Kennedy/Jenks Consultants

200 S.W. Market Street, Suite 500
Portland, Oregon 97201
503-295-4911
FAX: 503-295-4901

City of Longview
Mint Farm Regional Water Treatment Plant
Preliminary Design Report

Part 2A
Hydrogeologic Characterization

March 2010

Prepared for

City of Longview
1525 Broadway Street
Longview, WA 98632

K/J Project No. 0997003*00

Table of Contents

List of Tables ..... *iii*

List of Figures ..... *iii*

List of Appendices ..... *iv*

List of Acronyms ..... *v*

Section 1: Introduction and Purpose 1-1

Section 2: Geology and Hydrogeology, Longview-Kelso Basin 2-1

2.1 Physical Setting 2-1
2.2 Geologic Setting 2-1
2.3 Local Geology 2-2
2.3.1 Geology of the Mint Farm Area 2-4
2.3.1.1 Silt/Clay Unit 2-4
2.3.1.2 Sand Unit 2-4
2.3.1.3 Gravel Unit ("Target Aquifer") 2-5
2.3.2 Relocation of Well Field Site 2-5

Section 3: Sentinel Well Program 3-1

3.1 Sentinel Well Drilling and Sampling 3-1
3.2 Well Development 3-2
3.3 Investigation Derived Waste 3-2
3.4 Sentinel Well Surveying 3-5
3.5 Geophysical Survey 3-5
3.6 Well Field Relocation 3-5
3.7 Baseline Groundwater Sampling 3-5
3.7.1 Groundwater Sampling During Well PW-1 Pumping Test 3-6
3.8 Transducer Installation 3-6

Section 4: Test Production Well No. PW-1 4-1

4.1 Design of Test Production Well PW-1 4-1
4.2 Drilling and Construction Discussion 4-2
4.3 Adjustments to Deep Groundwater Level Data (Columbia River Tidal Influence) 4-3
4.4 Step-Rate Pumping Test 4-4
4.5 Constant-Rate Pumping Test 4-4
4.5.1 Additional Adjustments to Deep Groundwater Level Data (Longer-Term Regional Trend) 4-5
4.5.2 Pumping Test Analysis 4-5
4.5.2.1 Pumping Well PW-1 4-6
4.5.2.2 Sentinel Well DW-9 4-7

4.5.2.3 Other Deep Sentinel Wells 4-10
4.5.2.4 Shallow Sentinel Wells 4-10
4.5.3 Pumping Test Conclusions 4-10

Section 5: Hydrogeology 5-1

5.1 Introduction 5-1
5.2 Longview-Kelso Basin 5-1
5.3 Aquifer Definition 5-1
5.3.1 Shallow Groundwater System 5-1
5.3.2 Deep Gravel Aquifer (“Target Aquifer”) 5-2
5.4 Groundwater-Level Data 5-3
5.5 Isotopic Analysis 5-4
5.6 General Hydrogeochemistry 5-7
5.7 Conceptual Groundwater Flow 5-8

Section 6: Groundwater Model Development 6-1

6.1 Introduction 6-1
6.1.1 Objectives 6-1
6.1.2 General Approach 6-1
6.1.3 Model Application 6-2
6.2 Model Development 6-3
6.2.1 Model Setup 6-3
6.2.2 Model Domain 6-3
6.2.3 Model Layers 6-4
6.2.4 Aquifer Properties 6-4
6.2.5 Boundary Conditions 6-5
6.2.5.1 Groundwater Recharge and Evapotranspiration 6-5
6.2.5.2 Columbia and Cowlitz Rivers 6-6
6.2.5.3 Consolidated Diking Improvement District Drainage Ditches 6-6
6.3 Model Calibration 6-7
6.3.1 Calibration Process 6-7
6.3.2 Base-Case Calibration 6-8
6.3.3 Pumping-Case Calibration 6-9
6.3.4 Calibration Evaluation 6-9
6.4 Sensitivity Analysis 6-10
6.5 Model Results 6-11
6.5.1 Groundwater Assessment of Pumping 6-11
6.5.2 Groundwater Model Scenario Results 6-12
6.5.3 Source Area Delineation 6-12
6.6 Preliminary Environmental Analysis 6-13
6.6.1 Particle Tracking from PCA Locations 6-13
6.6.2 Hypothetical Contamination Scenarios 6-14

Table of Contents (cont'd)

6.7 Conclusions 6-14
6.7.1 Summary 6-14
6.7.2 Conclusions 6-15

References i

List of Tables

3.1 Sentinel Well Construction Details
4.1 Deep Aquifer Parameter Estimates
5.1 Oxygen and Hydrogen Isotope Ratios (per mil, relative to V-SMOW)
6.1 Hydraulic Conductivities for the Longview-Kelso Basin and the Groundwater Flow Model
6.2 Simulated Drawdown at PW-1 for Six Different Combinations of Hydraulic Conductivity

List of Figures

2.1 Base Map (vicinity map)
2.2 Sentinel Well Location Map
2.3 Surface Representation of Geologic Cross-Sections
2.4 Geologic Cross-Section A-A'
2.5 Geologic Cross-Section B-B'
2.6 Geologic Cross-Section C-C'
2.7 Geologic Cross-Section D-D'
2.8 Geologic Cross-Section E-E'
4.1 Record Drawing, Production Well No. 1 Section and Detail
4.2 Time Drawdown Plot for Production Well PW-1, Step Rate Pumping Test
4.3 Production Well PW-1 Hydrograph
4.4 Time Drawdown Plot for Production Well PW-1, Constant Rate Pumping Test
4.5 Time Recovery Plot for Production Well PW-1
4.6 Time Drawdown Plot for Sentinel Well DW-9
4.7 Time Recovery Plot for Sentinel Well DW-9
4.8 Residual Drawdown Plot for Sentinel Well DW-9
5.1 Key Hydrogeologic Features Within the Longview-Kelso Basin
5.2 Near Surface Geology in Longview-Kelso Basin to Define Extent of Confining Layer
5.3 Distribution of Gravel and Sand Aquifers in Longview-Kelso Basin
5.4 Shallow Aquifer Groundwater Map, September Mean Groundwater Elevations

Table of Contents (cont'd)

5.5 Deep Aquifer Groundwater Map, September Mean Groundwater Elevations
5.6 Columbia River and Sentinel Well DW-1 Hydrograph
5.7 Groundwater and Surface Water Deuterium and Oxygen-18
5.8 Piper Diagram of Major Cations and Anions
5.9 Conceptual Groundwater Flow in Deeper Aquifer in Longview-Kelso Basin
6.1 Model Cross-Sections
6.2 Cross-Section Showing Grid and Layers
6.3 Simulated Hydraulic Heads, Shallow
6.4 Close-up of Figure 6.3
6.5 Simulated Hydraulic Heads & Flow Vectors
6.6 Base Case Observed vs. Simulated Heads
6.7 Distribution of Residuals
6.8 Base Case Sensitivity Analysis
6.9 Pumping Simulation Sensitivity Analysis
6.10 Shallow Hydraulic Heads – 12 mgd
6.11 Simulation Results – 12 mgd
6.12 Delineation of Source Area for Mint Farm Wellfield
6.13 Pathlines from PCAs after 30 Years
6.14 Pathlines from PCAs after 30 Years
6.15 Hypothetical Contamination Scenarios A
6.16 Hypothetical Contamination Scenarios B

List of Appendices

H Additional Well Logs Used for Basin Characterization
I Sentinel Well Boring and Well Construction Logs
J Laboratory Results of Grain Size Analysis and Hydraulic Conductivity
K Laboratory Analytical Reports
L Well Development Field Data Sheets
M Geophysical Logs
N Well Sampling Field Data Sheets
O Record of Plumbness and Alignment Testing on Production Well PW-1
P DVD of Video Well Inspection of Production Well PW-1
Q Washington Department of Ecology Water Well for Production Well PW-1
R Sentinel Well Hydrographs

List of Acronyms

Abbreviation	Definition
bgs	below ground surface
CAS	Columbia Analytical Services
CDID	Consolidated Diking Improvement District
City	City of Longview
cm/sec	centimeters per second
DEM	digital elevation model
DW	deep sentinel wells
EC	electrical conductivity
Ecology	Washington Department of Ecology
EPA	Environmental Protection Agency
ft bgs	feet below ground surface
ft/day	feet per day
gpd/ft	gallons per day per foot
gpm	gallons per minute
GMWL	Global Meteoric Water Line
HCID	hydrocarbon Identification
IDW	Investigative derived waste
K	hydraulic conductivity
Kennedy/Jenks	Kennedy/Jenks Consultants
mgd	million gallons per day
Model	Longview MODFLOW model
NAVD	North American Vertical Datum
NOAA	National Oceanic and Atmospheric Association
NCDC	National Climatic Data Center
NTUs	Nephelometric Turbidity Units
NWTPH	Northwest Total Petroleum Hydrocarbons
PCA	potentially contaminating activity
PSI	pounds per square inch
PVC	polyvinyl chloride
REVENUE	representative elementary volume
RWTP	Regional Water Treatment Plan
Site	Wellfield site
SVOCs	semi-volatile organic compounds
SW	shallow sentinel wells
T	transmissivity
TOC	total organic carbon
transducers	pressure transducers
USGS	U.S. Geological Survey
WAC	Washington Administrative Code
WHPP	Wellhead Protection Plan

This page intentionally blank.

Section 1: Introduction and Purpose

This report is Part 2 of the Preliminary Design Report (PDR Part 2) for the City of Longview (City) Mint Farm Regional Water Treatment Plant and Well Field and covers the hydrogeologic characterization of the Mint Farm area for use as a potable water source.

PDR Part 2 is divided into three reports, as follows:

- Part 2A: Hydrogeologic Characterization of the Mint Farm Area, includes a description of the geology and hydrogeology, details of the sentinel well installation program, the results of aquifer testing, and development of the groundwater model
- Part 2B: Water Quality and Environmental Risk Assessment.
- Part 2C: Preliminary Wellhead Protection Plan.

This page intentionally blank.

Section 2: Geology and Hydrogeology, Longview-Kelso Basin

2.1 Physical Setting

Longview is situated along the north bank of the Columbia River in southwest Washington and is bounded on the east by the Cowlitz River, which separates it from the City of Kelso, Washington. Both Longview and Kelso are located in a topographic basin that is surrounded on all sides by bedrock uplands. Topography within the basin is predominantly flat with a shallow regional slope towards the Columbia River. Prominent surface features in the area include the Columbia River to the south, the Cowlitz River (which discharges to the Columbia between the two cities), and Mt. Solo, an isolated prominent bedrock feature located in the western portion of Longview.

The proposed Longview Mint Farm Wellfield Site (Site) is located within the Mint Farm Industrial Park located on the west side of Longview, within Section 31 of Township 8N, Range 2W. Figure 2.1 displays the proposed wellfield site and surrounding vicinity. The proposed wellfield site is located at 1155 Weber Avenue on tax lot 10193033. The Mint Farm Industrial Park property consists of approximately 335 acres of developable property, in addition to approximately 100 acres of open space/public right-of-ways.

The proposed Mint Farm Wellfield Site is situated on a relatively flat floodplain at an elevation of approximately 10 feet above mean sea level. A network of dikes and drainage ditches in the southwest portion of the Longview-Kelso basin lowers the overall shallow groundwater elevations and protects the basin from flooding during high river levels and large storm events. This flood control system is operated and maintained by the Consolidated Diking Improvement District #1 (CDID). The northeastern portion of the Site consists of a constructed and managed wetland that is approximately 5 feet lower than the main portion of the Site. The Columbia River is located approximately 1 mile southwest of the center of the Site. Other surface water features in the immediate area include Lake Sacajawea, 1 mile to the east, and the Cowlitz River, approximately 2.5 miles to the east.

The proposed Site is surrounded by a mixture of industrial and commercial businesses to the south and west, managed wetlands and residential properties to the east, and residential and undeveloped property to the north. Railroad tracks operated by the Columbia and Cowlitz Railway Company (a short-line subsidiary of the Weyerhaeuser Company) border the southern and eastern portions of the Site.

2.2 Geologic Setting

The Longview-Kelso Basin is one of several topographic and structural depressions comprising the Puget-Willamette forearc trough of the Cascadia subduction zone (Evarts et al. 2009). Compared to the much larger Portland Basin, located immediately upriver to the south and also part of the Puget-Willamette trough, the Longview-Kelso Basin is less well-studied, although the Longview-Kelso Basin and the Portland Basin appear to share many of the same

characteristics. The modern and ancestral Columbia River has played a major role in shaping the geologic histories of both basins.

Bedrock geology in the area consists of Quaternary and Tertiary sedimentary and volcanic rocks (Phipps 1987; Walsh 1987). The oldest bedrock formation in the Longview-Kelso Basin is the Grays River Volcanics. Locally, basalt of the Grays River Volcanics outcrops at the base of Mt. Solo northwest of the Mint Farm Site. The sedimentary Cowlitz Formation overlies the Grays River Volcanics and consists of massive to thin-bedded sandstone with interbedded siltstone and shale. Basaltic andesite flows belonging to the Goble Volcanics are also present but confined to areas east of Longview-Kelso and east of the I-5 Interstate corridor. The Grande Ronde Basalt, a member of the Columbia River Basalt Group, is present in areas to the north–northwest of Longview and as cap rock on the summit of Mt. Solo. The sedimentary Troutdale Formation crops out in isolated regions north of Longview and east of the I-5 Interstate corridor. The Troutdale consists of unconsolidated to consolidated sandstone, conglomerate, and sandy siltstone associated with the ancient Columbia River system.

During the Late Pleistocene, approximately 16,000 to 12,000 years ago, the area was inundated by up to 40 catastrophic floods that originated from Glacial Lake Missoula (Swanson et al. 1993; Evarts et al. 2009). Glacial Lake Missoula formed when part of the Cordilleran Ice Sheet blocked the Clark Fork River in northwestern Montana. These floods were the result of repeated ice dam failures. Floods as large as 8,000 acre-feet raged across parts of eastern Washington, through the Columbia River Gorge, and into the Portland and Longview-Kelso Basins.

In the Portland Basin, coarse gravel deposits that form prolific aquifers, such as the Blue Lake Gravel, have been attributed to deposition by the Glacial Lake Missoula floods (Swanson et al. 1993; McFarland and Morgan 1996). The Blue Lake Gravel is present in the subsurface adjacent to and beneath the Columbia River in eastern Portland. It is over 200 feet thick in places and evidence suggests it is in contact with the Columbia River (McCarthy et al. 1992). Similar gravel aquifers adjacent to the Columbia River also occur in the subsurface near Washougal, Camas, and Vancouver. Wells in these gravels produce 1,000 to 6,000 gpm with less than 10 feet of drawdown. Also present in eastern Portland is the Columbia River Sand Aquifer, which fills a Pleistocene channel segment of ancestral Columbia (Hartford and McFarland 1989).

The youngest materials in the Longview-Kelso area consist of Quaternary alluvium. In the Longview area along the Columbia River, the upper portion of the alluvium consists of fine-grained sand, silt, and clay overlying coarser-grained gravels and cobbles. Many of the high-production wells in the Longview area are completed within these underlying coarse-grained gravel deposits. The silt and clay deposits may have formed along floodplains of the Columbia and Cowlitz Rivers and other major area creeks.

2.3 Local Geology

The geologic and hydrogeologic interpretations presented in this section are based on publicly available reference materials, consultants' reports, well logs of area wells, the analogous geologic history of the Portland Basin, and drilling activities conducted by Kennedy/Jenks Consultants (Kennedy/Jenks) as part of the sentinel well installation program.

As part of the hydrogeologic characterization of the proposed Mint Farm wellfield, a network of 17 paired shallow and deep sentinel wells was installed around the approximate perimeter of the Mint Farm (one deep well, DW-8, does not have a shallow sentinel well associated with it). Figure 2.2 is a site map that displays the locations of the sentinel wells. All but one of the deep sentinel wells (DW) were completed in the approximate middle of the coarse-grained alluvial deposits, ranging in depth from 240 to 370 feet below ground surface (ft bgs). The shallow sentinel wells (SW) were completed within a shallow, overlying sequence of silt and fine-grained sand sediments at depths ranging from 30 to 50 ft bgs. Bedrock encountered during the sentinel well installation program consisted of semi- to well-consolidated sandstone, siltstone and claystone. Where encountered, only the upper 2 to 10 feet of bedrock materials was penetrated during drilling of sentinel wells. A more thorough discussion of the sentinel well installation program is provided in Section 3 of this report.

Figure 2.3 shows the locations of five geologic cross-sections of the Longview-Kelso basin that were prepared to facilitate the subsurface characterization effort (Figures 2.4 through 2.8). Two sections longitudinal to the Columbia River and three transverse sections were prepared. Information obtained from existing well logs (see Appendix H) and during installation of the 17 sentinel wells was used to create the cross-sections. Where data were lacking, geologic interpretations were based on our understanding of the regional geologic setting and the analogous geologic history of the well-studied Portland Basin.

The longitudinal cross-section A-A' is shown on Figure 2.4. A-A' includes four of the deep sentinel wells installed at the Mint Farm site. All four of these sentinel wells penetrate an unconsolidated coarse gravel unit. This gravel unit is interpreted to be analogous to the Blue Lake Gravel found in the Portland Basin. Six other wells were used to complete A-A'. Five of these additional wells are completed in bedrock. The sixth well (Port of Longview) penetrates a sand unit, a silty interval, and bedrock. Clay- and silt-bound gravel and cemented gravel was reported on Port of Longview well log, but these gravels are interpreted to be part of the bedrock and not a continuation of the unconsolidated gravel unit encountered beneath the Mint Farm. The sand-filled channel-like feature depicted on the western portion of A-A' is an interpreted extension of a feature more easily seen on subsequent cross-sections. This bedrock trough is interpreted to be sand-filled Pleistocene channel of the Columbia River, analogous to the channel occupied by the Columbia River Sand Aquifer in the Portland Basin.

Cross-section B-B' (Figure 2.5) is also a longitudinal section that passes through the northern portion of the Mint Farm site. Sentinel well DW-4 encountered a bedrock high that is interpreted to be a subsurface extension of Mt. Solo. This bedrock extension apparently separates the sand-filled Pleistocene channel noted on section A-A' from portions of the subsurface to the south. The northward limit of the unconsolidated gravel unit was encountered by sentinel well DW-3.

Transverse cross-section C-C' (Figure 2.6) trends across the Longview-Kelso Basin to the northwest of the Mint Farm site. Mt. Solo is seen to separate the Pleistocene sand-filled channel to the north from a gravel-filled channel to the south. The present channel of the Columbia River is seen to cut through the silts, silty sands, and clays, encountered in the 3BS and US Gypsum wells, and down into the unconsolidated gravel unit.

Cross-section D-D' (Figure 2.7) is a transverse section that passes through the Mint Farm site. The bedrock extension of Mt. Solo can be seen where it is encountered by sentinel well DW-4.

McCutcheon (2003) mapped a fault immediately north of Mt. Solo. It is indicated on C-C' as the queried contact between the sand-filled Pleistocene channel and the silt unit. The unconsolidated gravel unit was encountered by several wells, but the clay unit penetrated by the Weyerhaeuser 2 well and the West Rainier Water Association well is interpreted to be too thick for the Columbia River to be in direct contact with the unconsolidated gravel unit. Mt. Coffin, a small isolated erosional remnant of basalt that was leveled and covered with fill before the mid-1900s, is located about 1,000 feet south of the Weyerhaeuser 2 well. Subsurface investigations at the Weyerhaeuser site noted the depth to the basalt ranged from 5 feet at the former location of Mt. Coffin to over 300 feet at locations less than about 1,000 feet away (CH2M Hill, 2009). Therefore, Mt. Coffin is considered to represent an isolated feature that is not shown on cross-section D-D'.

Transverse cross-section E-E' (Figure 2.8) crosses the Longview-Kelso Basin to the southeast of the Mint Farm site. The unconsolidated gravel is not found in this area. On the southern side of the section, the Columbia River channel is in direct contact with the sand unit.

A general interpretation of subsurface conditions at the Mint Farm Site suggests the presence of a valley that was eroded into underlying bedrock and subsequently infilled with sediments deposited by the Glacial Lake Missoula floods and by the Columbia River system. The geology beneath the Mint Farm and surrounding area consists of thick deposits of silt, clay, sand and gravel covered by thinner deposits of silty sand, silt, and clay.

2.3.1 Geology of the Mint Farm Area

Three general geologic units underlie the Mint Farm Site: (1) a low-permeability zone consisting of silt, silty sand, clay with interbedded fine-grained sand, (2) a fine- to medium-grained sand unit, and (3) an unconsolidated coarse-grained deposit of gravel and cobbles with minor occurrences of sand.

2.3.1.1 Silt/Clay Unit

The upper fine-grained materials consist of silt with varying percentages of clay and fine sand, and typically contain some fraction of wood debris and organic material. These fine-grained, low-permeability deposits tend to coarsen with depth, grading into fine to medium sand.

The upper silt/clay sequence is thickest in the southern part of the Mint Farm area, nearer to the Columbia River, where it ranges from 100 to 200 feet thick, but thins appreciably to the north and east. At both the SW-4/DW-4 and SW-3/DW-3 sentinel well locations (Figure 2.2), the surficial silt deposits are only about 15 feet thick and are underlain by fine- to medium-grained sand of the sand unit discussed below.

2.3.1.2 Sand Unit

Occasional layers of fine- to medium-grained sand exist within the upper silt/clay unit described in the previous section. However, for discussion purposes in this report, the sand unit is considered to consist of just the sandy deposits below the last occurrence of low-permeability silt/clay unit at a specific location.

The sand unit, consisting of fine- to medium-grained sand with minor amounts of very fine sand and silt, is prevalent across the northern portion of the Mint Farm Site and ranges in thickness from approximately 30 feet in sentinel wells located to the south along Industrial Way to approximately 250 feet in sentinel wells DW-3 and DW-4 located to the north and east.

2.3.1.3 Gravel Unit ("Target Aquifer")

The gravel unit is present in the southwestern part of the Longview-Kelso Basin. In deep sentinel wells installed just south of the Mint Farm area along Industrial Way, the gravel unit ranges from about 150 to 220 feet in thickness. In the area of sentinel well DW-4 at the northern edge of the Site, a 1- to 2-foot thickness of unconsolidated gravel is encountered just above bedrock. For purposes of this study, the gravel encountered at DW-4 is not considered to be continuous with the gravel unit that forms the target aquifer. At the DW-3 sentinel well location east of the site, the gravel unit is approximately 50 feet thick.

2.3.2 Relocation of Well Field Site

Based on suitability of available land and expected hydrogeological characteristics from previous consultant work, the initial wellfield for the project was proposed to be on a parcel of WREDCO land south of Crocker Avenue and east of Prudential Boulevard in the immediate vicinity of sentinel well DW-8. Based on findings from initial hydrogeological investigation, adequate target aquifer thickness was not encountered in the northeastern portion of the Site. The proposed wellfield site was subsequently relocated farther to the south in the Mint Farm Industrial Park on a parcel north of the existing Huber Chemical property.

This page intentionally blank.

Section 3: Sentinel Well Program

From February to July 2009, eight shallow and nine deep sentinel wells were installed to facilitate aquifer characterization of the Mint Farm Area. The location of each well is illustrated on Figure 2.2. With the exception of sentinel well location DW-8, each location consists of a pair of shallow and deep wells. All but one of the deep borings were drilled to the bottom of the coarse alluvial deposit/top of bedrock contact. The deep sentinel wells were installed with the screened interval (20 feet of screen) constructed in the approximate middle of the coarse alluvial deposits. The total depths of the completed deep sentinel wells range from 240 to 370 ft bgs. The shallow sentinel wells were completed in a thick sequence of generally silty sediments at depths ranging from 30 to 50 ft bgs. Each well boring was continuously cored for geologic identification. The geologic logs/well construction diagrams for all sentinel wells are included in Appendix I.

3.1 Sentinel Well Drilling and Sampling

All sentinel wells were drilled and installed using sonic drilling methods with equipment operated by Boart Longyear Company under direct contract with the City. Deep sentinel wells DW-1 through DW-9 and shallow sentinel well SW-9 were installed under the supervision of Kennedy/Jenks. The geologic logs/well construction diagrams for sentinel wells DW-1 through DW-9 and SW-9 were submitted to the City as an appendix to Technical Memorandum 6, Preliminary 7-Day Pumping Test Analysis at Test Production Well PW-1 (Kennedy/Jenks 2009a). Shallow wells SW-1 through SW-7 were drilled, installed, and developed under the supervision of Robinson Noble Saltbush, Inc. (Robinson Noble). A letter report dated 3 April 2009 documenting the installation of sentinel wells SW-1 through SW-7 (including the geologic/well construction diagrams) was submitted to the City by Robinson Noble.

During drilling of the deep sentinel wells, a temporary conductor casing was installed and sealed to a depth within the silt in the upper portion of the borings to prevent potential cross-contamination between the upper and lower zones. The depths of the temporary conductor casings varied based on the thickness of the silt zone and ranged from 90 to 165 ft bgs, with the exception of sentinel well DW-3, where the temporary conductor casing was sealed at a depth of 26 ft bgs.

Representative soil samples were collected during drilling of the deep sentinel wells for analysis of hydraulic conductivity (DW-2, DW-3, DW-4, DW-6 and DW-8), grain size analysis (all deep sentinel wells), and total organic carbon (TOC) (DW-1, DW-2, DW-3, DW-5, and DW-7). The purpose of the hydraulic conductivity analysis was to provide Site-specific data for development of a groundwater flow model (Section 6). The grain size analysis was conducted to provide information used in the design of the production well and to confirm the identification of various lithologies observed during drilling. The TOC analysis was collected to support potential contaminant fate and transport modeling and was used in the evaluation of Site soil and groundwater samples discussed in the *Water Quality and Environmental Risk Assessment* (Kennedy/Jenks 2010).

Hydraulic conductivity soil samples were collected using a Dames and Moore split-spoon sampler hydraulically driven into undisturbed soil or by driving a 2.25-inch-diameter brass sleeve into undisturbed core retrieved with the sonic core sampler. Grain size analysis samples

were collected by placing soil retrieved using the sonic core sampler into plastic buckets. The soil samples collected for hydraulic conductivity and grain size analysis were submitted under chain of custody to Soil Technologies of Bainbridge Island, Washington, for analysis. The samples collected for TOC analysis were submitted under chain of custody to Columbia Analytical Services (CAS) laboratory in Kelso, Washington, for analysis.

The laboratory reports of grain size analysis and hydraulic conductivity are included as Appendix J. The laboratory reports for the TOC analysis are included in Appendix K.

Table 13.1 presents a summary of sentinel well construction details. All wells were installed in accordance with Washington Administrative Code (WAC) 173-160. In general, the sentinel wells are constructed using 2-inch-diameter schedule 40 polyvinyl chloride (PVC)(shallow wells) or schedule 80 PVC (deep wells) casing and 15 to 20 feet of PVC screen (0.020-inch machine slotted [0.010-inch machine slotted used on SW-9]). A filter pack of 10x20 or 8x12 silica sand was installed in the annular space between the well screen and borehole to approximately 1.5 to 3 feet above the top of the screened interval. A transition seal of 20x40 silica sand was installed above the 10x20 or 8x12 filter pack in the deep sentinel wells. A bentonite chip (or pellet) seal was installed above the filter pack, and a bentonite grout seal was installed from the top of the bentonite seal to just below the ground surface. Each sentinel well was completed with either an aboveground or flush-mounted monument. Three traffic bollards were installed around each aboveground monument.

3.2 Well Development

Following construction, each deep sentinel well and shallow sentinel well SW-9 was developed, under the supervision of Kennedy/Jenks, to provide relatively sediment-free groundwater for representative sampling. The wells were developed by moving a vented surge block up and down within the screened interval of the casing and then pumping. During well development, field personnel recorded measurements of temperature, electrical conductivity (EC), pH, and turbidity. Well development continued until the field-measured parameters were stable and turbidity values were less than 10 Nephelometric Turbidity Units (NTUs). The well development field data sheets are included as Appendix L.

3.3 Investigation Derived Waste

Investigative derived waste (IDW) consisted of drill cuttings, water used in the drilling process, purge water, equipment decontamination water, and development water. The IDW was temporarily stored on property owned by the City located at the intersection of Prudential Boulevard and Hoehne Avenue. The upper 3 feet of soil from each monitoring well boring was contained in 55-gallon drums. Drill cuttings were placed in 10-yard steel drop bins and covered. Water used for drilling, well development water, and decontamination water was stored in three 4,000-gallon poly tanks.

For IDW characterization purposes, samples were collected from the soil drums, soil bins, and poly tanks for analysis. The water and soil bin samples were analyzed for petroleum hydrocarbons using the Northwest Total Petroleum Hydrocarbons (NWTPH) Hydrocarbon Identification (HCID) method and semi-volatile organic compounds (SVOCs) using Environmental Protection Agency (EPA) Method 8270C. The drum samples were analyzed for

petroleum hydrocarbons using the NWTPH HCID method and organochlorine pesticides using EPA Method 8081A.

Table 3.1: Sentinel Well Construction Details

Well Number	Surface Completion	Total Depth of Boring (ft bgs)	Total Depth of Casing (ft bgs)	Well Casing (All Casing is PVC)	Screen Interval	Screen Slot Size	Depth of Temporary Conductor Casing (ft bgs)	Northing	Easting	Top of Casing Elevation
DW-1	Aboveground	374	300	2-inch Schedule 80	280-300	0.02	126	301098.9459	1012563.515	17.302
DW-2	Aboveground	351	350	2-inch Schedule 80	330-350	0.02	90	304930.1189	1009540.664	11.342
DW-3	Aboveground	370	345	2-inch Schedule 80	325-345	0.02	26	304515.1894	1016492.599	14.319
DW-4	Aboveground	276	240	2-inch Schedule 80	220-240	0.02	165	307044.9508	1013745.59	10.683
DW-5	Aboveground	456	340	2-inch Schedule 80	320-340	0.02	140	303845.5087	1009492.067	11.054
DW-6	Aboveground	340	340	2-inch Schedule 80	320-340	0.02	90	302929.9832	1010593.304	14.451
DW-7	Aboveground	375	304	2-inch Schedule 80	284-304	0.02	90	302115.3502	1011481.091	16.063
DW-8	Aboveground	390	370.5	2-inch Schedule 80	350.5-370.5	0.02	136	305230.478	1011781.143	13.486
DW-9	Aboveground	404	320	2-inch Schedule 80	300-320	0.02	96	302407.945	1012142.096	14.371
SW-1	Aboveground	50	35	2-inch Schedule 40	15-30	0.02	n/a	301109.3073	1012553.106	16.836
SW-2	Aboveground	50	35	2-inch Schedule 40	15-30	0.02	n/a	304924.4057	1009551.57	10.609
SW-3	Flush	50	40	2-inch Schedule 40	20-40	0.02	n/a	304514.8137	1016476.296	11.092
SW-4	Aboveground	40	40	2-inch Schedule 40	20-40	0.02	n/a	307044.6345	1013680.684	10.315
SW-5	Aboveground	50	35	2-inch Schedule 40	15-35	0.02	n/a	303878.5805	1009498.669	11.042
SW-6	Aboveground	40	31	2-inch Schedule 40	16-31	0.02	n/a	303010.1262	1010507.491	12.851
SW-7	Aboveground	40	30	2-inch Schedule 40	12-27	0.02	n/a	302076.7587	1011522.368	14.354
SW-9	Aboveground	56	50	2-inch Schedule 40	30-50	0.01	n/a	302428.701	1012119.926	13.394

The results of the IDW analyses indicated that none of the constituent concentrations exceed appropriate screening values. Based on these results, the City authorized the IDW to be disposed of on City property. The poly tanks were drained onto the ground, the soil bins were transported to City property located approximately 0.25 mile north of the temporary storage area, and the soil was spread on the ground as fill material. The soil in the drums was also used for fill material in this location. The laboratory report for the IDW samples is included as Appendix K.

3.4 Sentinel Well Surveying

The top of casing elevation and horizontal (northing and easting) coordinates per Washington South State Plain Coordinate System, NAD 83 CORS 96, of all sentinel wells were surveyed by Mackay and Sposito, Inc., of Vancouver, Washington. Well elevations were surveyed relative to the North American Vertical Datum (NAVD) 88 datum. The sentinel well elevation and horizontal coordinate data are summarized in Table 3.1.

3.5 Geophysical Survey

On 22 and 23 June 2009, sentinel wells DW-2, DW-3, DW-4, DW-7, and DW-8 were geophysically surveyed to assist in characterizing the lithology at each location. The geophysical logging was conducted by Northwest Geophysical Associates of Corvallis, Oregon, under contract to Boart Longyear. The geophysical logging consisted of conductivity and natural gamma. Conductivity and natural gamma logs for all wells are included in Appendix M.

3.6 Well Field Relocation

As described in Section 2, the target aquifer was not encountered in the northeast portion of the Site area. Subsequently, the proposed well field was relocated to the southern portion of the former Mint Farm on property currently owned by Weyerhaeuser Real Estate Development Company (WREDCO).

3.7 Baseline Groundwater Sampling

Upon completion of installation and development of shallow sentinel wells SW-1 through SW-7 and deep sentinel wells DW-1 through DW-8, groundwater samples were collected for analysis to characterize shallow and deep groundwater quality in the Mint Farm area. In addition, water samples were collected from an industrial supply well at the Puget Sound Energy Mint Farm Generating Station (Puget Sound Energy Well #1, formerly named the Mirant well) located adjacent to the Site to the southwest, from a production well at the Chinook Ventures facility located adjacent to the Columbia River west of the Site, from the Columbia River at the Weyerhaeuser facility surface water intake southwest of the Site, and from the Cowlitz River at the current water treatment plant (the current City raw water source). Samples from these potential raw water sources for the City were collected to provide data used as part of the human health risk assessment.

The baseline sampling was conducted during the week of 8 June 2009. Groundwater samples were collected from each sentinel well after purging a minimum of three well casing volumes.

Parameters of pH, temperature, conductivity, and dissolved oxygen were measured and recorded periodically during the purge process. All of these parameters were stable for at least two consecutive measurements prior to collection of groundwater samples. Copies of the groundwater sampling data sheets are included in Appendix N. Groundwater samples from the Puget Sound Energy and Chinook Ventures wells were collected from water taps located near each well. Surface water samples from the Columbia and Cowlitz Rivers were collected from taps that dispense raw river water at the intake structure for each location.

The baseline groundwater and surface water samples were submitted under chain of custody to CAS laboratories located in Kelso, Washington, for analysis of Tier 2 analytes described in *Technical Memorandum 2, Water Quality Sampling Protocol* (Kennedy/Jenks 2009b). Laboratory reports for the baseline groundwater and surface water samples are included in Appendix K. The results of the baseline groundwater and surface water sampling are described in the *Water Quality and Environmental Risk Assessment* (Kennedy/Jenks 2010).

3.7.1 Groundwater Sampling During Well PW-1 Pumping Test

As described in Section 4, a constant rate pumping test was performed on production well PW-1 in October and November 2009. Groundwater samples were collected before, during, and after the pumping test. The purpose of the sampling and analysis during the production well pump test was threefold: (1) to collect water quality data required to design the treatment processes; (2) to obtain water quality data necessary for groundwater characterization; and (3) to evaluate the groundwater for appropriate water quality as a drinking water source to support for City Council and State approval of this source of supply.

The groundwater samples were collected using the methods described above. Water quality analysis was conducted in accordance with *Technical Memorandum 2A, Water Quality Sampling Protocol for First Production Well Pumping Test* (Kennedy/Jenks 2009c). The results of the well PW-1 pumping test sampling are described in the *Water Quality and Environmental Risk Assessment* (Kennedy/Jenks 2010). Laboratory reports for the pumping test samples are included in Appendix K.

3.8 Transducer Installation

Transducers were installed in all 17 sentinel wells to record fluctuations in groundwater elevation for aquifer characterization. In addition, transducers were installed in production well PW-1 and two domestic water wells. The domestic water wells are located on the southwestern side of Mt. Solo at 129 Solo View Drive (owner-Vansant) and 114 Bradford Place (owner – Bradford). Each data logger was configured to record pressure (feet of head), depth to groundwater, and temperature measurements on an hourly basis. Transducers in sentinel wells SW-9, DW-9 and production well PW-1 were set to record measurements at intervals shorter than 1 hour during the step drawdown pumping test and portions of the constant rate pumping test described in Section 1.5. The transducers are vented Level TROLL® 500, manufactured by In-Situ, Inc., with a rating of 30 pounds per square inch (PSI).

Data recorded by the transducers were periodically downloaded using an In-Situ, Inc. Rugged Reader® field computer. The data were then downloaded to desktop computers for processing.

Section 4: Test Production Well No. PW-1

To fully characterize the deep groundwater system, including estimating sustainable wellfield yield under full build-out conditions, the City of Longview installed a new deep test production well, PW-1, at the Site (Figure 2.2). Test production well PW-1 is intended to be the first well in the development of a municipal wellfield at the Site. The wellfield is anticipated to have a short-term maximum production capacity of 25-million gallons per day (mgd).

This section discusses the design, drilling, construction, and testing of test production well PW-1. The results of the pumping test conducted at PW-1, particularly the derivation of aquifer parameters, were used as inputs to a numerical groundwater model developed for the Longview-Kelso groundwater basin. Groundwater model development and results are discussed in Section 6 of this report.

4.1 Design of Test Production Well PW-1

The target aquifer for test production well PW-1 was the highly transmissive gravel unit described previously. The target yield for test production well PW-1 was 3,000 gallons per minute (gpm), based primarily on specific capacity values reported for other large supply wells in the area and T estimates available for the gravel aquifer.

The initially proposed location for the first production well was adjacent to sentinel well DW-8 in the undeveloped north-central portion of the Mint Farm Industrial Park (Figure 2.2). However, observations made while drilling DW-8 indicated that the gravel deposits there are only about 65 feet thick, resulting in concerns about adequate well yield. Subsequent drilling of other deep sentinel wells, particularly those to the south along Industrial Way, indicated that the gravel unit in that location is significantly thicker, ranging from 150 to 220 feet thick. Consequently, the location for PW-1 was moved south to the location shown on Figure 2.2.

Prior to committing to drilling the large-scale production well, an additional pair of sentinel wells, SW-9 and DW-9, was installed close to the selected location to confirm the adequacy of subsurface conditions. Drilling of DW-9 indicated that the gravel unit was approximately 125 feet thick at that location, and drilling of PW-1 commenced.

PW-1 was located approximately 55 feet from sentinel well DW-9 so that DW-9 could function as a nearby observation well for testing PW-1 and to facilitate the design of PW-1. Sentinel well DW-9, as were all sentinel wells, was installed using the sonic drilling method that provides continuous core samples of subsurface materials. Because the DW-9 boring was so well characterized and its location was near the proposed PW-1 location, the formation materials obtained from DW-9 were used to design production well PW-1. Therefore, design of PW-1 could be completed while the borehole for the production well was being drilled.

At the DW-9 location, the gravel unit extends from about 217 ft bgs to the top of bedrock at approximately 399 ft bgs. Grain-size sieve analyses of select samples from within this depth interval were evaluated and used to design the well screen for production well PW-1 (copies of the sieve analyses are included in Appendix J of this report). Based on the sieve analysis results and observations made during drilling, a screened interval from 230 to 370 was selected

with an intermediate blank section installed from 285 to 300 ft bgs in a relatively fine-grained section of the formation.

Based on the target well yield of 3,000 gpm, an 18-inch diameter well screen and lower casing assembly was selected. With an 18-inch casing, flows up to approximately 3,600 gpm do not exceed the maximum up-hole axial velocity of 5 feet per second recommended by the American Water Works Association for water well designs. However, preliminary well pump design calculations indicated that a 24-inch nominal diameter casing would be required for installation of a submersible pump. Consequently, PW-1 was designed with an upper 24-inch production casing extending to 230 ft bgs, with the 18-inch casing/screen assembly telescoped approximately 45 feet up into the 24-inch casing. Although Washington State standards for water well construction require only a minimum 18 feet of surface seal, the surface seal for PW-1 was designed to extend to approximately 150 ft bgs. This depth is almost the total thickness of the overlying silty deposits at the PW-1 location.

The finest of the representative grain-size analyses obtained from DW-9, from 241, 335, and 347 ft bgs, were used to size the filter pack material and screen slot size. These analyses indicated a distinctly bimodal distribution of sand size, particularly in the 241-foot samples. Consequently, two different filter pack / slot size combinations were used for the well. The upper portion, from 230 to 285 ft bgs, was designed for a 40-slot (0.040 inch) screen with 8x12 Colorado Silica Sand filter pack. The lower screened portion, from 300 to 370 ft bgs, was designed for a 70-slot (0.070 inch) screen with 6x9 Colorado Silica Sand filter pack. The filter pack gradation selected for the upper screen section is also suitable for the lower screen section; that is, if significant settlement of the upper filter pack were to occur, then only the maximum acceptable percentage of the upper, finer filter pack would still pass the lower, coarser screen section.

4.2 Drilling and Construction Discussion

From 19 August to 2 October 2009, production well PW-1 was drilled, installed, and developed using cable tool drilling methods with equipment operated by Boart Longyear under direct contract to the City. Figure 4.1 is a record drawing showing the final construction of production well PW-1. The final construction of well PW-1 is consistent with the well design described in Section 4.1. Production well PW-1 was drilled, installed, and completed in accordance with WAC 173-160.

The initial step in drilling well PW-1 was to install a 28-inch nominal diameter conductor casing to a depth of 150 feet. A 24-inch nominal diameter production casing was then advanced to a depth of 385 feet within the 28-inch casing.

After the 24-inch casing drive shoe was cut off at a depth of 378 feet, the well screen assembly, consisting of 18-inch diameter 304 stainless-steel wire-wrapped well screen and steel casing, was installed within the 24-inch production casing. The lower screen section has a 0.070-inch slot size and extends from 299 to 370 ft bgs with a 4-foot-long sump installed at the bottom of the screen section. A blank casing section extends from the bottom of the upper screen section (285 ft bgs) to the top of the lower screen section (299 ft bgs). The upper screen section consists of 0.040-inch slot size and extends from 230 to 285 ft bgs. A blank riser extends from a

depth of 195 to 230 ft bgs with a 5-foot section of relief screen (0.040-inch slot size) positioned within the riser section.

The 24-inch-diameter production casing was withdrawn as the well filter pack was installed in the annular space between the screen assembly and production casing. A thickness of at least 5 feet of filter pack material was maintained within the production casing as the production casing was withdrawn. The filter pack consists of 6x9 silica sand in the lower screen section, which extends to the top of the intermediate blank section. The filter pack in the upper screened section is 8x12 silica sand and extends up into the 24-inch production casing to within 5 feet of the top of the well screen assembly. The bottom of the production well casing is 230 ft bgs.

A cement grout seal was installed between the 28-inch and 24-inch casing. The 28-inch casing was withdrawn as the seal was placed, leaving a cement seal in direct contact with the formation.

The completed production well was developed by surging, bailing, and pumping using an air lift pump for several days. Final production well development was conducted using a shaft line pump and pumping rates up to approximately 5,000 gpm. The development water was discharged through piping to the CDID ditch located adjacent to Industrial Way.

Upon completion of the pumping tests described below, Boart Longyear performed a plumbness and alignment test and a video inspection of the well. The record of the plumbness and alignment test is included in Appendix O. A DVD of the video inspection was submitted to the City by Boart Longyear. A copy of the video inspection DVD is included in Appendix P.

After the video inspection, Boart Longyear disinfected well PW-1 by installing a chlorine solution into the well and allowing it to stand for approximately 24 hours. The well was then pumped to remove the chlorine. The discharge water was treated prior to discharging to the ground surface.

Production well PW-1 was completed by welding a casing riser to a height of 36 inches above ground surface, welding a plate over the top of the casing, and installing a 2-inch access port on the plate for the purpose of sampling and collection of water level data.

As required by WAC 173-160, Boart Longyear completed a Water Well Report and submitted the report to Washington Department of Ecology (Ecology). A copy of the Water Well Report is included as Appendix Q.

4.3 Adjustments to Deep Groundwater Level Data (Columbia River Tidal Influence)

Highly variable groundwater levels in the deep monitoring wells preclude straightforward determinations of groundwater flow directions, gradients, or other related measures. To facilitate estimating these conditions, mean groundwater levels were calculated for the deep well data. The method used to calculate the mean groundwater levels is identical to that used by NOAA to establish daily mean tide levels for surface water bodies (Serfes 1991). The rationale for using this method for tidally influenced groundwater data is that the magnitude and direction of the instantaneous hydraulic gradient fluctuate about the mean hydraulic gradient. The net

displacement of groundwater is thus driven by the mean hydraulic gradient. The adjustment method involves calculating a sequence of three sequential 24-hour moving averages, which effectively removes the semi-diurnal sinusoidal tidal pattern. When these calculations are repeated for each successive hourly data point, a mean groundwater elevation line is derived. With a few noted exceptions, mean groundwater levels calculated in this manner were used for analytical purposes.

4.4 Step-Rate Pumping Test

A diesel-engine powered shaft-driven turbine test pump was installed in test production well PW-1 to complete final well development and perform step-rate and constant-rate pumping tests. The test pump intake was set to approximately 55 ft bgs. Pump discharge was measured and recorded using a digital totalizing flow meter. Discharge rate was controlled primarily with a gate valve installed within the pump discharge pipe, with secondary control provided by regulating the diesel engine operating speed.

Following completion of well development on 2 October 2009, a step-rate pumping test was conducted in test production well PW-1 on 5 October 2009. Each step consisted of pumping for approximately 60 minutes at four rates ranging from 3,000 to 4,600 gpm in increments of approximately 500 gpm.

Figure 4.2 is a time-drawdown plot for PW-1 data recorded during the step-rate test. About midway through the step-rate test, water levels were observed to begin rising with increasing pumping rates. This increase in pumping water levels was attributable to a rising tide in the Columbia River occurring while the test was performed, and the data were corrected for the tidal influence. Shown on Figure 4.2 are both the uncorrected measurements and levels corrected for tidal influence. Using the corrected levels, specific capacity values corresponding to the end of each step ranged from approximately 1,900 to 980 gpm per foot of drawdown at 3,000 and 4,600 gpm, respectively. These are extremely high specific capacity values, and indicate both a prolific aquifer and a highly efficient well.

Groundwater discharged during the step-rate and constant-rate pumping tests was conveyed to CDID Ditch No. 5 located approximately 750 feet south of PW-1 and parallel to Industrial Way (Figure 2.1). This ditch discharges to the Columbia River several miles from the Mint Farm site. Water level and flow within the ditch are managed by the CDID via a series of pump stations and flow control structures.

4.5 Constant-Rate Pumping Test

A constant-rate pumping test was conducted in production well PW-1 beginning at approximately 12 PM on 6 October 2009. At the start of the test, the planned duration was 30 days, with an option to extend to 60 days if observed conditions indicated additional benefits could be derived from the longer-duration test. When it was determined there was no further benefit to be obtained by continuing the pump test, the constant-rate pumping test was concluded at approximately 11:00 AM on 11 November 2009. The actual total duration of the constant rate pump test was exactly 36 days.

The pumping rate over the entire 36 days of testing averaged 3,918 gpm (+/- 115 gpm). The maximum drawdown in PW-1 was anticipated to range from approximately 2.5 to 4 feet, based on the results of the step-rate test.

4.5.1 Additional Adjustments to Deep Groundwater Level Data (Longer-Term Regional Trend)

A vented pressure transducer / data logger was installed in PW-1 to record periodic water level measurements. Figure 4.3 is a hydrograph of PW-1 depth-to-water measurements obtained from the data logger for the duration of the constant-rate pumping test (a reference elevation was not available for test well PW-1, so all data for PW-1 are presented as either depth-to-water measurements or as relative changes in groundwater level). Shown on Figure 4.3 are raw depth-to-water data exhibiting strong tidal influence, as well as data adjusted for the tidal influence using the multiple moving average method discussed previously. The raw data show that at times during the test, the pumping water level in PW-1 fluctuated almost 4 feet over one-half tidal cycle (approximately 6 hours). This typical deep well response to tidal fluctuations in the Columbia River was previously discussed in Section 4.3 of this report.

Additionally, the tidally adjusted data for PW-1 shown on Figure 4.3 indicate longer-period trends in the deep groundwater levels. These mostly upward trends, also observed in other deep well levels, correlate closely with general stage changes in the Columbia River (see Appendix R). Thus, in addition to adjusting for the shorter-term tidal influences, adjustments were also made to resolve the longer-term regional groundwater trends. All deep well data were adjusted by accounting for the average relative hourly change, starting from the beginning of the constant-rate test in water levels recorded in seven of the deep wells (data from DW-4 and DW-9 were not used to calculate the correction, the former because it does not show hydraulic behavior typical of the other deep wells, and the latter because it is most likely to show a response to pumping at PW-1 only 50 feet away). The average relative change in deep groundwater levels was applied to all deep well data to account for the longer-term regional trends.

The PW-1 Fully-Adjusted Mean Depth-to-Water curve shown on Figure 4.3 incorporates adjustments for both the tidal influence and longer-period regional groundwater trends. This curve is useful for determining groundwater level behavior during most of the test, except for those periods within approximately 1.5 days of the start and end of the test. The reason for this exception is that the method used to adjust for the tidal influence incorporates hourly measurements from both before and after the start (or end) of pumping, and thus tends to obscure both short-term drawdown and recovery responses in a well. Therefore, detailed water level responses during initial drawdown and recovery periods are presented in additional graphs included in the Section 4.5.2 of this report.

4.5.2 Pumping Test Analysis

In addition to pumping well PW-1, drawdown responses were observed in sentinel well DW-9. Sentinel well DW-9 is approximately 55 feet from DW-1 and is screened across the lower portions of the deep aquifer. A drawdown response of a few hundredths of a foot at DW-9 was determined, but no other sentinel wells exhibited discernible responses to pumping at PW-1

(discussed later in this report). Water level data obtained from pumping well PW-1 and sentinel well DW-9 were used to derive aquifer parameters for the deep aquifer system.

4.5.2.1 Pumping Well PW-1

Figure 4.4 is a time-drawdown curve developed using measurements obtained from pumping well PW-1. As shown on Figure 4.4, the transducer output suggests that drawdown was erratic during approximately the first 150 minutes of pumping. However, this erratic response was attributed to vibration of the transducer caused by pump operation, and thus does not represent actual high-frequency water-level changes in the well during pumping. Manual water-level measurements obtained during the initial (Figure 4.4) and final hours of pumping confirm this assertion. Most importantly, the manual measurements indicate the fluctuating raw transducer output centers approximately around the actual water levels. After approximately 150 minutes of pumping, hourly transducer data was obtained to facilitate tidal corrections, so the higher-frequency transducer fluctuations are not apparent in that portion of the drawdown curve.

Aquifer transmissivity (T) was estimated graphically from the PW-1 time-drawdown curve (Figure 4.4) using the Cooper-Jacob modification of the equation. This non-equilibrium equation, uses the relationship presented below (Driscoll 1986):

$$T = 264Q / \Delta s$$

Where:

T = coefficient of transmissivity (in gpd/ft)
Q = pumping rate (in gpm)
Δs = slope of time-drawdown graph within one log cycle (on a base-10 log)

As indicated on Figure 4.4, an early-time portion of the curve was used to calculate a T value of approximately 4,100,000 gallons per day per foot of aquifer thickness (gpd/ft). Assuming a gravel thickness of 165 feet, the hydraulic conductivity (K) would be approximately 25,000 gallons per day per foot squared (gpd/ft^2) or 3,300 feet per day (ft/d).

A downward inflection in the drawdown curve begins after approximately 60 minutes. This inflection is also apparent in the drawdown curve for sentinel well DW-9 (discussed in the next section), so it likely reflects a nearby slight negative boundary condition for the deep aquifer. The T value calculated for this mid-time portion of the PW-1 drawdown curve results in an estimated 1,900,000 gpd/ft. Assuming a gravel thickness of 165 feet, the K value would be approximately 11,500 gpd/ft^2 or 1,530 ft/d.

Most notable on Figure 4.4 (and Figure 4.3) is that after an elapsed pumping time of approximately 1,800 minutes (1.25 days), the drawdown curve for PW-1 becomes virtually flat, implying near-infinitesimal T from this time to test completion. This is almost certainly the period when the recharge influence of the Columbia River begins to be realized on the deep aquifer at the PW-1 location. However, it must be emphasized that this hydraulic relationship between the river and the aquifer represents the propagation of pressure through the aquifer, not the migration of actual river water to PW-1. The migration of river water to the PW-1 location is considered to take two months to over 10 years. Additional analyses evaluating the travel times from the Columbia River the Mint Farm Wellfield are discussed in Section 6.

Figure 4.5 is a time-recovery graph of data obtained from pumping well PW-1. “Recovery” refers to the rise in groundwater level that occurs after the pump has been turned off. A plot of the rate of recovery can be used in a manner similar to drawdown measurements to graphically derive aquifer parameters. For pumping wells, recovery data are often preferable to pumping data for calculating parameters because the former are not subjected to pump discharge fluctuations that are often experienced during pumping tests. Recovery water-level data can be used to calculate a T value using the following relationship (Driscoll 1986):

$$T = 264Q / \Delta (s\text{-}s')$$

Where:

T = coefficient of transmissivity (in gpd/ft)
Q = pumping rate (in gpm)
Δ (s-s’) = slope of calculated recovery graph within one log cycle (on a base-10 log)

Using the above relationship applied to the time-recovery graph of PW-1 data yields an early-time T value of approximately 4,500,000 gpd/ft. Assuming a gravel thickness of 165 feet, the K value would be approximately 27,250 gpd/ft^2 or 3,600 ft/d.

Aquifer T values can also be estimated using specific capacity estimates obtained from pumping test measurements. Specific capacity is the ratio between the well production rate (Q) in gpm and drawdown (s) in feet, and is a measure of the productivity of a well and the aquifer system. In confined aquifers, specific capacity can be related to T values by the following (Driscoll 1986):

$$\text{Specific Capacity } Q/s = T / 2000$$

Where:

T = coefficient of transmissivity (in gpd/ft)
Q = pumping rate (in gpm)
s = drawdown (in feet)

This relationship, with Q = 3,900 gpm and s = 3.3 ft, which is the average sustained drawdown observed through the duration of the 36-day test, yields a T value estimate of approximately 2,400,000 gpd/ft.

Using various methods applied to the PW-1 data, calculated T values for the deep aquifer range from 1,900,000 to 4,500,000 gpd/ft. These values compare favorably with T value estimates reported for other wells in the area and represent a prolific aquifer. The K values would range from 11,500 to 20,000 gpd/ft^2 or 1,530 to 3,600 ft/d. Table 4.1 summarizes aquifer parameter values calculated using data obtained from pumping well PW-1 and sentinel well DW-9 (Section 4.5.2.2).

4.5.2.2 Sentinel Well DW-9

Sentinel well DW-9 is a deep aquifer well located approximately 55 feet from pumping well PW-1. A vented pressure transducer / data logger was installed in DW-9 to record periodic water level measurements before, during, and after the constant-rate pumping test at PW-1.

Figure 4.6 is a time-drawdown curve developed using measurements obtained from sentinel well DW-9 during the test. This curve was generated using hourly measurements recorded by the pressure transducer. Notable on Figure 4.6 are seemingly large and periodic water-level fluctuations. These fluctuations are actually evident soon after pumping begins, but are not visibly prominent on the logarithmic time scale of Figure 4.6 until after approximately 6,000 minutes (or about 4 days) after the start of the test.

Similar fluctuations appear on both the hydrograph and drawdown curve for PW-1 (Figures 4.3 and 4.4, respectively). These fluctuations are actual aquifer responses to longer-period trends in the Columbia River, which occur about every 2 to 3 days. Comparison of other deep well hydrographs and Columbia River stage levels (Appendix R) with the DW-9 and PW-1 drawdown curves shows approximate correlation of high and low longer-period peaks. The variations in calculated drawdown at DW-9 range from 0.21 to 0.46 feet; therefore, the average drawdown of 0.33 feet was used for analytical purposes.

The time-drawdown curve for DW-9 on Figure 4.6 shows a downward inflection similar to that seen in the PW-1 curve, also beginning after approximately 60 minutes of pumping. Using the Cooper-Jacob straight-line method applied to the DW-9 drawdown curve at the steepest part of the downward inflection, a T estimate of approximately 10,300,000 gpd/ft was calculated. Assuming a gravel thickness of 165 feet, the K would be approximately 62,000 gpd/ft^2 or 8,300 ft/d. As with PW-1, after about 1,800 minutes of pumping, the drawdown curve for DW-9 also becomes virtually flat (except for the longer-period fluctuations discussed previously). These values are much higher than others calculated from this pumping test. One possibility is that the early time hydraulic communication between the two wells, which are only about 50 feet apart, was dominated by the most highly permeable interlayers of the gravel unit, and that this has skewed the results.

Time-drawdown data for observation wells can also be used to calculate the storage coefficient, or storativity, of an aquifer. Storativity is a dimensionless quantity defined as the volume of water that a permeable unit will absorb or expel from storage per unit surface area per unit change in head. Calculated values of storativity are useful for characterizing aquifers as being unconfined or confined. Unconfined aquifers typically have storativity values ranging from 0.02 to 0.30, whereas confined aquifer storativity values are typically on the order of 0.005 or less (Fetter 1994).

Using the time-drawdown curve for DW-9 (Figure 4.6), the deep aquifer storativity can be calculated using the following relationship (Driscoll 1986):

$$S = 0.3\ Tt_0 / r^2$$

Where:

S = storage coefficient, or storativity
T = transmissivity (in gpd/ft)
t_0 = intercept of the straight line at zero drawdown (in days)
r = distance from pumped well to observation well (in feet)

Using the parameter values shown on Figure 4.6, a storativity value of 0.20 was calculated using the DW-9 drawdown data. This storativity is typically associated with an unconfined

aquifer condition. However, the deep aquifer at the Mint Farm wellfield cannot readily be classified as either wholly unconfined or confined on the basis of this storativity value. The head differences between shallow and deep sentinel wells (except at SW-4 and DW-4) clearly indicate confined conditions throughout most of the deep aquifer, with a strong pressure (head) differential between the two systems.

In addition, as discussed in Section 2.3, well installation records indicate the deep aquifer is overlain by relatively impermeable silty deposits, with the thickest portions (150 to 250 feet) in areas closest to the Columbia River. The overlying silt deposits thin appreciably in the north portion of the Mint Farm area near sentinel wells SW-4 / DW-4, where measured groundwater levels are virtually identical, suggesting the degree of confinement is much lower in this area. However, the clearly demonstrated hydraulic connection between the deep aquifer and the Columbia River is likely the principal reason the calculated storativity value is not indicative of fully confined conditions. The relatively constant head condition of the river provides a virtually limitless specific yield to the deep aquifer which, from an analytical standpoint, behaves more like a prolific unconfined aquifer. This would indicate the gravel unit is in direct communication with the Columbia River just upstream from the Mint Farm area. This connection forms a significant recharge boundary for the aquifer which, over the duration of this test, would lead to a storativity value more consistent with an unconfined aquifer.

Figure 4.7 is a time-recovery graph of data obtained from sentinel well DW-9. Using early-time recovery data, a T of approximately 3,300,000 gpd/ft and a storativity of 0.13 were calculated. Assuming a gravel thickness of 165 feet, the K would be approximately 20,000 gpd/ft^2 or 2,675 ft/d. For this analysis, the early-time recovery data shown on Figure 4.7 were not adjusted for tidal influences because such effects are inconsequential over short time periods (measurements made after about 25 minutes of recovery begin to show tidal influence, but these were not used for parameter estimation on Figure 4.7).

Figure 4.8 is another graph of DW-9 recovery data that shows residual drawdown versus the ratio t/t', where t is the total time since pumping began and t' is the time since the pump was stopped. This plotted relationship can be used to calculate an aquifer T value and is also useful for evaluating either recharge or incomplete recovery conditions at the well. As indicated on Figure 4.8, a T value of 3,400,000 gpd/ft was calculated using this method. Assuming a gravel thickness of 165 feet, the K value would be approximately 20,000 gpd/ft^2 or 2,675 ft/d.

On Figure 4.8, under normal confined aquifer conditions, the curve theoretically should pass through the origin at a residual drawdown of 0 feet and a t/t' value of 1. The limited amount of drawdown data shown on Figure 4.8 obviously is not trending toward this origin, and actually tails away markedly because it has not been corrected for tidal influence. The strong tidal influence on water level data likely precludes any meaningful conclusions related to either recharge or incomplete recovery conditions using Figure 4.8.

Aquifer parameter values calculated using data obtained from sentinel well DW-9 is summarized in Table 4.1.

4.5.2.3 Other Deep Sentinel Wells

Hydrographs for the other deep sentinel wells are included in Appendix R of this report. It is possible that a drawdown response was recorded at sentinel well DW-1, located approximately 1,400 feet south-southwest of production well PW-1. Upon pump shutdown on 11 November, a slight up-tick of 0.04 to 0.05 foot in the mean groundwater level elevation for DW-1 is apparent (see hydrograph, Appendix R). Review of the corrected mean water level plots shows that no discernible drawdown due to pumping at PW-1 is apparent in any of the other deep wells.

The very high T value calculated for the deep aquifer suggests that a small amount of drawdown would be expected to have occurred in deep wells, even at fairly great distances from the pumping well. However, the pumping rate used for the constant-rate test, which was the maximum rate governed by well screen design parameters, resulted in relatively low drawdown in both pumping well PW-1 and the nearest sentinel well DW-9. The adjustments made to account for both diurnal tidal fluctuations of up to several feet and longer-period trends effectively resolved these influences in deep well water levels. However, the resulting adjusted data do not provide enough resolution to either clearly discern slight drawdown magnitudes at a deep sentinel well, or, in the case of DW-1, to use the resulting data for accurate parameter estimation.

No discernible response occurred in the two domestic water wells (Vansant and Bradford) located on the southeastern side of Mt. Solo during the constant-rate pumping test at PW-1.

4.5.2.4 Shallow Sentinel Wells

Hydrographs for all shallow sentinel wells are included in Appendix R of this report (note that no shallow sentinel well is associated with deep sentinel well DW-8). Water level trends observed in the shallow sentinel wells, unlike with the deep wells, were not consistent enough to derive and apply a regional correction for external (non-pumping) influences. The variable magnitudes of water-level fluctuations measured in the shallow wells are likely due, in large part, to different geologic characteristics at each well location, thus leading to variable dampening of tidal (or other) influences.

No discernible drawdown occurred in any shallow sentinel wells due to pumping at PW-1. On the contrary, during the constant-rate test period, groundwater levels rose in all shallow sentinel wells, likely in response to localized recharge caused by the onset of seasonal precipitation events.

4.5.3 Pumping Test Conclusions

Results from the 36-day constant-rate pumping test conducted in test production well PW-1 lead to the following conclusions:

- The deep gravel aquifer is very prolific, with calculated parameters comparable to, or in some cases greater than, the values reported by others for wells located nearby and completed within the same aquifer.

- Calculated early-time T values ranged from 1,900,000 to 10,300,000 gpd/ft. The most reliable T values derived from recovery water level data ranged from 3,300,000 to 4,500,000 gpd/ft.

- Calculated early-time K values ranged from 11,500 to 62,000 gpd/ft^2 (1,530 to 8,300 ft/d). The most reliable K values derived from recovery water level data ranged from 20,000 to 28,000 gpd/ft (2,600 to 3,600 ft/d).

- Recharge influence of the Columbia River on the deep aquifer at the PW-1 location became apparent after approximately 1.25 days of pumping, when drawdown curves for both pumping well PW-1 and sentinel well DW-9 became virtually flat.

- Calculated storativity ranged from 0.13 to 0.20, values typically associated with unconfined aquifers. Borehole data from the Mint Farm wells shows the presence of a thick silt/clay confining layer. That the storativity value reflects an unconfined condition indicates a hydraulic connection between the deep aquifer and the Columbia River that is likely responsible for the seemingly anomalous storativity values derived. Other stratigraphic and hydraulic evidence indicates the deep aquifer is confined throughout most of its extent in the Mint Farm wellfield area.

Table 4.1 Deep Aquifer Parameter Estimates

Estimated Transmissivity (T) Values	Derivation
4,100,000 gpd/ft	PW-1 early-time drawdown measurements
1,900,000 gpd/ft	PW-1 mid-time drawdown measurements
4,500,000 gpd/ft	PW-1 early-time recovery measurements
2,400,000 gpd/ft	PW-1 specific capacity relationship
10,300,000 gpd/ft	DW-9 early-time drawdown measurements
3,300,000 gpd/ft	DW-9 early-time recovery measurements
3,400,000 gpd/ft	DW-9 early-time recovery measurements (using t/t' ratio)
Estimated Storativity Values	**Derivation**
0.20	DW-9 early-time drawdown measurements
0.13	DW-9 early-time recovery measurements

This page intentionally blank

Section 5: Hydrogeology

5.1 Introduction

The key hydrogeological data from the Longview-Kelso Basin provide the basis for an interpretation of how groundwater flows through the Basin. This characterization is based on stratigraphic conditions observed during the sentinel well installation program; review of area water well reports; review of other consultant reports; analysis of groundwater-level data recorded by the transducers in each sentinel well; and results of oxygen and hydrogen isotopic data obtained from select sentinel wells and the Columbia and Cowlitz rivers. This section provides a discussion of groundwater data collected during this investigation and a discussion of the hydrogeological conceptual model based on these data.

5.2 Longview-Kelso Basin

The Longview-Kelso Basin covers approximately 35 square miles in the vicinity of Longview, Washington, near the confluence of the Cowlitz and Columbia Rivers (Figure 5.1). The Basin has a northwest-southeast orientation and is about 13 miles long by 4.5 miles wide at its widest point. The valley floor is relatively level but slopes gently toward the south. The valley is surrounded by highlands that are primarily composed of basaltic and older sedimentary rocks (Phipps 1987; Walsh 1987).

General subsurface conditions in the Longview-Kelso Basin consist of a valley eroded into the underlying bedrock. Near the surface over a large portion of the Basin is a clayey silt deposit that typically thickens to the south toward the Columbia River. It tends to be present in the eastern portion of the basin but is thin to absent in areas of the western portion of the basin (Figure 5.2). This clayey silt deposit forms an effective confining layer in the areas where it is present.

5.3 Aquifer Definition

Two distinct groundwater systems underlie most portions of the Site: a shallow system and a deep system.

5.3.1 Shallow Groundwater System

The shallow system consists primarily of fine-grained silt and clays with silty sand interbeds, including a thick silt/clay overlies much of the basin. Where the silt/clay layer is present it acts as a confining layer to the underlying sand and gravel aquifers. Where it is absent, the sand and gravel aquifers are considered to behave as unconfined systems (Figure 5.3).

Shallow groundwater in the upper, low-permeability silt unit is under water table (unconfined) conditions in the Site vicinity. Based on measurements obtained from the Site sentinel wells from June through November 2009, static groundwater levels in the shallow system range from approximately 5 to 10 ft bgs.

The clear hydraulic distinction between the shallow system and the underlying deep system diminishes towards the northernmost portion of the Site. The loss of distinction between the two systems, is based largely on water level information obtained from sentinel wells SW-4/DW-4 in the far northern perimeter of the Site. Sentinel wells SW-4 and DW-4 were both completed within the intermediate, fine- to medium-grain sand unit at depths of approximately 40 and 240 ft bgs, respectively. The overlying silt deposits are only about 15 feet thick in this area, and only a 1- to 2-foot thickness of gravel was found at the bottom of DW-4. Groundwater levels at SW-4 and DW-4 are virtually the same, and it is believed that the heads at this location are influenced to some degree through hydraulic connection with the underlying confined system.

Eleven representative samples of the shallow silt deposits were obtained at varying depths as part of the sentinel well installation program and submitted for laboratory determination of K values. Nine of the samples were in the 10^{-7} and 10^{-8} cm/sec range ($3x10^{-5}$ and $3x10^{-6}$ ft/d), and the remaining two were in the 10^{-3} and 10^{-4} cm/sec (0.3 and 0.03 ft/d) range. The lower K values correspond to typical silty layers observed while drilling through the upper system, whereas the two higher values are associated with the most permeable strata (relatively more sandy) observed within the upper unit. Physical testing and grain size distribution analyses are discussed further in Section 3.1.

Analysis of several months of hourly groundwater-level data obtained from the sentinel wells indicates that groundwater flow in the shallow groundwater system flows is strongly influenced by the CDID drainage canals and that groundwater in the shallow system primarily flows radially towards the CDID drainage canals. Figure 5.4 is a groundwater map of the shallow system created using hourly groundwater level measurements averaged over a 2-week period in September 2009 (the CDID drainage canals are prominently highlighted in Figure 6.13). Evaluations of water-level data measured over other periods of the year (beginning in July 2009) show similar results, thus Figure 5.4 is representative of shallow groundwater flow directions and gradients for the period of data collection. A detailed interpretation of groundwater flow dynamics of both the shallow and deep systems is presented in Section 6 of this report.

5.3.2 Deep Gravel Aquifer ("Target Aquifer")

The deep aquifer forms the primary water-bearing zones, and it can be subdivided into a sand aquifer and a gravel aquifer that have distinct hydrogeologic characteristics.

- The gravel unit is typically 100 to 150 feet thick, but it is present only in a limited area of the southwestern portion of the Basin (Figure 5.3). It is found at depths ranging from near the surface in the west to about 200 ft bgs in the eastern portion of its distribution area.

- The sand unit is typically 50 to 200 feet thick and is found primarily in the areas where the gravel is absent; however, a thin extension of the sand does overlie the gravel layer in several areas (Figure 5.3). It is found at depths ranging from near the surface in the west to about 30 to 50 ft bgs in the eastern portion of its distribution area.

Where the gravel and sand units are covered by the clayey silt deposits, the aquifer conditions are confined; in areas where the clayey silt deposits are thin to absent, the aquifer conditions

are unconfined (Figure 5.3). The degree of confinement appears to be greatest in the south, nearer to the Columbia River, where the upper silty deposits are thickest. Where these silty deposits thin to the north and east, the lower gravel unit appears to be less confined.

Based on data collected between late June and November 2009, the upper silty deposits appear to be creating confined to semi-confined conditions for the underlying "target aquifer." In paired sentinel wells, groundwater heads measured in most shallow wells are typically from 2 to 5 feet lower than the heads in adjacent deep wells, indicating an upward vertical hydraulic gradient from the deep to shallow system. In addition, water levels in most of the deep sentinel wells exhibit a strong correlation with tidal fluctuations in the Columbia River, typically fluctuating about 2 to 3 feet over half a tidal cycle. Conversely, water levels in the shallow sentinel wells show a greatly diminished response to tidal changes, with periodic fluctuations in groundwater levels being only a few hundredths of a foot.

Previously reported estimates of hydraulic conductivity for the gravel aquifer, based on results from production wells at the Weyerhaeuser and Chinook Ventures properties south of the Site area, range from 20 to 2,500 feet per day (ft/day), with an average of about 725 ft/day. Corresponding estimated transmissivity values, based on aquifer thicknesses of 100 to 200 feet, range from 100,000 to 2,000,000 gallons per day per foot (gpd/ft), with an average of 800,000 gpd/ft (Golder 2002). Transmissivity in the gravel aquifer beneath the Site area was estimated from data collected during the constant rate pump test of test production well PW-1 (discussed in Section 4).

Analysis of several months of hourly groundwater-level data obtained from the sentinel wells indicates that groundwater flow in the deep aquifer flows generally toward the east. Figure 5.5 is a groundwater map of the deep system created using hourly groundwater level measurements averaged over a 2-week period in September 2009. Evaluations of water-level data measured over other periods of the year (beginning in July 2009) show similar results, thus Figure 5.5 is representative of deep groundwater flow directions and gradients for the period of data collection.

5.4 Groundwater-Level Data

Each of the 17 sentinel wells was equipped with vented data-logging pressure transducers (transducers) following its construction. Each data logger was configured to record depth to groundwater (pressure) and temperature measurements on an hourly basis. Section 3.8 provides details about the installation and setting of the transducers.

Groundwater level changes in the deep monitoring wells are highly variable, and reflect the daily tidally-influenced surface water level changes in the Columbia River. Columbia River tidal data were obtained from National Oceanic and Atmospheric Association (NOAA) Station 9440422, Columbia River at Longview, Washington (http://tidesandcurrents.noaa.gov/geo.shtml?location=9440422). Hydrographs of other monitoring wells are presented in Appendix R of this report.

The highly variable groundwater levels in the deep monitoring wells preclude straightforward determinations of groundwater flow directions, gradients, or other related measures. To facilitate estimating these conditions, mean groundwater levels were calculated for the deep well data.

The method used to calculate the mean groundwater levels is identical to that used by NOAA to establish daily mean tide levels for surface water bodies (Serfes 1991). This method is discussed in Section 4.3.

Figure 5.6 is a hydrograph that shows actual and mean hourly water levels for the Columbia River and monitoring well DW-1 (note that the water levels are plotted on different vertical axes to facilitate comparison). As indicated on Figure 5.6, water levels recorded in DW-1 show a strong correlation with surface water level changes in the Columbia River for both the actual and mean hourly data. This signifies a strong hydraulic connection between the Columbia River and the gravel aquifer. Hydrographs of other deep monitoring wells completed in the gravel aquifer also exhibit strong correlation with water levels in the Columbia River (Appendix R). The range of water levels measured in the deep monitoring wells over one-half tidal cycle is typically 2 to 3 feet, with an average tidal efficiency of about 60 percent.

Conversely, hydrographs of shallow well data (Appendix R) show that water levels in shallow wells appear to be only very slightly affected by changes in the Columbia River, with poorer correlation and tidal efficiencies of only a few percent at most. Although groundwater levels in most of the shallow monitoring wells do not exhibit particularly good correlation or tidal efficiency with the Columbia River, the same method was applied to establish mean groundwater levels for the shallow system. This was done primarily to facilitate data and water level trend comparisons by reducing the tidal influence where it was most pronounced in several of the shallow wells.

Water levels in deep monitoring well DW-4 do not show a strong correlation with the Columbia River, and are virtually identical to water levels in the adjacent shallow monitoring well SW-4, because DW-4 is completed in the sand aquifer instead of the gravel aquifer tapped by the other deep sentinel wells. As discussed in more detail in Section 5.7, the sand aquifer and gravel aquifer are hydraulically connected, but the large contrast in hydraulic conductivity between the two aquifers limits groundwater flow across the sand-gravel contact.

5.5 Isotopic Analysis

Evaluation of hydrogen and oxygen isotopic ratios in water samples, specifically the relationship between $^{2}H/^{1}H$ and $^{18}O/^{16}O$, can sometimes effectively evaluate recharge sources for groundwater systems where there is a possible contribution from a nearby surface water body. A specific aspect of the Columbia River system facilitates this evaluation for areas located in western Washington.

The Columbia River possesses a very large and geographically diverse drainage basin. Much of the basin is located in semi-arid to arid portions of Oregon and Washington located east of the Cascade Mountains. Precipitation that falls in these drier areas is isotopically lighter, or depleted in the hydrogen-2 isotope deuterium and oxygen-18, compared to precipitation that falls in the much wetter areas west of the Cascades. In Columbia River water, even at locations far west of the Cascades, deuterium and oxygen-18 values still remain quite depleted compared to local precipitation values. Consequently, the isotopic ratio of Columbia River water can be an effective parameter to investigate the hydraulic relationship between the river and local aquifer systems.

Water samples from several Mint Farm shallow and deep sentinel wells, the Columbia River, the Cowlitz River, and a nearby deep industrial supply well (Puget Sound Energy Well #1) have been collected at various periods and analyzed for deuterium and oxygen-18. Results from these analyses are summarized in Table 5.1 and depicted graphically on Figure 5.7.

Results from the isotopic surface water and groundwater samples reveal a distinct differentiation of water types. As seen on Figure 5.7, the Columbia River sample is isotopically depleted compared to the Cowlitz River sample. This difference reflects the more localized drainage basin of the Cowlitz River, where the river is largely replenished by isotopically heavier precipitation falling in the western Cascades.

Most notable on Figure 5.7 is the extensive distribution of groundwater sample results. In summary, the findings of the isotopic data with respect to groundwater include:

- All shallow groundwater samples (except SW-4) plot toward the heavy end of the isotopic ratio scales, implying that recharge to the shallow groundwater system is principally from local precipitation (SW-4, as discussed previously, appears to be in some degree of hydraulic connection with the deep aquifer system, which results in a mixed isotopic signature).

- Deep groundwater samples from DW-3 and DW-4 plot in an intermediate range similar to the isotopic values for the Cowlitz River. This suggests that a relatively high portion of groundwater at those locations may be recharged by the Cowlitz River, which is logical, given the relative locations of those two wells (especially DW-3), and the fact that DW-4 is completed in the sand aquifer rather than the gravel aquifer. The Cowlitz River signature at these two deep wells may further be influenced by the use of City water to maintain water levels in the engineered wetland in the northeastern corner of the Mint Farm and Lake Sacajawea. City water is currently sourced from the Cowlitz River.

- Finally, isotopic values for the other deep sentinel wells sampled, which are completed in the gravel aquifer, plot at the lighter end of the isotopic ratio scale, close to the values for the Columbia River. This suggests that groundwater in the deep aquifer system is in better hydraulic connection with the Columbia River than with shallow groundwater.

The analysis of isotopic ratios in natural waters is accomplished by comparing samples to the Global Meteoric Water Line (GMWL). The GMWL plotted on Figure 5.7 represents approximate compositions of rain and snow, expressed as relative changes in deuterium and oxygen-18 compositions compared to a global standard (V-SMOW, or Vienna Standard Mean Ocean Water) for samples collected around the globe. Values that plot along the GMWL represent waters in relatively cool or temperate environments, and generally, values below the GMWL are from lower-latitude regions with higher temperatures and evaporation rates.

On Figure 5.7 and Table 5.1, samples collected on 7 October 2009 from the Columbia River, Cowlitz River, and deep aquifer wells PW-1 and DW-7 plot anomalously below the GMWL. From these river values, it might be surmised that these outliers represent late-summer evaporative conditions in the surface water bodies. However, the similarly depleted value for the deep groundwater samples suggests that the 7 October results for all four samples are more likely the result of evaporative losses experienced during sampling.

The shallow groundwater samples are significantly isotopically heavier than deep groundwater samples, which supports findings from other data sets that there are two distinct groundwater systems. Static head differences in paired sentinel wells, observations of site stratigraphy made while drilling the Mint Farm sentinel wells, and relative responses in sentinel wells to test pumping at PW-1 all indicate the presence of two distinct groundwater systems at the Mint Farm site. The clear groupings of deuterium and oxygen-18 ratios depicted on Figure 5.7 further corroborate the other lines of evidence that the deep aquifer system at the Mint Farm area is a confined to semi-confined system in good hydraulic connection with the Columbia River.

Table 5.1 Oxygen and Hydrogen Isotope Ratios (per mil, relative to V-SMOW)

Date	Sample Location	$d_{18}O$	d_2H
6/09/09	SW-1	-9.33	-69.32
11/12/09	SW-1	-10.99	-77.59
6/09/09	DW-1	-14.92	-115.31
11/11/09	DW-1	-16.46	-120.89
6/12/09	SW-3	-10.04	-70.31
6/12/09	DW-3	-11.53	-80.33
6/11/09	SW-4	-13.96	-96.70
6/11/09	DW-4	-12.69	-87.72
10/07/09	SW-7	-9.91	-79.68
10/21/09	SW-7	-10.14	-67.41
11/04/09	SW-7	-10.24	-75.70
11/12/09	SW-7	-10.08	-70.30
10/07/09	DW-7	-13.56	-127.43
10/21/09	DW-7	-15.27	-113.21
11/04/09	DW-7	-16.32	-119.00
11/12/09	DW-7	-16.14	-118.21
11/12/09	SW-9	-9.89	-68.84
11/12/09	DW-9	-15.93	-116.69
10/07/09	PW-1	-13.01	-119.61
10/15/09	PW-1	-14.79	-108.15
10/21/09	PW-1	-14.74	-110.01
10/29/09	PW-1	-16.04	-117.59
11/04/09	PW-1	-16.34	-115.93
11/11/09	PW-1	-16.04	-117.54
6/09/09	Columbia River	-15.26	-116.21
10/07/09	Columbia River	-13.53	-129.71
11/04/09	Columbia River	-16.42	-119.06
6/09/09	Puget Sound Energy Well #1 (Mirant)	-14.88	-111.44
6/09/09	Cowlitz River	-12.08	-84.05
10/07/09	Cowlitz River	-11.21	-98.29
11/04/09	Cowlitz River	-13.96	-92.56

5.6 General Hydrogeochemistry

In addition to the isotopic sample analyses discussed in the previous section, water samples from several Mint Farm shallow and deep sentinel wells, the Columbia River and the Cowlitz River were analyzed for general geochemical parameters. This preliminary geochemical analysis provides an additional tool to further evaluate the degree of connection between the deep aquifer system with both the shallow groundwater system and the Columbia River.

As part of the June 2009 baseline groundwater sampling event described in Section 3.7 of this report, samples collected from the Columbia River, the Cowlitz River, and all Site sentinel wells (except for the SW-9 / DW-9 well pair) were analyzed for major geochemical cations and anions. Samples from SW-9 and DW-9 were collected later in mid-August 2009, soon after both wells had been completed and developed, and submitted to CAS Laboratory for the same analyses.

Figure 5.8 is a trilinear, or Piper, diagram that depicts the percentage distribution of major cations and anions from each of the groundwater and surface water samples. Piper diagrams are useful to characterize different general types of waters, characterized on the basis of dominant cation and anion groups. Often the results plotted on a Piper diagram can be used to make inferences related to recharge sources (for groundwater) or mixing of two distinctly different water types.

As shown on Figure 5.8, both the Columbia River and Cowlitz River samples are characterized as "Ca-Na-Mg-HCO_3"-type water. The river water is differentiated from the groundwater by its higher sulfate percentages. For the cations, the river water has a slight shift of higher sodium and potassium to magnesium. Calcium percentages are similar for groundwater and river water.

The distribution of the groundwater samples shows a shift between the shallow and deep groundwater. The shallow groundwater samples tend to group together and are characterized by having an anion signature that is almost exclusively bicarbonate with low percentages of chloride or sulfates. This is consistent with a young groundwater derived from precipitation that has not been exposed to other influences.

The deep groundwater differs from the shallow groundwater by having a higher percentage of chlorides (Figure 5.8). These range from 20 to 55 percent chloride, but with little sulfates. The cation distribution is similar between the shallow and deep groundwater. There is only a slight shift with the shallow groundwater having slightly higher magnesium whereas the deeper groundwater has slightly more sodium and potassium. The calcium distribution is similar for both the shallow and deep groundwater.

The deep groundwater differs from the Columbia River by having a higher percentage of bicarbonate and a lower percentage of sulfate. Other data, such as the hydrogen and oxygen isotopic results discussed in the previous section, indicate that the deep groundwater is from the Columbia River. If this is so, this geochemical data may indicate the residence time of the Columbia River water in the deep aquifer is sufficiently long that the water character changes to become more bicarbonate rich.

5.7 Conceptual Groundwater Flow

The hydrogeological conceptual model summarizes the key hydrogeological data from the Longview-Kelso Basin and is an interpretation of how groundwater flows through the Basin. This narrative discussion is based upon the hydrogeologic data compiled for this project as discussed in this report and from previous investigations.

The primary groundwater recharge sources for the Basin are precipitation and infiltration from rivers. Precipitation falls primarily as rain on the valley floor; however, a combination of rain and snow occurs at higher elevations in the surrounding mountains. Precipitation averages about 44 inches per year. Typically, most of the annual precipitation occurs during December through April. The Columbia River and the Cowlitz River form key hydrogeological features in the Basin.

The primary groundwater outflows from the Basin are discharge to the CDID drainage network and evapotranspiration. Much of the Basin is only slightly higher than the elevations of the Columbia and Cowlitz Rivers. Therefore, 35 miles of stormwater collection ditches have been constructed across the Basin for flood protection. The system consists of six primary pumping stations with a total capacity of 628,000 gpm that is discharged to the Columbia River. Active pumping of these ditches has resulted in lowering of the shallow groundwater levels. Water levels in the drainage ditches are maintained at levels several feet below the typical stage of the Columbia River, especially in the western portions of the Basin.

The interactions of the aquifer heterogeneity and the groundwater-surface water interactions with the rivers and drainage ditches cause a complex groundwater flow pattern in the Basin. The shallow groundwater flow is dominated by the CDID drainage ditches. Shallow groundwater flow is interpreted to be recharged primarily from rainfall, flow through the shallow deposits, and discharge to the drainage ditches. Oxygen-hydrogen stable isotope data indicate that the source of groundwater in the shallow deposits is primarily from local precipitation, with some contribution from the Cowlitz River. The Cowlitz River signature seen in some wells may be due to the use of City water, which is currently sourced from the Cowlitz River to maintain water levels in the engineered wetland in the northeast corner of the Mint Farm and in Lake Sacajawea.

Groundwater flow in the sand aquifer is primarily from southeast to northwest across the Basin (Figure 5.9). Recharge is considered to be primarily from precipitation and infiltration from the Cowlitz River. Available geologic data indicate the clayey silt confining layer is present across the eastern portion of the Basin. However, it is assumed that recharge from the surface can occur where the confining layer is thin or absent in the eastern Basin. Oxygen-hydrogen stable isotope data suggest that the Cowlitz River is a groundwater source in the sand aquifer north of the Mint Farm.

Discharge from the sand aquifer is predominantly to the CDID drainage ditches. In the western portion of the Basin, the confining layer is thin to absent; thus the aquifer is unconfined in this area (Figure 5.9). In these areas, the sand aquifer would be in direct communication with the CDID drainage ditches. This is also the location where the CDID discharge ditches are maintained at their lowest water elevations, below sea level at the western edge.

Groundwater flow in the gravel aquifer is from west to east (Figure 5.9), and recharge is primarily from the Columbia River. Available geologic data indicate the clayey silt confining layer

is thin to absent across the western portion of the area underlain by the gravel aquifer. The Columbia River flows through this area, thus allowing direct contact between the river and the gravel aquifer. Oxygen-hydrogen stable isotope data also indicate the Columbia River is the major source of groundwater in the gravel aquifer underlying the Mint Farm.

Groundwater in the gravel aquifer is interpreted to discharge to the sand aquifer along the areas where the sand and gravel aquifers are in direct contact (Figure 5.9). Groundwater elevation data indicate that groundwater levels in the gravel aquifer are typically 2 to 3 feet higher than those in the sand aquifer, indicating the presence of some type of resistance across the sand-gravel contact that limits groundwater flow. This is also supported by the low groundwater gradients across the Mint Farm in the gravel aquifer. As discussed above, the primary discharge for the sand aquifer is the CDID drainage ditches; therefore, the ultimate discharge of groundwater in the gravel aquifer is also to the CDID drainage ditches, and ultimately back to the Columbia River.

This page intentionally blank

Section 6: Groundwater Model Development

6.1 Introduction

A numerical groundwater model was developed to simulate groundwater flow and water quality in the Longview-Kelso Basin based upon the hydrogeologic data compiled for this project, as discussed in Sections 1 through 5 of this report. This section documents the development, calibration, and application of the groundwater model.

6.1.1 Objectives

Several complex hydrogeologic factors within the Longview-Kelso Basin impact the design of the proposed Regional Water Treatment Plan (RWTP) located in the Mint Farm Industrial Park. These factors include complex groundwater-surface water interactions and aquifer heterogeneity. Therefore, a three-dimensional numerical groundwater model using the United States Geological Survey code MODFLOW 2000 (Harbaugh et al. 2000) was developed. This model is termed the Longview MODFLOW model (Model).

The objectives for the Model include the following:

- Test understanding of the hydrogeological conceptual model.
- Evaluate sustainability of long-term pumping for the Mint Farm Wellfield.
- Delineate the wellhead protection source areas for the Wellhead Protection Plan (WHPP).
- Perform a preliminary pathway analysis to address potential future water quality issues.

The primary objective of this groundwater modeling study is to develop a calibrated basin-wide numerical model of the Longview-Kelso Basin. The purpose of the model is to provide a tool to enhance the City's and PUD's ability to manage and protect the groundwater resource in the Longview-Kelso Basin. To this end, the calibrated numerical model is used to calculate the long-term sustainable yield for the Mint Farm Wellfield. To forecast future trends in groundwater levels and water quality, model runs or scenarios are developed by modifying specified sets of input parameters to simulate potential future conditions. In this way, the City and PUD can use the model to evaluate the impacts of management practices on the long-term groundwater resource in the basin.

6.1.2 General Approach

The first step toward developing a sound, defensible numerical model is to ensure consistency with the hydrogeological conceptual model of the study area. Because of the complexity of a natural system, assumptions are necessary to define the aquifer properties and boundary conditions required for the numerical model. Although a model is a simplification of the natural system, the numerical model must be constructed in a manner that properly represents the key features of the groundwater basin in order to provide accurate and useful simulation results. In

support of numerical model development, a range of reasonable values is defined for aquifer properties and the hydrologic budget based on measured field data and hydrogeological analysis. The general procedure for this process is to define values for a representative elementary volume (REV) as described by Bear and Verruijt (1987). These values represent the major physical features of the basin, including surface water-groundwater interactions, recharge and discharge components, definition of model layers, and the distribution of aquifer properties.

During model calibration, model parameters are varied within the range prescribed by the conceptual model, and the simulated results are compared to measured data. A calibrated model represents the best fit, obtained by comparing simulated groundwater elevations with measured water levels obtained at groundwater monitoring wells. Areas where the numerical model is considered poorly calibrated may indicate locations where initial estimates of input data were inadequate, or that a key component of the hydrogeological conceptual model was not adequately recognized. The former serves as a valuable quality assurance check. The latter may provide guidance on the nature and extent of future monitoring or identify locations where additional data evaluation is needed.

Once calibration is achieved, the model is considered capable of forecasting future conditions with reasonable accuracy. Input parameters can be set to simulate a wide range of potential future groundwater use, water quality, or hydrogeologic scenarios. The results can be evaluated for overall trends and more localized effects. The horizontal and vertical resolution used to construct the model dictate the range of scales that the model can evaluate. For example, a regional or basin-wide model will not likely contain the site-specific details of a more localized model, but a regional model will better evaluate a local area within the broader regional context.

A calibrated groundwater model can also be applied to provide key support to other tasks, including well design and groundwater management. In this manner, development of a groundwater model can help the City and other stakeholders to optimize design and minimize capital costs for related tasks and projects.

6.1.3 Model Application

The Longview MODFLOW Model was based on the available hydrogeological data and characterization of the basin. Prior to this study, only limited groundwater data were available in the Longview-Kelso Basin, especially for the deep aquifer. Therefore, the investigations performed for this project provided a significant amount of new data to be reconciled into the hydrogeological conceptual model. By calibrating the model to available field measurements, the Model provides a mechanism to verify that the assumptions and interpretations used in developing the conceptual model provide a viable explanation of groundwater flow.

When evaluating model results, it is important to consider the strengths and limitations of the numerical model. The primary advantage of a numerical model is that it requires a balance between the amount of water entering and exiting the basin and the rate of groundwater flow through the basin. In this way, a numerical model provides a way to estimate the long-term sustainable yield of the aquifer, even in complex settings such as the Longview-Kelso Basin.

The Model is designed as a basin-wide model to evaluate long-term regional trends and the overall groundwater inflow and outflow to the basin. The Model includes groundwater-surface water interactions, especially with the Columbia River. The model analysis is for steady-state

conditions. The horizontal and vertical resolution used to construct the model dictates the range of scales that the model can evaluate, and conditions are averaged within that scale. Therefore, the model does not contain site-specific details throughout the Longview-Kelso Basin. Instead, interpretations based on standard hydrogeological practices have been used to extrapolate aquifer conditions throughout the basin. These are considered appropriate to meet the objectives of this project.

6.2 Model Development

The basic components of the conceptual model required to construct a numerical model describe how groundwater enters and exits a defined system and the geologic factors that control groundwater flow. The key physical features of the study area include surface water-groundwater interactions (e.g., the Columbia River), incorporating the hydrologic water balance components (e.g., precipitation and flow to drainage canals) as boundary conditions, and the distribution of aquifer properties (e.g., aquifer thickness and hydraulic conductivity).

6.2.1 Model Setup

The groundwater flow model was set up using MODFLOW 2000 (Harbaugh et al. 2000), a finite-difference numerical model developed by the United States Geological Survey. The MODFLOW processor Groundwater Vistas 5 (ESI 2007) was used to facilitate construction and operation of the numerical model. Use of the industry standard modeling code MODFLOW 2000 along with a commercial processor supports future usability and portability of the model.

6.2.2 Model Domain

The model domain is the geographical area covered by the numerical model, with active portions of the domain representing areas of the model where groundwater elevations are simulated. The extent of the model is shown on Figure 5.1. For this project, the model domain encompasses the areal extent of the alluvial sediments surrounded by bedrock uplands. The Longview-Kelso Basin is bounded on all sides by bedrock uplands. Three geographic gaps occur in the continuity of the surrounding bedrock—one in the southeast, where the Columbia River enters the basin; one on the northern side of Longview, where the Cowlitz River enters the basin; and one on the northwest side, where the Columbia River exits the basin.

The inactive portion of the model represents areas where bedrock is present. No-flow boundary conditions are applied to these areas so that groundwater simulation of these areas is not included in this model. The entire model domain covers approximately 43,100 acres; however, the active area of the groundwater model is limited to approximately 23,000 acres of the model domain. Of the active portion, about 13,930 acres is underlain by a sand aquifer, and about 9,100 acres is underlain by a gravel aquifer. Figure 5.3 shows the distribution of these aquifers beneath the surficial soil and silt/clay confining unit.

The model grid provides the mathematical structure for developing and operating the numerical model. In MODFLOW, the groundwater elevation is calculated at the center of each grid cell; therefore, the grid size dictates the model resolution. A uniform grid spacing of 200 feet was used to provide sufficient resolution for the model. This grid size is considered appropriate to

provide the resolution necessary to evaluate pumping effects and provides sufficient resolution to place each individual production well in one grid cell in the proposed wellfield.

A three-dimensional MODFLOW model was constructed for the model domain. The model grid contains 176 rows and 229 columns; therefore, each model layer consists of 40,304 model grid cells. The MODFLOW was subdivided into 17 model layers. The entire 17-layer model contains a total of 685,168 model grid cells. Of this total, 292,218 grid cells are active.

6.2.3 Model Layers

The alluvial aquifer system in this study is complex. The geology in the study area can be divided into five units: gravel, sand, silt/clay, surficial soil, and bedrock. The complicating factor is that the geologic units in Longview-Kelso Basin do not extend laterally across the entire basin. Rather, the basin is dominated by gravel in the southwestern portion, which in places is contiguous with the sand that dominates in the northern and eastern portions of the basin. The gravel and sand are partially covered by, or are contiguous with, up to approximately 200 feet of silt, silty sand, and clay.

To accommodate the complex geometry and geology of the Longview-Kelso Basin, the basin was subdivided into 17 model layers (Figure 6.2). Each layer represents a horizontal depth range. Tops and bottoms of different geologic layers, however, are not horizontal. The variable elevations are interpolated from well logs and mapped three dimensionally onto the vertical grid. The extra model layers provide the flexibility for spatially defining the discontinuous units. Furthermore, the model layers were defined to provide additional mathematical resolution for calculating groundwater elevations, which enables the model to simulate the vertical groundwater gradients observed at the site.

The upper surface of the model represents the topography and is based on the most recent digital elevation model (DEM) available from the U.S. Geological Survey (USGS). The DEM is shown as the background image in Figures 5.1 through 5.3. These elevation data were imported into the numerical model as the top layer elevations for Model Layer 1.

The hydrogeologic conceptual model was developed based on dozens of well logs (Appendix H) and the regional geologic setting. To transfer this information to the groundwater flow model, contour maps depicting the elevation of the tops of the bedrock, gravel, and sand were developed. The base of the deepest layer was set to 440 feet below sea level to approximate the elevation of the deepest encountered bedrock (well DW-5 at -445 feet). Grid cells in each layer were designated as bedrock, gravel, or sand based on the contour maps of the tops of the respective geologic units. Consistent with well logs, silt/clay was designated where the gravel and sand were absent. The surficial soil was designated throughout Model Layer 1. Cross-sections showing the model layers are provided on Figures 6.1 and 6.2.

6.2.4 Aquifer Properties

For the steady-state simulations conducted for this study, the aquifer properties of hydraulic conductivity represent the physical characteristics of the aquifer materials and fluids as they pertain to groundwater flow. These properties must be assigned to each active model cell. Aquifer properties were based on aquifer tests performed in the Longview-Kelso Basin. The

conceptual model provides the appropriate range for the aquifer property values. The values used in the model were defined within that range during model calibration.

The hydraulic conductivities applied to the model are given in Table 6.1 and are consistent with the conceptual model discussed above. The vertical hydraulic conductivity was set to 0.01 of the horizontal hydraulic conductivity for all layers except the gravel, which was assumed to be isotropic with respect to hydraulic conductivity due to its likely deposition during massive flood events emanating from Glacial Lake Missoula (see Section 2). This assumption was tested by a sensitivity analysis, to be discussed below.

Table 6.1: Hydraulic Conductivities for the Longview-Kelso Basin and the Groundwater Flow Model

	Range of Measured Values (cm/s)	Range of Measured Values (ft/d)	Range of Acceptable Values (Freeze and Cherry 1979) (ft/d)	Numerical Model Horizontal (ft/d)	Numerical Model Vertical (ft/d)
Surficial soil	N/A	N/A	3×10^{-2} to 300	10	10^{-1}
Silt/Clay	10^{-8} to 10^{-7}	3×10^{-5} to 3×10^{-4}	3×10^{-7} (clay) to 3 (silt)	10^{-3}	10^{-5}
Sand	10^{-4} to 10^{-3}	3×10^{-1} to 3	3×10^{-1} to 3000	10	10^{-1}
Gravel	0.67 to 1.34	1900 to 3800	300 to 300,000	2000	2000

MODFLOW (Harbaugh et al. 2000) calculates the transmissivity of each model cell as the assigned hydraulic conductivity multiplied by the saturated thickness as defined by either the simulated groundwater elevation or the top of the model layer, and the base of model layer. Therefore, the hydraulic conductivity represents the overall transmissivity across the entire thickness of the aquifer system, rather than for a specific gravel or sand zone.

6.2.5 Boundary Conditions

Model boundary conditions simulate groundwater entering and exiting the model domain and are based on components of the hydrologic balance. In the absence of aquifer stresses, the water elevations calculated by groundwater flow models are strongly controlled by boundary conditions.

6.2.5.1 Groundwater Recharge and Evapotranspiration

The initial estimate for aquifer recharge was derived from National Climatic Data Center (NCDC) Cooperative Stations 454769 and 454775 for the period 1925 to 1995. Based on these data, the average annual rainfall in the study area is 44.5 inches per year. Evapotranspiration was initially estimated from the US Bureau of Reclamation's AgriMet network for the Forest Grove, Oregon, station (the closest station to Longview). Based on these data, potential evapotranspiration was 40.9 inches per year for the period 1991 to 2008. These values were modified slightly during calibration.

Precipitation recharge represents the portion of rainfall that falls directly onto the aquifer sediments and percolates downward to the groundwater. Groundwater recharge was applied uniformly over the entire basin exposed at the surface using the MODFLOW recharge package (Harbaugh et al. 2000). No precipitation recharge was applied to the areas representing the Columbia or Cowlitz Rivers. Evapotranspiration was applied in the upland areas of the basin away from the two rivers using the MODFLOW evapotranspiration package (Harbaugh et al. 2000).

6.2.5.2 Columbia and Cowlitz Rivers

The Columbia River is a major water body that is a primary factor in the hydrogeologic dynamics of the Longview-Kelso Basin. Input of the river into the model was accomplished by a three-step process. Bathymetric data were obtained from the Army Corps of Engineers for the five river sections in the study area. These data were joined digitally to the DEM to complete the representation of Earth's surface in the study area (Model Layer 1).

Next, as a surrogate representation of open channel flow, which MODFLOW does not simulate, cells in the river channel in Model Layer 1 was assigned a hydraulic conductivity of 10,000 feet/day to mimic numerically a region with little to no flow resistance. All other model layers beneath the river channel and cells in other areas of Model Layer 1 retained their original hydraulic conductivity as depicted in Table 6.1. The geometry of the river channel is defined by the bathymetric data, and can be seen in Figures 6.1 and 6.2. Finally, the river cells in Model Layer 1 were assigned a constant head value based on the calculated average hydraulic gradient of the Columbia River between St. Helens, Oregon and Skamokawa, Washington, 7.6×10^{-6}, and the average river stage for the period 9/12/09 to 9/24/09 at the Longview river gage.

The Cowlitz River is a significant water body and appears to play a role in groundwater elevations and composition in the sand aquifer. This observation is supported by isotopic data (see Section 4.6).

Because detailed bathymetric data were not available for the Cowlitz River, the channel depth was assumed to extend 10 ft bgs. As a surrogate representation of open channel flow, which MODFLOW does not simulate, the hydraulic conductivity of Model Layer 1 in the river channel was set to 10,000 feet/day to mimic numerically a region with little to no flow resistance. All other models layers beneath the river channel retained their original hydraulic conductivity as described above for the layers beneath the Columbia River channel. Finally, the river cells in Model Layer 1 were assigned a constant head value based on calculated average hydraulic gradient of the Cowlitz River between Castle Rock, Washington, and Longview, Washington, 2.9×10^{-4}, and the river stage at the Castle Rock gage.

6.2.5.3 Consolidated Diking Improvement District Drainage Ditches

Groundwater elevations in the Mint Farm area and elsewhere in the Longview-Kelso Basin are lowered artificially by an extensive system of drainage ditches. Without these ditches, the area would consist of extensive swamps and marshes. Little direct evidence exists regarding the water elevations in these open-channel ditches. The water elevations are controlled by a series of pumping stations, whose pumps cycle on and off based on the water elevation at the individual station.

The “on” elevations at the individual pump stations were used as a surrogate variable for estimating water elevations in the drainage-ditch network. Elevations were linearly interpolated between the stations and input to the model using the MODFLOW drain package (Harbaugh et al. 2000). The CDID drainage ditches are highlighted in Figure 6.13.

6.3 Model Calibration

Model calibration is the step in which the simulation results are compared to measured data. Typically, a range of reasonable values is defined for aquifer properties and the hydrologic budget based on measured field data and hydrogeological analysis. During model calibration, these values are varied within the range prescribed by the conceptual model.

Long-term records of groundwater elevations in the study area are not available. Therefore, the primary goal of the model calibration was to evaluate, within a reasonable degree of certainty, whether the model can reproduce the overall features of the groundwater flow system with a minimal amount of adjustment to the basic model parameters and boundary conditions. It should be noted that some degree of difference or residual is expected between observed and simulated groundwater elevations. Residuals may be due in part to localized effects or data quality issues.

6.3.1 Calibration Process

Model calibration is the process of comparing model results to measured data to test the model's ability to simulate observed conditions. During model calibration, aquifer properties and boundary conditions are varied within an acceptable range until the closest fit is achieved between the simulated and measured data. The amount and type of data that are available in large part dictate the model calibration steps.

The calibration process consisted of the following steps:

- The simulated hydraulic heads in a base-case model were qualitatively matched to the general pattern of observed groundwater elevations by adjusting the aquifer recharge and evapotranspiration values.
- The base-case model was evaluated with respect to the 12 September 2009 to 24 September 2009 sentinel well water elevations.
- A pumping-case model was evaluated with respect to the drawdown response in PW-1 during the October 2009 aquifer test.

These three steady-state calibration evaluations tested the model's ability to simulate long-term groundwater flow conditions and the overall hydrologic balance in the Longview-Kelso Basin. Multiple combinations of aquifer properties and boundary conditions can be used to match a single set of groundwater elevation data. In most cases, the process of calibrating to multiple data sets under differing stresses is used to reduce this “non-uniqueness,” which in turn reduces the uncertainty of the model results. This level of calibration is considered appropriate for the present purpose of determining the source areas for and sustainability of long-term groundwater production at the Mint Farm wellfield.

6.3.2 Base-Case Calibration

The first step in the base-case model calibration was to qualitatively match the simulated hydraulic head distribution to the generally observed groundwater elevation. The only adjustments made in this step were to the recharge, evapotranspiration, and the hydraulic conductivity of the surficial soil. A recharge value equal to 1 percent of the average annual rainfall was applied to entire basin, with the exception of the Columbia and Cowlitz Rivers. Evapotranspiration was applied in the upland areas in the basin at a rate equal to the potential evapotranspiration, using an extinction depth of 2 feet. The hydraulic conductivity of the surficial soil was changed during the qualitative calibration from 1 ft/day to 10 ft/day.

Once the spatial distribution of hydraulic heads matched qualitatively the observed data, calibration statistics were calculated and a sensitivity analysis was performed. No further parameter estimation was performed, either manually or with inverse methods.

Results of the qualitatively calibrated base-case groundwater flow simulation for the shallow subsurface are presented on Figure 6.3, with a close-up of the Mint Farm area on Figure 6.4. A cross-sectional view is shown on Figure 6.5. Major elements of the conceptual model reproduced by the model are:

- At the Mint Farm, shallow groundwater flow (essentially radial flow) is toward the drains. Flow toward the drains is also apparent in other areas (Figure 6.3).
- A steep upward hydraulic gradient is simulated beneath the Mint Farm area (Figure 6.5).
- Water flows from the Columbia River downward into the deep gravel aquifer. Beneath the Mint Farm, groundwater flows upward through the sand and silt/clay and into the drainage ditches.

Comparison of observed groundwater elevations with simulated groundwater elevations shows a good correlation. A scatter plot of observed versus simulated groundwater elevations (Figure 6.6) depicts this relationship. The general trend shows a good correlation, considering that the major boundary conditions and aquifer parameters were not continually adjusted in an attempt to match the observed data. Furthermore, no systematic bias is present in the simulation results. As indicated by Figure 6.7, the majority of residuals are less than or equal to 1 foot.

The results for well SW-2 deviate from the observed data more than the results from the other sentinel wells. The observed head of −1.6 feet is most likely due to the influence of the adjacent drainage canal. Without direct measurements of the water elevation in the canals, only an interpolated estimate is available for setting boundary conditions in the ditches. Nevertheless, the close overall fit illustrated on Figure 6.6 indicates that the general spatial distribution of aquifer properties and boundary conditions is appropriate for evaluating the effects of pumping at the Mint Farm wellfield.

Next, a more rigorous evaluation was performed that involved a statistical analysis to further compare the difference or residual between measured and simulated groundwater elevations. The residual mean is computed by dividing the sum of the residuals by the number of residual

data values. The closer this value is to zero, the better the calibration. The residual mean for the model is −0.8 feet.

The residual standard deviation evaluates the scatter of the data. A lower standard deviation indicates a closer fit between the simulated and observed data. The standard deviation for the calibrated model is 1.4 feet.

The absolute residual mean is a measure of the overall error in the model. The absolute residual mean is computed by taking the square root of the square of the residuals and dividing that by the number of residuals. The absolute residual mean for the model is 1.3 feet.

6.3.3 Pumping-Case Calibration

The pumping test analysis (discussed in Section 4) was used as a backdrop for a separate calibration exercise to assess the model's ability to meet the objective of source area evaluation. Production well PW-1 was added to the base case model to evaluate the model's response to aquifer stress. PW-1 was active in layers 12 through 15, which corresponds to elevations for the screened interval of −215 feet to −355 feet (230 to 370 ft bgs). The 14-foot gap in the screened interval between −270 feet and −284 feet was not simulated. The screened interval is entirely within the gravel aquifer. During the pumping test, a steady-state drawdown of approximately 3.3 feet was observed after about 1 day of continuous pumping at 3,900 ± 115 gpm.

For the pumping-test calibration exercise, the horizontal and vertical hydraulic conductivities of the gravel aquifer were systematically changed to assess the impact on simulated drawdown. The steady-state pumping rate used for the simulations was 3,900 gpm. Six separate simulations were conducted. The results are summarized in Table 6.2. The closest match to the observed drawdown for the range of values tested was for both horizontal and vertical hydraulic conductivities equal to 2,000 feet/day.

Table 6.2: Simulated Drawdown at PW-1 for Six Different Combinations of Hydraulic Conductivity

	Drawdown at PW-1 (ft)	
K_h:K_v	K_h = 2,000 ft/d	K_h = 1,000 ft/d
1:1	3.6	7.2
2:1	3.7	7.4
10:1	3.9	7.8

6.3.4 Calibration Evaluation

The elevations and gradients of the Columbia and Cowlitz rivers were defined in the model, aquifer parameters were estimated and input to define homogenous hydrogeologic units, and estimated water levels in the drainage ditches were input directly as boundary conditions.

The two calibration exercises indicate that the model is well-calibrated for simulating base-case groundwater flow and groundwater flow associated with the pumping test. Moreover, the model is well positioned to simulate projected groundwater flow associated with full build-out of the Mint Farm wellfield.

The primary objective of the steady-state model calibration was to match the overall features of the groundwater flow system. These matched features are:

- The shallow groundwater system operates independently from the deep groundwater system, i.e., shallow groundwater flow is controlled by the drainage network, and the deep groundwater is strongly influenced by the Columbia River.
- Hydraulic heads in the shallow groundwater system in the Mint Farm area are lower than hydraulic heads in the deep gravel aquifer, i.e., there is an upward hydraulic gradient in the Mint Farm area.
- A steep, upward vertical hydraulic gradient is present in the shallow subsurface, and a much gentler upward gradient is present in the deep subsurface in the Mint Farm area.
- Because of the influence of the drainage network, groundwater flow in the Mint Farm area is from the Columbia River (base level for the region), northward through the deep gravel aquifer.
- Groundwater flow to the drainage ditches lowers the shallow hydraulic heads in the Mint Farm area from what would be observed if the ditches were not present. Flow to the ditches creates an upward hydraulic gradient in the base-case aquifer system, which induces a low flux of groundwater from the deep gravel aquifer into the shallower sand aquifer, upward into the silt/clay (where present), which discharges to the drainage ditch network.
- Drawdown at PW-1 at high pumping rates (e.g., 3,900 gpm) is minimal, or on the order of 3 feet.

The model may be further calibrated and updated in the future as additional data become available. Based on the model calibration results, a recommendation for future data collection should focus on developing a long-term database of measured groundwater elevations in the aquifer and comprehensive effort to better characterize the water elevations in the drainage ditches.

6.4 Sensitivity Analysis

Sensitivity analyses were conducted for the base-case model and the pumping-case model. For both cases, the horizontal hydraulic conductivity of all four hydrogeologic units was systematically changed ±50 percent, in 10 percent increments. Each hydrogeologic unit was step-wise modified while the hydraulic conductivities of the other three units were held constant. The analysis for each hydrogeologic unit for each case thus required 11 simulations, or a total of 44 simulations for each case (88 total simulations for the two cases). The results of each sensitivity analysis were evaluated by comparing the sum of squared residuals for each

individual run. The simulation that yields the lowest value of the sum of squared residuals identifies the most sensitive parameter tested.

The results of the base-case sensitivity analysis are presented on Figure 6.8. On the plot in Figure 6.8, the horizontal axis shows the multiplier value applied to the horizontal hydraulic conductivity for a particular simulation, and the vertical axis shows the sum of squared residuals. The lowest value of the sum of squared residuals occurs for the sensitivity simulation in which the horizontal hydraulic conductivity of the surface silt was reduced by 50 percent, or changed to 5 feet/day. This change indicates the horizontal hydraulic conductivity of the surface silt is the most sensitive parameter of the four which were analyzed.

Although the most sensitive parameter was identified, it is instructive to compare the actual change in the sum of squared residuals to provide a context for the sensitivity analysis results. The residuals were computed for the 17 sentinel wells (observed minus simulated heads). The sum of squared residuals for the base-case simulation was 43.7. When the horizontal hydraulic conductivity of the surface silt was reduced to 50 percent of its base-case value, the sum of squared residuals was reduced to 42.9, a reduction of 1.7 percent. This small change indicates the model is not very sensitive to the range of horizontal hydraulic conductivity values tested, and suggests the base-case model may be more sensitive to other model inputs, such as water elevation in the drainage ditches.

A similar sensitivity analysis was also performed on the pumping-case model. The purpose of this analysis was to further examine how changes in hydraulic conductivity impact simulated drawdown. For this analysis, the calibration target for assessing changes to the sum of squared residuals was the head at the pumping well. Only one calibration target was used because measurable drawdowns were not observed during the pumping test at any of the observation wells except DW-9, which is only 50 feet from pumping well PW-1. The distance between these two wells is too small for the model to resolve, because they are in the same grid cell.

The results of the pumping-case sensitivity analysis are presented on Figure 6.9. As might be expected, the horizontal hydraulic conductivity of the gravel aquifer is the most sensitive parameter for simulated drawdown occurring at PW-1 (which is screened in the gravel aquifer). Furthermore, only changes to the horizontal hydraulic conductivity of the gravel aquifer caused significant changes to the sum of squared residuals. The lowest value for the sum of squared residuals occurred when the horizontal hydraulic conductivity of the gravel aquifer was set to the base-case value of 2,000 feet/day, which suggests that value appropriately represents aquifer conditions.

6.5 Model Results

The modeling objective was to evaluate the source areas which will provide water to the Mint Farm wellfield. Average day demand of 12 mgd projected for 2059 was used for the simulation described below.

6.5.1 Groundwater Assessment of Pumping

The 12 mgd of groundwater withdrawal was divided among six proposed production wells at the Mint Farm wellfield, PW-1 through PW-6. The location of PW-1 is the same as in the pumping-

case calibration simulation described above. Five additional production wells were added to the model on 200-foot centers, as shown on Figure 6.10. The steady-state pumping rate for each of the six production wells in the simulation was 1,390 gpm, or 2.0 mgd. Additional groundwater pumping of 4.1 mgd was also simulated to occur at Puget Sound Energy (2.05 mgd) and at Chinook Ventures (2.05 mgd), where wells are constructed in the same aquifer.

6.5.2 Groundwater Model Scenario Results

The major results from the 12 mgd pumping scenario are as follows:

- Shallow groundwater elevations in the Mint Farm area are (1) still controlled by flow to drainage ditches and (2) largely unaffected by pumping from the deep gravel aquifer (Figure 6.10).
- Total pumping of 16.1 mgd is derived from the gravel aquifer.
  - The Columbia River supplies 16.7 mgd to the gravel aquifer.
  - The sand aquifer supplies 0.012 mgd to the gravel aquifer.
  - 0.6 mgd flows out of the gravel aquifer to the silt/clay or surface soil.
- The dominant source of water to the gravel aquifer, and hence the Mint Farm production wells, is the Columbia River (Figure 6.11).
- Maximum drawdown at the Mint Farm wellfield is approximately 6 feet.

6.5.3 Source Area Delineation

The particle-tracking program MODPATH (Pollock 1994) was used to identify areas of the Longview-Kelso Basin that contribute water to the Mint Farm wellfield. MODPATH calculates groundwater flow paths by tracing the paths of hypothetical particles, based on the hydraulic gradient calculated by a MODFLOW simulation. Conceptually, these particles can be thought of as water molecules, although they are not subject to mechanical dispersion or diffusion.

In MODPATH, particles can be tracked forward from an assumed source area, or they can be tracked backward from a production well or wellfield. In the former case, particle traces that terminate at a production well would have originated in a source area. Hence, forward particle tracking amounts to a trial-and-error search. In the latter case, particles start at the production well and move opposite the prevailing hydraulic gradient. Backward-tracked particles terminate in source areas. In both cases, the time of travel along a flow path is calculated by MODPATH, based on the hydraulic gradient, hydraulic conductivity, and porosity (i.e., advective transport).

To delineate the source areas for the Mint Farm wellfield, particles were placed around the perimeter of the Mint Farm wellfield in Model Layer 13. A backward particle tracking MODPATH simulation was conducted using as input the results of the MODFLOW simulation described above, with a Mint Farm production rate of 12 mgd. The porosity of a typical gravel is approximately 20 percent (Fetter 1994). For this analysis, porosity values were conservatively

set to 8 percent for the surficial soils, 8 percent for the sand, 5 percent for the silt/clay, and 10 percent for the gravel.

Figure 6.12 shows the extent of the source area after 6 months, 1 year, 5 years, and 10 years of simulated time. Also shown on Figure 6.12 are selected path lines in the gravel aquifer.

The hatched areas shown on the extreme western portion of the source areas in Figure 6.12 indicate where the Columbia River channel is in direct contact with the gravel aquifer. It should be pointed out that the hatched areas represent the only locations where the calculated source areas intersect the riverbed surface. Water at or near the riverbed or ground surface within the rest of source areas shown in Figure 6.12 does not contribute significantly to the source water for the Mint Farm wellfield, because the groundwater flow paths are beneath the silt/clay confining unit, in most cases more than 150 bgs. In the simulations presented here, greater than 99.9 percent of the water produced by the Mint Farm wellfield is supplied by the Columbia River.

The travel times for water from the Columbia River to the Mint Farm Wellfield takes from approximately 2 years to over 35 years. The most direct pathways are those that go directly west from the Mint Farm Wellfield towards the unconfined portion of the gravel aquifer. This shortest pathway also has the highest velocity due to the hydraulic gradients. Travel times along these direct pathways are approximately 2 years. The longest pathways also have the slowest velocity due to the lower hydraulic gradients. Travel times along these pathways can take 35 years or more to reach the Columbia River.

6.6 Preliminary Environmental Analysis

A preliminary environmental analysis was conducted to provide a screening-level evaluation of the potential for contaminants released at the surface to reach the Mint Farm Wellfield based on the Longview MODFLOW model. Changes to simulated shallow groundwater flow patterns caused by Mint Farm production wells that might influence Potentially Contaminating Activities (PCAs) and lead to potential contamination of the production wells were analyzed by (1) particle tracking from identified PCAs and (2) forward simulations of two hypothetical worst-case contamination scenarios.

6.6.1 Particle Tracking from PCA Locations

Twenty-one PCAs were identified by GSI (2008). These locations are not current groundwater contaminant sites, but if a contamination event were to occur at one or more of these locations, knowledge of the likelihood of contamination reaching the Mint Farm wellfield is valuable. To delineate the potential groundwater flow paths from the PCA locations, a forward-in-time particle-tracking simulation was conducted with MODPATH (Pollock 1994). One particle was assigned to each PCA. The starting locations for each particle are shown on Figure 6.13.

The particle-tracking simulation was conducted for 30 years of simulated time. The same porosity values were used as for the MODPATH source area delineation analysis (Section 6.5.3). The results are shown on Figures 6.13 and 6.14. The simulated flow paths are indicated by the red traces, with arrows showing the flow direction. In most cases, flow paths are directed toward drainage ditches (dark green jagged lines on Figure 6.13). Two of the particles traces are directed toward Lake Sacajawea. Figure 6.14 is an east-west cross-section

through the Mint Farm wellfield, showing that after 30 years of simulated time, none of the particles have approached the wellfield. As shown on Figure 6.14, after 30 years of simulated time, all particle traces are either in the surficial soil or in the silt/clay and have not penetrated the sand or gravel aquifers.

6.6.2 Hypothetical Contamination Scenarios

Two hypothetical, worst-case contamination scenarios were developed. Both scenarios were simulated with the solute transport program MT3D (Zheng and Wang 1999). Each simulation used the hydraulic head distribution from the 12 mgd wellfield groundwater flow simulation. The same porosity values were used as for the MODPATH source area delineation analysis (Section 6.5.3). The longitudinal dispersivity for the simulations is 100 feet, the horizontal transverse dispersivity is 10 feet, and the vertical transverse dispersivity is 1 foot. Retardation was not considered for these simulations. The concentration for both scenarios was defined as a dimensionless parameter set to a value of 100 as the initial condition. This initial value represents 100 percent of a maximum concentration, such that the attenuation caused by advection and dispersion can be interpreted at any time and location as a percentage of the maximum or starting concentration. Grid cells in the hypothetical contamination areas were defined as constant concentration sources, a boundary condition that assumes a constant source for the duration of the simulations.

Scenario A was designed to represent the unlikely case in which the entire Mint Farm property becomes subjected to widespread contamination at the surface. The hypothetical contamination area for Scenario A is shown as the red area on Figure 6.15. After 30 years of simulated advection and dispersion, the maximum percentage of the surface contamination found in any Mint Farm production well was 1×10^{-6}, or eight orders of magnitude smaller than the concentration at the surface. This value is the result of numerical calculations and, for practical purposes, is zero or non-detect.

Scenario B was designed to represent the unlikely case in which the entire Chinook Ventures and Weyerhaeuser properties become severely contaminated at the surface. The hypothetical contamination area for Scenario B is shown as the red area on Figure 6.16. After 30 years of simulated advection and dispersion, the maximum percentage of surface contamination found in any Mint Farm production well was, for practical purposes, zero or non-detect.

6.7 Conclusions

The overall objectives of the groundwater modeling portion of this study were to characterize the source areas for the proposed Mint Farm wellfield and assess the gravel aquifer's ability to sustain groundwater production at full build-out levels.

6.7.1 Summary

A three-dimensional numerical groundwater model was developed using the United States Geological Survey code MODFLOW 2000 (Harbaugh et al. 2000). The purposes of the numerical model were to test the hydrogeological conceptual model that was developed for this study and to evaluate the impacts of long-term groundwater production at the proposed Mint Farm Wellfield. The hydrogeological conceptual model accounts for complex basin geology and

geometry, groundwater-surface water interactions, and aquifer heterogeneity found in the Longview-Kelso Basin.

The aquifer system in the basin consists of a sand aquifer in the northern portion of the basin that abuts and in places overlies the target gravel aquifer, which is present in the southwestern portion of the basin. The sand and gravel are both partially overlain by, and in some places are contiguous with, a silt/clay unit. Deep groundwater flow in the basin originates dominantly from the Columbia River, flows through the gravel and sand aquifers and lower permeability materials, and discharges to the CDID network of drainage ditches. Water is pumped from the ditches and is ultimately discharged back to the Columbia River downstream from Longview. The MODFLOW model incorporates these elements of the conceptual model through boundary conditions and appropriate values for aquifer parameters.

The Model was calibrated against two independent data sets. The base-case model was calibrated using river stages, river gradients, and sentinel well groundwater elevations for the period 12 September 2009 through 24 September 2009. The base-case model was found to be in good agreement with the observed data. Water elevations in the drainage ditches, which are a primary control on shallow groundwater elevations, were estimated based on the on-off levels at CDID pumping stations. The calibration could be improved by incorporating more detailed drainage ditch water elevations. A pumping-case model was also calibrated against data from the pumping test described in Section 4 of this report. The Model was found to reasonably match the aquifer response observed during the pumping test.

Full build-out of 12 mgd (average day demand for year 2059) pumping from the deep gravel aquifer at the Proposed Mint Farm Wellfield was simulated. The simulation indicates that water from the Columbia River recharges the deep gravel aquifer. A relatively small amount of drawdown was shown to occur at the wellfield. The full build-out model was also used to delineate the source areas for the Wellhead Protection Plan and to evaluate potential impacts to groundwater quality. No potential water quality threats were indentified.

6.7.2 Conclusions

The primary objective of this groundwater modeling study was to develop a calibrated basin-wide numerical model to enhance the City's ability to manage and protect the groundwater resource in the Longview-Kelso Basin. To meet this objective, a detailed conceptual model was developed that includes the basin geometry, geology, and hydrologic budget.

In the conceptual model, groundwater flow in the Longview-Kelso Basin is dominated by the Columbia River and the CDID drainage ditches. This conceptual model was tested by developing a three-dimensional groundwater model with MODFLOW. Using an acceptable range of aquifer parameters and boundary conditions, the conceptual model was found to be a valid representation of groundwater flow in the Longview-Kelso Basin. Water is pumped from the drainage ditches and ultimately discharged to the Columbia River on the western side of the basin. The presence of the CDID ditches reverses the natural groundwater flow throughout the basin, especially in the Mint Farm area. The aquifer system is recharged by the Columbia River to the deep gravel aquifer and groundwater ultimately discharges through the sand aquifer and lower permeability materials to the CDID drainage ditches.

Two model scenarios were conducted to evaluate the sustainability of long-term pumping from the deep gravel aquifer for the Mint Farm Wellfield. The first scenario simulated a single-well pumping test that was conducted at the Mint Farm site and documented in Section 4 of this report. Using conservative hydraulic conductivity estimates for the gravel aquifer derived from the pumping test, the model was able to reasonably reproduce the aquifer response observed during the test.

The second scenario was designed to simulate full build-out (average day demand in year 2059) of the Mint Farm Wellfield. The total simulated production was 12 mgd, divided equally among six production wells spaced 200 feet apart. Also included was an additional 4.1 mgd of pumping at the neighboring properties of Puget Sound Energy and Chinook Ventures. Drawdown at the wellfield in the simulation scenario was approximately 6 feet, which is small compared to the approximately 150-foot gravel aquifer thickness. The results of this scenario confirm that the Mint Farm Wellfield is capable of sustaining the planned pumping rates.

The wellhead protection source areas for the Wellhead Protection Plan were delineated using the results from the wellfield simulation. The source of water to the wellfield was found to be over 99 percent from the Columbia River, transmitted through the gravel aquifer. Source water enters the aquifer at locations where the Columbia River channel intersects the gravel unit west of the Mint Farm site. The model results indicate that travel times for water from the Columbia River to the Mint Farm Wellfield takes from approximately 2 years to over 35 years.

Potential threats to groundwater quality caused by 12 mgd of pumping at the Mint farm wellfield were evaluated with three model scenarios. In the first scenario, forward particle tracking from indentified potentially contaminating activities (PCAs) indicated that groundwater flow paths from these PCAs do not extend beyond the surficial soil or the silt/clay confining layer within a 30-year time frame. Two hypothetical, constant concentration sources were placed at the ground surface to simulate the hypothetical severe contamination. One for the Mint Farm and a second for the industrial area along the Columbia River defined by Weyerhaeuser and Chinook Ventures. The results indicate that contamination from neither source reaches the Mint Farm production wells within a 30-year time frame.

References

Bear, J. and A. Verruijt. 1987. *Modeling Groundwater Flow and Pollution*. D. Reidel Publishing Company, Boston, 414 p.

CH2M Hill. 2009. 2009 *Groundwater Monitoring Report. CH2M Hill Technical Memorandum*, dated 10 June 2009.

Driscoll, F.G. 1986. *Groundwater and Wells* (2nd Edition). US Filter / Johnson Screens, St. Paul, Minnesota.

Environmental Solutions International (ESI). 2007. *Guide to Using Groundwater Vistas Version 5*. Environmental Simulations, Inc., Reinholds, Pennsylvania, 366 p.

Evarts R.C., O'Connor, J.E., Wells, R.E., and Madin, I.P. 2009. *The Portland Basin: A (Big) River Runs Through It*. GSA Today 19(9), p. 4-10.

Fetter, C.W. 1994. *Applied Hydrogeology*. Prentice-Hall, Upper Saddle River, NJ, 691 p.

Golder Associates. 2002. *Memorandum, Mint Farm Well(s) – Hydrogeological Impact Assessment.* Addressed to Mike Gonnella, Mirant Corporation, dated 15 April 2002.

GSI, 2008. City of Longview, *Proposed Mint Farm Wellfield Area Environmental Review*. GSI Water Solutions, Inc. Technical Memorandum dated 5 May 2008.

Harbaugh, A.W., E.R. Banta, M.C. Hill and M.G. McDonald. 2000. MODFLOW 2000, *The U.S. Geological Survey Modular Ground-Water Model – User Guide to Modularization Concepts and the Ground-water Flow Process*. U.S. Geological Survey Open-File Report 00-92. Reston, Virginia.

Hartford, S.V. and McFarland, W.D. 1989. *Lithology*, *Thickness, and Extent of Hydrogeologic Units Underlying the East Portland Area*, Oregon. U.S. Geological Survey Water-Resources Investigations Report 88-4110.

Kennedy/Jenks, 2009a, *Preliminary 7-Day Pumping Test Analysis at Test Production Well PW*-1.

Kennedy/Jenks 2009b *Technical Memorandum 2, Water Quality Sampling Protocol.*

Kennedy/Jenks 2009c *Technical Memorandum 2A, Water Quality Sampling Protocol for First Production Well Pumping Test.*

Kennedy/Jenks Consultants. 2010*. Water Quality and Environmental Risk Assessment, Mint Farm RWTP Part 2B Preliminary Design Report*, *Longview, Washington*.

McCarthy, K.A., McFarland, W.D, Wilkinson, J.M., and White, L.D. 1992. *The Dynamic Relationship between Ground Water and the Columbia River: Using Deuterium and Oxygen- 18 as Tracers*. Journal of Hydrology, 135 1-12.

McCutcheon, M.S. 2003. Stratigraphy and Sedimentology of the Middle Eocene Cowlitz *Formation and Adjacent Sedimentary and Volcanic Units in the Longview-Kelso Area*, Southwest Washington, Oregon State University Masters Thesis.

McFarland, W.D. and Morgan, D.S. 1996. *Description of the Gorund-Water Plow System in the Portland Basin, Oregon and Washington*. U.S. Geological Survey Water-Supply Paper 2470-A.

Phipps, W.M. 1987. Geologic Map of the Mount St. Helens Quadrangle, Washington and Oregon, *Open File Report 87-4. Division of Geology and Earth Resources*, Washington Department of Natural Resources.

Pollock, D. 1994. User's Guide for MODPATH/MODPATH-PLOT, *Version 3: A Particle Tracking Post-Processing Package for MODFLOW, the U.S. Geological Survey Finite-Difference Ground-Water Flow Model*. U.S. Geological Survey Open-File Report 94-464. Reston, Virginia.

Robinson Noble Saltbush, Inc. (Robinson Noble), 2009. A letter report dated 3 April 2009 documenting the installation of sentinel wells SW-1 through SW-7.

Serfes, Michael. 1991. *Determining the Mean Hydraulic Gradient of Ground Water Affected by Tidal Fluctuations*. Ground Water 29(4). July-August 1991, pp. 549-555.

Swanson, R.D., McFarland, W.D, Gonthier, J.B., and Wilkinson, J.M. 1993. *A Description of Hydrogeologic Units in the Portland Basin, Oregon and Washington*. U.S. Geological Survey Water-Resources Investigations Report 90-4196.

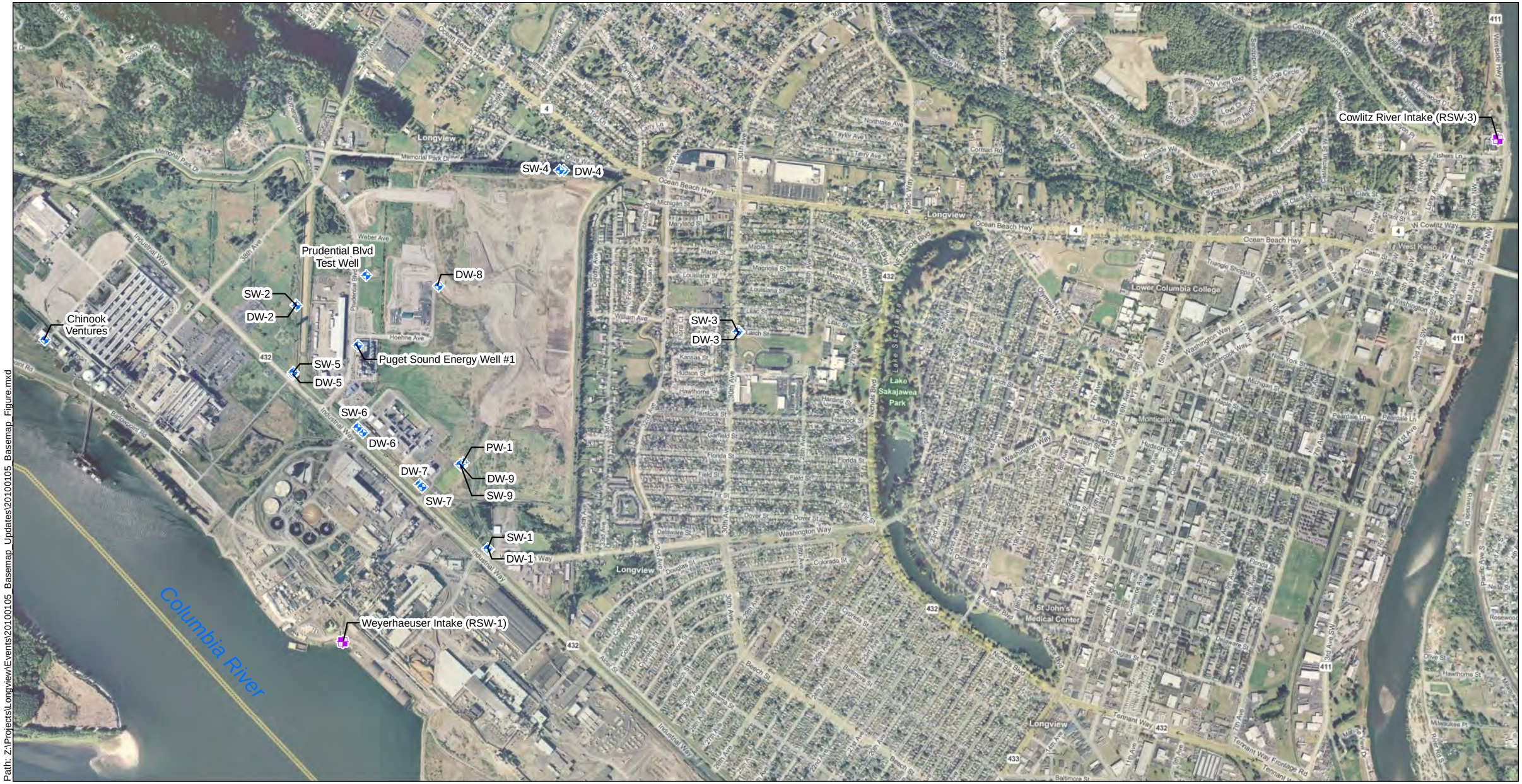
Walsh, T.J. 1987. Geologic Map of the Astoria and Ilwaco Quadrangles, Washington and Oregon, *Open File Report 87-2. Division of Geology and Earth Resources*, Washington Department of Natural Resources.

Washington Division of Geology and Earth Resources 1987.

Zheng, C. and Wang, P. 1999. MT3DMS: *A Modular Three-Dimensional Multispecies Transport Model for Simulation of Advection, Dispersion, and Chemical Reactions of Contaminants in Groundwater Systems; Documentation and User's Guide*. U.S. Army Corps of Engineers. December 1999.

Figures

Path: Z:\Projects\Longview\Events\20100105_Basemap_Updates\20100105_Basemap_Figure.mxd



Aerial Source: (c)2009 Microsoft Corporation

Legend

- Well Location
- Surface Water Sample Location

N

0 750 1,500

Scale: Feet

Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Basemap

KJ 0997003*00
January 2010

Figure 2.1

Path: Z:\Projects\Longview\Events\20100105_Basemap_Updates\20100105_Fig2-2_Site_Map.mxd

Aerial Source: (c)2009 Microsoft Corporation

Legend

Monitoring Well

N

0 600 1,200

Scale: Feet

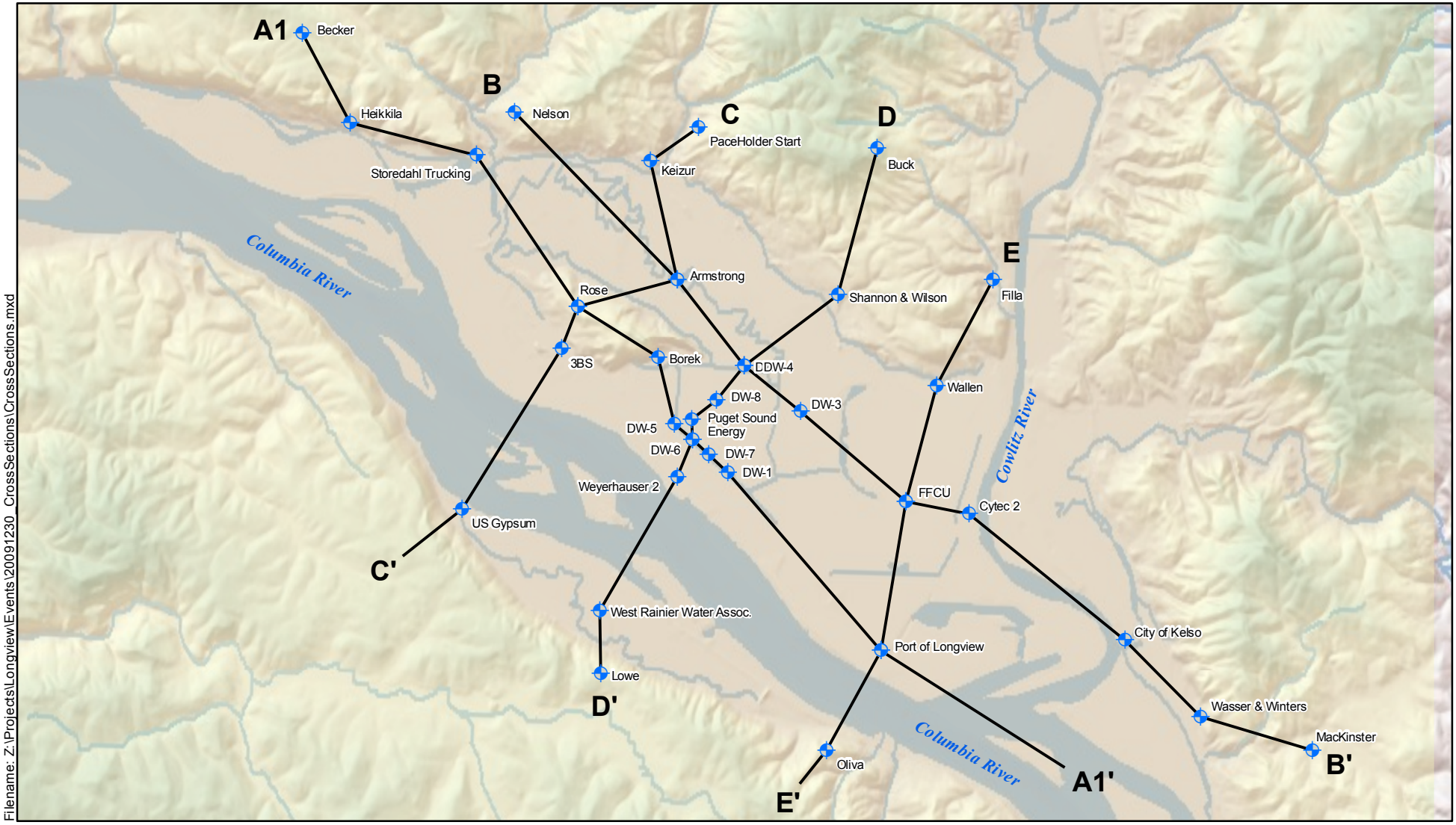
Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Site Map

KJ 0997003*00
January 2010

Figure 2.2



Filename: Z:\Projects\Longview\Events\20091230_CrossSections\CrossSections.mxd

N

0 7,000

Scale: Feet

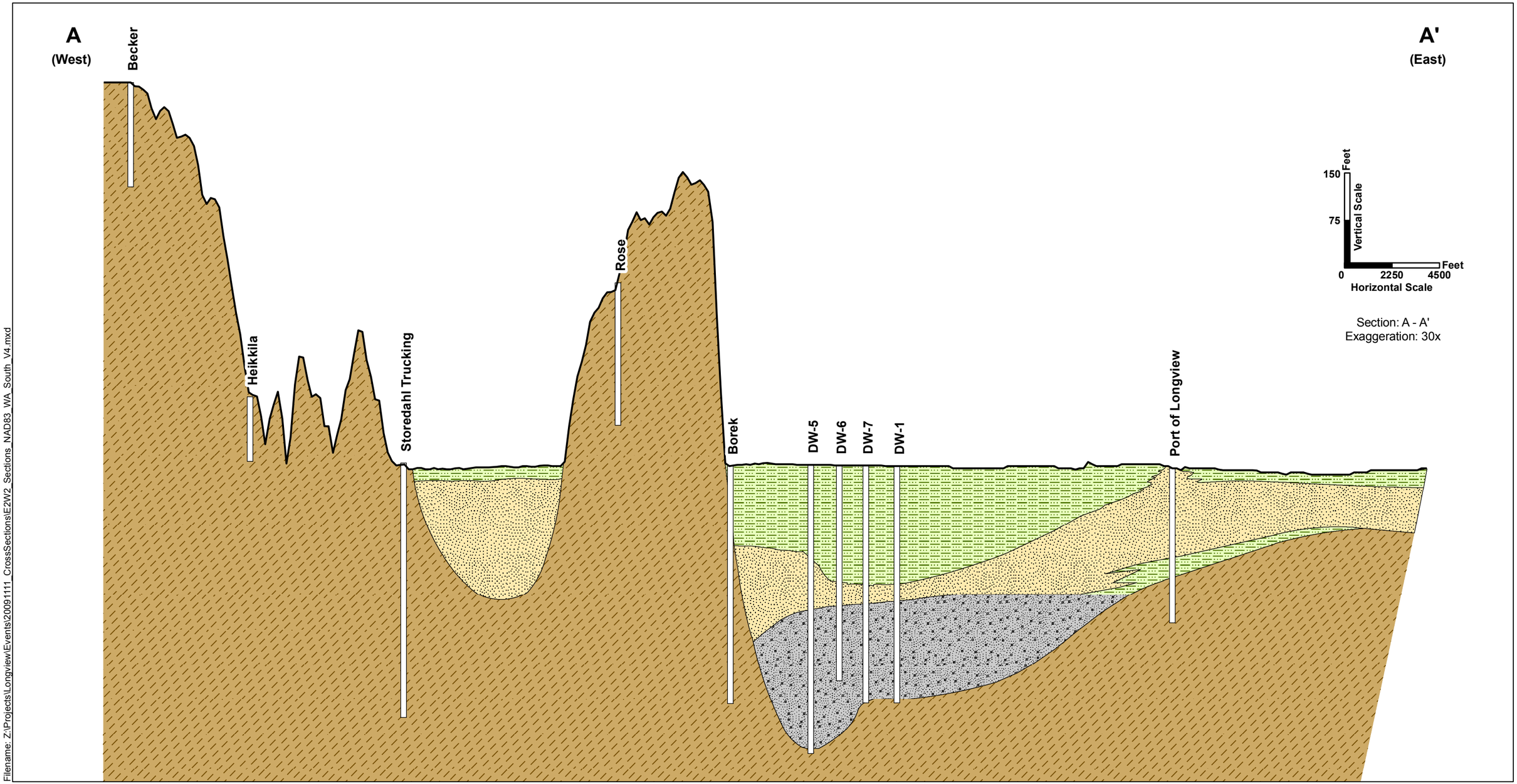
Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Surface Representation of Geologic Cross Sections

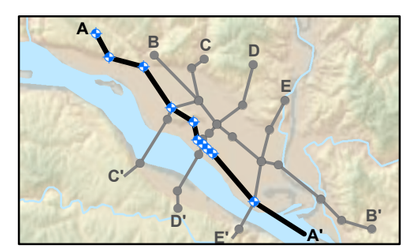
KJ 0997003*00
December 2009

Figure 2.3



Filename: Z:\Projects\Longview\Events\20091111_CrossSections\E2W2_Sections_NAD83_WA_South_V4.mxd

Silt
Sand
Gravel
Bedrock
Ground Surface



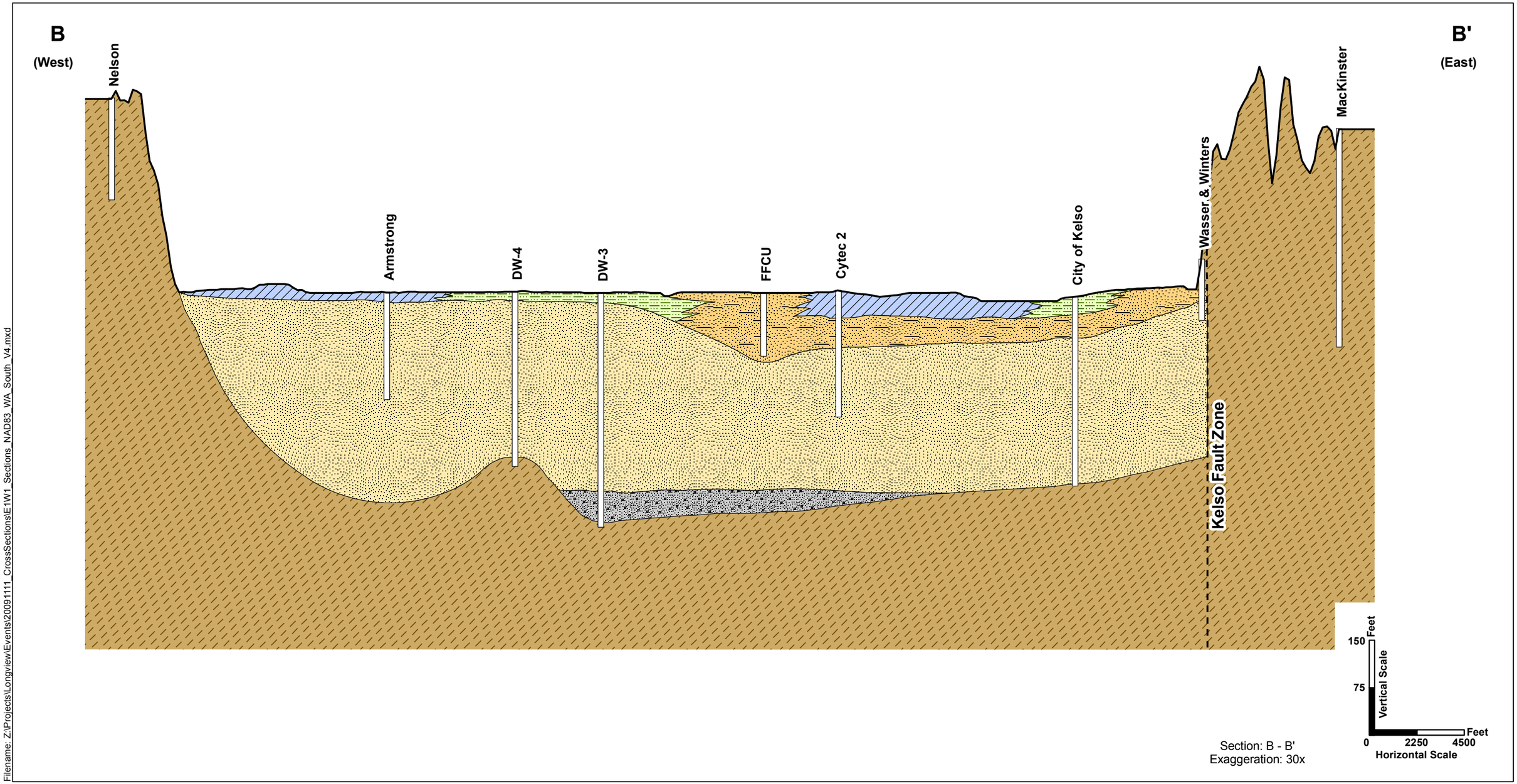
Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Geologic Cross Section A-A'

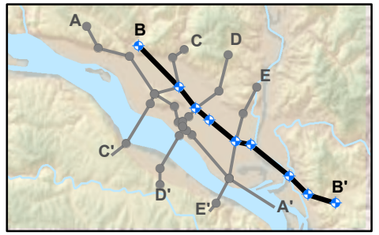
KJ 0997003*00
December 2009

Figure 2.4



Filename: Z:\Projects\Longview\Events\20091111_CrossSections\E1W1_Sections_NAD83_WA_South_V4.mxd

- Clay
- Silt
- Silty Sand
- Sand
- Gravel
- Bedrock
- Ground Surface



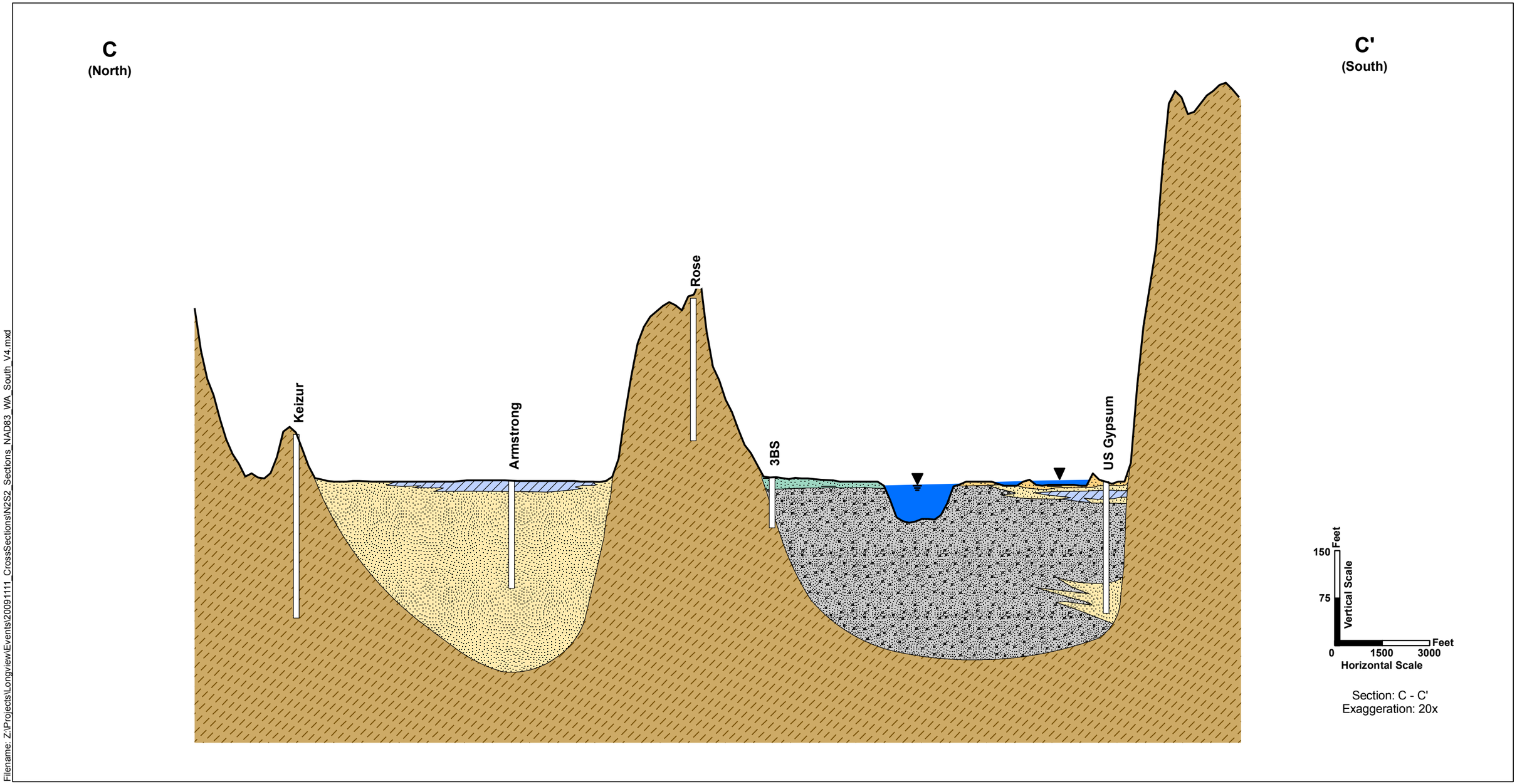
Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Geologic Cross Section B-B'

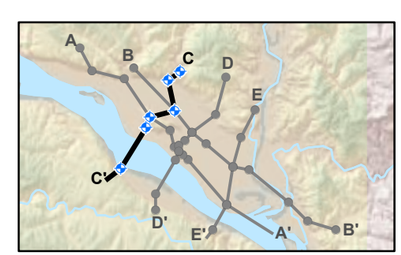
KJ 0997003*00
December 2009

Figure 2.5



Filename: Z:\Projects\Longview\Events\20091111_CrossSections\N2S2_Sections_NAD83_WA_South_V4.mxd

Water
Clay
Silty Sand
Silty Sand/Gravel
Sand
Gravel
Bedrock
Ground Surface



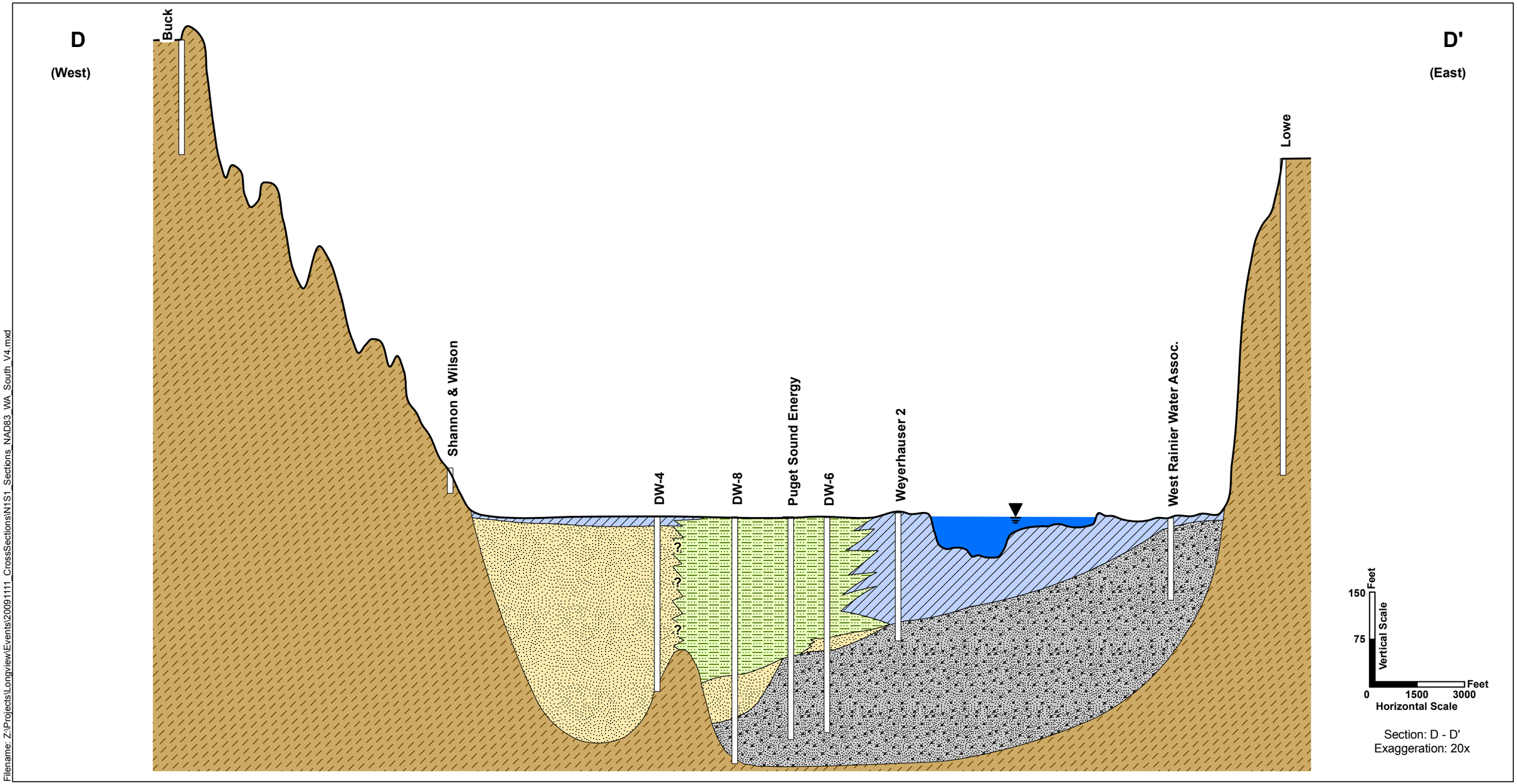
Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Geologic Cross Section C-C'

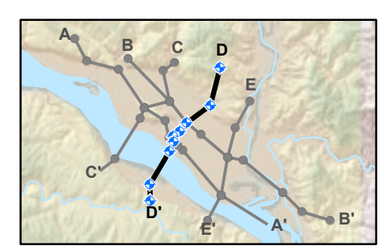
KJ 0997003*00
December 2009

Figure 2.6



Filename: Z:\Projects\Longview\Events\20091111_CrossSections\N1S1_Sections_NAD83_WA_South_V4.mxd

- Water
- Clay
- Silt
- Silty Sand
- Sand
- Gravel
- Bedrock
- Ground Surface



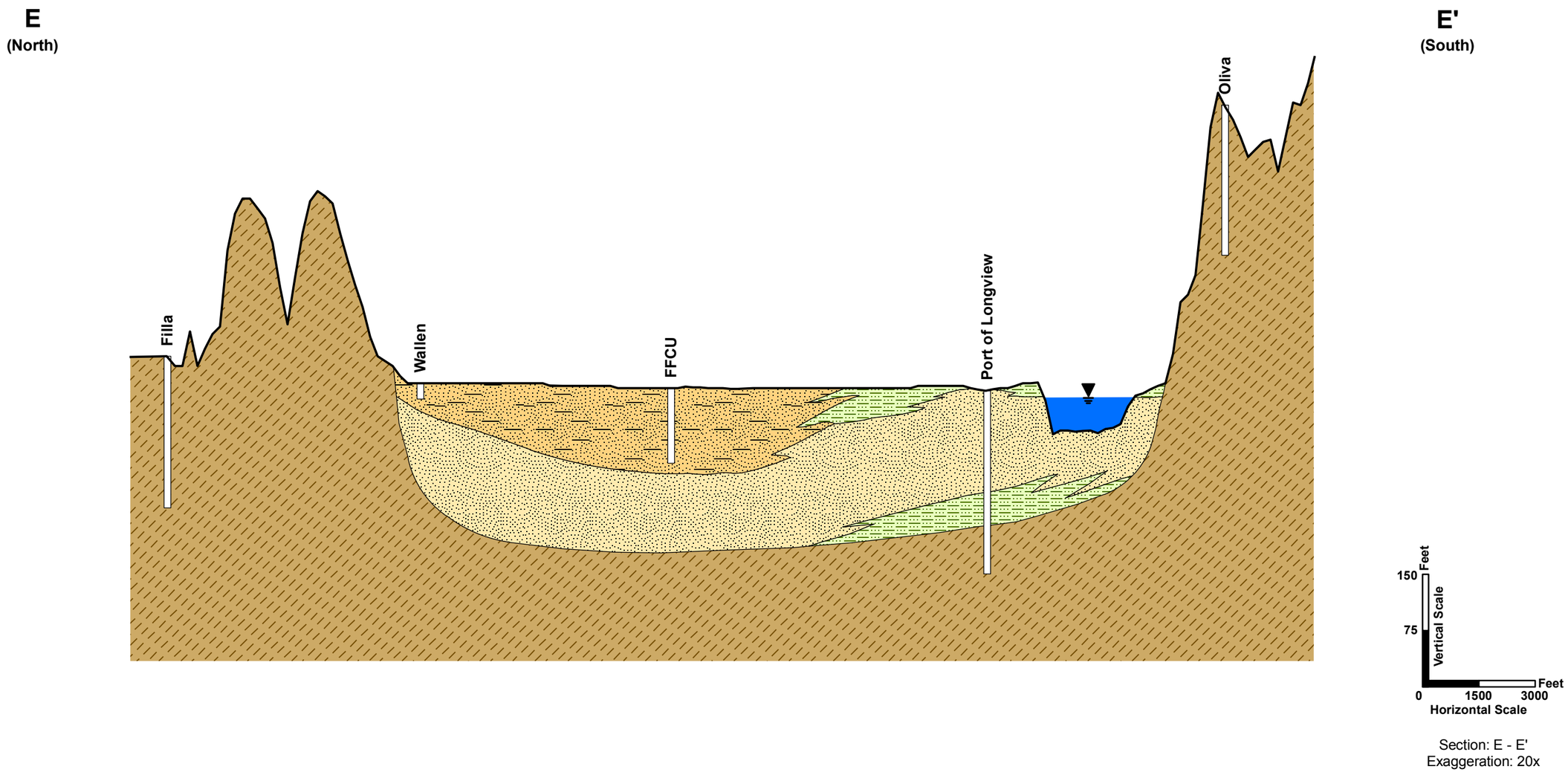
Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Geologic Cross Section D-D'

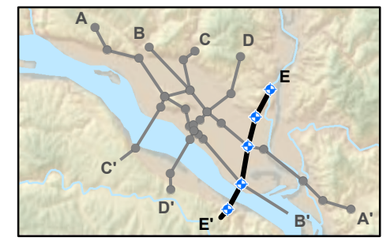
KJ 0997003*00
December 2009

Figure 2.7



Filename: Z:\Projects\Longview\Events\20091111_CrossSections\N3S3_Sections_NAD83_WA_South_V4.mxd

Water
Silt
Silty Sand
Sand
Bedrock
Ground Surface



Kennedy/Jenks Consultants

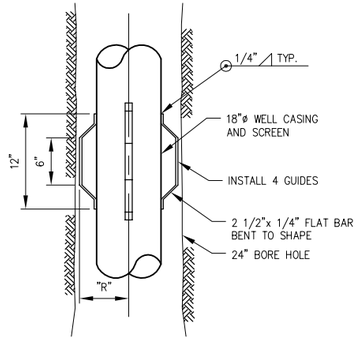
Mint Farm RWTP Design
Longview, Washington

Geologic Cross Section E-E'

KJ 0997003*00
December 2009

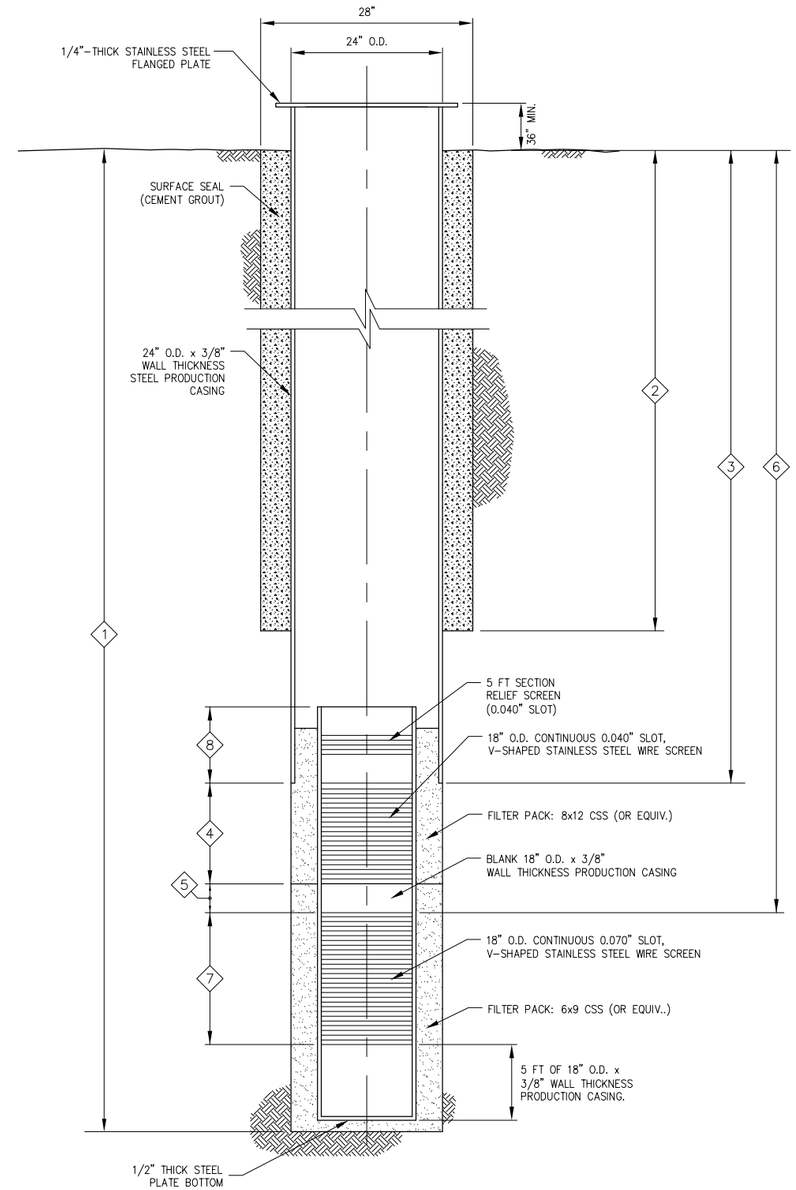
Figure 2.8

WELL LEGEND		
ITEM	DESCRIPTION	QUANTITY
1	TOTAL BOREHOLE DEPTH	385 FT BGS
2	DEPTH OF SURFACE SEAL	150 FT BGS
3	DEPTH TO TOP OF UPPER SCREEN / BOTTOM OF PRODUCTION CASING	230 FT BGS
4	UPPER SCREEN LENGTH (0.040"-SLOT)	55 FT
5	LENGTH OF 18" INTERMEDIATE BLANK CASING	14 FT
6	DEPTH TO TOP OF LOWER SCREEN SECTION	299 FT BGS
7	LOWER SCREEN LENGTH (0.070"-SLOT)	71 FT
8	LENGTH OF 18" RISER (ABOVE SCREEN)	35 FT



NOTES:
1. 4 GUIDES ARE EQUIDISTANT AROUND CIRCUMFERENCE.
2. SHOP FABRICATED CASING GUIDES ARE INSTALLED AT APPROXIMATELY 195', 230', 262', 299', 330', 348', AND 370'.
3. "R" = RADIUS OF BORE MINUS 1/2".

CASING GUIDE DETAIL
N.T.S.



PRODUCTION WELL SECTION
N.T.S.

USE OF DOCUMENTS

THIS DOCUMENT, INCLUDING THE INCORPORATED DESIGNS, IS AN INSTRUMENT OF SERVICE FOR THIS PROJECT AND SHALL NOT BE USED FOR ANY OTHER PROJECT WITHOUT THE WRITTEN AUTHORIZATION OF KENNEDY/JENKS CONSULTANTS.

NO.	REVISION	DATE	BY

DESIGNED DRO
DRAWN SLG
CHECKED DL

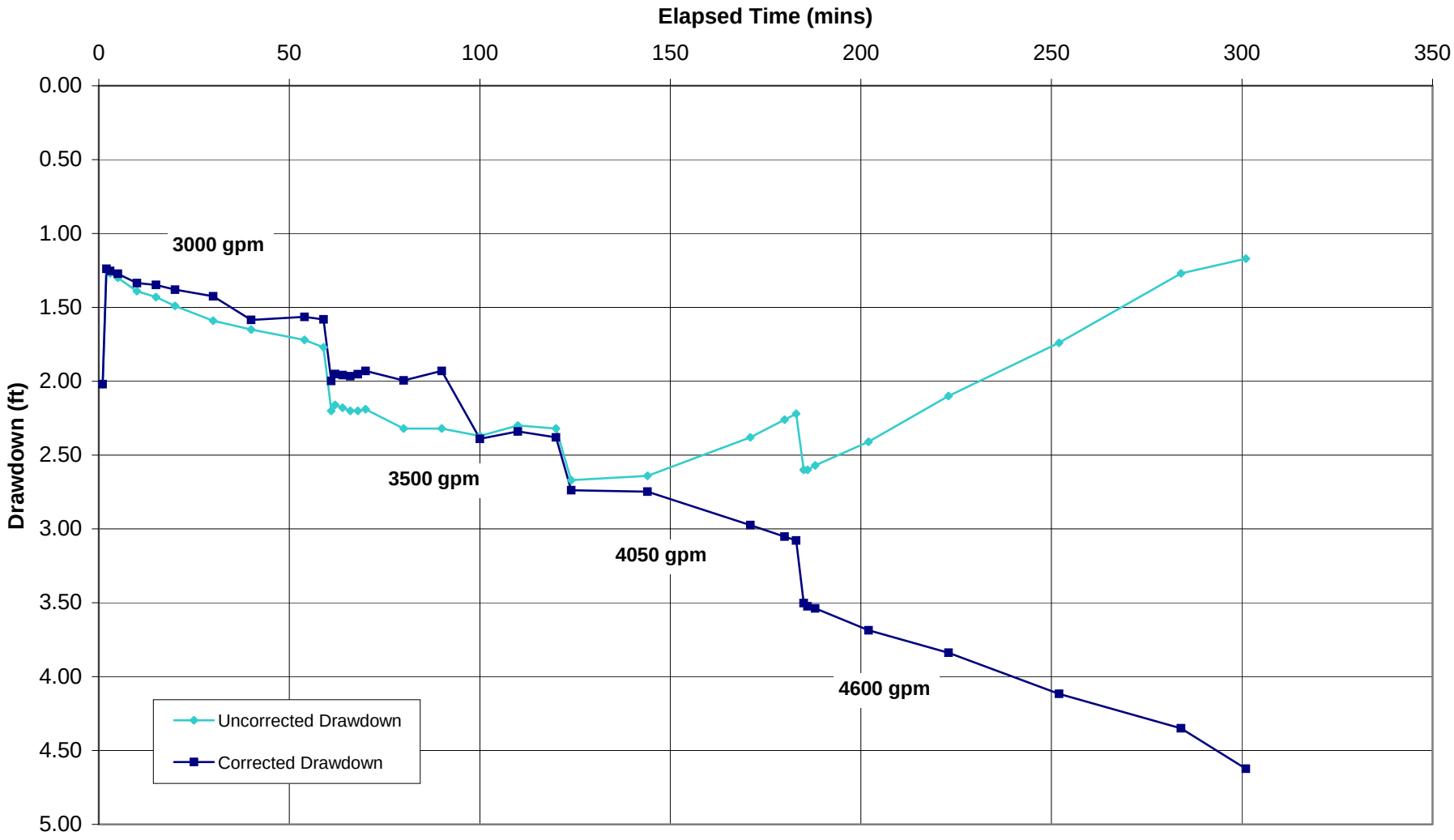
CITY OF LONGVIEW
LONGVIEW, WASHINGTON
MINT FARM WELLFIELD

Kennedy/Jenks Consultants
200 SW MARKET STREET, SUITE 500, PORTLAND, OREGON 97201

PRODUCTION WELL NO 1 SECTION AND DETAIL

FILE NAME
JOB NO. 0997003.00
DATE 08/19/2009
SHEET OF
FIG 4.1

STEPHANIE GOTSCH 12/10/2009 4:11 PM
P:\cad\09\0997003_00_LONGVIEW\PDR_NO2\0997003-PDR_FIG4-1.dwg



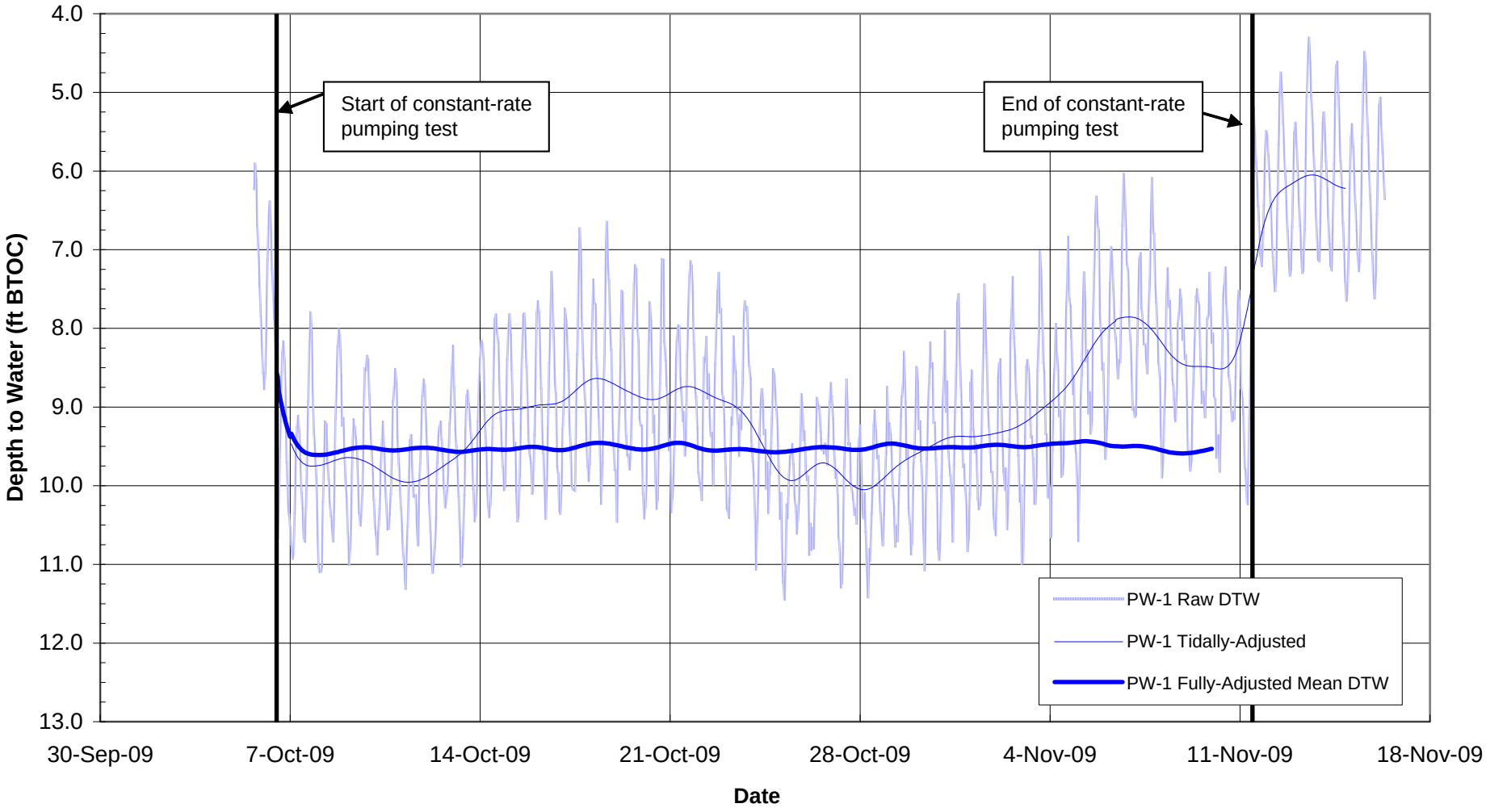
Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Pumping Well PW-1 Time-Drawdown (Step-Rate Test)

KJ 0997003*00
December 2009

Figure 4.2



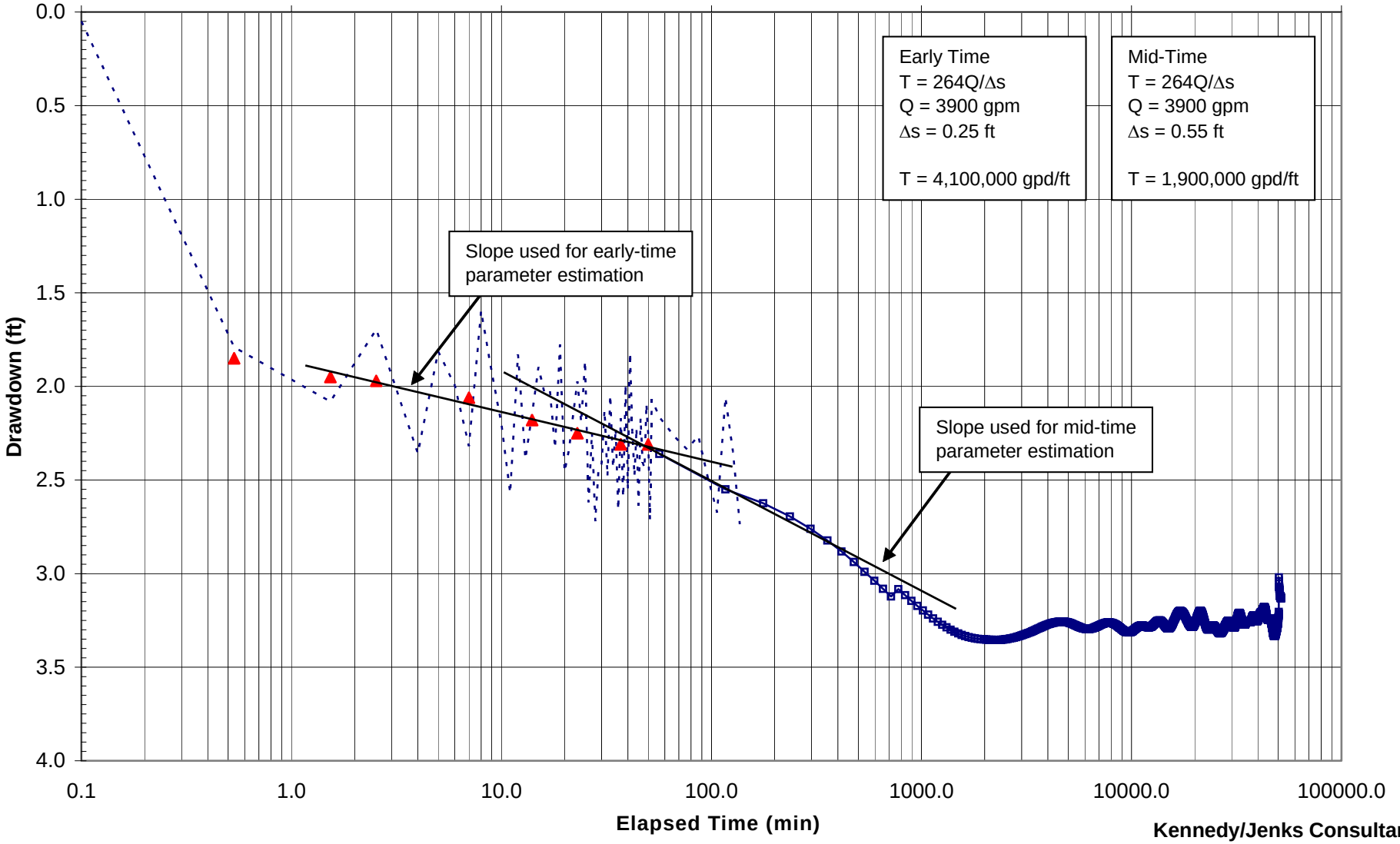
Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Pumping Well PW-1 Hydrograph

KJ 0997003*00
December 2009

Figure 4.3



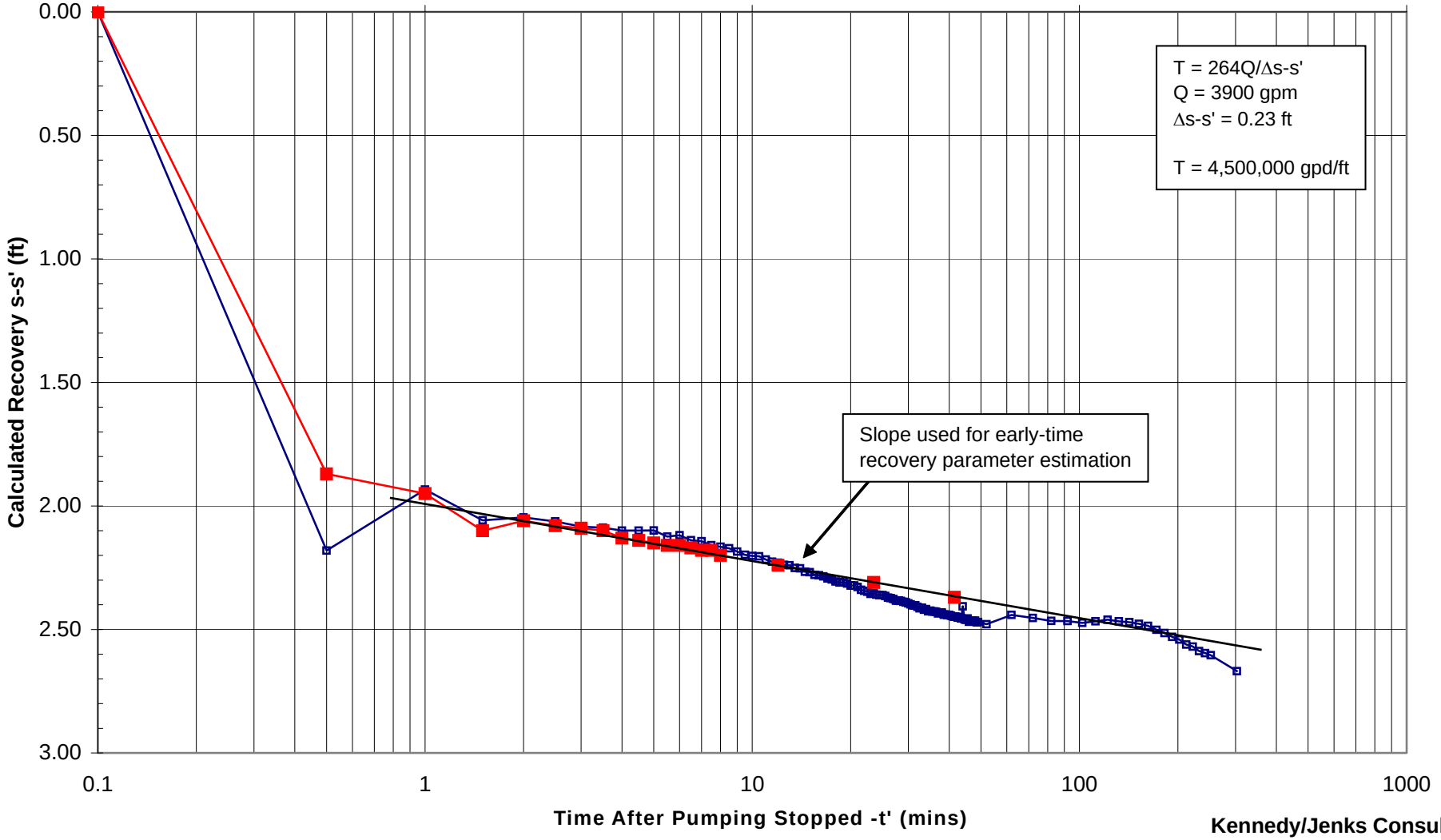
Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Pumping Well PW-1 Time-Drawdown (Constant-Rate)

KJ 0997003*00
December 2009

Figure 4.4



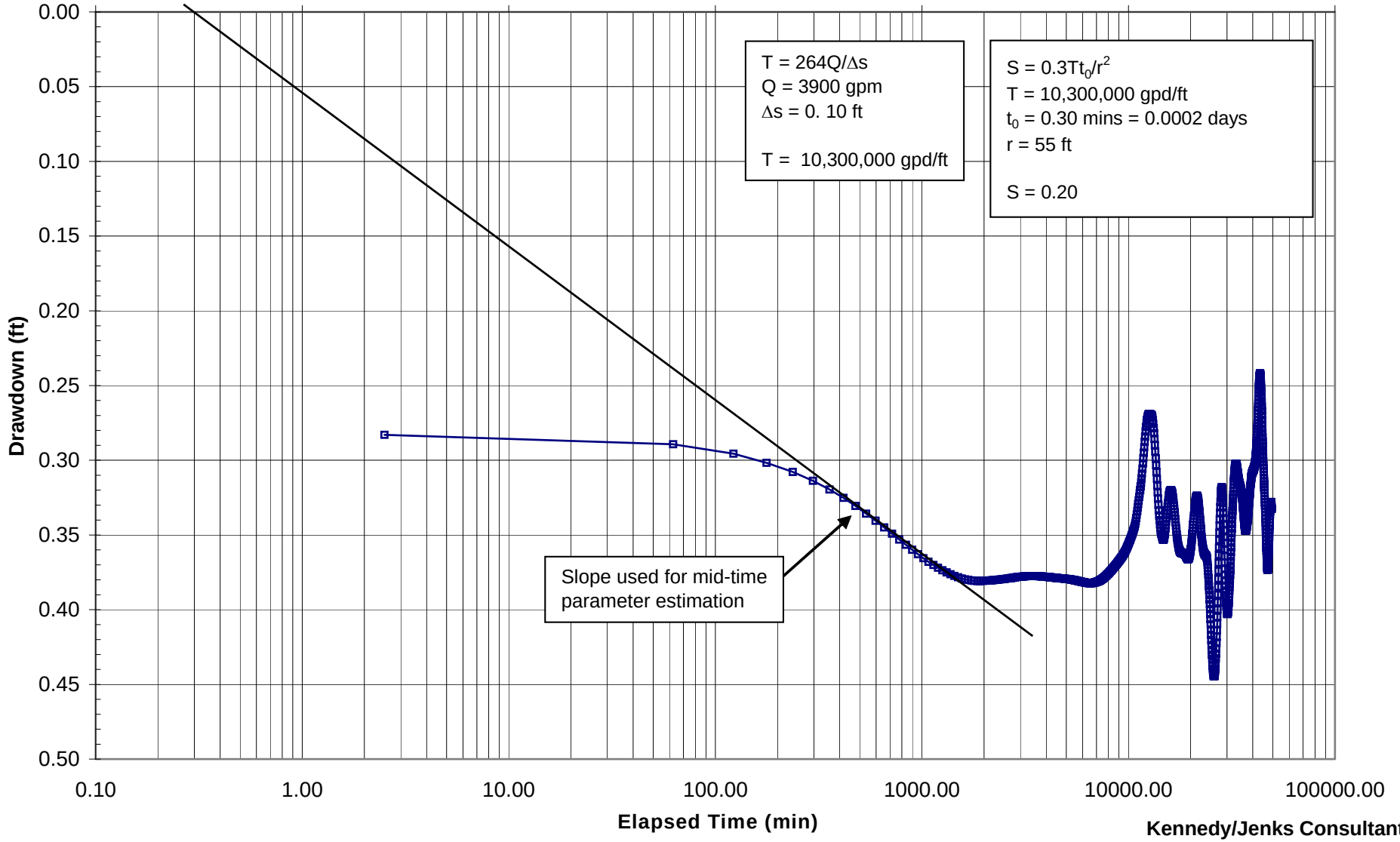
Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Pumping Well PW-1 Time-Recovery (Constant-Rate)

KJ 0997003*00
December 2009

Figure 4.5



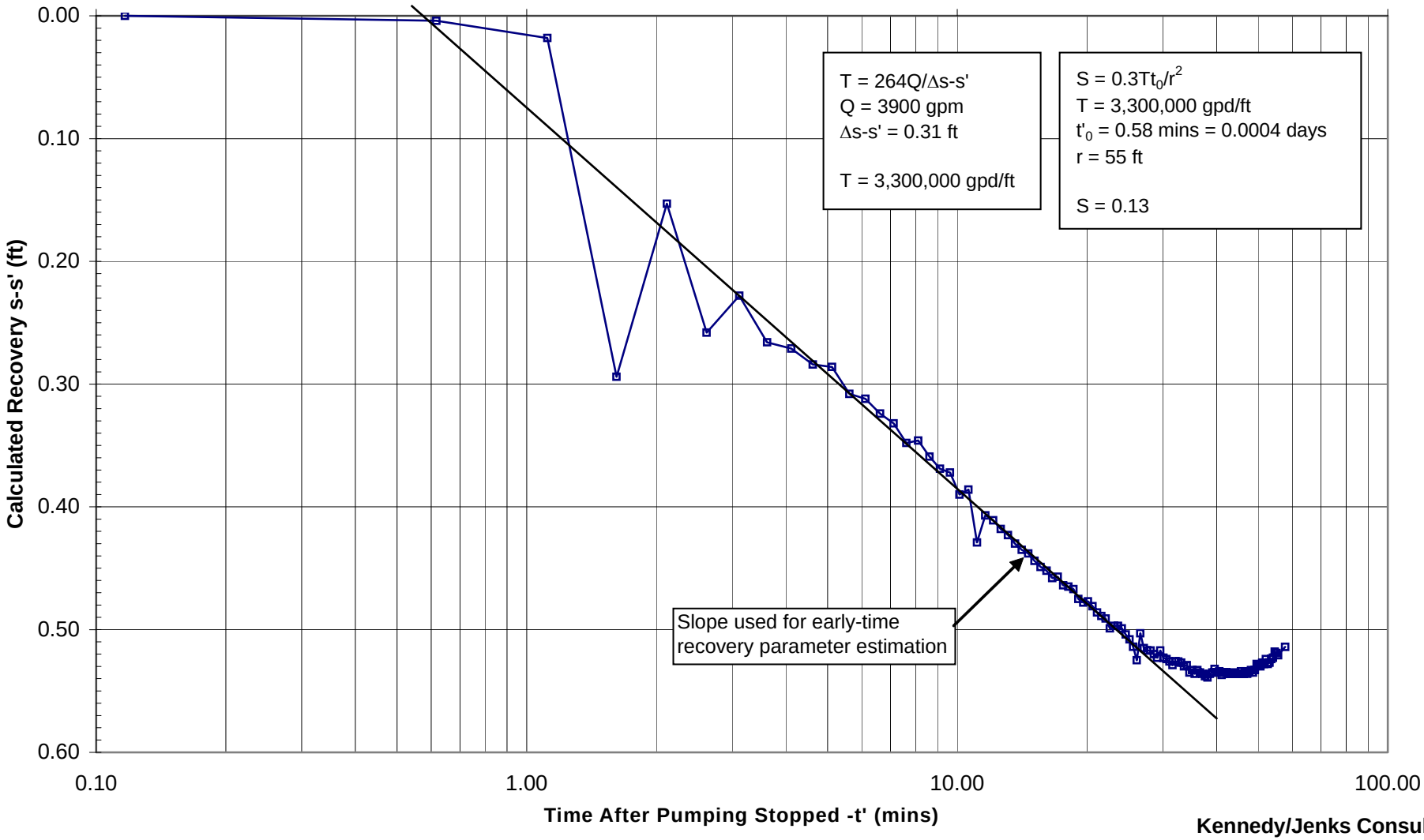
Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Observation Well DW-9 Time-Drawdown (Constant-Rate)

KJ 0997003*00
December 2009

Figure 4.6



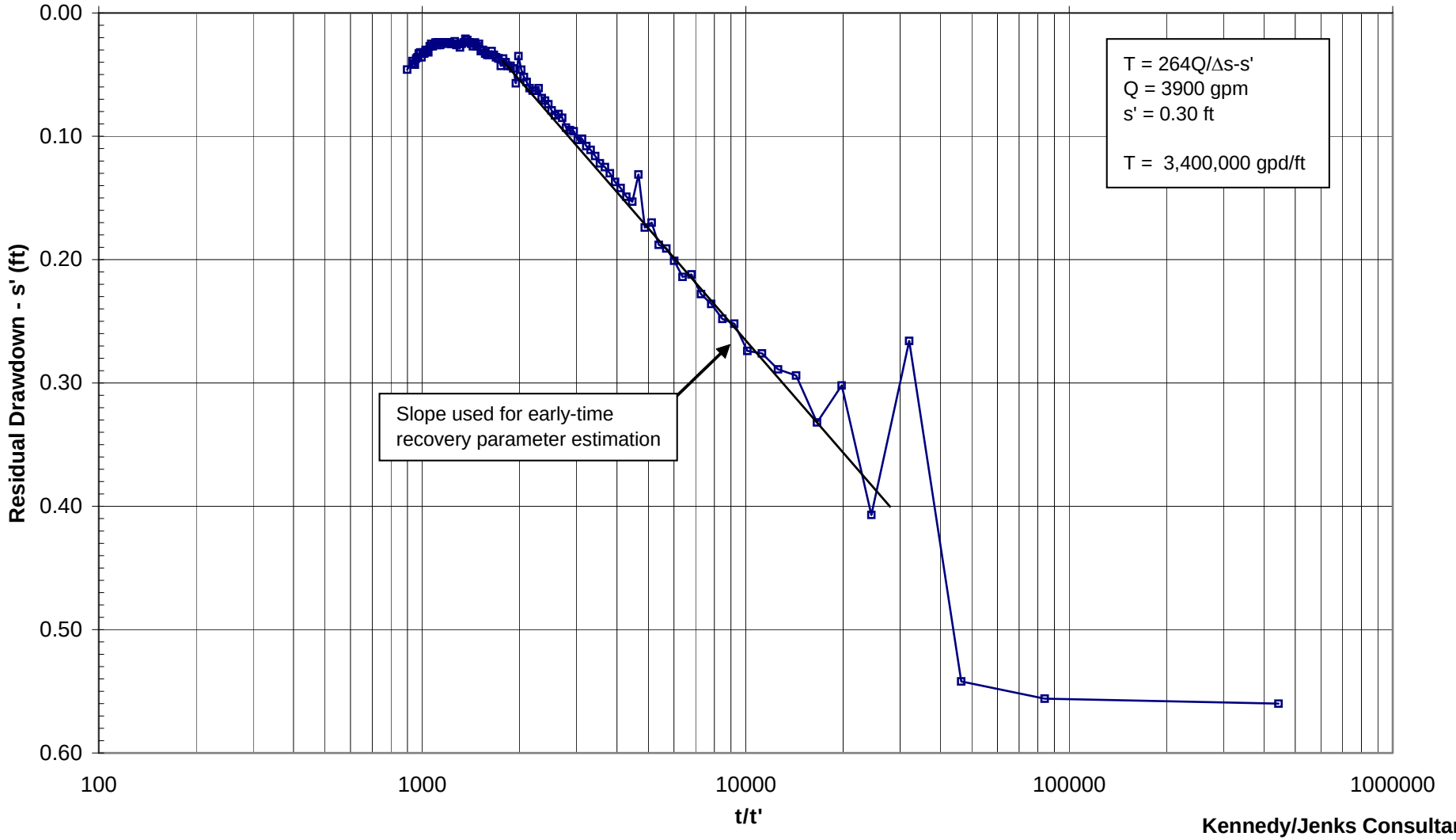
Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Observation Well DW-9 Time-Recovery (Constant Rate)

KJ 0997003*00
December 2009

Figure 4.7



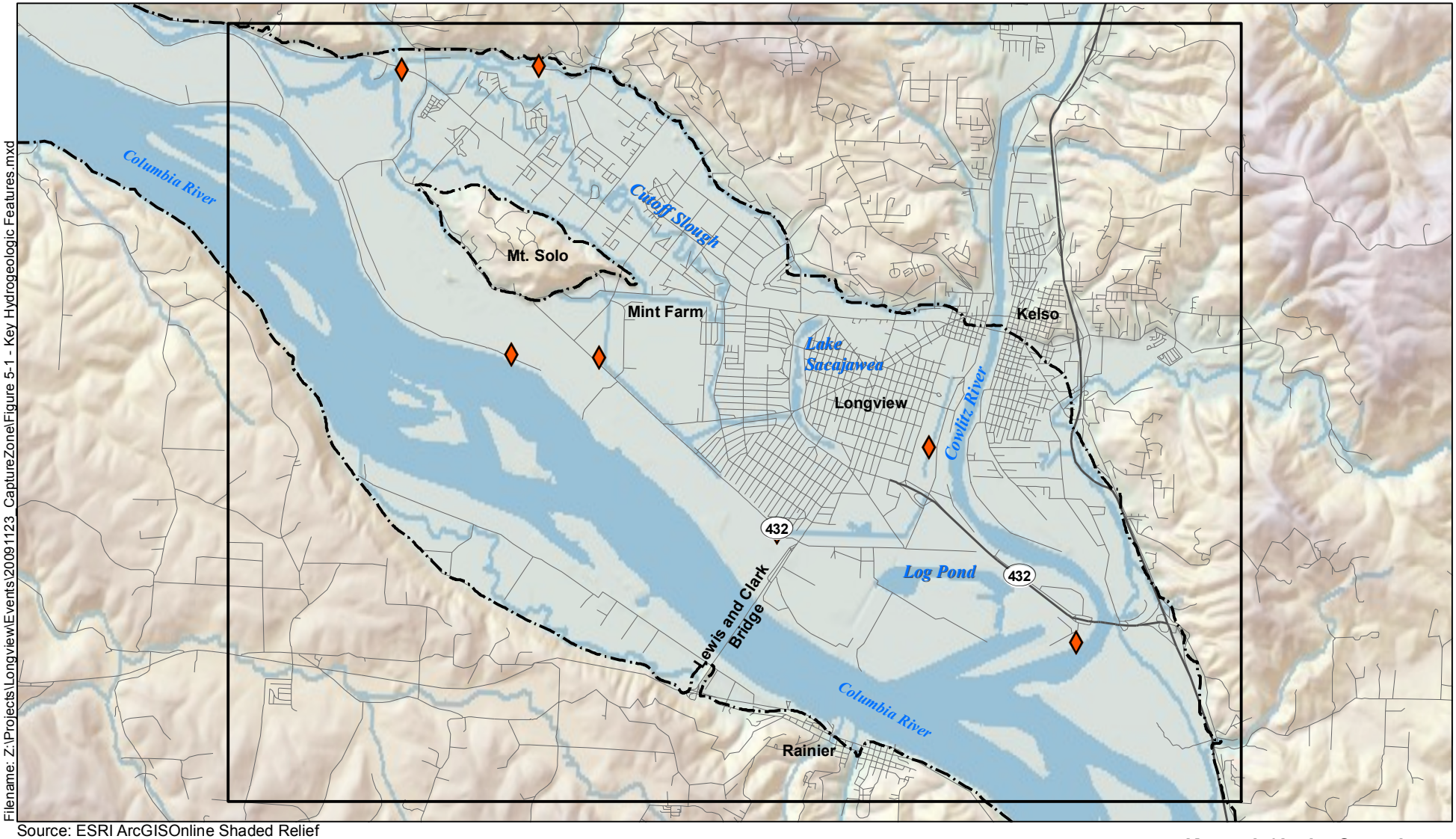
Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Observation Well DW-9 Residual Drawdown (Constant Rate)

KJ 0997003*00
December 2009

Figure 4.8



Filename: Z:\Projects\Longview\Events\20091123_CaptureZone\Figure 5-1 - Key Hydrogeologic Features.mxd

Source: ESRI ArcGISOnline Shaded Relief

Consolidated Diking Improvement District (CDID) Pumping Station

Longview-Kelso Basin

Model Domain Boundary

N

0 7,000

Scale: Feet

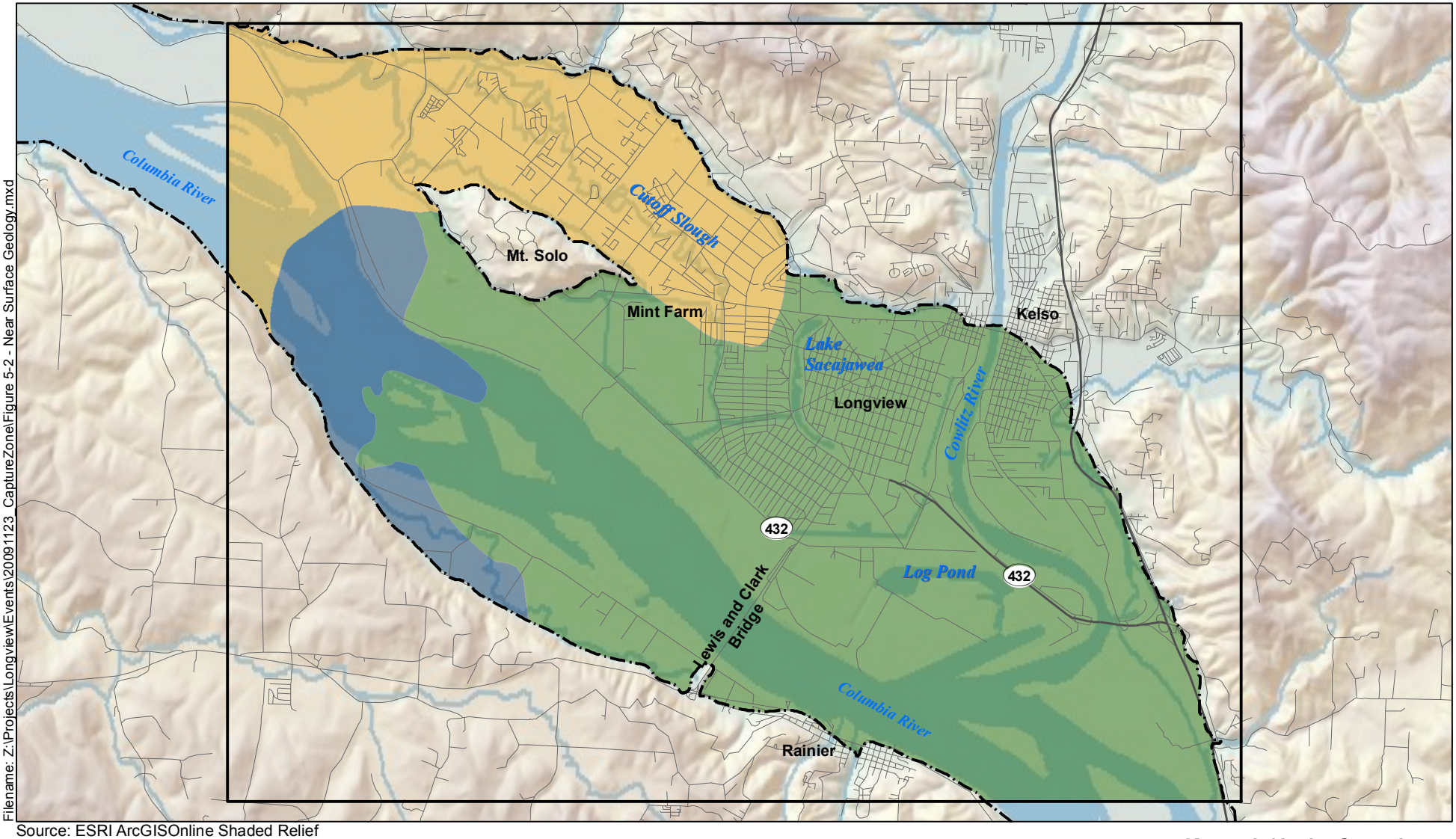
Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Key Hydrogeologic Features Within the Longview-Kelso Basin

December 2009

Figure 5.1



Filename: Z:\Projects\Longview\Events\20091123_CaptureZone\Figure 5-2 - Near Surface Geology.mxd

Source: ESRI ArcGISOnline Shaded Relief

Longview-Kelso Basin
Model Domain Boundary
Sand
Gravel
Silt/Clay

N

0 7,000
Scale: Feet

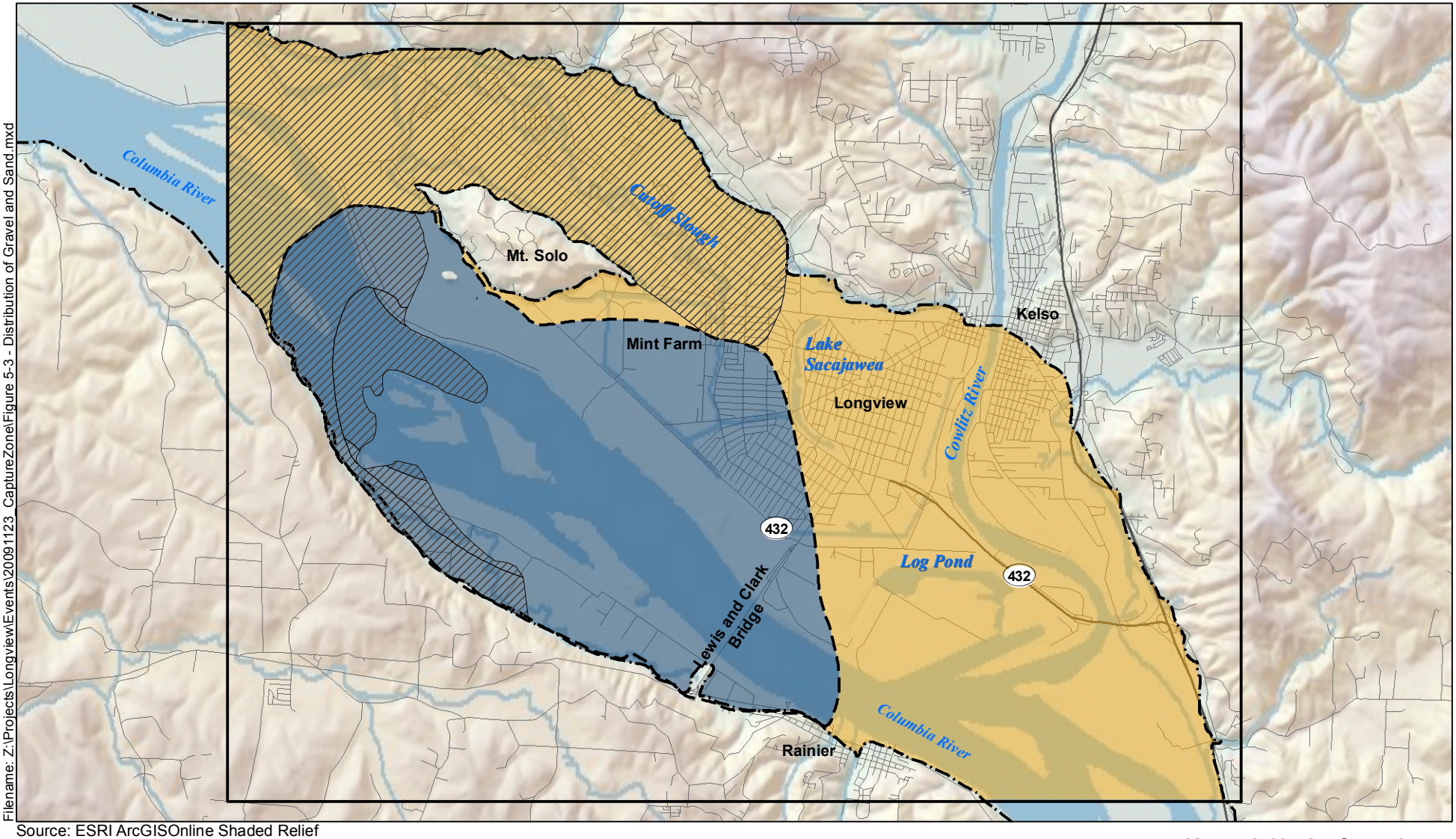
Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Near Surface Geology in Longview-Kelso Basin to Define Extent of Confining Layer

December 2009

Figure 5.2



Filename: Z:\Projects\Longview\Events\20091123_CaptureZone\Figure 5-3 - Distribution of Gravel and Sand.mxd

Source: ESRI ArcGISOnline Shaded Relief

- Longview-Kelso Basin
- Model Domain Boundary
- Unconfined Aquifr Conditions
- Gravel Aquifer Boundary
- Areas Underlain by Only Sand Aquifer
- Areas Underlain by Gravel Aquifer

N

0 7,000

Scale: Feet

Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Distribution of Gravel and Sand Aquifers in Longview-Kelso Basin

December 2009

Figure 5.3

Path:Z:\Projects\Longview\Events\20091211_GW_Elev\20091211_GW_Elev_Shallow.mxd

Aerial Source: (c)2009 Microsoft Corporation

Legend

- Monitoring Well (Groundwater Elevation)
- Groundwater Contours (Dashed Where Approximate)

Note: Contours shown on this map represent the mean water level elevations from 9/12/09 to 9/24/09.

N

0 600 1,200

Scale: Feet

Contour Interval: 1.0 Foot

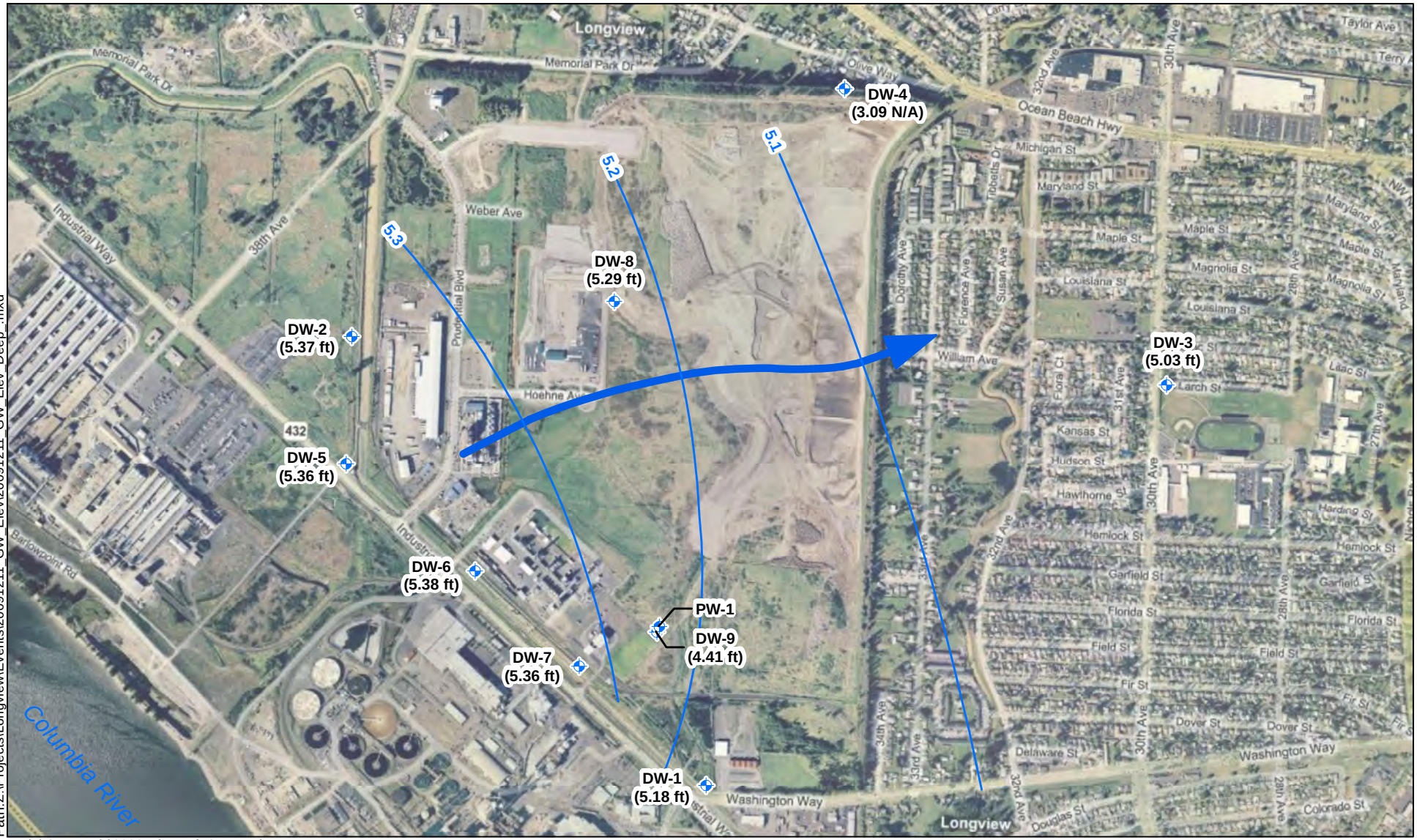
Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Shallow Aquifer Groundwater Map
September Mean Groundwater Elevations

KJ 0997003*00

Figure 5.4



Path:Z:\Projects\Longview\Events\20091211_GW_Elev\20091211_GW_Elev_Deep_.mxd

Chinook Ventures

Aerial Source: (c)2009 Microsoft Corporation

Legend

- Monitoring Well (Groundwater Elevation)
- Groundwater Contours
- Inferred Groundwater Flow Direction

Note: Contours shown on this map represent the mean water level elevations from 9/12/09 to 9/24/09.

N

0 600 1,200

Scale: Feet

Contour Interval: 0.1 Foot

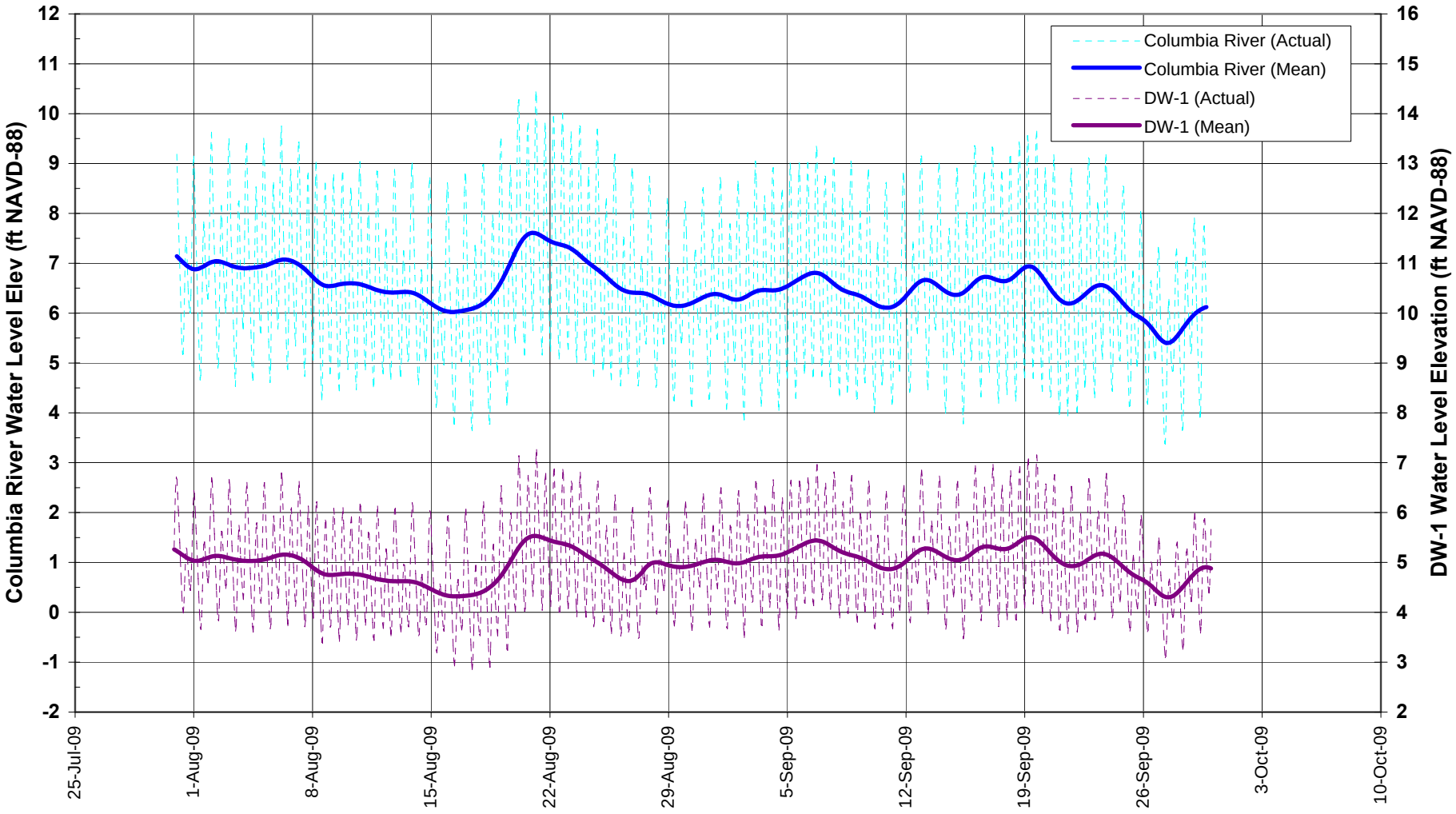
Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Deep Aquifer Groundwater Map
September Mean Groundwater Elevation

KJ 0997003*00

Figure 5.5



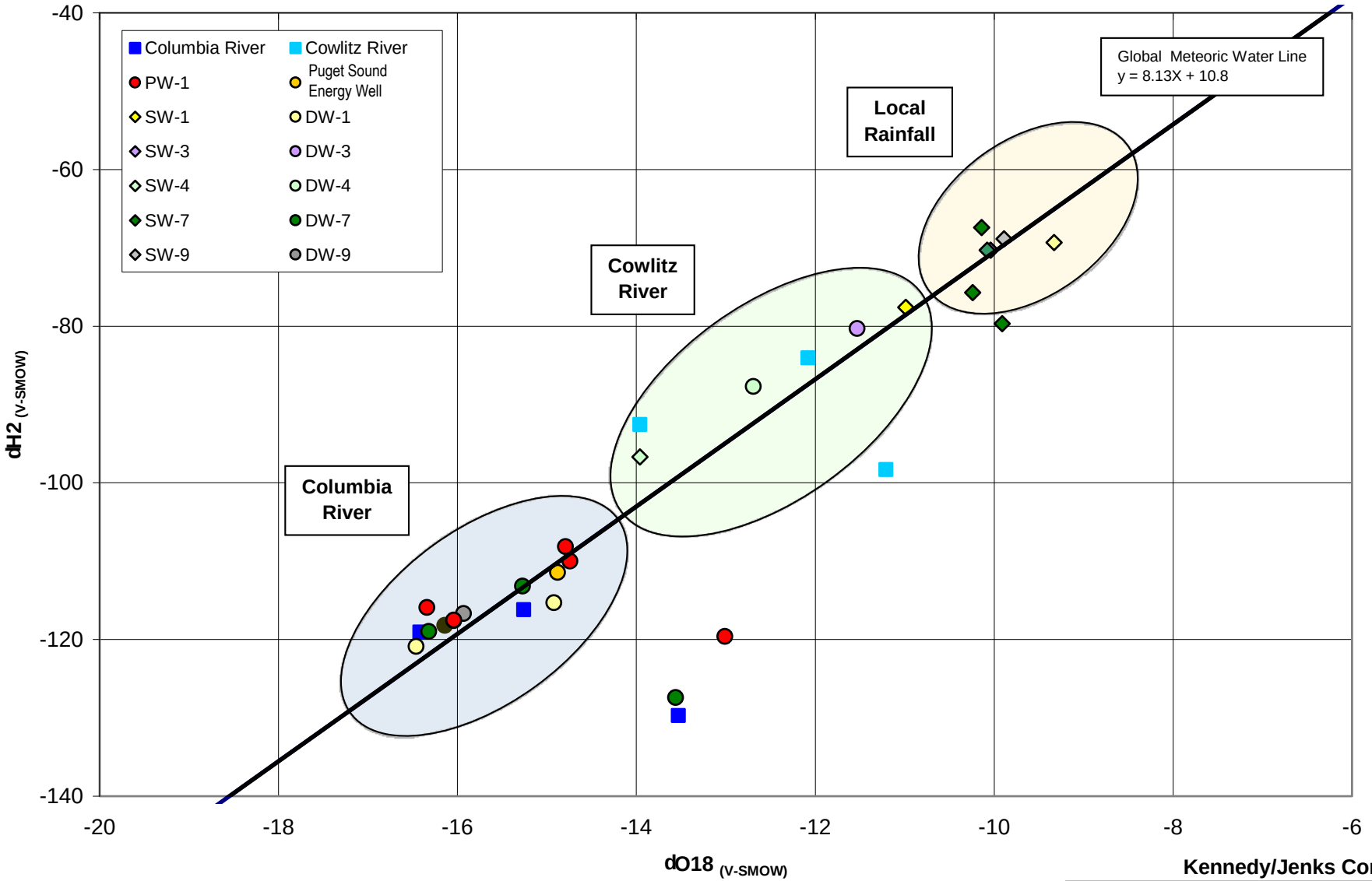
Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Columbia River and Sentinel Well DW-1 Water Level Elevations

KJ 0997003*00
December 2009

Figure 5.6



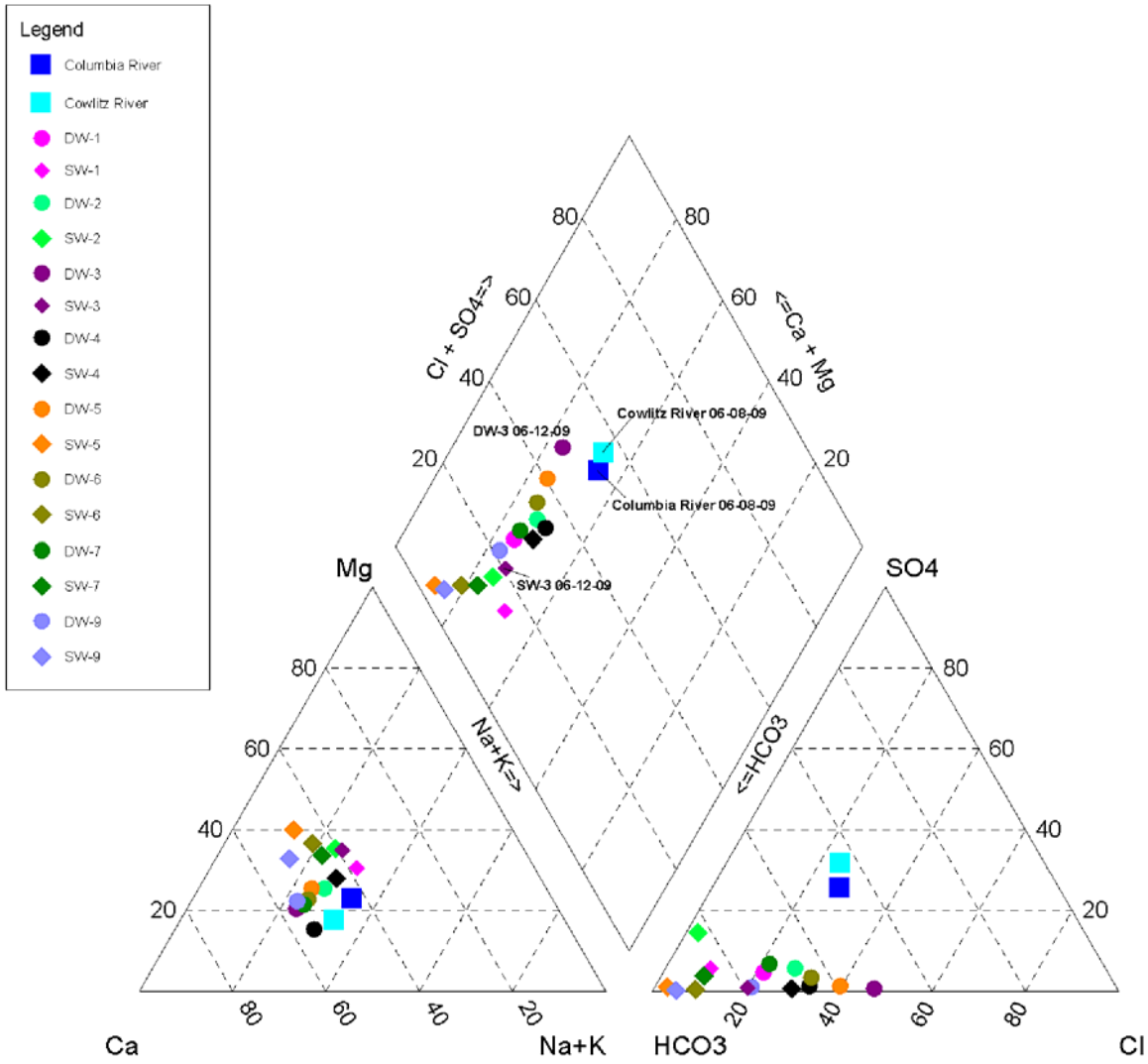
Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Groundwater and Surface Water
Deuterium vs Oxygen-18

KJ 0997003*00
December 2009

Figure 5.7



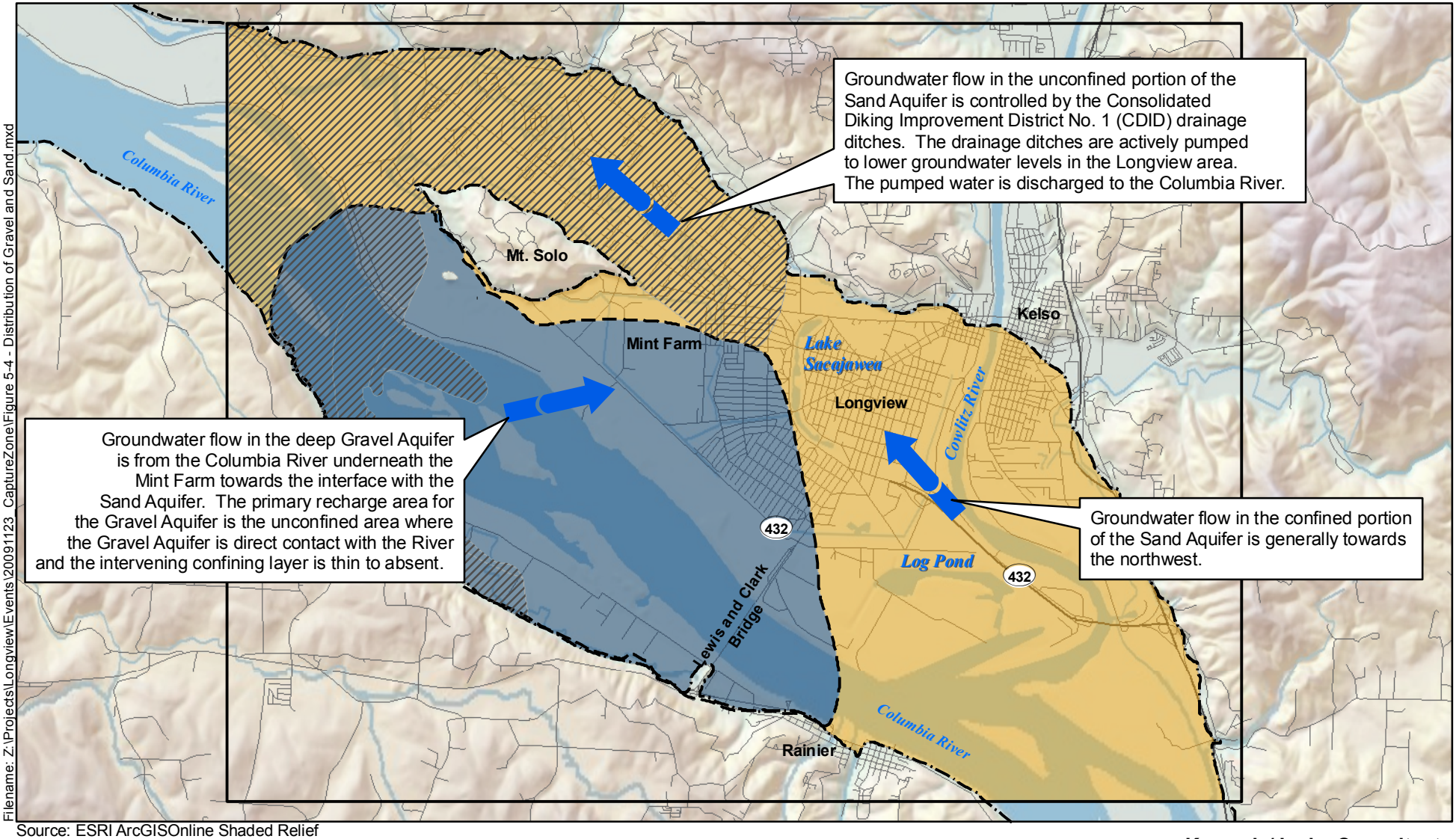
Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Trilinear (Piper) Plot

KJ 0997003*00
December 2009

Figure 5.8



Filename: Z:\Projects\Longview\Events\20091123_CaptureZone\Figure 5-4 - Distribution of Gravel and Sand.mxd

Source: ESRI ArcGISOnline Shaded Relief

Longview-Kelso Basin
Model Domain Boundary
Unconfined Aquifer Conditions
Gravel Aquifer Boundary
Areas Underlain by Only Sand Aquifer
Areas Underlain by Gravel Aquifer

N

0 7,000
Scale: Feet

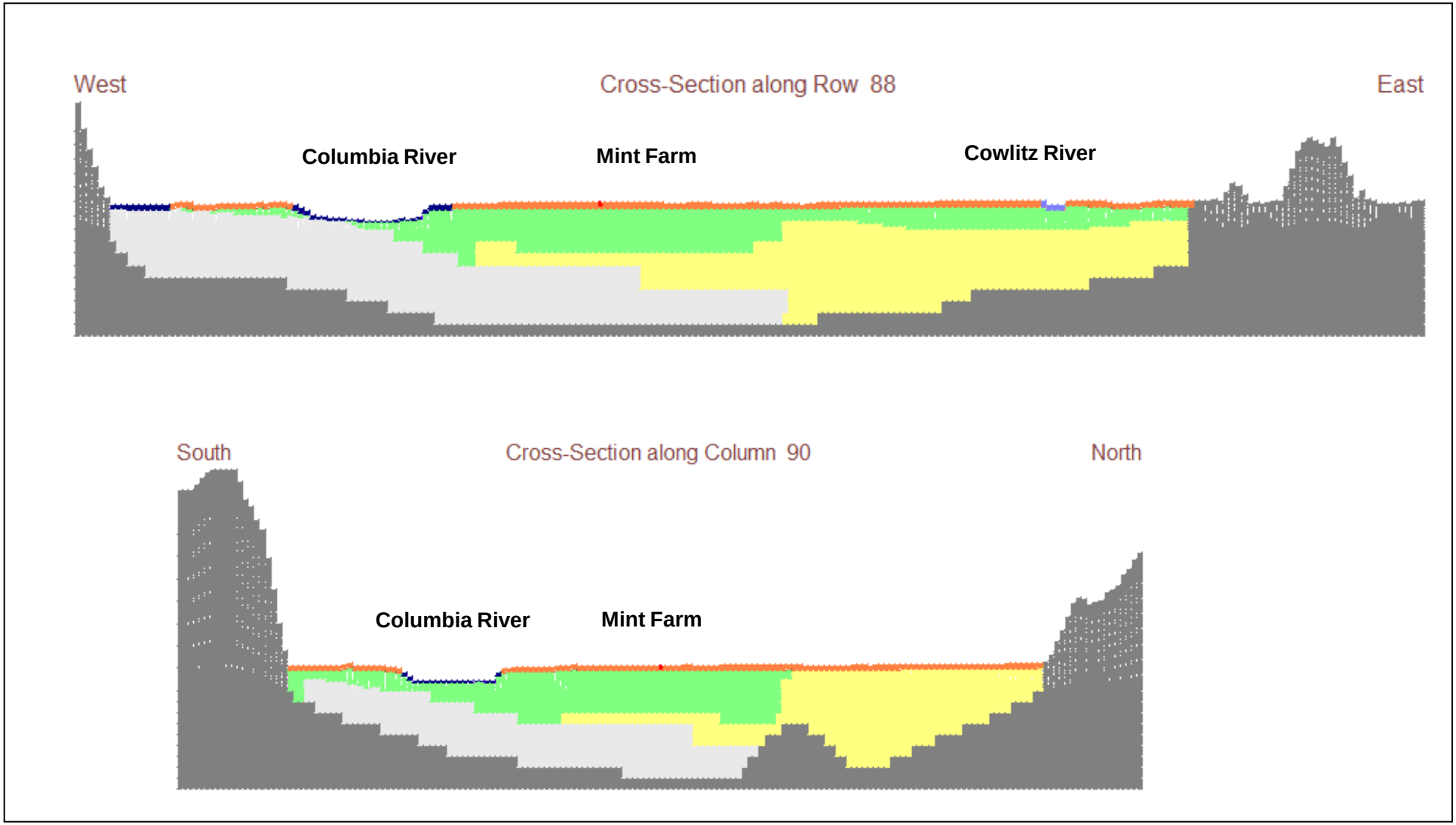
Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Conceptual Groundwater Flow in Deeper Aquifer in the Longview-Kelso Basin

December 2009

Figure 5-9



Legend

- Bedrock
- Surficial silt/sand
- Silt/clay
- Sand
- Gravel

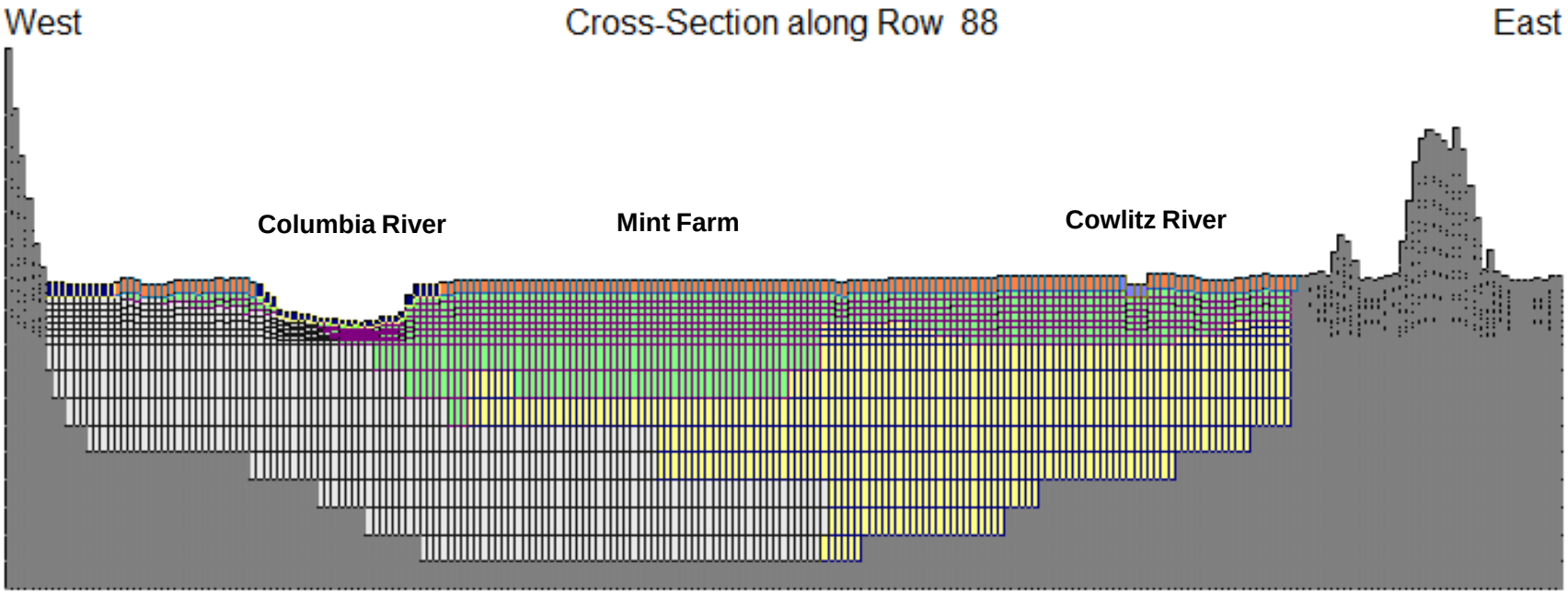
Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Model Cross Sections

KJ 0997003*00
December 2009

Figure 6.1



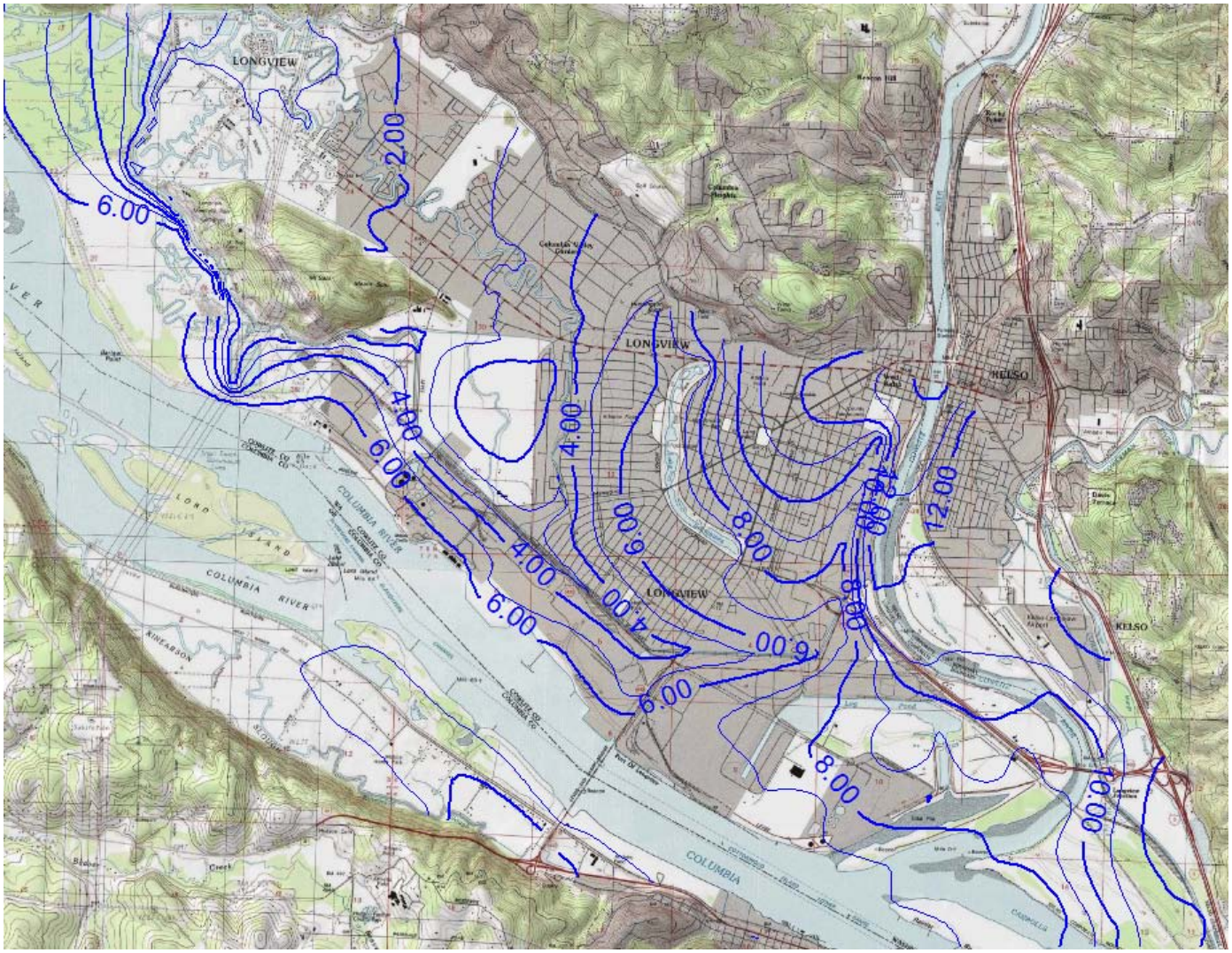
Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Cross Section Showing Grid and Layers

KJ 0997003*00
December 2009

Figure 6.2



Legend

Line of equal simulated hydraulic head (feet)

N

0 3750 7500

Scale: Feet

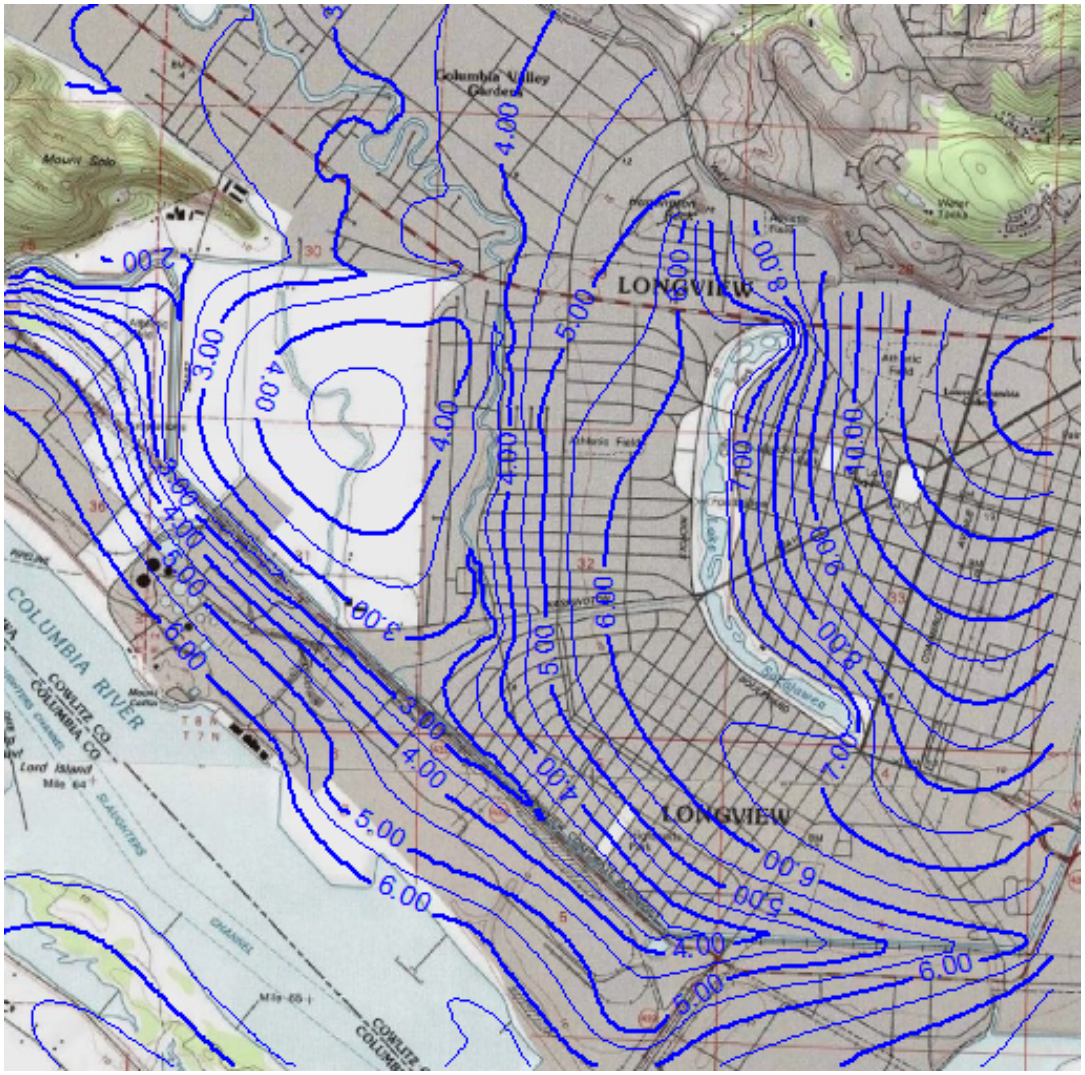
Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Simulated Hydraulic Heads, Shallow

KJ 0997003*00
December 2009

Figure 6.3



Legend

Line of equal simulated hydraulic head (feet)

N

0 2250 4500

Scale: Feet

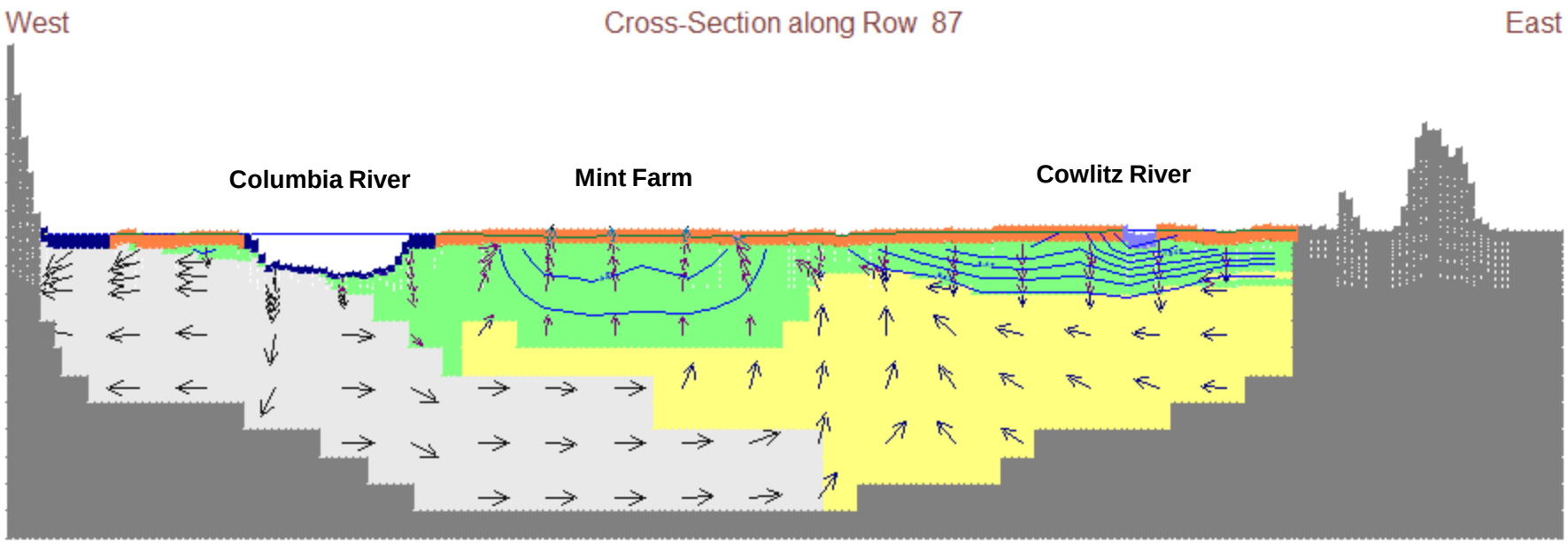
Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Close-up of Figure 6.3

KJ 0997003*00
December 2009

Figure 6.4



Legend

Line of equal simulated hydraulic head (feet)

Groundwater flow direction

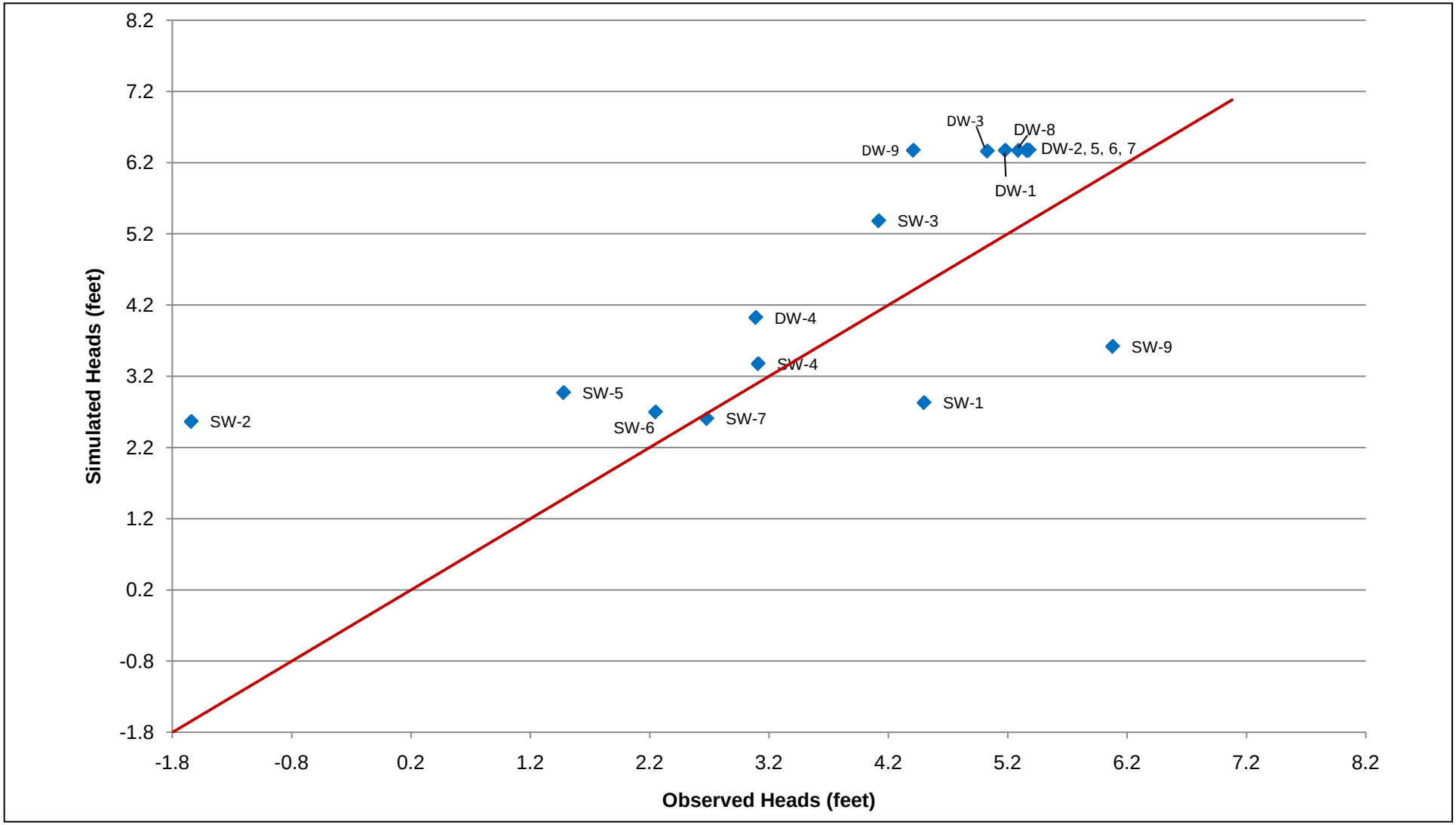
Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Simulated Hydraulic Heads & Flow Vectors

KJ 0997003*00
December 2009

Figure 6.5



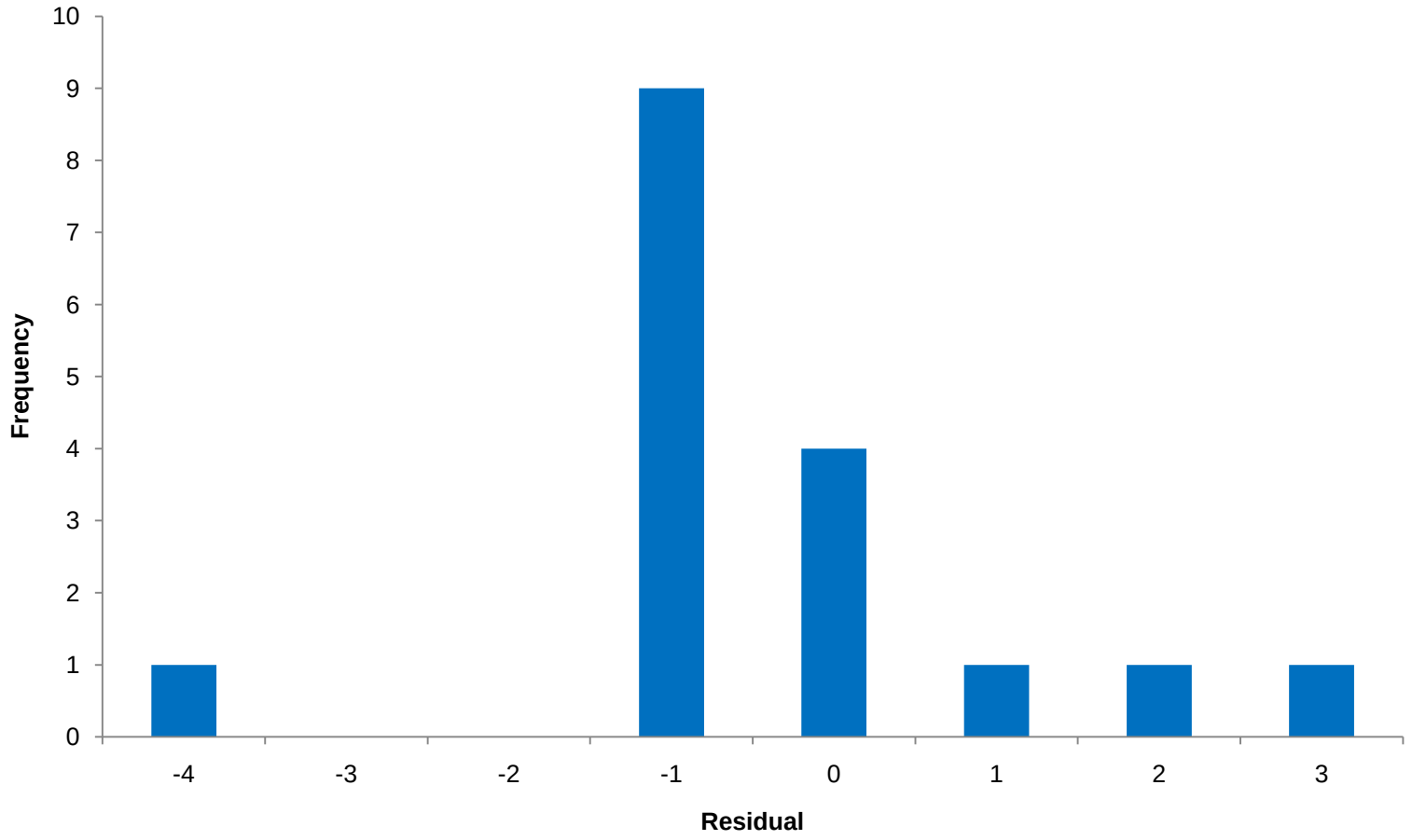
Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Base Case Observed vs. Simulated Heads

KJ 0997003*00
December 2009

Figure 6.6



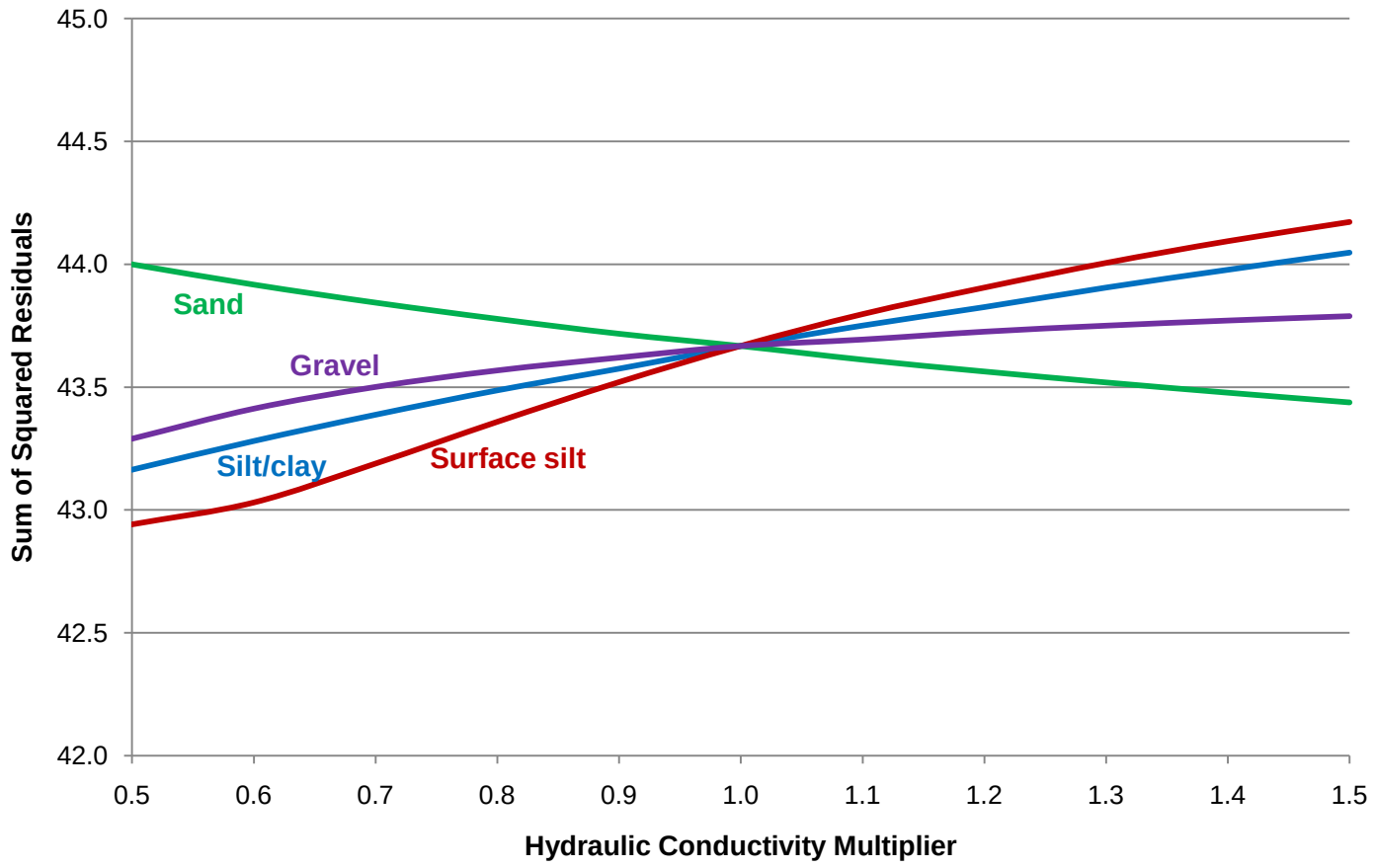
Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Distribution of Residuals

KJ 0997003*00
December 2009

Figure 6.7



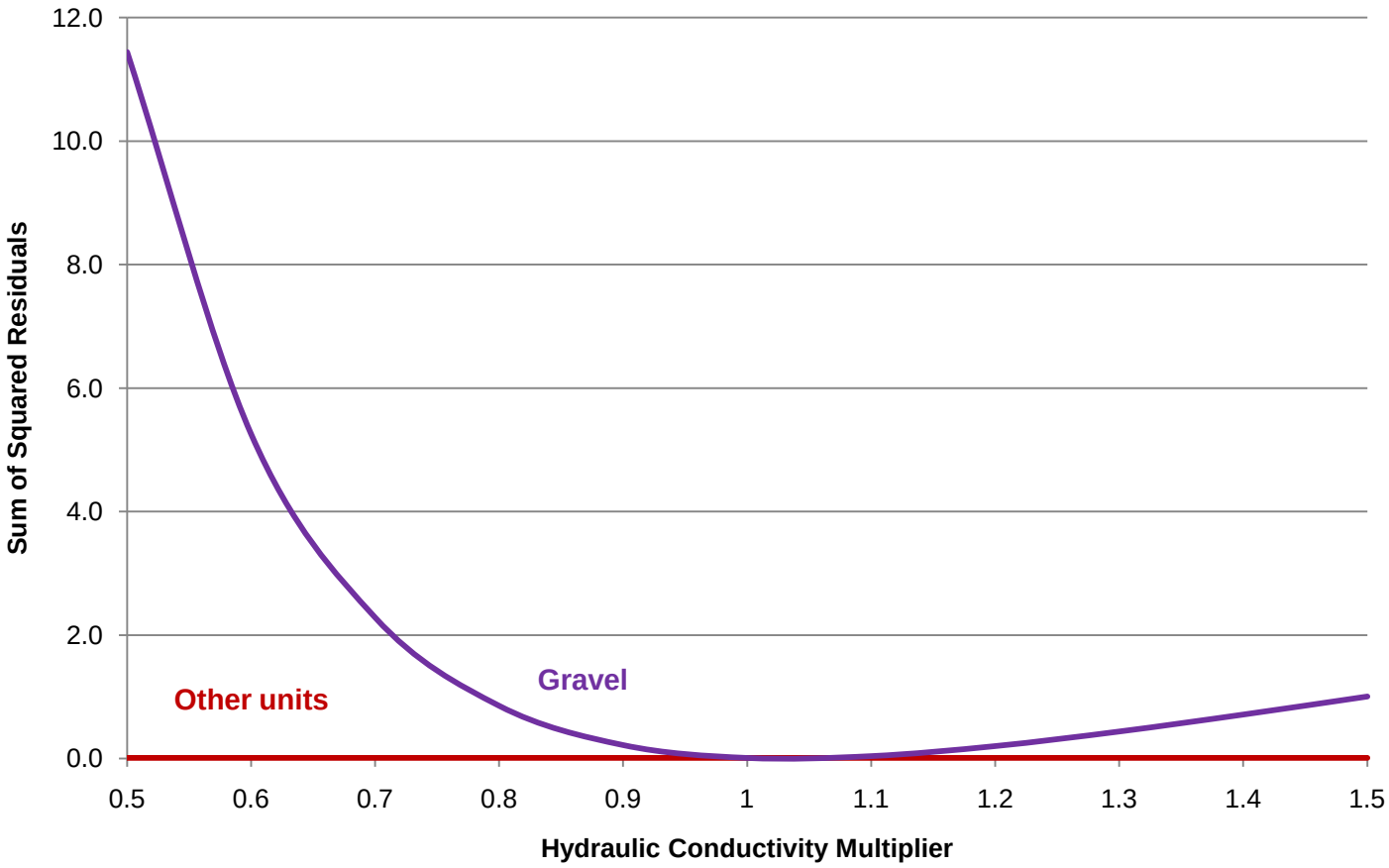
Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Base Case Sensitivity Analysis

KJ 0997003*00
December 2009

Figure 6.8



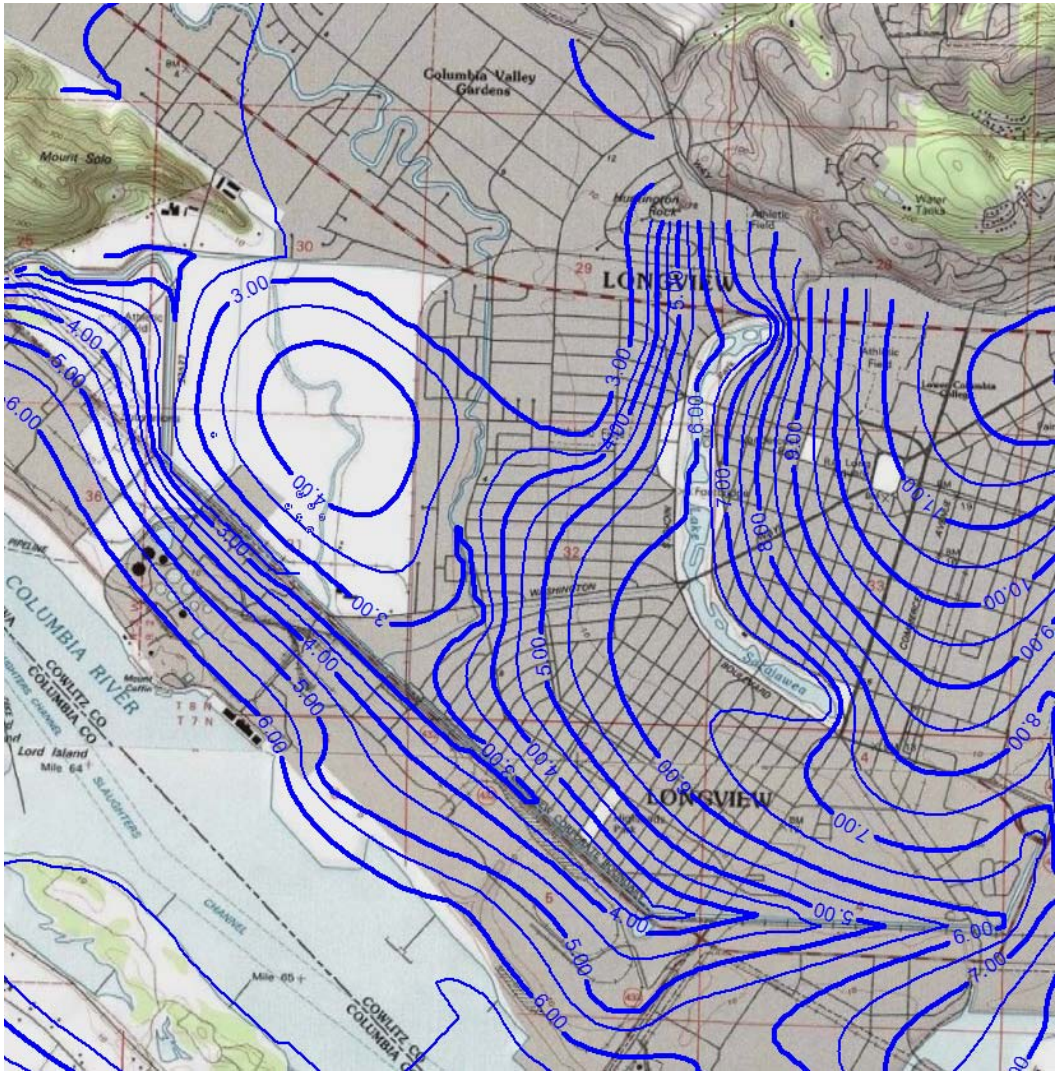
Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Pumping simulation Sensitivity Analysis

KJ 0997003*00
December 2009

Figure 6.9



Legend

Line of equal simulated hydraulic head (feet)

N

0 2250 4500

Scale: Feet

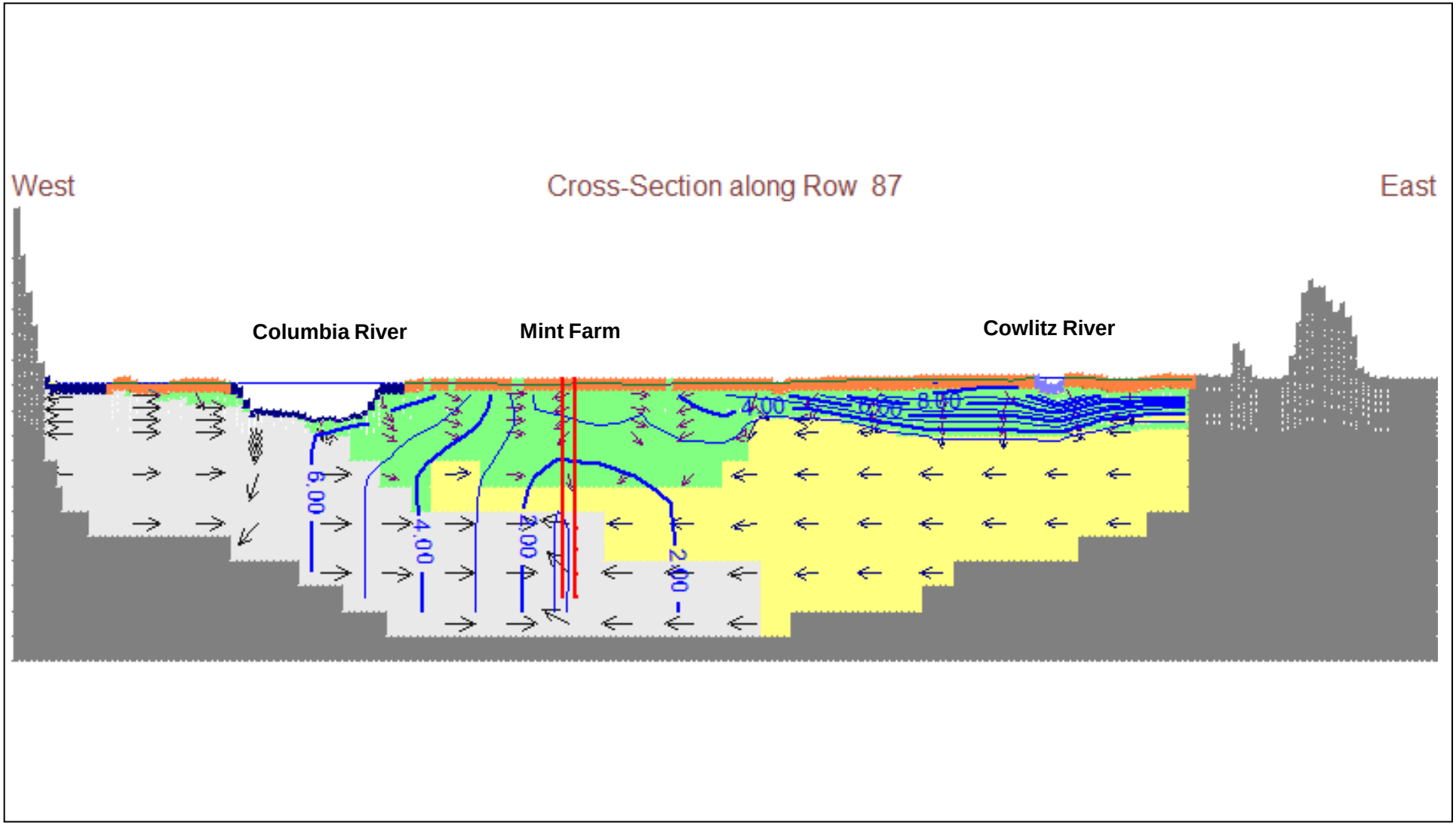
Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Shallow Hydraulic Heads – 12 MGD

KJ 0997003*00
December 2009

Figure 6.10



Legend

Line of equal simulated hydraulic head (feet)

Groundwater flow direction

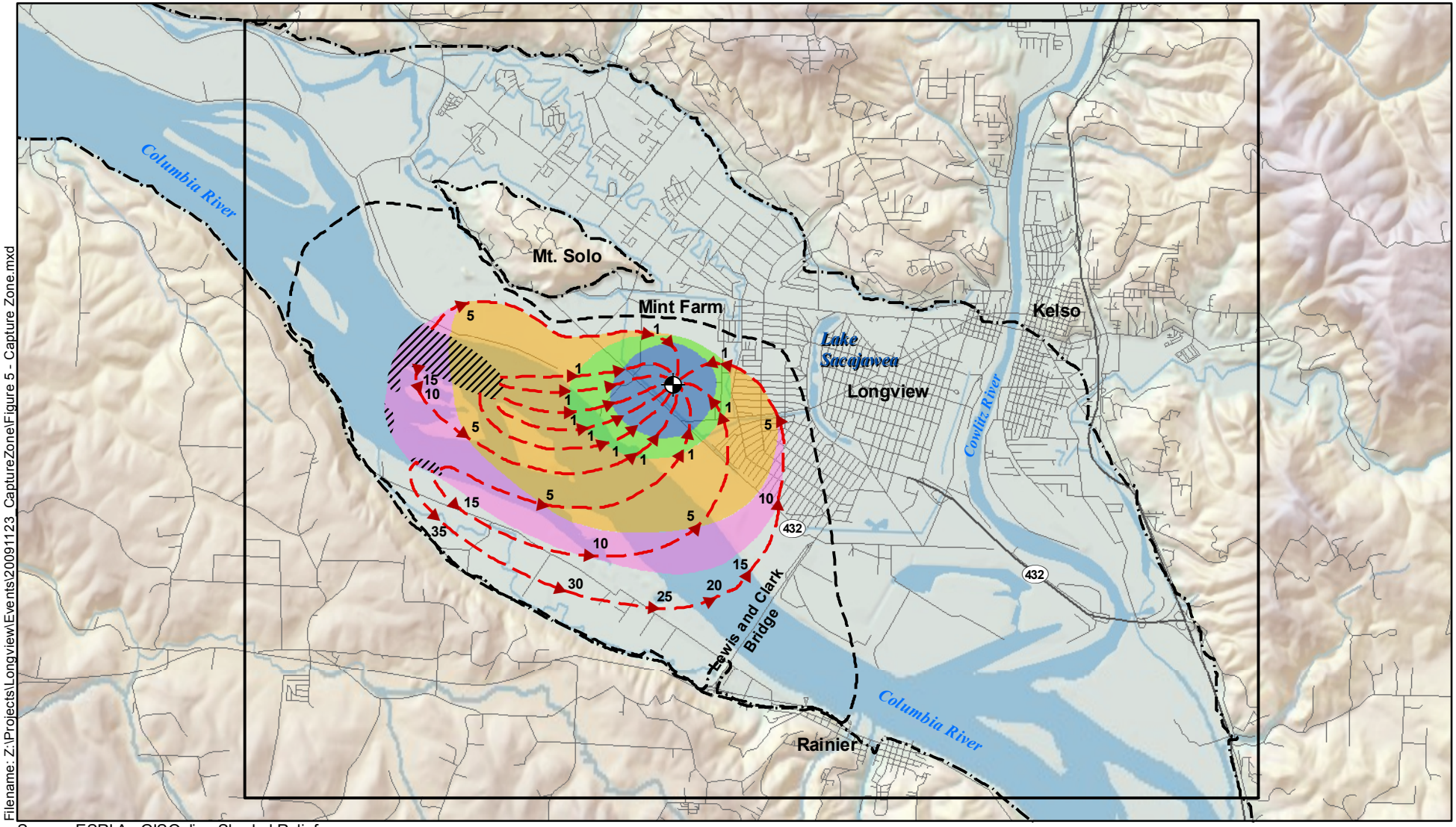
Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Simulation Results – 12 MGD

KJ 0997003*00
December 2009

Figure 6.11



Filename: Z:\Projects\Longview\Events\20091123_CaptureZone\Figure 5 - Capture Zone.mxd

Source: ESRI ArcGISOnline Shaded Relief

Legend

- Wellfield
- Gravel Aquifer Flow Path
- 20 Flow Direction Arrow with Years of Travel to Mint Farm Wellfield
- Longview-Kelso Basin
- Extent of Study Area
- Gravel Aquifer Boundary
- Unconfined Aquifer Conditions
- 6-Month WHPP Source Area
- 1-Year WHPP Source Area
- 5-Year WHPP Source Area
- 10-Year WHPP Source Area

N

0 7,000

Scale: Feet

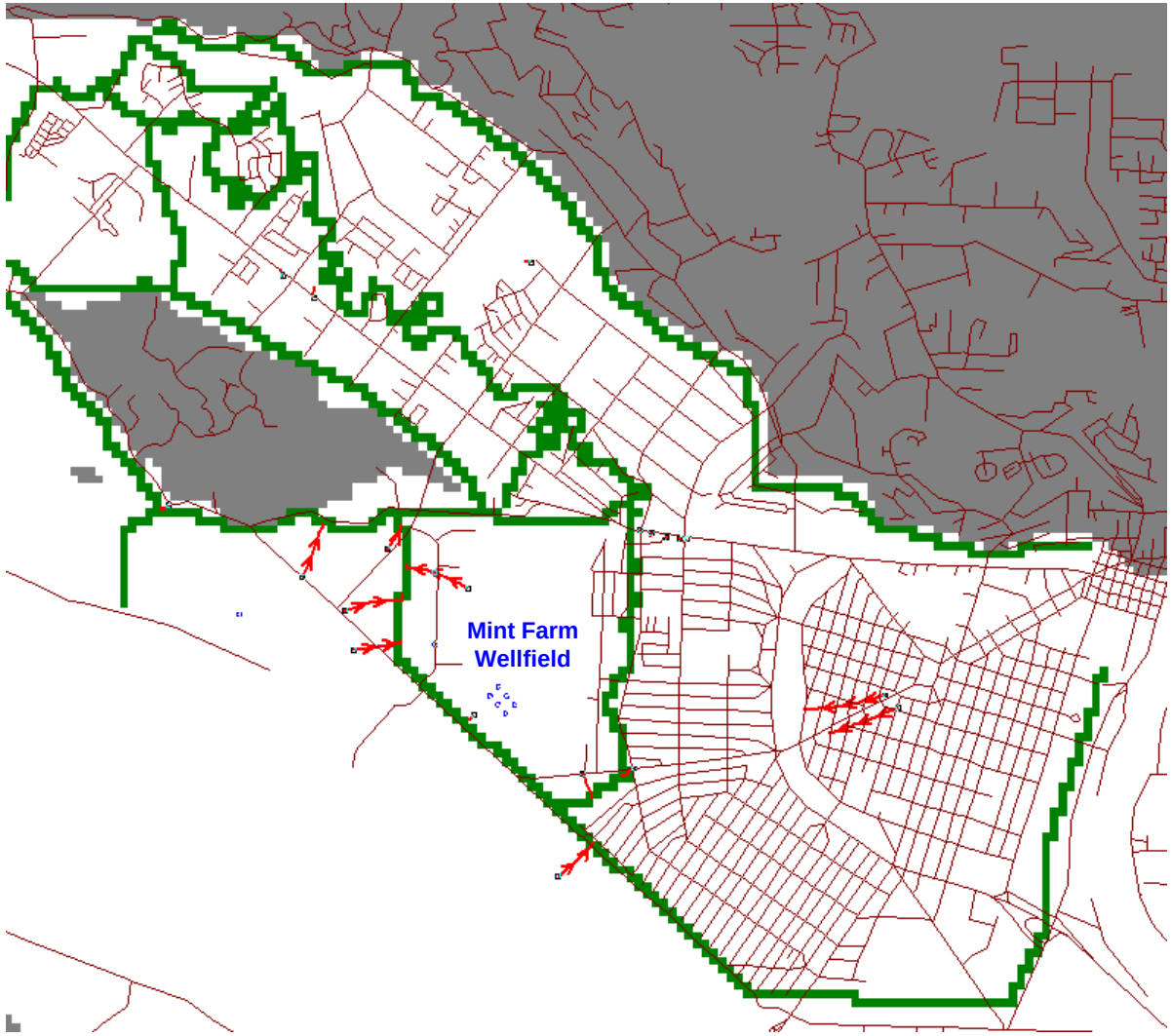
Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Delineation of Source Area for the Mint Farm Wellfield

December 2009

Figure 6.12



Legend

CDID drainage ditch

Groundwater flow path

N

0 2250 4500

Scale: Feet

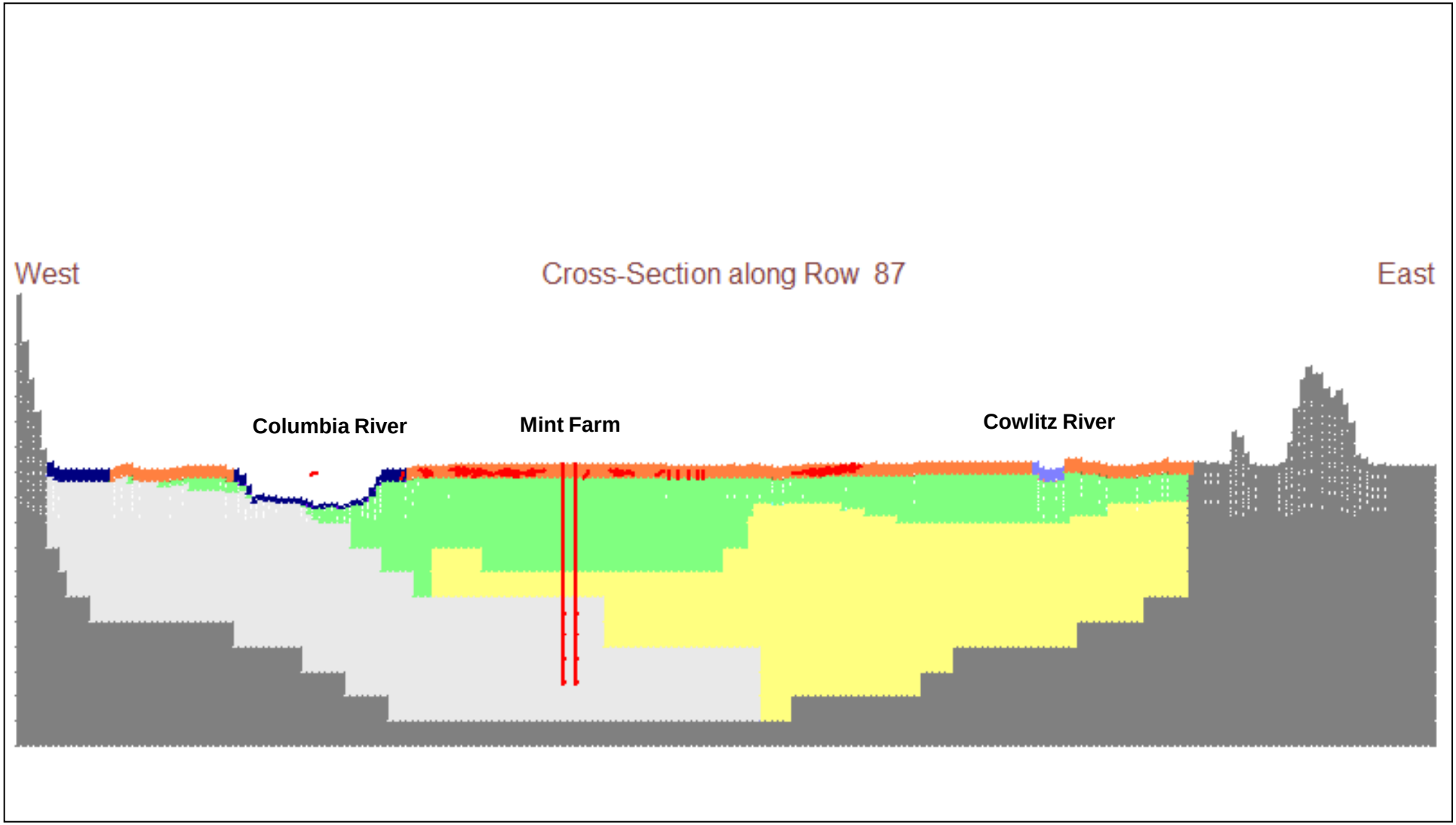
Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Pathlines from PCAs after 30 Years

KJ 0997003*00
December 2009

Figure 6.13



Legend

Groundwater flow path

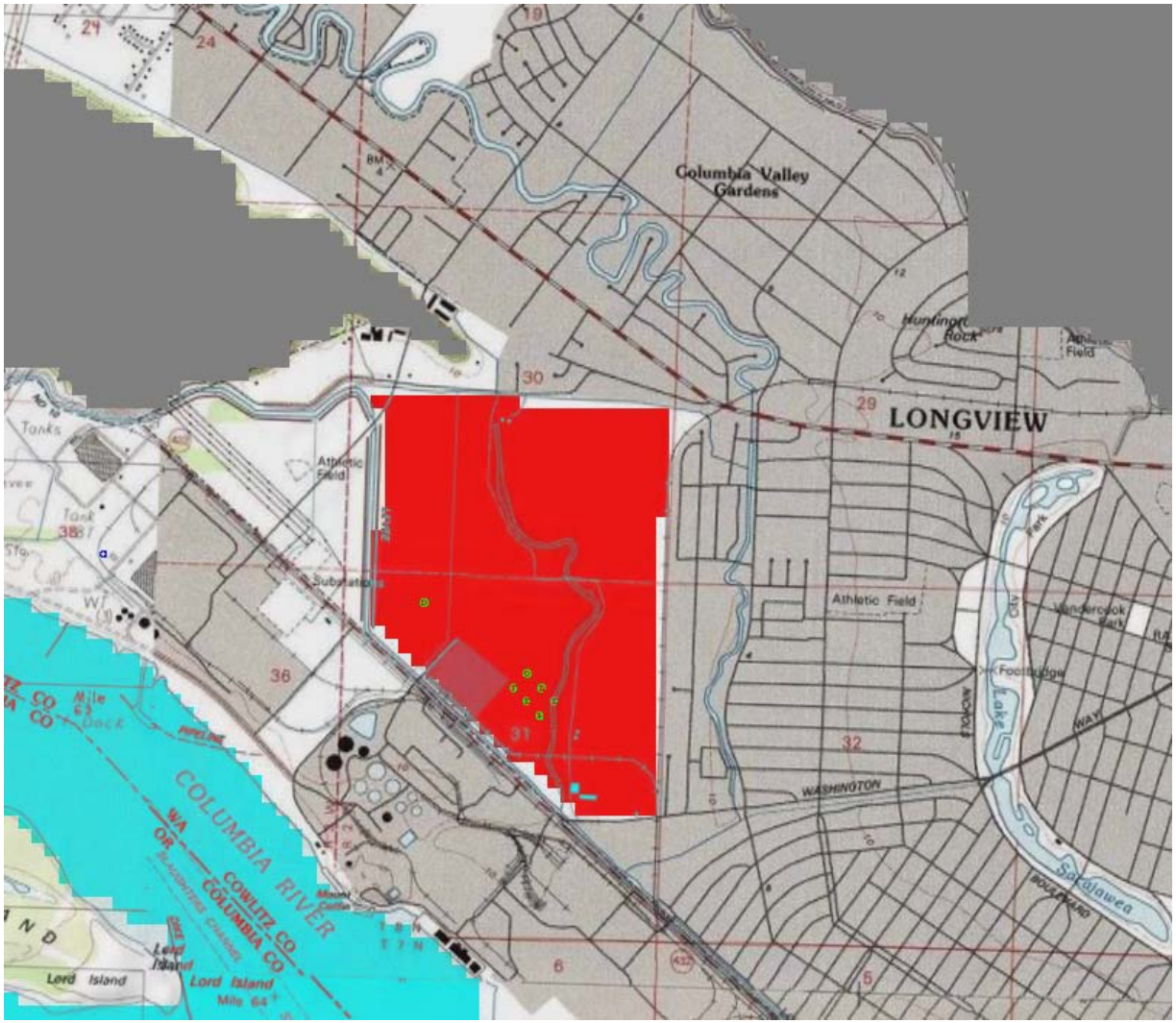
Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Pathlines from PCAs after 30 Years

KJ 0997003*00
December 2009

Figure 6.14



Legend

Hypothetical contamination area

N

0 2250 4500

Scale: Feet

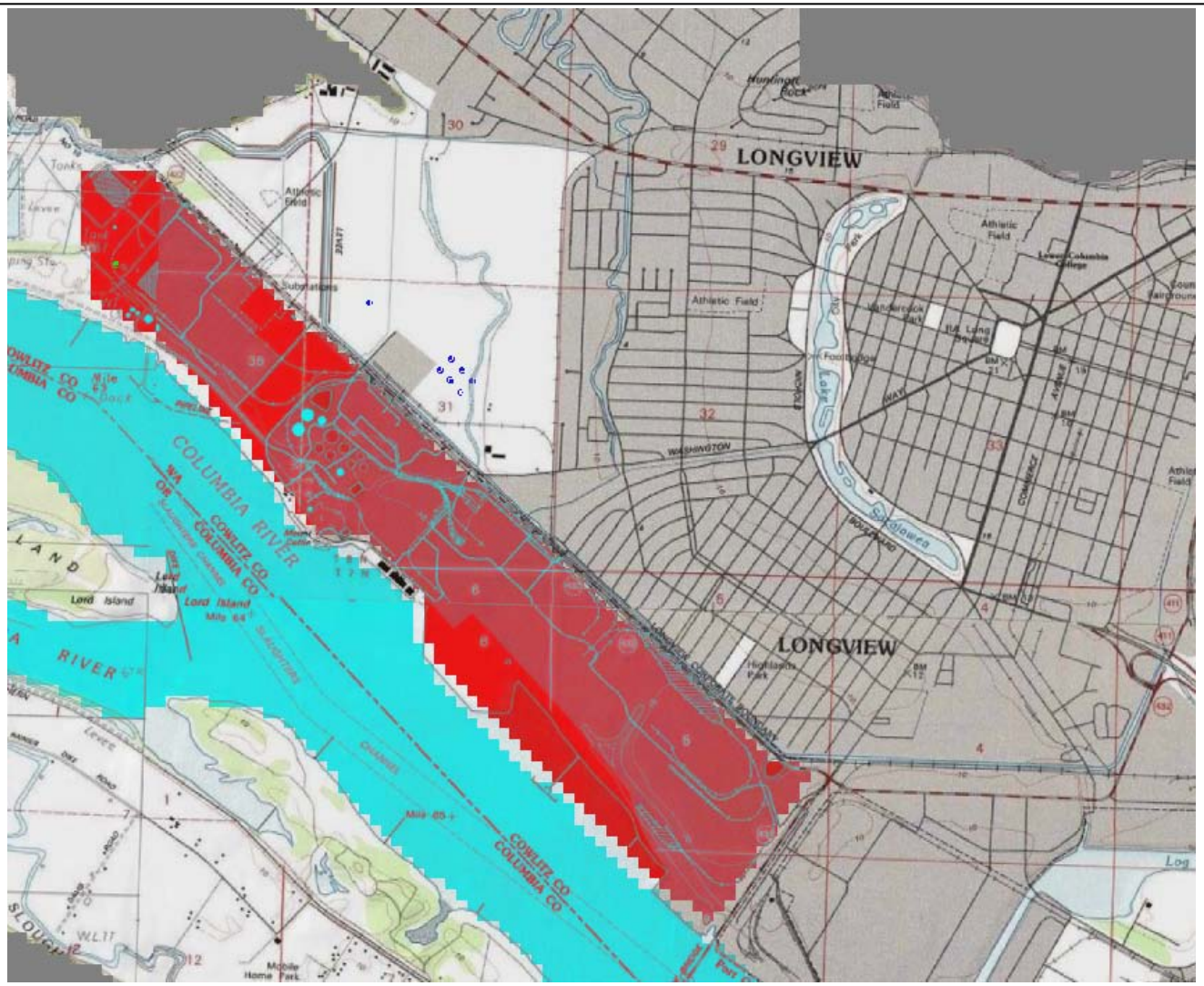
Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Hypothetical Contamination Scenario A

KJ 0997003*00
December 2009

Figure 6.15



Legend

Hypothetical contamination area

N

0 2250 4500

Scale: Feet

Kennedy/Jenks Consultants

Mint Farm RWTP Design
Longview, Washington

Hypothetical Contamination Scenario B

KJ 0997003*00
December 2009

Figure 6.16