Evaluation of Sea Level Rise on Groundwater in Downtown Olympia, WA

Olympia, Washington

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Executive Summary

The City of Olympia, Port of Olympia, and the LOTT Clean Water Alliance (collectively, the "Project Partners") collaborated to develop a Sea Level Rise (SLR) Response Plan for Olympia, Washington. The SLR Response Plan provides a shared strategy for the partners to prepare for and adapt to overland flooding due to SLR in downtown Olympia. This report presents an evaluation of SLR on groundwater in the planning area using a numerical groundwater model, which is a simplified simulation of a complex hydrogeological system. The model was designed to provide a decision-making tool for specific concerns related to groundwater rise due to SLR.

The primary conclusions from this evaluation include:

- Groundwater levels around Capitol Lake are predicted to lower by over 4.5 feet after the Capitol Lake Estuary Restoration Project is completed. This effect will radiate across the southwestern project area, with diminishing impact as distance from the lake's shoreline increases. The lowered groundwater levels will help to mitigate the impacts from groundwater rise due to SLR in this area.
- Routine dewatering at LOTT's Budd Inlet treatment Plant (BITP) contributes to lower groundwater levels in proximity to the plant and this influence is expected to grow as SLR increases.
- Shallow groundwater (i.e., less than two feet below surface grade) will become increasingly common in Olympia's downtown commercial core with SLR.
- The possibility of surface water ponding across Olympia's downtown commercial core increases as SLR exceeds 36 inches. Significant areas of the downtown core may experience surface water ponding at 60 inches of SLR, with substantial coverage at 68 inches of SLR.[1]
- Rising groundwater levels due to SLR won't significantly impact shoreline barrier construction, as long as inland surface water ponding is taken into account and sheet piling walls are not used (sheet piling walls can impede groundwater flow).

The primary recommendations from this evaluation include:

- Conduct a visual stormwater line survey in downtown Olympia to determine where groundwater is infiltrating the stormwater lines. Locating the infiltration points will increase the calibration of the model and reduce uncertainty regarding the impact of SLR on groundwater levels.
- Conduct a stormwater line survey in downtown Olympia to determine the location and depth of the stormwater lines and their outfalls. When a stormwater line becomes submerged in a low-lying area with groundwater seeps, surface ponding may occur. Knowing the top elevation of a gravity stormwater line that drains groundwater will allow the determination of the magnitude of sea level rise that will submerge the drain and cause it to stop functioning.
- Revise this groundwater evaluation taking into account the locations of infiltration into the stormwater lines and the elevations of outfalls.
- Conduct an engineering evaluation to determine if the predicted increases in groundwater levels could significantly impact subsurface utilities.

[1] Lift stations would enable stormwater lines to continue to drain groundwater and minimize ponding in low lying areas

Professional Certification

This document is, to the best of my knowledge and belief, true, accurate and complete. I hereby certify that I was in responsible charge of the work performed for this document that was associated with my certifications.

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List of Acronyms

Acronym	Definition / Description
ARM	Absolute residual mean
b	Aquifer thickness
BITP	Budd Inlet Treatment Plant
BNR	Biological Nutrient Removal
City	City of Olympia
CH	Constant Head Boundary
ft	Foot or Feet
HFB	Horizontal Flow Barrier
K_h	Horizontal hydraulic conductivity
MWs	Groundwater monitoring wells
LOTT	LOTT Clean Water Alliance
msl	Mean sea level
NGVD	National Geodetic Vertical Datum
Port	Port of Olympia
RMSE	Root mean squared error
SLR	Sea Level Rise
S_c	Storage coefficient
S_s	Specific storage
S_y	Specific yield
T	Transmissivity
USGS	United States Geological Survey

SECTION 1: INTRODUCTION

The City of Olympia (City), Port of Olympia (Port), and the LOTT Clean Water Alliance (LOTT; collectively referred to as the "Project Partners") worked together to develop a Sea Level Rise (SLR) Response Plan (AECOM 2019). The Olympia SLR Response Plan focuses on the downtown peninsula and upland areas that are susceptible to surface water flooding from Budd Inlet and the Deschutes River (see Figure 1-1). The project area encompasses the downtown peninsula from the eastern shoreline of the 4th Avenue Bridge in West Bay to the intersection of East Bay Drive and Olympia Avenue in East Bay. The planning area includes the Capitol Lake/Lower Deschutes Watershed shoreline along Heritage Park. The southern boundary of the planning area reaches to uplands on the southern side of downtown. The entire Port property and the LOTT Budd Inlet Treatment Plant (BITP) are included. This area includes the key publicly-owned infrastructure and services of the urban corridor.

The Olympia SLR Response Plan includes a variety of physical, operational, governance, and informational strategies to prepare for and respond to the impacts of the sea level rise in downtown Olympia. Examples of some of the physical adaptation strategies include raising landscaping and constructing raised shoreline barriers to prevent SLR enhanced high tides from overtopping the shoreline and flooding downtown streets and low-lying areas.[2]

This report presents an evaluation of SLR on groundwater in the project area using a numerical groundwater model. The groundwater model is a simplified simulation of a complex hydrogeological system. The model was designed to provide a decision-making tool for the following specific concerns related to groundwater rises due to SLR:

- Surface water ponding due to daylighting groundwater
- Construction impacts from groundwater on proposed adaptation measures (i.e., raised shoreline barriers)
- Impacts to buried storm and sewer lines.

1.1 Scope of Work

The scope of the work completed for this report included:

- Gathering information on shallow groundwater monitoring wells (MWs) in the project area and identifying accessible MWs (see Figure 1-2)
- Conducting groundwater elevation gauging events
- Developing a conceptual understanding of hydrogeology in the project area
- Constructing and calibrating a groundwater flow computer model using Groundwater Vistas as a graphical user interface with MODFLOW-2005 (Environmental Simulations, Inc 2020; Harbaugh 2005).

[2] This evaluation does not cover the effectiveness of raised shoreline barriers in protecting against surface water floods caused by SLR-enhanced water bodies (such as SLR-enhanced king tides in Budd Inlet and Capitol Lake). However, raised shoreline barriers are commonly and effectively used around the world to protect against surface water flooding.

- Using the calibrated model to simulate groundwater rises due to 24-, 36-, 48-, 60- and 68-inches of SLR.[3]

[3] The evaluated levels of SLR are based on the Olympia SLR Response Plan's selection of 24- and 68 inches of SLR to guide mid-term and long-term SLR response actions.

SECTION 2: BACKGROUND INFORMATION

This section presents background information for the vicinity of the downtown peninsula and the shallow groundwater bearing layer.

2.1 Topography and Fill History

The topography of the Olympia region is largely influenced by historical land reclamation efforts. The entire peninsula north of downtown Olympia, a significant portion of the downtown area itself, and the BITP are situated on flat land created by fill material starting in the late 1800s (PIONEER 2010). This fill area is bordered to the south and southeast by topographic rises of primarily glacial till (see Figure 2-1).

Figure 2-2 (Thurston Regional Planning Council 2010) illustrates Olympia's original, pre-development shoreline. The majority of the fill material is sediment dredged from Budd Inlet during civic improvement projects aimed at expanding shipping channels and increasing urban land (Stevenson 1982). The most extensive dredging occurred from 1909 to 1911, when over 2 million cubic yards of sediment were used to create 29 blocks of land north of Olympia Avenue (Stevenson 1982). Smaller-scale dredging and land reclamation projects continued from 1924 into the 1970s (Stevenson 1982). The current shoreline was established by the final fill event in 1982 (Stevenson 1982; PIONEER 2010).

2.2 Climatological Setting

Olympia is located within Western Washington, which is typified by relatively mild temperatures and a marine-influenced climate (Western Regional Climate Center 2023). The average annual precipitation for Olympia is approximately 50 inches, with most precipitation falling between October and April (Thurston County 2013).

2.3 Geologic Setting

Fill thicknesses in the vicinity of the BITP are typically on the order of five to 20 feet (ft) (GeoEngineers and PIONEER 2008; Landau Associates 2009; PIONEER 2010). The fill material is generally light or dark sand, with some woody debris from historic lumber milling operations and construction debris. Native fine sands are the predominant soil type underneath the fill material (GeoEngineers and PIONEER 2008; Landau Associates 2009; PIONEER 2010). Underneath the native fine sands is a low permeability silt and clay aquitard. This aquitard, which is the regional confining layer that creates artesian groundwater conditions in Olympia, is estimated to be at least 30 ft thick in the vicinity of the BITP (GeoEngineers and PIONEER 2008; Landau Associates 2009).

2.4 Hydrogeologic Setting

The upper limit of the shallow groundwater bearing layer is defined by the ground surface. The upper portion of the layer consists of fill and the lower portion consists of native fine sands. The bottom of the shallow groundwater bearing layer is defined by the top of the underlying aquitard. The shallow groundwater layer is represented in the groundwater model and is discussed in Section 3.3. Insufficient

information is known about the underlying aquitard and confined artesian aquifer that produce artesian conditions in the Olympia downtown area, making it unfeasible to include them as layers in the model.

2.5 Aquifer Properties

In a steady-state groundwater system, where inflows equal outflows, the fundamental aquifer property controlling groundwater flow is horizontal hydraulic conductivity (K_h), which is in units of length/time. In a transient groundwater system, where there is either a gain or loss of groundwater in storage, the aquifer storage, which is defined by the specific yield (S_y) for a water table system, and the specific storage (S_s) for a confined aquifer system, also become important. S_y is the volume of water removed per unit area of aquifer per unit decline in groundwater elevation (e.g., cubic ft per square ft per ft or dimensionless). S_s is the volume of water removed per volume of aquifer per unit decline in groundwater elevation (e.g., 1/ft). Both S_y and S_s are volume-specific properties, meaning that they are 3-dimensional properties of the aquifer. The volume of aquifer that the particular value applies to is a function of the scale of the test used to estimate them. For example, a laboratory test on a core sample may provide a value applicable to approximately 0.2 cubic ft (ft^3) of aquifer, whereas an aquifer test may provide a value applicable to thousands of ft^3. When values for these parameters are averaged over a specific thickness of aquifer material, their depth-averaged or 2-dimensional form is used. For K_h this becomes transmissivity (T), which equals K_h times the aquifer thickness (b) and is in units of ft^2/day. For S_s this becomes the storage coefficient (S_c) or S_s times b, which is dimensionless.

Because the feasible range of values of aquifer storage is so much smaller than for K_h, K_h is the most important aquifer parameter in the majority of groundwater models. Groundwater flow models are typically calibrated to water levels by modifying K_h values.

Site specific MW slug tests in the vicinity of the BITP indicate that the K_h ranges from approximately 1.4 to 14 ft/day (Brown and Caldwell 2017). This is in the middle of the range of published values of K_h for silty sand (Freeze and Cherry 1979).

Because the uppermost groundwater-bearing zone would be considered an unconfined aquifer, the storage value would be defined by the S_y. Appropriate bulk S_y values may range from 0.10 to 0.20, with extremes of <0.05 to 0.30 being found in subunits (Morris and Johnson 1967).

SECTION 3: NUMERICAL GROUNDWATER MODEL

A groundwater flow model was developed to simulate groundwater rises in the shallow groundwater layer due to 24-, 36-, 48-, 60- and 68 inches of SLR. The model code used to simulate the system was MODFLOW-2005, a three-dimensional groundwater modeling software designed for the simulation of porous media. MODFLOW was developed by the United States Geological Survey (USGS; Harbaugh 2005) and uses block-centered, finite-difference techniques to simulate groundwater flow within an aquifer system. Groundwater Vistas (Environmental Simulations, Inc. 2020), in conjunction with ArcGIS (Geographic Information System software), was used as a pre- and post-processor to facilitate the development of input files for model parameters and facilitate analysis of the output.

Groundwater flow modeling has two primary phases. The initial phase focuses on developing a calibration model. This is achieved by adjusting model input parameters to simulate observed field conditions as accurately as possible. The second phase involves creating predictive models based on the calibrated model. In this phase, model input parameters are modified to reflect predicted changes. For instance, to simulate SLR, the shoreline's surface water level in the predictive model is raised from the current surface level by the predicted amount of SLR.

This section details the groundwater model construction parameters, which are also summarized in Table 3-1. Section 4 discusses model calibration and Section 5 presents the predictive models.

3.1 Model Units

Inputs and parameters for MODFLOW numerical models must use consistent units of length, volume, and time. This is essential for accurate calculations of head (groundwater elevation), velocity, and flux. The model's spatial coordinate system, aquifer properties, and aquifer flow are all expressed in units of feet or days.

3.2 Coordinate System

The model domain's horizontal coordinate system was based on the Transverse Mercator projection, North American Datum 1983, State Plane, Washington South, FIPS 4602. The vertical datum was based on NGVD 1988.

3.3 Model Domain and Layer

The model study area and grid domain are presented on Figure 3-1. The model grid measures 9,000 ft in the north/south direction and 4,500 ft in the east/west direction. Cell size is 10 by 10 ft and is uniform throughout the domain. The model domain is discretized into 900 rows by 450 columns. The active model domain was defined by the following features (see Figure 3-2): the northwest, north, and northeast boundaries follow the Budd Inlet shoreline, the southwest boundary follows the Capitol Lake shoreline, and the southern and southeastern boundaries are located on topographic rises south and southeast of downtown Olympia.

The model consists of one layer that represents the shallow groundwater bearing layer located in the vicinity of the Olympia downtown area. The top of the layer is the ground surface (see Figure 2-1) and the bottom of the layer is set to an elevation of minus 20 ft.[4] As is discussed in Section 2.4, little is known about the underlying aquitard and confined artesian aquifer that produce artesian conditions in the Olympia downtown area, making it unfeasible to include them as layers in the model.

3.4 Stress Periods

The model is made up of nine stress periods (see Table 3-2). The first two stress periods are steady state and are designed to allow the modeled groundwater elevations to reach theoretical groundwater elevations that existed before the groundwater drains were operating (see Section 3.9 for drain details). Stress periods 3 through 9 are transient and are designed to calibrate the model to observed groundwater elevations.

3.5 Hydraulic Parameters

3.5.1 Hydraulic Conductivity

The K_h value for the model was calculated during model calibration as 12 ft/day, which is within the upper range documented by Brown and Caldwell's well testing at BITP (2017; calibration is discussed in Section 4). Vertical K was assigned 1.2 ft/day, but is an unused parameter in one-layer models such as this one.

3.5.2 Specific Yield

Storage parameters were developed during calibration of the model. The model layer is defined as a MODFLOW Type 1 unconfined layer with a specific yield of 0.185 and a porosity of 0.25.

3.6 Recharge and Evapotranspiration

The active model domain consists of the downtown Olympia area, which is primarily covered with impervious surfaces (e.g., paved roads, buildings, parking lots) with a stormwater system that is designed to quickly remove precipitation from the area. This minimizes the ability of precipitation to recharge groundwater. In addition, the impervious surfaces and limited tree population significantly reduce evapotranspiration within the model domain.

Recharge in the model represents water entering the shallow groundwater bearing layer via two mechanisms: (1) upward migration of groundwater from the pressurized (artesian) lower confined layer and (2) precipitation infiltration. There is insufficient data on the lower artesian aquifer to model the lower confined artesian aquifer and it is likely recharged in an elevated area outside of the model domain. Recharge was calculated during the calibration of the model (see Table 3-2). Stress Periods 1, 2, 3, 5, 6, and 9 represent wet season conditions and Stress Periods 4, 7, and 8 represent dry season

[4] Ground surface elevation contours were generated using kriging interpolation of ground surface elevation points including the ground surface at the surveyed groundwater monitoring wells shown on Figure 1-2 and surveyed utility manhole rim elevations which are generally flush with the surrounding hardscape (e.g., paved surface). Anomalously high utility manhole rim elevations were determined by comparing manhole elevations to lidar surveys of the area, and were removed from the data set.

conditions. Recharge within the Cascade Pole Cleanup Site slurry wall was set to the dry season recharge value for all stress periods to simulate the Cascade Pole impervious surface cap and remedial groundwater pumping.[5] Evapotranspiration has not been applied to the model.

3.7 Constant Head Boundaries

Constant head boundaries (CHs) maintain the groundwater level at a specified level in the model cells they are assigned to. Constant head boundaries were applied along the shorelines of Budd Inlet and Capitol Lake and along the upland model boundaries (see Figure 3-3). The upland model CHs allow groundwater to flow into the model domain from adjacent upland areas. The upland model CHs remain the same in the calibration and SLR predictive models (see Table 3-1 for details). To simulate current conditions, CHs in the calibration model along the shorelines of Budd Inlet and Capitol Lake were set at elevations of 4.28 and 9 ft, respectively.[6] The planned Capitol Lake estuary restoration project is expected to remove the dam between Capitol Lake and Budd Inlet, which will result in the surface water level in Capitol Lake matching the surface water level of Budd Inlet (https://deschutesestuaryproject.org/). To simulate the post-Capitol Lake estuary restoration project water levels, a predictive model without SLR was developed with the constant heads along the shorelines of Budd Inlet and Capitol Lake set to 4.28 ft (see Section 5). The SLR predictive models simulate SLR by raising the Budd Inlet and Capitol Lake shoreline CHs by the level of SLR being simulated (e.g., 24-inches of SLR was simulated by raising the shoreline constant heads to 6.28 ft; see Table 3-1 and Section 5).

3.8 No Flow Boundaries

No flow boundaries are located along the perimeter of the domain where constant heads are not located (see Figure 3-3). Specifically, no flow boundaries are located in the following two locations: (1) the northern edge of the model between Budd Inlet and the eastern upland model boundary, and (2) the southwestern edge of the model between Capitol Lake and the CHs on the southern upland model boundary. No flow boundaries are not ideal as they do not allow water to move in or out of the model and do not represent natural groundwater flow conditions. However, these boundaries are located in areas where groundwater flow is close to parallel to the no flow boundaries, minimizing their negative impact on the model's simulation of groundwater conditions.

3.9 Dewatering Drains

Groundwater dewatering in downtown Olympia currently occurs via passive dewatering at the BITP (to prevent structural damage to infrastructure due to shallow groundwater levels) and via infiltration into

[5] The model's representation of groundwater flow at the Cascade Pole Cleanup Site is overly simplistic and the model should not be used to evaluate the northern area of the model domain in the vicinity of the Cascade Pole Cleanup Site.

[6] Groundwater levels along shorelines are generally the same as the surface water level at the shoreline. Budd Inlet Mean Tide Level and Capital Lake Typical Water Level are from the Olympia Sea Level Rise Response Plan (March 2019).

the Chestnut Street SE stormwater line (PIONEER 2023).[7, 8] To represent dewatering via these two mechanisms, MODFLOW drains were applied to the cells within the footprint of the BITP's Biological Nutrient Removal (BNR) Basin and along the Chestnut Street SE stormwater line (see Figure 3-4). The drains operate during Stress Periods 3 through 9.

Passive groundwater dewatering at the BITP is conducted by opening groundwater pressure release valves in the BNR Basin. The BNR Basin is underlain by an engineered gravel layer, which has a much higher hydraulic conductivity than the underlying compacted fill (PIONEER 2023). When pressure release valves are opened to lower the shallow groundwater level, groundwater migrates through the gravel layer from the underlying shallow water layer and is removed from the groundwater table when it flows out of the pressure release valves.[9] The BNR Basin drains were assigned an elevation of 3.22 ft msl, which is the level to which the pressure release valves can drain groundwater (PIONEER 2023). The drain bed thickness and hydraulic conductivity are 3 ft and 0.001 ft/day, respectively, and represent the compacted fill material under the BNR Basin (See Table 3-1).[10]

Groundwater dewatering along the Chestnut Street SE stormwater line occurs via infiltration into the stormwater line at distinct locations (e.g., cracks, leaky pipe joints, and connection failures). The locations of the leaks have not been determined, and as such the stormwater line was modeled as having uniform drainage parameters along its entire length. The stormwater drain outfall is currently assumed to be at 5.04 ft. Predictive SLR models raise the drain outfall elevation to match the surface water level of Budd Inlet.[11] The stormwater drain bed thickness and hydraulic conductivity are 2 ft and 0.15 ft/day, respectively (see Table 3-1).

3.10 Horizontal Flow Barriers

The sheet piling wall along Percival Park and the Cascade Pole Cleanup Site slurry wall, both installed as groundwater flow barriers (Ecology 2015, Landau 1999), have been incorporated into the model using MODFLOW Horizontal Flow Barriers (HFBs). These HFBs have been applied to the relevant cell boundaries to accurately simulate the impact of these features on groundwater flow (see Figure 3-5).[12] To accurately reflect that these features extend from the ground surface down to the underlying

[7] Discharge from Chestnut Street SE stormwater line's outfall into Budd Inlet's East Bay was observed (N. Starr per observations) to be in the hundreds of gallons per minute during the dry season. The discharge is likely a combination of water from surface seeps (e.g., springs in Watershed Park) and groundwater infiltration within the model domain.

[8] Dewatering may be occurring at other stormwater lines within the model domain.

[9] The shallow water layer consists of heterogenous fill; as such, higher rates of groundwater flow into the gravel layer are occurring in areas of the fill that have higher hydraulic conductivity. It is not feasible to determine the distribution of the heterogenous hydraulic conductivity values within the fill.

[10] Drain bed thickness and hydraulic conductivity are primary controls for limiting water to leave the model via drains. Thinner beds and higher hydraulic conductivities allow more water to leave the model via the drain.

[11] Gravity drained stormwater lines are unable to drain water to a level lower than the water body they discharge into.

[12] MODFLOW HFBs simulate thin, vertical low-permeability features that impede the horizontal flow of groundwater. These features are modeled as boundaries between pairs of adjacent model cells and therefore can be assigned to the boundaries of cells that have other boundary conditions (e.g., CHs and HFBs can be assigned to the same cell).

aquitard, the model HFBs are represented as spanning the full vertical extent of the model layer. The parameters assigned to the HFBs are presented on Table 3-1.

3.11 Initial Conditions

Due to the absence of observed pre-dewatering groundwater elevations, the initial conditions (i.e., theoretical pre-dewatering groundwater elevations) for the model were developed through the following process: the model's first two stress periods are steady state periods without active drains. During the steady state periods the primary groundwater inflows are from recharge and the upland CHs and the primary outflow is at shoreline CHs. This allows the model to produce theoretical pre-dewatering groundwater elevations that are used as the starting point for the first transient stress period used for calibrating the model to observed groundwater levels (Stress Period 3; see Table 3-2).

3.12 Solver and Closure Criteria

The Preconditioned Conjugate-Gradient 2 Solution Package was used for simulations of flow in the model. The groundwater elevation change criterion for convergence was 0.001 ft.

SECTION 4: MODEL CALIBRATION

Groundwater models require calibration to observed data (e.g., observed groundwater elevations). The primary parameters that were adjusted during the model calibration, in order of decreasing importance, were: (1) Recharge, (2) Drain bed thickness and drain bed hydraulic conductivity representing the BNR Basin and Chestnut Street SE stormwater line, and (3) hydraulic conductivity and specific yield.

4.1 Calibration Targets and Time Period

The model was calibrated using groundwater elevation data collected on June 16, 2022; September 29, 2022; March 1, 2023; August 21, 2023; and April 16, 2024, which are the end dates for transient stress periods 3, 4, 5, 7 and 9, respectively. Observed groundwater elevations for stress periods 3, 4, and 5 are limited to MWs in the vicinity of BITP and were collected prior to initiation of this SLR groundwater evaluation (see Figures 4-1, 4-2, and 4-3). Observed groundwater elevations for stress periods 7 and 9 were collected from twenty-seven MWs dispersed across downtown Olympia (see Figures 4-4 and 4-5).[13] Groundwater monitoring well survey details are presented on Table 4-1 and observed and modeled groundwater elevations are presented on Table 4-2.

4.2 Residuals and Calibration Statistics

During calibration, a residual is calculated to assess the fit of the model to observed conditions. The residual is the calibration target (i.e., observed) groundwater elevation minus the simulated (model-calculated) groundwater elevation. Positive residuals represent a model-calculated value that is low and negative residuals represent a model-calculated value that is high (e.g., a residual of positive 1 indicates the observed groundwater elevation is 1 ft higher than the model-calculated groundwater elevation). A residual value of 0 represents a perfect fit between the model-calculated and field-observed values.

Plotting the residuals on a model-calculated water level contour map provides an indication of the spatial distribution of error. Trends in the distribution of error, such as clusters of values that are all too high or too low, indicate spatial bias. Similarly, bias in a particular model layer can easily be identified using this method of analysis.

Calibration statistics based on the residual are used to mathematically represent the ability of the model to simulate observed conditions. Two main calibration statistics calculated to quantify the average error are absolute residual mean (ARM) and root mean squared error (RMSE; the standard deviation). ARM is an average of the absolute value of the residuals. Assuming the calibration targets have been selected with some degree of confidence, published guidance suggests that the ARM should be less than 5 percent of the total observed water level change across the model (i.e., a model with 46 ft of water

[13] Observed groundwater levels in the vicinity of the Cascade Pole Cleanup Site were identified as anomalous during the groundwater elevation gauging events and were removed from the data set prior to developing the calibration model.

level change across the model should have an ARM of less than 2.3; Anderson and Woessner, 1992). RMSE is the average of the squared residuals. RMSE is a useful measure of the variability of the error.

4.3 Qualitative Analysis of Calibration

Prior to the calculation of calibration statistics, a qualitative review of the model-calculated flow regime is desirable to provide a subjective indication of the difference between model-derived heads and field-measured heads.

Figures 4-1 through 4-5 present the model-calculated water levels and residuals for Stress Periods 3, 4, 5, 7, and 9. Observed and model-calculated water levels and residual values are also presented on Table 4-2. Residuals were below 1 foot and did not display a spatial bias (i.e., positive and negative residuals are well distributed) with the following exceptions:

- Observed groundwater elevations in MW KM (located up the eastern slope from Chestnut Street SE) were over nine feet higher than the modeled groundwater elevations (see Figures 4-4 and 4-5). As such, observed groundwater elevations from KM were not included in model calibration and the model should not be used to evaluate areas east of the Chestnut Street SE stormwater line.
- Observed groundwater elevations in the central portion of downtown (MWs IS, KB, PV, MJ, and PT) are generally 1 to 3 feet lower than the modeled groundwater elevations (see Figures 4-4 and 4-5). This may be due to unidentified infiltration into stormwater lines in this area.
- The absence of observed groundwater elevations southeast of MWs EG and OQ (the vicinity of the Lee Creighton Justice Center and the intersection of Union Avenue SE and Plum Street SE) indicates that the model has not been calibrated to this area. The model should not be used to evaluate this area.

4.4 Quantitative Analysis of Calibration

Statistics based on the residuals were calculated to further quantify the calibration. Table 4-3 is a summary of the calibration target statistics, calculated based on residuals. The mean of the residuals for the model's 55 transient targets is -0.22 ft with a total head range of 46.07 ft. The scaled mean of the residuals is -0.5 percent.[14] The ARM is 0.75 ft and the scaled ARM is 1.6 percent.

4.5 Findings from Calibration

The groundwater contours on Figures 4-1 through 4-5 indicate the following:

- Groundwater enters into the project area from the topographic rises located to the south and southeast and discharges along the shorelines of Budd Inlet and Capitol Lake.
- Groundwater dewatering at the BNR Basin and Chestnut Street SE stormwater line significantly lowers the groundwater table in downtown Olympia. Leaky stormwater lines appear to be acting as groundwater drains.
- Significant areas of downtown currently have shallow groundwater (less than 2 ft below surface grade; see Figure 4-6).

[14] Scaled values are the value divided by range in observations (total groundwater level change).

- Groundwater is currently shallow along the shoreline.
- The model is well calibrated in the commercial core of downtown Olympia, including the vicinity of BITP.

Analysis of the calibrated model indicates that the model is not designed to evaluate the following areas (see Figure 4-7):

- The northern area of the model domain in the vicinity of the Cascade Pole Cleanup Site;
- Adjacent to the upland CHs along the eastern and southern model perimeters;
- East of the Chestnut Street SE stormwater line; and
- The vicinity of the Lee Creighton Justice Center and the intersection of Union Avenue SE and Plum Street SE.

SECTION 5: PREDICTIVE MODEL

The calibrated model input parameters were modified to develop six predictive models. The six predictive models are listed in the table below with their modified input parameters (no other input parameters were modified).

Predictive Models and Modified Input Parameters

Predictive Model Description	Budd Inlet Contant Heads Change	Capitol Lake Contant Heads Change	Chestnut St SE Drain Stage
Post Capitol Lake estuary restoration project without SLR	No change (4.28 ft)	Decreased from 9 to 4.28 ft	No change (5.04 ft)
24- inches of SLR	Increased to 6.28 ft	Increased to 6.28 ft	Increased to 6.28 ft
36- inches of SLR	Increased to 7.28 ft	Increased to 7.28 ft	Increased to 7.28 ft
48- inches of SLR	Increased to 8.28 ft	Increased to 8.28 ft	Increased to 8.28 ft
60- inches of SLR	Increased to 9.28 ft	Increased to 9.28 ft	Increased to 9.28 ft
68- inches of SLR	Increased to 9.95 ft	Increased to 9.95 ft	Increased to 9.95 ft

The results of the predictive models were evaluated using the predictive models' groundwater elevation output of Stress Period 9.[15] The results of the predictive models are presented on the following figures:

- Figure 5-1 presents the predicted groundwater decrease after the completion of the Capitol Lake Estuary Restoration Project without SLR.
- Figures 5-2 through 5-6 present predicted groundwater contours for the five SLR increases.
- Figures 5-7 through 5-11 present predicted groundwater increases for the five SLR increases.
- Figures 5-12 through 5-16 present the depth to groundwater and sewer line relative depth to groundwater for the five SLR increases.
- Figures 5-17 through 5-21 present possible groundwater surface emergence for the five SLR increases.

5.1 Predictive Model Findings

The following observations were derived from review of the figures described above:

- Upon completion of the Capitol Lake Estuary Restoration Project, groundwater levels along Capitol Lake are expected to drop by over 4.5 feet. This effect will radiate across the southwestern project area, with diminishing impact as distance from the lake's shoreline increases (Figure 5-1).
- The decrease in groundwater levels along Capitol Lake will lessen with each increase in SLR until it reaches 57 inches. At this point, the surface water elevation of Capitol Lake will match the current 9-foot surface water level (Figures 5-7 through 5-11).

[15] Changes in groundwater conditions were made by comparing the predictive models' groundwater elevation output of Stress Period 9 to the calibrated model's elevation output of Stress Period 9.

- The influence of dewatering at BITP on lowering groundwater levels will grow as SLR increases, due to the static elevation of the BNR Basin drain (Figures 5-7 through 5-11).
- Shallow groundwater (i.e., less than two feet below surface grade) will become increasingly common in Olympia's downtown commercial core with rising SLR (tan colored areas in Figures 5-12 through 5-16).
- A significant portion of the sewer lines in the low-lying area of Olympia's commercial core currently appear to be below the groundwater table (see Figure 4-6). Additional sewer lines in this low-lying area become submerged by groundwater as SLR increases (see Figures 5-12 through 5-16). However, increased groundwater levels due to SLR will not have a significant effect on inflow at LOTT's BITP due to this area encompassing less than 4% of LOTT's service area.[16, 17]
- Groundwater surface seeps will likely increase at the base of the slopes around 7th Avenue SE and Jefferson Street as SLR increases. There is a potential for surface water ponding in this area at 36 inches of SLR (Figures 5-17 and 5-18).[18]
- The possibility of surface water ponding across Olympia's downtown commercial core increases as SLR levels exceed 36 inches (most likely SLR projection for Olympia in 2100 and high-range projection for 2065 [AECOM 2019]; Figures 5-18 and 5-19). Significant areas of the downtown core may experience surface water ponding at 60 inches of SLR (Figure 5-20), with substantial coverage at 68 inches of SLR (high-range projection for Olympia in 2100 [AECOM 2019]; Figure 5-21).
- Shoreline barrier designs factor in shallow groundwater, as the surface water they block reaches down to the groundwater level. Rising groundwater levels due to SLR won't significantly impact shoreline barrier construction as long as inland surface water ponding is taken into account and sheet piling walls are not used (sheet piling walls can impede groundwater flow).
- The limited extent of existing sheet piling in the project area (see Figure 3-5) does not appear to increase rising groundwater levels due to SLR in low-lying areas of Olympia's commercial core. If additional sheet piling is proposed in the project area, an evaluation should be conducted to determine if it will increase groundwater levels due to SLR.

[16] This low-lying area consists of less than 200 acres of the over 5,000 acres that make up LOTT's service area.

[17] This finding has no bearing on surface water entering LOTT's system during SLR enhanced tides (see the Sea Level Rise Response Plan for possible impacts from surface water entering LOTT's system).

[18] Seepage occurs when the groundwater table rises above the ground surface and either the ground surface is sloped or the stormwater system can remove surface water. If the seepage occurs near a low-lying area and the stormwater system is unable to remove surface water (for example, if gravity stormwater lines become submerged and cease to drain), then ponding will occur.

SECTION 6: UNCERTAINTIES

The uncertainties present in this groundwater model can be grouped into two categories: (1) uncertainties that arise from the use of a simplified one-layer model to represent a complex hydrogeological system, and (2) uncertainties associated with new stresses introduced by SLR, which differ from the stresses that were present during model calibration.

The main uncertainties are as follows:

- The specific locations where groundwater enters the stormwater line(s) (e.g., pipe joints) are unknown.
- Groundwater may be drained through gravel bedding surrounding sewer and stormwater lines.
- Elevation data are not available for the stormwater lines, including the Chestnut Street SE stormwater line. If the top of a gravity stormwater line that is draining groundwater falls below mean sea level due to SLR, it will no longer function as a drain.[19]
- The model's single layer represents the shallow groundwater bearing layer, with the bottom of the layer defined by the top of the underlying aquitard. There is insufficient information about the underlying aquitard and confined artesian aquifer that causes artesian conditions in the Olympia downtown area. This lack of data makes it unfeasible to incorporate them as layers in the model.
- Recharge in the model and inflow from CHs in the upland areas represent a simplified simulation of real-world recharge to the shallow water bearing unit from precipitation, groundwater flow into the model domain from upland adjacent upland areas, and upward flow through "windows" in the aquitard from the confined aquifer.
- This evaluation assumed that groundwater recharge would not be changed by climate change. However, shifts in weather patterns due to climate change could impact groundwater recharge to the upper aquifer (e.g., changes in precipitation amounts and patterns may alter the shallow water bearing zone and the recharge zone of the confined artesian aquifer).

[19] Lift stations would enable stormwater lines to continue to drain groundwater.

SECTION 7: CONCLUSIONS AND RECOMMENDATIONS

The primary conclusions from this evaluation of SLR on groundwater in Olympia's downtown area include:

- Groundwater levels around Capitol Lake are predicted to lower by over 4.5 ft after the Capitol Lake estuary restoration project is completed. This effect will radiate across the southwestern project area, with diminishing impact as distance from the lake's shoreline increases (Figure 5-1). The lowered groundwater levels will help to mitigate the impacts from groundwater rise due to SLR in this area.
- Routine dewatering at LOTT's BITP contributes to lower groundwater levels in proximity to the plant and this influence is expected to grow as SLR increases.
- Shallow groundwater (i.e., less than two feet below surface grade) will become increasingly common in Olympia's downtown commercial core with rising SLR (tan colored areas in Figures 5-12 through 5-16).
- The possibility of surface water ponding across Olympia's downtown commercial core increases as SLR levels exceed 36 inches (Figures 5-18 and 5-19). Significant areas of the downtown core may experience surface water ponding at 60 inches of SLR (Figure 5-20), with substantial coverage at 68 inches of SLR (Figure 5-21). [20]
- Rising groundwater levels due to sea level rise won't significantly impact shoreline barrier construction as long as inland surface water ponding is taken into account and sheet piling walls are not used (sheet piling walls can impede groundwater flow).
- Increased groundwater levels due to SLR will not have a significant effect on inflow at LOTT's BITP due to this area encompassing less than 4% of LOTT's service area.

The primary recommendations from this evaluation of SLR on groundwater in Olympia's downtown area include:

- Conduct a visual stormwater line survey in downtown Olympia to determine where groundwater is infiltrating the stormwater lines. Locating the infiltration points will increase the calibration of the model and reduce uncertainty regarding the impact of SLR on groundwater levels.
- Conduct a stormwater line survey in downtown Olympia to determine the location and depth of the stormwater lines and their outfalls. When a stormwater line becomes submerged in a low-lying area with groundwater seeps surface ponding may occur. Knowing the top elevation of a gravity stormwater line that drains groundwater will allow the determination of the magnitude of sea level rise that will submerge the drain and cause it to stop functioning.
- Revise this groundwater evaluation taking into account the locations of infiltration into the stormwater lines and the elevations of outfalls.

[20] Lift stations would enable stormwater lines to continue to drain groundwater and minimize ponding in low lying areas

- Conduct an engineering evaluation to determine if the predicted increases in groundwater levels could significantly impact subsurface utilities.

SECTION 8: REFERENCES

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Figures

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Olympia Sea Level Rise Response Plan Project Area
Sea Level Rise Groundwater Study
Olympia, Washington

Figure 1-1

Document Path: G:\Projects\LOTT\Maps\2025\January\Sea Level Rise Groundwater Study\Figure 1-1 Olympia SLR Response Plan Project Area.mxd; Author: ; Date Saved: 1/13/2025

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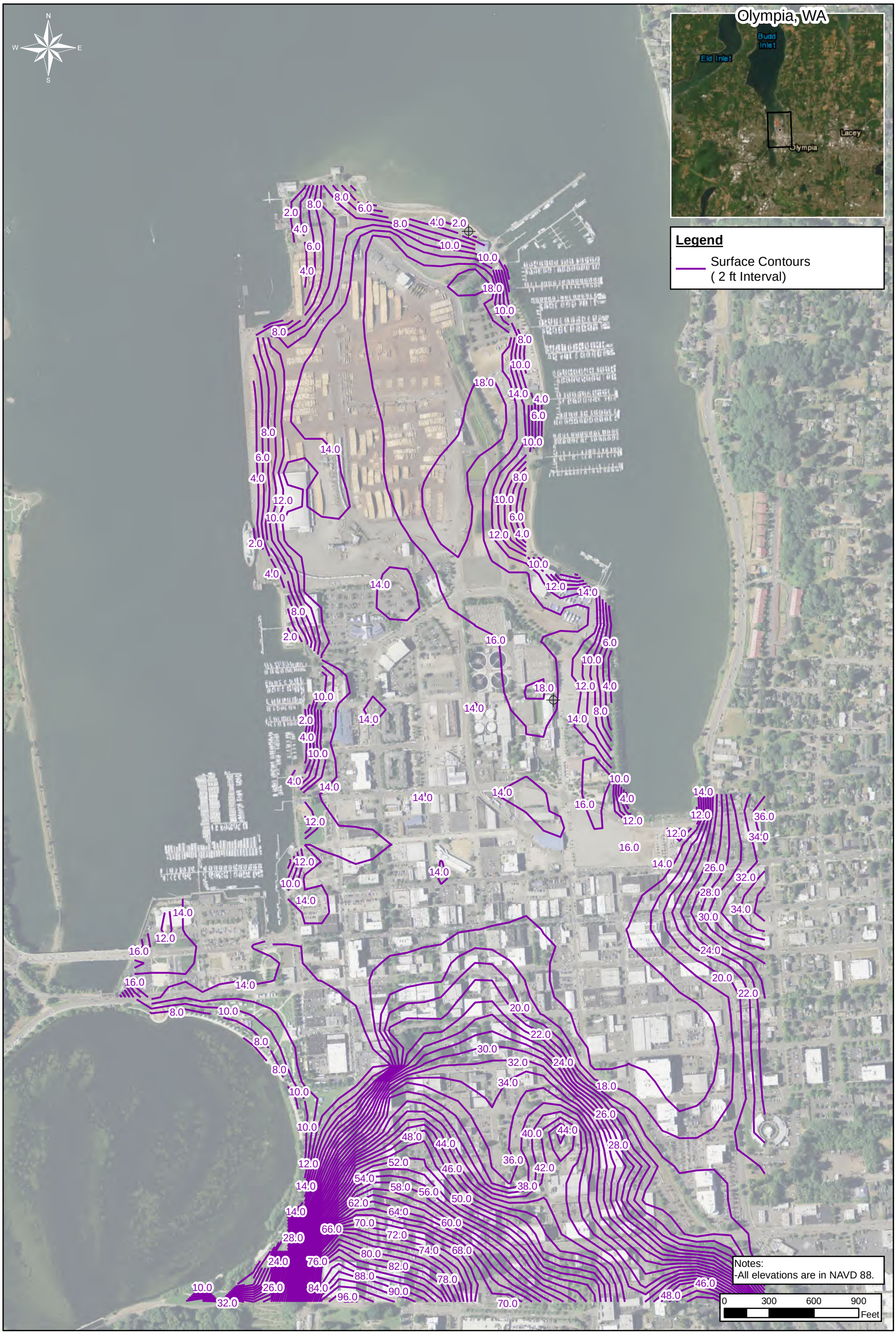
Monitoring Well Locations
Sea Level Rise Groundwater Study
Olympia, Washington

Figure 1-2

Document Path: G:\Projects\LOTT\Maps\2025\January\Sea Level Rise Groundwater Study\Figure 1-2 Monitoring Well Locations.mxd; Author: MCK; Date Saved: 1/13/2025



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Ground Surface Elevation
Sea Level Rise Groundwater Study
Olympia, Washington

Figure 2-1

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Original Predevelopment Shoreline
Sea Level Rise Groundwater Study
Olympia, Washington

Figure 2-2

Document Path: G:\Projects\LOTT\Maps\2025\January\Sea Level Rise Groundwater Study\Figure 2-1 Original Predevelopment Shoreline.mxd; Author: Melody Feden; Date Saved: 1/13/2025

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Study Area Domain and Model Grid
Sea Level Rise Groundwater Study
Olympia, Washington

Figure 3-1

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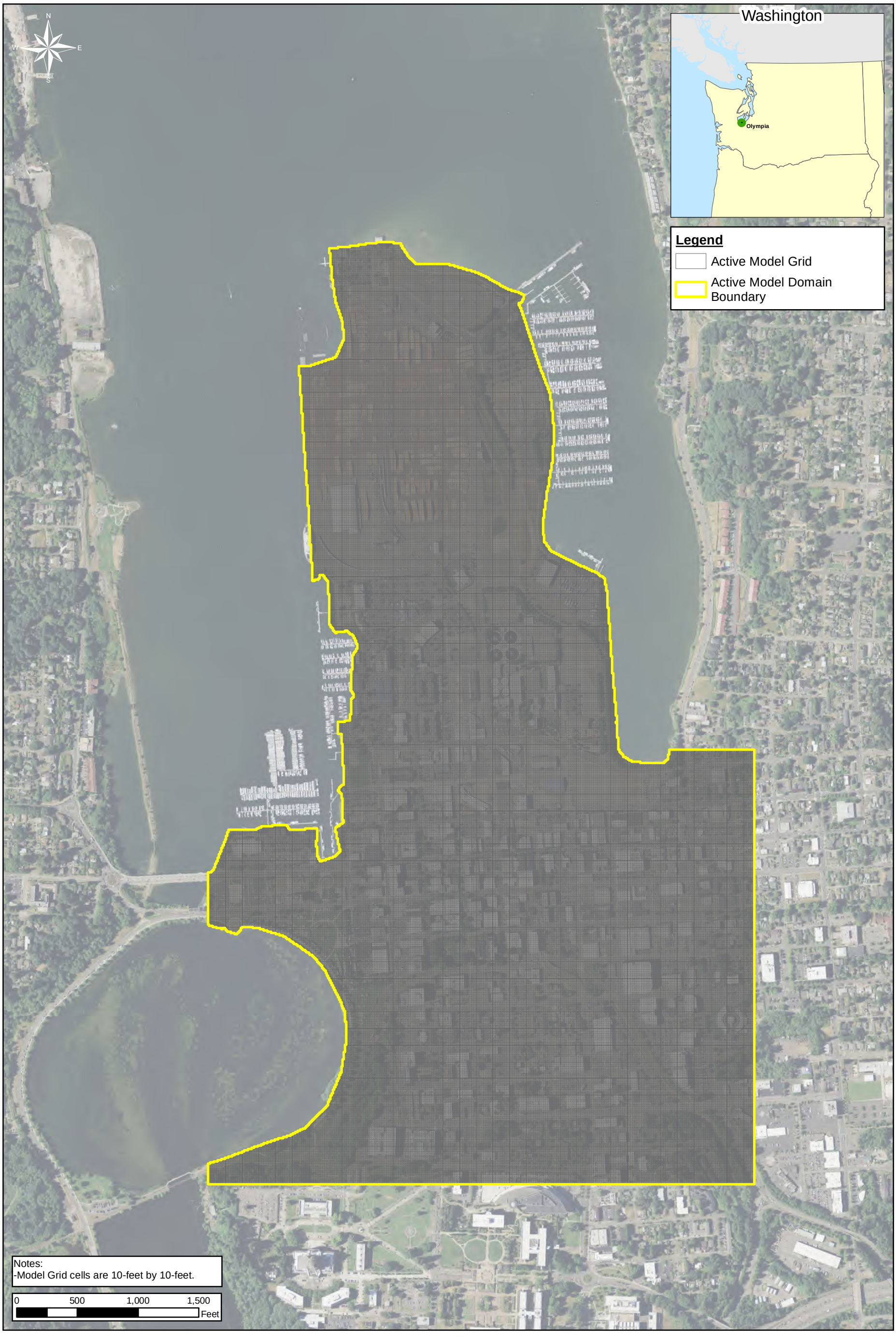

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Active Model Domain
Sea Level Rise Groundwater Study
Olympia, Washington

Figure 3-2

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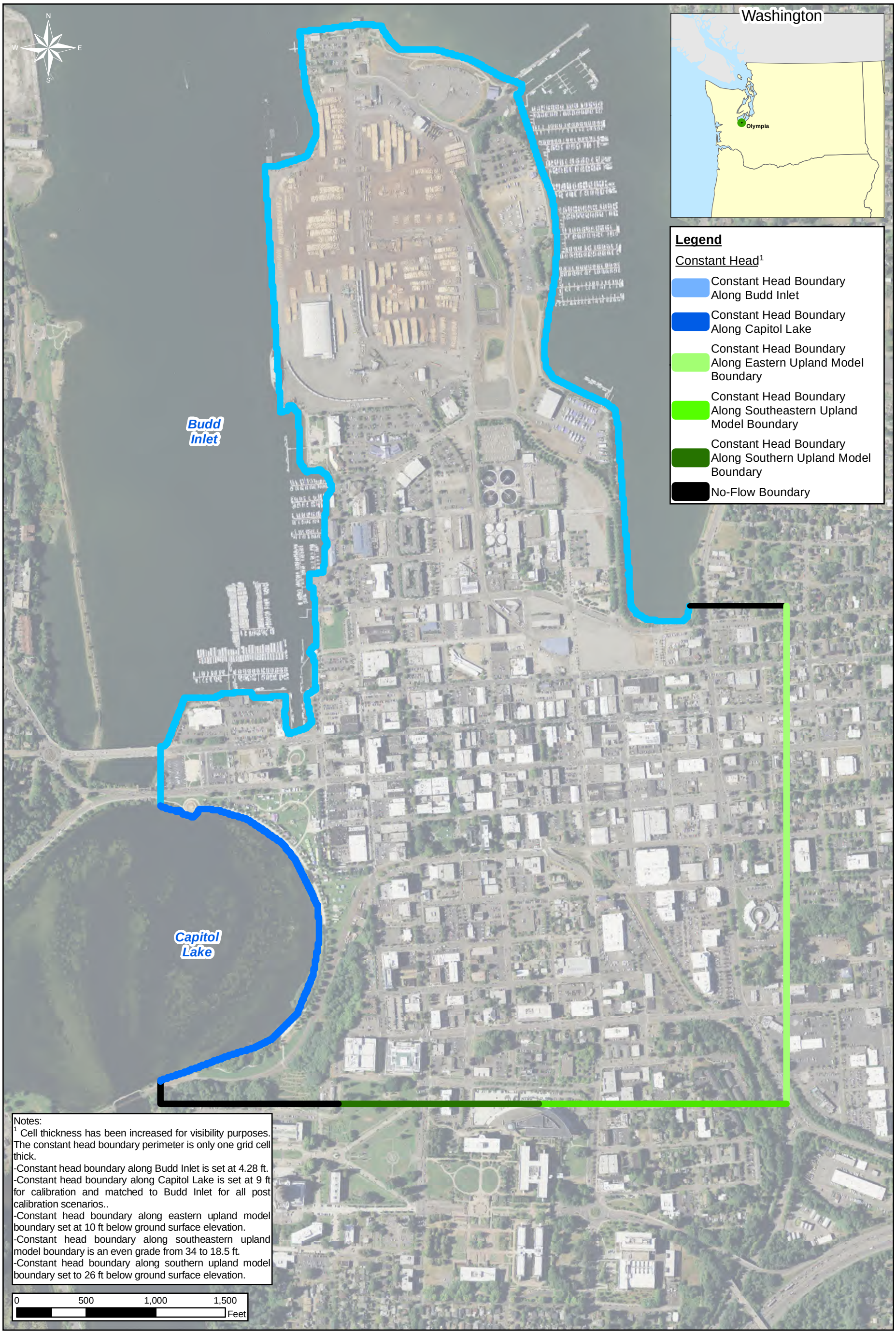

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Constant Head Boundaries
Sea Level Rise Groundwater Study
Olympia, Washington

Figure 3-3

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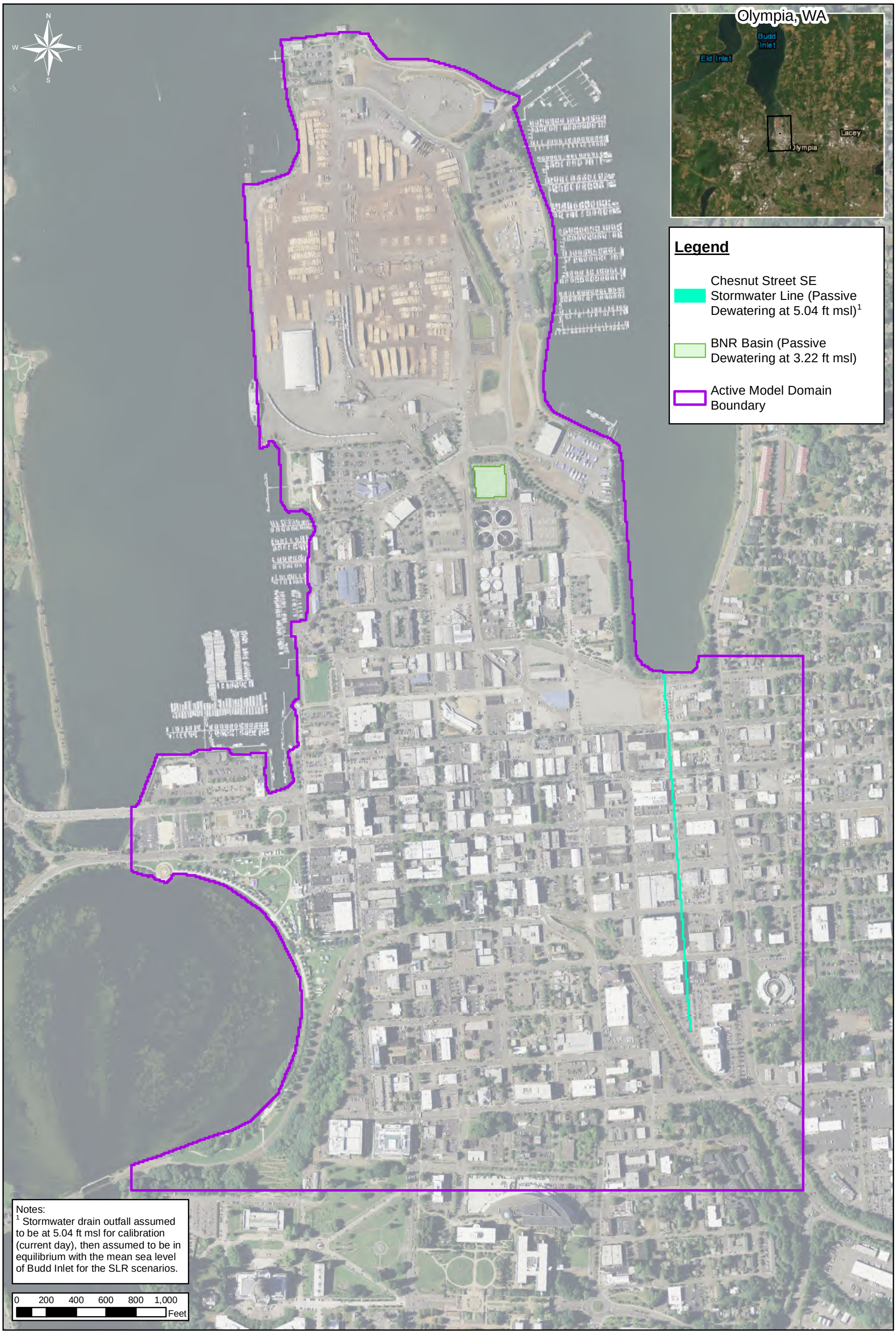

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Drain Boundaries
Sea Level Rise Groundwater Study
Olympia, Washington

Figure 3-4

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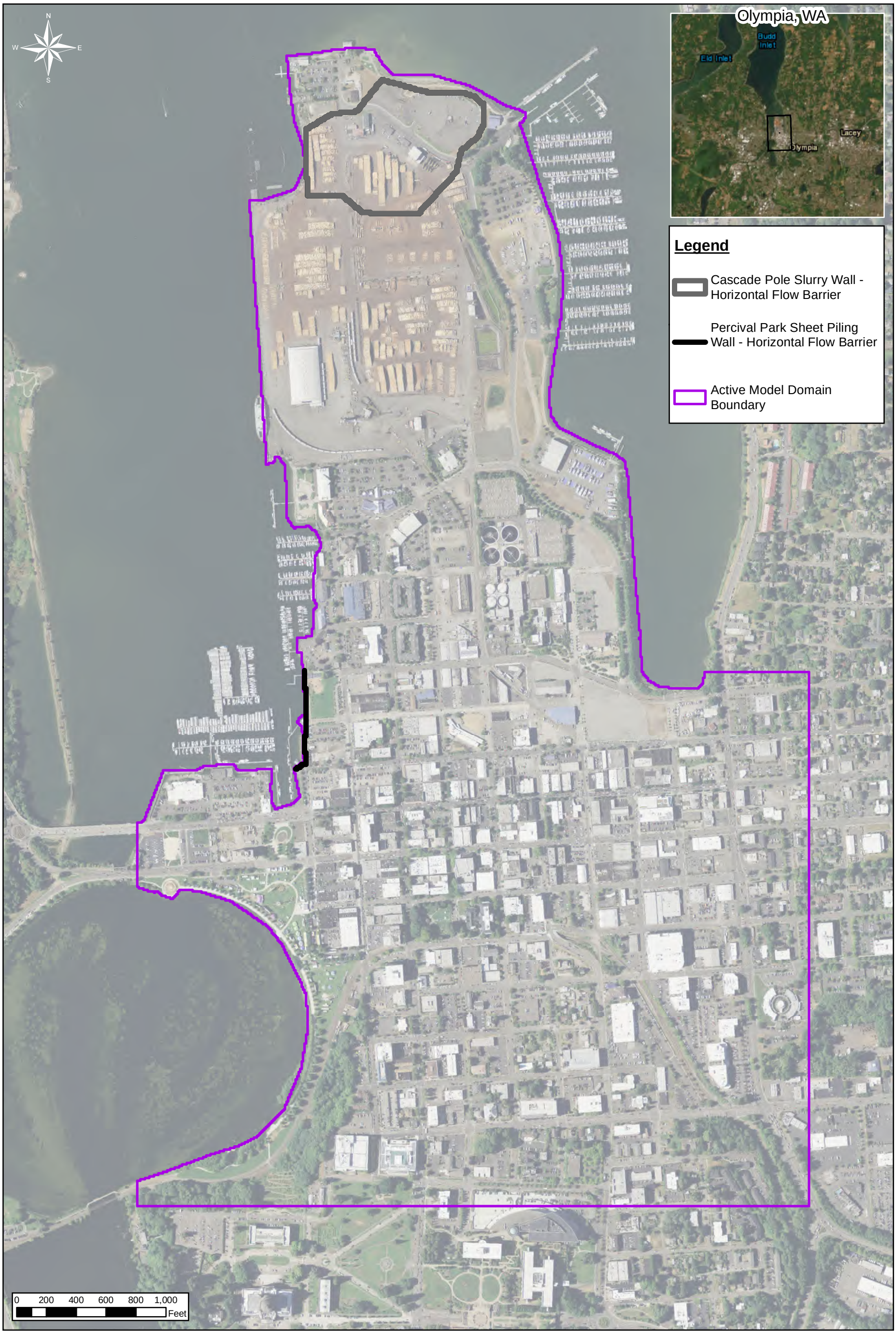

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Horizontal Flow Barriers
Sea Level Rise Groundwater Study
Olympia, Washington

Figure 3-5

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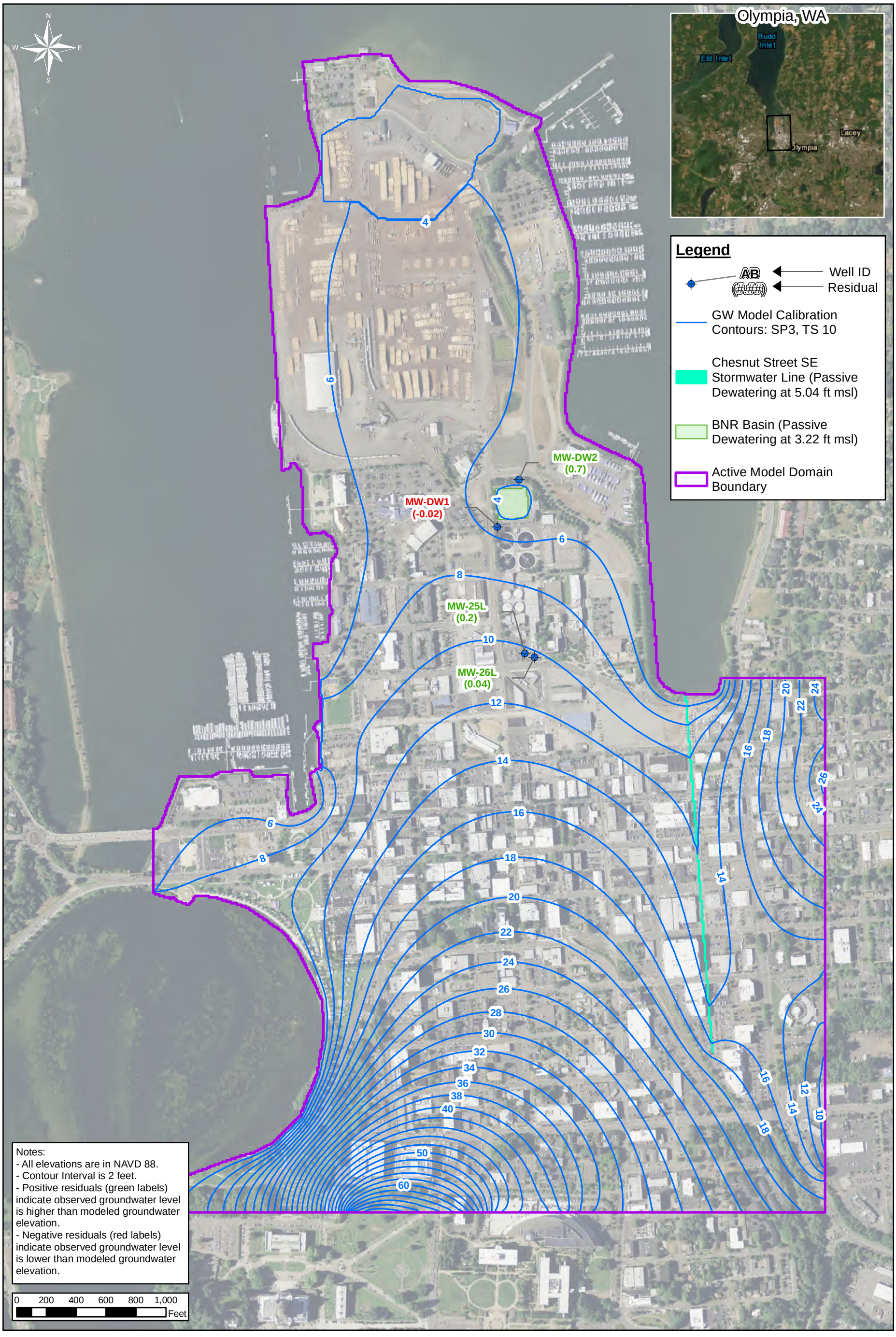

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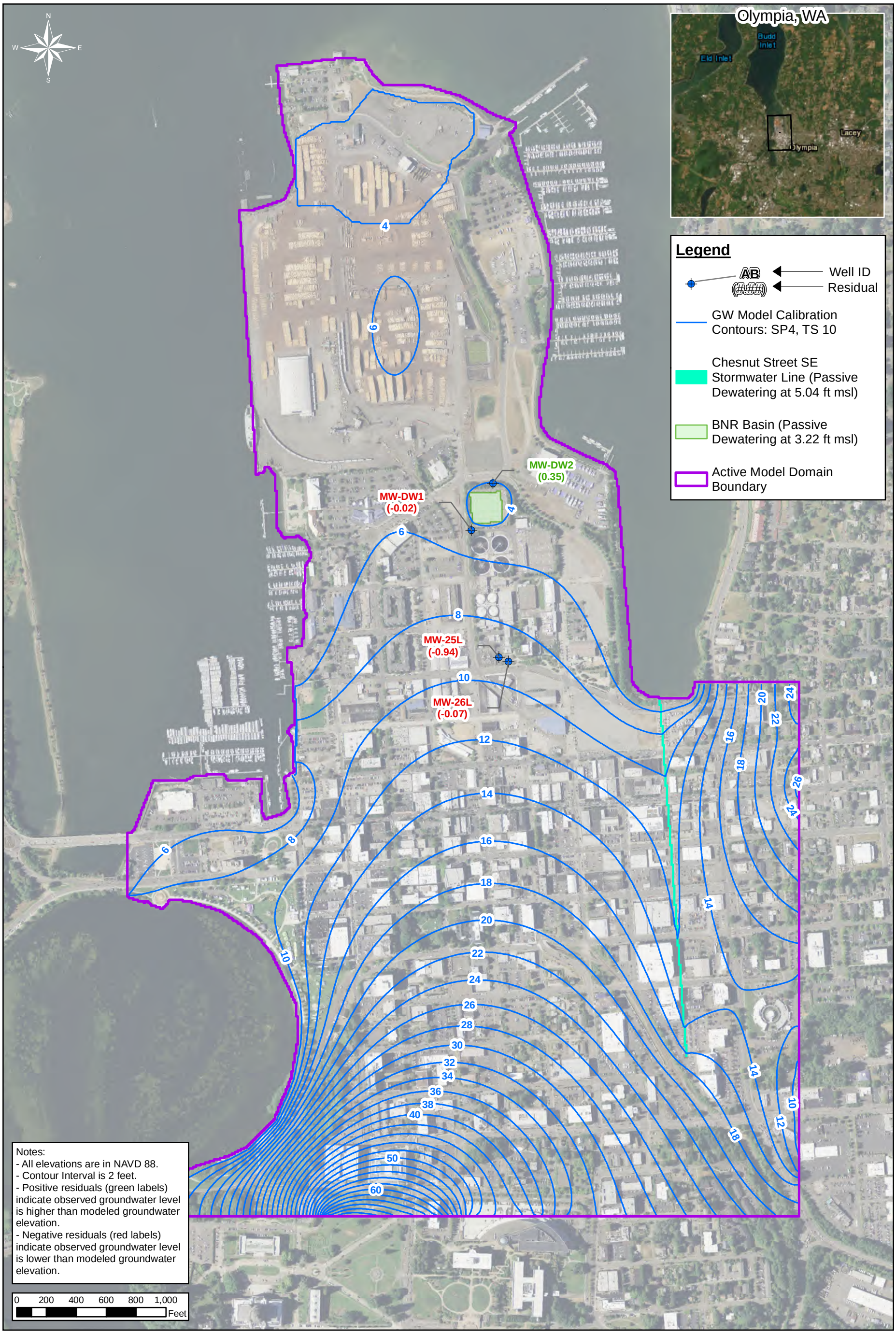
Groundwater Calibration Contours
16 June 2022 (Stress Period 3, Time Step 10)
Sea Level Rise Groundwater Study
Olympia, Washington

Figure 4-1

Document Path: G:\Projects\LOTT\Maps\2025\January\Sea Level Rise Groundwater Study\Figure 4-1 Groundwater Calibration Contours June 16, 2022 (Stress Period 3 Time Step 10.mxd; Author: AR; Date Saved: 1/13/2025



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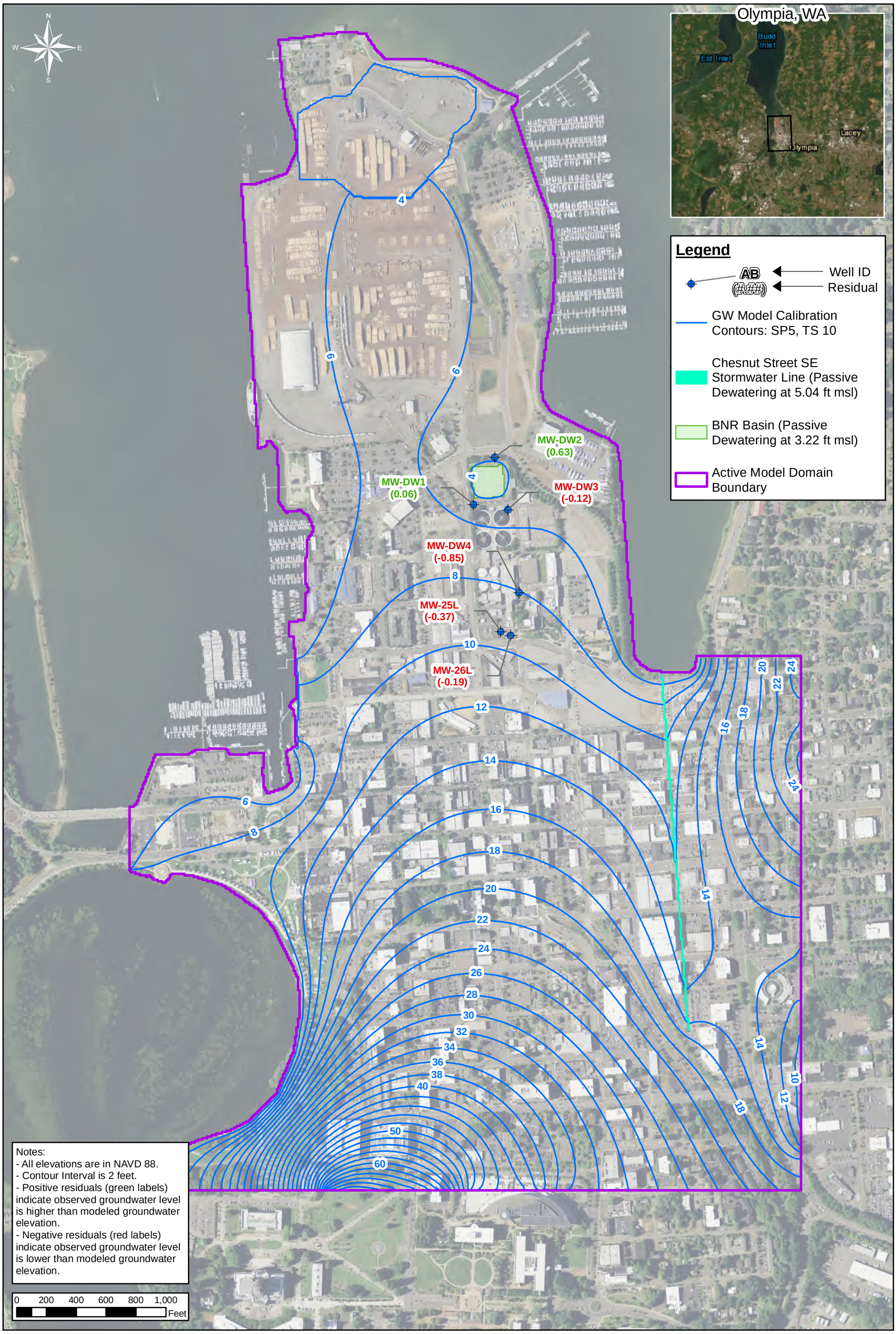
Groundwater Calibration Contours
29 Sept. 2022 (Stress Period 4, Time Step 10)
Sea Level Rise Groundwater Study
Olympia, Washington

Figure 4-2

Document Path: G:\Projects\LOTT\Maps\2025\January\Sea Level Rise Groundwater Study\Figure 4-2 Groundwater Calibration Contours Sept. 29, 2022 (Stress Period 4 Time Step 10).mxd; Author: AR; Date Saved: 1/13/2025



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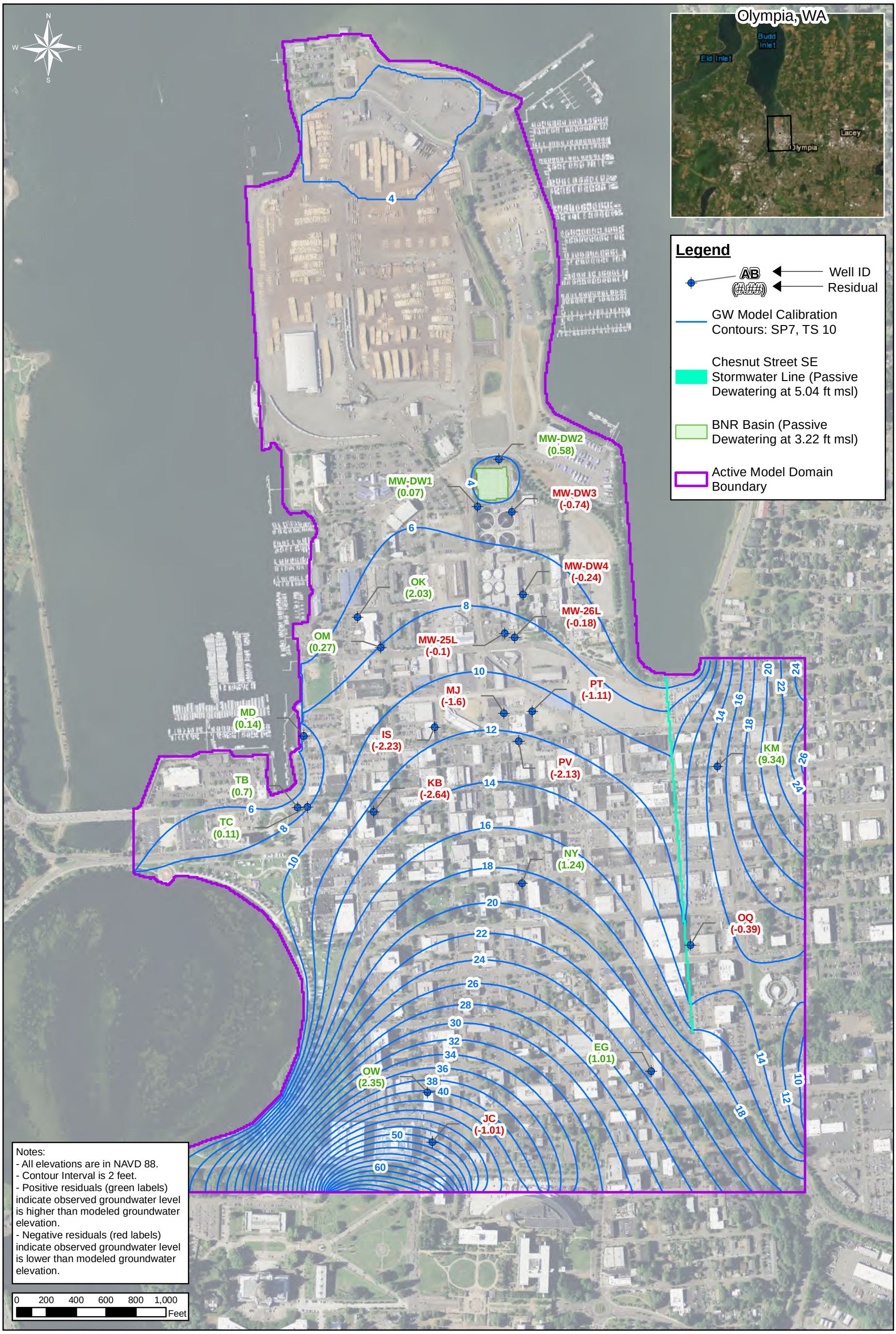
Groundwater Calibration Contours
1 March 2023 (Stress Period 5, Time Step 10)
Sea Level Rise Groundwater Study
Olympia, Washington

Figure 4-3

Document Path: G:\Projects\LOTT\Maps\2025\January\Sea Level Rise Groundwater Study\Figure 4-3 Groundwater Calibration Contours Stress Period 5 Time Step 10 (March 1, 2023).mxd; Author: AR; Date Saved: 1/13/2025



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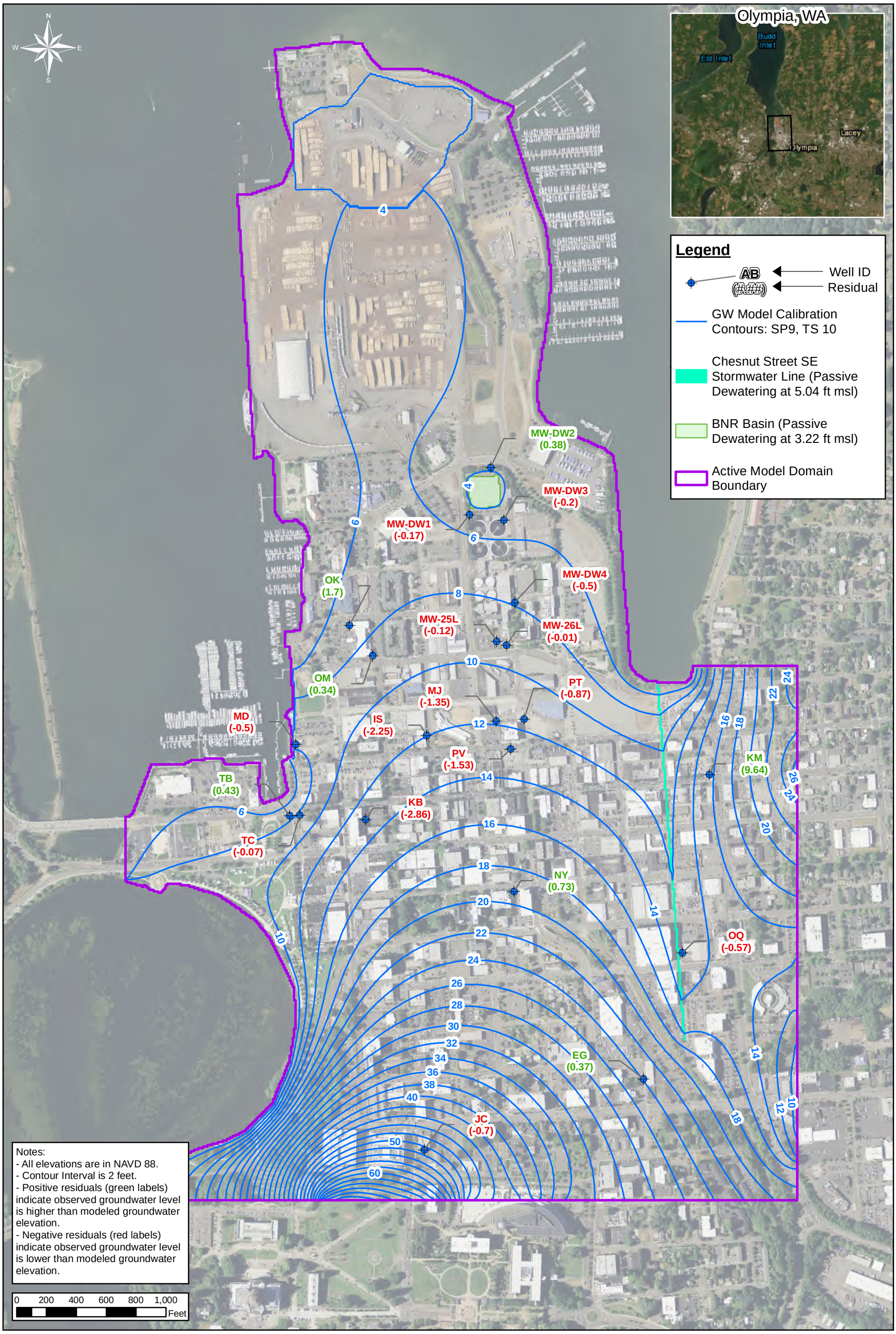
Groundwater Calibration Contours
21 Aug. 2023 (Stress Period 7, Time Step 10)
Sea Level Rise Groundwater Study
Olympia, Washington

Figure 4-4

Document Path: G:\Projects\LOTT\Maps\2025\January\Sea Level Rise Groundwater Study\Figure 4-4 Groundwater Calibration Contours August 21, 2023 (Stress Period 7 Time Step 10).mxd; Author: AR; Date Saved: 1/13/2025



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Groundwater Calibration Contours
16 April 2024 (Stress Period 9, Time Step 10)
Sea Level Rise Groundwater Study
Olympia, Washington

Figure 4-5

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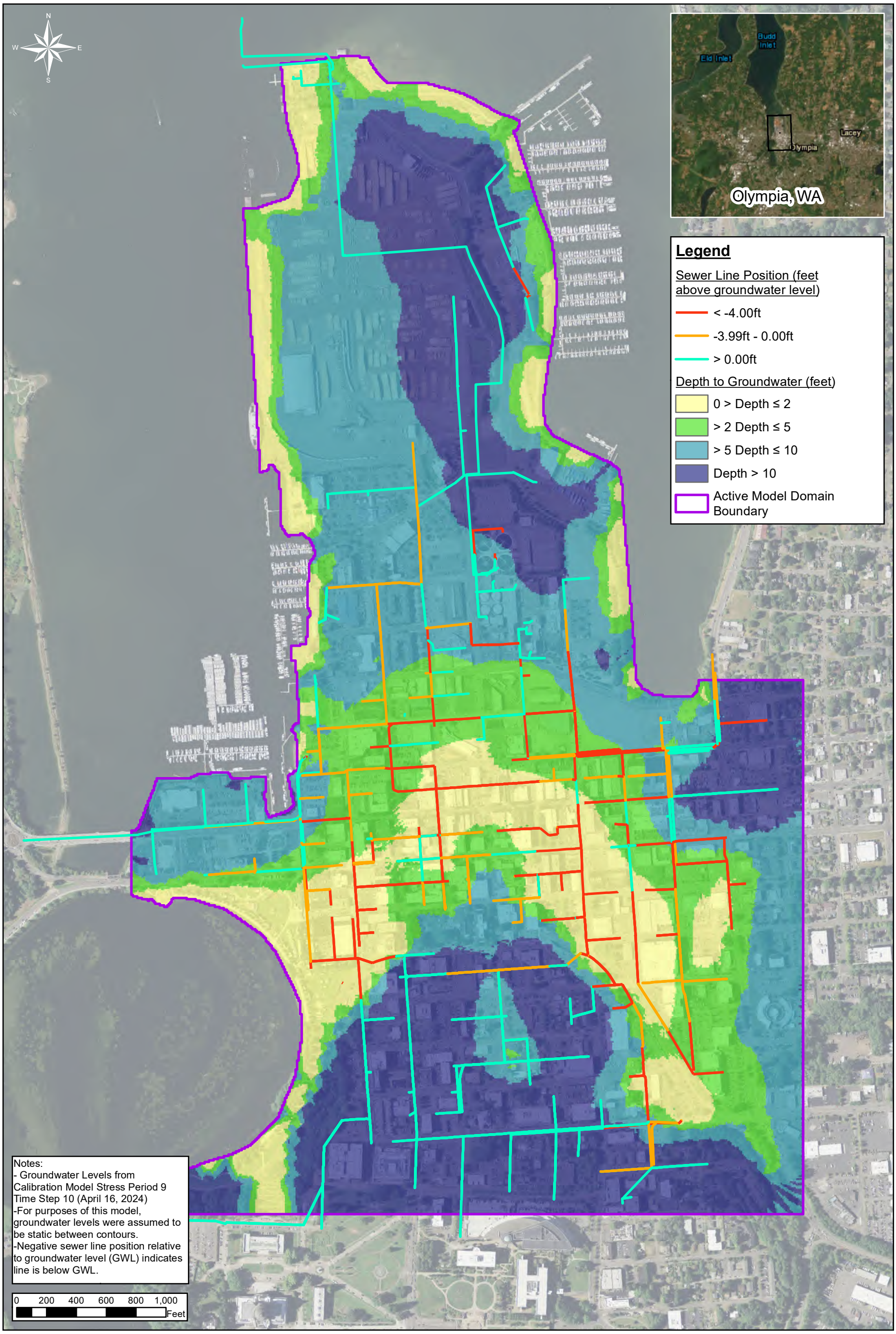

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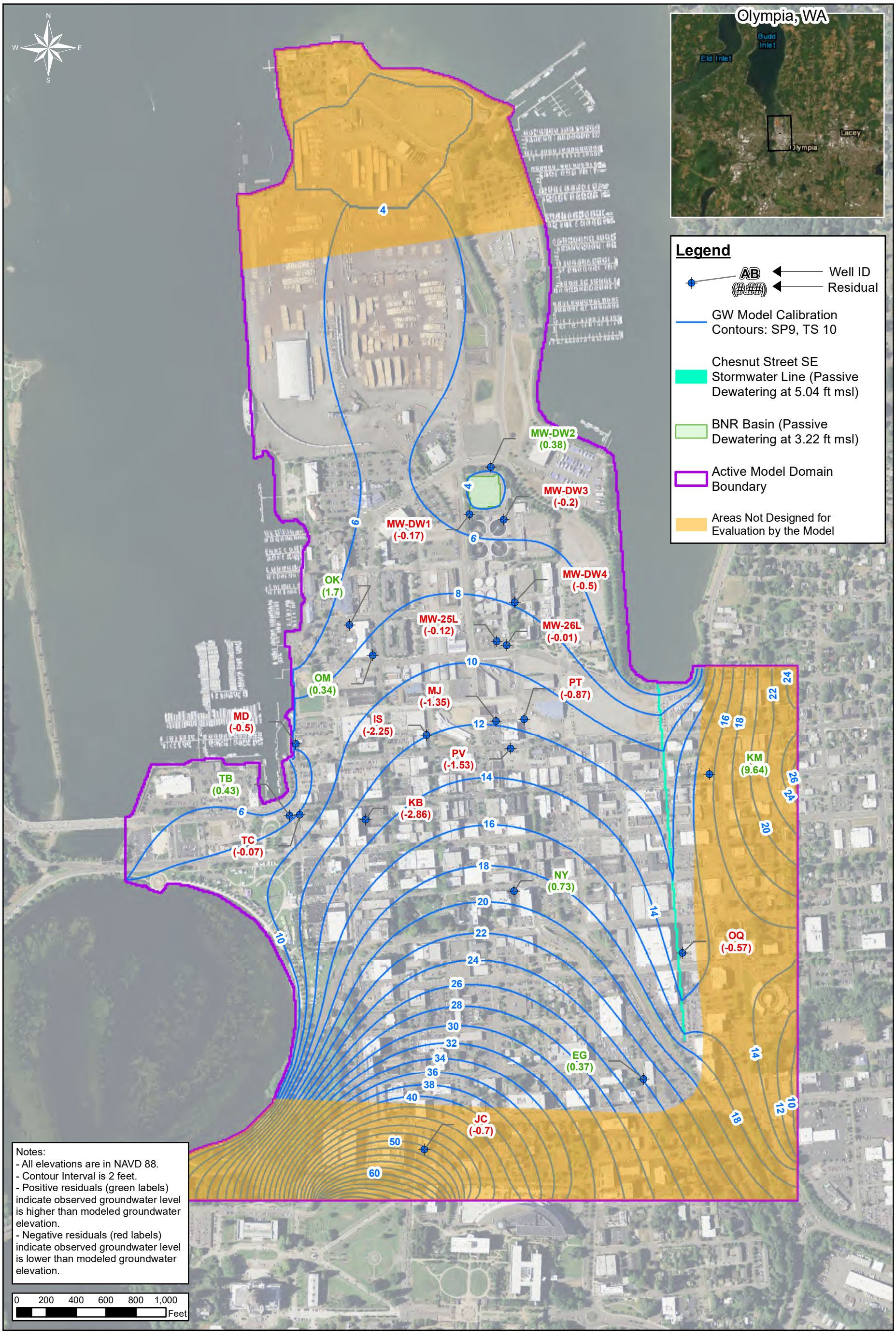
Depth to Groundwater and Sewer Line Depth Relative to Groundwater without Sea Level Rise
Sea Level Rise Groundwater Study
Olympia, Washington

Figure 4-6

Document Path: G:\Projects\LOTT\Maps\2025\January\Sea Level Rise Groundwater Study\Figure 4-6 Depth to Groundwater and Sewer Line Depth Relative to Groundwater without SLR.mxd; Author: MCK; Date Saved: 1/13/2025



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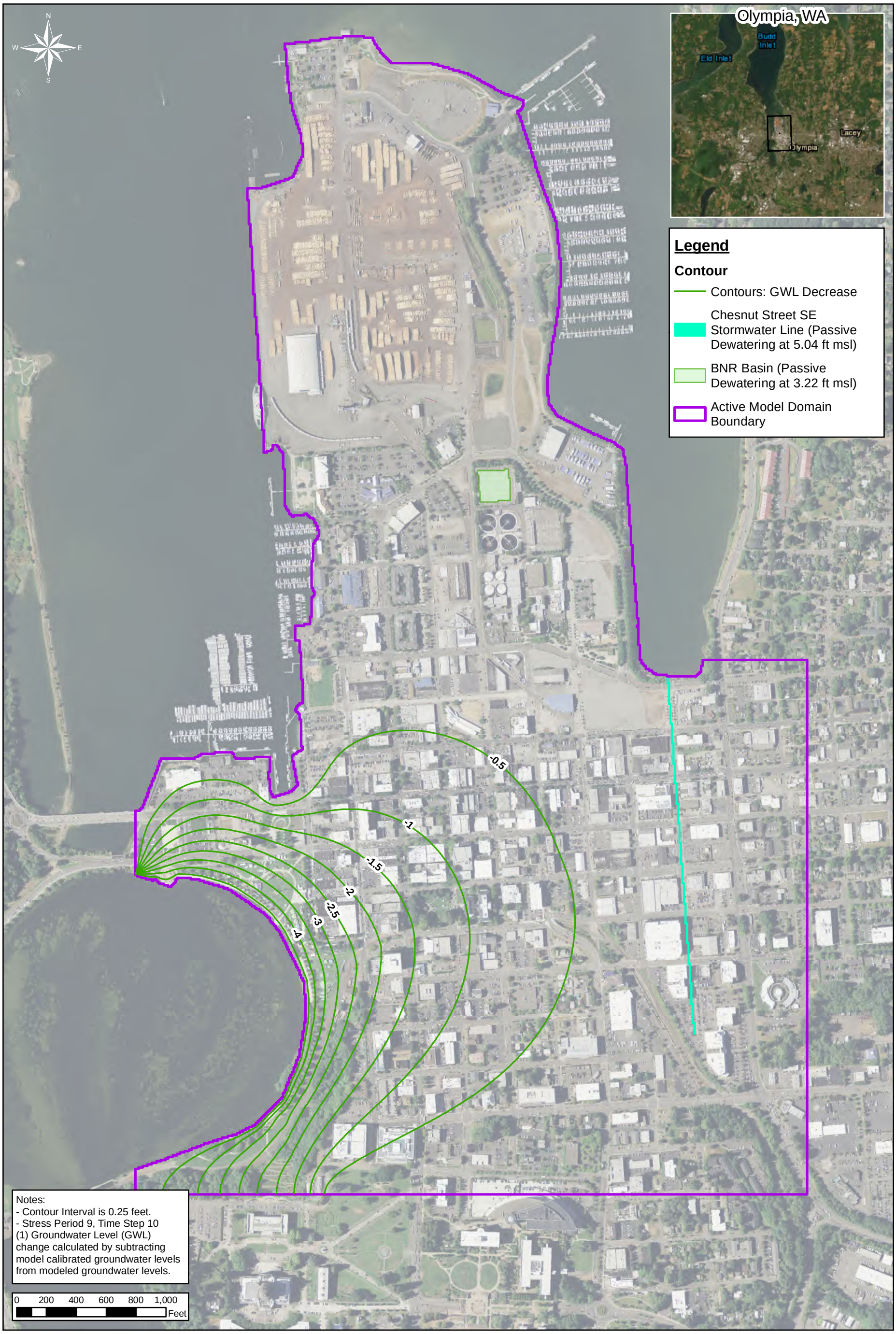
Areas that the Model is Not Designed to Evaluate Sea Level Rise Groundwater Study Olympia, Washington

Figure 4-7

Document Path: G:\Projects\LOTT\Maps\2025\January\Sea Level Rise Groundwater Study\Figure 4-6 Areas Model not Designated to Evaluate.mxd; Author: AR; Date Saved: 2/12/2025



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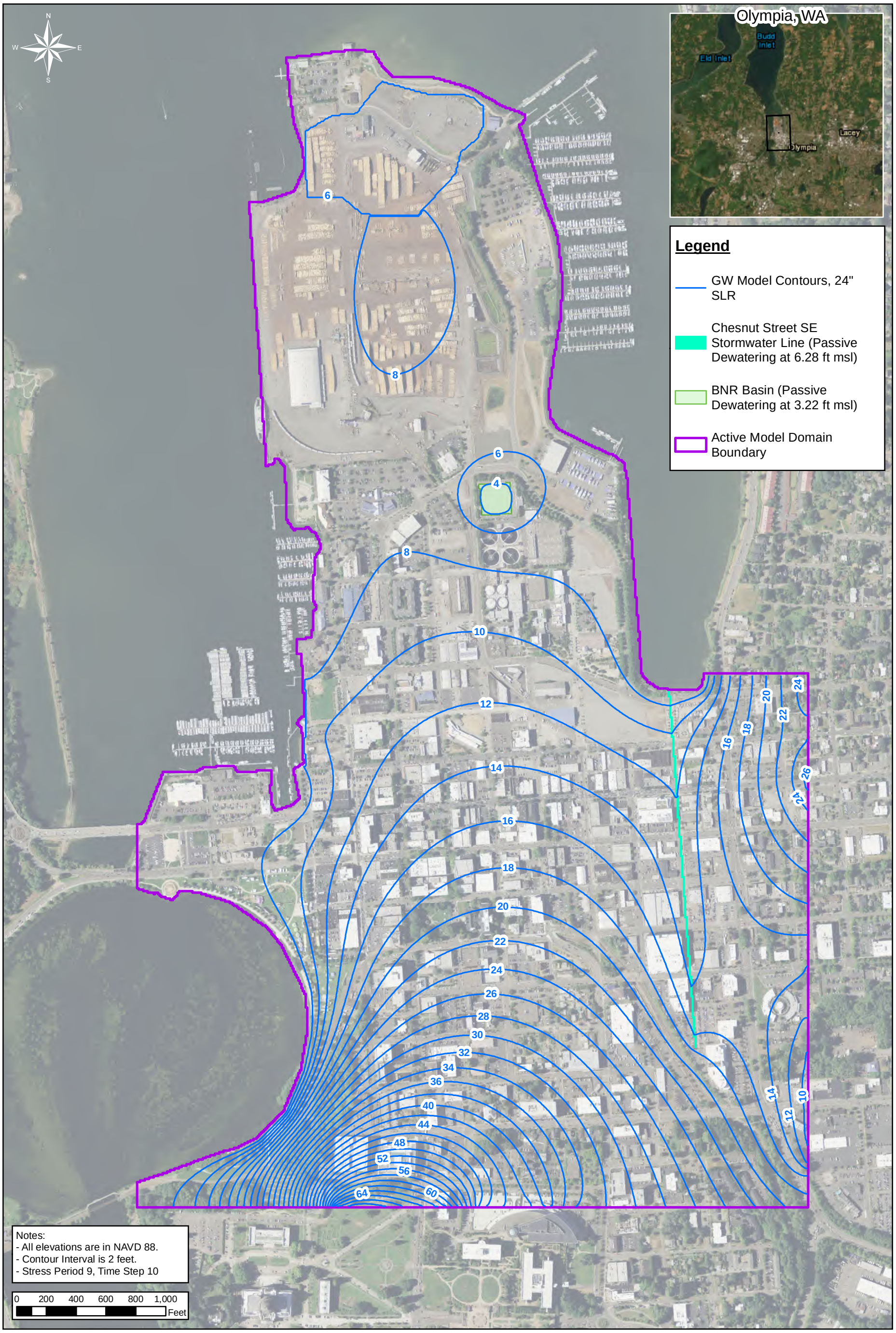
Modeled Groundwater Decrease Post Capital Lake Estuary Restoration Project Sea Level Rise Groundwater Study Olympia, Washington

Figure 5-1

Document Path: G:\Projects\LOTT\Maps\2025\January\Sea Level Rise Groundwater Study\Figure 5-1 Modeled Groundwater Decrease Post Capital Lake Estuary Restoration Project.mxd; Author: CO; Date Saved: 1/13/2025



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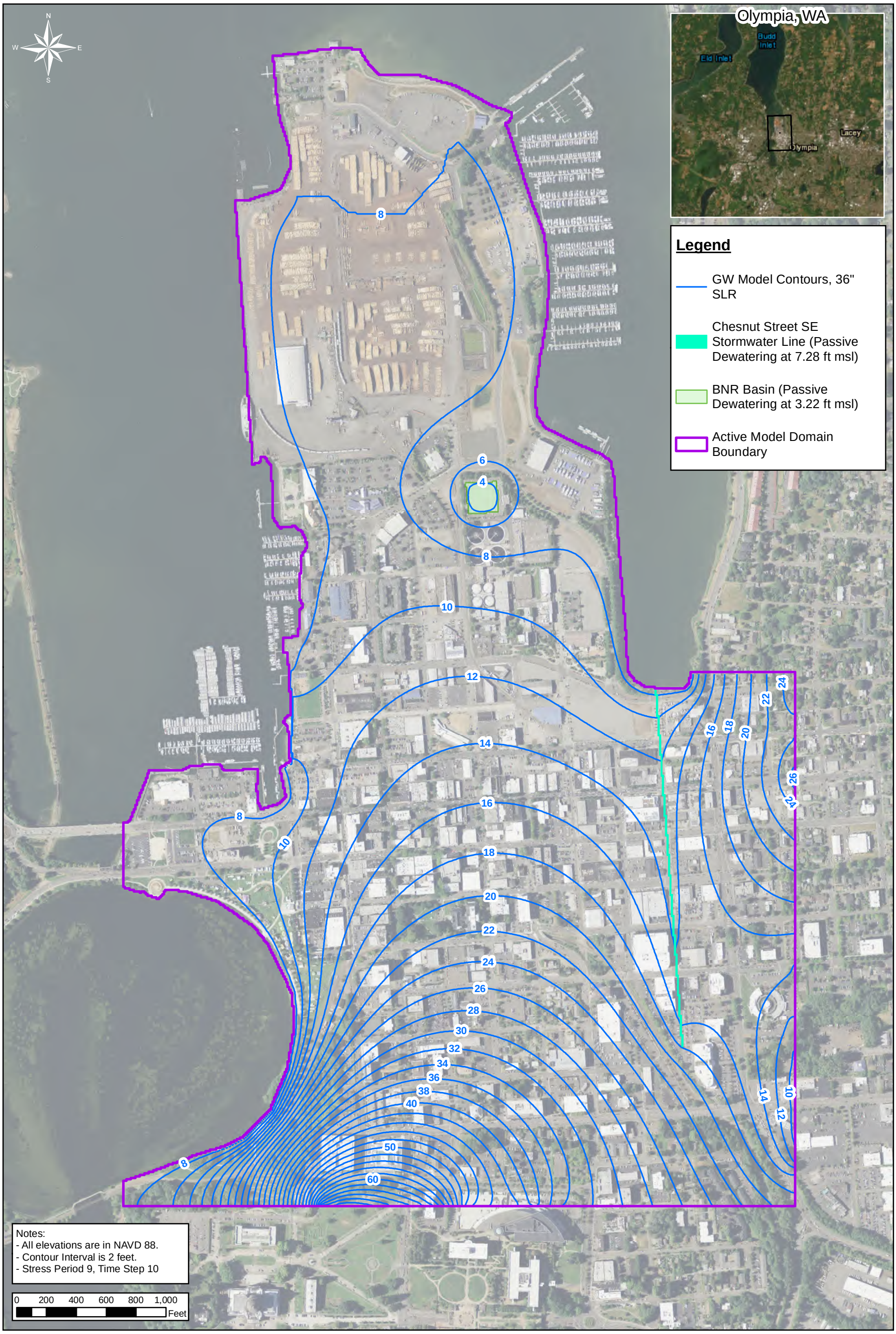
Modeled Groundwater Contours
24-inch Sea Level Rise
Sea Level Rise Groundwater Study
Olympia, Washington

Figure 5-2

Document Path: G:\Projects\LOTT\Maps\2025\January\Sea Level Rise Groundwater Study\Figure 5-2 Modeled Groundwater Contours 24-inch Sea Level Rise.mxd; Author: CO; Date Saved: 1/13/2025

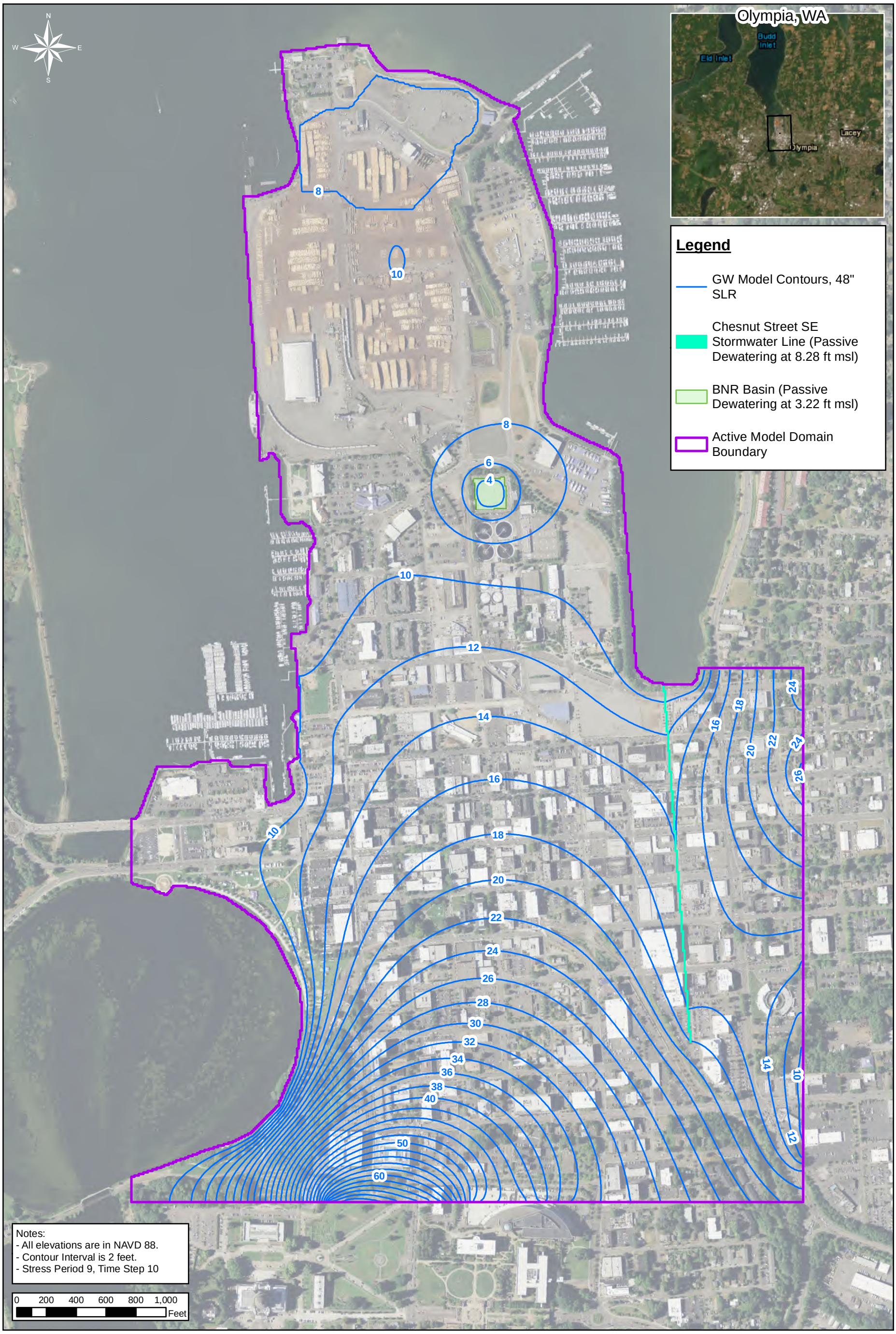


PIONEER TECHNOLOGIES CORPORATION

Modeled Groundwater Contours
36-inch Sea Level Rise
Sea Level Rise Groundwater Study
Olympia, Washington

Figure 5-3

Document Path: G:\Projects\LOTT\Maps\2025\January\Sea Level Rise Groundwater Study\Figure 5-3 Modeled Groundwater Contours 36-inch Sea Level Rise.mxd; Author: CO; Date Saved: 1/13/2025

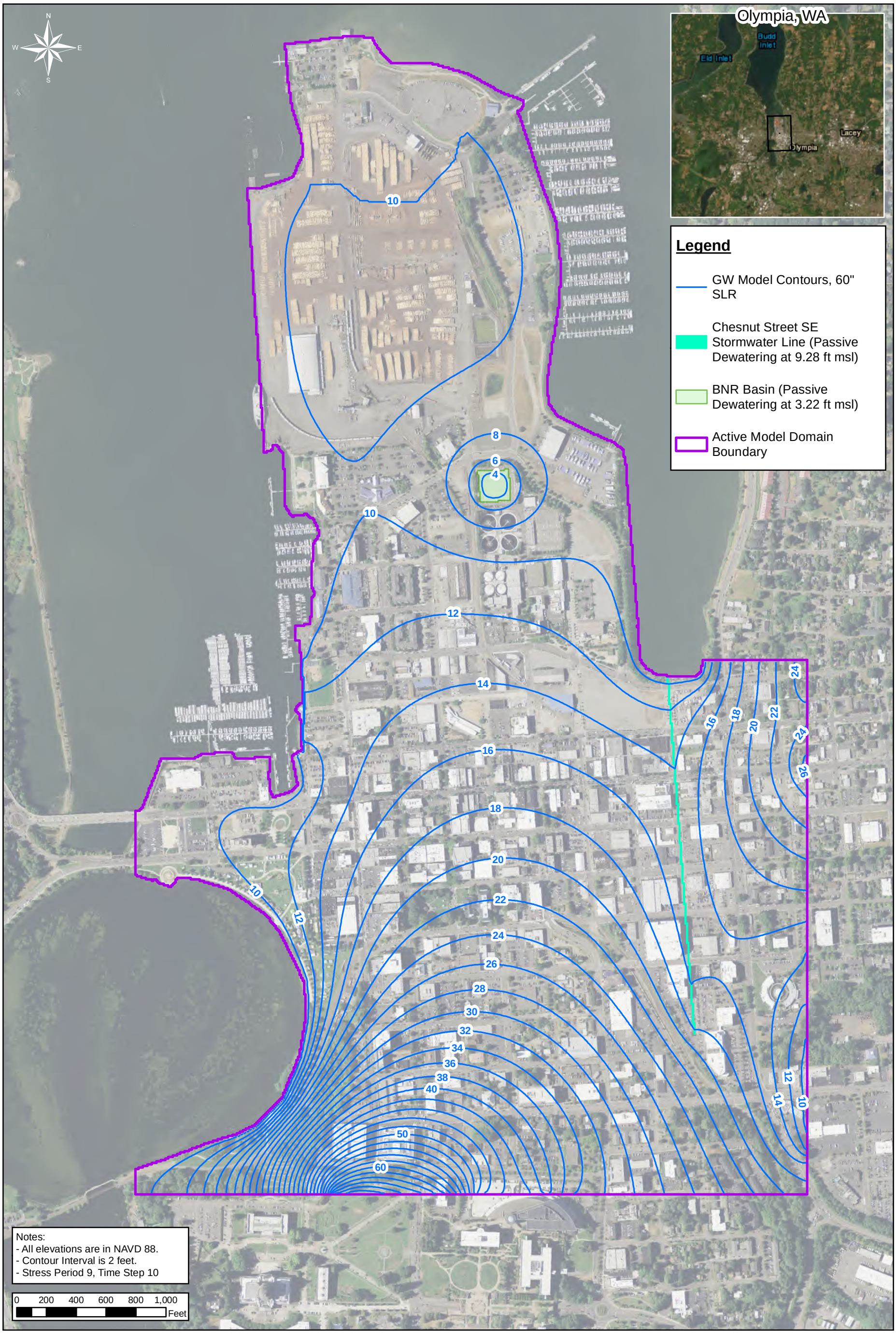


PIONEER TECHNOLOGIES CORPORATION

Modeled Groundwater Contours
48-inch Sea Level Rise
Sea Level Rise Groundwater Study
Olympia, Washington

Figure 5-4

Document Path: G:\Projects\LOTT\Maps\2025\January\Sea Level Rise Groundwater Study\Figure 5-4 Modeled Groundwater Contours 48-inch Sea Level Rise.mxd; Author: CO; Date Saved: 1/13/2025

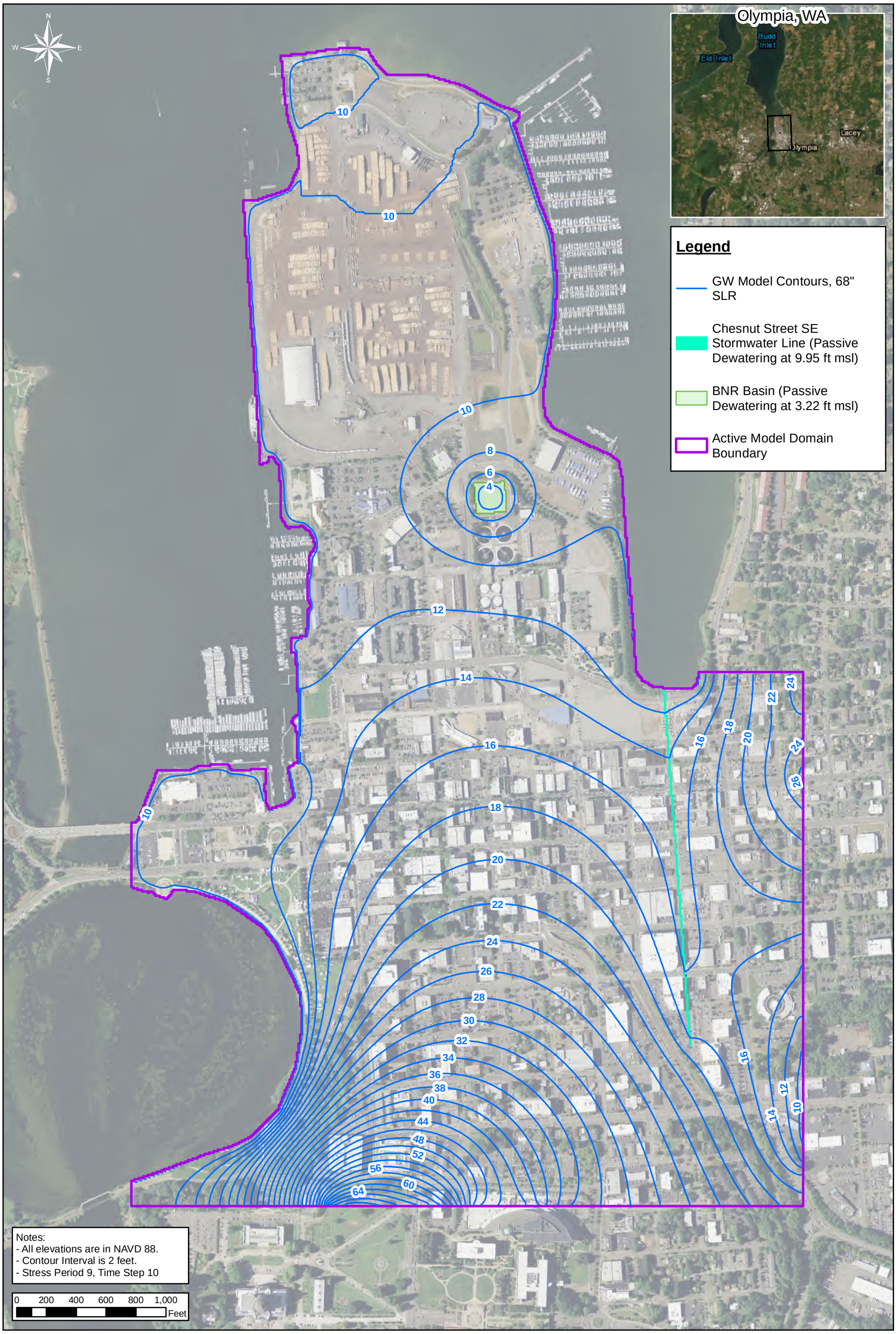


PIONEER TECHNOLOGIES CORPORATION

Modeled Groundwater Contours
60-inch Sea Level Rise
Sea Level Rise Groundwater Study
Olympia, Washington

Figure 5-5

Document Path: G:\Projects\LOTT\Maps\2025\January\Sea Level Rise Groundwater Study\Figure 5-5 Modeled Groundwater Contours 60-inch Sea Level Rise.mxd; Author: CO; Date Saved: 1/13/2025

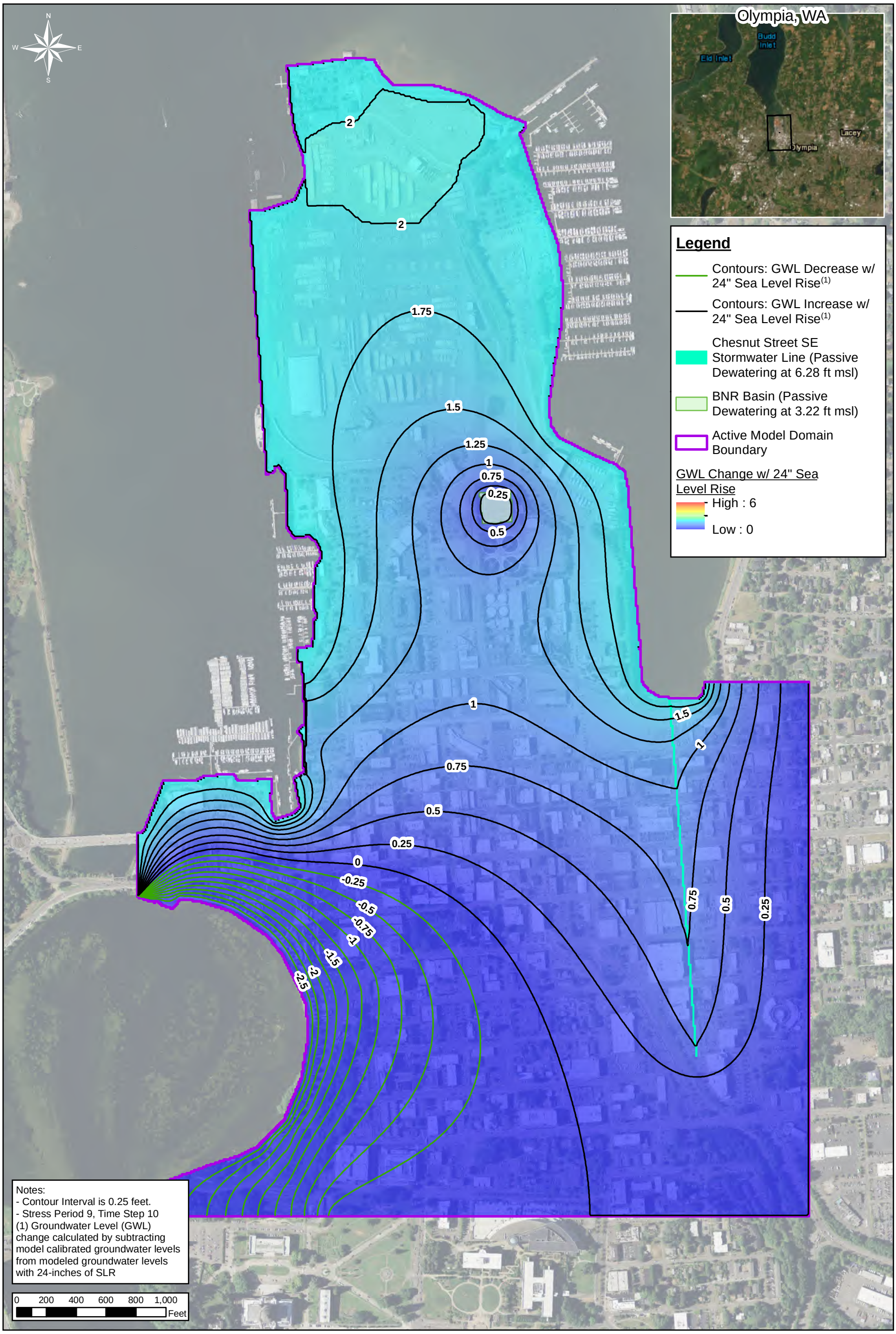


PIONEER TECHNOLOGIES CORPORATION

Modeled Groundwater Contours
68-inch Sea Level Rise
Sea Level Rise Groundwater Study
Olympia, Washington

Figure 5-6

Document Path: G:\Projects\LOTT\Maps\2025\January\Sea Level Rise Groundwater Study\Figure 5-6 Modeled Groundwater Contours 68-inch Sea Level Rise.mxd; Author: CO; Date Saved: 1/13/2025

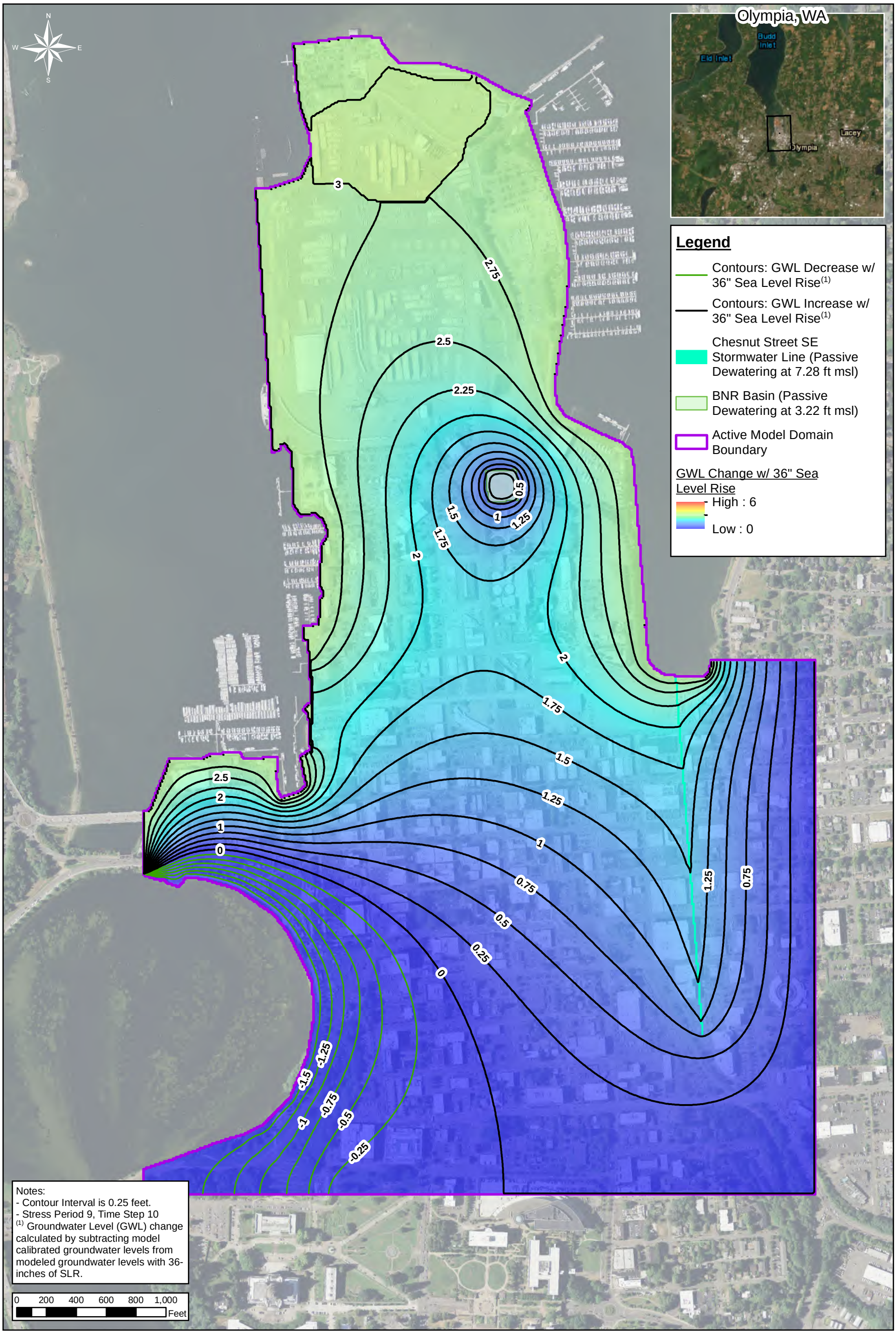


PIONEER TECHNOLOGIES CORPORATION

Modeled Groundwater Rise (feet)
24-inch Sea Level Rise
Sea Level Rise Groundwater Study
Olympia, Washington

Figure 5-7

Document Path: G:\Projects\LOTT\Maps\2025\January\Sea Level Rise Groundwater Study\Figure 5-7 Modeled Groundwater Rise 24-inch Sea Level Rise.mxd; Author: CO; Date Saved: 1/13/2025

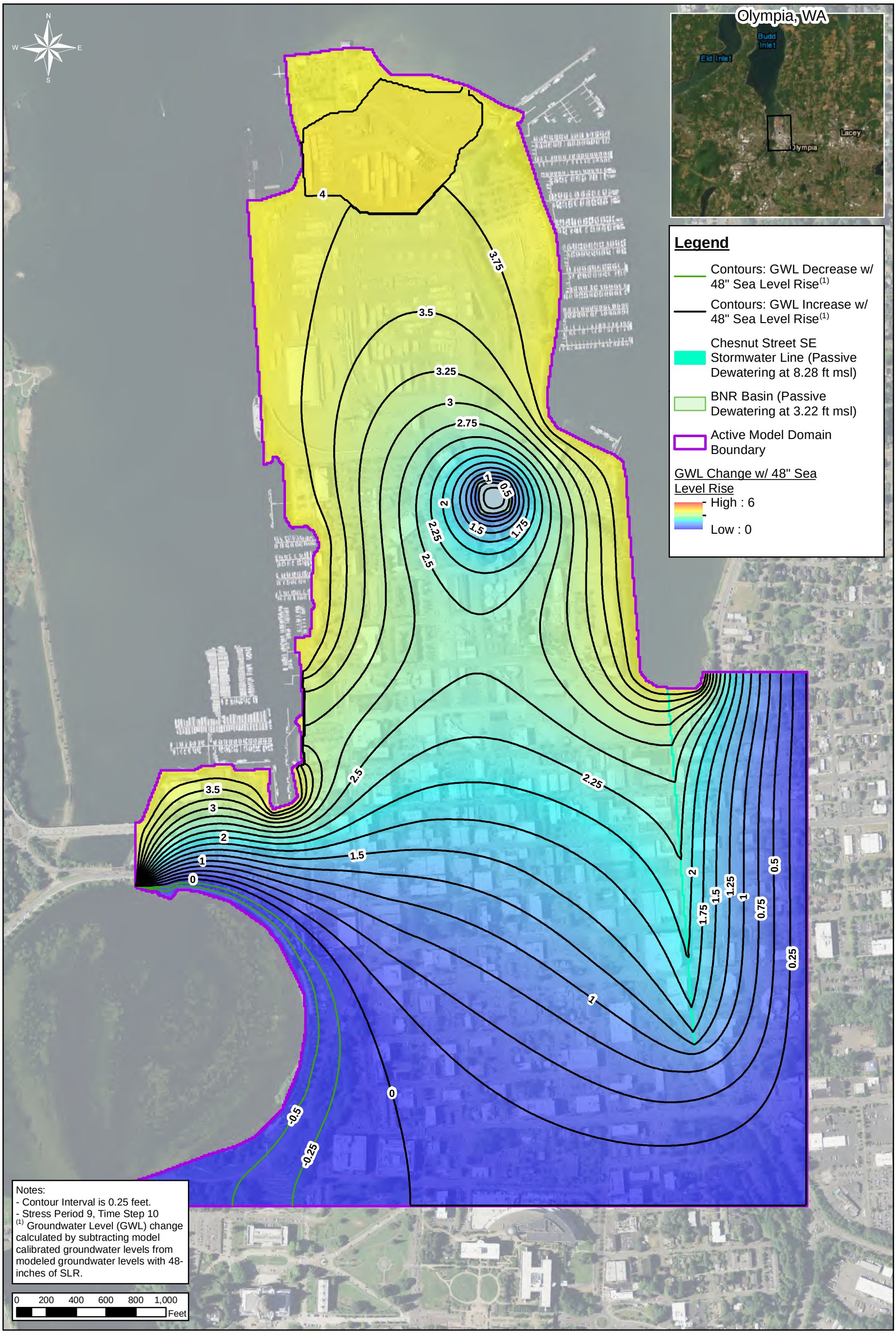


PIONEER TECHNOLOGIES CORPORATION

Modeled Groundwater Rise (feet)
36-inch Sea Level Rise
Sea Level Rise Groundwater Study
Olympia, Washington

Figure 5-8

Document Path: G:\Projects\LOTT\Maps\2025\January\Sea Level Rise Groundwater Study\Figure 5-8 Modeled Groundwater Rise 36-inch Sea Level Rise.mxd; Author: CO; Date Saved: 1/13/2025

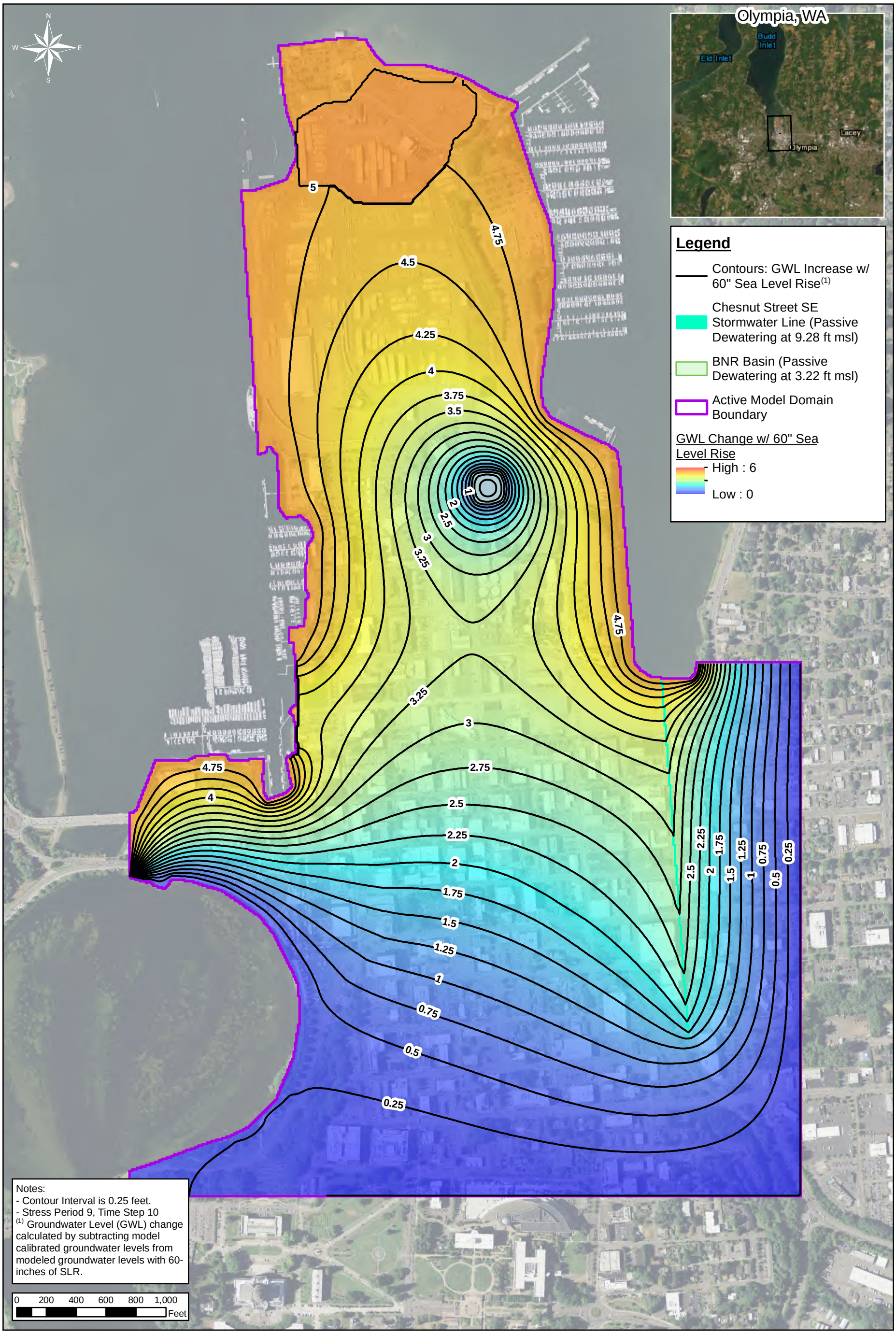


PIONEER TECHNOLOGIES CORPORATION

Modeled Groundwater Rise (feet)
48-inch Sea Level Rise
Sea Level Rise Groundwater Study
Olympia, Washington

Figure 5-9

Document Path: G:\Projects\LOTT\Maps\2025\January\Sea Level Rise Groundwater Study\Figure 5-9 Modeled Groundwater Rise 48-inch Sea Level Rise.mxd; Author: CO; Date Saved: 1/13/2025

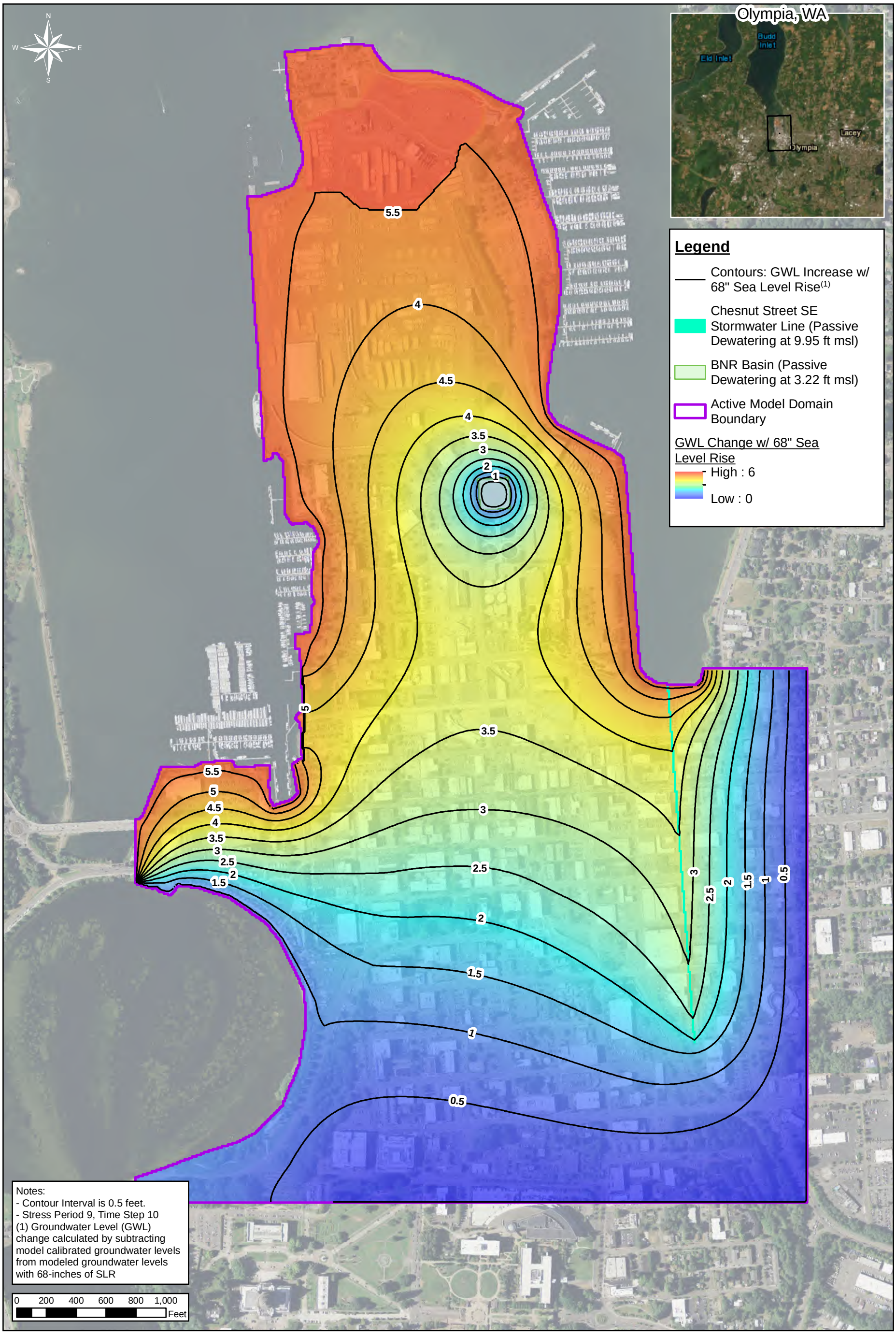


PIONEER TECHNOLOGIES CORPORATION

Modeled Groundwater Rise (feet)
60-inch Sea Level Rise
Sea Level Rise Groundwater Study
Olympia, Washington

Figure 5-10

Document Path: G:\Projects\LOTT\Maps\2025\January\Sea Level Rise Groundwater Study\Figure 5-10 Modeled Groundwater Rise 60-inch Sea Level Rise.mxd; Author: CO; Date Saved: 1/13/2025

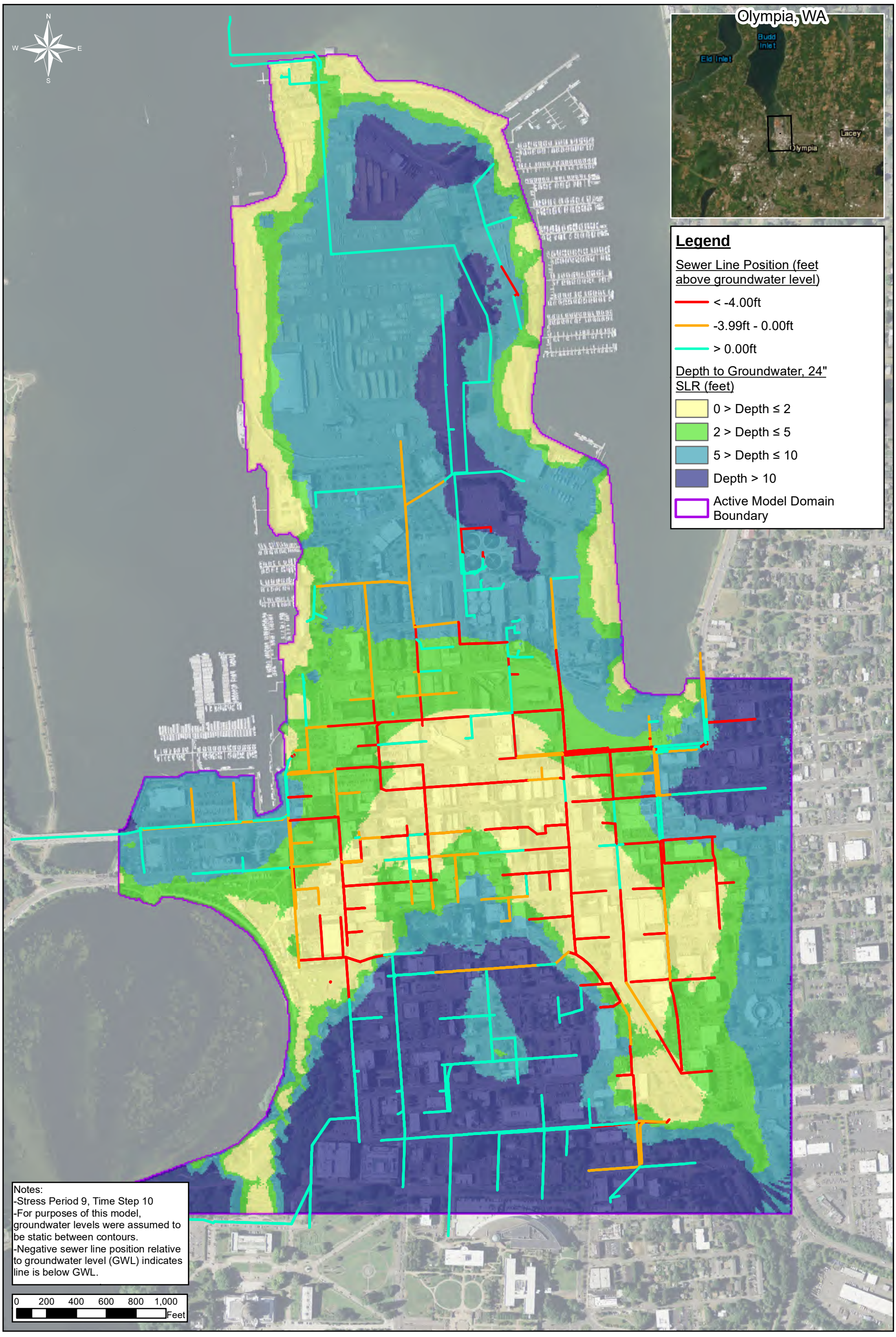


PIONEER TECHNOLOGIES CORPORATION

Modeled Groundwater Rise (feet)
68-inch Sea Level Rise
Sea Level Rise Groundwater Study
Olympia, Washington

Figure 5-11

Document Path: G:\Projects\LOTT\Maps\2025\January\Sea Level Rise Groundwater Study\Figure 5-11 Modeled Groundwater Rise 68-inch Sea Level Rise.mxd; Author: CO; Date Saved: 1/13/2025

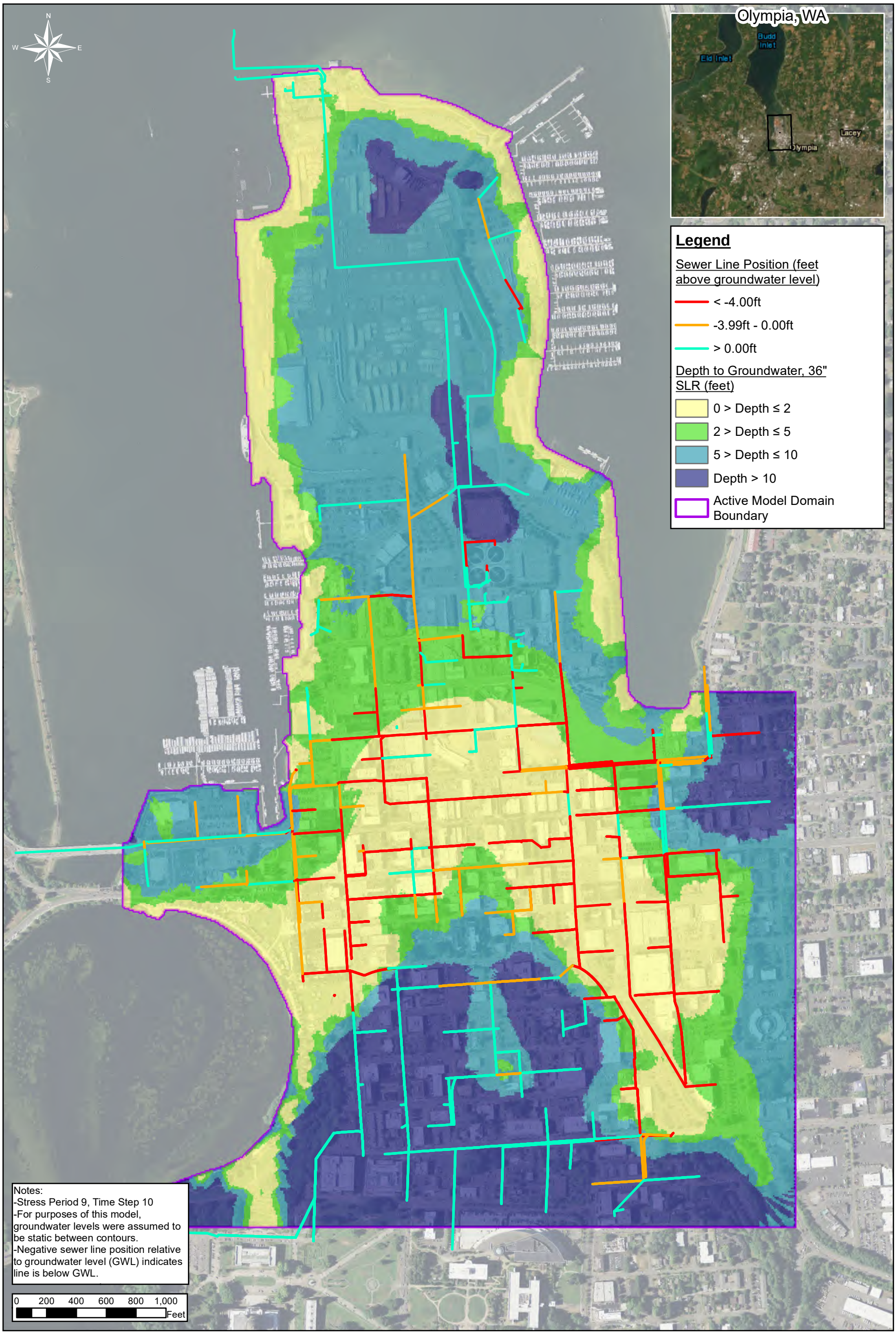


PIONEER TECHNOLOGIES CORPORATION

Depth to Groundwater and Sewer Line Depth Relative to Groundwater 24-inch SLR
Sea Level Rise Groundwater Study
Olympia, Washington

Figure 5-12

Document Path: G:\Projects\LOTT\Maps\2025\January\Sea Level Rise Groundwater Study\Figure 5-12 Depth to Groundwater and Sewer Line Depth Relative to Groundwater 24-inch SLR.mxd; Author: CO; Date Saved: 1/13/2025

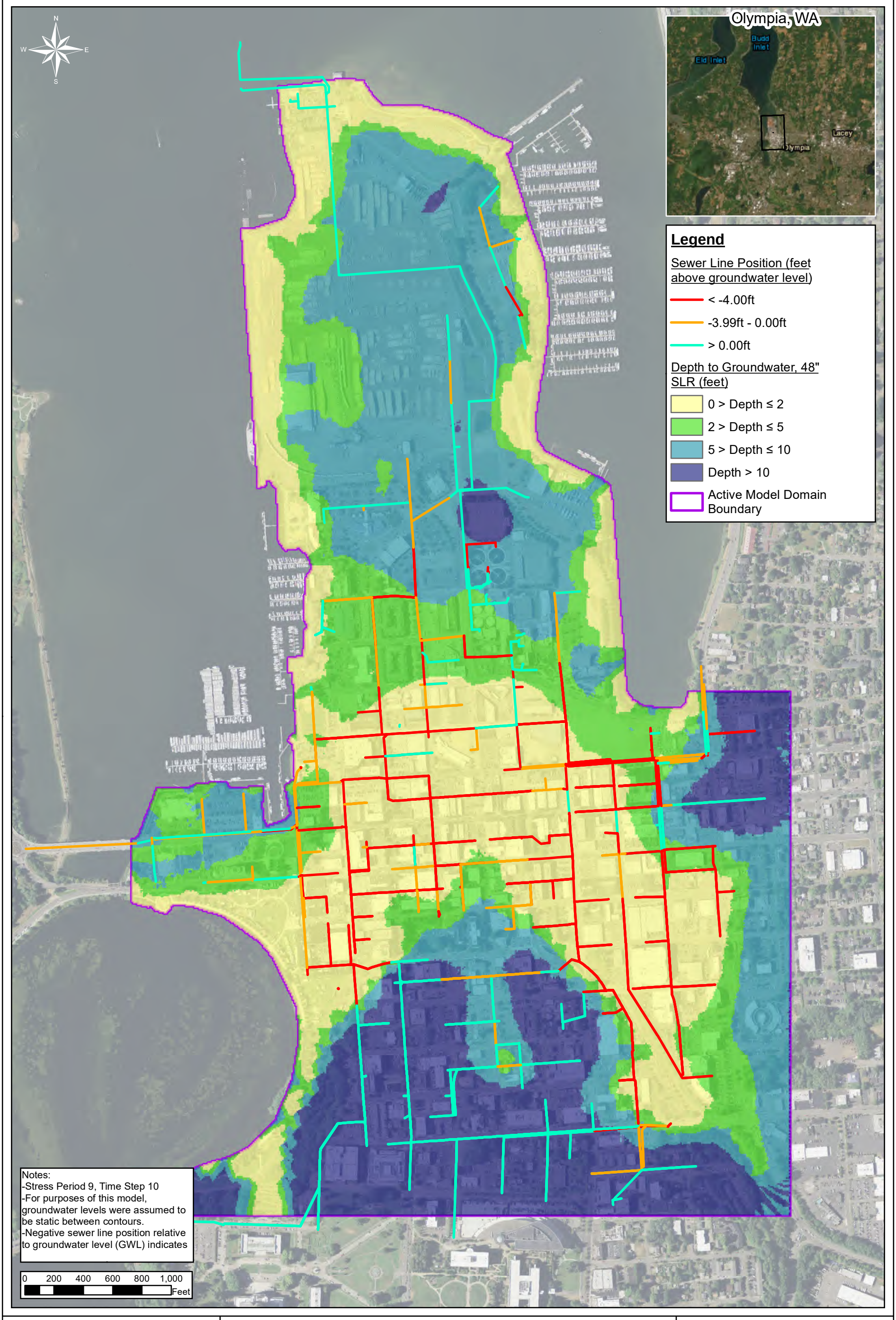


PIONEER TECHNOLOGIES CORPORATION

Depth to Groundwater and Sewer Line Depth Relative to Groundwater 36-inch SLR
Sea Level Rise Groundwater Study
Olympia, Washington

Figure 5-13

Document Path: G:\Projects\LOTT\Maps\2025\January\Sea Level Rise Groundwater Study\Figure 5-13 Depth to Groundwater and Sewer Line Depth Relative to Groundwater 36-inch SLR.mxd; Author: CO; Date Saved: 1/13/2025

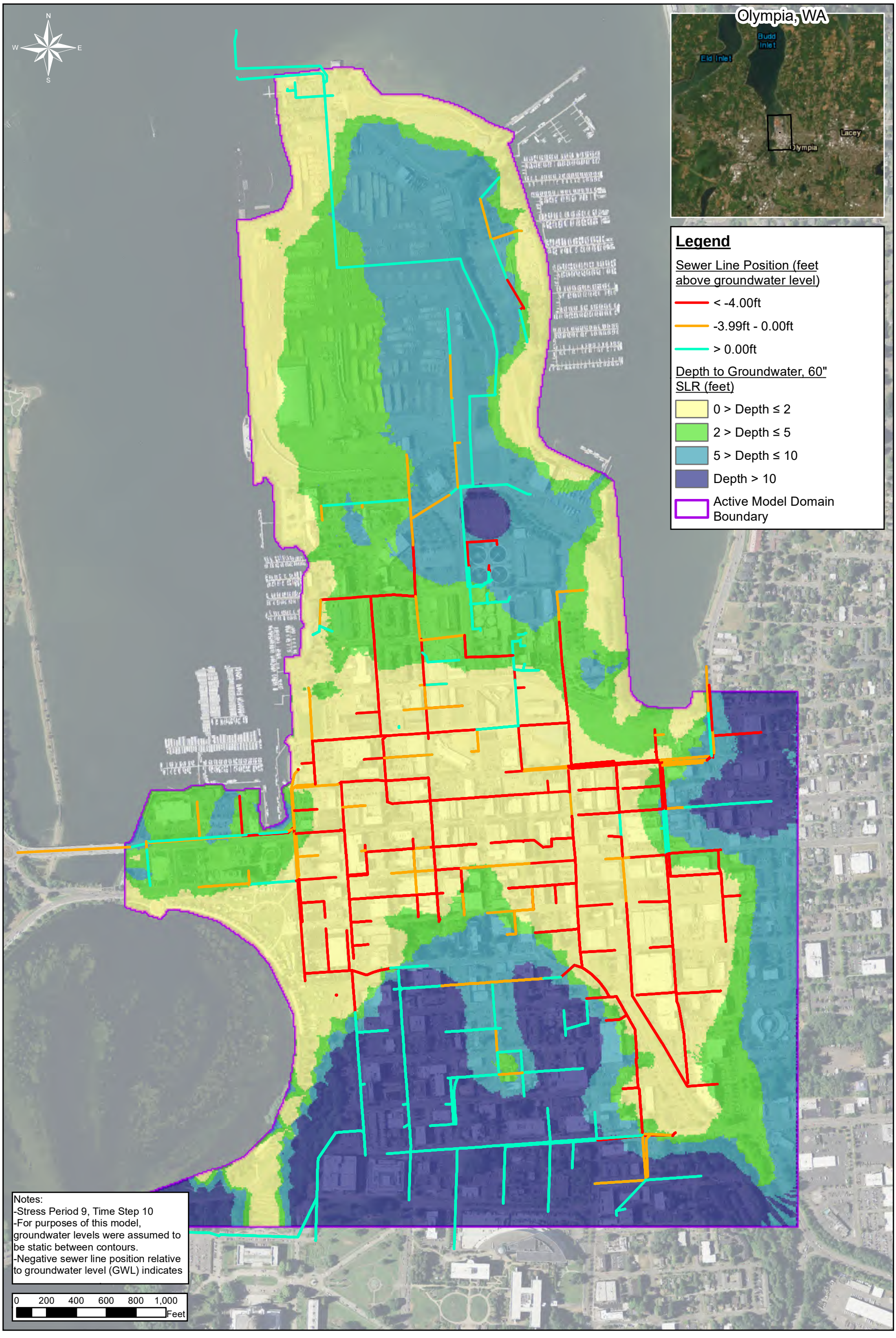


PIONEER TECHNOLOGIES CORPORATION

Depth to Groundwater and Sewer Line Depth Relative to Groundwater 48-inch SLR
Sea Level Rise Groundwater Study
Olympia, Washington

Figure 5-14

Document Path: G:\Projects\LOTT\Maps\2025\January\Sea Level Rise Groundwater Study\Figure 5-14 Depth to Groundwater and Sewer Line Depth Relative to Groundwater 48-inch SLR.mxd; Author: CO; Date Saved: 1/13/2025

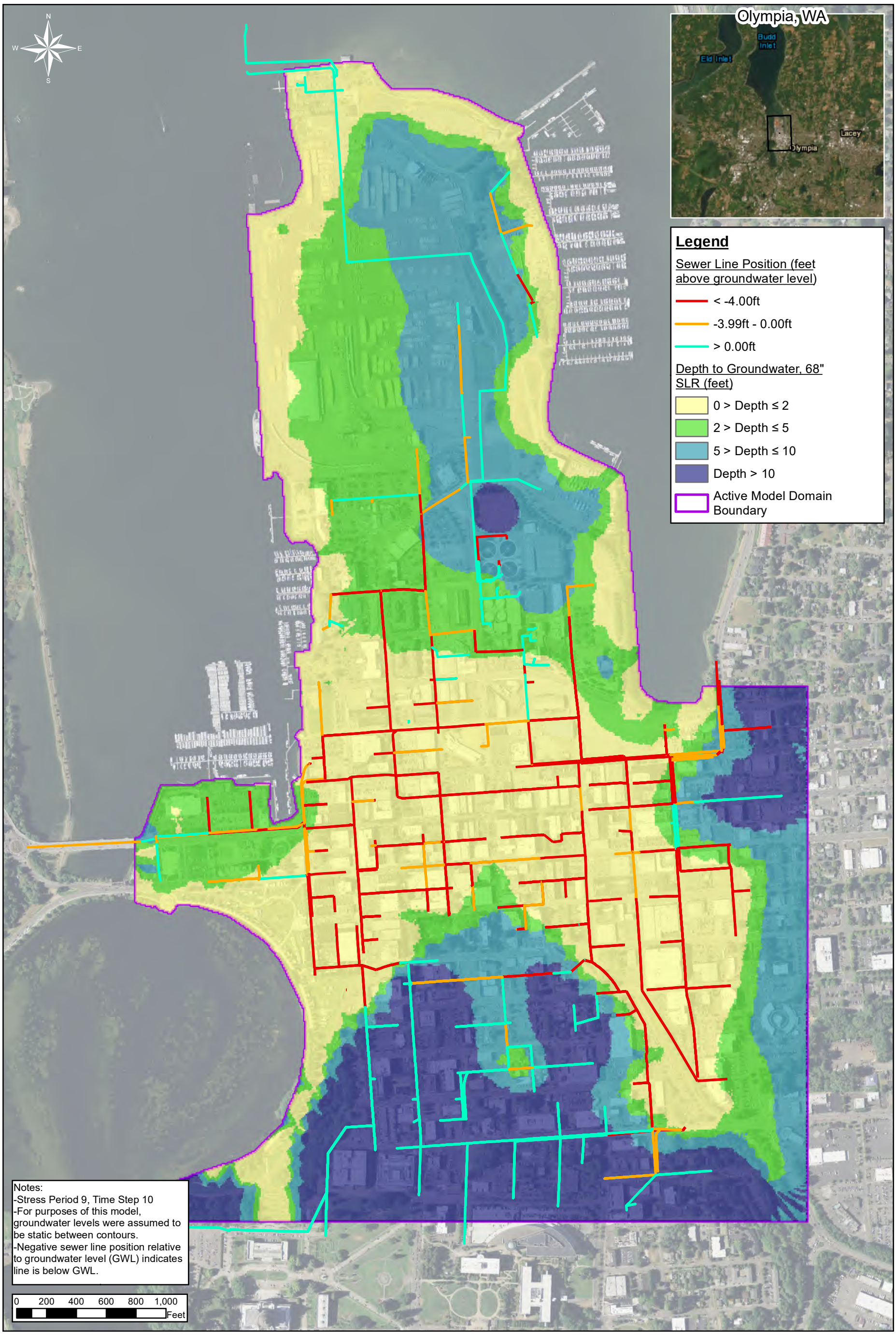


PIONEER TECHNOLOGIES CORPORATION

Depth to Groundwater and Sewer Line Depth Relative to Groundwater 60-inch Sea Level Rise
Sea Level Rise Groundwater Study
Olympia, Washington

Figure 5-15

Document Path: G:\Projects\LOTT\Maps\2025\January\Sea Level Rise Groundwater Study\Figure 5-15 Depth to Groundwater and Sewer Line Depth Relative to Groundwater 60-inch SLR.mxd; Author: CO; Date Saved: 1/13/2025

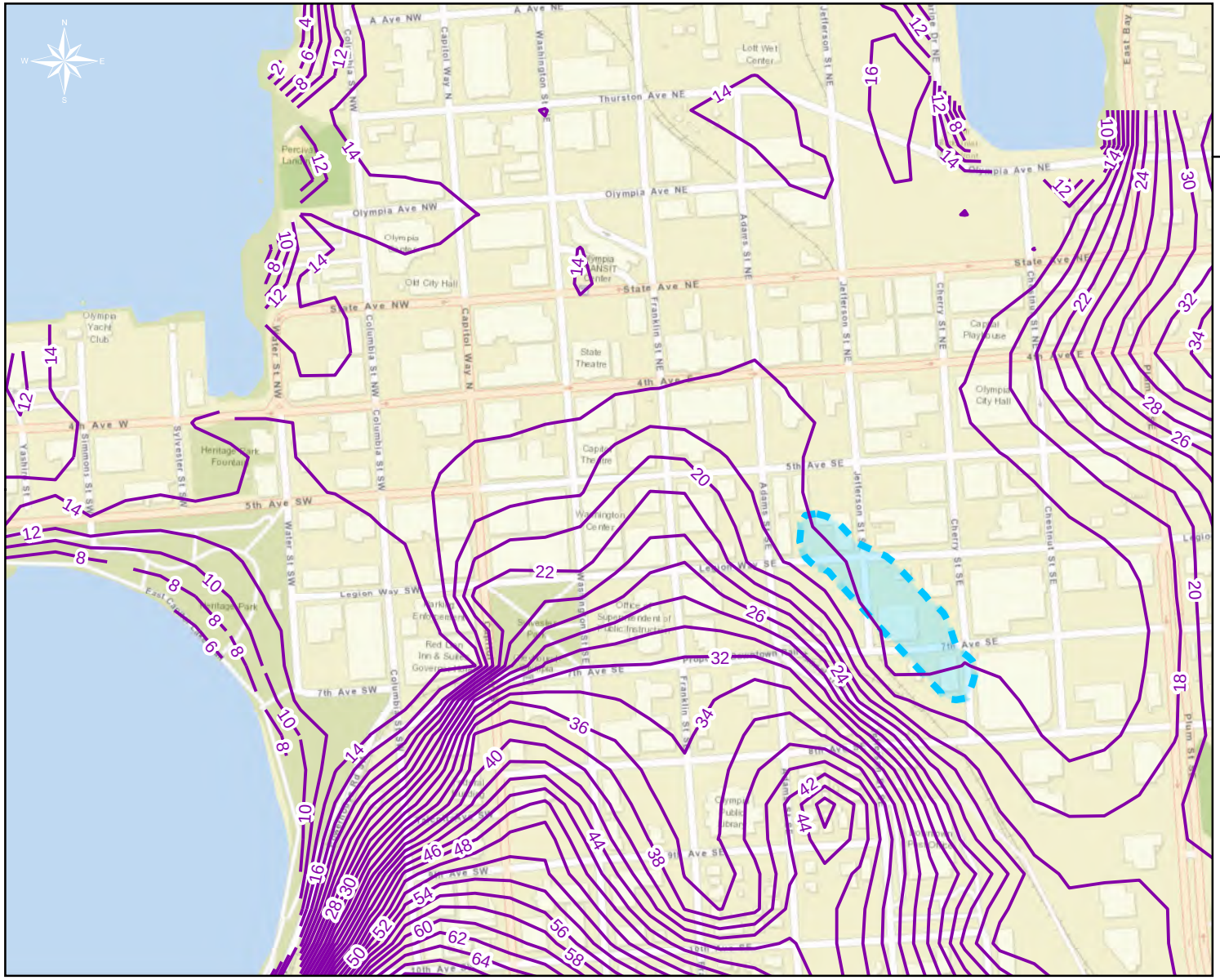


PIONEER TECHNOLOGIES CORPORATION

Depth to Groundwater and Sewer Line Depth Relative to Groundwater 68-inch Sea Level Rise
Sea Level Rise Groundwater Study
Olympia, Washington

Figure 5-16

Document Path: G:\Projects\LOTT\Maps\2025\January\Sea Level Rise Groundwater Study\Figure 5-16 Depth to Groundwater and Sewer Line Depth Relative to Groundwater 68-inch SLR.mxd; Author: CO; Date Saved: 1/13/2025



Legend

- Possible Groundwater Seepage
- Ground Surface Contours (2 ft Interval)

Notes:
-All elevations are in NAVD 88.
-Stress Period 9, Time Step 10

0 200 400 600 800 Feet

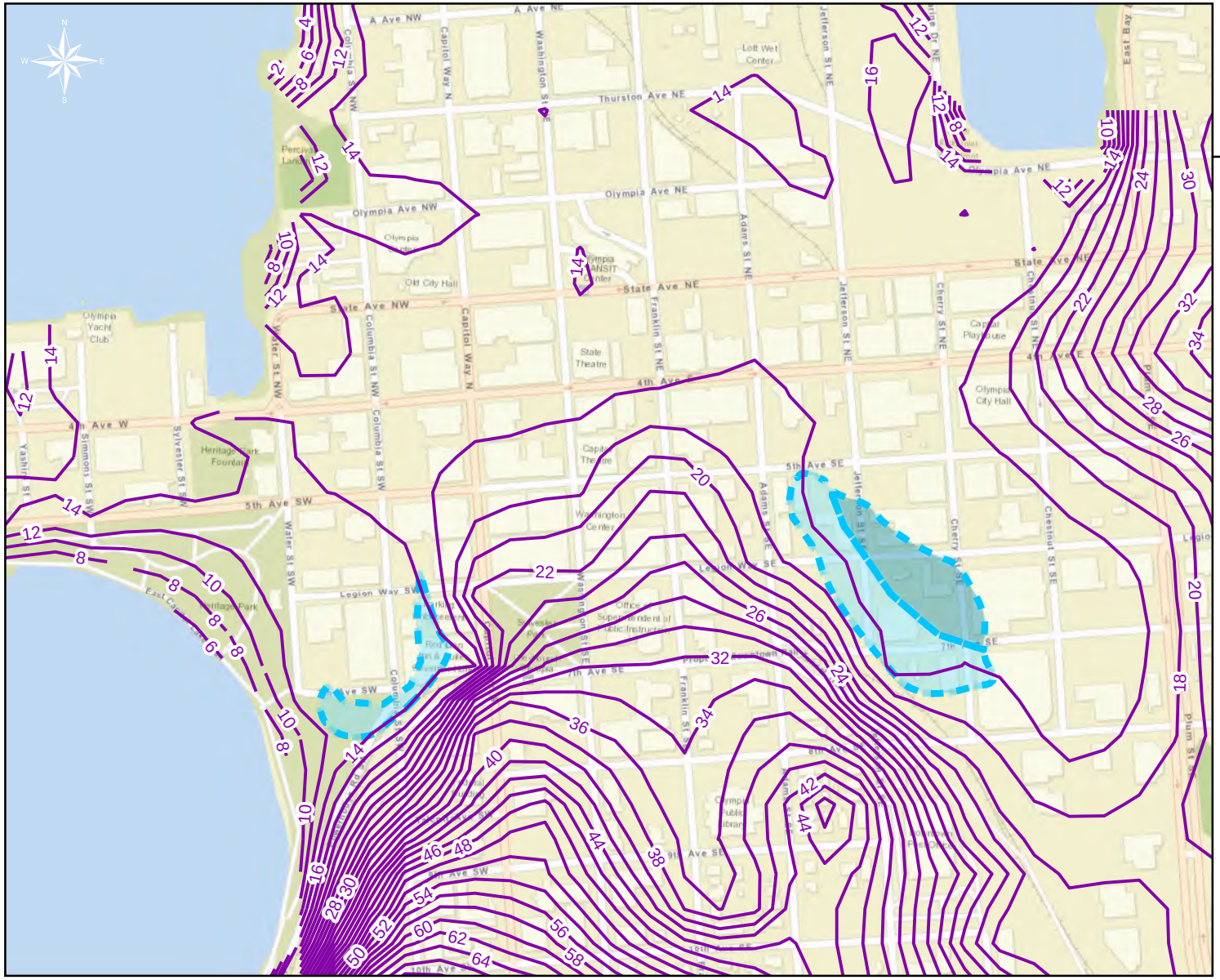
PIONEER TECHNOLOGIES CORPORATION

Possible Groundwater Surface Emergence 24-inch Sea Level Rise
Sea Level Rise Groundwater Study
Olympia, Washington

Figure 5-17

Document Path: G:\Projects\LOTT\Maps\2025\January\Sea Level Rise Groundwater Study\Figure 5-17 Possible Groundwater Surface Emergence 24-inch Sea Level Rise.mxd; Author: CO; Date Saved: 1/13/2025

Document Path: G:\Projects\LOTT\Maps\2025\January\Sea Level Rise Groundwater Study\Figure 5-18 Possible Groundwater Surface Emergence 36-inch Sea Level Rise.mxd; Author: CO; Date Saved: 1/13/2025



Legend

- Possible Groundwater Seepage
- Possible Surface Ponding of Groundwater
- Ground Surface Contours (2 ft Interval)

Notes:
-All elevations are in NAVD 88.
-Stress Period 9, Time Step 10

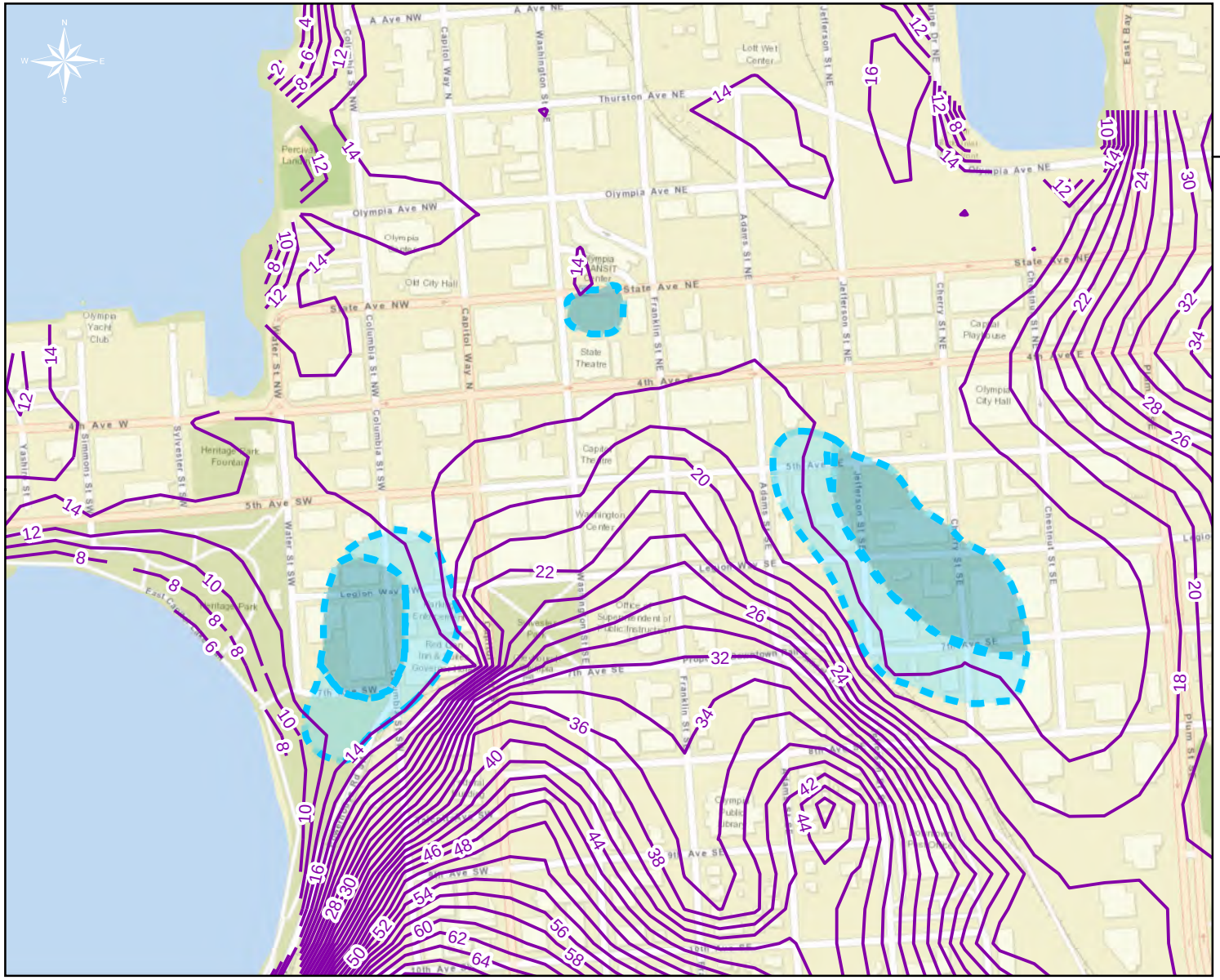
0 200 400 600 800 Feet

PIONEER TECHNOLOGIES CORPORATION

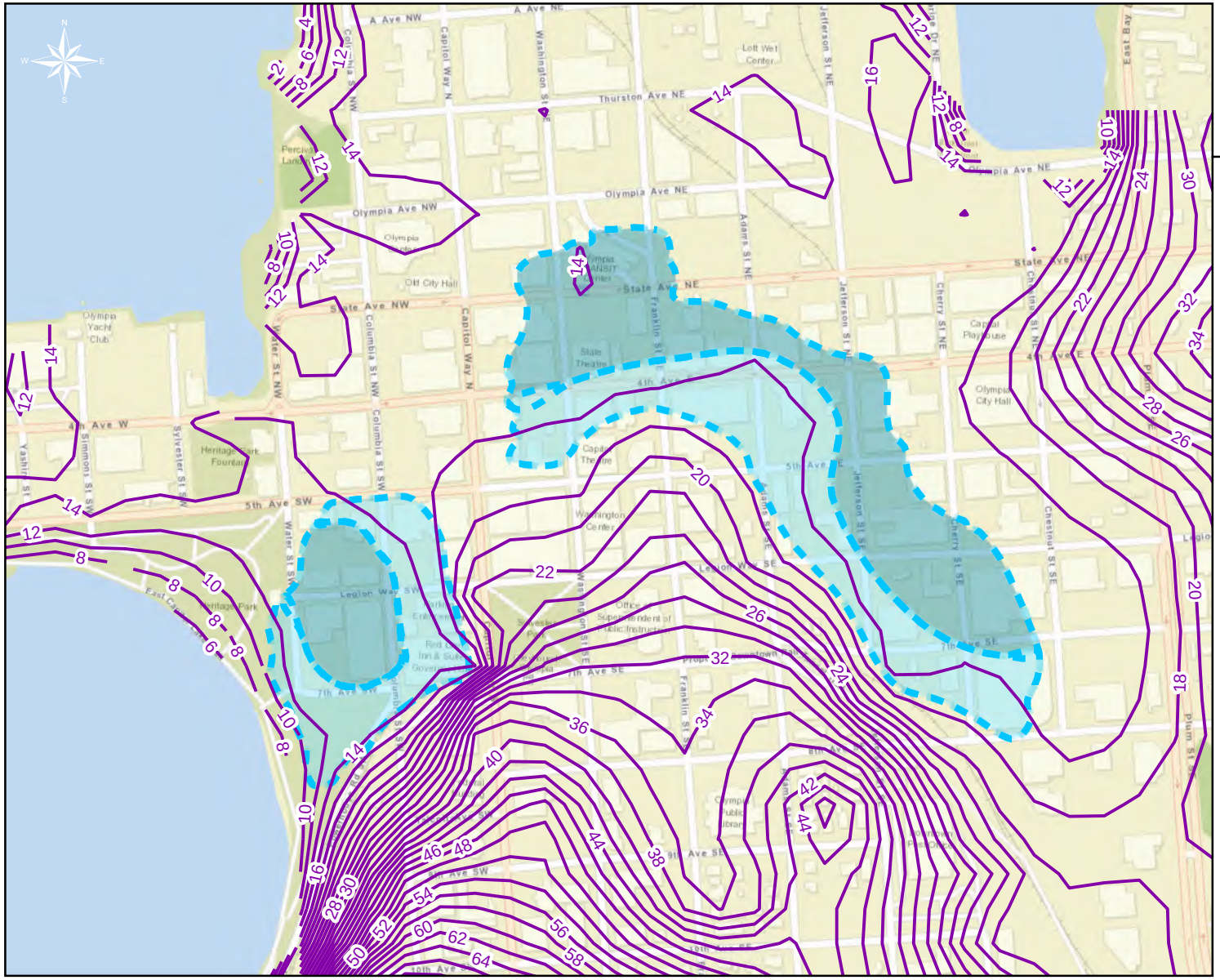
Possible Groundwater Surface Emergence 36-inch Sea Level Rise
Sea Level Rise Groundwater Study
Olympia, Washington

Figure 5-18

Document Path: G:\Projects\LOTT\Maps\2025\January\Sea Level Rise Groundwater Study\Figure 5-19 Possible Groundwater Surface Emergence 48-inch Sea Level Rise.mxd; Author: CO; Date Saved: 1/13/2025


A Ave NW
A Ave NE
Thurston Ave NE
Olympia Ave NE
Olympia Ave NW
State Ave NE
State Ave NW
4th Ave W
4th Ave E
5th Ave SW
5th Ave SE
7th Ave SE
Capitol Way N
Washington St NE
Jefferson St NE
Adams St NE
Franklin St NE
Cherry St NE
Columbia St NW
Water St NW
Water St SW
Legion Way SE
Old City Hall
State Theatre
Capitol Theatre
Olympia City Hall
Capitol Playhouse
Olympia Yacht Club
East Bay
Lott Wet Center
Heritage Park Fountain
Washington Center
Office Superintendent of Public Instruction
Olympia Public Library
Olympia Transit Center
Percival Landing
East Bay Park
Red Lion Inn & Suites Olympia
Phoenix Inn Suites Downtown
Courtyard Olympia Downtown
Hampton Inn & Suites Olympia Downtown
Governor House Hotel
Quality Inn & Suites Capitol Hill
Best Western Plus Olympia Hotel
Hotel RL by Red Lion
Hilton Garden Inn Olympia
Residence Inn by Marriott Olympia Downtown
Courtyard by Marriott Olympia
Fairfield Inn & Suites by Marriott Olympia
Hotel Indigo Olympia
Hotel Captain Cook
Olympia Hotel
Hotel Deschutes
Hotel Olympia
Hotel Budd Bay
Hotel Olympian
Hotel Olympic
Hotel Olympus
Hotel Olympia
Hotel Olympia
Hotel Olympia

Document Path: G:\Projects\LOTT\Maps\2025\January\Sea Level Rise Groundwater Study\Figure 5-20 Possible Groundwater Surface Emergence 60-inch Sea Level Rise.mxd; Author: CO; Date Saved: 1/13/2025



Legend

- Possible Groundwater Seepage
- Possible Surface Ponding of Groundwater
- Ground Surface Contours (2 ft Interval)

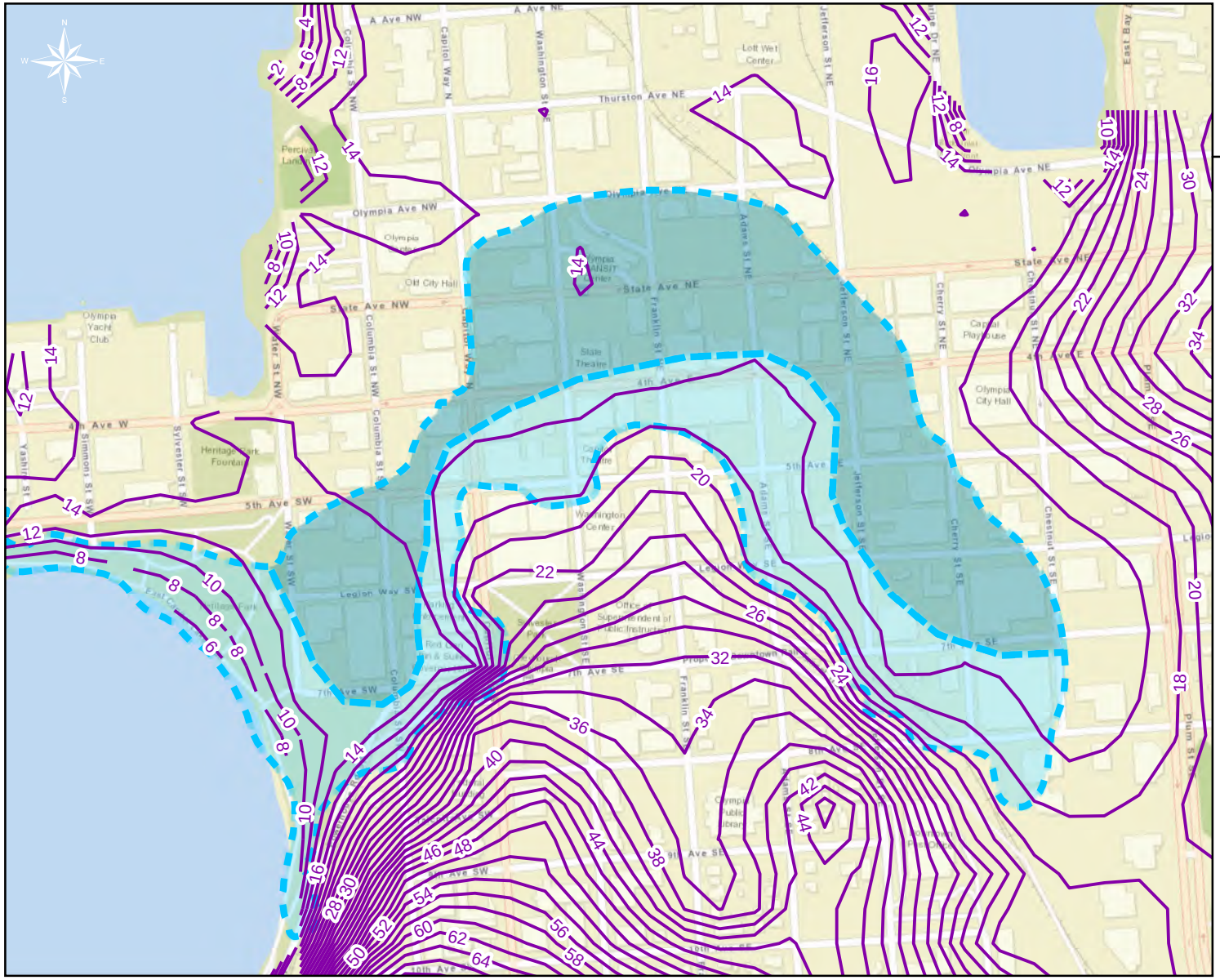
Notes:
-All elevations are in NAVD 88.
-Stress Period 9, Time Step 10

0 200 400 600 800 Feet

PIONEER TECHNOLOGIES CORPORATION

Possible Groundwater Surface Emergence 60-inch Sea Level Rise
Sea Level Rise Groundwater Study
Olympia, Washington

Figure 5-20



Legend

- Possible Groundwater Seepage
- Possible Surface Ponding of Groundwater
- Ground Surface Contours (2 ft Interval)

Notes:
-All elevations are in NAVD 88.
-Stress Period 9, Time Step 10

0 200 400 600 800 Feet

PIONEER TECHNOLOGIES CORPORATION

Possible Groundwater Surface Emergence 68-inch Sea Level Rise
Sea Level Rise Groundwater Study
Olympia, Washington

Figure 5-21

Document Path: G:\Projects\LOTT\Maps\2025\January\Sea Level Rise Groundwater Study\Figure 5-21 Possible Groundwater Surface Emergence 68-inch Sea Level Rise.mxd; Author: CO; Date Saved: 1/13/2025

Tables

Table 3-1: Groundwater Model Construction Parameters

Item	Description
Computer Code	MODFLOW-2005
Pre- and Post-Processor	Groundwater Vistas
Horizontal Coordinate System	State Plane Washington South NAD 83/91
Vertical Datum	NAVD 1988 DATUM
Volume Units	Cubic Feet
Distance Units	Feet
Time Units	Days
Model Domain Dimensions	9,000 North-South and 4,500 East-West
Model Domain Total Area	40,500,000
Model Domain Active Area	21,550,500
Cell Size	10 by 10
Total Active Cells	215,505
Rows	900
Columns	450
Layers	1
Layer Bottom (ft msl)	minus 20
Solver	Preconditioned Conjugate-Gradient 2
Closure Criteria for Head Change	0.001
Horizontal Hydraulic Conductivity	12
Vertical Hydraulic Conductivity	1.2
Specific Storage	0.005
Specific Yield	0.185
Porosity	0.25
Constant Head - Budd Inlet Mean Tide Level[1]	4.28
Constant Head - Budd Inlet Mean Tide Level with 24-inches of SLR	6.28
Constant Head - Budd Inlet Mean Tide Level with 36-inches of SLR	7.28
Constant Head - Budd Inlet Mean Tide Level with 48-inches of SLR	8.28
Constant Head - Budd Inlet Mean Tide Level with 60-inches of SLR	9.28
Constant Head - Budd Inlet Mean Tide Level with 68-inches of SLR	9.95
Constant Head - Capitol Lake Typical Water Level[1, 2]	9
Constant Head - Eastern Upland Model Boundary	10 ft Below Ground Surface
Constant Head - Southeastern Upland Model Boundary[4,5]	34 to 18.5
Constant Head - Southern Upland Model Boundary[4]	26 ft Below Ground Surface
Drain Stage - Aeration Basin	3.22
Drain Width - Aeration Basin	250
Drain Length - Aeration Basin	250
Drain Bed Thickness - Aeration Basin	3
Drain Bed Hydraulic Conductivity - Aeration Basin	0.001
Drain Bed Hydraulic Conductivity - Chestnut Street NE Stormwater Line	0.15
Drain Stage - Chestnut Street SE Stormwater Line[3]	5.04
Drain Width - Chestnut Street SE Stormwater Line	8
Drain Length - Chestnut Street SE Stormwater Line	10
Drain Bed Thickness - Chestnut Street SE Stormwater Line	1
Horizontal Flow Barrier Thickness - Cascade Pole Slurry Wall	2
Horizontal Flow Barrier Hydraulic Conductivity - Cascade Pole Slurry Wall	1.70E-04
Horizontal Flow Barrier Thickness - Percival Park Sheet Piling Wall	1
Horizontal Flow Barrier Hydraulic Conductivity - Percival Park Sheet Piling Wall	1.42E-06

Notes:

[1]- Budd Inlet Mean Tide Level and Capital Lake Typical Water Level are from the Olympia Sea Level Rise Response Plan (March 2019).

[2]- Capitol Lake water level assumed to be in equilibrium with the mean sea level of Budd Inlet for the SLR scenarios.

[3]- Stormwater drain outfall assumed to be at 5.04 ft msl for calibration (current day), then assumed to be in equilibrium with the mean sea level of Budd Inlet for the SLR scenarios.

[4]- Southeastern and Southern Upland Model Boundaries join at model column 295.

[5]- Constant Head Boundary along South Eastern Upland Model Boundary is an even grade going from 34 to 18.5 ft to the east.

Table 3-2: Groundwater Model Stress Periods, Recharge, and Drain Schedule

Stress Period	Stress Period Type	Period Length (days)	No. Time Steps	Time Step Multiplier[1]	Cumulative Days	Modeled Date	Recharge (ft/day)[2, 3]	Drains Operating[4]
1	Steady State	100	1	1.2	100	N/A	2.00E-03	No
2	Steady State	100	1	1.2	200	N/A	2.00E-03	No
3	Transient	240	10	1.2	440	6/16/2022	2.00E-03	Yes
4	Transient	105	10	1.2	545	9/29/2022	4.20E-05	Yes
5	Transient	153	10	1.2	698	3/1/2023	2.00E-03	Yes
6	Transient	68	10	1.2	766	5/8/2023	2.00E-03	Yes
7	Transient	105	10	1.2	870	8/21/2023	4.20E-05	Yes
8	Transient	41	10	1.2	911	10/1/2023	4.20E-05	Yes
9	Transient	228	10	1.2	1139	5/16/2024	2.00E-03	Yes

Notes:

[1]- The time step multiplier is the factor used to increment the time step size within each stress period (i.e. it is the ratio of the value of each time step to that of the preceding time step). The MODFLOW default value is 1.2.

[2]- Recharge represents water entering the shallow water bearing unit via two mechanisms: (1) Upward migration of groundwater from the pressurized (artesian) lower confined unit, and (2) Precipitation infiltration.

[3]- Recharge within the Cascade Pole Cleanup Site slurry wall was set to the dry season recharge value for all stress periods to simulate the Cascade Pole impervious surface cap and remedial groundwater pumping.

[4]- Drains are active for stress periods 3 through 9.

Table 4-1: Shallow Groundwater Monitoring Well Location Survey

Monitoring Well ID	Northing	Easting	Top of Casing Elevation
MW-DW1	635196.0	1042305.2	13.86
MW-DW2	635512.8	1042449.4	16.68
MW-25L	634346.5	1042488.7	13.29
MW-26L	634319.1	1042554.1	13.83
MW-20R[1]	634837.4	1042866.4	15.47
MW-DW3	635161.0	1042536.1	17.39
MW-DW4	634607.3	1042610.8	14.33
EG	631413.2	1043470.9	24.45
IS	633717.9	1042018.6	13.86
JC	630939.0	1042002.9	86.71
KB	633151.3	1041609.8	15.65
KM[1]	633454.7	1043913.0	30.35
MD	633659.1	1041141.2	14.73
MJ	633812.4	1042482.9	14.76
NY	632671.6	1042604.1	23.14
OK	634455.0	1041502.1	15.34
OM	634252.0	1041658.2	14.28
OQ	632258.2	1043732.7	15.46
OW	631270.7	1041971.5	69.31
PT	633824.1	1042672.4	13.98
PV	633625.2	1042582.0	14.12
TB	633178.0	1041100.2	14.11
TC	633182.1	1041167.8	13.71
TM	635196.2	1042305.1	13.86
TN	635512.9	1042449.4	16.68
TO	634346.5	1042489.0	13.29
TP	634319.1	1042554.5	13.83
TR	635161.7	1042536.1	17.39
TS	634607.7	1042611.3	14.33

Notes:

[1]- Measured groundwater levels in MW-20R and KM were anomalous and were not used to calibrate the model. Listed MWs are screened across the shallow groundwater bearing unit.

Table 4-2: Observed and Modeled Groundwater Elevations

Monitoring Well ID	Date	Model Day	Observed Groundwater Elevation	Modeled Groundwater Elevation	Residual[1]
MW-DW1	6/16/2022	440	5.18	5.20	-0.02
MW-DW1	9/29/2022	545	4.63	4.65	-0.02
MW-DW1	3/1/2023	698	4.96	4.90	0.06
MW-DW1	8/21/2023	870	4.58	4.51	0.07
MW-DW1	5/16/2024	1139	4.68	4.85	-0.17
MW-DW2	6/16/2022	440	5.07	4.37	0.70
MW-DW2	9/29/2022	545	4.33	3.98	0.35
MW-DW2	3/1/2023	698	4.85	4.22	0.63
MW-DW2	8/21/2023	870	4.49	3.91	0.58
MW-DW2	5/16/2024	1139	4.59	4.21	0.38
MW-25L	6/16/2022	440	10.41	10.21	0.20
MW-25L	9/29/2022	545	8.16	9.10	-0.94
MW-25L	3/1/2023	698	9.05	9.42	-0.37
MW-25L	8/21/2023	870	8.57	8.67	-0.10
MW-25L	5/16/2024	1139	9.10	9.22	-0.12
MW-26L	6/16/2022	440	10.25	10.21	0.04
MW-26L	9/29/2022	545	9.05	9.12	-0.07
MW-26L	3/1/2023	698	9.26	9.45	-0.19
MW-26L	8/21/2023	870	8.52	8.70	-0.18
MW-26L	5/16/2024	1139	9.23	9.24	-0.01
MW-DW3	3/1/2023	698	5.01	5.13	-0.12
MW-DW3	8/21/2023	870	3.94	4.68	-0.74
MW-DW3	5/16/2024	1139	4.89	5.09	-0.20
MW-DW4	3/1/2023	698	7.18	8.03	-0.85
MW-DW4	8/21/2023	870	7.06	7.30	-0.24
MW-DW4	5/16/2024	1139	7.38	7.88	-0.50
EG	8/21/2023	870	24.25	23.24	1.01
EG	5/16/2024	1139	24.25	23.88	0.37
IS	8/21/2023	870	9.22	11.45	-2.23
IS	5/16/2024	1139	9.70	11.95	-2.25
JC	8/21/2023	870	49.38	50.39	-1.01
JC	5/16/2024	1139	50.01	50.71	-0.70
KB	8/21/2023	870	9.76	12.40	-2.64
KB	5/16/2024	1139	10.07	12.93	-2.86
KM[2]	8/21/2023	870	24.37	15.03	9.34
KM[2]	5/16/2024	1139	25.18	15.54	9.64
MD	8/21/2023	870	7.96	7.82	0.14
MD	5/16/2024	1139	7.77	8.27	-0.50
MJ	8/21/2023	870	9.75	11.35	-1.60
MJ	5/16/2024	1139	10.50	11.85	-1.35
NY	8/21/2023	870	19.90	18.66	1.24
NY	5/16/2024	1139	19.94	19.21	0.73
OK	8/21/2023	870	8.65	6.62	2.03
OK	5/16/2024	1139	8.78	7.08	1.70
OM	8/21/2023	870	8.33	8.06	0.27
OM	5/16/2024	1139	8.92	8.58	0.34
OQ	8/21/2023	870	12.06	12.45	-0.39
OQ	5/16/2024	1139	12.39	12.96	-0.57
OW	8/21/2023	870	42.57	40.22	2.35
PT	5/16/2024	870	9.91	11.02	-1.11
PT	8/21/2023	1139	10.67	11.54	-0.87
PV	5/16/2024	870	10.17	12.30	-2.13
PV	8/21/2023	1139	11.27	12.80	-1.53
TB	5/16/2024	870	7.85	7.15	0.70
TB	8/21/2023	1139	7.91	7.48	0.43
TC	5/16/2024	870	8.02	7.91	0.11
TC	8/21/2023	1139	8.22	8.29	-0.07

Notes:

[1]-Residual is the observed groundwater elevation minus the modeled groundwater elevation.

[2]-Groundwater elevation and residuals from MW KM were excluded from model calibration (see Section 4.2 for details).

Table 4-3: Groundwater Model Calibration Statistics

Statistic	Value
Residual Mean	-0.22
Absolute Residual Mean	0.75
Residual Std. Deviation	1.03
Root Mean Square Error	1.06
Min. Residual	-2.86
Max. Residual	2.35
Number of Observations	55
Range in Observations	46.07
Scaled Residual Std. Deviation	2.2%
Scaled Absolute Residual Mean	1.6%
Scaled RMS Error	2.3%
Scaled Residual Mean	-0.5%

Notes:

Scaled values are the value divided by range in observations (total groundwater level change).