.6**	**10.6**
Screen Length in Feet	**3.5**	**3.5**	**3.5**	**3.0**	**3.0**	**3.0**	**10.0**	**10.0**	**10.0**	**10.0**	**10.0**	**10.0**	**10.0**	**10.0**	**10.0**	**10.0**	**10.0**	**3.0**	**9.0**
Depth to Screen in Feet	**9.0**	**9.0**	**9.0**	**12.5**	**12.5**	**12.5**	**17.0**	**17.0**	**17.0**	**13.0**	**13.0**	**13.0**	**12.0**	**12.0**	**12.0**	**35.0**	**35.0**	**54.6**	**1.6**
Depth to Aquitard in Feet	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**90**
Depth to Water in Feet	**9.83**	**9.83**	**9.83**	**7.90**	**7.90**	**7.90**	**16.00**	**16.00**	**16.00**	**9.54**	**9.54**	**9.54**	**9.96**	**9.96**	**9.96**	**15.84**	**15.84**	**15.69**	**7.14**
Depth to Sandpack in Feet	**8.0**	**8.0**	**8.0**	**10.0**	**10.0**	**10.0**	**16.0**	**16.0**	**16.0**	**12.0**	**12.0**	**12.0**	**11.0**	**11.0**	**11.0**	**32.0**	**32.0**	**47.0**	**1.5**
Slug Displacement (H_o) in Feet	**0.22**	**0.63**	**0.42**	**0.90**	**2.97**	**3.76**	**0.93**	**1.30**	**1.42**	**5.08**	**3.48**	**1.78**	**1.77**	**2.10**	**2.39**	**0.17**	**0.36**	**5.65**	**5.27**
Porosity (n)	**0.20**	**0.20**	**0.20**	**0.20**	**0.20**	**0.20**	**0.20**	**0.20**	**0.20**	**0.20**	**0.20**	**0.20**	**0.20**	**0.20**	**0.20**	**0.20**	**0.20**	**0.20**	**0.20**
Radius of Casing (r_c) in Feet	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**	**0.17**	**0.17**	**0.17**	**0.17**	**0.17**	**0.08**	**0.08**
Radius of Borehole (r_w) in Feet	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**	**0.33**	**0.33**	**0.33**	**0.33**	**0.33**	**0.25**	**0.25**
Saturated Aquifer Thickness (H) in Feet	80.2	80.2	80.2	82.1	82.1	82.1	74.0	74.0	74.0	80.5	80.5	80.5	80.0	80.0	80.0	39.2	39.2	104.3	71.9
Saturated Well Thickness (L_w) in Feet	2.7	2.7	2.7	7.6	7.6	7.6	11.0	11.0	11.0	13.5	13.5	13.5	12.0	12.0	12.0	29.2	29.2	41.9	3.5
Effective Radius (r_{eff}) in Feet	0.13	0.13	0.13	0.08	0.08	0.08	0.13	0.13	0.13	0.08	0.08	0.08	0.17	0.17	0.17	0.17	0.17	0.08	0.13
Effective Screen Length (L_e) in Feet	2.7	2.7	2.7	3.0	3.0	3.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	3.0	3.5
Rising/Falling Head Test	Rising	Falling	Falling	Rising	Rising	Rising	Rising	Rising	Rising	Rising	Rising	Rising	Rising	Rising	Rising	Rising	Rising	Falling	Falling
Fully Submerged Sandpack	No	No	No	Yes	No	No	No	No	No	No	No	Yes	No	No	No	Yes	Yes	Yes	No
Transiently Exposed Sandpack	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	No	No	Yes
Transiently Exposed Screen	Yes	Yes	Yes	No	No	No	No	Yes	Yes	Yes	Yes	No	No	Yes	Yes	No	No	No	Yes
Partially Submerged Screen	Yes	Yes	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes
Bouwer and Rice Parameters																			
Normalized Head at t_1 (y_1) in Feet	0.51	0.22	0.46	0.50	0.75	0.72	0.74	0.88	0.78	0.77	0.85	0.79	0.79	0.84	0.86	0.87	0.98	1.00	0.30
Time - t_1 in Seconds	255	122	510	60	29	36	31	11	22	30	8	8	25	20	23	300	10	2	287
Normalized Head at t_2 (y_2) in Feet	0.13	0.11	0.20	0.11	0.21	0.21	0.14	0.09	0.08	0.08	0.15	0.09	0.08	0.18	0.17	0.58	0.24	0.10	0.10
Time - t_2 in Seconds	1316	1056	1784	300	240	259	298	298	309	150	90	90	330	231	258	4961	9990	1808	806
L_e/r_w	11	11	11	12	12	12	40	40	40	40	40	40	30	30	30	30	30	12	14
Coefficient A [a]	1.8	1.8	1.8	1.9	1.9	1.9	2.8	2.8	2.8	2.8	2.8	2.8	2.5	2.5	2.5	2.5	2.5	1.9	1.9
Coefficient B [a]	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.3
Coefficient C [a]	1.2	1.2	1.2	1.3	1.3	1.3	2.3	2.3	2.3	2.3	2.3	2.3	1.9	1.9	1.9	1.9	1.9	1.3	1.3
Partially Penetrating Well																			
ln(Re/rw) b	1.3	1.3	1.3	1.6	1.6	1.6	2.4	2.4	2.4	2.5	2.5	2.5	2.2	2.2	2.2	2.7	2.7	2.0	1.5
K in cm/sec	**2E-04**	**1E-04**	**8E-05**	**4E-04**	**3E-04**	**3E-04**	**4E-04**	**5E-04**	**5E-04**	**5E-04**	**5E-04**	**7E-04**	**7E-04**	**7E-04**	**6E-04**	**1E-05**	**2E-05**	**9E-05**	**2E-04**
Average K in cm/sec		**1E-04**			**3E-04**			**5E-04**			**6E-04**			**7E-04**		**1E-05**		**9E-05**	**2E-04**

Notes:

Data analysis by method of Bouwer and Rice (1976; 1989)

Bold values are entered from field data and other values are calculated

All depths are below ground surface.

[a] A, B, and C coefficients are calculated using regression equations of Van Rooy (1988).

[b] R_e/r_w is the effective radial distance over which y is dissipated, divided by the radial distance of well development.

Legend

- GWSA
- Metro Property Monitoring Well
- Gas Works Monitoring Well
- Hydraulically Tested Well (2010)

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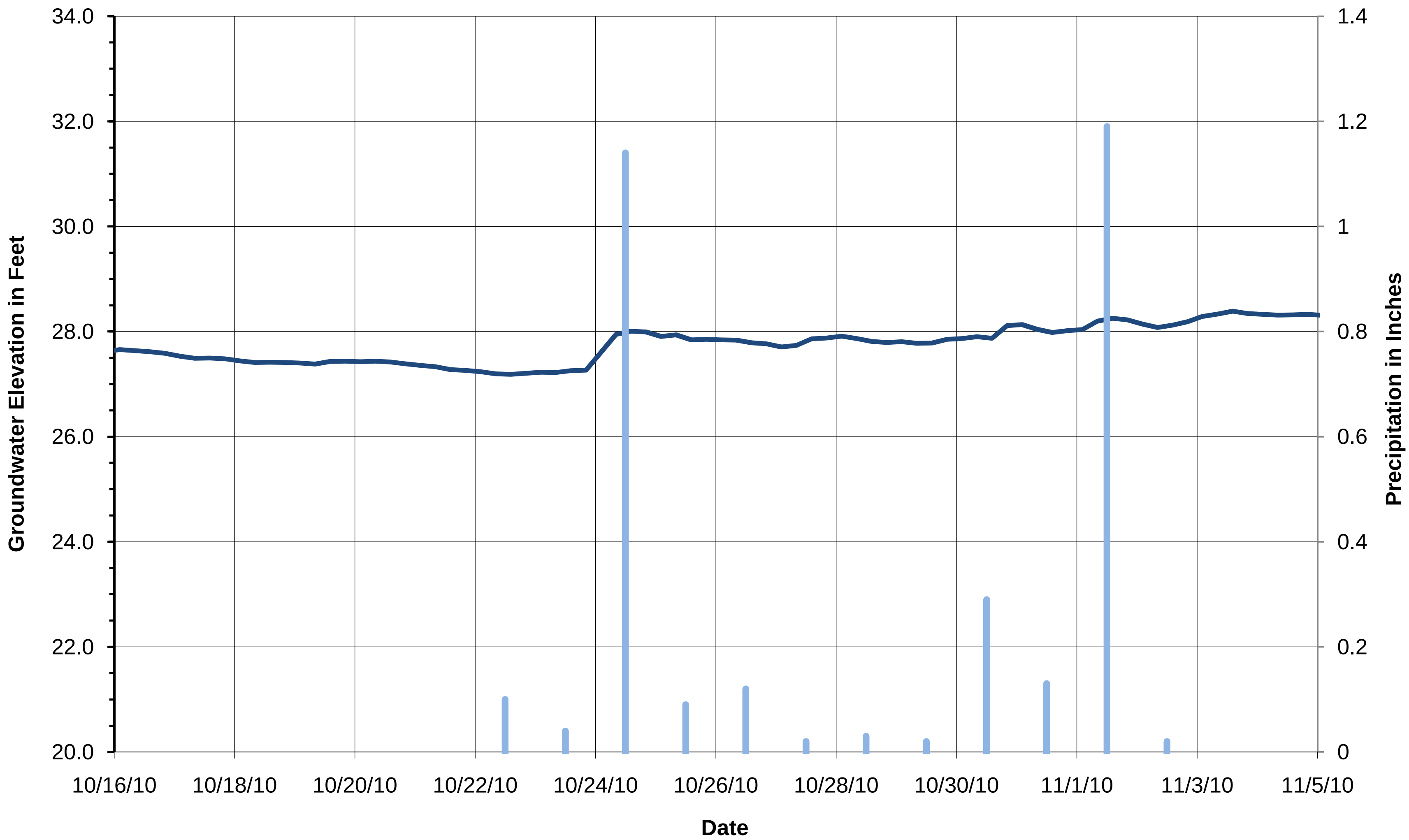
Groundwater Monitoring Well Location Map

Hydrogeologic Testing Report

Seattle, Washington

DATE: Dec 2010	PROJECT NO. 060102
DESIGNED BY: ACM	
DRAWN BY: SCC	FIGURE NO. 1
REVISED BY: SCC	

Path: T:\projects_8\Gas_Works_2010\Working\GW_MWs-2010-Dec_Update_v2.mxd



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S:\Floyd Snider\Gas Works 060102\GWSA Groundwater Modeling\Hydro Data Report (Aspect)\Background Hydrographs (Figs 2 through 9)

Figure 2

MW-27 Baseline Groundwater Hydrograph

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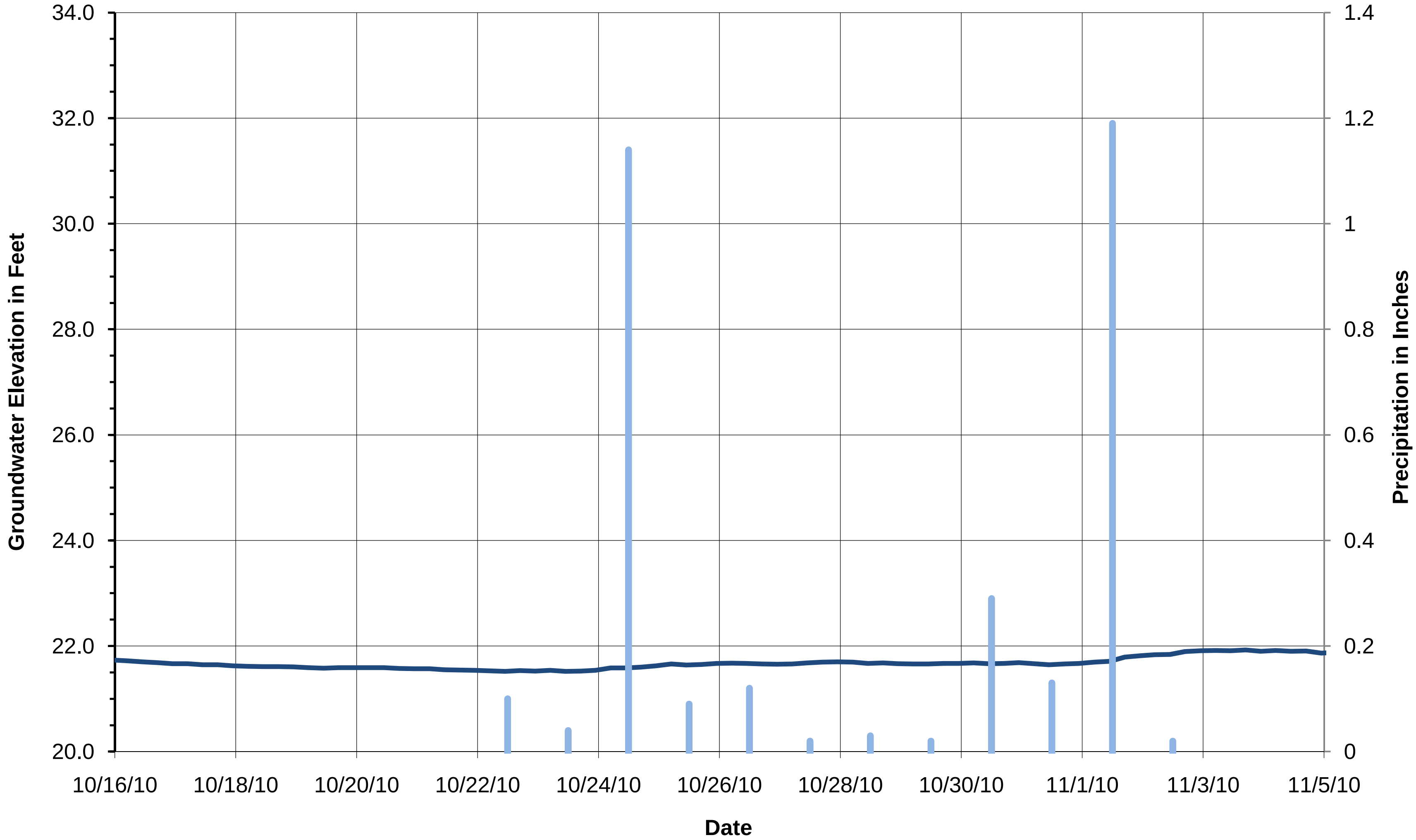

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Figure 3
MW-28 Baseline Groundwater Hydrograph
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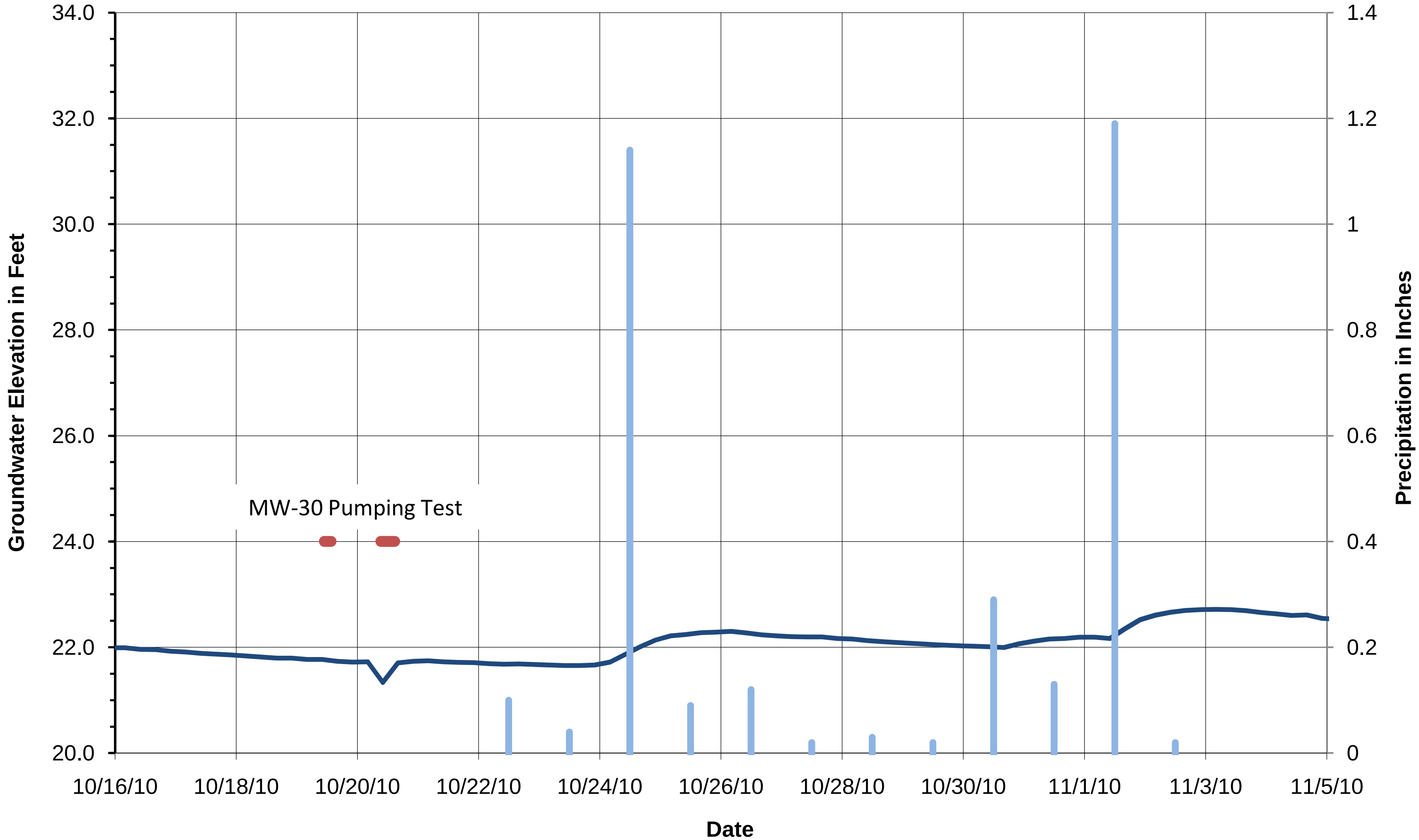
Seattle, WA



Note: Complete pumping test hydrograph(s) shown on Figures 10 through 12.

Figure 4

MW-29 Baseline Groundwater Hydrograph

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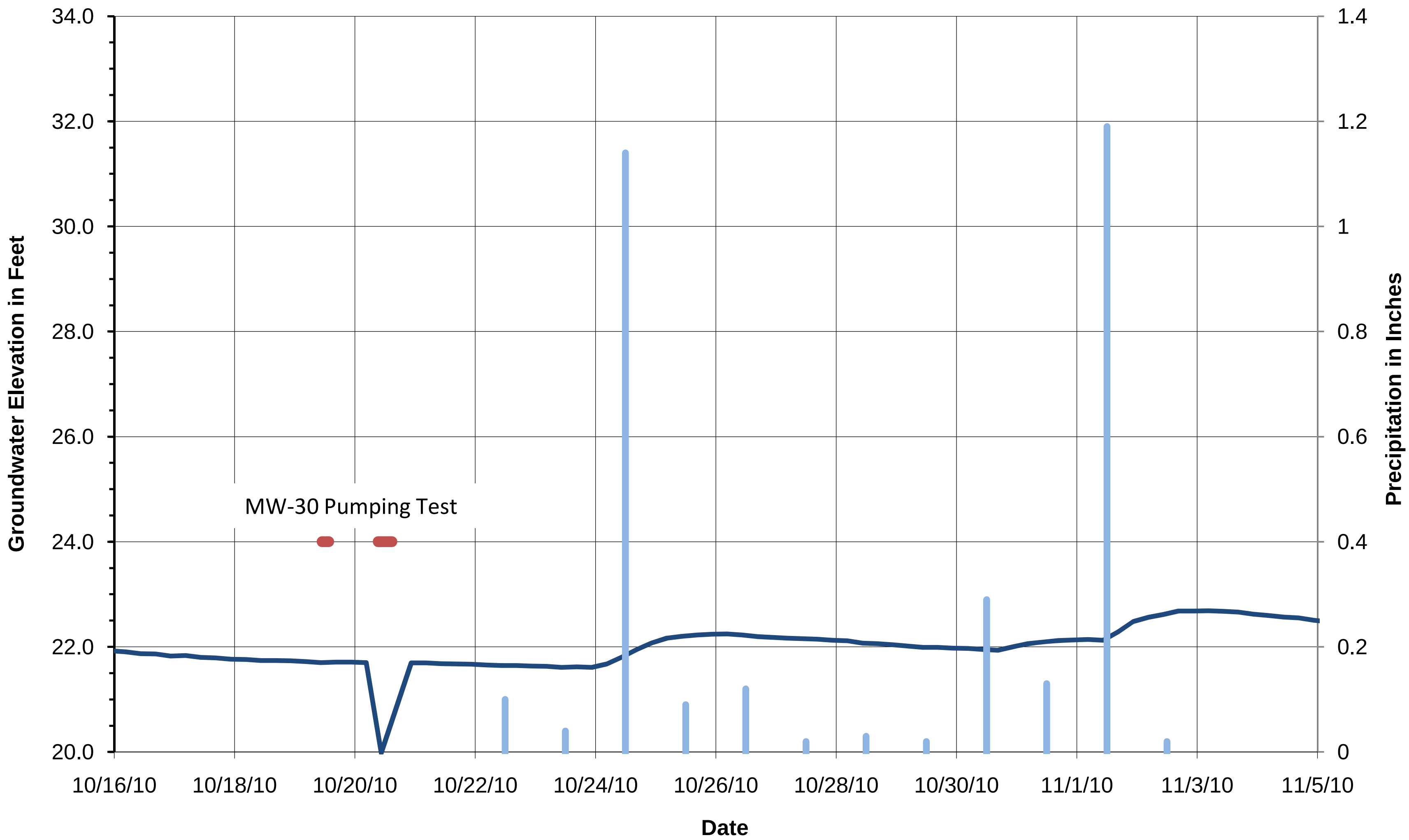

Note: Complete pumping test hydrograph(s) shown on Figures 10 through 12.

Figure 5

MW-30 Baseline Groundwater Hydrograph

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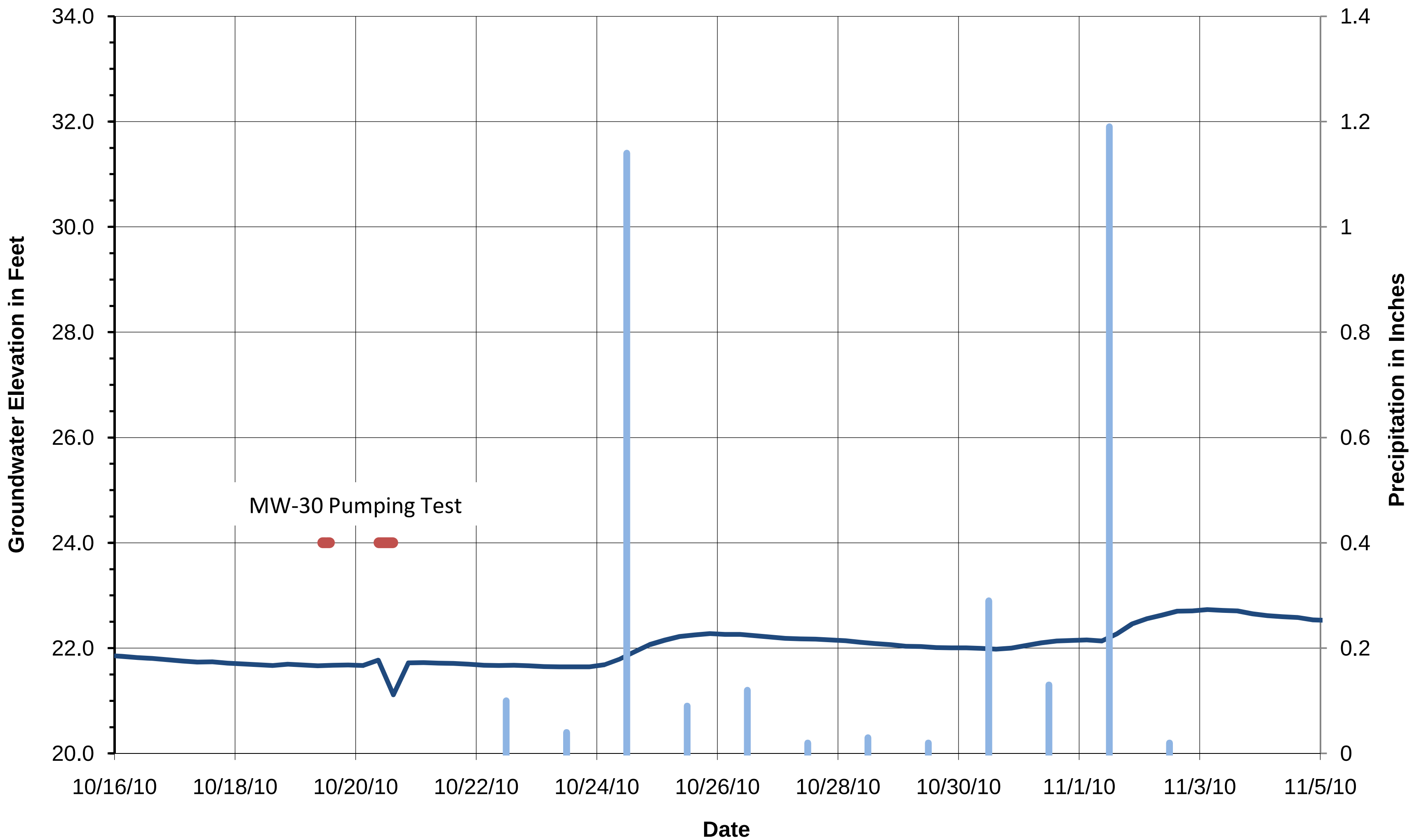

Note: Complete pumping test hydrograph(s) shown on Figures 10 through 12.

Figure 6
MW-10 Baseline Groundwater Hydrograph
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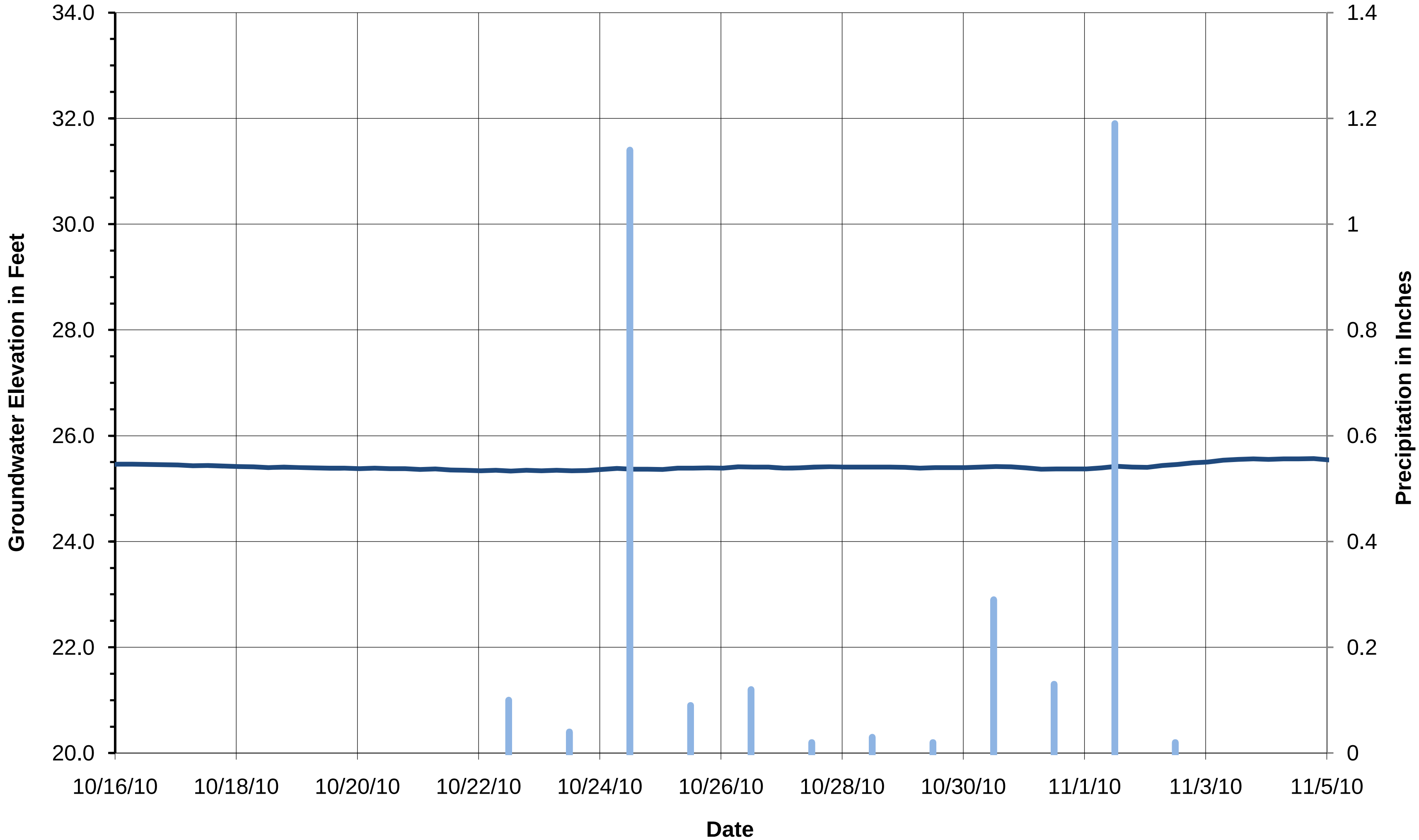

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Figure 7
MW-31 Baseline Groundwater Hydrograph
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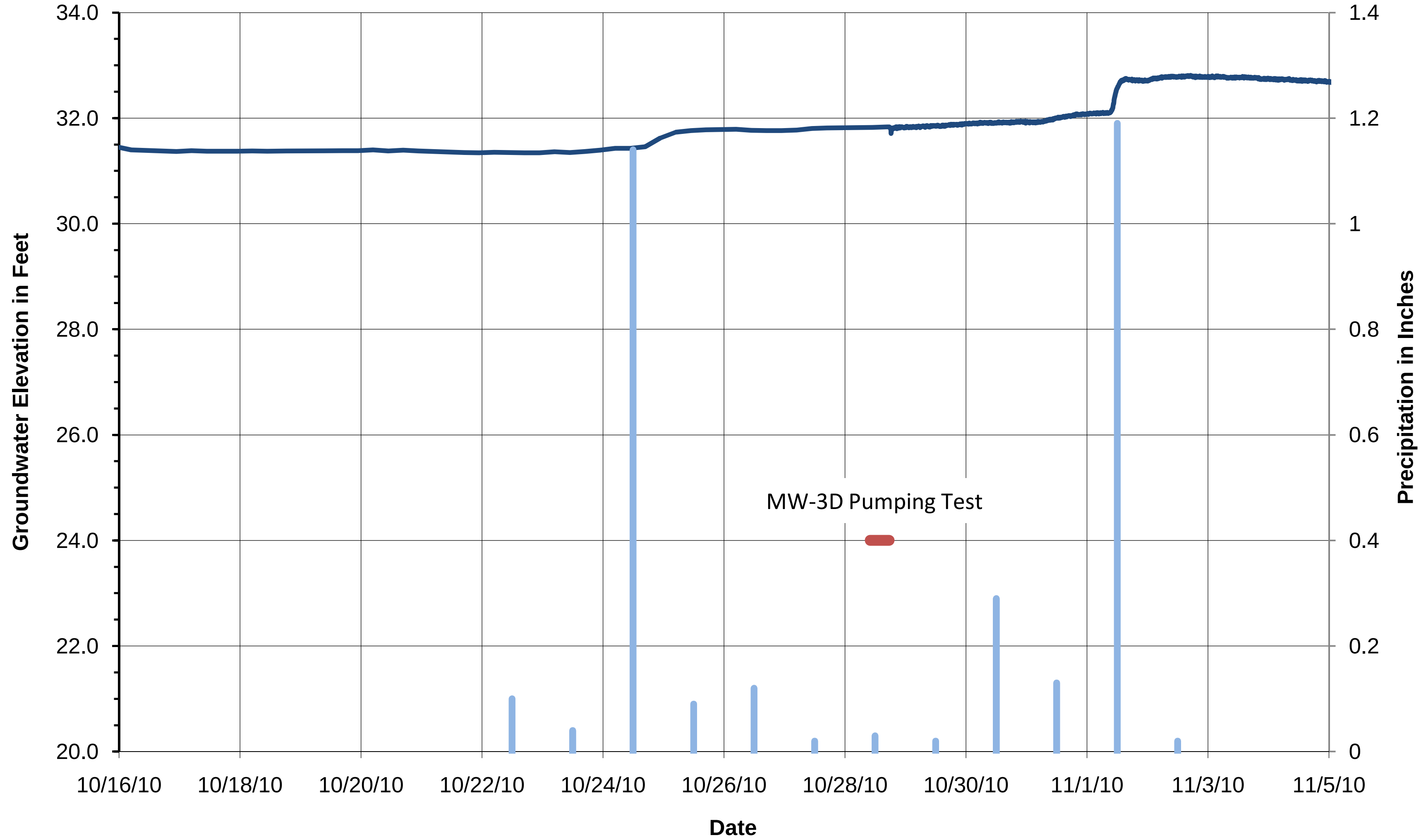

Note: Complete pumping test hydrograph(s) shown on Figure 13.

Figure 8

MW-3 Baseline Groundwater Hydrograph

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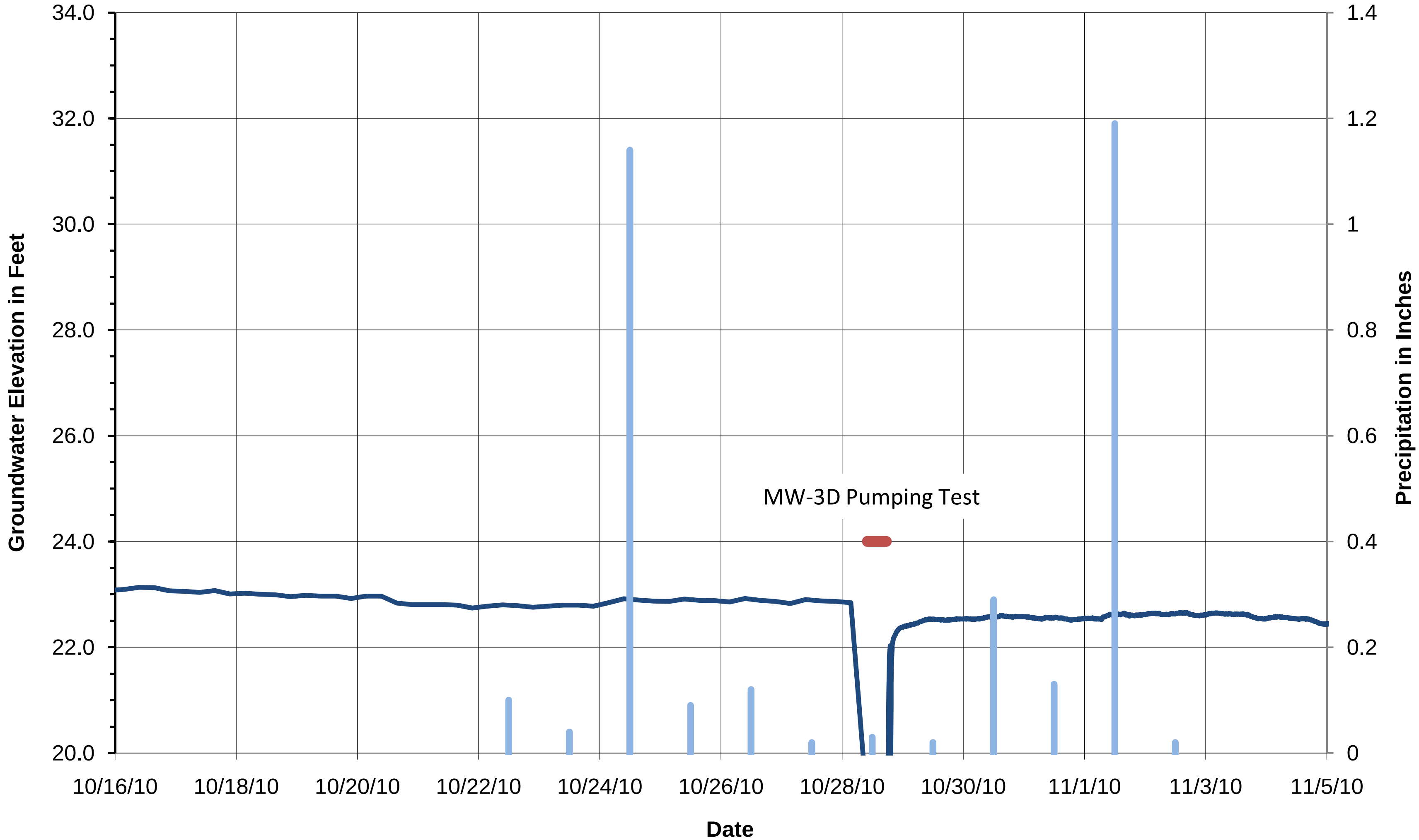

Note: Complete pumping test hydrograph(s) shown on Figure 13.

Figure 9

MW-3D Baseline Groundwater Hydrograph

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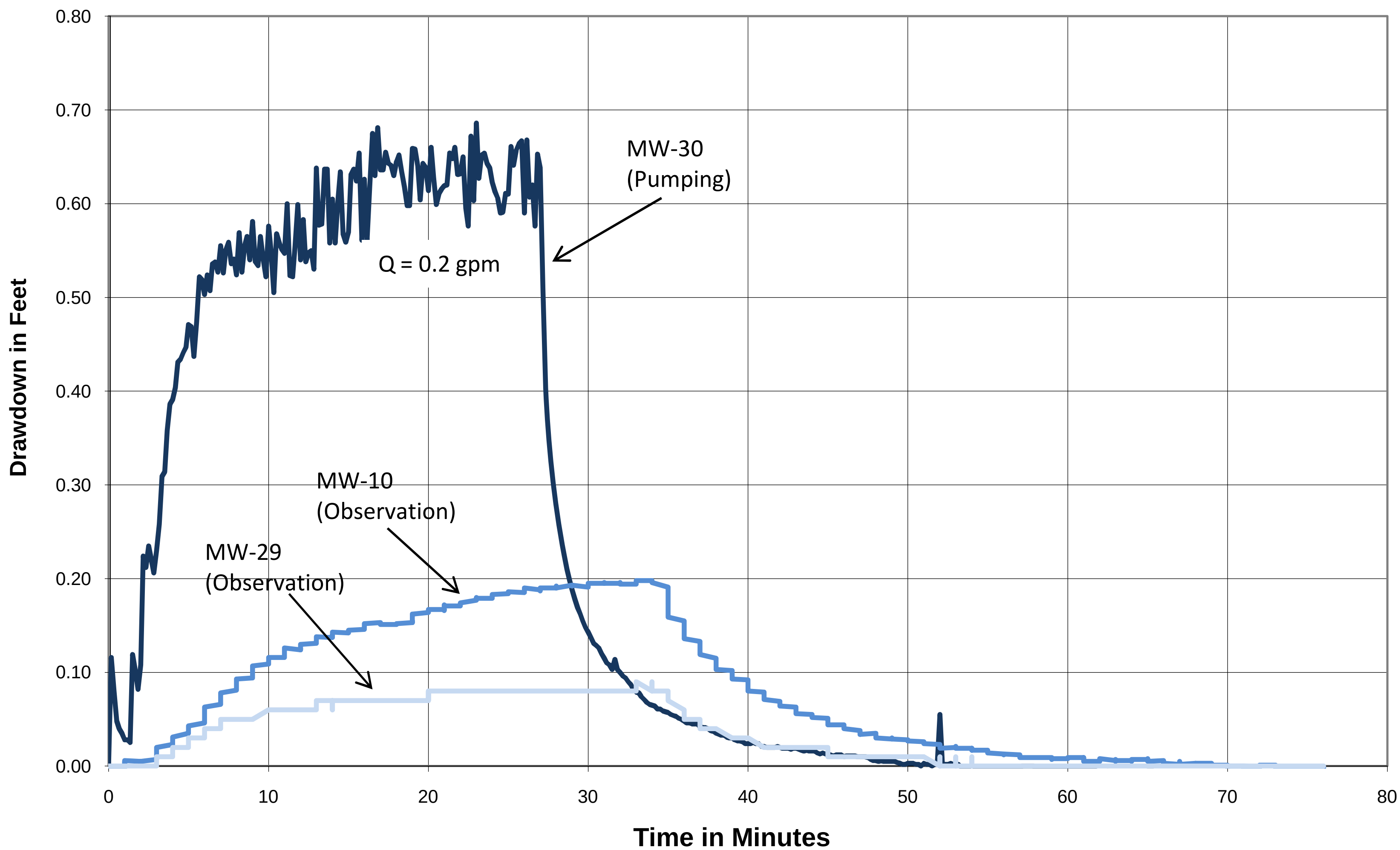

Note: Radial distance from MW-30 to MW-10 (5.39 feet) and MW-29 (10.18

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Figure 10
MW-30 Constant Rate (0.2 gpm) Hydrograph
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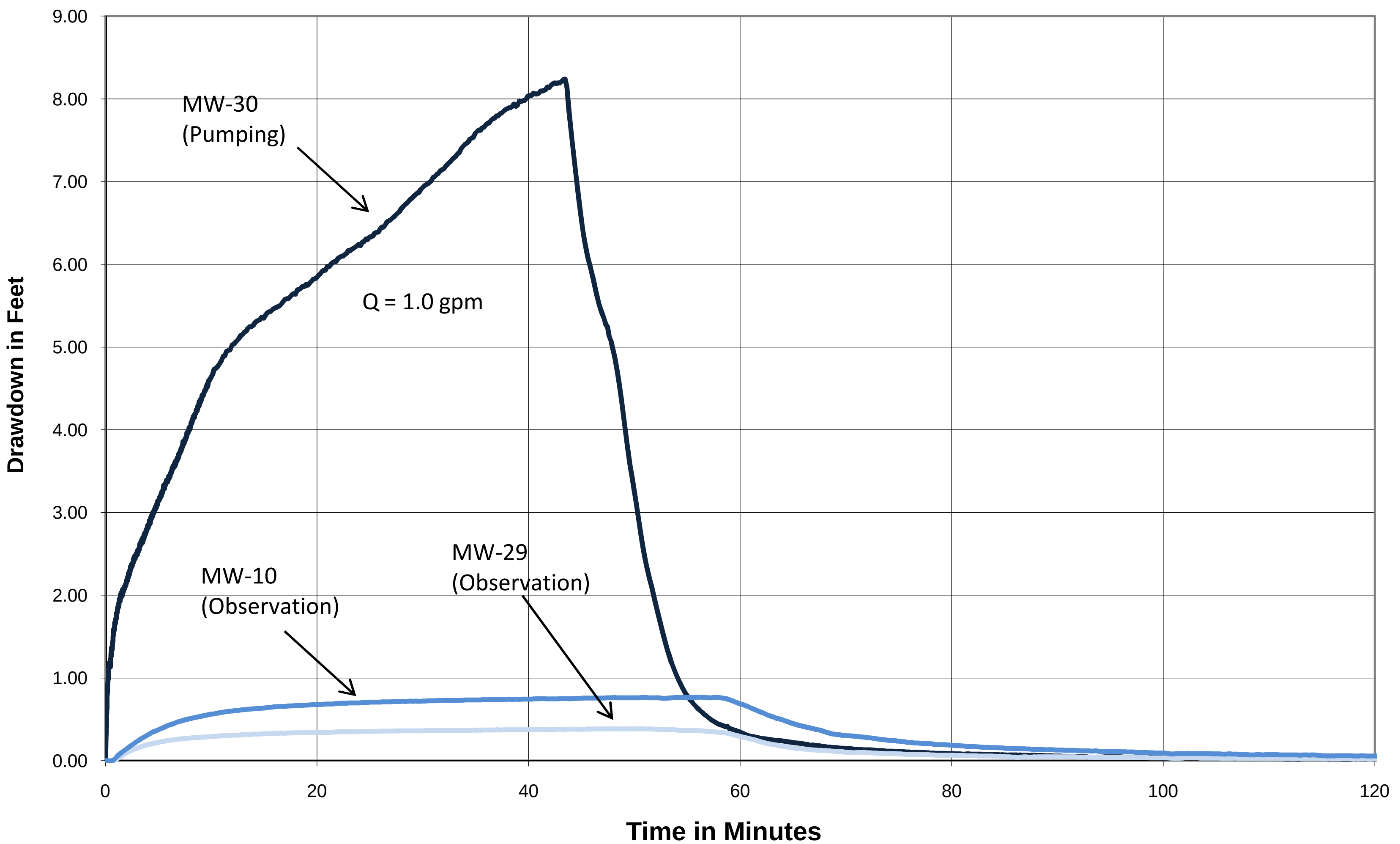

Note: Radial distance from MW-30 to MW-10 (5.39 feet) and MW-29 (10.18 feet).

Figure 11
MW-30 Constant Rate (1.0 gpm) Hydrograph
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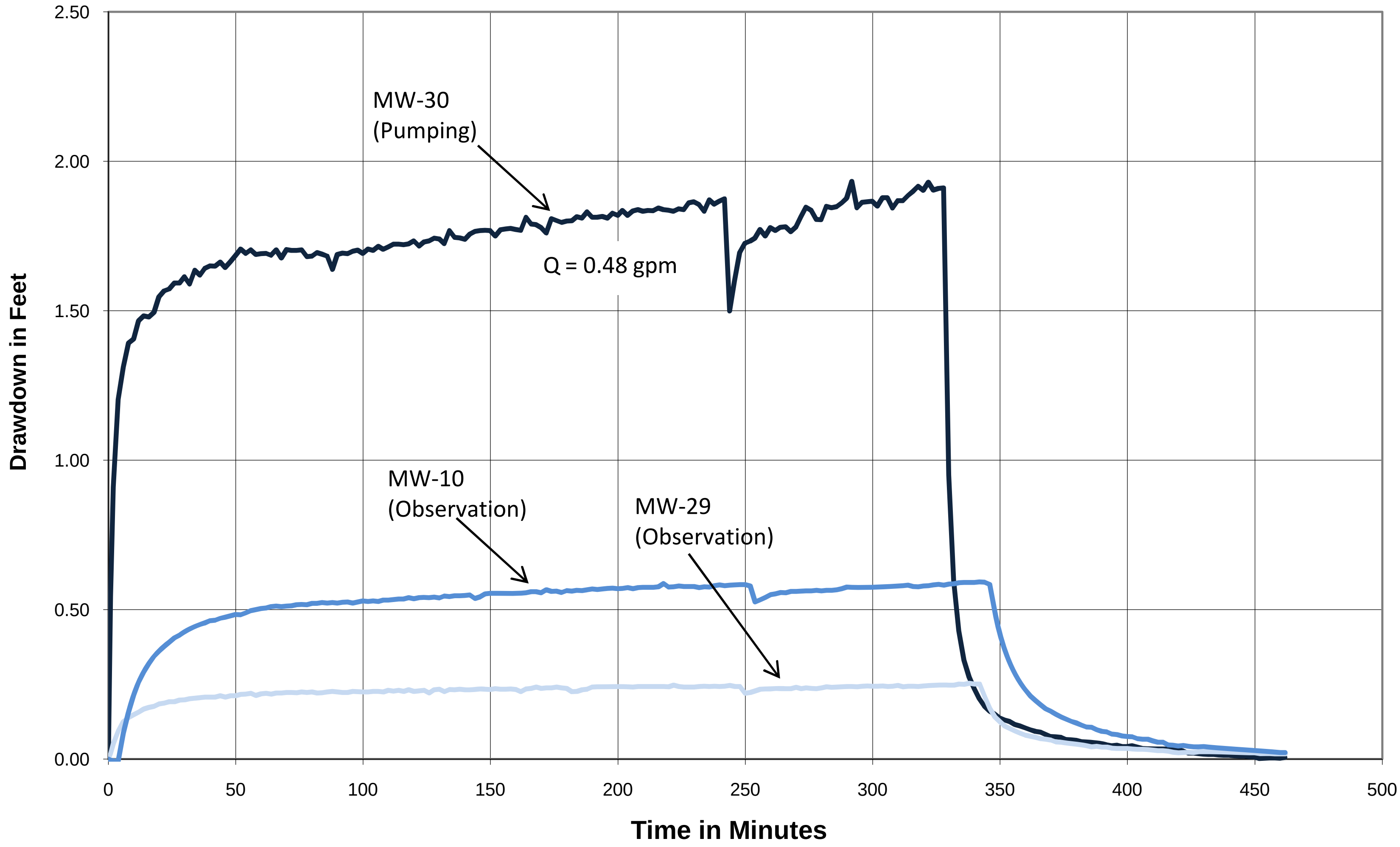

Note: Radial distance from MW-30 to MW-10 (5.39 feet) and MW-29 (10.18 feet).

Figure 12
MW-30 Constant Rate (0.48 gpm) Hydrograph
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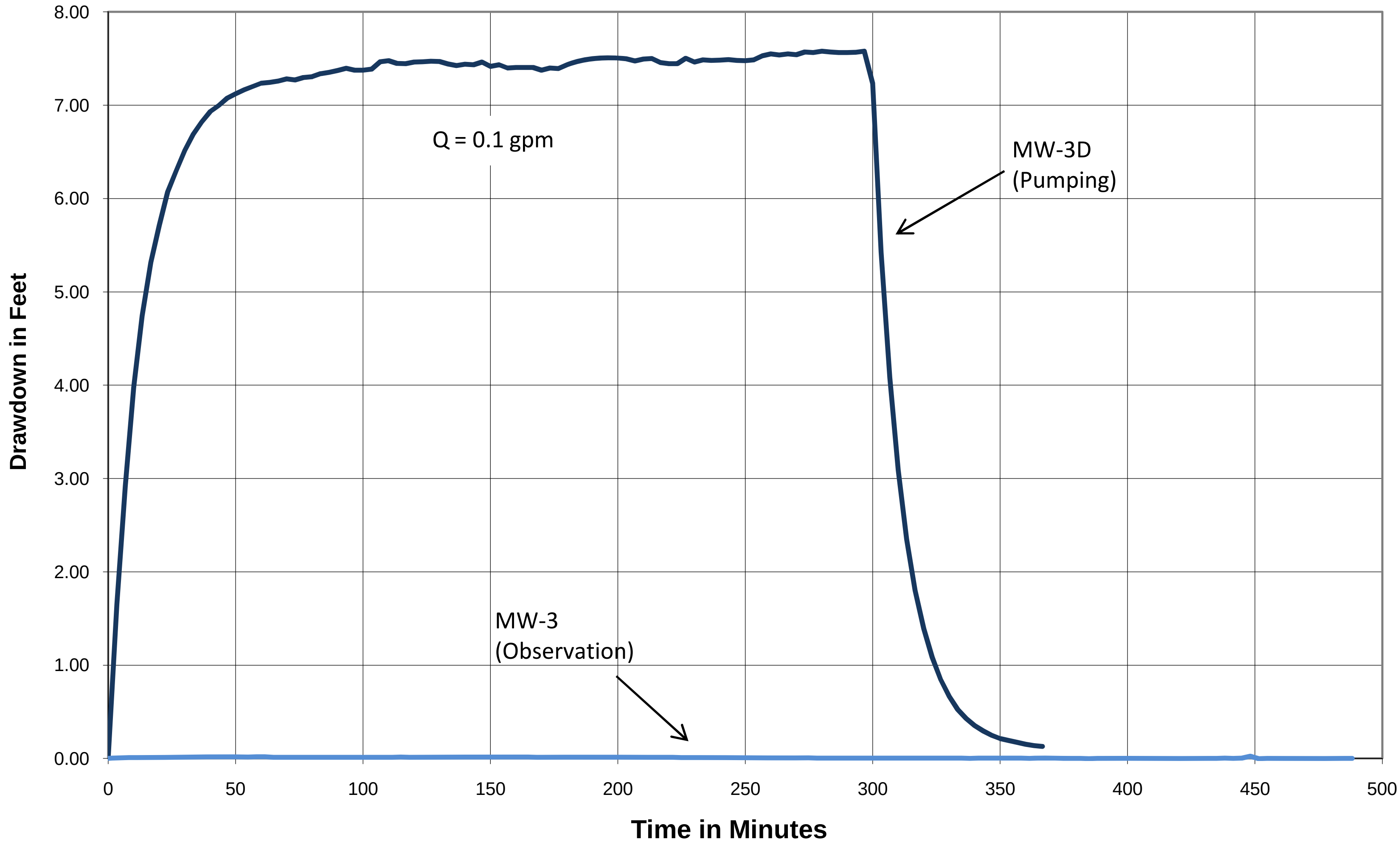

Note: Radial distance from MW-3D to MW-3 is 12.93 feet.

Figure 13

MW-3D Constant Rate (0.1 gpm) Hydrograph

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APPENDIX A

Pumping Test Data Analysis Methods

A.1 Pumping Test Data Analysis Methods

Select data collected from pumping and observation well(s) during each pumping test were used for analysis to estimate transmissivity and storage coefficient of the water-bearing unit. To calculate hydraulic conductivity (= transmissivity divided by effective saturated thickness of water-bearing unit), all analyses assumed a saturated thickness equal to that of the well screen length (typically 10 feet).

Results of the pumping test analysis are presented in Table 1 of the main report. Figures A-1 and A-2 in this appendix present the data observed in MW-30 and MW-10, respectively, in semi-log space for the constant-rate pumping test conducted in MW-30 (0.48 gpm pumping rate). The distance-drawdown analysis for the MW-30 test is illustrated on Figure A-3. The constant rate recovery analysis for the MW-30 test is presented in Figure A-4. Time-drawdown and recovery data from the MW-3D pumping test are shown in semi-log space on Figures A-5 and A-6, respectively.

A summary of each method of data analysis used is included below.

A.1.1 Time-Drawdown Analysis

Data collected from the MW-30 constant-rate pumping test conducted at 0.48 gallons per minute (gpm) was analyzed by fitting time-drawdown data with the most appropriate type curve. The shape of the time drawdown curves deviates from a typical Theis pumping response, suggesting the likelihood of delayed yield flow to the well (unconfined water-bearing unit). Therefore, the Boulton (1963) solution was used to fit the data as illustrated on Figures A-1 and A-2. The analytical method resembles the curve-fitting method described by Kruseman and de Ridder (1994) using the well functions developed by Hunt (2003). This method also allows for the determination of the storage coefficient.

Similar methodology was used in the analysis of the MW-3D constant rate test. However, the shape of the time drawdown curve did not fit any one type curve. Considering the well construction characteristics and surrounding soil profile, several assumptions and conditions underlying standard aquifer test methods are violated. Most notably, the well has a short screen (3 feet), which does not fully penetrate the unit being tested, which creates vertically converging radial flow. Therefore, because no one aquifer model fit well, several type curves were matched to the most appropriate part of the drawdown curve, depending on the characteristic of the solution. The analytical fits to Theis (1935), Boulton (1963), and the Hantush and Jacob (1955) leaky-aquifer solution are illustrated on Figure A-5.

A.1.2 Recovery Analysis

The Cooper and Jacob (1946) straight-line method was used to evaluate recovery data from both MW-30 and MW-3D constant-rate pumping tests. The linear fit to the recovery curve is presented on Figure A-4 for the MW-30 pumping test and Figure A-6 for the

MW-3D test. The line was fit to the portion of the recovery curve deemed most representative of aquifer response during recovery.

A.1.3 Distance-Drawdown Analysis

The Cooper and Jacob (1946) method of distance-drawdown analysis was applied to drawdown data observed in MW-30 and adjacent observation wells (MW-10 and MW-29) after 230 minutes of pumping at 0.48 gpm, resulting in a good linear fit. Due to the low pumping rate, turbulent well losses in the pumping well were assumed negligible.

No discernible drawdown was observed in MW-3 during pumping of MW-3D (Figure 13); therefore, no analysis was performed on the MW-3 data.

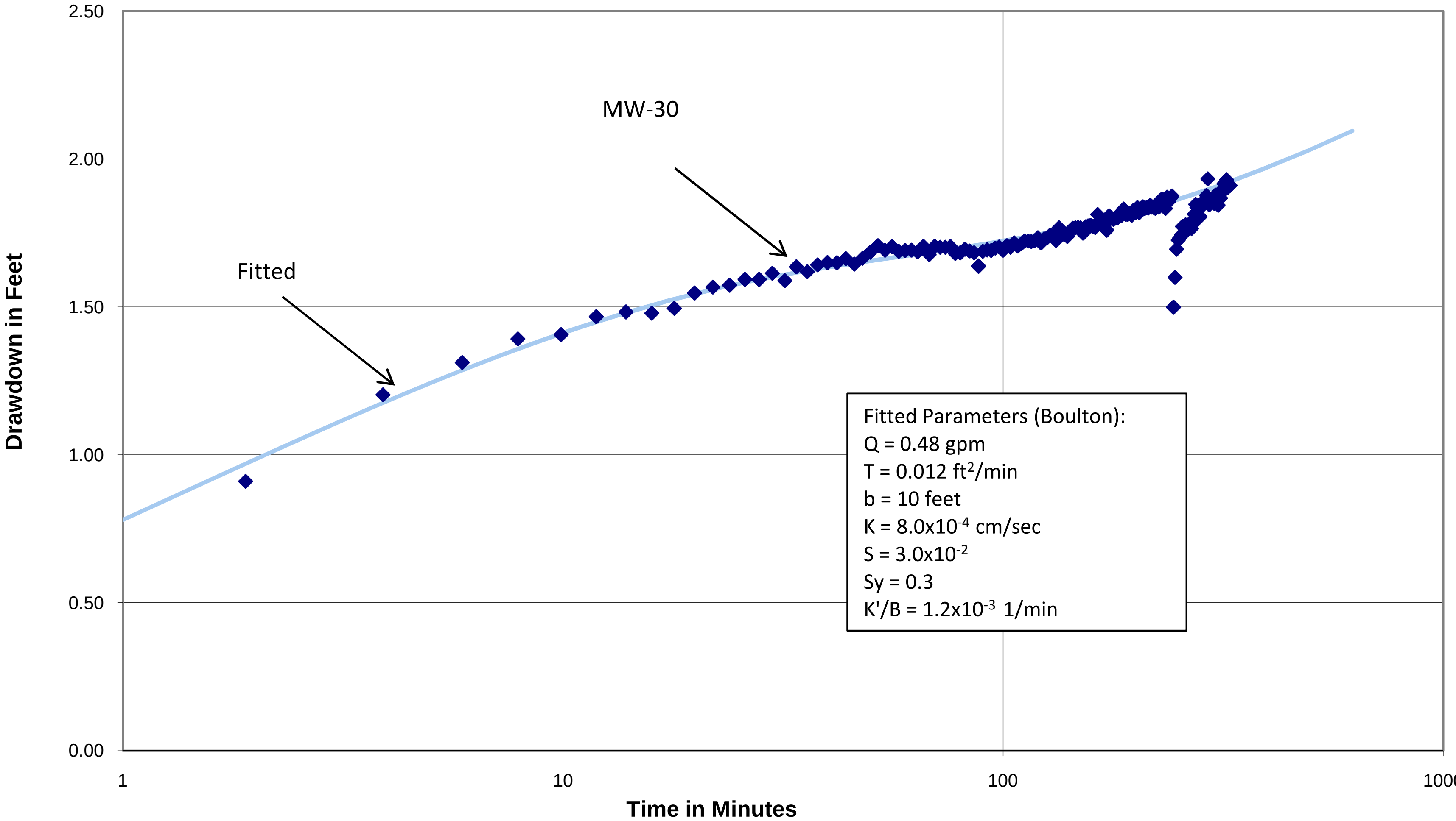

Figure A-1
MW-30 Constant Rate Drawdown
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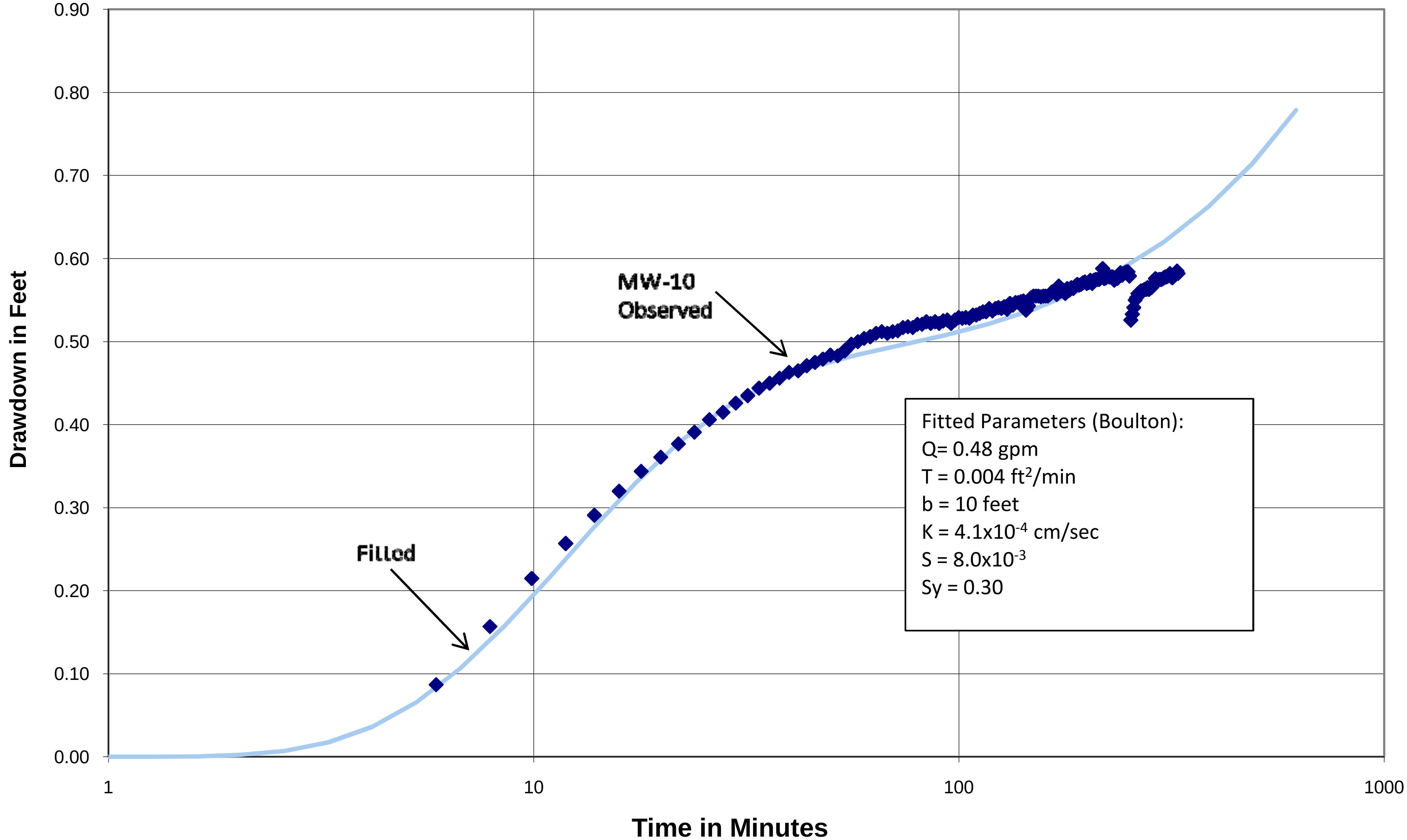

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Figure A-2
MW-30 (MW-10 Observation) Constant Rate Drawdown
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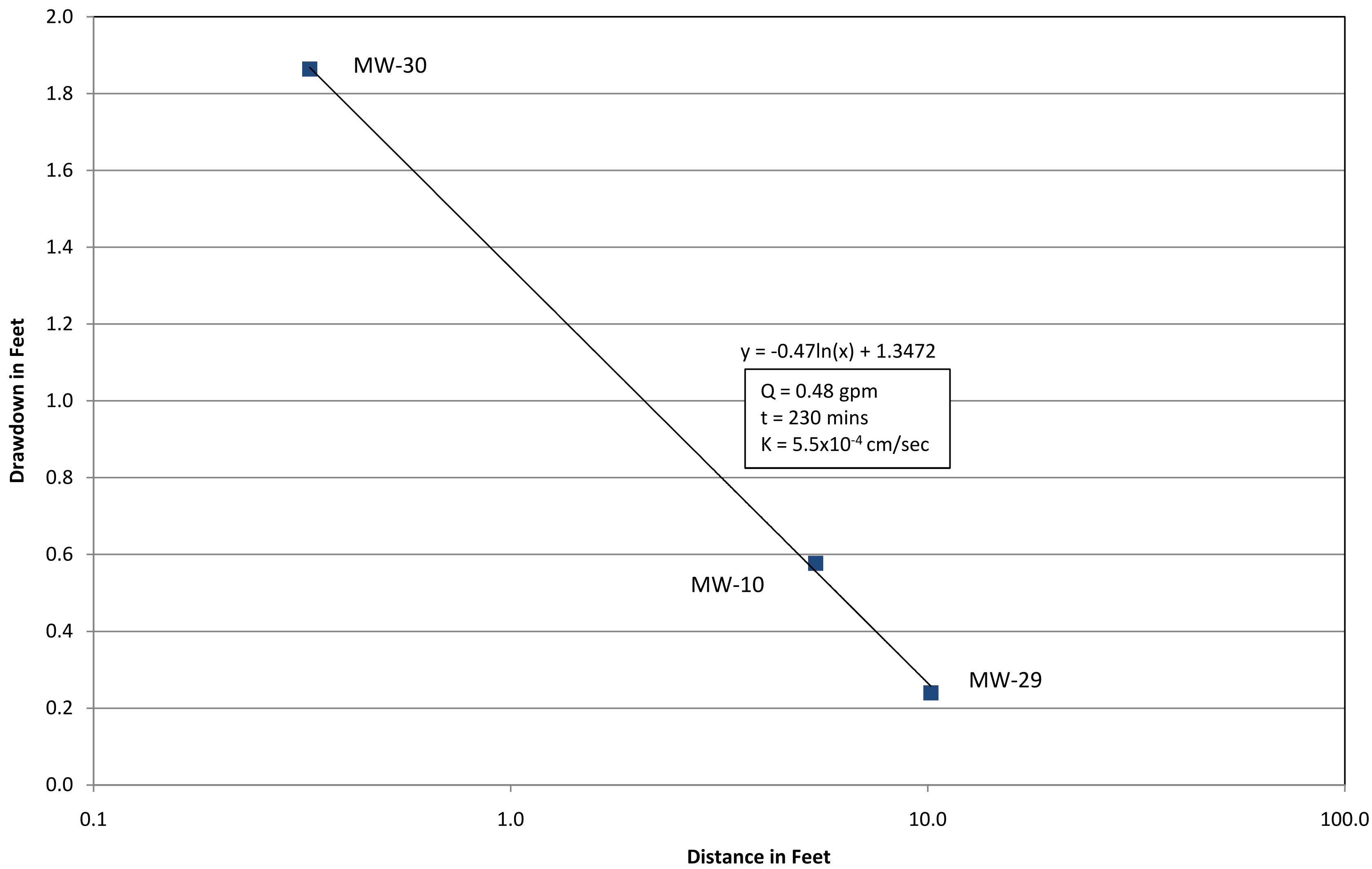

Figure A-3

MW-30 Constant Rate Distance-Drawdown

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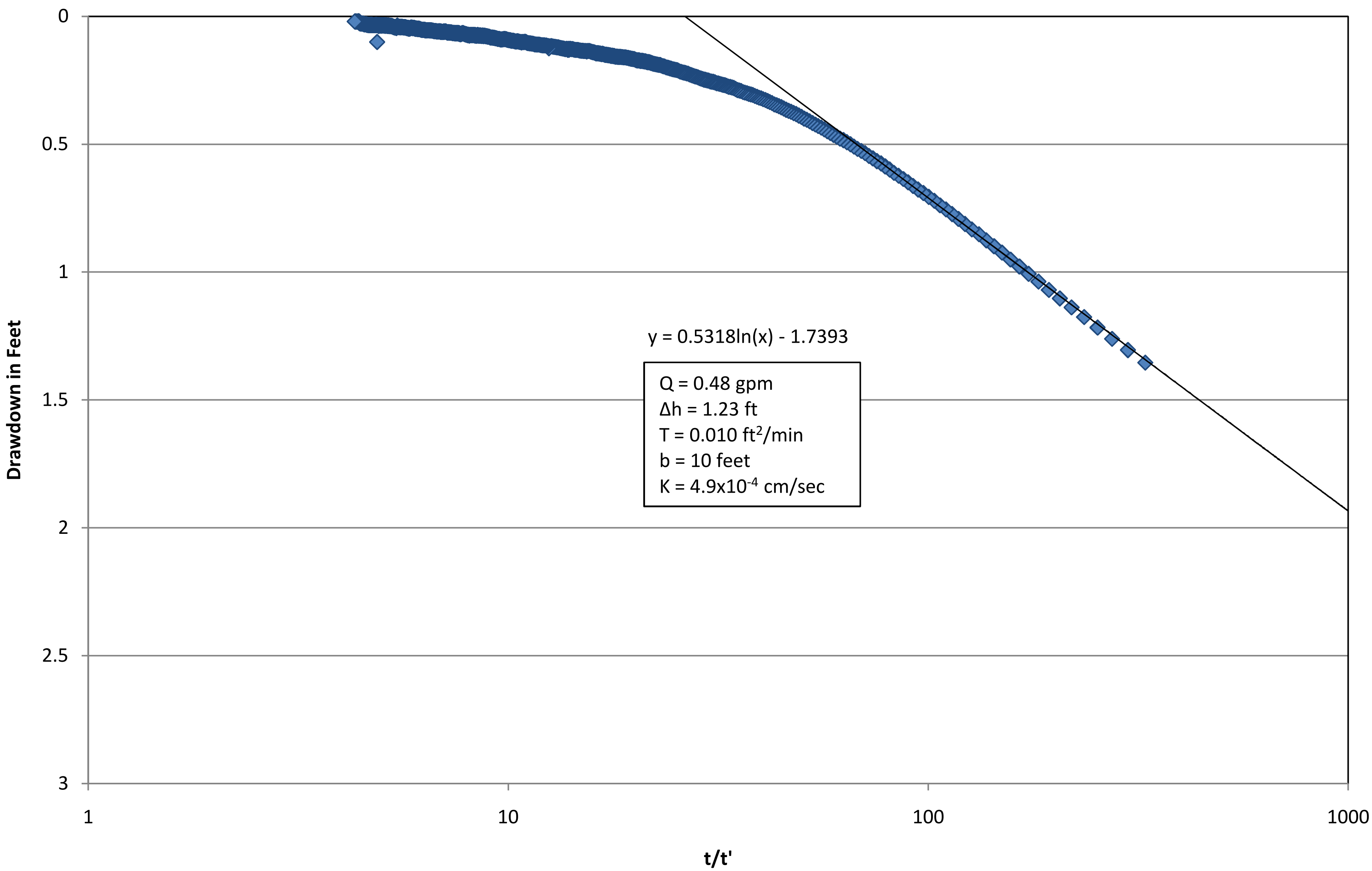

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Figure A-4
MW-30 Constant Rate Recovery
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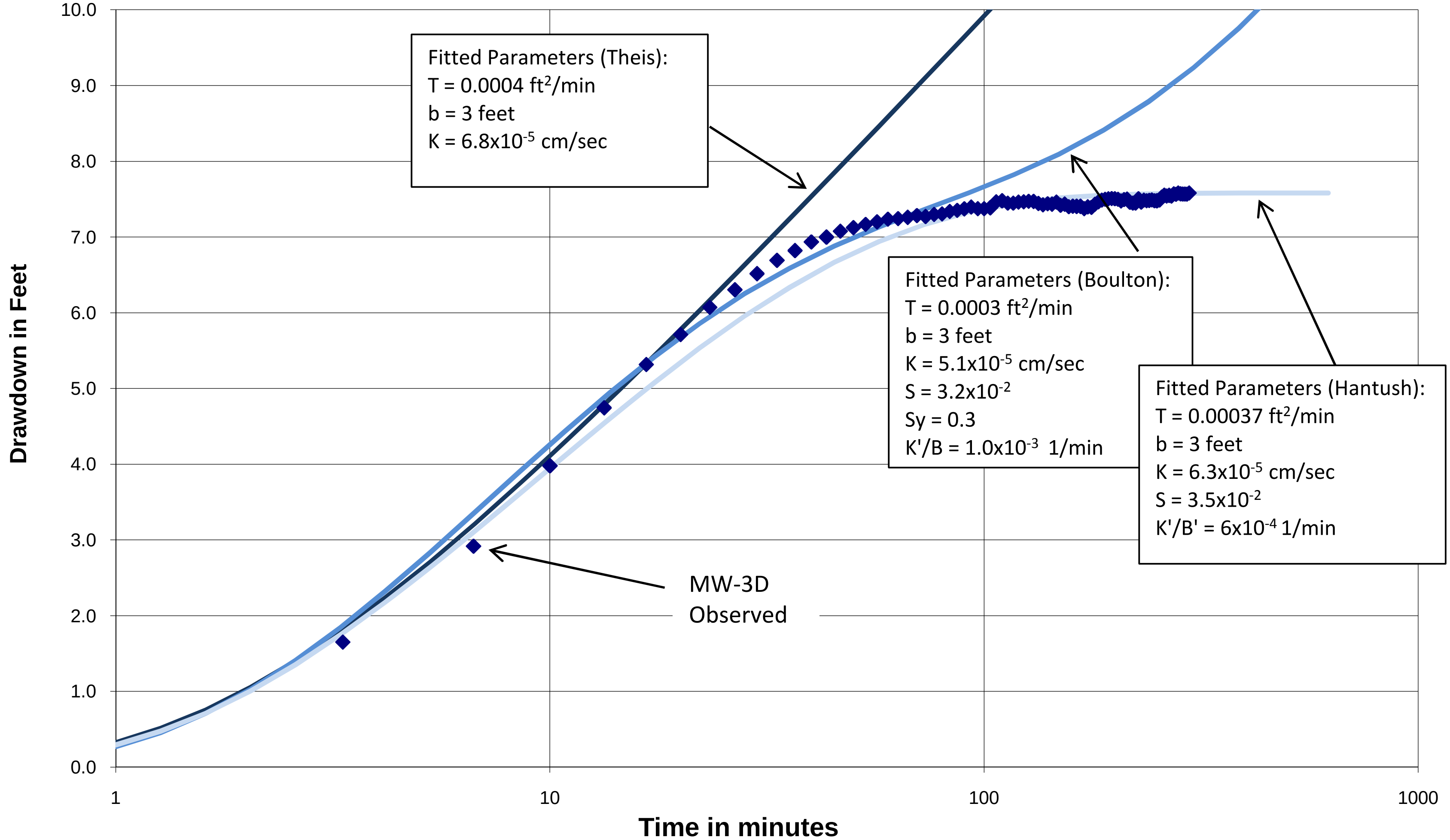

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Figure A-5
MW-3D Constant Rate Drawdown
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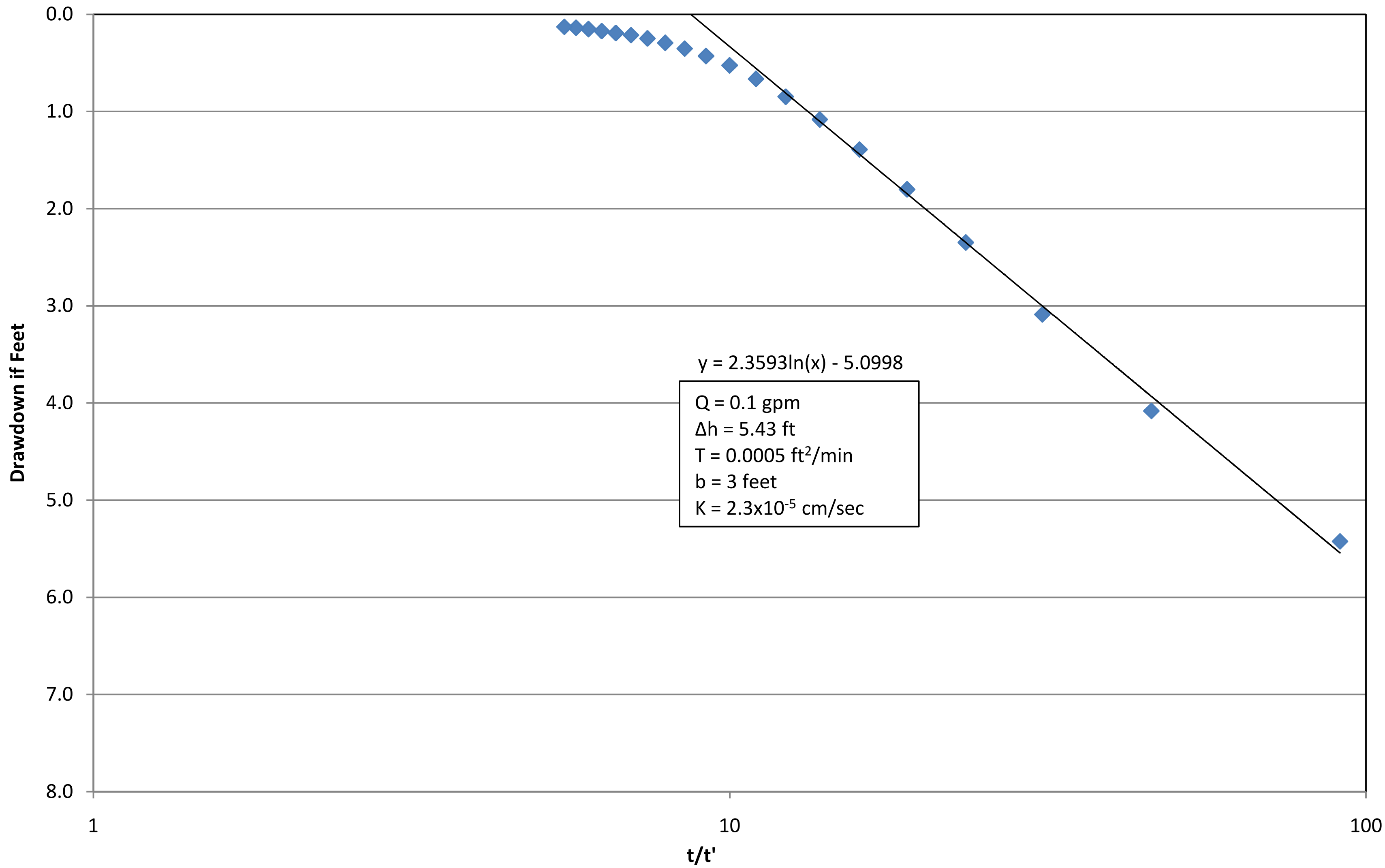

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S:\Floyd Snider\Gas Works 060102\GWSA Groundwater Modeling\Hydro Data Report (Aspect)\Pumping Test Results (Figs A-1 through A-6)

Figure A-6
MW-3D Constant Rate Recovery
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APPENDIX B

Slug Testing Procedures and Analysis Method

B.1 Slug Test Methods

Slug testing was conducted in eight monitoring wells (MW-26 through MW-31, MW-3, and MW-3D) to estimate hydraulic conductivity. The slug test method generally involves quickly displacing a volume of water within the standpipe and monitoring the water level recovery to the “static” condition. The water level recovery data were then reduced to estimate the hydraulic conductivity of the surrounding soil. This method is generally considered to provide an order-of-magnitude estimate of hydraulic conductivity of the water-bearing unit immediately adjacent to the well’s screened interval.

B.1.1 Test Procedure

The standpipe was sealed and the water level was depressed by pressurizing the well casing using a pneumatic instrument specifically designed for this purpose. This pneumatic method typically allows a larger “slug” to be displaced than a conventional physical slug rod. After stable pressure was reached for the displaced water level, an exhaust valve was opened to rapidly release the built-up air pressure, allowing the water level in the well to recover (rise) in the standpipe. Throughout the test, the change in water level was measured with a down-hole 15-psi pressure transducer equipped with a datalogger collecting measurements at 1-second increments. When well construction characteristics did not allow the use of a pneumatic slug (i.e., water table screen), a conventional solid PVC slug rod was used (MW-26 and MW-3).

Before and after the transducer installation, the static water level was manually measured using an electric sounder to verify static conditions. Multiple repeated slug tests were conducted at most wells, and water levels were allowed to stabilize between repeating tests. The criterion for sufficient recovery was considered to be 95 percent of the previous change in head.

B.1.2 Data Analysis

The Bouwer and Rice (1976) method was applied to the slug test data in general accordance with the American Society for Testing and Materials (ASTM) Method D 4104-96. Table 2 in the main report presents the slug test assumptions and results. Figures B-1 through B-8 in this appendix present the slug test hydrographs (field data).

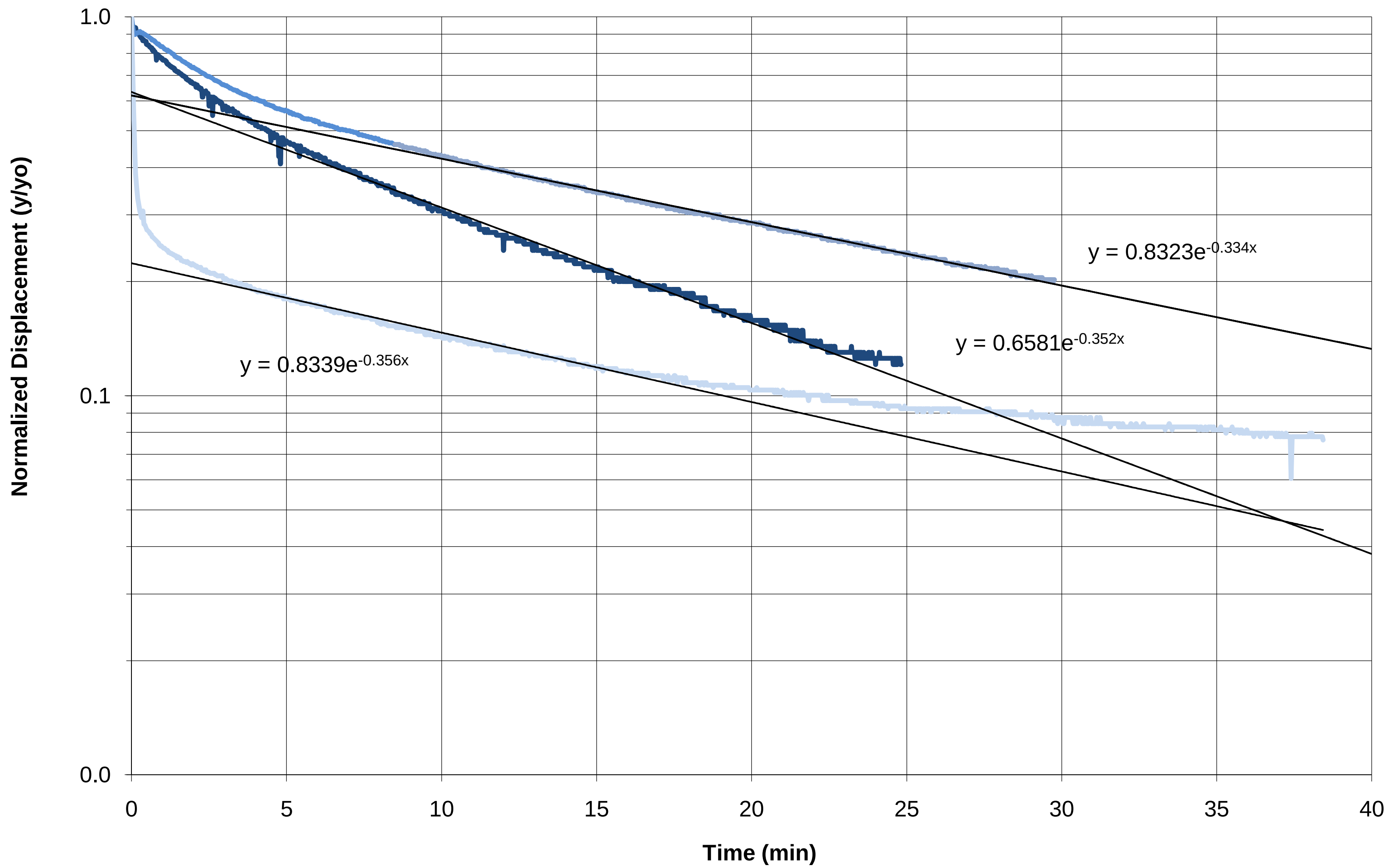

Figure B-1
MW-26 Slug Test Response
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12/14/2010
S:\Floyd Snider\Gas Works 060102\GWSA Groundwater Modeling\Hydro Data Report (Aspect)\Slug Test Results (Figs B-1 through B-8)

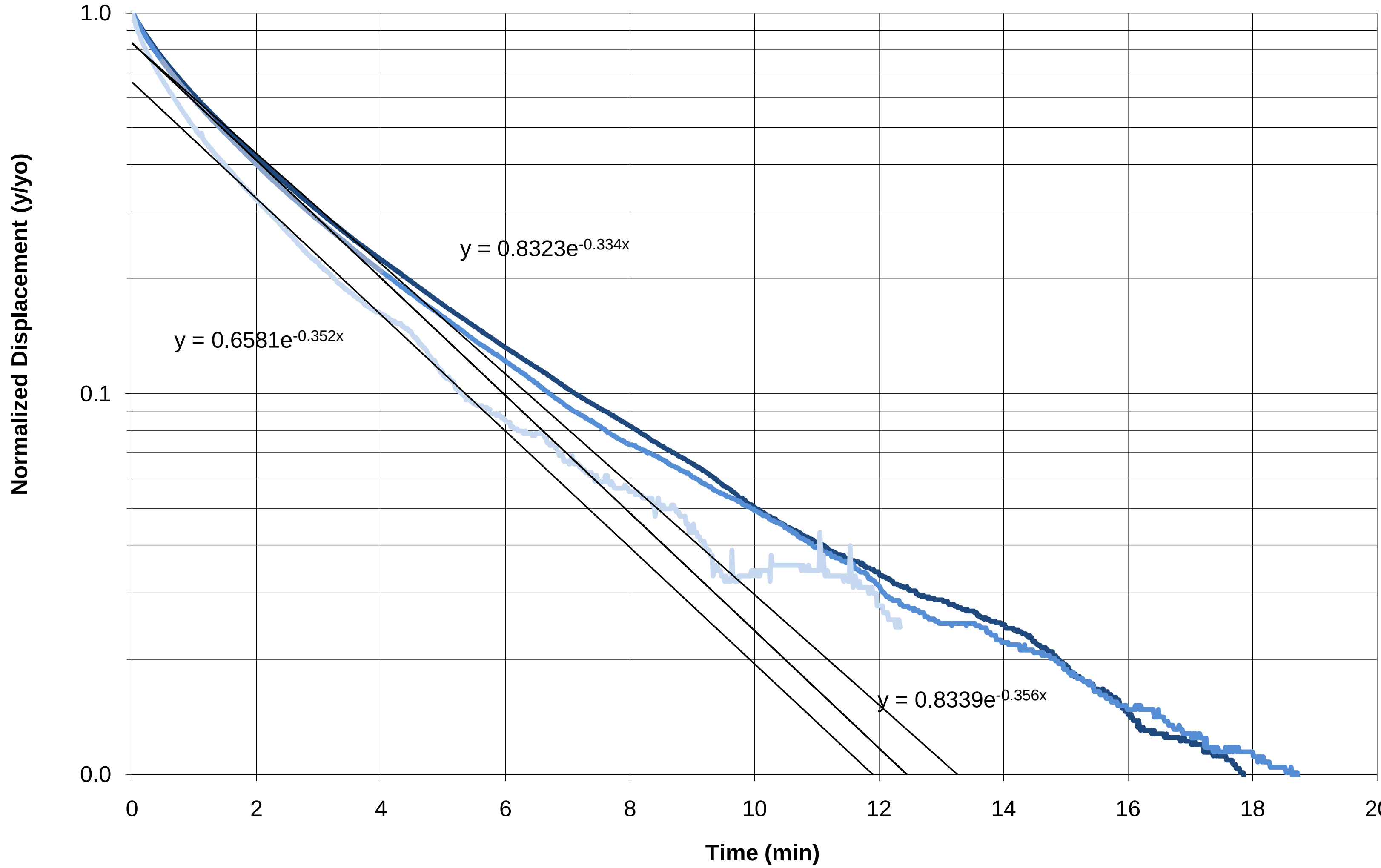

Figure B-2
MW-27 Slug Test Response
Hydrogeologic Investigation
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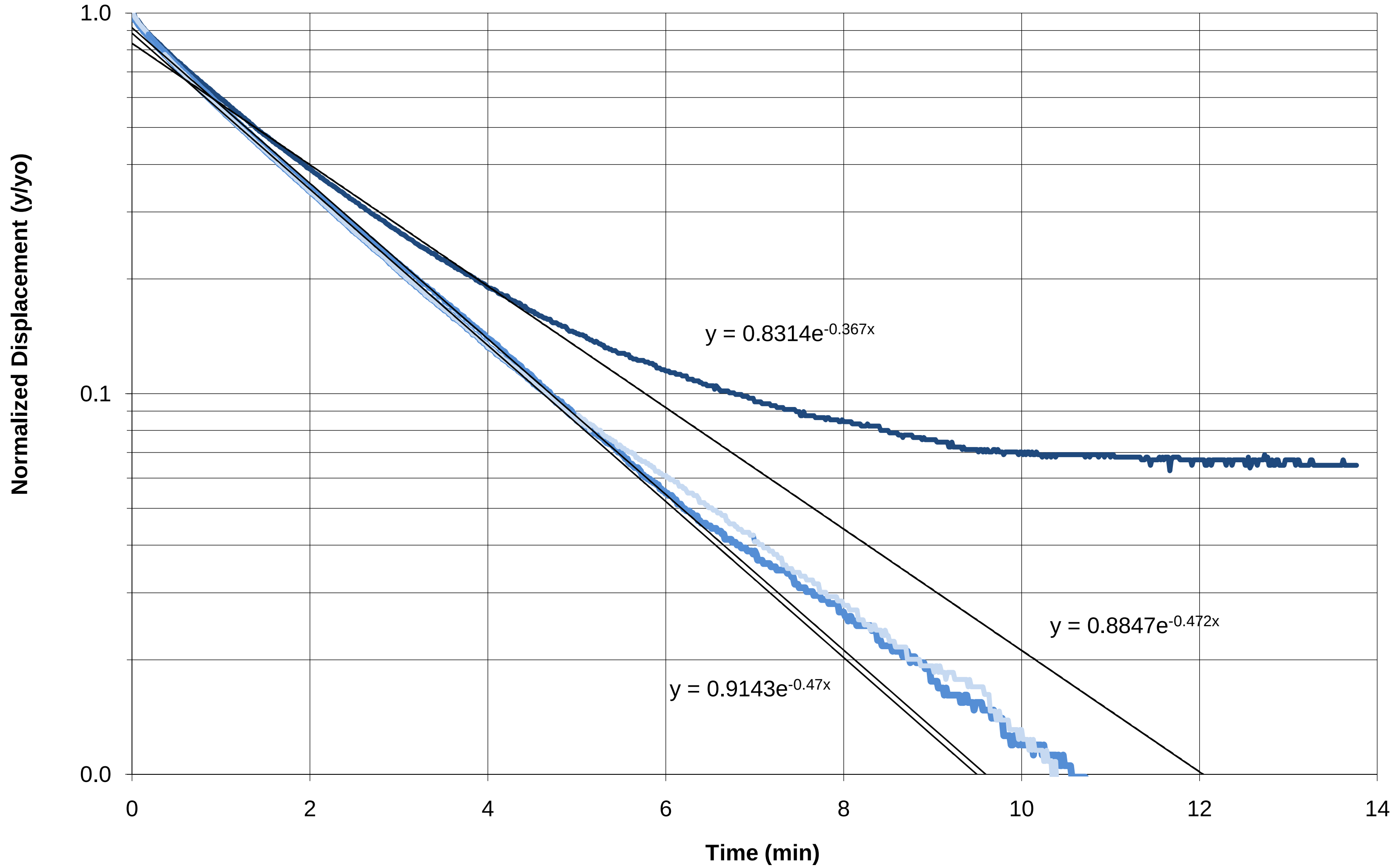

Aspect Consulting
12/14/2010
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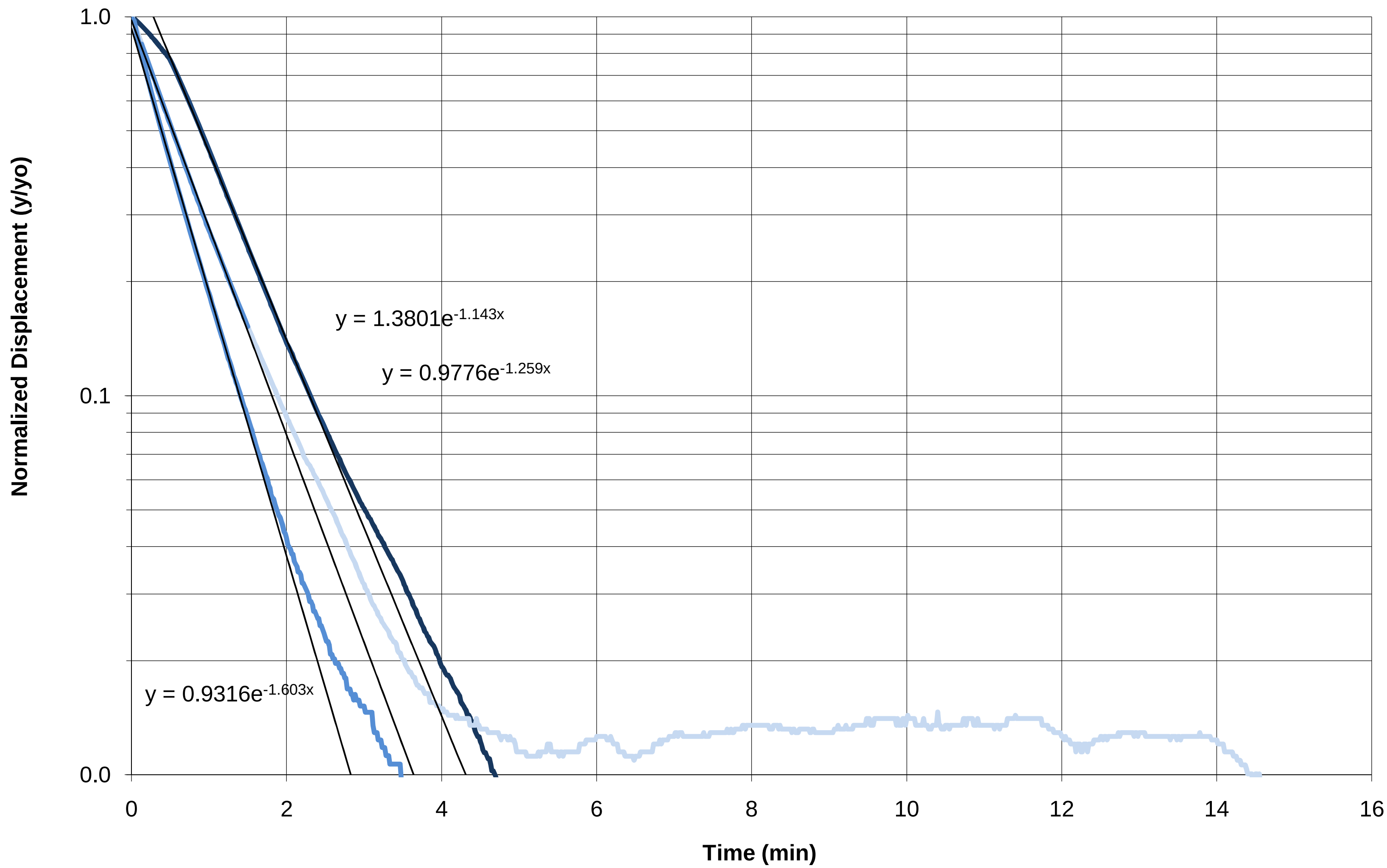
Figure B-3
MW-28 Slug Test Response
Hydrogeologic Investigation
Seattle, WA



Aspect Consulting
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Figure B-4
MW-29 Slug Test Response
Hydrogeologic Investigation
Seattle, WA

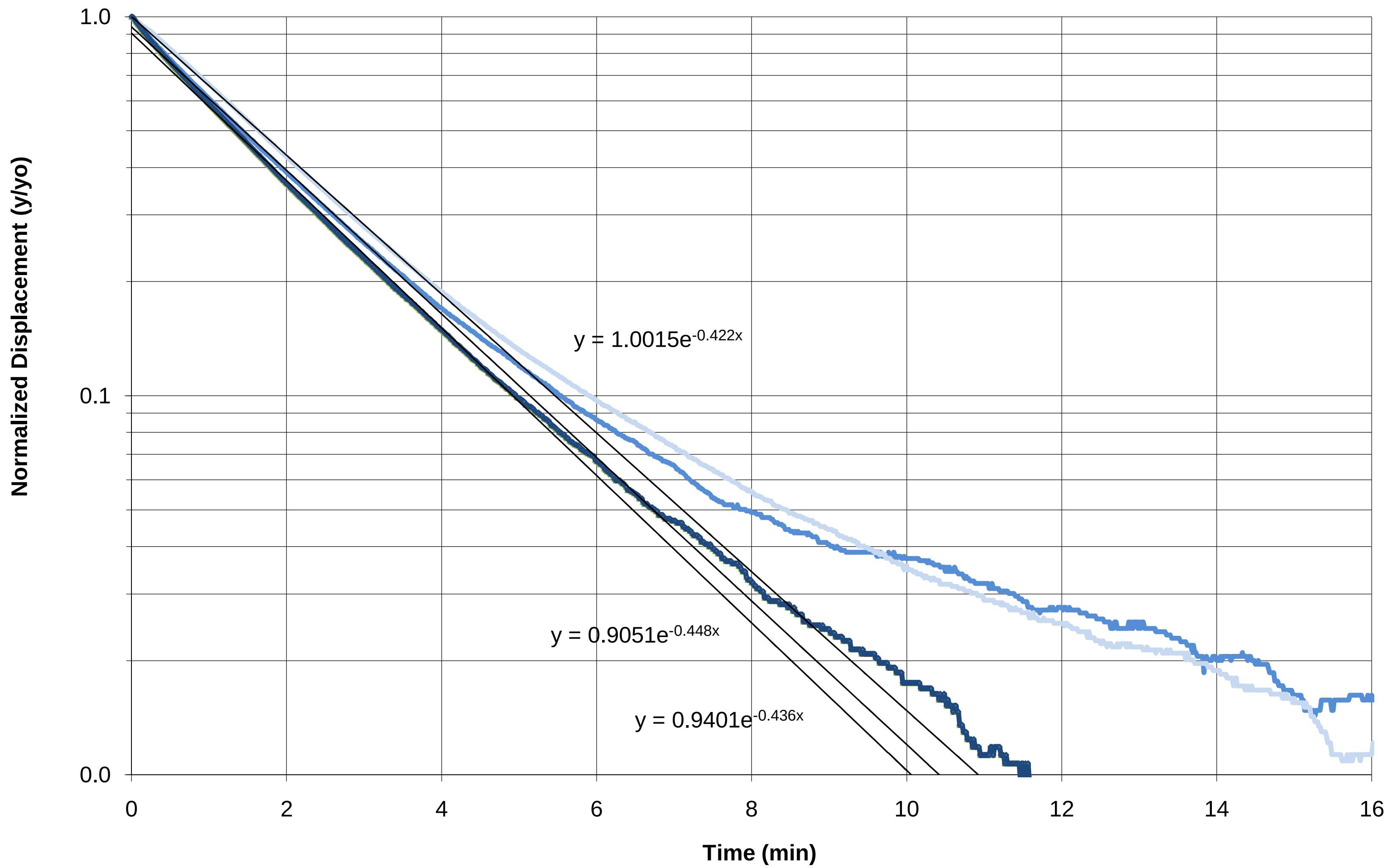

Figure B-5
MW-30 Slug Test Response
Hydrogeologic Investigation
Seattle, WA

Aspect Consulting
12/14/2010
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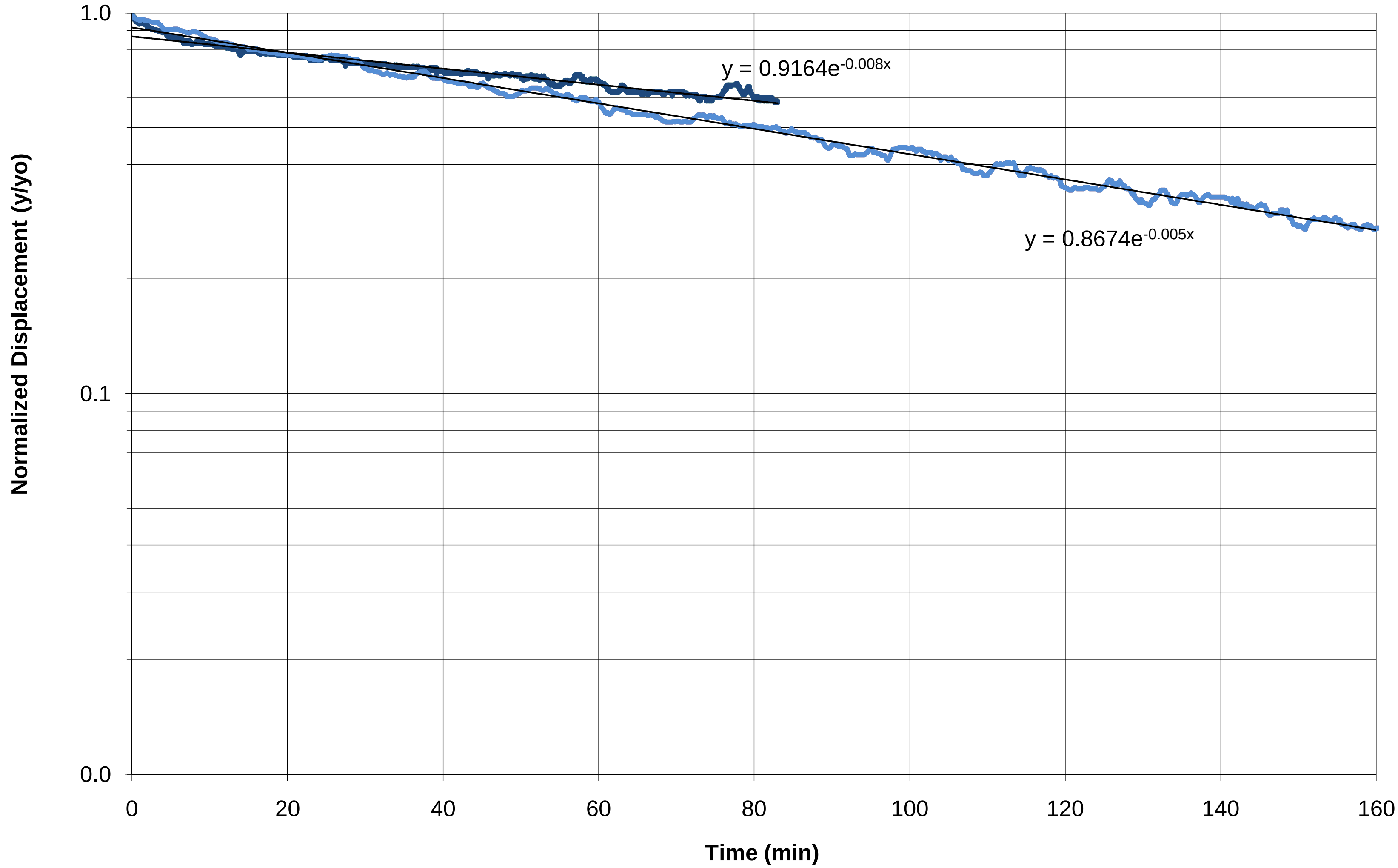

Aspect Consulting
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Figure B-6
MW-31 Slug Test Response
Hydrogeologic Investigation
Seattle, WA

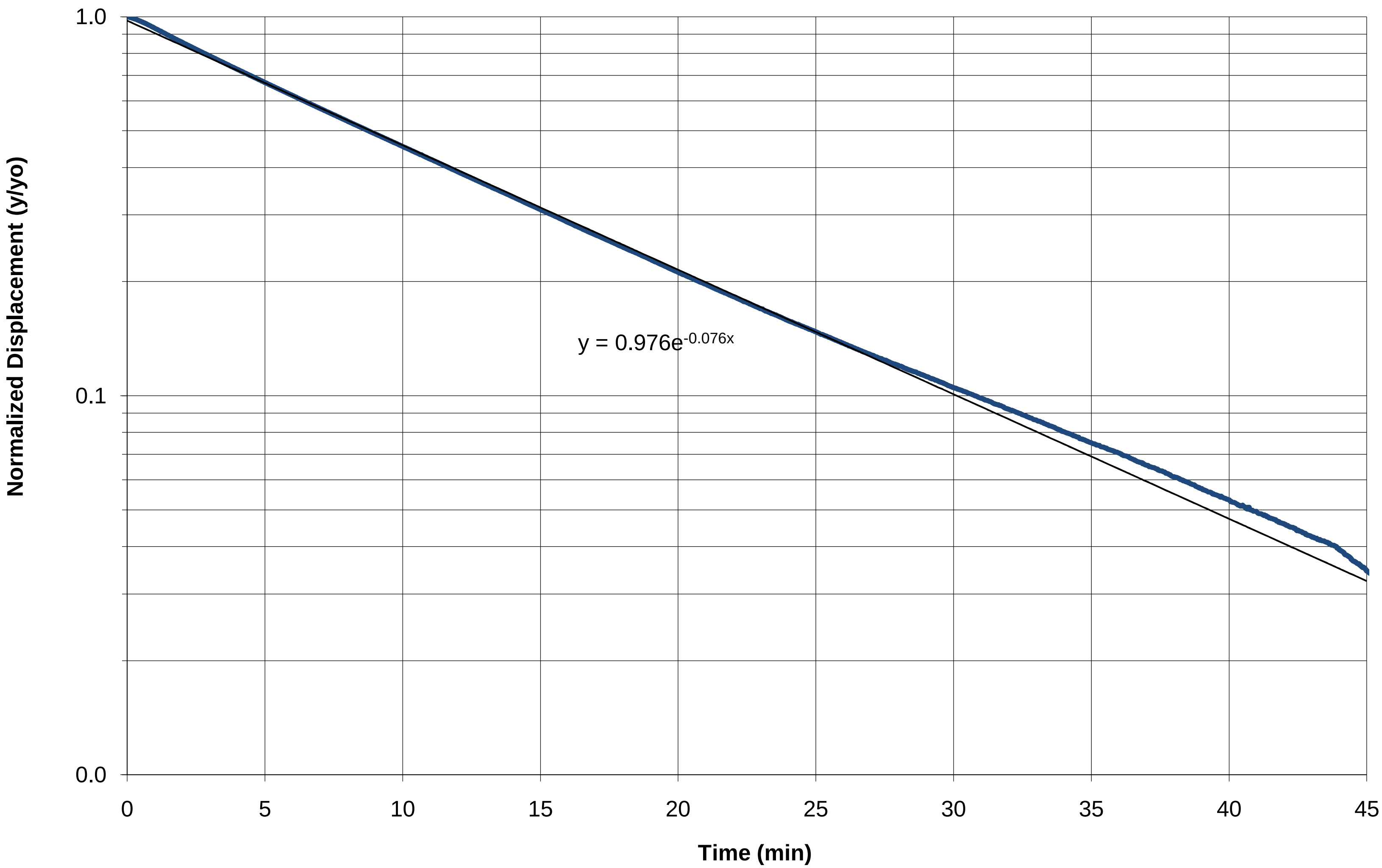

Figure B-7
MW-3D Slug Test Response
Hydrogeologic Investigation
Seattle, WA

Aspect Consulting
12/14/2010
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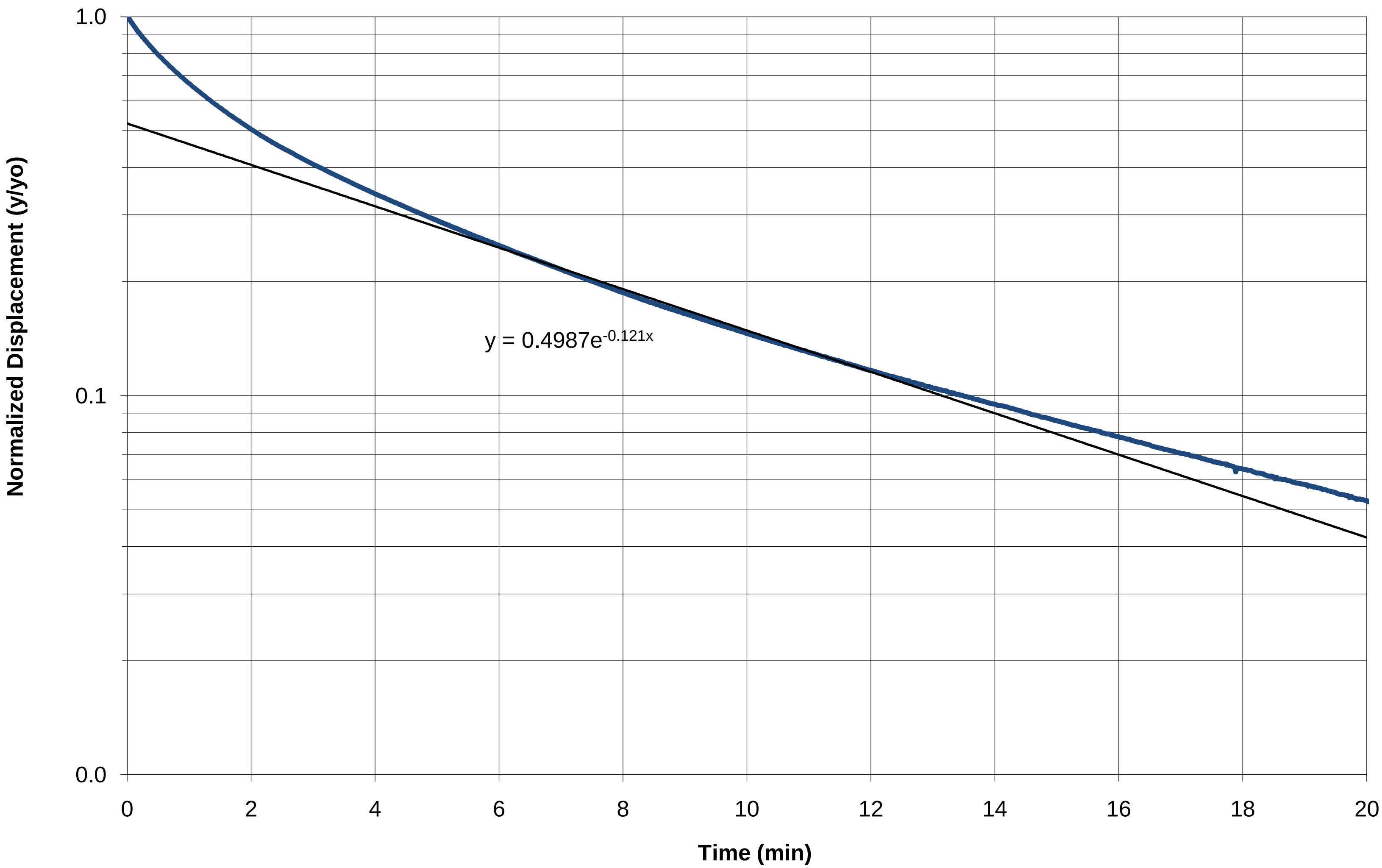

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Figure B-8
MW-3 Slug Test Response
Hydrogeologic Investigation
Seattle, WA