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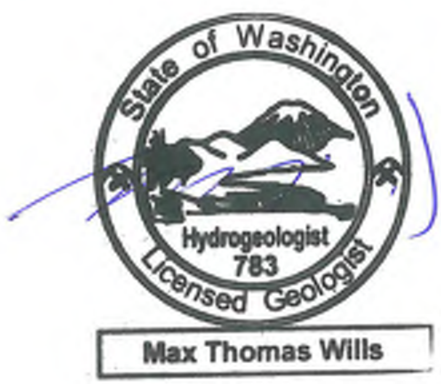
OLYMPIC VIEW WATER AND SEWER DISTRICT
WELLHEAD PROTECTION AREA DELINEATION
DEER CREEK SPRINGS AND 228TH STREET WELLFIELD

August 2018

by

Max T. Wills, LHG
Associate Hydrogeologist



2105 South C Street
Tacoma, Washington 98402
P: 253.475.7711 | F: 253.472.5846

www.robinson-noble.com

17625 130th Avenue NE, Suite 102
Woodinville, Washington 98072
P: 425.488.0599 | F: 425.488.2330

Olympic View Water and Sewer District
Wellhead Protection Area Delineation
Deer Creek Springs and 228th Street Wellfield
August 2018

FIGURES

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1.0 Introduction and Background

The Olympic View Water & Sewer District (District) provides water to an estimated 13,000 customers within an approximately two square mile service area in southwestern Snohomish County (PACE, 2009). The District currently receives about 60% of their supply water through an intertie with the City of Seattle. The remaining 40% is derived from the District's water treatment plant at Deer Creek Springs. The District is also currently in the process of developing an additional groundwater source at their 228th Street wellfield. This wellfield will augment the supply from Deer Creek Springs and reduce dependency on the water purchased from Seattle. The District recently completed the construction and testing of two supply wells at the 228th Street site and is currently in the process of constructing site infrastructure. Figure 1 presents a map of the District's service area and shows the locations of the Deer Creek Springs and 228th Street wellfield source areas.

In anticipation of bringing the new wellfield online, the District is updating their existing Wellhead Protection Program (WHPP) to include the new wellfield source and a more current assessment of the spring source. As part of the WHPP update, Robinson Noble was retained to delineate wellhead protection areas (WHPAs) for the 228th Street wellfield and to re-delineate and update the WHPAs for the spring source. This report documents the methods utilized to complete the delineation process and presents the new wellfield WHPAs and the updated WHPAs for the existing spring source.

2.0 Wellhead Protection Area Delineation

2.1 General

The Washington State Department of Health's (DOH) Wellhead Protection Program Guidance (DOH, 2010) states that all Group A public water systems[1] must prepare a Water System Plan (WAC 246-290-100), which will include a Wellhead Protection Program (WHPP). The WHPP will in turn include Wellhead Protection Areas (WHPAs) delineated for each well, wellfield, or spring source (WAC 246-290-135). DOH requires that each source have three designated WHPAs, labeled Zone 1, Zone 2, and Zone 3, based respectively on the one-year, five-year, and ten-year time-of-travel capture zones[2]. Per DOH guidance (DOH, 2010), Zone 1 (the one-year capture zone) should also include a six-month capture zone to focus greater protection on potential viral and microbial contamination that may pose a higher degree of risk to the drinking water supply.

[1] A Group A public water system is defined by WAC 246-290 generally as any pubic water system that serves 15 or more connections on a year-round bases.

[2] The capture zone refers to the zone of groundwater contribution for a given source. Specific time-of-travel capture zones (i.e. one-year capture zone) refer to that portion of the total capture zone in which water will travel to the source within the specified travel time. Travel times to the source, and consequently the size and shape of the time-of-travel capture zone, will vary depending on the hydrogeologic properties associated with that specific zone (i.e. gradient, porosity, pumping rates, etc.).

DOH has also established the use of a buffer zone as required to provide additional source protection up-gradient of the ten-year capture zone. According to DOH guidance (DOH, 2010), buffer zones may incorporate the entire capture zone for a given source or select portions of it and, as appropriate, may also include areas outside of a given capture zone. As described in this report, buffer zones which incorporate the entirety of the defined capture zones for both the 228th wellfield and Deer Creek Spring sources are included with the WHPAs for each source.

The WHPAs for both the 228th Street wellfield and the Deer Creek Springs sources were delineated using a numerical groundwater model that was specifically developed for this project. Because there is a reasonably sufficient amount of geologic and hydrogeologic data available for the study area, a modeling approach for WHPA delineation was deemed to be more accurate (and more appropriate) than the standard calculated-fixed radius (CFR) method. Model development and calibration are described below in Section 2.2. WHPA delineation is described in Section 2.3.

2.2 Numerical Groundwater Model

The development of a numerical groundwater model involves several key steps, starting with the review and compilation of data from existing studies and other sources, which provide information pertaining to the various model inputs. Once the available data have been compiled and evaluated, model construction begins with the development of a conceptual model. The conceptual model, which is typically diagrammatic, provides a generalized overview of the major model components and guides the overall groundwater model construction. Once a basic groundwater model is constructed, it is then finalized by calibrating outputs to known data points (i.e. head values, discharge, etc.). The calibrated model can then be used to perform a number of analytical tasks, which for this project includes the delineation of the wellfield and spring source WHPAs.

2.2.1 Previous Studies and Other Model Input Sources

Parameter inputs for the groundwater model developed for this project were obtained from a number of sources, including well construction and testing reports, geologic and hydrogeologic studies, government databases, and geologic maps. The following is a summary of the key data sources utilized for this project.

King County, Department of Natural Resources and Parks, Wastewater Treatment Division, 2003; Brightwater Treatment Plant, Final Environmental Impact Statement, Appendix 6-B (Geology and Groundwater). This study provides key data pertaining to subsurface geologic conditions and aquifer elevations. Groundwater monitoring data and potentiometric maps from this study were also utilized in part for final model calibration.

Liesch, B.A., Price, C.E., and Walters, K.C., 1963; *Geology and Groundwater Resources of Northwest King County, Washington*. Washington State Department of Conservation, Water Supply Bulletin No. 20. This study provides key information for the southern portion of the modeled area, including recharge and model unit descriptions.

Minard, J.P., 1983; Geologic Map of the Edmonds East and Edmonds West Quadrangles, Washington; USGS Miscellaneous Field Studies, Map MF-1541. This map was utilized for a variety of model inputs, including the surficial distribution of geologic units, estimated recharge values, and aquifer elevations.

Newcomb, R.C., 1952; *Groundwater Resources of Snohomish County, Washington*; USGS Water Supply Paper 1135. This report provides detailed information about the geologic and hydrogeologic units within the project area, as well as information pertaining to general flow characteristics of area aquifers.

Robinson Noble, Inc., 2003; Olympic View Water & Sewer District, Modification and Testing of the 228th Street Production Well (Shop Well). This report provides key model input data for the area around the 228th Street wellfield. This includes hydraulic conductivity values and aquifer elevation data. Groundwater elevation data for this site was also utilized in part for final model calibration.

Robinson Noble, Inc., 2015; Olympic View Water & Sewer District, 8605 228th Street Test Well. This report provides additional information pertaining to model feature elevations in the area of the 228th Street wellfield, hydraulic conductivity values, and other hydrogeologic parameters. Survey data from this study also provided key information pertaining to the gradient and flow directions of groundwater in the area of the 228th Street wellfield. Water level data from this study was also used for model calibration.

Robinson Noble, Inc., 2018; Olympic View Water & Sewer District, Construction and Testing of Production Well 2. This report provides key model input data for the area around the 228th Street wellfield. This includes hydraulic conductivity values, production rates, and aquifer elevation data. Water level and drawdown data from this study were also used in part for final model calibration.

Shannon and Wilson, Inc., 2016; Hydrogeologic Report New Madrona K-8 Project, 9300 236th Street SW, Edmonds, Washington. This report provides specific model input data, including hydraulic conductivity values, water level data, and flow directions, in the up-gradient areas east of Deer Creek Springs. Monitoring data from this study was also used in part for final model calibration.

Thomas, B.E., Wilkenson, J.M., and Embrey, S.S., 1997; *The Groundwater System and Groundwater Quality in Western Snohomish County, Washington*; USGS Water Resources Investigations Report 96-4312. This report provides detailed information regarding the characteristics of the hydrogeologic units within the project area. It also provides key information regarding aquifer elevations, recharge values, and flow data that was utilized in part for final model calibration.

In addition to the reports and studies listed above, this project utilized a number of other miscellaneous sources to support model development. Between 2004 and 2010, in conjunction with the Brightwater sewer tunnel construction, Robinson Noble conducted extensive groundwater monitoring at the both the Deer Creek Springs site and the original shop well (located near the current 228th Street wellfield). Hydrographs created during this monitoring were used for final model calibration, and precipitation data collected during the monitoring effort were used to evaluate the modeled recharge values. We also accessed the Washington State Department of Ecology's (Ecology) online well log data base. We estimate that this database contains approximately 1,200 well reports (well logs) for the study area. These logs were first screened for reliability, and then reliable logs were utilized for a variety of model input information (i.e. aquifer elevation, water levels for calibration, etc.).

2.2.2 Conceptual Model

A hydrogeologic conceptual model is a representation of a groundwater flow system that simplifies and organizes various geologic and hydrologic information so that the flow system can be more readily analyzed (Anderson and Woessner, 1992). The conceptual model synthesizes available data (maps, cross-sections, hydrographs, well logs, etc.) into a generalized representation of the geology as it affects the groundwater flow system in a given area. Ideally, a conceptual model should be as simple as possible but still contain all of the applicable components necessary to recreate flow system behavior. Once it is developed, the conceptual model serves as a guide for the construction of the final groundwater model.

Figure 2 presents the conceptual model that was developed for this project as a schematic cross section. The conceptual model for this project contains three major components: hydrostratigraphic units, model boundaries, and general flow system inflow and outflow information. These components are described in detail below.

2.2.2.1 Hydrostratigraphic Units

A key step in developing the conceptual model is to define the various hydrostratigraphic units that will affect the flow system being modeled. Hydrostratigraphic units are groupings of sediments that exhibit similar hydrogeologic properties. They are typically divided into two general groups which include aquifers and confining units and may or may not correspond with the area geologic units.

Within the project area, the hydrostratigraphic units modeled do generally correspond with the area geologic units. Figure 3 shows the surficial geology within the study area (Minard, 1983). Table 1 summarizes the hydrostratigraphic units applicable to this project, which are listed from top to bottom in stratigraphic order (youngest to oldest or in general order of deposition).

Table 1: Hydrostratigraphic Units

Hydrostratigraphic Unit	Hydrogeologic Classification	Unit Description
Younger Alluvium (Qyal)	Aquifer (when in direct contact with Qva)	Fluvial sands and gravels with lesser organic material. Thin and limited lateral extent. For modeling purposes, this unit is grouped with the Qva aquifer when it is in direct contact with Qva materials.
Vashon Recessional Outwash (Qvr)	Aquifer (when in direct contact with Qva)	Sands and gravels with lesser clay and silt. For modeling purposes, this unit is grouped with the Qva aquifer when it is in direct contact with Qva materials.
Vashon Till (Qvt)	Confining Unit	Dense, unsorted clay-through gravel- and cobble-size material. This is the most extensive surficial deposit in the study area. It has a low permeability, is upwards of 100 feet thick, and forms a protective cap over the Qva aquifer.
Vashon Advance Outwash (Qva)	Aquifer	Sands with lesser gravel. Laterally extensive across the study area with thicknesses ranging from 100 to 150 feet. This unit is partially saturated and considered an unconfined aquifer system.
Transitional Beds (Qtb)	Confining Unit	Low permeability sequence of layered clay-through find sand-size material. This unit is relatively thick across the model area and forms the base of the model.

Both the Deer Creek Springs and the 228th Street wellfield derive groundwater from the Vashon advance outwash (Qva), which is referred to in this study as the Qva aquifer. As shown on Figure 3, the Qva aquifer is exposed at the surface in several parts of the study area, but is largely overlain by Quaternary Vashon till (Qvt). As shown in Figure 2, the Qvt forms the upper surface of the model where it is present. In areas where the Qvt is absent, the Qva forms the upper surface of the model. The Qva aquifer is underlain across the study area by pre-Vashon transitional beds (Qtb). This unit constitutes the lower surface of the model (see Figure 2). A detailed description of the hydrostratigraphic units utilized for this project is presented below.

Younger Alluvium (Qyal)

As shown in Figure 3, the Qyal hydrostratigraphic unit has limited aerial extent within the study area, and is generally constrained to narrow zones along stream corridors. As described by various authors (see Section 2.2.1), the Qyal consists of fluvial sand and gravel deposits with some organic materials. The Qyal is relatively thin and typically underlain by adjacent map units. Because the Qyal is relatively porous, when it is in direct contact with the Qva aquifer, it responds hydraulically as an extension of the aquifer. In these situations, the Qyal is considered part of the Qva aquifer. In situations where the Qyal is geologically isolated from the Qva, there isn't hydraulic continuity with the Qva aquifer, so it is grouped with the Qvt hydrostratigraphic unit.

Vashon Recessional Outwash (Qvr)

Similar to the Qyal, the Qvr has limited aerial extent within the study area and is relatively thin. The Qvr is comprised of stratified sands and gravels with lesser silt- and clay-size material, which were deposited by the receding Vashon continental glacier. Similar to the Qyal, the Qvr is relatively porous, so when it is in direct contact with the Qva aquifer, it responds hydraulically as an extension of the aquifer. As such, the Qvr is considered part of the Qva aquifer in these situations. Where the Qvr is geologically isolated from the Qva it is grouped with the Qvt hydrostratigraphic unit.

Vashon Till (Qvt)

The Qvt consists of a dense, unsorted mixture of clay- through gravel- and cobble-size sediments that were deposited in situ by the Vashon continental glacier. The Qvt is the predominant surficial deposit within the study area, and typically extends to depths of over 100 feet. The Qvt has a low permeability, and where present, it impedes infiltration of precipitation. This provides a protective cap for the underlying Qva aquifer. The Qvt often contains isolated pockets of more permeable material, which may contain perched groundwater[3]. However, these perched zones are usually very limited in extent, and the Qvt hydrostratigraphic unit, for the purpose of modeling, is considered to be unsaturated.

Vashon Advance Outwash (Qva)

The Qva is comprised of stratified sands with lesser gravel- and silt-size materials, which were laid down by meltwater issuing from the advancing Vashon continental glacier. The Qva is laterally extensive within the study area, but there are a few isolated areas, primarily along the study area boundaries, where the Qva is not present. The thickness of the Qva within the study area generally ranges from between 100 to 130 feet. The Qva materials are not fully saturated within the study area, and the Qva aquifer is considered an unconfined aquifer system. As

[3] Perched groundwater is groundwater that accumulates in isolated pockets of permeable material at elevations above that of the local water table (hence the term "perched").

mentioned previously, the Qva aquifer is the groundwater source for Deer Creek Springs and the 228th Street wellfield.

Pre-Vashon Transitional Beds (Qtb)

The Qtb is a layered sequence of very low permeability materials that were laid down in lakes and non-glacial fluvial systems prior to the deposition of the Qva sands. The Qtb consists of beds and laminae of clay-, silt-, and very fine sand-size material, with occasional zones of peat and organic material. The Qtb is consistently present across the study area and has an estimated thickness of approximately 130 feet within the model area. As mentioned previously, the Qtb forms the base of the model for this project (see Figure 2).

2.2.2.2 Boundary Identification

Generally there are two types of hydrologic boundaries: physical boundaries and hydraulic boundaries. Physical boundaries are formed by the presence of a physical impediment to groundwater flow such an impermeable geologic unit or the truncation/absence of an aquifer. Hydraulic boundaries are groundwater conditions that impede groundwater movement, such as a large lake or a groundwater divide. Ideally, model boundaries can be placed along naturally occurring boundaries such as groundwater divides or surface water bodies. However, this is not always feasible.

Figure 4 presents the aquifer boundaries and how they were represented in the model. The western edge of the modeled area corresponds to the exposure of the Qva aquifer in the cliffs along Puget Sound and where the Qva drops to sea level and is bounded by Puget Sound (in the extreme southwest corner of the model area). In the real world, this is a discharge boundary for the Qva aquifer. Water in the aquifer discharges through springs, as evapotranspiration to vegetation on the bluffs, and (where the boundary is below sea level) as underflow into Puget Sound. In the model, we've represented the western boundary with drains[4], set with relatively low conductance values along areas where minor seepage occurs and with relatively high conductance values at points were streams emanate from the exposed Qva aquifer. The most prominent of these is Deer Creek (which emanates from Deer Creek Springs), but also includes (to the north of Deer Creek) Shell Creek, Shelleberger Creek, and an unnamed creek.

A similar aquifer boundary occurs in the southeast corner of the model area where Lyon Creek has eroded down to and through the base of the Qva. Here water discharges from the aquifer as springs, seepage, and evapotranspiration above the creek. Again, this natural discharge boundary is represented in the model with drains.

Within the modelled area, there are a number creeks and lakes which are bedded in the Qva, or are in other ways in hydraulic continuity with the Qva (bedded in Qyal or Qvr materials that are in direct contact with the Qva). These include the before mentioned streams on the northwest and southeast sides of the model as well as Hall Creek, McAleer Creek, Hall Lake, and Lake Ballinger in the interior of the model. Where streams and lakes are in direct continuity with the aquifer, groundwater discharge or recharge naturally occurs depending on the head relationship

[4] A drain is a model condition that allows water to flow out of the model if the groundwater level in the model cell containing the drain exceeds the drain's assigned elevation. The amount of flow out of the drain is controlled by a conductance value assigned to the drain as well as the groundwater elevation. Drains are often used to model springs and groundwater seepage. Drains only allow water to exit (discharge) from a model and not to enter (recharge).

of the surface water and the groundwater. These surface water bodies are represented in the model as general head boundaries[5].

The natural real-world northern, southern, and eastern boundaries of the Qva aquifer system are not present within the study area. In order to keep the size of the model reasonable, these distant boundaries are represented in the model as groundwater streamlines. Streamlines represent a direction of groundwater flow (flow line) within an aquifer. Within the project area, flow in the aquifer in the northern and southern portions of the modeled area is generally east-west. Because these areas are distant from the portion of the model that will be affected by modeled production from the 228th Street wellfield, it is very unlikely that there is any significant contribution of flow into the aquifer from either the north or south sides of these streamlines. Therefore, in the model, they are represented by no-flow boundaries placed parallel to the general flow direction.

Such no-flow boundaries are conceptually valid for the model as long as no modeled stresses are placed near the boundaries that would alter the direction of the natural flow lines that are essentially parallel to the boundaries. Consequently, the northern, southern and eastern model boundaries, were also purposely located a significant distance away from the main areas of interest, namely the Deer Creek Springs and 228th Street wellfield source areas. This was done specifically to minimize any significant boundary effect in these areas of the model. In the model, flow is generally parallel to these boundaries except for near the lower reaches of Hall Creek. However, this area is distant enough from the area of interest that it does not likely impact the model results.

2.2.2.3 General Flow System

The final step in developing a conceptual model is to define the general flow system. This essentially amounts to diagraming the basic pathways by which water enters, passes through, and exits the model. Figure 2 presents the conceptual model that was developed for this project, which diagrams the various flow pathways in cross-section view.

As shown on Figure 2, water enters the system primarily as precipitation. When precipitation falls on the land surface, only a portion of it actually infiltrates into the ground. The portion that is not infiltrated may flow overland as runoff or evaporate back to the atmosphere. Runoff may be infiltrated further down-slope or flow overland out of the model area. A portion of the water that infiltrates into the ground may be taken up through the roots of plants and trees and transpire back to the atmosphere through their leaves. Typically, the combined effects of evaporation and plant transpiration are considered together as evapotranspiration. That portion of water that infiltrates into the ground and is able to replenish the aquifer system is referred to as recharge. Recharge is always a percentage of the total precipitation value and varies from place to place depending on specific conditions (i.e. plant cover, temperature, soil permeability, etc.).

For this study, recharge is largely a function of the surficial geology. For the surface areas mapped with Qvt (see Figure 3), because the Qvt has relatively low permeability, recharge rates are fairly low and much of the precipitation that falls on these areas flows overland as runoff. Conversely, because the Qva is fairly permeable, in areas where the Qva is exposed at

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[5] General-head boundaries are model conditions that allow water to flow out of the model (discharge) if the groundwater level in the model cell containing the general-head boundary exceeds the assigned boundary elevation or into the model (recharge) if the groundwater level is lower than the assigned boundary elevation. The amount of flow into or out of the boundary is controlled by a conductance value assigned to the drain as well as the groundwater elevation.

land surface, infiltration (and recharge) is significantly higher. Furthermore, much of the precipitation that runs off in the Qvt covered areas is readily infiltrated when it reaches areas of exposed Qva. Additional recharge occurs where streams (or lakes) have losing reaches (when streams lose water through infiltration into the ground).

As shown on Figure 2, groundwater that reaches the Qva aquifer flows primarily horizontally down-gradient through the aquifer. This occurs because the underlying Qtb has a very low permeability compared to the Qva, which impedes downward migration of water. As with most confining units, there is some vertical leakage from the Qva aquifer downward through the Qtb. However, it is minor and is not considered a significant out-flow for this modeling project.

Aside from minor leakage to the underlying Qtb, groundwater exits the Qva aquifer through one of several routes. As shown on Figure 2, groundwater may be extracted from the system through production withdrawal from a well (i.e. the 228th Street wellfield). It may also flow out of the system through one of the major springs (i.e. Deer Creek Springs), it may exit the system as minor seepage through the Qva exposures in the cliffs along the west side and southeast corner of the model, it can become stream (or lake) flow in gaining reaches, or it can be discharged into Puget Sound (which is not shown on Figure 2 and only occurs in the extreme southwestern corner of the model area).

2.2.3 Numerical Model Construction

The numerical groundwater model developed for this project was constructed using the Department of Defense Groundwater Modeling System (GMS). GMS is a comprehensive graphical user program that serves as a pre- and post-processing interface for a variety of groundwater modelling and analytical programs. For this project, GMS was used to interface with MODFLOW, which is an open-source and widely utilized finite-difference groundwater model[6] developed and distributed by the USGS (Harbaugh, 2005). The model developed for this project was constructed as a steady-state groundwater model[7].

2.2.3.1 Numerical Model Inputs

Once a conceptual model is developed, the initial step for constructing the numerical model is to create a finite difference grid to cover the horizontal (aerial) and vertical space to be modeled. The horizontal model area for this project is shown on Figure 4, which covers the area within the model boundaries previously described in Section 2.2.2.2. Figure 4 also shows the finite difference grid (grid) used for the final model. As shown on Figure 4, horizontal dimensions of the individual grid cells are refined around the two primary source areas (Deer Creek Springs and the 228th Street wellfield) to provide more detail in the near-field areas around these two sources. The horizontal dimension of the cells adjacent to the two sources is 50 feet square. The cell size was increased at increments of 10% away from the source areas to a maximum cell size of 250 feet square. The horizontal elements of the model are geographically referenced to NAD83/UTM Zone 10[8].

For the vertical space, the model utilizes a single layer of grid cells (a one-layer model) to represent the Qva aquifer flow system. Because the Qvt is unsaturated, it is not necessary to set up a separate layer to represent the till because there is no flow within the Qvt to simulate. As

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[6] The finite difference approach utilizes a grid system to represent individual flow cells, which are hydraulically (mathematically) connected to surrounding cells and manipulated together to simulate a flow system.

[7] In a steady-state groundwater model, the magnitude and direction of flow is constant with time, versus a transient model where the magnitude and direction of flow varies with time. For a steady-state model, the volume of water within the model domain is constant (flow into the model is equal to the flow out of the model).

[8] The North American Datum of 1983 (NAD83)/Universal Transverse Mercator (UTM) Zone 10; EPSG:26910.

discussed previously in Section 2.2.2.3, leakage through the underlying Qtb is negligible, and the top surface of the Qtb was used to represent the base of the model. Cell elevations for the top of the model were incorporated into the model by importing LIDAR[9] data available for the study area. Cell elevations for the base of model were derived by importing and interpolating data from a combination of sources, including published USGS maps of the top surface of the Qtb (Thomas, et al, 1997), the elevations of the exposed contact between the Qtb and the Qva (Minard, 1983), and several cross sections that traverse the study area generated by King County during the construction of the Brightwater sewer tunnel (King County, 2003).

Once the model grid was established, additional model inputs were incorporated into the model. The elevations of the drains and general-head boundaries shown on Figure 4 were set respectively to the mapped elevations along the Qtb/Qva contact and the mapped elevations of the streams and lakes bedded in the Qva (see Section 2.2.2.2). There are no established conductance values for the drains and general-head boundaries for the study area. As such, somewhat arbitrary conductance values were initially set for these features, and these values were adjusted during the calibration process. Initial conductance values for the drains corresponding to major springs (i.e. Deer Creek Springs) were set relatively high as compared to the other drain features without obvious discharge points. Similar proportions were maintained during the calibration process.

As discussed in Section 2.2.2.3, recharge is largely a function of surficial geology, with highest recharge occurring in areas where the Qva is exposed at the surface, and lessor recharge occurring in areas covered by the Qvt. Aerial recharge values were applied to the model using this assumption by creating aerial coverage-polygons[10] corresponding to the areas mapped as Qvt and Qva (Minard, 1983). During monitoring efforts conducted by Robinson Noble between 2004 and 2010 (see Section 2.2.1), it was established that the average annual precipitation for the study area is approximately 37 inches/year. This is in agreement with other area studies (see Section 2.2.1). Regression analyses conducted by the USGS (Woodward, et al, 1995) and other information provided specifically for Snohomish County (Thomas, et al, 1997) indicate recharge values of 13 and 26 inches/year, respectively for areas mapped as Qvt and Qva. These values were applied accordingly to the current model for the areas mapped as Qvt and Qva.

Similar to the recharge, different values of hydraulic conductivity (K) were applied to the model (again using a series of polygons created in GMS). Pumping test data for the wells constructed at the 228th Street wellfield (Robinson Noble, 2003, 2015, and 2018) indicate K values of 50 feet/day for the near-field area around the wellfield. Testing of injection wells at the recently constructed Madrona Elementary School (Shannon & Wilson, 2016), which is located just south of the 228th Street wellfield, indicate similar K values of 55 feet/day. These K values were applied to these two areas of the model accordingly.

Elsewhere, the K values are less known. However, the USGS (Thomas, et al, 1997) indicates that K values for the Qva in the southwest corner of Snohomish County ranges from 3 to 310 feet/day with a median value of 42 feet/day. This is comparable to the K values established for the 228th Street wellfield and the Madrona School site. Median K values were initially applied to all of the areas of the model, save for the areas around the 228th Street wellfield and the Madrona School site, and then adjusted accordingly during the calibration process (see Section 2.2.3.2). For the final calibrated model, in 24 separate polygons used to designate K values

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[9] Light imaging, detection, and ranging (LIDAR) is a surveying method that uses lasers to produce high-resolution digital maps, including topographic maps.

[10] GMS utilizes polygons that are created by the user to apply aerial or map-view features such a recharge and hydraulic conductivity to groups of cells within the model area.

across the model area, K values ranged from 10 to 60 feet/day with a median value of 50 feet/day. This is comparable to the K values determined by the USGS for the Qva aquifer in this portion of Snohomish County.

2.2.3.2 Model Calibration

Following initial model construction, the overall flow pattern simulated using the initial model inputs was compared to known flow patterns (potentiometric surface maps) developed for the area by previous workers. These include potentiometric maps created by the USGS (Newcomb, 1952; and Thomas, et al, 1997) and by King County during the construction of the Brightwater sewer tunnel (King County, 2003). The initial flow pattern simulated by the model was noted to approximate the general flow patterns and heads (water level elevations) of these other potentiometric maps.

At this point, select model parameters were systematically modified to adjust simulated heads to approximate observed heads in a series of model observation wells[11]. Select model parameters were also modified to adjust the modelled discharge rate for Deer Creek Springs to approximate actual rates recorded by the District. For this project, the model parameters available for calibration were limited to drain and general-head conductance values, and the K within the specified range of values determined by 1997 USGS study (Thomas, et al, 1997). Recharge, the known areas of K, and various elevation information are considered fixed values and were not modified during the calibration process.

The final groundwater model was considered calibrated when the simulated heads and discharge rate from Deer Creek Springs were in general agreement with observed conditions. Figure 5 presents a plot of the calibration results for the observation wells. It should be noted that the three outliers indicated in red on Figure 5 are for observation wells located along the northern and southern margins of the model, areas where the model might be expected to be less calibrated due to the boundary conditions. The calibration residuals[12] for the remaining observation wells (disregarding the noted outliers) range from -13.1 to 8.7 feet, with a mean residual value of 1.5 feet and a root mean squared (RMS) error of the residuals of 5.1 (see Table 2). The calibrated residual value for the flow of Deer Creek Springs is 60 gpm. These are all considered acceptable calibration values. Figure 6 presents a potentiometric map of the Qva aquifer showing simulated heads that were generated from the final calibrated model.

Table 2: Model Calibration Statistics

Number of Water Level Observations	23	Mean Error of Water Level Residuals	1.5
Mean Absolute Error of Water Level Residuals	3.2	Root Mean Squared Error of Water Level Residuals	5.1
Deer Creek Springs Observed Flow	840 gpm	Deer Creek Springs Modeled Flow	780 gpm

2.3 Wellfield and Spring Source WHPA Delineation

Using the calibrated groundwater model, WHPAs were delineated for the 228th Street wellfield and Deer Creek Springs sources using the MODPATH module of GMS. MODPATH is a particle-

[11] Observation wells are calibration points that are incorporated into the model at the corresponding locations of real-world wells with recorded water levels.
[12] The difference between observed and computed head.

tracking post-processing program[13] designed to work directly within MODFLOW (Pollock, 2017). Within the MODPATH interface, a porosity value of 20% was set for the Qva aquifer. This value, which is near the lower end of typical porosity values for sand aquifers like the Qva (Heath, 2004), was used to generate conservative WHPAs.

The WHPAs for the 228th Street wellfield were delineated using a simulated withdrawal rate of 500 gallons per minute (gpm), which is the full instantaneous quantity (Qi) allocated by District's current water right[14]. The current allocated annual quantity (Qa) for the water right is 560 acre-feet/year, so the wellfield can feasibly only be pumped at a maximum continuous rate of 347 gpm without exceeding the allocated Qa. However, there are only minimal deference's between the WHPAs delineated using a rate of 347 gpm and those delineated using a rate of 500 gpm. Delineation at the higher rate results in slightly larger, more conservative WHPAs for the wellfield, which is intended to cover all conceivable pumping conditions.

Using MODPATH, particles were introduced at the 228th Street wellfield and Deer Creek Springs, and then tracked up-gradient for specified time intervals. Particle tracking at both sources was conducted for six-month, one-year, five-year, and ten-year intervals. Additional particle tracking was also conducted using the "to beginning" option in MODPATH to track the particles to their ultimate origin within the model. This allowed delineation of the entire zone of contribution for the two sources. MODPATH was then used to convert the particle tracks to specific time-of-travel capture zones (see Section 2.1) for the two sources. Figure 7 presents the time-of-travel capture zones (WHPAs) that were delineated for the two sources. In addition to the standard six-month, one-year, five-year, and ten-year WHPAs, the capture zones that were calculated for the entire zone of contribution for each of the two sources were used to define the recommended buffer zones.

3.0 Summary

DOH requires the definition of wellhead protection zones based on travel rates of groundwater (DOH, 2010). DOH defines five zones for which wellhead protection strategies should be considered. These include the following:

- *The sanitary control area*: Typically the 100-foot radius of control around a wellhead or a spring (WAC 246-290-135).
- *Zone 1*: The one-year time-of-travel capture zone. Zone 1 also includes an additional six-month time-of-travel capture zone to focus greater protection on potential viral and microbial contamination.
- *Zone 2*: The five-year time-of-travel capture zone.
- *Zone 3*: The ten-year time-of-travel capture zone.
- *The buffer zone*: This zone may extend up-gradient of Zone 3 to include the entire zone of contribution for a given source.

The first four of these zones are required components of a WHPP and define areas requiring differing levels of response to a contamination event based on the expected time of travel to a given groundwater source. The buffer zone is considered optional, but is often vital in planning

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[13] MODPATH mathematically tracks particles from a given source, up-gradient along the flow lines in a MODFLOW model for a user specified time-frame.

[14] Water right G1-26021 allocates an instantaneous withdrawal (Qi) of 500 gpm and an annual withdrawal (Qa) of 560 acre-feet/year for the District's 228th Street wellfield.

for comprehensive protection of the supply sources (DOH, 2010). These specific WHPAs, including buffer zones, have been delineated for the 228th Street wellfield and the Deer Creek Springs sources and are presented in Figure 7.

4.0 Recommendations

The recommended WHPAs, which correspond to the one-year, five-year, and ten-year time-of-travel zones (Zones 1, 2, and 3, respectively), for both the Deer Creek Springs and the 228th Street wellfield are shown on Figure 7. However, the Qva aquifer is a relatively shallow system which is directly exposed at the surface in many places within the study area and extra protection is recommended. As such, we also recommend the incorporation of a buffer zone as part of the WHPAs for both sources. The recommended buffer zones, which incorporate the entire zone of contribution up-gradient of Zone 3 for both sources, are shown on Figure 7.

Within the recommended WHPAs presented on Figure 7, there is cause for additional concern in the areas where the Qva is mapped as the surficial geologic unit. Figure 8 presents a composite map that identifies these specific areas. The Qva aquifer has no natural geologic protection in these locations and is highly vulnerable to impact from various activities that may occur within these areas. As such, additional precautions are warranted for these specific areas.

Additionally, the buffer zone (zone of contribution) for the 228th Street wellfield reaches Hall Creek (see Figure 8). This indicates that water from Hall Creek directly recharges a portion of the aquifer that supplies water to the wellfield. Based on the current modeling, water from the creek will reach the wellfield within an estimated period of about 18 years. It is recommended that the District interface with any agencies or entities monitoring water quality along this portion of the creek and request that the Department of Ecology and Snohomish County Environmental Health inform the District of any catastrophic pollution events that may occur in this reach of Hall Creek.

5.0 References

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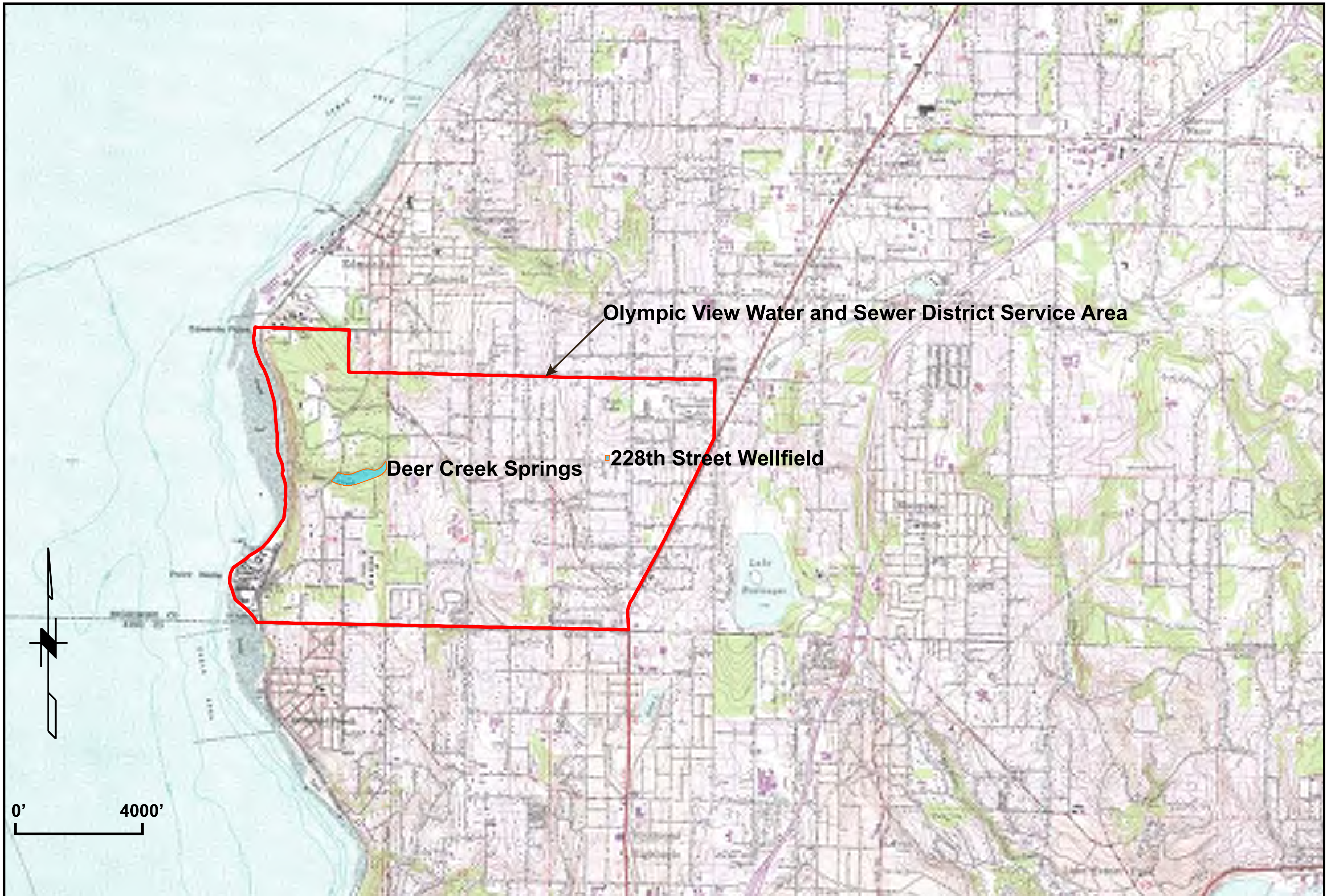
Figures



ROBINSON NOBLE

Note: Basemap from USGS Edmonds West and East Quadrangles

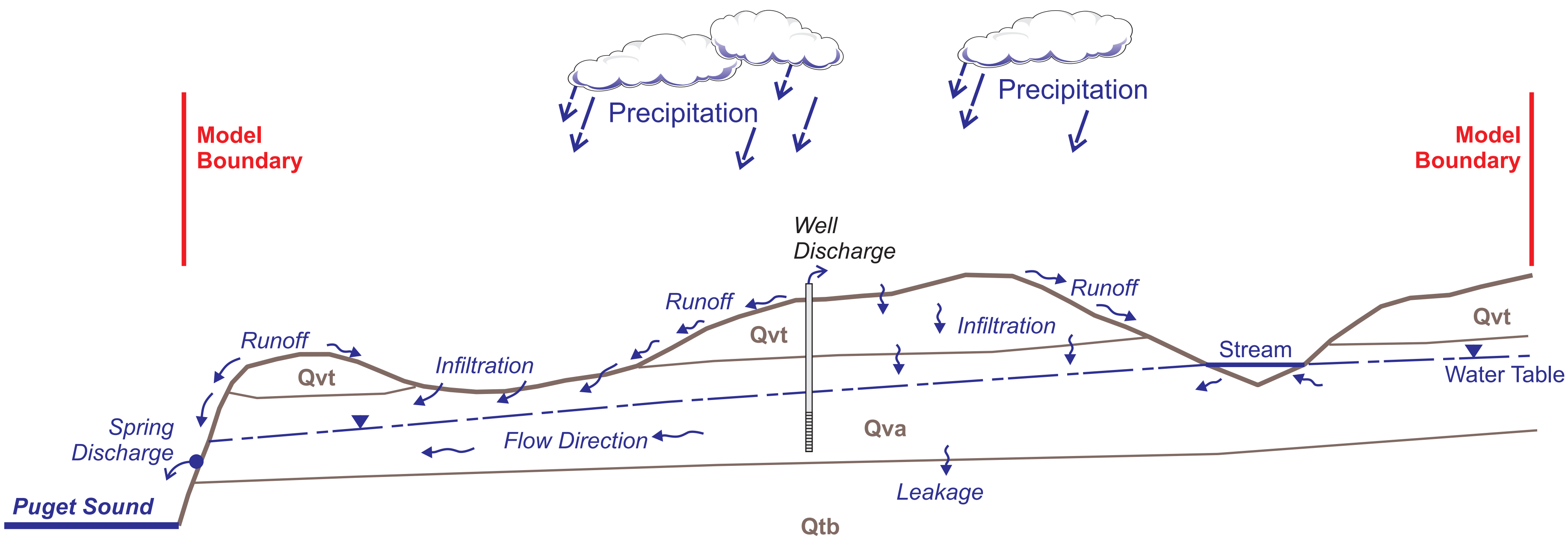
PM: MTW
August 2018
1686-007A

Snohomish County
T 27 N/R 3,4 E
Scale 1" = 4000'

Figure 1

Vicinity Map with Service Area

Olympic View Water and Sewer District: 2018 WHPA



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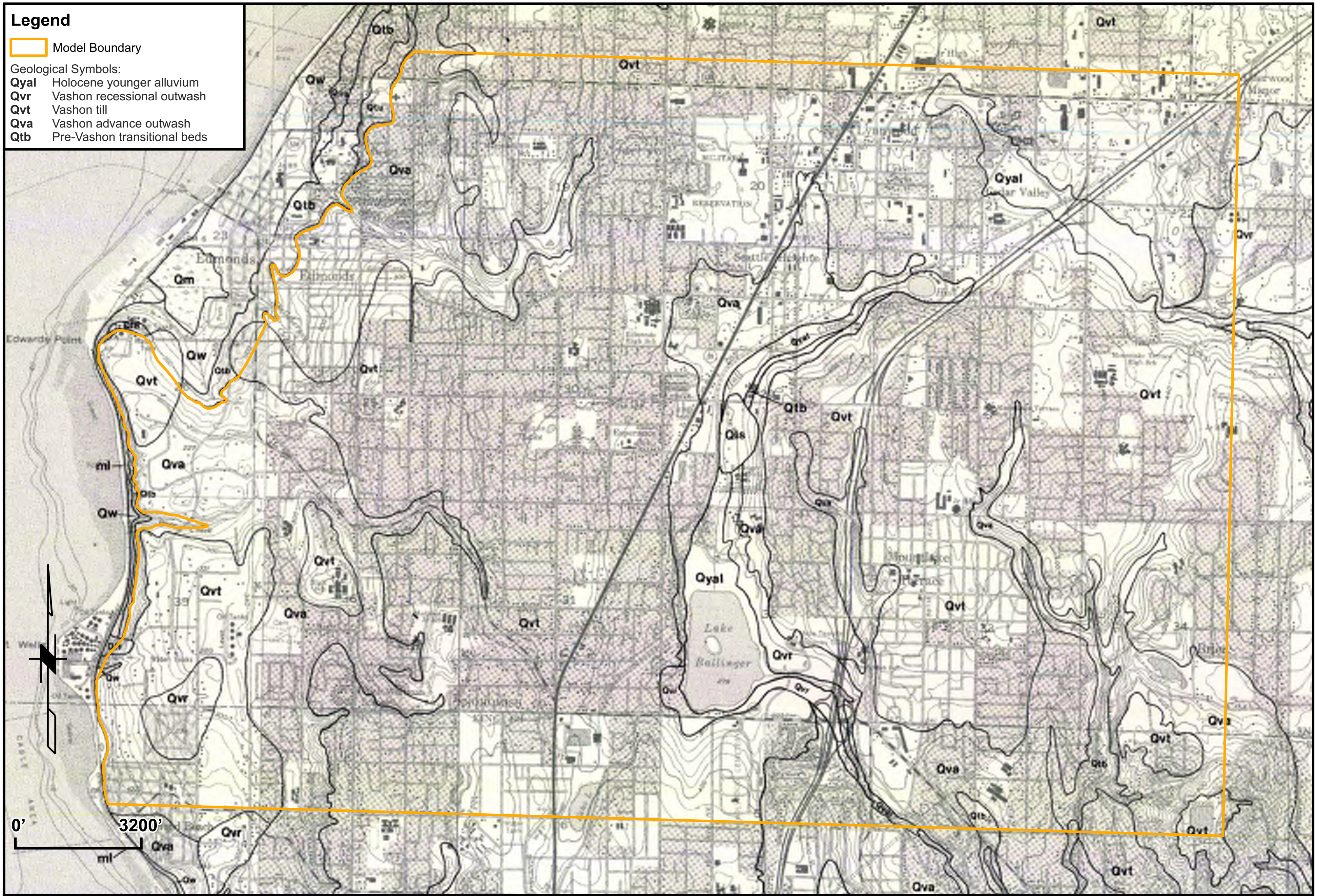
PM: MTW
August 2018
1686-007A

Snohomish County
T 27 N/R 3,4 E
Drawing Not to Scale

Figure 2
Conceptual Model
Olympic View Water and Sewer District: 2018 WHPA



ROBINSON NOBLE

Note: Geological Map from Minard 1983 USGS Edmonds East and West Quadrangles

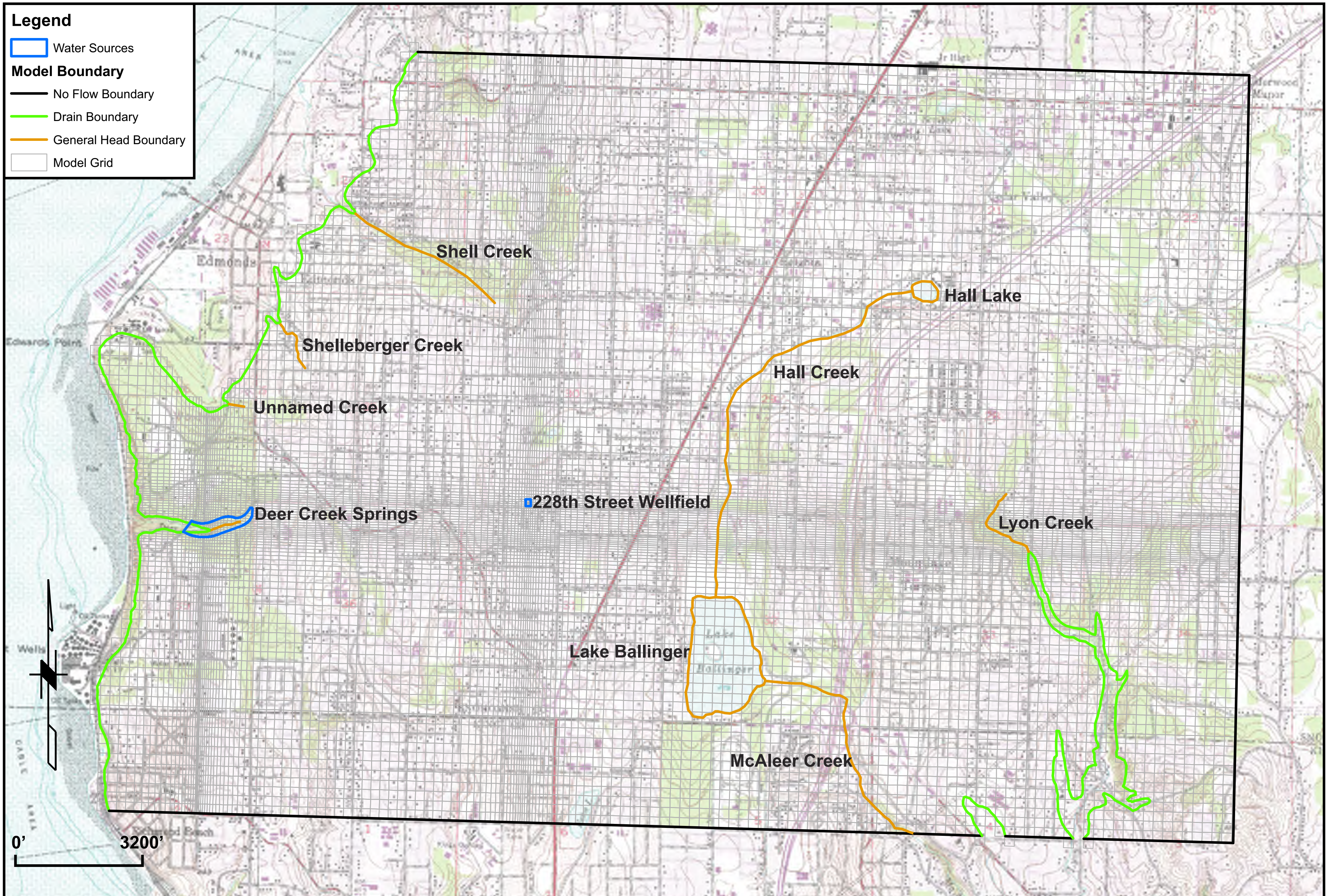
PM: MTW
August 2018
1686-007A

Snohomish County
T 27 N/R 3,4 E
Scale 1" = 3200'

Figure 3

Surficial Geology Map

Olympic View Water and Sewer District: 2018 WHPA



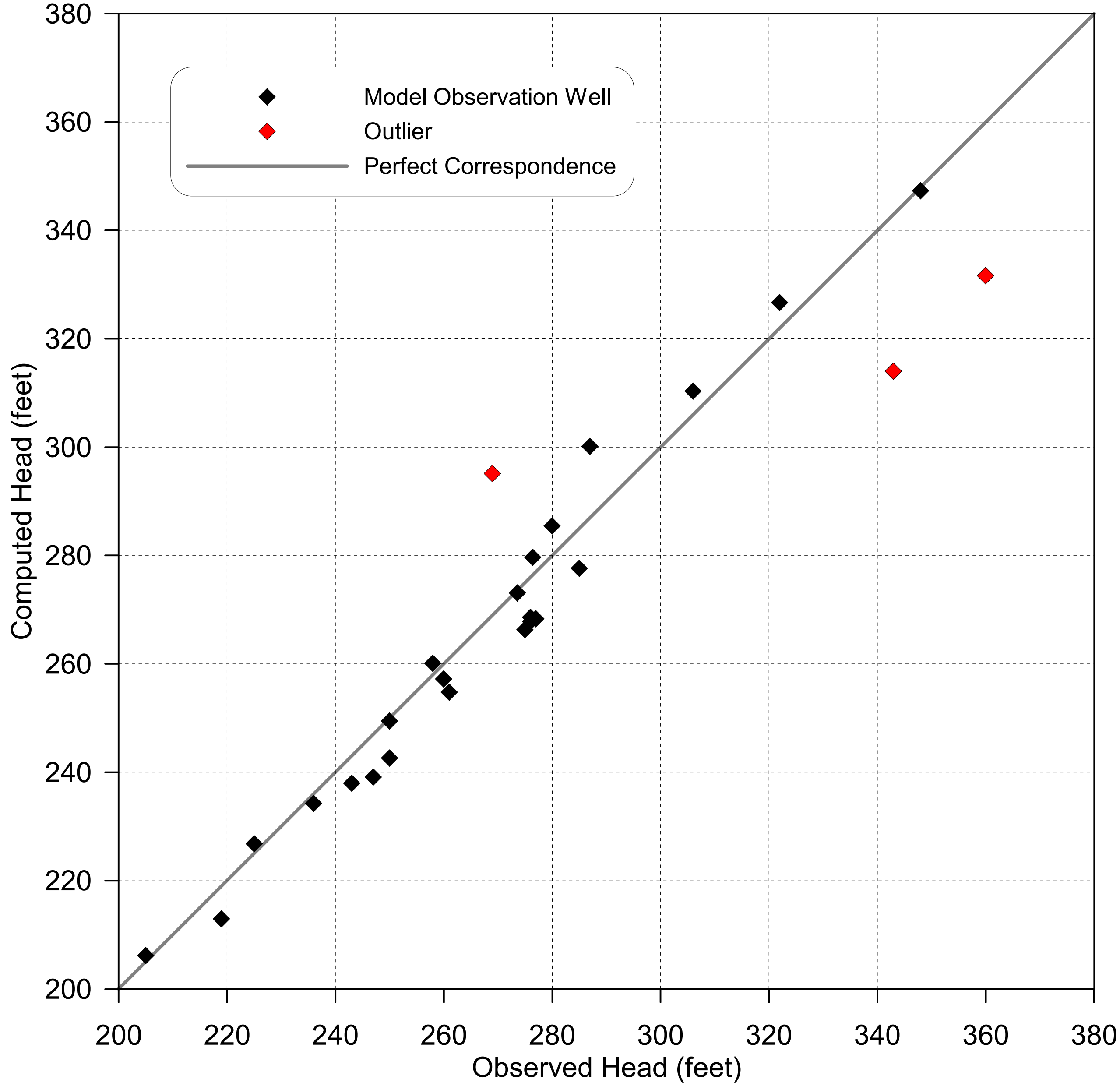
ROBINSON NOBLE

Note: Basemap from USGS Edmonds West and East Quadrangles

PM: MTW
August 2018
1686-007A

Snohomish County
T 27 N/R 3,4 E
Scale 1" = 3200'

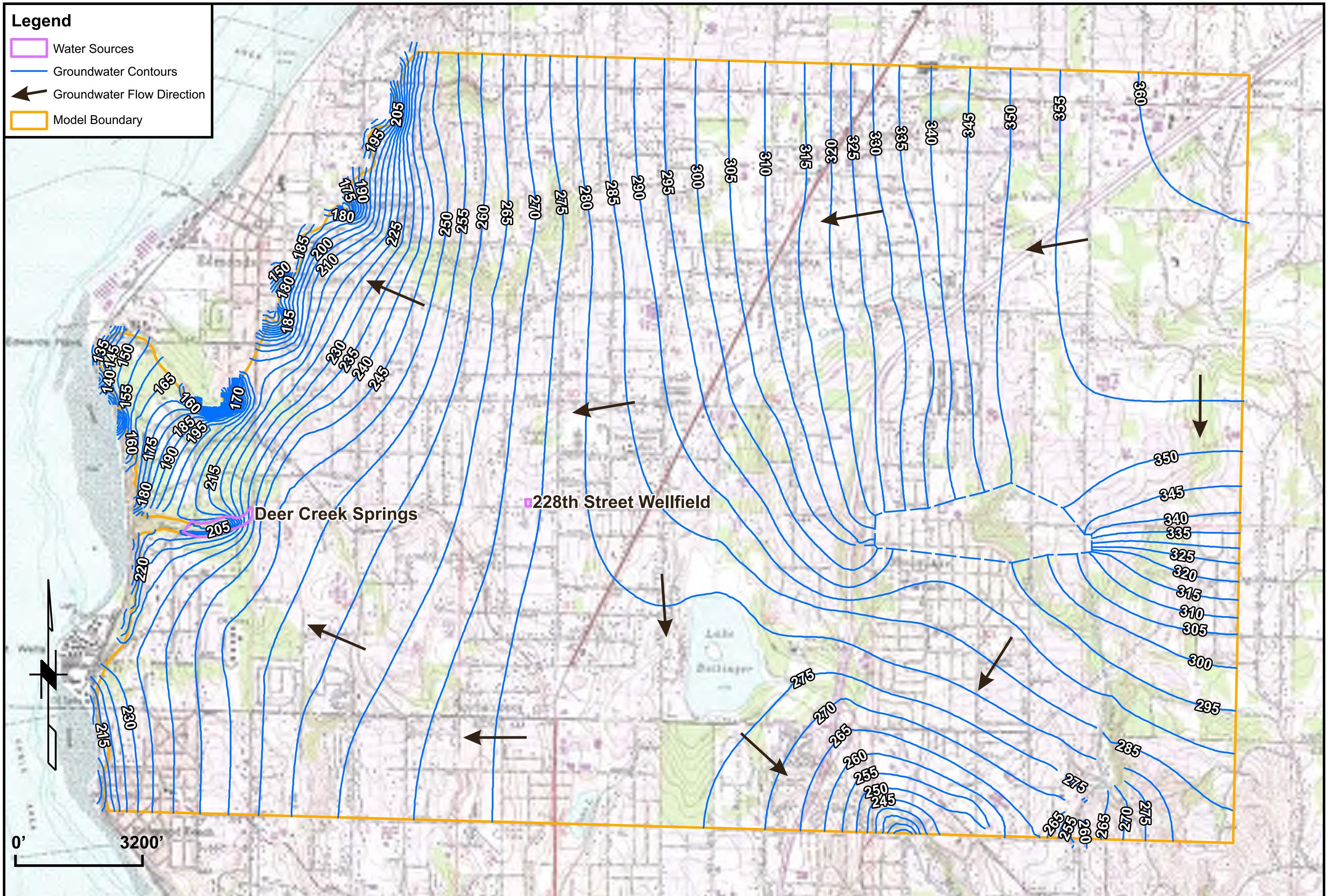
Figure 4
Model Boundaries
Olympic View Water and Sewer District: 2018 WHPA



ROBINSON NOBLE

PM: MTW
August 2018
1686-007A

Figure 5
Model Calibration
Olympic View Water and Sewer District: 2018 WHPA

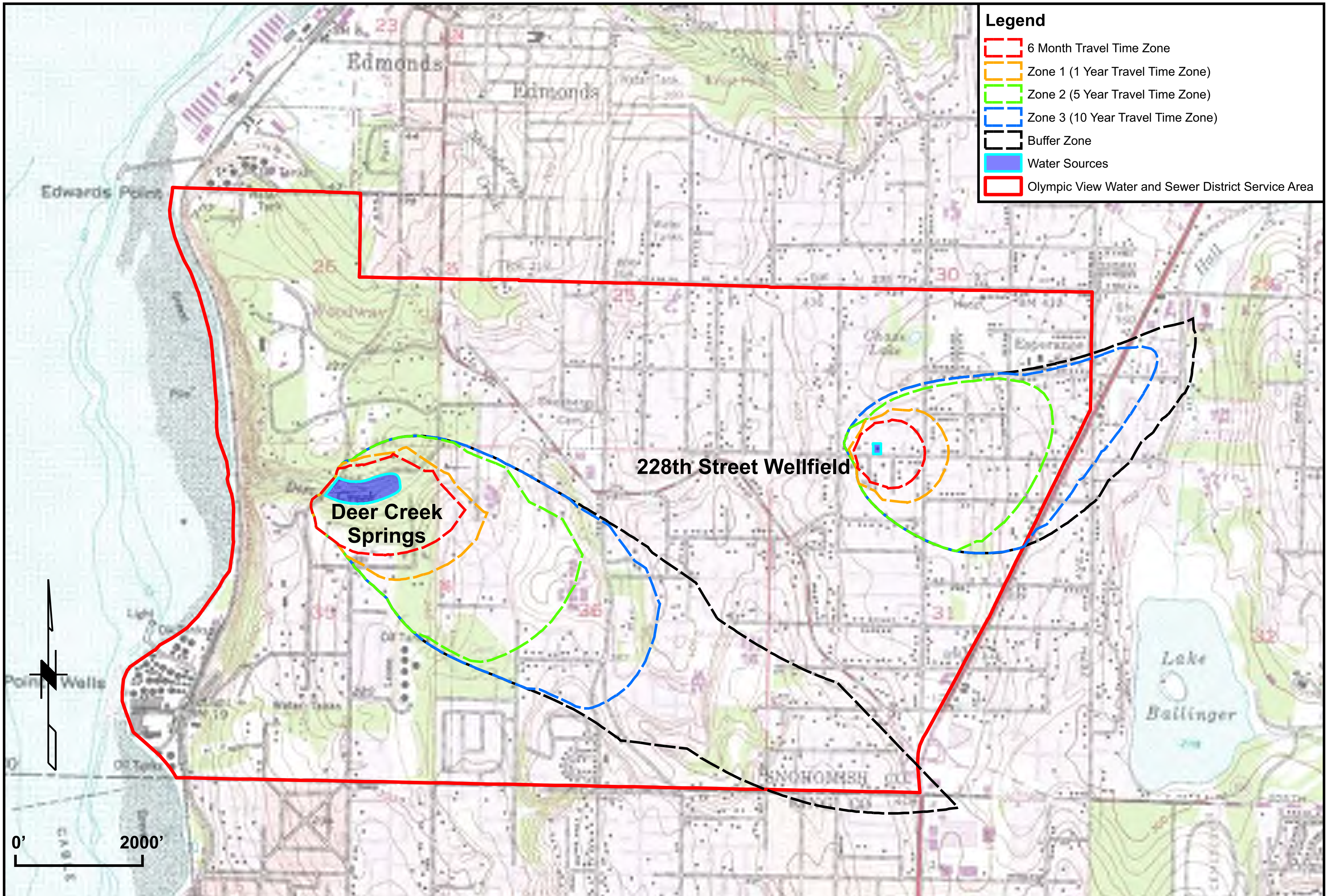


Note: Basemap from USGS Edmonds West and East Quadrangles

PM: MTW
August 2018
1686-007A

Snohomish County
T 27 N/R 3,4 E
Scale 1" = 3200'

Figure 6
Potentiometric Contour Map
Olympic View Water and Sewer District: 2018 WHPA



ROBINSON NOBLE

Note: Basemap from USGS Edmonds West and East Quadrangles

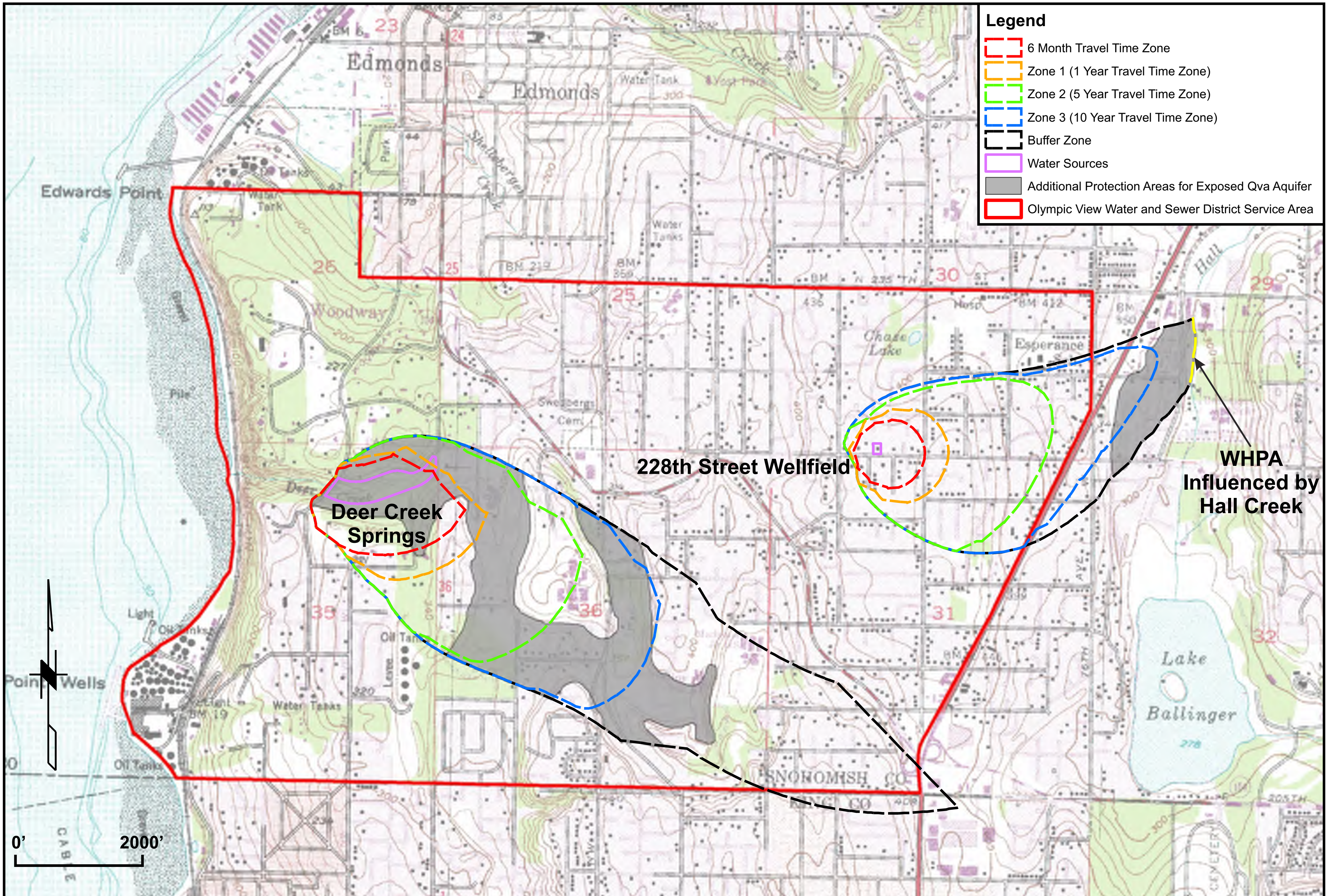
PM: MTW
August 2018
1686-007A

Snohomish County
T 27 N/R 3,4 E
Scale 1" = 2000'

Figure 7

Well Head Protection Area Map

Olympic View Water and Sewer District: 2018 WHPA



ROBINSON NOBLE

Note: Basemap from USGS Edmonds West and East Quadrangles

PM: MTW
August 2018
1686-007A

Snohomish County
T 27 N/R 3,4 E
Scale 1" = 2000'

Figure 8
Additional Protection Areas
Olympic View Water and Sewer District: 2018 WHPA