HYDRAULIC SOURCE CONTROL AND CONTAINMENT SYSTEM GROUNDWATER MODEL UPDATE REPORT NW NATURAL GASCO SITE

Prepared for

NW Natural

Prepared by

Anchor QEA, LLC

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LIST OF ACRONYMS AND ABBREVIATIONS

CDR	*Revised Groundwater Source Control Construction Design Report*
CHD	time-variant specified head
DEQ	Oregon Department of Environmental Quality
EPA	U.S. Environmental Protection Agency
HAI	Hahn and Associates, Inc.
HC&C	hydraulic control and containment
LNG	liquefied natural gas
Plan	Groundwater Source Control Extraction System Test Plan
PLC	programmable logic control
RAO	Remedial Action Objective
Report	Hydraulic Source Control and Containment System Groundwater Model Update Report
Site	Gasco site
WBZ	water bearing zone

1 INTRODUCTION

1.1 Background

The Oregon Department of Environmental Quality (DEQ) and the U.S. Environmental Protection Agency (EPA) provided comments in July 2012 in response to the groundwater model documentation provided as Appendix F of the *Revised Groundwater Source Control Construction Design Report* (CDR; Anchor QEA 2012). DEQ and EPA also provided responses to NW Natural's responses to DEQ and EPA's comments on the groundwater model development report provided as part of the *Draft Groundwater Source Control Final Design Report* (Anchor QEA 2011). In Section 3.2.3 of the CDR, NW Natural proposed to update the model with aquifer property information derived from the step drawdown tests conducted on the extraction wells.

Construction of the source control extraction wells, pipelines, and control system is complete. This Hydraulic Source Control and Containment System Groundwater Model Update Report (Report) describes the work accomplished to update the model with new information from installation and testing of new extraction wells, monitoring wells, and piezometers that have been installed since the submittal of Appendix F to the CDR. This Report was prepared consistent with the *Groundwater Model Update Plan* submitted to DEQ on February 15, 2013 (Anchor QEA 2013a) and was also prepared consistent with DEQ and EPA's April 8, 2013 comments on the update plan, as addressed in NW Natural's May 24, 2013 response to comments memorandum (Anchor QEA 2013b).

This Report is a companion to the Groundwater Source Control Extraction System Test Plan (Plan) that is scheduled for submittal to DEQ on August 1, 2013. That Plan describes the design of a two-phase program of testing the extraction system that will take approximately 1 year. Section 3.1 describes how the Plan is designed to provide a calibration dataset for the groundwater model.

The Plan also describes the Remedial Action Objectives (RAOs) for groundwater source control measures. On page 7, paragraph 1, of DEQ's September 22, 2011 letter, DEQ states that the RAOs for groundwater source control are as follows:

1. prevent migration of contaminated groundwater from the uplands to the Willamette River along shoreline Segments 1 and 2, in a manner that;

2. minimizes [dense non-aqueous phase liquid] DNAPL mobilization resulting from groundwater [source control measures] SCMs along the portion of Segment 1 where DNAPL occurs.

1.2 Previous Model Development Efforts

Groundwater modeling has been an integral part of the evaluation of remedial technologies for the Gasco site (Site). The model has evolved over time with increasing refinement as new data became available, in response to DEQ and EPA comments and as new objectives for remedial actions were developed. The following subsections summarize the groundwater modeling effort at the Site. The summary is organized by the year when major model refinements were made.

1.2.1 *2007 Model*

The initial groundwater flow modeling analysis for the Site was prepared in 2007 to evaluate the feasibility of controlling Site groundwater using an extraction system in possible combination with a containment wall. The 2007 model boundaries extended from the foot of the Tualatin Mountains at Highway 30 to the southwest of the Site and across the Willamette River navigation channel to the northeast. The model extended from the BNSF Railway bridge over the river upstream of the Siltronic property to the boat basin on the U.S. Moorings property downstream of the Site.

The model used a 40- by 40-foot uniform grid and consisted of 14 model layers extending from the ground surface to bedrock. One model layer represented the Fill water bearing zone (WBZ), two model layers represented the shallow silt, and the remaining model layers represented the Alluvium WBZ. The Alluvium WBZ was divided into a relatively low hydraulic conductivity Upper Alluvium WBZ and a higher conductivity Lower Alluvium WBZ. The Lower Alluvium WBZ in the model extended upland approximately 200 feet from the river based on the change in water level gradients between upland and nearshore wells. Model layers within the Alluvium WBZ were set at specific depth intervals related to the depth of proposed containment walls and various screen intervals of extraction wells.

Model boundaries included the following:

- Areal recharge (this recharge boundary is constant across the entire model domain)
- Steady-state constant head in the river

- Constant heads along the upland boundary at Highway 30 of the Upper Alluvium WBZ
- No flow boundaries at the upstream river bridge and downstream U.S. Moorings boat basin model boundaries where groundwater flow is expected to be approximately parallel to the model boundary
- No flow at the lower model boundary (bedrock)

In addition, a general head boundary was applied to the Upper Alluvium WBZ layers on the east side of the river to represent groundwater flow to the river from that direction.

The above-described model structure with respect to model layers and boundary conditions continued to be used in the post-2007 modeling except for the refinements described in Sections 1.2.2 through 1.2.4.

1.2.2 *2008 Model*

The model was refined in 2008 to extend the Lower Alluvium WBZ hydraulic conductivity zone to the upland model boundary at Highway 30 and to increase the Upper Alluvium WBZ hydraulic conductivity by 50 percent. These changes were made in response to comments from DEQ concerning the difference between the upland boundary flux in the model compared to predicted flux in the vicinity of the Site in a regional model developed by the U.S. Geologic Survey (Morgan and McFarland 1996).

The 2008 model was used to simulate the pumping test at extraction well PW-3 (designated as PW-4 at that time). In this model application, the river boundary condition was changed from a steady-state constant head to a time-varying constant head. After 2008, both steady-state and time-varying constant head boundary conditions were used for the river boundary depending on whether the simulation was for a steady-state or transient application.

1.2.3 *2009 Model*

The model was refined in 2009 to include the liquefied natural gas (LNG) basin sump and the Alluvium WBZ aquitard. The basin was incorporated using the MODFLOW drain package. The drain package conductance was calibrated to dry weather LNG basin flows when the flow at the sump is due to groundwater entering the sump.

The Alluvium WBZ aquitard was identified in TarGost borings at an elevation of approximately -100 to -120 feet. The model layering was modified to represent the depth, thickness, and extent of the Alluvium WBZ aquitard. This model was used in support of the *Groundwater Source Control Interim Design Report* (Anchor QEA 2009).

1.2.4 *2011 Model*

Between 2009 and 2011, the groundwater flow model was changed in several ways to address DEQ comments on the *Groundwater Source Control Interim Design Report*. These changes included the following:

- The model area was extended in the downstream direction to include the U.S. Moorings site. The original model extended approximately mid-way through the U.S. Moorings site.
- The model grid spacing was redefined from 40 by 40 feet to 20 by 20 feet. As in the original model, a uniform grid spacing was used throughout the model area.
- The hydraulic conductivity of the Upper Alluvium was modified to represent spatial heterogeneity observed in pumping test results at PW-1-80, PW-3-85, and PW-8-39.

The 2011 model was used in support of the *Groundwater Source Control Interim Design Report* and the *Draft Groundwater Source Control Final Design Report* (Anchor QEA 2009, 2011).

1.3 Objectives and Scope of the Current Model

The constructed hydraulic control and containment (HC&C) system is designed to contain Site groundwater by extraction wells screened in the Upper and Lower Alluvium WBZ. The extraction wells will be controlled by a programmable logic control (PLC) system that will operate the pumps to maintain a water level difference (ΔH) between the river and selected monitoring wells known as control wells. Transducers in the control wells and a transducer at an in-river stilling well will be connected to the PLC, which will monitor the water level difference between each control well and the river. If the water level difference at a control well is less than ΔH, then the PLC will increase the pumping rate at the extraction well that is assigned to that control well. The objective is to maintain a net average gradient from the river to the HC&C system, which will ensure that Site groundwater is contained.

The groundwater model in this report is being developed to serve as a mechanistic tool that can support the evaluation of system-wide containment of groundwater under a range of operating

conditions. Specifically, it will be used to evaluate whether the selected ΔH values between the HC&C wells and the river attain groundwater containment across tidal and seasonal fluctuations in water surface elevation at the Willamette River. The model will also serve as a basis for identifying long-term operational parameters (for example, ΔH) for the HC&C system. In addition, in conjunction with data analysis from the full-system start-up tests described in the Plan (Anchor QEA 2013), the model will be applied to provide guidance on selecting wells from the suite of existing wells to support a long-term monitoring program.

To support the objectives, the 2011 model has been redeveloped to consider new information that has become available during the construction and the extraction system and will be calibrated and applied under transient conditions. This report describes the redevelopment of the 2011 model. From hereon the redeveloped 2011 model is referred to as the current model. The dataset for calibration will be collected during full system start-up testing. Details of the full system testing are described in the Plan. Details of the transient calibration of the current model will be documented in 2014 after the completion of the initial phase of full system start-up tests.

2 MODEL DEVELOPMENT

The current model was redeveloped to use improved interpretations of the stratigraphic units obtained from the installation and testing of the extraction wells, monitoring wells, and piezometers.

2.1 Model Grid Development

The current model footprint is unchanged from the 2011 groundwater model (see Section 1.2.4), which was developed for the CDR (Anchor QEA 2012). Figure 1 shows the domain for the current model. It extends from the BNSF Railway bridge upstream of the Siltronic property to the downstream side of the small boat basin in the U.S. Moorings property and from the foot of the Tualatin Mountains at Highway 30 southwest of the Site and across the navigation channel to the northeast. Horizontally, the model grid cells are developed at a uniform spatial resolution of 20 by 20 feet. The vertical resolution of the model is described in greater detail in the following sections.

2.1.1 *Model Layering*

The layers of the current model were refined to reflect the constructed screen intervals of the extraction wells. Overall, the current model contains 12 layers of varying thickness. The layer thicknesses were adjusted in the vicinity of extraction wells to entirely capture the screen interval within one model layer. The layering in the current model differs from the 2011 model in that the layers in the current model follow the topography, and therefore, the stratigraphic units are not necessarily limited to a single or few layers that pinch out toward upland, as in the 2011 model.

2.1.2 *Revisions to Geological Contacts*

Interpretations of geological contacts were revised following issuance of the CDR using new lithology information from the geologic logs of newly completed extraction wells, monitoring wells, and piezometers. Figure 2 shows the locations of all the borings that were used in developing and revising the stratigraphic interpretations. The revisions focused on improving the interpretation for all stratigraphic units to the extent the new wells provided additional information for each unit.

The revised interpretations of the alluvial soil layers from the new borings were applied to refine the contacts between the hydrogeologic WBZs in the model. The new data did not

change the sequence or nomenclature for the WBZs, but the thickness, elevation, and lateral extent of some of the alluvial layers were modified. Based on the new geologic information the WBZ contact elevations were adjusted in the model.

Figures 3a, 3b, and 3c show the up to date boundaries of the geological contacts along Section A-A′, which is parallel to the Willamette River near the top of the riverbank (see Figure 2 for location of cross sections). Figure 4 shows the stratigraphic zones represented in Row 59 of the model; the location of Row 59 near the shoreline is about the same as Section A-A′ on Figure 3. The lower boundary of the bottommost layer of the model is the contact with the basalt bedrock, which is not shown in the model cross sections, but coincides with the bottom of the cross section shown on Figure 4. Figure 4 shows that the WBZs and the extraction well screen zones are correctly represented in the model. Not all of the wells shown on Figure 3 are represented on Figure 4 because some wells are projected onto the Figure 3 cross section, whereas Figure 4 accurately preserves the spatial locations of the wells in the model. Thus, some of the extraction wells were placed in adjacent model rows (Rows 57 through 61), depending on the surveyed coordinates of the wells.

Figures 5 through 10 show subsurface geology and the corresponding translations to the model at cross sections B-B′, C-C′, and F-F′ that are oriented from upland to the Willamette River. These cross sections cover extraction wells PW-8-39 and PW-8-68, PW-6-U and PW-6-L, and PW-3-U and PW-3-118, respectively. As with some of the wells in cross section A-A′, PW-3-118 is not shown on the Figure 10 model profile because the well is not located in the 20- by 20-foot model node that crosses the cross section line. All three sets of cross sections show that the approximate elevations of the WBZs, the extent of the deep aquitard, contact with basalt bedrock (lower interface of the bottommost model layer), and the positions of the extraction wells are well represented in the model. In some portions of the geological cross sections, an interpretation was not possible due to limitations in data availability (for example, in cross section F-F′ shown on Figure 9, direct push borings were extended to refusal, but soil samples could not be obtained below the upper stratigraphic units). These are shown as blank white spaces on Figures 5, 7, and 9. A full geospatial specification of stratigraphic units is required for the model, which was achieved through geospatial interpolation. Thus, the model cross sections show the interpolated units on Figures 6, 8, and 10 in the corresponding spaces.

2.2 Boundary Conditions

The boundary conditions applied to the model are shown on Figure 11. Each boundary condition is described in greater detail in the following sections.

2.2.1 *No-Flow Boundaries*

The upstream and downstream model boundaries adjacent to the U.S. Moorings and Siltronic properties, respectively, are modeled as no-flow boundaries. This was based on the Site-wide groundwater level contours developed during the *Remedial Investigation Report* (HAI 2007), which concluded that the groundwater flow direction in both the Fill and Upper Alluvium WBZ (shallower than 85 feet below ground surface) were predominantly north-northeast toward the Willamette River. The report indicated that the flow direction is more northerly in the Lower Alluvium WBZ but cast doubts over this conclusion because of insufficient data in the Lower Alluvium. For the purposes of the current model, the no-flow boundary conditions specified for the Fill WBZ and Upper Alluvium WBZ are extended down to the Lower Alluvium WBZ. The sensitivity of the model predicted water levels to this assumption will be evaluated during model calibration by performing simulations that employ a constant head boundary for the Lower Alluvium WBZ.

A no-flow boundary is also assumed at the Alluvium WBZ and bedrock contact at the bottom of the model.

2.2.2 *Constant Head Boundaries*

A constant head boundary is applied to the southwest upland boundary at Highway 30. The value of the constant head will be based on the contours developed from new water level measurements made during full system start-up tests.

The Willamette River boundary will be specified as a constant head boundary using the time-variant specified head (CHD) package. The CHD package allows for specification of a tidal and time-varying river stage boundary that changes within and between MODFLOW stress periods[1], thus supporting the simulation of transient conditions encountered during the full-system start-up tests. The stress period durations will be determined based on the river

[1] Each model simulation period is divided into one or more stress periods. During each stress period, boundary conditions are usually kept constant. However, some specific packages (such as time-variable constant head) permit limited variations in boundary conditions within a stress period.

stage hydrograph measured during the start-up tests and are likely to be on the order of an hour.

The Willamette River ordinary high water line was used to identify cells interfacing with the Willamette River (see Figure 11). The model grid is structured such that only the topmost model layer interfaces with the Willamette River boundary. Thus, the Willamette River boundary condition does not extend beyond the first layer of the model, whereas the upland constant head boundary is applied over all 12 layers of the model. As described in Section 2.1.1, even though the upland boundary condition is applied over all 12 layers in the current model, it extends only to the Fill and Upper Alluvium WBZs because the Lower Alluvium WBZ and the deep aquitard do not extend upland. Thus, effectively the upland constant boundaries are applied over the same stratigraphic units as the 2011 model.

2.2.3 *General Head Boundary*

As with the 2011 model, the northeast boundary of the model below the Willamette River is specified as a general head boundary. This will allow bi-directional exchanges from the far shore depending on the river stage.

2.2.4 *Recharge*

Site-wide recharge will be estimated based on the precipitation records reported at the Portland International Airport National Oceanic and Atmospheric Administration Weather Station. Recharge will be minimally simulated in model cells that are below impervious areas, such as paved areas or buildings. The 2011 groundwater model used a recharge rate of 2 inches per year for paved areas (Anchor QEA 2012), which will be carried forward here. In the 2007 model, a constant areal recharge of 10 inches per year was determined for the unpaved areas (see Appendix F in Anchor QEA 2009), and this value was carried forward in subsequent modeling efforts. In the current model, a similar approach will be adopted to specify recharge in the unpaved areas (i.e., it will be specified to enter the uppermost active layer in model, and the infiltration rate will be developed based on precipitation records, estimated runoff, and model calibration).

2.2.5 *Pumping*

A total of 21 extraction wells are represented in the model, as shown in Table 1. The previous models were applied to simulate only a subset of extraction wells because many wells currently

developed at the Site were not present at that time. Thus, the current model is the first attempt to simulate the full set of extraction wells currently installed at the Site. As described in Section 2.1.1, the current model was constructed so that each extraction well screen interval does not cross model layer boundaries (see Figures 4, 6, 8 and 10). Extraction well pumping rates during system testing will vary to maintain a constant ΔH between the river and the control wells due to changing river stage and groundwater elevations. These variations in extraction well discharge rates during the model stress periods will be recorded by the PLC and will be accounted for in the transient simulations to be conducted after the full system startup tests.

Table 1
Extraction Wells Specified in the Groundwater Model

Well ID	Easting[1] (feet)	Northing[1] (feet)	Top of Screen (feet[(2)])	Bottom of Screen (feet[(2)])	Model Row	Model Column	Model Layer
PW-1U	7,624,718.0	705,053.1	-20.1	-35.1	58	139	4
PW-2U	7,624,549.5	705,175.1	-23.3	-38.3	57	128	4
PW-3U	7,624,359.0	705,220.4	-17.2	-32.2	60	119	3
PW-4U	7,624,207.1	705,313.8	-18.9	-33.9	60	110	3
PW-5U	7,624,057.8	705,377.5	-17.4	-32.4	61	102	3
PW-6U	7,623,927.7	705,490.4	-17.9	-32.9	59	93	3
PW-8-39	7,623,605.5	705,683.0	-1.0	-16.0	59	75	2
PW-11U	7,624,435.7	705,191.3	-25.8	-40.8	59	123	4
PW-12U	7,624,297.6	705,265.9	-21.6	-36.6	60	115	3
PW-13U	7,624,144.5	705,333.4	-25.4	-40.4	61	107	4
PW-14U	7,623,986.9	705,437.0	-25.9	-35.9	60	97	3
PW-1L	7,624,730.3	705,046.4	-79.9	-99.9	58	139	6
PW-2L	7,624,558.3	705,165.7	-85.6	-105.6	58	129	7
PW-3-118	7,624,353.0	705,238.0	-82.5	-92.5	60	118	6
PW-4L	7,624,216.3	705,309.2	-77.2	-97.2	60	110	6
PW-5L	7,624,049.3	705,380.6	-73.4	-93.4	61	101	6
PW-6L	7,623,921.5	705,497.0	-72.7	-92.7	59	93	6
PW-7-93	7,623,757.9	705,591.1	-49.3	-69.3	59	84	4
PW-8-68	7,623,605.5	705,683.0	-23.4	-43.4	59	75	3
PW-9-92	7,623,393.3	705,809.3	-39.6	-59.6	59	62	9
PW-10L	7,623,189.4	705,921.9	-28.3	-48.3	59	51	9

Notes:
1 = Easting and Northing are in the Oregon State Plane system.
2 = Elevations are referenced to City of Portland's Vertical Datum.

2.2.6 *Liquefied Natural Gas Basin*

The LNG basin at the Site collects shallow groundwater that seeps from the Fill WBZ. Based on the volume of water pumped to maintain water levels within the collection sump, it is estimated the annualized rate at which groundwater and stormwater enters the basin is approximately 20 gallons per minute (HAI 2013). Stormwater entering the basin are represented in the model through recharge. The groundwater entering the LNG basin during dry conditions is specified as a drain boundary in the model. The drain boundary was introduced in the 2009 model (Anchor QEA 2009), and its representation has been carried forward unchanged in the subsequent models, including the current model.

2.3 Initial Conditions

Initial groundwater levels will be determined based on water level measurements from the full system startup testing.

2.4 Model Parameterization

A key aquifer property that is input to the model is the hydraulic conductivity of the WBZs. Extraction well step tests were recently conducted to determine the hydraulic conductivity in the Upper and Lower Alluvium WBZs. These tests are discussed further in the following subsection. Conductance at the drain boundary will be determined during model calibration.

For transient simulations, the model requires an aquifer storage coefficient to determine the change in storage per unit area per unit change in head. This parameter is usually determined through calibration. The model layers will be set up as variably confined (i.e., the Fill and Upper Alluvium WBZ model layers will dynamically switch between confined and unconfined conditions depending on the groundwater elevations encountered over the course of the simulation). The storage coefficient under confined conditions will be orders of magnitude smaller than the storage coefficient during unconfined conditions. Thus, the storage coefficient used in the model for the Fill and Upper Alluvium WBZs will be considerably higher (typically in the range of 0.05 to 0.3) compared to the Lower Alluvium WBZ (typically in the range of 0.00001 to 0.001).

2.4.1 *Summary of Extraction Well Pump Tests*

Pump tests were conducted at extraction wells PW-1-80, PW-3-85, PW-3-118, PW-7-93, PW-8-39, PW-8-68, and PW-9-92. The findings from the test of PW-1-80 were reported by Hahn and

Associates, Inc. (HAI; 2006). The findings from the tests of PW-3-85 and PW-3-118 were reported by Anchor Environmental and S.S. Papadopulos and Associates (Anchor and SSPA 2008). The findings from the tests of PW-7-93, PW-8-39, and PW-9-92 were previously incorporated into the 2011 groundwater flow model (see Section 1.2.4). In 2012 and 2013, Upper Alluvium extraction wells PW-1U, PW-2U, PW-3U, PW-4U, PW-5U, PW-6U, PW-11U, PW-12U, PW-13U, and PW-14U were installed, developed, and step tested using the procedures described in the CDR (Anchor QEA 2012). During the same time period, Lower Alluvium extraction wells PW-1L, PW-2L, PW-4L, PW-5L, and PW-6L were installed and step tested. Extraction well PW-9-92 was redeveloped in 2012, and an additional step test was performed. These tests provide estimates of hydraulic conductivity in the vicinity of the wells, which were not available for the 2011 model. The results of the step test analyses are summarized in Table 2. A memorandum describing the derivation of the step test results will be submitted to DEQ separately.

Table 2
Summary of Hydraulic Conductivities Derived from Step Tests

Test	Geological Unit	Hydraulic Conductivity (feet per day)
PW-1U	Upper Alluvium	200
PW-2U	Upper Alluvium	100
PW-3U	Upper Alluvium	80
PW-4U	Upper Alluvium	10
PW-5U	Upper Alluvium	170
PW-6U	Upper Alluvium	115
PW-8-39	Upper Alluvium	2
PW-11U	Upper Alluvium	25
PW-12U	Upper Alluvium	15
PW-13U	Upper Alluvium	25
PW-14U	Upper Alluvium	40
PW-1L	Lower Alluvium	100
PW-2L	Lower Alluvium	260
PW-3-118	Lower Alluvium	190
PW-4L	Lower Alluvium	400
PW-5L	Lower Alluvium	380
PW-6L	Lower Alluvium	370
PW-7-93	Lower Alluvium	400(1)
PW-8-68	Lower Alluvium	400(1)

Test	Geological Unit	Hydraulic Conductivity (feet per day)
PW-9-92	Lower Alluvium	1,250
PW-10L	Lower Alluvium	490

Notes:
1 = Pump tests were not conducted at these wells. Therefore, these values were estimated from PW-4L, PW-5L, and PW-6L.

2.4.2 *Hydraulic Conductivity Zones Used in Model*

As described in the following section, the final hydraulic conductivities used in the model will be calibrated to match the groundwater elevations measured during the full system start-up tests. The starting hydraulic conductivity values for calibration will be the values in Table 2. As with the 2011 model, the conductivity zones were delineated from the midpoint of the extraction wells. The conductivity zones for the Upper Alluvium and Lower Alluvium WBZs are shown on Figures 12 and 13, respectively. For the areas at or upland of the LNG basin, initial conductivity values of 70 feet per day and 400 feet per day will be used in the Upper Alluvium and Lower Alluvium WBZs, respectively, which are approximately the average values of the conductivities derived from the step tests for the respective units.

3 MODEL CALIBRATION AND VALIDATION APPROACH

This section describes the datasets used for model calibration and the overall approach that will be employed to calibrate and validate the model. Model calibration will be conducted in the fall of 2013 after completion of initial phase of the full system tests.

3.1 Calibration/Validation Datasets

The primary dataset for calibration and validation will be groundwater elevations measured during the planned Phase 1 and Phase 2 system tests scheduled to begin in fall 2013. The data collection objectives, setup of the tests, and the period of testing are described in the Plan (Anchor QEA 2013). Phase 1 will include short-term tests that will evaluate ΔHs of 0.1 feet and 0.15 feet; Phase 2 is being planned as long-term testing that will begin in January 2014 and continue through August 2014. The ΔH to be used in Phase 2 will be determined from the Phase 1 results.

During the Phase 1 tests, the transducers in the monitoring wells, extraction wells, and piezometers will measure water levels at 15-minute intervals. The transducer recording interval for Phase 2 will be determined based on the Phase 1 results. The Phase 1 tests will provide the hydrology dataset during the dry season over a shorter period, while the Phase 2 test will provide a dataset that reflects seasonal changes and also the highest river stages likely to be encountered during the year. Combined, the two test phases will provide a robust dataset for calibrating and validating the model.

In addition to the start-up tests, additional Site data may be used for constraining model parameters and testing model performance. For instance, conductance for the model cells representing the drain boundary may be refined based on the monthly extraction sump discharge records maintained for the LNG basin (HAI 2013).

3.2 General Approach

The primary model calibration parameters will be the hydraulic conductivity values in the Fill and the Upper and Lower Alluvial WBZs. The hydraulic conductivities derived from the extraction well pump tests and step tests and listed in Table 2 will be used as starting values for the calibration. The calibration strategy is to use the water elevations measured during the first Phase 1 test to calibrate the model parameters (i.e., hydraulic conductivities, storage coefficients, drain boundary conductance, and recharge). Data from the second Phase 1 test (at ΔH of

0.15 feet) will be used to validate the model by simulating the Phase 2 test without changing parameters that represent material properties (i.e., hydraulic conductivity and storage coefficient).

The long-term dataset from the Phase 2 test will provide a second validation of the model. However, the model is anticipated to be applied to interpret the results of the Phase 1 tests and data collected prior to initiation of Phase 2 testing.

Model simulations will be setup in transient mode to cover the period over which data are collected. The Willamette River stage specified in the model will correspond to the measurements from the testing period. Similarly, the pumping rates specified in the model will reflect those measured during the tests. Recharge will be reviewed to ensure that the recharge rates used are consistent with precipitation records during the testing period.

Several lines of evidence will be applied to determine model calibration and validation. These will include the following:

- Groundwater elevation contour maps will be prepared for the Upper and Lower Alluvium WBZs
- Comparison of model predicted and observed groundwater elevation contour maps will be made for different time intervals during the test
- Point-by-point comparisons of hydrographs of predicted and observed groundwater elevations and drawdowns at multiple wells
- Probability distributions and cross-plots of predicted and observed elevations to determine bias in model predictions
- Comparison of predicted volume of water lost at the drain boundary to water volumes treated from the LNG Basin during the calibration period
- Statistical goodness-of-fit measures, such as sums of squared errors and correlation between predicted and observed water levels (R^2)

The statistical measures and the comparisons described previously will provide an estimate of uncertainty in model predictions. The uncertainty in model predictions will be interpreted from the context of the accuracy needed for the intended model application of evaluating containment.

3.3 Model Application

The calibrated and validated model will be applied to evaluate containment at different ΔHs through a particle tracking analysis. The model will be applied over different seasonal and tidal conditions to determine whether the selected ΔH values are sufficient to assure containment. In addition, the model predictions will also be used to assess vertical transport from the Lower Alluvial WBZ below the deep aquitard to the Upper Alluvial WBZ. Finally, the model results will be used to assess the adequacy and redundancy of the monitoring wells and would ultimately support the development of a long-term monitoring plan when the system is operational.

4 REFERENCES

Anchor Environmental, L.L.C. and SS Papadopulos Associates (Anchor and SSPA), 2008. *Groundwater Flow Model and DNAPL Evaluation Supplemental Report*. NW Natural, Gasco Site. Prepared for NW Natural. October 2008.

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HAI, 2013. *Environmental Monitoring Report, First and Second Quarter 2012*. NW Natural – Gasco Facility. May 7, 2013.

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FIGURES

Groundwater Model Footprint

NOTES:
1. LNG - Liquefied Natural Gas

Feet
0 325 650 975 1,300

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Figure 1
Groundwater Model Domain
Hydraulic Source Control and Containment System Groundwater Model Update Report
NW Natural Gasco Site

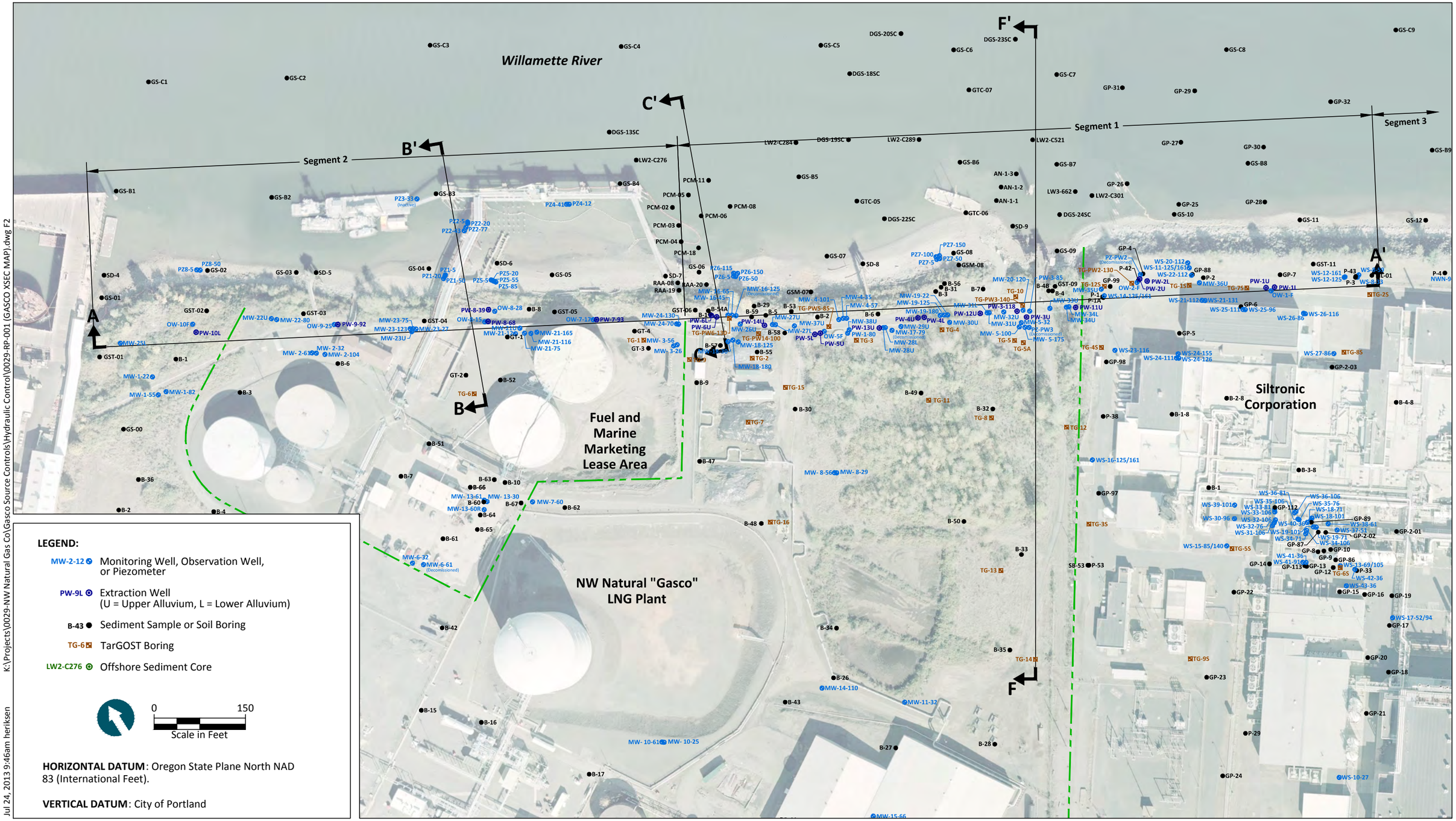

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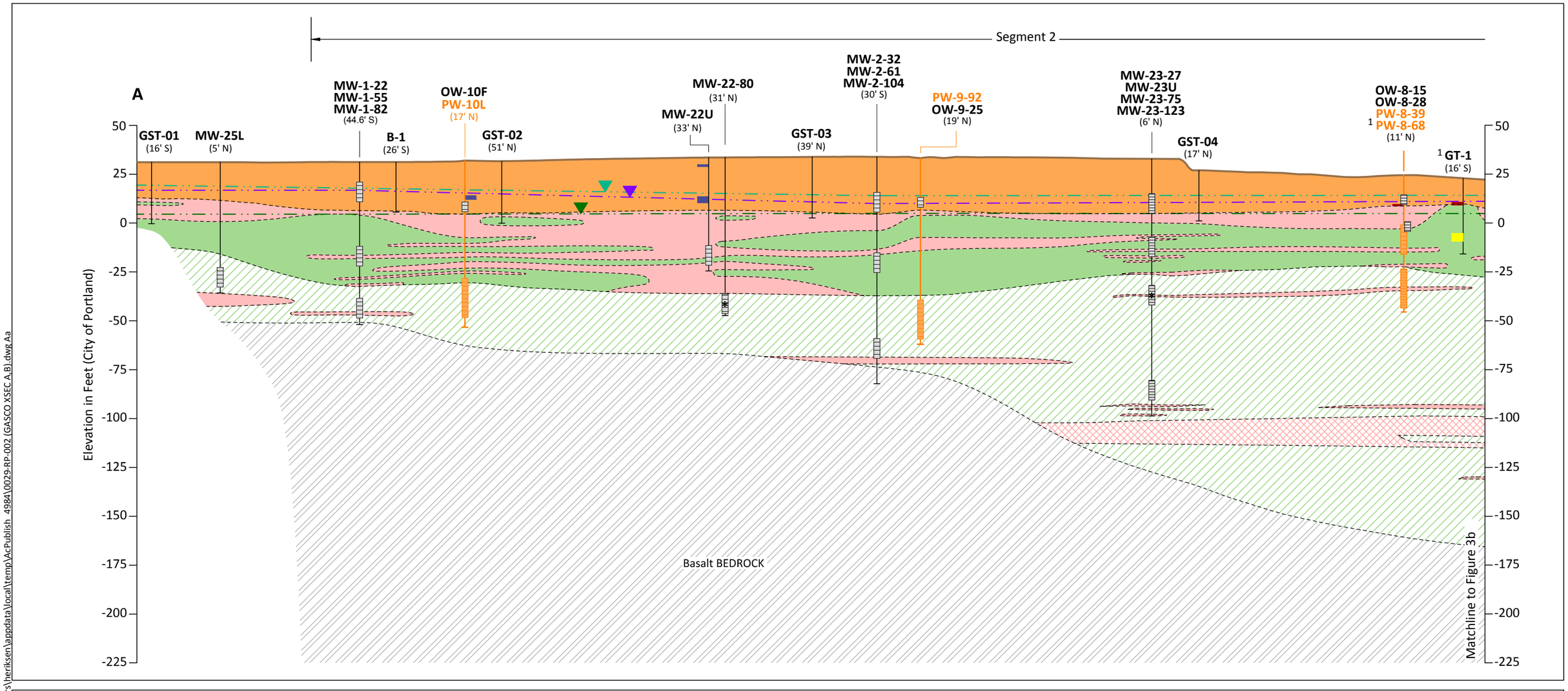
Figure 2

Monitoring Well and Cross Section Location Map

Hydraulic Source Control and Containment System Groundwater Model Update Report

NW Natural Gasco Site



LEGEND:

- **Fill WBZ** - Fill composed of gravel, silt, sand, metal, brick, and concrete debris
- **Upper Alluvium WBZ** - Primarily fine to medium grained SAND and SILTY-SAND interbedded with thin silt and sandy-silt layers
- **Lower Alluvium WBZ** - Primarily medium grained SAND with generally less than 5% fines.
- **Aquitard** - Primarily SILT and SANDY-SILT interbedded with thin sand and silty-sand layers
- Primarily SILT and SANDY-SILT interbedded with thin sand and silty-sand layers
- Alluvial GRAVEL, sandy gravel, gravelly sand, and gravelly silt
- Basalt BEDROCK
- Potentiometric Surface of Surficial Fill (measured June 3, 2009)
- Potentiometric Surface of Surficial Fill (measured August 5, 2009)
- Potentiometric Surface of Alluvium (measured August 5, 2009)
- Existing Ground Surface

MW-21-16 — Boring ID
(57' E) — Offset Distance in Feet

Existing Extraction Well
Existing Well or Piezometer

- Tar Interval
- Oil or Mixed Oil and Tar Interval
- Sheen Interval
- Well Screen
- * — Control Well

0 50
Scale in Feet

NOTE: Geologic contacts are inferred between borings.
[1] Based on visual observations and analytical testing conducted by Hahn and Associates (Remedial Investigation Report, Hahn and Associates, April 2007), the oil and sheen detected in the fill unit does not appear to be MGP-related, but appears to be associated with petroleum products stored in the FAMM storage tanks.

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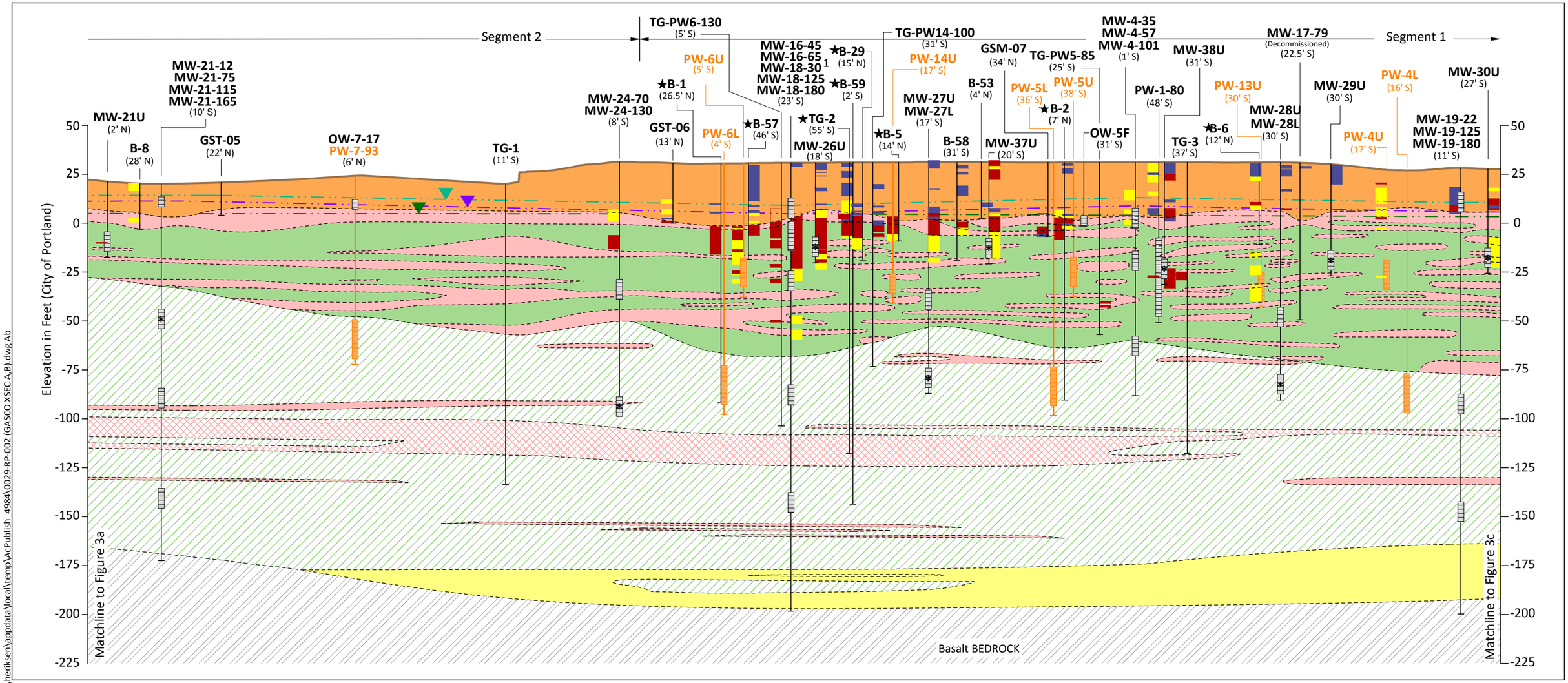
Figure 3a
Geologic Cross Section A-A'
Hydraulic Source Control and Containment System Groundwater Model Update Report
NW Natural Gasco Site



LEGEND:

- **Fill WBZ** - Fill composed of gravel, silt, sand, metal, brick, and concrete debris
- **Upper Alluvium WBZ** - Primarily fine to medium grained SAND and SILTY-SAND interbedded with thin silt and sandy-silt layers
- **Lower Alluvium WBZ** - Primarily medium grained SAND with generally less than 5% fines.
- **Aquitard** - Primarily SILT and SANDY-SILT interbedded with thin sand and silty-sand layers
- Primarily SILT and SANDY-SILT interbedded with thin sand and silty-sand layers
- Alluvial GRAVEL, sandy gravel, gravelly sand, and gravelly silt
- Basalt BEDROCK
- Potentiometric Surface of Surficial Fill (measured June 3, 2009)
- Potentiometric Surface of Surficial Fill (measured August 5, 2009)
- Potentiometric Surface of Alluvium (measured August 5, 2009)
- Existing Ground Surface

MW-21-16 — Boring ID
(57' E) — Offset Distance in Feet

Existing Extraction Well
Existing Well or Piezometer

- Tar Interval
- Oil or Mixed Oil and Tar Interval
- Sheen Interval
- Well Screen
- * — Control Well

0 50
Scale in Feet

NOTE: Geologic contacts are inferred between borings.

★ Not used for geologic interpretation.

1 Data from MW-18-125 used for geologic interpretation from ground surface to -94 feet elevation. Data from MW-18-180 used for geologic interpretation from -94 to -198 feet elevation.

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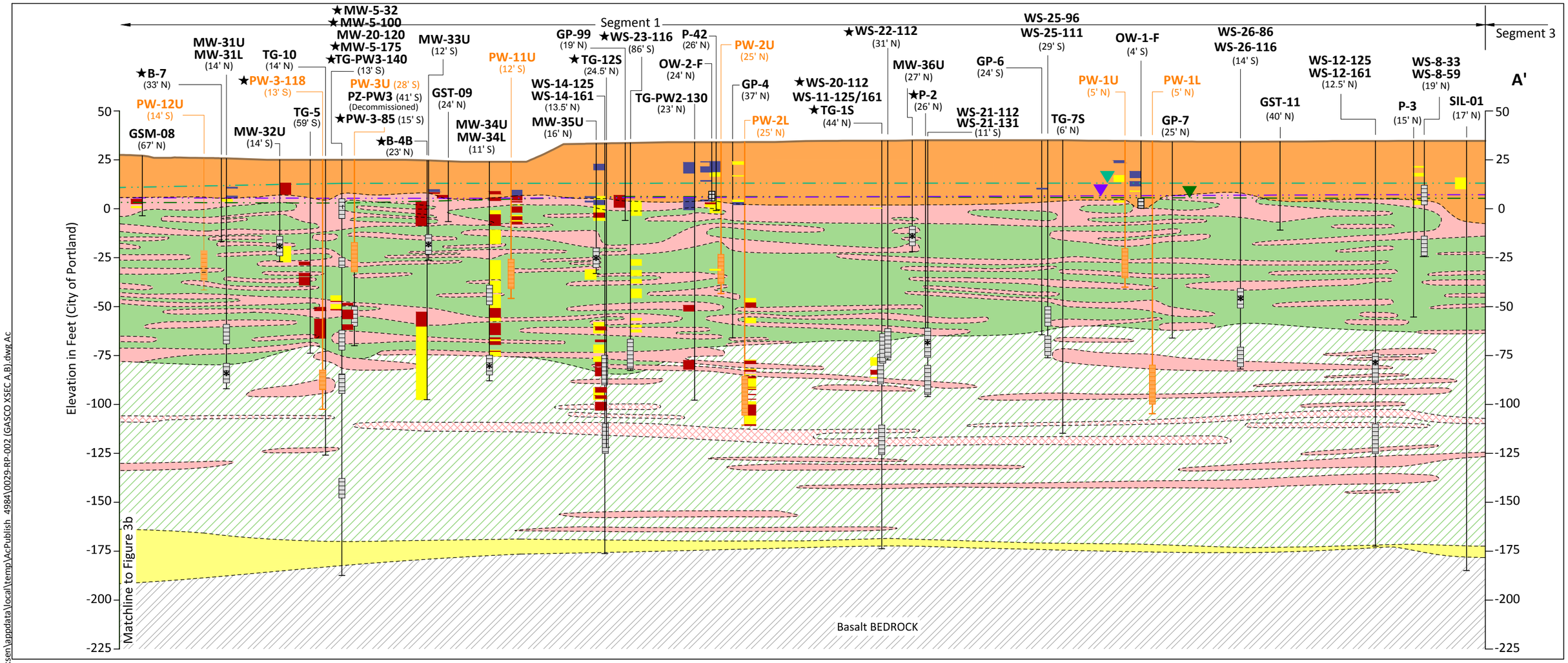
Figure 3b
Geologic Cross Section A-A'
Hydraulic Source Control and Containment System Groundwater Model Update Report
NW Natural Gasco Site



LEGEND:

- **Fill WBZ** - Fill composed of gravel, silt, sand, metal, brick, and concrete debris
- **Upper Alluvium WBZ** - Primarily fine to medium grained SAND and SILTY-SAND interbedded with thin silt and sandy-silt layers
- **Lower Alluvium WBZ** - Primarily medium grained SAND with generally less than 5% fines.
- **Aquitard** - Primarily SILT and SANDY-SILT interbedded with thin sand and silty-sand layers
- Primarily SILT and SANDY-SILT interbedded with thin sand and silty-sand layers
- Alluvial GRAVEL, sandy gravel, gravelly sand, and gravelly silt
- Basalt BEDROCK
- Potentiometric Surface of Surficial Fill (measured June 3, 2009)
- Potentiometric Surface of Surficial Fill (measured August 5, 2009)
- Potentiometric Surface of Alluvium (measured August 5, 2009)
- Existing Ground Surface

MW-21-16 — Boring ID
(57' E) — Offset Distance in Feet

Existing Extraction Well
Existing Well or Piezometer

- Tar Interval
- Oil or Mixed Oil and Tar Interval
- Sheen Interval
- Well Screen
- * — Control Well

0 50
Scale in Feet

NOTE: Geologic contacts are inferred between borings.

★ Not used for geologic interpretation.

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Figure 3c
Geologic Cross Section A-A'
Hydraulic Source Control and Containment System Groundwater Model Update Report
NW Natural Gasco Site

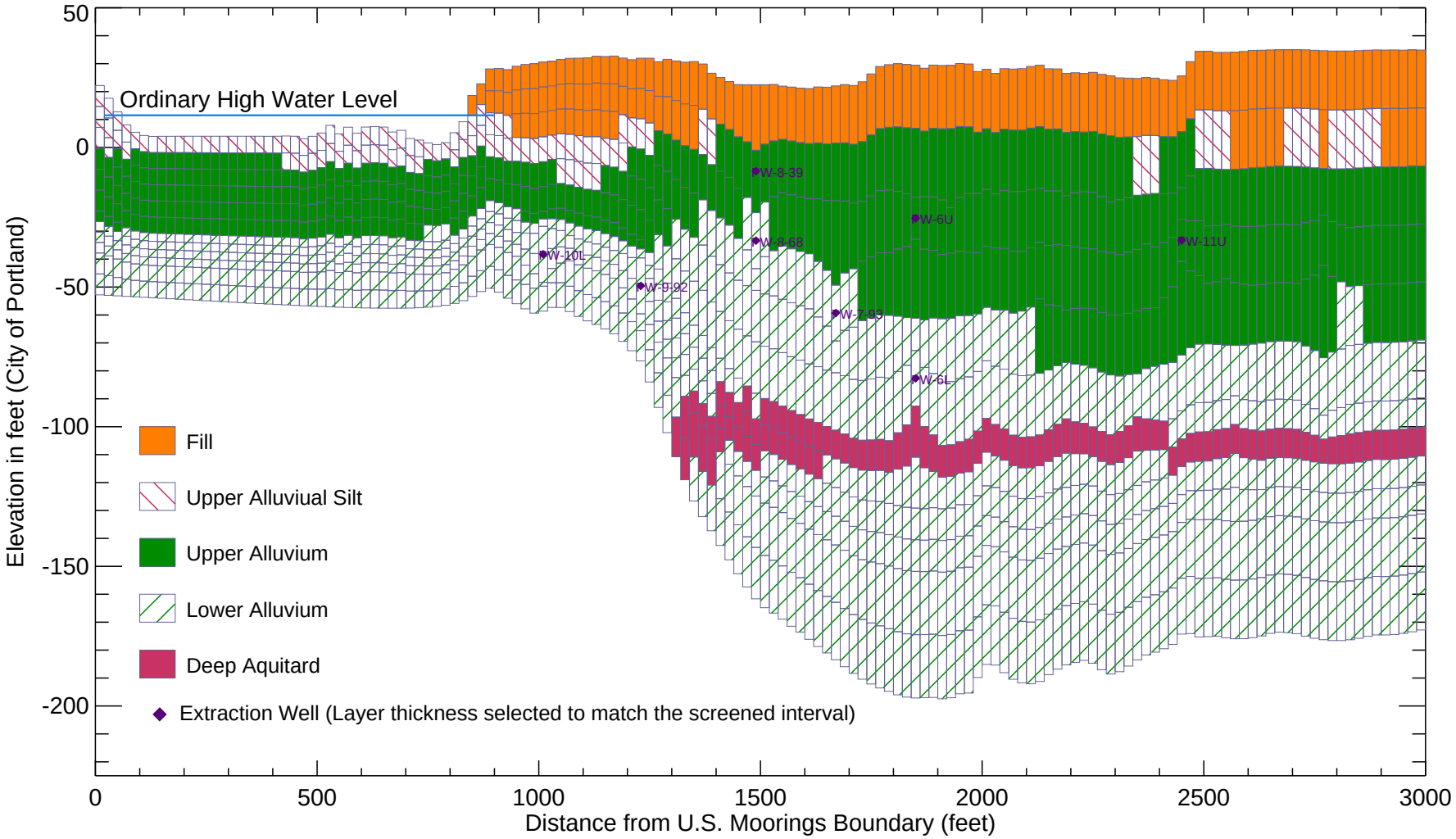

Figure 4

Stratigraphic Units Represented in Model Row 59, Approximately Comparable to Cross-Section A-A'

Hydraulic Source Control and Containment System Groundwater Model Update Report
NW Natural Gasco Site

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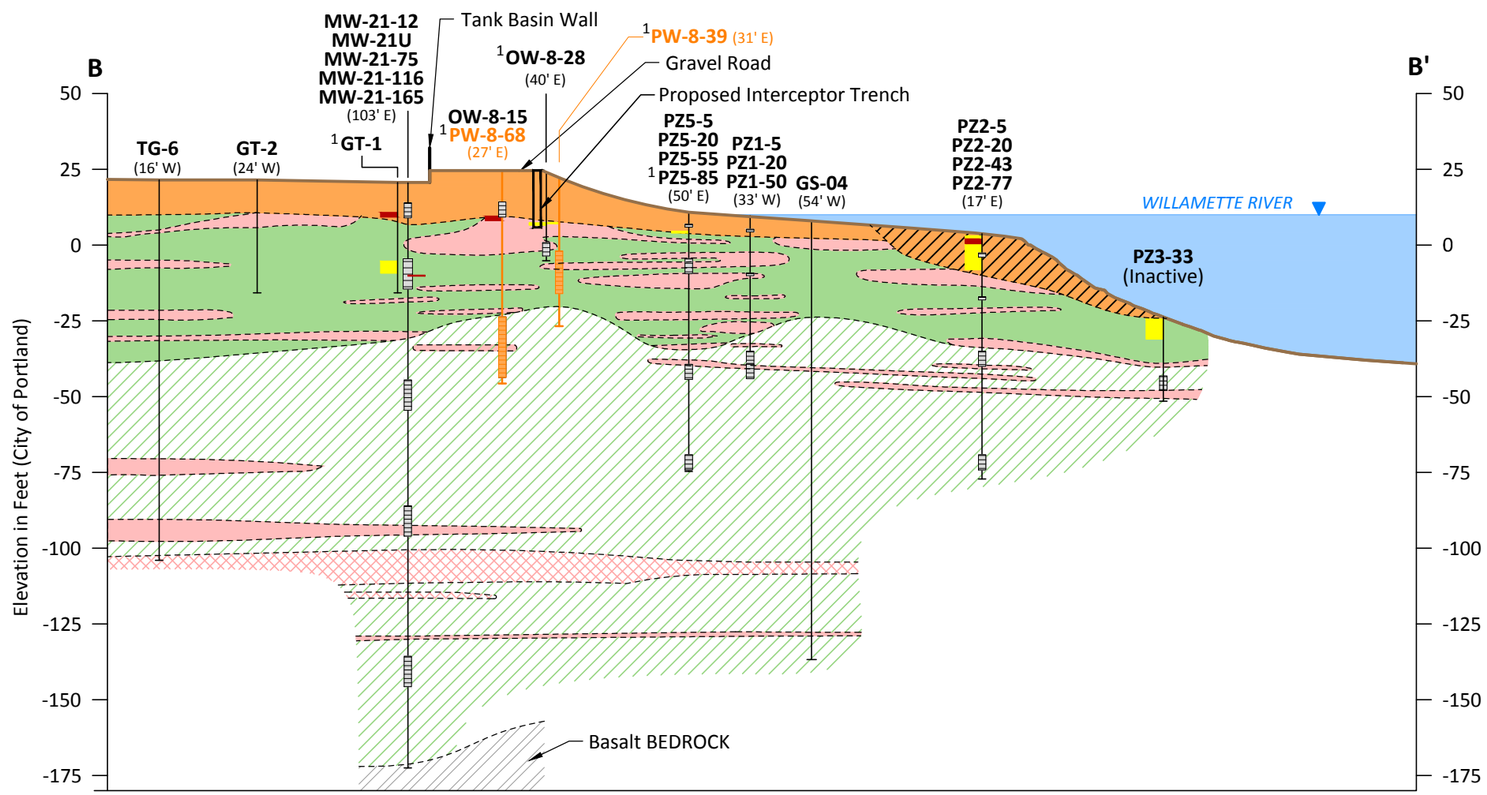

LEGEND:

- **Fill WBZ** - Fill composed of gravel, silt, sand, metal, brick, and concrete debris
- **Upper Alluvium WBZ** - Primarily fine to medium grained SAND and SILTY-SAND interbedded with thin silt and sandy-silt layers
- **Lower Alluvium WBZ** - Primarily medium grained SAND with generally less than 5% fines.
- **Aquitard** - Primarily SILT and SANDY-SILT interbedded with thin sand and silty-sand layers
- Primarily SILT and SANDY-SILT interbedded with thin sand and silty-sand layers
- Alluvial GRAVEL, sandy gravel, gravelly sand, and gravelly silt
- Basalt BEDROCK
- Existing Ground Surface
- Approximate Willamette River Elevation

TG-6 (16' W) — Boring ID — Offset Distance in Feet

Existing Extraction Well — Existing Well or Piezometer

- Tar Interval
- Oil or Mixed Oil and Tar Interval
- Sheen Interval
- Well Screen

0 — 50
Scale in Feet

NOTE: Geologic contacts are inferred between borings.
[1] Based on visual observations and analytical testing conducted by Hahn and Associates (Remedial Investigation Report, Hahn and Associates, April 2007), the oil and sheen detected in the fill unit does not appear to be MGP-related, but appears to be associated with petroleum products stored in the FAMM storage tanks.

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Figure 5
Geologic Cross Section B-B'
Hydraulic Source Control and Containment System Groundwater Model Update Report
NW Natural Gasco Site

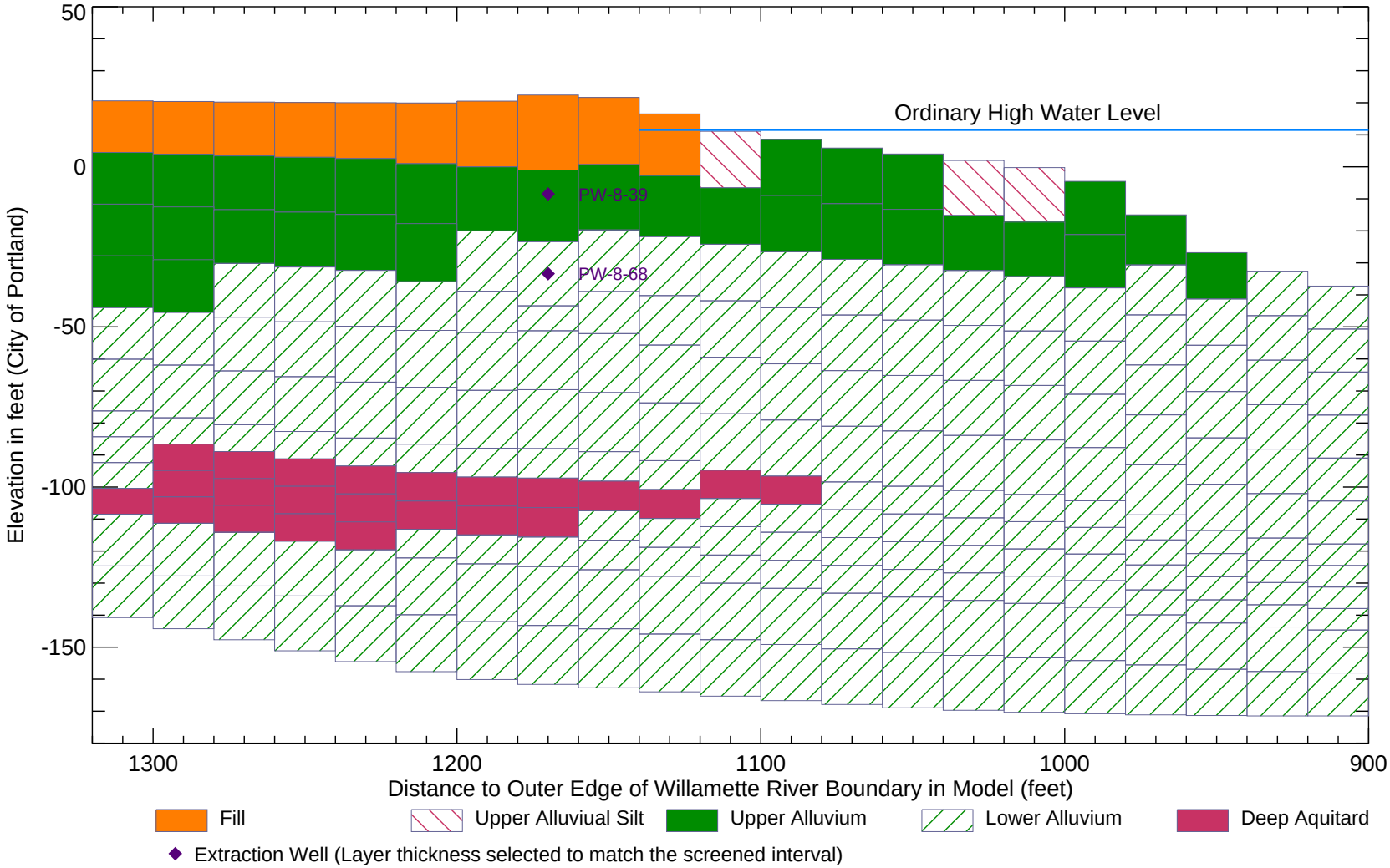

Figure 6

Stratigraphic Units Represented in Model Column 75, Approximately Comparable to Cross-Section B-B'

Hydraulic Source Control and Containment System Groundwater Model Update Report
NW Natural Gasco Site

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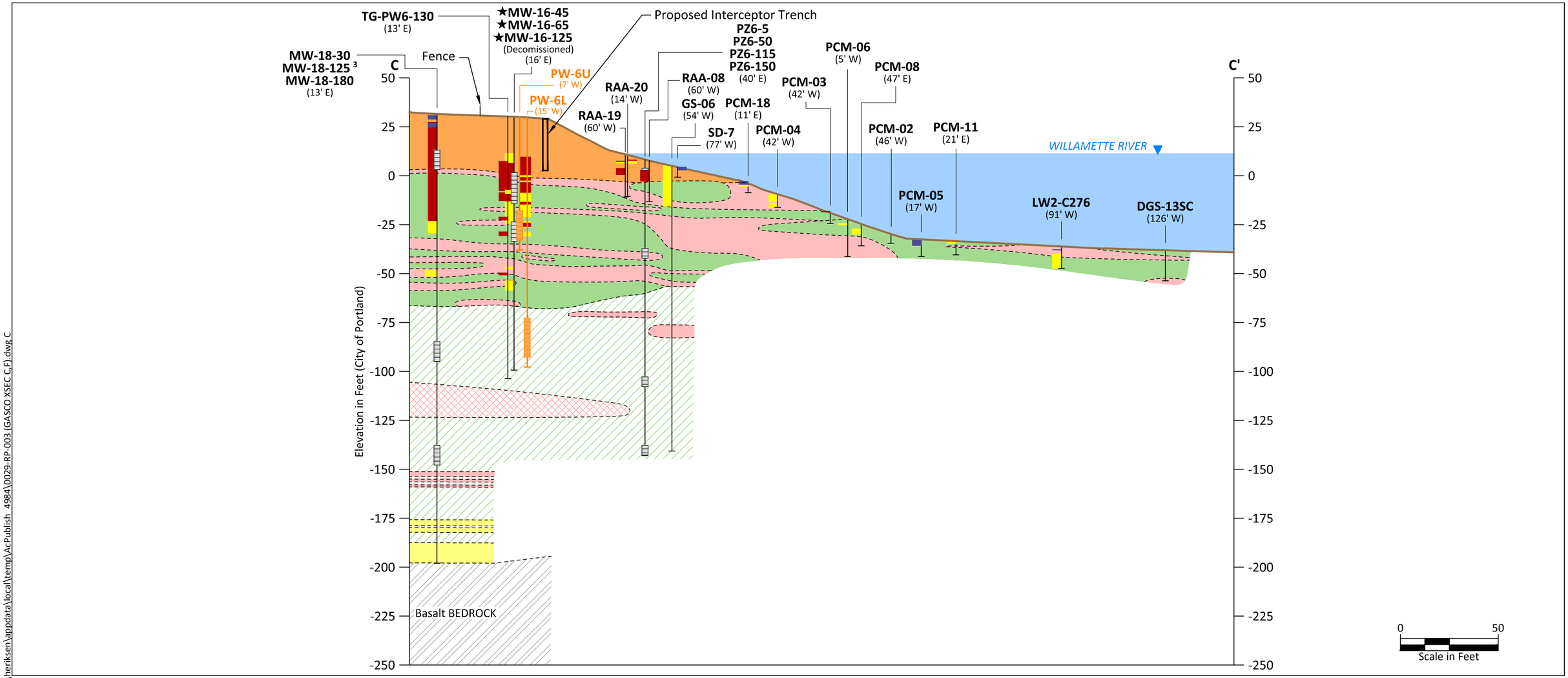

LEGEND:

- **Fill WBZ** - Fill composed of gravel, silt, sand, metal, brick, and concrete debris
- **Upper Alluvium WBZ** - Primarily fine to medium grained SAND and SILTY-SAND interbedded with thin silt and sandy-silt layers
- **Lower Alluvium WBZ** - Primarily medium grained SAND with generally less than 5% fines.
- **Aquitard** - Primarily SILT and SANDY-SILT interbedded with thin sand and silty-sand layers
- Primarily SILT and SANDY-SILT interbedded with thin sand and silty-sand layers
- Alluvial GRAVEL, sandy gravel, gravelly sand, and gravelly silt
- Basalt BEDROCK
- Existing Ground Surface
- Approximate Willamette River Elevation

GS-06 — Boring ID
(54' W) — Offset Distance in Feet

Soil Boring or Sediment Core
Existing Extraction Well
Existing Well or Piezometer

- Tar Interval
- Oil or Mixed Oil and Tar Interval
- Sheen Interval
- Well Screen

NOTES:

1. Geologic contacts are inferred between borings.
2. Tar interval in SD-7 is approximately 3 feet higher in elevation than shown on cross section.
3. MW-18-125 used for geologic interpretation from ground surface to -94 feet elevation. MW-18-180 used for geologic interpretation from -94 to -198 feet elevation.

★ Not used for geologic interpretation.

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Figure 7
Geologic Cross Section C-C'
Hydraulic Source Control and Containment System Groundwater Model Update Report
NW Natural Gasco Site

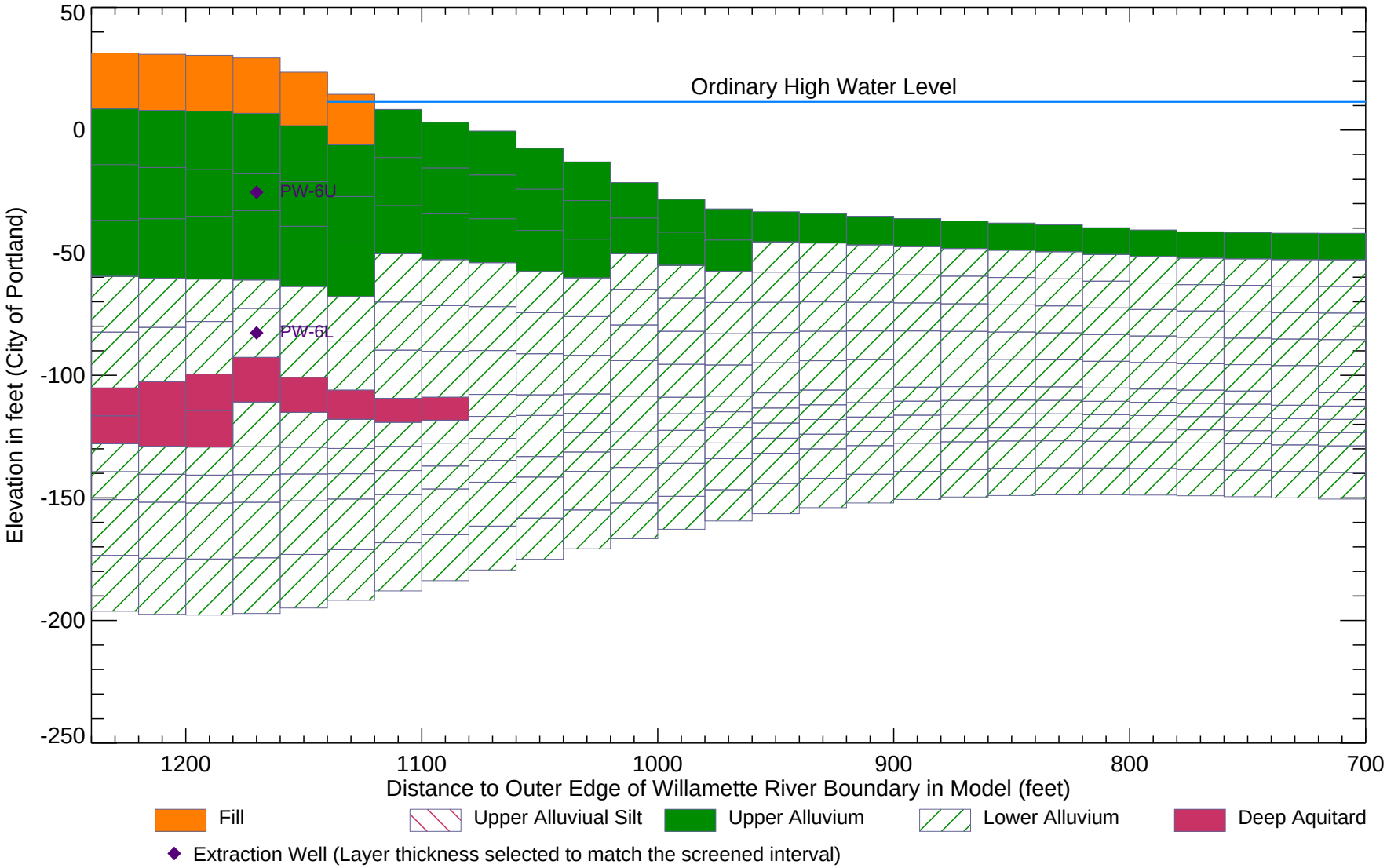

Figure 8

Stratigraphic Units Represented in Model Column 93, Approximately Comparable to Cross-Section C-C'

Hydraulic Source Control and Containment System Groundwater Model Update Report
NW Natural Gasco Site

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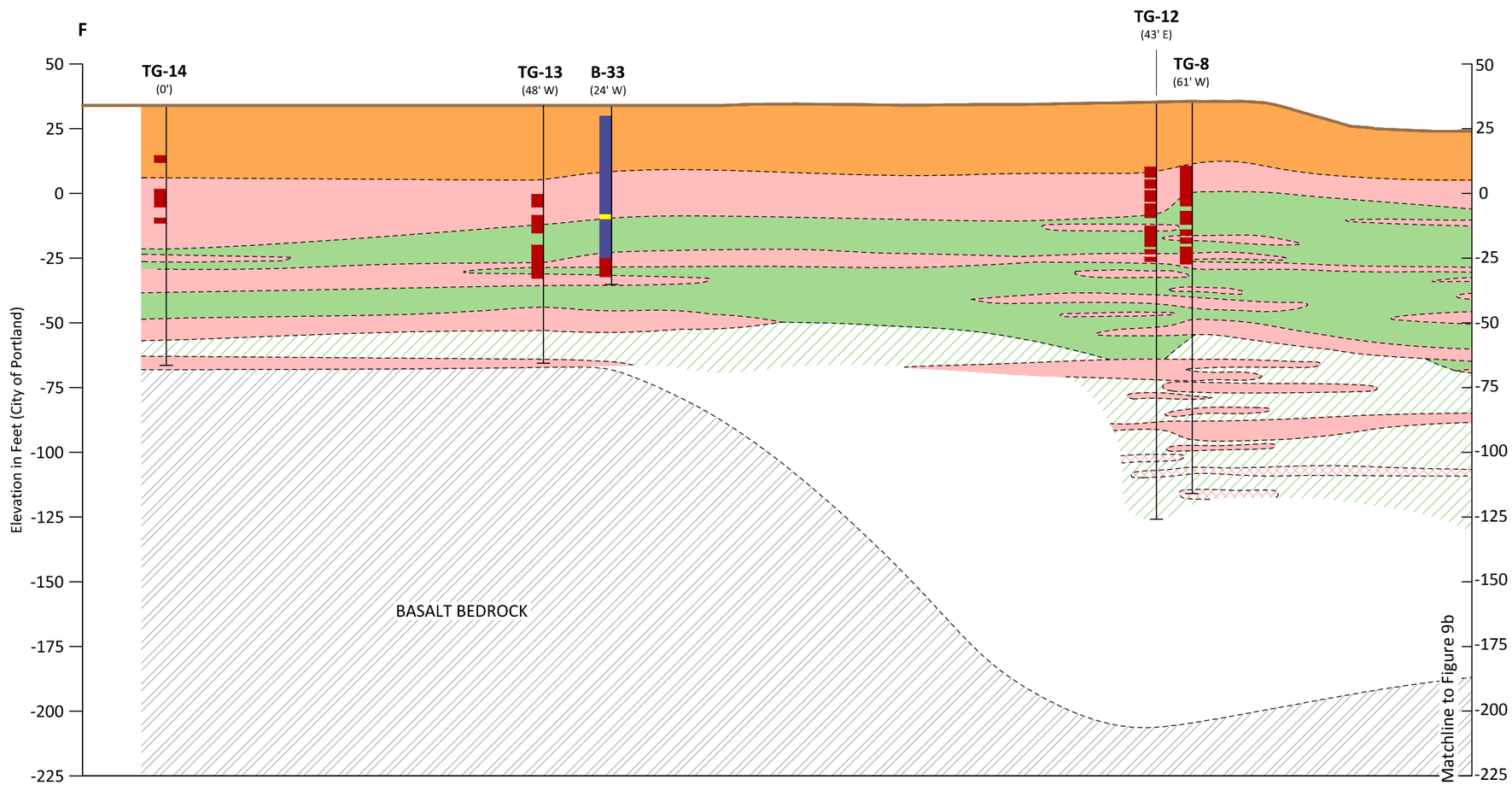

LEGEND:

- **Fill WBZ** - Fill composed of gravel, silt, sand, metal, brick, and concrete debris
- **Upper Alluvium WBZ** - Primarily fine to medium grained SAND and SILTY-SAND interbedded with thin silt and sandy-silt layers
- **Lower Alluvium WBZ** - Primarily medium grained SAND with generally less than 5% fines.
- **Aquitard** - Primarily SILT and SANDY-SILT interbedded with thin sand and silty-sand layers
- Primarily SILT and SANDY-SILT interbedded with thin sand and silty-sand layers
- Alluvial GRAVEL, sandy gravel, gravelly sand, and gravelly silt
- Basalt BEDROCK
- Existing Ground Surface
- Approximate Willamette River Elevation

GS-06 — Boring ID
(54' W) — Offset Distance in Feet

Soil Boring or Sediment Core
Existing Extraction Well
Existing Well or Piezometer

- Tar Interval
- Oil or Mixed Oil and Tar Interval
- Sheen Interval
- Well Screen

0 50
Scale in Feet

NOTES:
1. Geologic contacts are inferred between borings.
2. PW-3-85 was initially intended as an extraction well, but it has been replaced by PW-3U.

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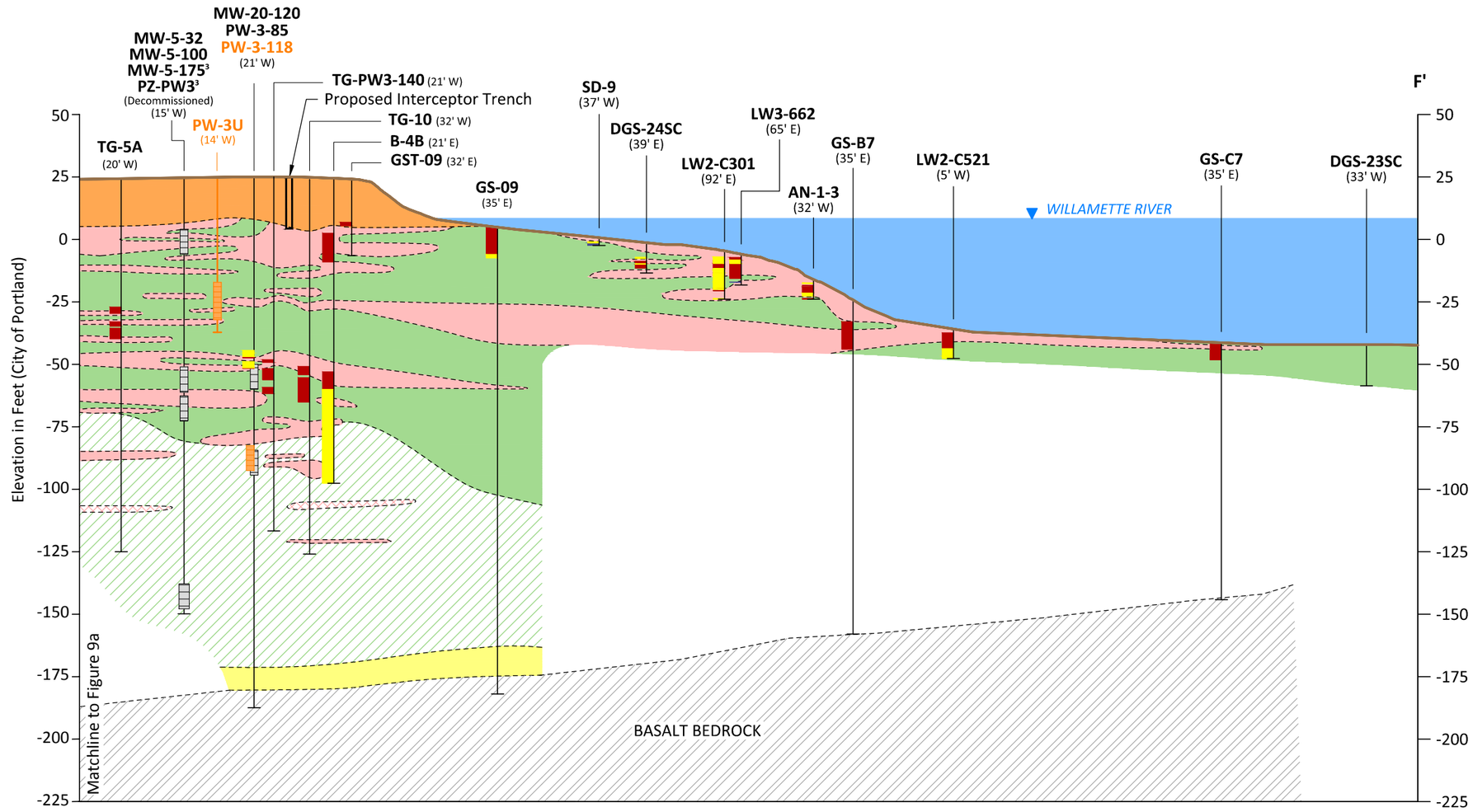
Figure 9a
Geologic Cross Section F-F'
Hydraulic Source Control and Containment System Groundwater Model Update Report
NW Natural Gasco Site



LEGEND:

- **Fill WBZ** - Fill composed of gravel, silt, sand, metal, brick, and concrete debris
- **Upper Alluvium WBZ** - Primarily fine to medium grained SAND and SILTY-SAND interbedded with thin silt and sandy-silt layers
- **Lower Alluvium WBZ** - Primarily medium grained SAND with generally less than 5% fines.
- **Aquitard** - Primarily SILT and SANDY-SILT interbedded with thin sand and silty-sand layers
- Primarily SILT and SANDY-SILT interbedded with thin sand and silty-sand layers
- Alluvial GRAVEL, sandy gravel, gravelly sand, and gravelly silt
- Basalt BEDROCK
- Existing Ground Surface
- Approximate Willamette River Elevation

GS-06 — Boring ID
(54' W) — Offset Distance in Feet

Soil Boring or Sediment Core
Existing Extraction Well
Existing Well or Piezometer

- Tar Interval
- Oil or Mixed Oil and Tar Interval
- Sheen Interval
- Well Screen

0 50
Scale in Feet

NOTES:

1. Geologic contacts are inferred between borings.
2. PW-3-85 was initially intended as an extraction well, but it has been replaced by PW-3U.
3. Data from PZ-PW3 used for geologic interpretation from ground surface to -30 feet elevation, and from MW-5-175 from -30 feet to -150 feet elevation.

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Figure 9b
Geologic Cross Section F-F'
Hydraulic Source Control and Containment System Groundwater Model Update Report
NW Natural Gasco Site

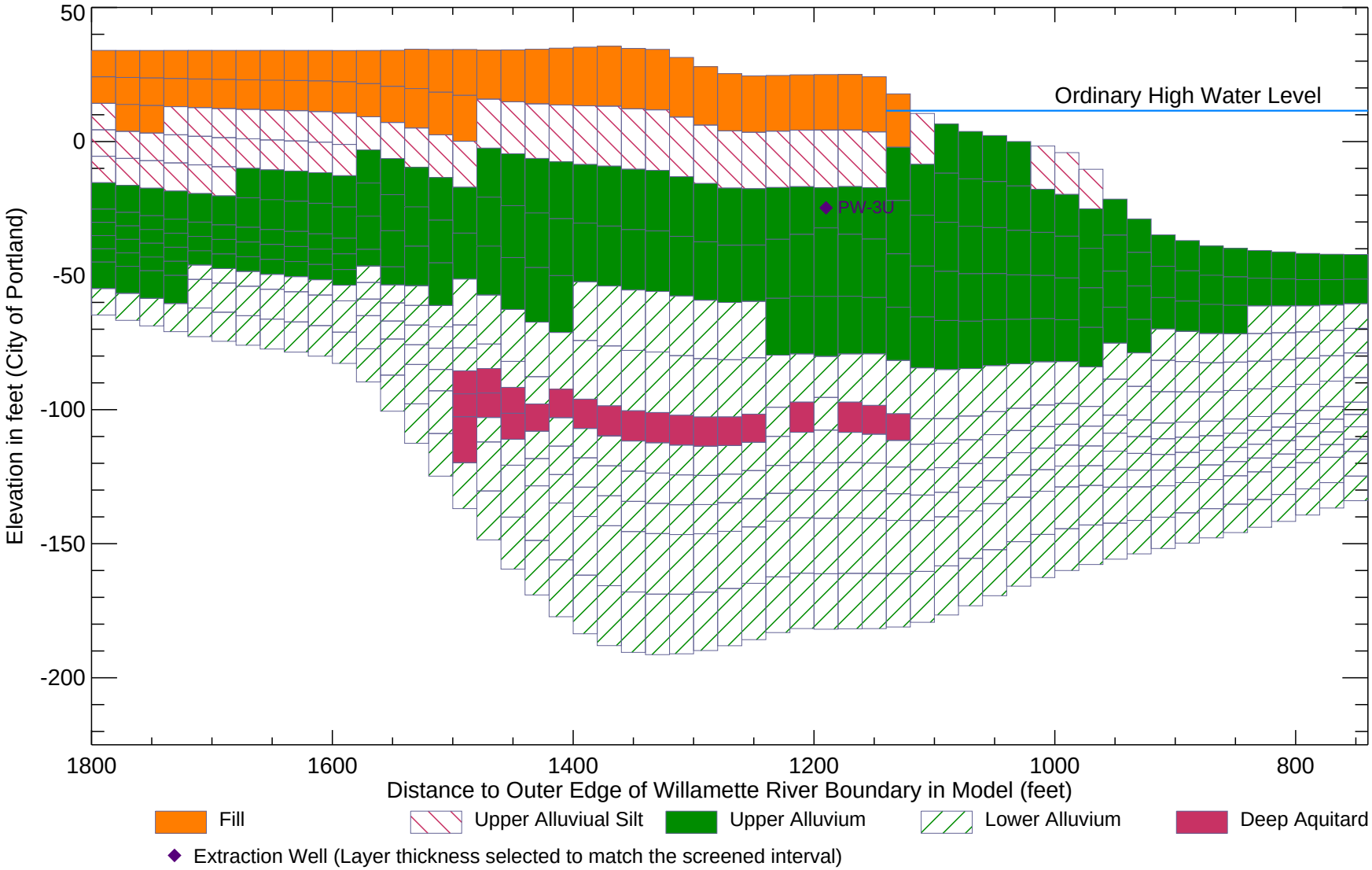

Figure 10

Stratigraphic Units Represented in Model Column 119, Approximately Comparable to Cross-Section F-F'

Hydraulic Source Control and Containment System Groundwater Model Update Report
NW Natural Gasco Site

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Boundary Conditions

- Constant Head
- Drain
- No flow
- Groundwater Model Footprint

NOTES:

1. LNG - Liquefied Natural Gas
2. See Figure 4 for location of wells.

Feet

0 250 500 750 1,000

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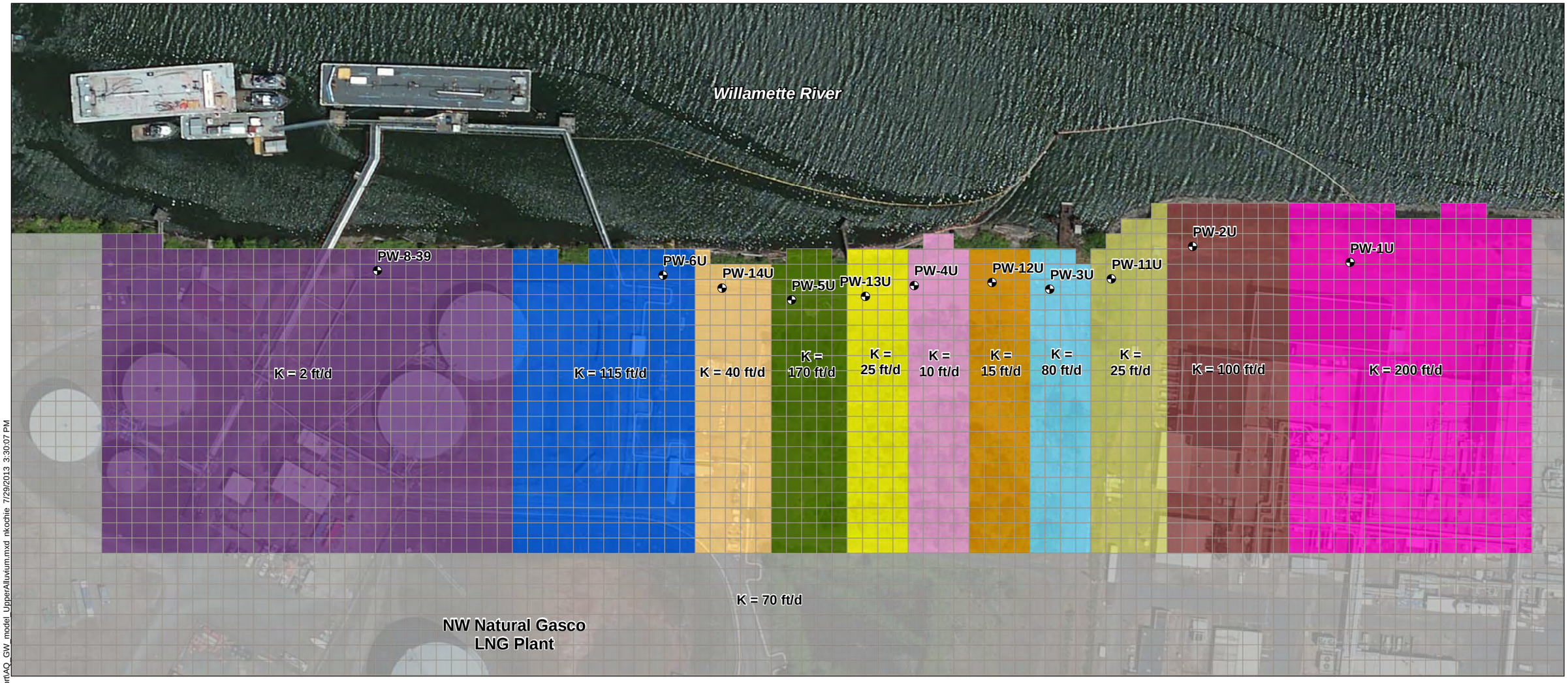
Figure 11
Model Boundary Conditions
Hydraulic Source Control and Containment System Groundwater Model Update Report
NW Natural Gasco Site



Upper Alluvium Zones

- 2 (PW-8-39)
- 3 (PW-6U)
- 4 (PW-14U)
- 5 (PW-5U)
- 6 (PW-13U)
- 7 (PW-4U)
- 8 (PW-12U)
- 9 (PW-3U)
- 10 (PW-11U)
- 11 (PW-2U)
- 12 (PW-1U)
- 13 (Upland)

Extraction Well

Feet
0 65 130 195 260

NOTE:
1. LNG - Liquefied Natural Gas

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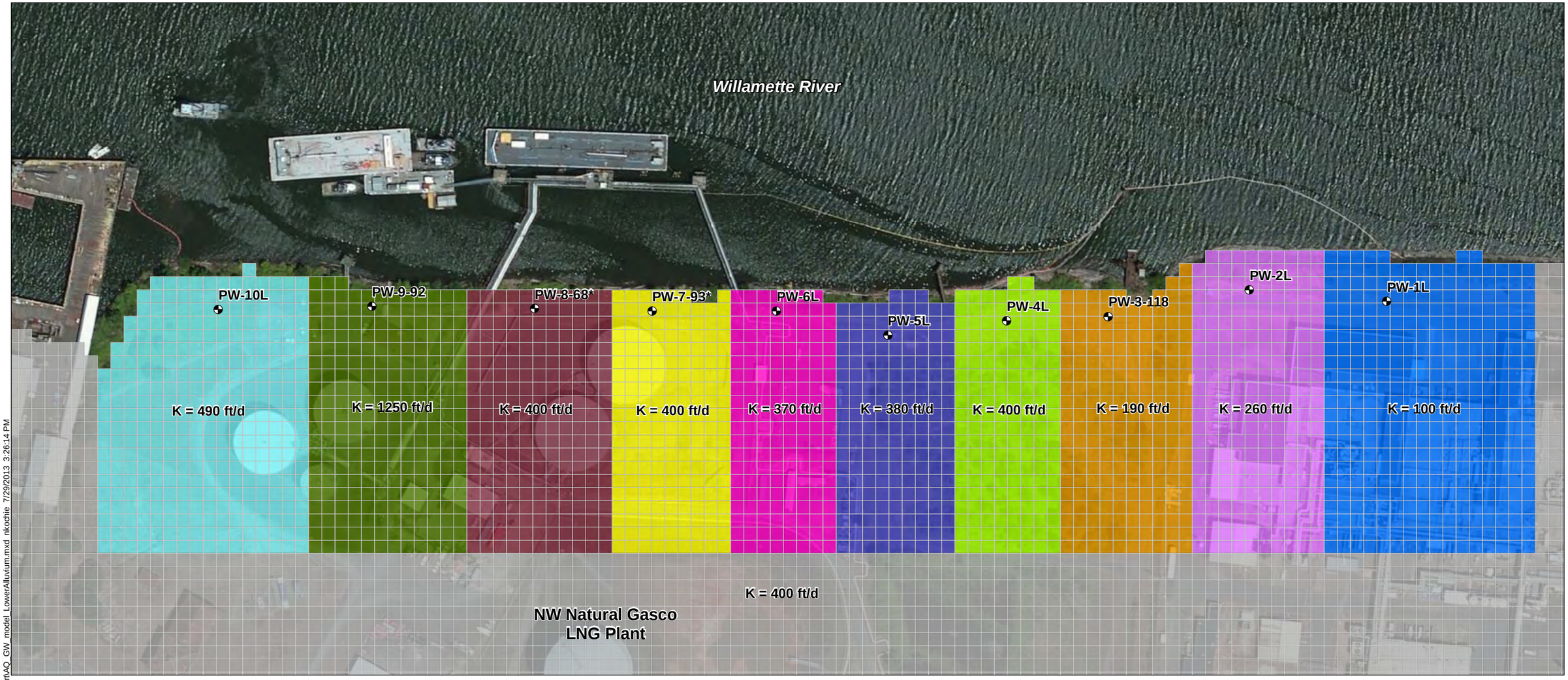
Figure 12
Initial Horizontal Hydraulic Conductivity Values Specified for the Upper Alluvial Water Bearing Zone
Hydraulic Source Control and Containment System Groundwater Model Update Report
NW Natural Gasco Site



Lower Alluvium Zones

- 14 (PW-10L)
- 15 (PW-9-92)
- 16 (PW-8-68*)
- 17 (PW-7-93*)
- 18 (PW-6L)
- 19 (PW-5L)
- 20 (PW-4L)
- 21 (PW-3-118)
- 22 (PW-2L)
- 23 (PW-1L)
- 24 (Upland)

Extraction Well

Feet
0 75 150 225 300

NOTES:
* Values estimated based on conductivity values for PW-4L, PW-5L and PW-6L
1. LNG - Liquefied Natural Gas

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Figure 13
Initial Horizontal Hydraulic Conductivity Values Specified for the Lower Alluvial Water Bearing Zone
Hydraulic Source Control and Containment System Groundwater Model Update Report
NW Natural Gasco Site