GROUNDWATER FLOW AND PFAS TRANSPORT MODELING REPORT

ISSAQUAH, WASHINGTON

Prepared for

City of Issaquah, Washington
1775 12th Avenue NW
Issaquah, Washington 98027

Prepared by

Geosyntec Consultants, Inc.
520 Pike Street, Suite 2600
Seattle, Washington 98101

Project Number: PNG0878

September 13, 2021

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Julie Chambon, Ph.D., P.E. (CA)
Senior Engineer

Robert Anderson, L.H.G.
Senior Principal Hydrogeologist

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ACRONYMS AND ABBREVIATIONS

μg/L	micrograms per liter
3D	three-dimensional
AFFF	aqueous film-forming foams
bgs	below ground surface
CARA	Critical Aquifer Recharge Area
City	City of Issaquah
Ecology	Washington State Department of Ecology
EFR	Eastside Fire & Rescue
Farallon	Farallon Consulting, LLC
Geosyntec	Geosyntec Consultants, Inc.
mg/kg	milligrams per kilogram
ng/L	nanograms per liter
Partnership	Issaquah Valley PFAS Partnership
PFAS	per- and poly- fluoroalkyl substances
PFHxA	perfluorohexanoic acid
PFHxS	perfluorohexanesulfonic acid
PFOA	perfluorooctanoic acid
PFOS	perfluorooctanesulfonic acid
PFPeA	perfluoropentanoic acid
PFBS	perfluorobutanesulfonic acid
School	Issaquah Valley Elementary School
USGS	United States Geological Survey

1. INTRODUCTION

Geosyntec Consultants (Geosyntec) has prepared this Groundwater Flow and Per- and Poly-Fluoroalkyl Substances (PFAS) Transport Modeling Report (Report) on behalf of the City of Issaquah (City). Geosyntec performed this work on behalf of the City, Eastside Fire and Rescue (EFR), and the Washington State Department of Ecology (Ecology), collectively referred to as the Issaquah Valley PFAS Partnership (the Partnership). The Partnership is conducting additional investigation of PFAS contamination of the Issaquah Valley Aquifer, through legislative funding provided to Ecology. Farallon Consulting, LLC (Farallon), on behalf of EFR, is the leading consultant for the field investigations that support the model development.

1.1 Purpose and Objectives

The following objectives were identified for the additional PFAS characterization study of the Issaquah Valley Aquifer being conducted for the Partnership (Farallon, 2021):

1. Further evaluate migration pathways between shallow and intermediate groundwater at 175 Newport Way Northwest, Issaquah Elementary School West Playfield and Dodd Fields Park, and Memorial Field;
2. Evaluate PFAS impacts to soil and groundwater and subsurface conditions (e.g., lithology, hydraulic conductivity, other relevant parameters) at 175 Newport Way Northwest sufficiently to develop and evaluate potential source remediation alternatives for this area of interest;
3. Further refine the nature and extent of PFAS impacts in shallow and intermediate groundwater at locations of interest and downgradient locations on both sides of the Lower Issaquah Valley that may affect drinking water production wells;
4. Further refine seasonal fluctuations in shallow and intermediate groundwater elevations and associated potential PFAS transport in shallow and intermediate groundwater on both sides of the Lower Issaquah Valley;
5. Review and document the Commercial Upholstery Shop history of use, including historical business listings and other publicly available information, to confirm the potential for PFAS use, and collect shallow groundwater data to further evaluate suspected impacts;
6. Collect adequate hydrostratigraphic and analytical data to support development of a groundwater model that can be used to evaluate potential source remediation alternative performance; and
7. Collect initial data that can be used to evaluate potential interaction between surface water and groundwater at three locations along the primary axis of the Lower Issaquah Valley.

To support this work and provide input to the PFAS characterization study, Geosyntec developed an initial groundwater and fate and transport model with the purpose of: 1) further evaluating the potential subsurface distribution of PFAS; and 2) providing recommendations for further plume characterization and potential remedial actions. The additional PFAS characterization outlined above focused on the shallow and intermediate aquifers and the area between 175 Newport Way Northwest and City Wells #4 and #5. Recognizing the focus of the additional characterization locations and the existence of a dominant groundwater flow path identified between 175 Newport Way Northwest and the City Wells #4 and #5, this initial modeling effort focused on the development of a cross-section model along this dominant flow path.

A cross-section model is a versatile initial approach to fate and transport modeling that can be run and calibrated more quickly than a three-dimensional (3D) model. Cross-sectional models can more easily evaluate vertical migration of contaminants using fine vertical discretization and therefore provide insights into the driving migration processes. The model presented herein is considered an initial step that provides better understanding of PFAS source(s) and fate and transport, particularly the processes driving downward plume migration and capture by City Well #4. Subsequent work may include developing a 3D model that will be based on additional future characterization and data availability.

The specific objectives of the groundwater modeling were to support the investigation as follows:

- Develop a cross-sectional model along the main flow paths between the EFR and City Well #4 and complete an initial calibration of water levels and PFAS concentrations;
- Develop a better understanding of PFAS fate and transport toward City Wells #4 and #5, particularly the processes driving downward plume migration and capture by City Well #4;
- Evaluate the fate and transport of a possible older PFAS source located between the EFR facility and City Well #4; and
- Provide a tool to support further evaluation of potential remedial actions.

The initial cross-section model developed and presented herein supports four of the PFAS characterization study objectives (at least partially), as follows:

- Objective #1: the model is specifically designed to evaluate vertical migration pathways.
- Objective #3: the model is used to evaluate transport pathways to City drinking water Wells #4 and #5.
- Objective #4: Although transient modeling was not part of this scope, the model is capable of evaluating seasonal fluctuations, and transient modeling may be considered as part of a second phase of modeling.
- Objective #6: data collected as part of the additional PFAS characterization study were specifically utilized in the construction of the cross-section model, as described in Section 2.2, and the model was used to evaluate source remediation (Section 2.4.3).

1.2 Existing Models

CDM Smith previously developed a 3D groundwater model for Sammamish Plateau Water to assess PFAS transport from the presumed primary source area (EFR) to Sammamish Plateau

Water drinking water supply wells on the eastern side of the Issaquah Valley (east of City Well #4) (CDM Smith, 2017). The groundwater flow model was developed in DYNFLOW, and solute transport was modeled in DYNTRACK. DYNFLOW is a CDM-proprietary 3D groundwater flow model code, and DYNTRACK is its companion solute transport code.

The City of Issaquah converted the CDM DYNFLOW model to MODFLOW, a public domain code developed by the United States Geological Survey (USGS), as part of the City's Critical Aquifer Recharge Area (CARA) update (Geosyntec, 2019). This existing 3D model developed for the City is referred to as the 3D CARA MODFLOW model in this report. The City's 3D CARA MODFLOW model was then used as the basis for development of the cross-section model described herein.

2. MODEL CONSTRUCTION AND CALIBRATION

2.1 Conceptual Model Overview

The City is located in the Lower Issaquah Valley, which spans approximately 61 square miles extending from the Issaquah-Hobart Gap to Lake Sammamish, and from Front Street to Tibbets Creek. The City location and significant creeks and Lake Sammamish are shown on Figure 1.

Subsurface geology in the Lower Issaquah Valley consists predominantly of recent fine-grained river (alluvial) sediments underlain by interbedded fine to coarse glacial sediments. The valley is surrounded by steep upland areas, including Tiger, Squawk, and Cougar Mountains, formed from a mix of denser glacial sediments and older volcanic rocks. The interbedded glacial and river sediments in the valley form significant groundwater aquifers from which the City operates high-yield production wells referred to as City Wells #4 and #5 and shown as COI-PW4 and COI-PW5 in the tables and figures of this report.

The regional groundwater flow direction is to the north towards Lake Sammamish, and the basin consists of three main aquifer units:

- Surficial water bearing unit, or shallow aquifer, present between approximately 5 and 60 feet below ground surface (bgs) and in direct hydraulic connection with surface streams;
- Intermediate aquifer, also refers to A Sand Aquifer, present between approximately 60 and 120 feet bgs, and where City Well #4 (COI-PW4) is screened; and
- Deep aquifer, also refers to B Sand Aquifer or B/C Sand Aquifer, present below approximately 120 feet bgs and is where City Well #5 (COI-PW5) is screened.

Shallow aquifer and A and B/C Sand Aquifers are used to refer to the three main aquifer units in this Report. It is important to note that the shallow and B Sand Aquifers generally consist of interlayering sand/gravel and lenses of low-permeability soils and do not represent distinct continuous transmissive layers. The B/C Sand Aquifer is separated from the shallow and A Sand Aquifers by a lacustrine silt layer (also referred to as the deeper silt layer), approximately 50-70 foot-thick based on the 3D CARA MODFLOW model. However, the lateral extent of this lacustrine silt layer is not known but is assumed to be regionally extensive.

The Partnership is in the process of characterizing the nature and extent of PFAS in the Lower Issaquah Valley. The primary suspected mechanism for release of PFAS to soil and groundwater is the historical use of aqueous film-forming foams (AFFF) during firefighting training exercises. Confirmed releases of AFFF resulting in concentrations of PFAS that exceed current Investigatory Levels[1] for unsaturated, and saturated soil have been confirmed at the following locations:

[1] The Investigatory Level for PFOS, PFOA, and the sum of PFOS and PFOA concentrations in soil for unrestricted (residential) contact is 1.6 milligrams per kilogram (mg/kg). The Investigatory Level for PFOS, PFOA, and the sum of PFOS and PFOA concentrations in soil for industrial contact is 70 mg/kg. The Investigatory Levels for PFOS and PFOA for protection of groundwater for unsaturated soil are 0.00088 and 0.00044 mg/kg, respectively. The

- 175 Newport Way Northwest (EFR Headquarters Facility, or EFR);
- Issaquah Valley Elementary West Playfield;
- Issaquah Valley Elementary East Ballfields (Dodd Fields Park);
- North of 190 East Sunset Way (Memorial Field); and
- West of 135 East Sunset Way on the former rail grade (Rainier Trail Area).

Groundwater samples have confirmed that the PFAS releases to the surface have reached the shallow aquifer for each area of interest, and PFAS concentrations in shallow groundwater exceed the Investigatory Levels[2] at 175 Newport Way Northwest (EFR), and Issaquah Valley Elementary School West Playfield and Dodd Fields Park at 555 Northwest Holly Street (the School). A preliminary cross-section of the area and characterization of the PFAS plume was developed as part of the PFAS Characterization Summary Report (Farallon, 2019).

2.2 Numerical Model Domain, Grid, and Layers

The two-dimensional cross-section model for groundwater flow was developed using MODFLOW-NWT, with MT3DMS for solute transport. MT3DMS is an industry standard, finite-difference code capable of simulating PFAS transport. The model domain is 13,500 feet long from upgradient of the EFR to Lake Sammamish. The cross-section, shown on Figure 2, follows the groundwater flow path simulated in the 3D CARA MODFLOW model. This is a standard approach to cross-sectional modeling. Appendix A includes figures illustrating the cross-section location relative to the estimated PFAS plume in the shallow and A Sand Aquifers and particle tracking evaluation performed with the 3D CARA MODFLOW model.

It is important to recognize that the groundwater flow and fate and transport model presented in this report is a simplified representation of the complex patterns of groundwater flow in the Issaquah Valley Aquifer. The model considers groundwater flow along an approximate flow path that is consistent with the pattern of groundwater movement in this area. The true groundwater-flow system, however, is 3D, and groundwater-flow paths, travel times, and PFAS migration are likely affected by off-cross-section influences that are not represented in this model.

The model extends to Lake Sammamish in order to provide a natural groundwater boundary condition. However, the focus of the modeling presented herein is on the area between the EFR and City Wells #4 and #5, which are located approximately 4,300 feet downgradient of the EFR (i.e., less than halfway between the northern and southern boundaries of the model domain). The model setup and calibration focus on the area between the southern model boundary and City Wells #4 and #5.

The model consists of a rectangular grid with 35,340 active cells representing eight hydrostratigraphic units. The initial layering for the model was based on the 3D CARA model

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Investigatory Levels for PFOS and PFOA for protection of groundwater for saturated soil are 0.000046 and 0.000028 mg/kg, respectively (Farallon, 2019).
[2] The Investigatory Level for PFOS, PFOA, and the sum of PFOS and PFOA concentrations in groundwater is 0.07 micrograms per liter (μg/L) (Farallon, 2019).

and was adjusted in some areas based on additional data boring logs provided by Farallon (2019) and on the conceptual south-north cross-section developed by Farallon (2021). The layering adjustments were performed in the middle portion of the Valley near the EFR and Issaquah Valley Elementary School and Dodd Fields Park, where detailed boring logs and well data are available. South of City Wells #4 and #5, the layering was not modified and remained consistent with the 3D CARA model. Borings/wells only provided data within the shallow and A Sand aquifers. Therefore, adjustments to model layering were not performed at and below the lacustrine silt layer overlying the deep aquifer (i.e. the deeper layering is the same as the 3D CARA model). A finer grid spacing, as compared to the 3D CARA model, was utilized to represent the upper four hydrostratigrahic units. The model hydrostratigraphy is shown on Figures 3a and along with the A-A' cross-section developed by Farallon (2021) on Figure 3b. An upper silt layer between the shallow and A Sand aquifers on the southern portion of the cross-section is less continuous in the model than in cross-section A-A', which allows vertical transport from shallow to A Sand aquifers in the model and explains observations at COI-MW06. Additional refinements of the model hydrostratigraphy may be considered with future site characterization data.

2.3 Groundwater Flow Model

2.3.1 Observation Data – Hydraulic Head

Water level measurements have been collected since 2018 for several monitoring wells located along the model cross-section. Water levels are known to fluctuate seasonally in response to precipitation and changes in production well pumping rates. For this evaluation, groundwater flow was simulated under steady-state conditions, and simulated water levels were qualitatively compared to average water levels measured at monitoring wells located along the cross-section. A full model "calibration" based on statistical analysis between observed data and modeled results was not conducted for this model. The objective was to obtain a reasonable match between observed conditions and model results and identify areas for future data collection or model refinement. Groundwater elevation and flow direction in the Lower Issaquah Valley fluctuate seasonally and is affected by surface water / groundwater interactions along Issaquah Creek; therefore, simulating groundwater flow along the cross-section at steady state is a simplification of the actual flow field. However, the steady-state flow field is intended to represent long-term average conditions over which PFAS migration would occur in the subsurface. This is common practice in groundwater modeling. Transient modeling may be considered as part of a second phase of modeling to assess impacts of varying recharge and production well operations on PFAS fate and transport.

2.3.2 Model Boundaries and Stresses

The model boundaries and stresses are shown in Figure 3. Groundwater flow is from south to north along the cross-section. A constant head boundary is applied to the north and south sides of the model. Constant head boundary values for the south side were based on the simulated water levels upgradient of the EFR in the 3D CARA MODFLOW model. The constant head boundary value for the north side represents the elevation of Lake Sammamish, consistent with the 3D CARA MODFLOW model setup. The constant head boundaries create a regional horizontal gradient along the cross-section of approximately 0.0033 feet/feet in the A and B/C Sand

Aquifers and 0.0039 feet/feet in the shallow aquifer, which is consistent with the observed horizontal gradient. The cross-section model does not include surface water / groundwater interactions in the vicinity of Issaquah Creek. Based on the 3D CARA MODFLOW model, surface water / groundwater interaction along Issaquah Creek influence groundwater flow field in the shallow aquifer, and this process may be considered for a next phase with development of a 3D model.

Recharge is applied at a constant rate based on the City's 3D CARA MODFLOW model. The recharge in the 3D CARA MODFLOW was defined taking into account land use and surficial geology (Geosyntec, 2019). The recharge rate is set at 0.0045 feet per day (20 inches per year), in the major northerly portion of the domain (Figures 3 and 4). This recharge rate is consistent with the 3D CARA MODFLOW model, which uses a recharge value of 23 inches per year in this area of the Valley, and the CDM DYNFLOW model, which uses a recharge value of 24 inches per year in the Valley. An increased recharge rate of 0.007 feet per day (31 inches per year) is used in the southwestern portion of the model in the vicinity of the EFR located at the foothills (Figure 3) to account for additional recharge from hillside runoff. Assuming approximately 15 to 20% of the precipitation on the hillside catchment that contributes to the EFR source area would runoff and infiltrate into the valley floor, the additional recharge from the foothill area would be 9 to 15 inches per year, as documented in Attachment B. The additional 11 inches per year of recharge used in this portion of the model is consistent with this estimate, but further evaluation of runoff from the hillside on the eastern side of the EFR site is warranted to understand whether it actually contributes additional valley recharge.

The two production wells located along the cross-section (COI-PW4 and COI-PW5) are represented with constant head boundary conditions along their respective screened intervals. The constant head boundary value is based on the head simulated with the 3D CARA MODFLOW model at the production well locations under pumping condition for pumping rates of 220 and 200 gallons per minute at COI-PW4 and COI-PW5, respectively.

2.3.3 Material Properties

There are eight hydrostratigraphic units in the model representing the layered system of aquifers and intervening aquitards. Each hydrostratigraphic unit was modeled with uniform hydraulic parameters (i.e., horizontal and vertical hydraulic conductivity). Sand and gravel units (aquifers) have higher hydraulic conductivity, while siltier units (aquitards) have lower hydraulic conductivity. The hydraulic properties were based on the 3D CARA MODFLOW model and slightly adjusted as part of model calibration. The material properties of the different silt layers were kept consistent with the 3D CARA MODFLOW model. The material properties from the 3D CARA MODFLOW model and those that were adjusted as part of model calibration are summarized in Table 1.

2.4 Fate and Transport Model

Based on the current expectations for regulatory limits on PFAS compounds, six PFAS compounds were selected for fate and transport simulation:

- Perfluorooctanesulfonic acid [PFOS]
- Perfluorooctanoic acid [PFOA]

- Perfluorohexanesulfonic acid [PFHxS]
- Perfluorohexanoic acid [PFHxA]
- Perfluorobutanesulfonic acid [PFBS]
- Perfluoropentanoic acid [PFPeA])

AFFF released to the soil surface consists of a complex mixture of PFAS compounds. The PFAS compounds listed above were present at different concentrations in the AFFF. In addition, transport properties, e.g., partitioning in unsaturated zone and sorption to aquifer sediments in the saturated zone of each PFAS vary significantly. Those transport properties determine the fate and transport, such as the downgradient migration rate for each compound. For example, Dcompounds with higher sorption will tend to migrate at a slower rate in the subsurface. The source concentrations for the six PFAS compounds used in the model are based on measured concentrations in shallow groundwater, as described in Section 2.4.3.

Based on historical usage of AFFF at potential sources, which started in 1970s, a 50-year (1970 to 2020) simulation period is used.

2.4.1 Observed data – PFAS

PFAS concentrations have been measured since 2018 for several monitoring wells located along the cross-section. PFAS concentrations fluctuate over time, and the average PFAS concentrations are used for comparison with the simulated concentrations. All six PFAS compounds were modeled, but model calibration focused on PFOS, PFHxS, and PFBS, consistent with the modeling scope for this work. These three PFAS are present in the plume represent a range of sorption properties and source concentrations. The simulated and observed PFAS concentrations were compared qualitatively (i.e., order of magnitude comparison and general plume behavior), and a full model "calibration" based on statistical analysis between observed data and modeled results was not conducted for this cross-section model. The objective was to obtain a reasonable match between observed conditions and model results, evaluate vertical migration mechanisms, and identify areas for future data collection or model refinement.

2.4.2 Transport Properties

Transport properties were defined uniformly in the model domain based on literature values and model scale.

The effective porosity for the entire model is defined at 15%, based on typical effective porosity of alluvial sands and gravel between 10% and 25% (McWhorter and Sunada, 1977) and the effective porosity used in the 3D CARA MODFLOW model to assess capture zone.

Longitudinal dispersivity was calculated using an empirical relationship between longitudinal dispersivity and scale of flow proposed by Schulze-Makuch (2005):

$$\propto = c(L)^m$$

Where:

$\propto$ = longitudinal dispersivity in meters
c = a parameter characteristic for a geologic medium
L = the flow distance in meters
m = a scaling exponent

Based on the values for the parameters c and m in unconsolidated sediments (0.085 and 0.81 using all considered studies, 0.112 and 0.70 for studies with high and intermediate reliabilities, and 0.20 and 0.44 for studies with high reliability only), and a scale of interest of approximately 3,000 feet (distances from the EFR to the School and to COI-PW4 are approximately 2,000 feet and 4,000 feet, respectively), the resultant longitudinal dispersivity varies between 10 and 70 feet. Acknowledging the contribution of numerical dispersion, a longitudinal dispersivity value of 20 feet, on the low end of the range, was selected for this evaluation. The sensitivity of the model results to this parameter was evaluated as part of the sensitivity analysis (Section 2.6). The transverse vertical dispersivity was adjusted through calibration to a value of 0.5%, which is consistent with literature values reporting transverse vertical dispersivity between 100 and 1,000 times lower than horizontal dispersivity (Gelhar et al., 1992).

Sorption is a process that slows the movement and mass of contaminants through attachment of contaminants to the matrix of the aquifer. It is defined by the partitioning (or distribution) coefficient (Kd). Kd is often correlated with the organic carbon content of the aquifer matrix and can be calculated as the product of fraction of organic carbon (foc) multiplied by the organic carbon distribution coefficient (Koc) for the contaminant. Koc varies depending on the specific contaminant compound being evaluated, while foc is a soil property. Sorption is assumed to vary linearly with concentration (linear isotherm), and foc is assumed equal to 0.1%. A foc value of 0.1% is consistent with sand and gravel materials in the Puget Sound. The Koc coefficients are based on literature values for PFAS (Table 1) (Interstate Technology Regulatory Council (ITRC), 2020). The retardation factor (R) is calculated based on Kd, bulk density (ρ_b), and porosity, and corresponds to the factor between groundwater velocity and solute transport velocity.

2.4.3 PFAS Sources

As previously mentioned in Section 2.1 and based on preliminary investigation results (Farallon, 2019), two potential PFAS sources were considered for this evaluation as shown in Figures 2 and 3. These two locations are the two areas of interest located along this groundwater pathway to COI-PW4, where complete PFAS migration pathways for confirmed releases include leaching from soil to groundwater, and lateral and vertical transport in one or more groundwater bearing zones (Farallon, 2021).

- 175 Newport Way (EFR Headquarters)

  Historical AFFF training occurring from the early 1980s to the late 1990s at the EFR Headquarters is believed to be the primary source of PFAS detected in COI-PW4. Typically, one to three 5-gallon buckets of AFFF were expended at the site up to 12 times per year (Farallon, 2019). Other activities at the site, such as washdown and equipment maintenance procedures, may also have contributed to PFAS detections in groundwater (Farallon, 2019). PFOA, PFOS, PFHxS, PFHxA, PFPeA, and PFBS were detected at average concentrations of 310, 5,400, 1,200, 640, 760, 200 nanograms per liter (ng/L), respectively, in shallow groundwater samples at the EFR Headquarters site. For the purposes of the model simulations, these concentrations were used as source concentrations in groundwater at EFR and assumed to remain constant from 1980 to 2020.

- 555 Northwest Holly Street, which includes Dodd Fields Park and Issaquah Valley Elementary School West Playfield (the School), was also identified as a former AFFF training area.

  Historical AFFF training occurred here from the early 1970s to the early 1980s approximately once or twice a year. The quantity of AFFF used per training event is assumed to have been similar to the EFR Headquarters (one to three 5-gallon buckets per event) (Farallon, 2019). PFOA, PFOS, PFHxS, PFHxA, PFPeA, and PFBS were detected at average concentrations of 550, 10, 230, 34, 30, 22 ng/L, respectively, in shallow groundwater samples at the site. For the purposes of the model simulations, these concentrations were used as source concentrations in groundwater at the School and assumed to remain constant from 1970 to 2020.

The model simulates the transport of PFAS originating at the water table, which becomes a “continuous” source of PFAS that can move to downgradient areas long after the release of AFFF at the ground surface. This model does not simulate AFFF releases to the unsaturated soil surface, AFFF partitioning in the soil following release, or the transport of PFAS in the unsaturated zone. Soil can be a significant reservoir for PFAS that then leaches to the water table and begins to flow with groundwater. Because of complex retention processes in soil and unsaturated zone, PFAS concentrations in soil are generally order of magnitude higher than concentrations in groundwater and significant retention of PFAS in the vadose zone over long timeframes is expected (Brusseau et al., 2020). Applying a continuous source concentration for PFAS at the water table beneath the source area that is lower than the soil concentration is an appropriate approach to defining the groundwater transport pathway in this evaluation.

The model simulates constant sources of PFAS at the water table beneath those source areas since the estimated start of the potential PFAS releases at each location (1980 to 2020 for EFR Headquarters and 1970 to 2020 for 555 Northwest Holly Street). The historical groundwater concentrations beneath the sources are unknown and likely varied over time. The model does not simulate the vadose zone processes that determine the volume and concentration of PFAS at the water table. However, this simplified approach is reasonable and common practice in groundwater modeling to simulate groundwater fate and transport and better understand contaminant migration in the subsurface in order to design effective remediation strategies.

2.5 Model Calibration

The groundwater flow model was calibrated using the average of available groundwater elevation measurements taken between August 2018 and April 2020. The observed and simulated water levels are shown on Figure 4. The simulated water levels provide a reasonable match to the observed water levels and reproduce the flow path within the shallow and A Sand aquifers. The model produces the observed downward gradient within the A Sand aquifer and a downward gradient between the A Sand and B/C Sand aquifers. The model does not simulate a downward gradient at one location (COI-MW03) adjacent to COI-PW4. This discrepancy is due to the cross-section model setup (COI-MW3 is not strictly along the flowpath) and the definition of the production well COI-PW4 as constant head. As a result, the model generally underpredicts the hydraulic heads in the downgradient area (COI-MW5 and COI-MW3)

Solute transport and hydraulic parameters were adjusted to fit the average concentrations of PFAS samples collected from 17 wells between July 2013 and July 2020. The average observed and simulated concentrations at each monitoring well are provided in Table 2 and Figure 5. The simulated PFOS, PFHxS, and PFBS concentrations are generally consistent (i.e., order of magnitude consistency) with the observed concentrations. Specifically, the model is able to reproduce the higher PFAS concentrations observed in the A Sand aquifer zone, such as COI-MW06 at a depth of 90 feet bgs, and the decrease in concentrations downgradient at COI-MW05, COI-MW03, and COI-MW02. Similarly, the simulated PFAS concentrations at COI-PW4 are in the same order of magnitude as observed concentrations. The cross-section model setup assumes that monitoring wells are along the plume centerline. Some of the wells are not located strictly along the flow path, which likely lead to varying PFAS concentrations because of horizontal transverse dispersivity, which is not accounted for in this 2D cross-section model. A more refined 3D modeling tool would be able to represent this process and allow for quantitative calibration to the observed hydraulic heads and PFAS concentrations. PFAS concentrations closer to the potential sources are expected to present higher variability depending on the distance from the groundwater flow path and plume centerline, which cannot be represented with the cross-section model. Therefore, the modeled PFAS concentrations show higher discrepancies with observed concentrations in the southern (upgradient) portions of the model.

The model is not able to reproduce the observed PFAS detections at COI-PW5. However, as previously indicated, the focus of the field investigation was on the shallow and A Sand aquifers, and the silt layer between the A Sand and B/C Sand Aquifers remains un-characterized. Therefore, the model stratigraphy for the B/C Sand Aquifer remains based on the 3D CARA MODFLOW model. Observed PFAS detections at COI-PW5 are both higher than model predictions and have been slowly increasing over the past two years. This suggests that the configuration of the silt layer (thickness, extent, or hydraulic properties) in the model is not likely representative of actual conditions. Additional data are necessary to understand the extent and thickness of this lacustrine silt layer and how PFAS is entering the deeper aquifer zones (which are being used for potable water supply), and the associated driving parameters.

2.6 Sensitivity Analysis

Three model simulations were run to illustrate model sensitivity compared to the base model results (Figure 5), as follows:

- Sensitivity simulation 1 - Removal of the PFAS source at the School: the simulated PFOS plume in 2020 is shown in Figure 6a and simulated concentrations for PFOA, PFOS, PFHxS, PFHxA PFBS, and PFPeA are provided in Table 2. This result illustrates that the PFAS source at the School is likely contributing to PFAS concentrations measured at the School shallow monitoring wells (simulated PFOS concentrations at wells IES-MW04, IES-MW05, IES-MW07, and DF-MW02 are significantly underpredicted in this simulation) but does not significantly affect the concentrations of PFAS modeled in COI-PW4, as shown in Figure 6a and Table 2. For example, PFOS concentrations only decrease from 244 to 214 ng/L, which is within the uncertainty range of these model simulations. Similarly, simulated concentrations of other PFAS (Table 2) decrease only slightly in this sensitivity simulation compared to the base model results. This result suggests that the PFAS source area at the School, while contributing to the PFAS plume observed in the shallow aquifer immediately downgradient of the School, does not significantly contribute to the PFAS plume in the A Sand Aquifer and specifically to the observed PFAS concentrations at the City production wells.

- Sensitivity simulation 2 – Increased longitudinal dispersivity (from 20 to 50 feet) and hydraulic conductivity of A Sand Aquifer (from 50 to 75 feet per day): the simulated PFOS plume in 2020 is shown in Figure 6b, and simulated concentrations for PFOA, PFOS, PFHxS, PFHxA, PFBS, and PFPeA are provided in Table 2. In this simulation, horizontal transport is enhanced; for example, the simulated PFOS concentrations are lower at depth closer to the EFR source (i.e., COI-MW06) and higher downgradient in the A Sand Aquifer (i.e., COI-MW03 and COI-MW05). Simulated PFOS concentrations at monitoring wells NWN-MW08, NWN-MW09, NDS-MW01, IES-MW06, and IES-MW07 increased in this sensitivity simulation and are closer to observed concentrations than the base model results. In contrast, simulated PFOS concentration at monitoring well COI-MW06 decreased (from 1,200 to 980 ng/L) and is lower than observed concentration (1,500 ng/L). Simulated PFOS concentrations at COI-MW05 and COI-MW03 increased, resulting in a higher difference with observed concentrations than for the base case model.
- Sensitivity simulation 3 – Decreased longitudinal dispersivity)from 20 to 10 feet)and hydraulic conductivity of A Sand Aquifer (from 50 to 25 feet per day): the simulated PFOS plume in 2020 is shown in Figure 6c, and simulated concentrations for PFOA, PFOS, PFHxS, PFHxA PFBS, and PFPeA are provided in Table 2. In this simulation, vertical transport is enhanced; for example, the simulated PFOS concentrations are higher at depth closer to the EFR source (i.e., COI-MW06) and lower downgradient in the A Sand Aquifer (i.e., COI-MW03 and COI-MW05). Simulated PFOS concentrations at monitoring wells NWN-MW08, NWN-MW09, and IES-MW01 increased and are closer to observed concentrations than the base model results. In contrast, simulated PFOS concentrations at monitoring wells IES-MW07, COI-MW03, and production well COI-PW4 significantly decreased and are much lower than observed PFOS concentrations. Finally, PFOS concentrations at monitoring wells NDS-MW02 and IES-MW06 significantly decreased and are closer to observed concentrations than the base case simulation.

2.7 Model Limitations and Conclusions

The groundwater flow and fate and transport model simulates average steady-state conditions and is not intended to reproduce seasonal fluctuations or temporal changes in the flow field. Similarly, model parameters were adjusted until a reasonable match between observed and simulated PFAS concentrations was achieved at multiple sampling locations, but a “good” match was not achieved at all locations. The cross-section model setup assumes that monitoring wells used for comparison with measured data are located exactly along the groundwater flow path and plume centerline from the EFR to COI-PW4. Because most of the monitoring wells are likely not located exactly along the flow path, a “good” match cannot be achieved at all locations. This limitation would be overcome with the development of a 3D model in a future phase of modeling. As an illustration, PFOS transport from EFR was simulated using the 3D CARA MODFLOW model, and the results are provided in Attachment C.[3]

Despite these limitations, the model calibration produces results that are consistent with observed concentrations and provide a basis for several conclusions that are relevant to the development of a PFAS remedial strategy.

- The School area appears to remain a source of PFAS to groundwater, despite the age of the source area and lower magnitude of AFFF application. This conclusion is based on the result of the sensitivity run where this source area was removed from the simulation. Removing this source resulted in a significantly poorer match between the observed and simulated PFAS concentrations at shallow monitoring wells.
- Although the model cannot be calibrated without including the School as a source area, the “core” of the PFAS plume and the highest PFAS concentrations at depth are associated with the EFR Headquarters source area. Removing the Dodd Field area as a source has a negligible effect on PFAS concentrations at COI-PW4 (Figure 6a and Table 2). Therefore, the EFR headquarters site remains the highest priority source area for remedial actions in relation to impacts to water supply.
- The higher concentrations of PFAS simulated in the intermediate aquifer zone, such as COI-MW6 at a depth of 90 feet bgs, are consistent with the observed concentrations of PFAS at the EFR Headquarters source area; the modeled hydraulic properties of the shallow and intermediate aquifer, and the modeled recharge to the aquifer system.
- The general distribution of PFAS in the aquifer system can be effectively simulated using a basic layering geometry. However, inclusion of (or refinements to) fine-scale stratigraphic layering, such as silt lenses, may improve the match between observed and modeled PFAS at specific locations. This fine-scale variability should be considered in developing a 3D modeling approach for future analysis of remediation strategies.

[3] The 3D CARA MODFLOW model was used for simulating PFOS transport without any modification. Future 3D modeling should include horizontal and vertical grid refinement to limit numerical dispersion.

3. SIMULATION OF REMEDIAL ACTIONS

Several example simulations were prepared to demonstrate how this model (or future refinements to it) could be used to evaluate remedial actions at the source areas or changes in pumping configurations of the water supply wells in the Lower Issaquah Valley. The simulations focused on general remedial actions (as opposed to specific remedial actions at source areas) and included partial and full source removals and three pumping change strategies. The Partnership is currently evaluating remedial technologies for soil and groundwater at one source area (EFR) to pilot test specific technologies. The remedies included in the model are intended to evaluate general remedial actions on a large scale to understand changes to plume behavior in the LIV system.

Five scenarios were modeled and compared to a "base case" with no change to the current configuration of source areas and pumping at COI-PW4. Each of the five scenarios was simulated for a 50-year time frame into the future, assuming no change to the hydraulic boundary conditions (i.e., constant head boundaries and recharge).

3.1 Description of Mitigation Scenarios

The mitigation scenarios simulated are as follows:

- Base case scenario – No action: This scenario illustrates the evolution of the PFAS plume in the absence of any remedial actions or changes to the groundwater flow field. No changes were made to the model inputs described in Section 2.
- Scenario 1 – Shutdown of COI-PW4: This scenario evaluates the effects of turning off COI-PW4 (City Well #4) on the PFAS plume. In the model, the constant head boundary condition at COI-PW4 was removed. This is the only change in the model. The PFAS sources at the EFR and the School remain unchanged (i.e., same constant concentrations are used as for 1970 – 2020 simulation period).
- Scenario 2 – Full Source Removal: This scenario evaluates the effects of full source removal at EFR and the School on downgradient PFAS concentrations. In the model, the source area concentrations at both areas are set to 0.
- Scenario 3 – Partial Source Removal: This scenario evaluates the effects of partial source removal at EFR on downgradient PFAS concentrations. In the model, the source area concentration at EFR is decreased by 50% and the source area at the School remains at its current level.
- Scenario 4 – Downgradient Hydraulic Containment: This scenario evaluates the effects of potential off-site hydraulic containment (i.e., via installation of remedial extraction well(s)) of the PFAS plume downgradient of EFR. In the model, downgradient hydraulic containment (i.e., extraction wells) is simulated with a constant head boundary in the A Sand Aquifer in the vicinity of IES-MW04, simulating a 6-foot drawdown. The PFAS sources at the EFR and the School remain unchanged, i.e., same constant concentrations are used as for 1970 – 2020 simulation period.

- Scenario 5 – Hydraulic Containment and Partial Source Removal: This scenario is a combination of Scenario 3 (partial source removal) and Scenario 4 (downgradient hydraulic containment). The source area concentration at EFR is decreased by 50%, and the source area at the School remains at its current level. Downgradient hydraulic containment (i.e., extraction wells) is simulated with a constant head boundary in the A Sand Aquifer in the vicinity of IES-MW04, simulating a 6-foot drawdown.

3.2 Mitigation Scenario Results

The simulated PFOS plumes for the base case and five mitigation scenarios are shown in Figures 7 through 12.

Base Case (Figure 7). The results indicate that the PFOS plume is expected to remain fairly stable under the base case scenario. The PFOS plume is shown to not migrate past COI-PW4 (City Well #4) in the A Sand Aquifer if this well remains in operation, indicating that the operation of COI-PW4 is currently providing plume containment. Limited leaching through the A/B aquitard to the B/C Aquifer is simulated starting in year 10, but simulated PFOS concentrations in the B/C Aquifer remain below 100 ng/L (Figure 7).

Scenario 1: Shutdown of COI-PW4 (Figure 8). A shutdown of COI-PW4 may result in further downgradient migration of the PFAS plumes in the A Sand Aquifer (Figure 8). Under this scenario, PFOS concentrations exceeding 500 ng/L are predicted downgradient of COI-PW4 within five years of a shutdown of City Well #4. In addition, additional leaching through the A/B aquitard to the B/C Aquifer is predicted, with PFOS concentrations above 100 ng/L in the B/C Aquifer within 30 years.

Scenario 2: Full Source Removal (Figure 9). Full source removal would result in a significant decrease in concentrations downgradient of the EFR source area. Full source removal is modeled as a zero concentration of PFAS at the water table underlying the source area. PFOS concentrations are predicted to decrease to below 500 ng/L in most of the A Sand Aquifer within 30 years and below 100 ng/L within 50 years. However, PFOS concentrations are predicted to remain above 15 ng/L for at least 50 years.

Scenario 3: Partial Source Removal (Figure 10). Partial source removal is modeled as a 50% reduction in the concentration of PFAS at the water table underlying the EFR source area. Partial source removal would also result in a decrease in concentrations downgradient of the EFR source area. However, a stable PFOS plume would still be present between the EFR source area and COI-PW4 with concentrations above 500 ng/L after 30 years. Partial source removal also results in continued migration of PFOS through the lacustrine silt layer. The partial source control scenario demonstrates the importance of remedial design objectives for PFOS concentrations at the water table beneath the source area. Full source control (“zero” PFOS concentration at the water table) may not be feasible, but partial source control alone may not be sufficient to achieve remedial objectives for the downgradient water supply at COI-PW4.

Scenario 4: Pumping without Source Control (Figure 11). Pumping in the A Sand Aquifer downgradient of the EFR source area without source control produces a similar plume geometry and time history to the base case, but does result in lower concentrations and a more rapid decrease in concentrations at COI-PW4 (Figure 11). Pumping downgradient of the EFR source area would stabilize the current "core" of the PFOS plume (where concentrations are above 1,000 ng/L) in its current position. The constant head boundary used in the model to represent downgradient extraction corresponds to an extraction rate of approximately 100 gallons per minute. Based on the A Sand Aquifer hydraulic properties and gradient, this extraction rate would produce a capture zone approximately 1,000 feet wide. However, additional evaluation using the 3D CARA MODFLOW model would be required to develop a full capture analysis.

Scenario 5: Pumping with Partial Source Control (Figure 12). A combination of partial source removal at the EFR source area and downgradient pumping is expected to result in faster and more significant concentration reductions, including downgradient of the remedial extraction well(s) and at COI-PW4. If source control at the EFR source area cannot achieve zero PFOS concentration at the water table, downgradient pumping may be considered to fully control PFOS migration toward COI-PW4. As remedial actions are considered and analyzed, the model can be used to help describe how downgradient PFOS concentrations change in relation to source control effectiveness.

4. DATA GAPS FOR VALLEY WIDE ASSESSMENT

The cross-section model and remedial mitigation strategies described above present an initial assessment that evaluates groundwater conditions along the dominant groundwater flow path from the primary source area (EFR) toward City well COI-PW4. However, the model is only a tool and does not constitute a thorough assessment of remedial strategies and how they could be designed and implemented to achieve remedial objectives and groundwater quality compliance throughout the Issaquah Valley Aquifer system. For example, PFAS concentrations are slowly increasing in the B/C Sand Aquifer tapped by COI-PW5, consistent with the findings of the model indicating leaching through the A/B aquitard to the B/C Aquifer under the Base Case scenario (Section 3.2), but a remedial strategy for the B/C Sand Aquifer system cannot be designed without additional data regarding connections between the B/C Sand Aquifer and PFAS source areas.

PFAS has also been observed at low levels in water supply wells on the eastern side of the Issaquah Valley. Additional data are needed to understand the connectivity between these wells and PFAS source areas. The model has shown that downward movement of PFAS from the primary source area at EFR is possible and that the migration pathways are predictable, but also sensitive to complexities in the glacial stratigraphy of the aquifer system. The model also has shown that the configuration of pumping wells relative to the PFAS plume will affect how the geometry of the plume evolves over time and that it will likely take decades to fully remediate the plume. However, additional data and a more refined 3D modeling tool are necessary to simulate how groundwater pumping for water supply will affect the movement of the plume and how remedial actions would interact with the continued use of the aquifer systems for potable water supply. Data gaps related to the assessment of the regional groundwater system and associated impacts from the PFAS plume include:

- Additional characterization of the deeper, lacustrine silt to evaluate transport pathways into the deepest groundwater production zones used for public water supply and to provide data to calibrate a 3D model of the groundwater system.
- Evaluation of surface water/groundwater interaction along Issaquah Creek to determine how it affects groundwater flow directions and PFAS migration.
- Evaluation of other pumping centers in the Issaquah Valley aquifer system, including the Sammamish Plateau, Darigold, and shallower City Wells, to determine how current and future pumping configurations at these wells would impact PFAS migration.
- Evaluation of specific remedial actions, including pump and treat, that would specifically address impacts from PFAS that have moved outside of the EFR source area property.
- More complete characterization of the other potential sources and the plume outside source areas (valley-wide).
- Further evaluation of the silt layer between the shallow and A Sand aquifers at EFR, including data from recently installed wells for the pilot study (August 2020).
- Pumping tests or other aquifer tests to provide site-specific hydrogeological parameters.

- More frequent water level measurements to account for seasonal fluctuations.
- Geological and hydrogeological data for the B/C Sand Aquifer, including depth, thickness, hydraulic conductivity, ground water flow paths, and PFAS concentrations.
- Vertical gradients between the shallow, A Sand, and B/C Sand Aquifers in different areas of the plume.

5. REFERENCES

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TABLES

Table 1
Model Parameters
Groundwater Flow and PFAS Transport Modeling Report

Description	Calibrated Value	3D CARA MODFLOW Model Value
Horizontal Hydraulic Conductivity (K_h) (ft/day)		
Hydrostratigraphic Unit 1 - Fine Sand	5	5
Hydrostratigraphic Unit 2 - Silt	0.1	0.1
Hydrostratigraphic Unit 3 - Sand	20	50
Hydrostratigraphic Unit 4 - Silt	1	1
Hydrostratigraphic Unit 5 - A Sand Aquifer	50	25 - 100
Hydrostratigraphic Unit 6 - Silt	0.5	0.5
Hydrostratigraphic Unit 7 - B Sand Aquifer	200	200
Hydrostratigraphic Unit 8 - Silt	0.1	0.1
Vertical Hydraulic Conductivity (K_v) (ft/day)		
Hydrostratigraphic Unit 1 - Fine Sand	0.5	0.5
Hydrostratigraphic Unit 2 - Silt	0.01	0.01
Hydrostratigraphic Unit 3 - Sand	2	1
Hydrostratigraphic Unit 4 - Silt	0.02	0.02
Hydrostratigraphic Unit 5 - A Sand Aquifer	5	0.5 - 2
Hydrostratigraphic Unit 6 - Silt	0.01	0.01
Hydrostratigraphic Unit 7 - B Sand Aquifer	4	4
Hydrostratigraphic Unit 8 - Silt	0.01	0.01
Transport Parameters		
Effective Porosity	0.15	Not Applicable
Horizontal Dispersivity (feet)	20	
Transverse Vertical Dispersivity (feet)	0.1	
Fraction of Organic Carbon (foc) (%)	0.1%	
Bulk Density (ρ_b) (kg/L)	1.9	
$LogK_{oc}$*		
PFOS	2.4	Not Applicable
PFOA	2.0	
PFHxS	2.5	
PFPeA	1.4	
PFHxA	1.3	
PFBS	1.5	
Retardation Coefficient (R)		
PFOS	4.2	Not Applicable
PFOA	2.3	
PFHxS	5.0	
PFPeA	1.3	
PFHxA	1.3	
PFBS	1.4	

Abbreviations:
PFAS per- and poly- fluoroalkyl substances
PFBS perfluorobutanesulfonic acid
PFHxA perfluorohexanoic acid
PFHxS perfluorohexanesulfonic acid
PFOA perfluorooctanoic acid
PFOS perfluorooctanesulfonic acid
PFPeA perfluoropentanoic acid
*from Interstate Technology Regulatory Council (ITRC), Table 4-1 (https://pfas-1.itrcweb.org/)

Table 2
Observed and Simulated PFAS Concentrations
Groundwater Flow and PFAS Transport Modeling Report

Well ID	Concentrations (ng/L)				
	Observed	Base Model	Sensitivity Analysis Simulations		
			1	2	3
Perfluorooctanoic acid (PFOA)					
COI-MW07	7	0	0	0	0
NWN-MW08	13	0	1	3	13
NWN-MW09	58	11	11	24	58
NDS-MW01	56	16	17	58	0
COI-MW06	94	69	72	57	106
NDS-MW02	10	73	74	94	1
IES-MW01	10	1	0	7	3
IES-MW06	1	83	79	75	4
DF-MW02	9	9	0	10	10
IES-MW05	22	10	0	10	10
IES-MW04	37	9	0	10	8
COI-MW05	15	40	38	49	6
IES-MW07	23	2	0	8	0
COI-MW03	11	13	13	26	1
COI-PW5	ND	0	0	0	0
COI-PW4	12	13	14	24	2
COI-MW02	ND	0	0	0	0
Perfluorooctanesulfonic acid (PFOS)					
COI-MW07	9	0	0	0	0
NWN-MW08	103	8	12	49	217
NWN-MW09	777	184	197	410	996
NDS-MW01	1080	284	302	997	4
COI-MW06	1543	1196	1249	981	1844
NDS-MW02	290	1270	1274	1631	12
IES-MW01	213	67	1	197	201
IES-MW06	8	1433	1375	1291	69
DF-MW02	495	552	0	521	596
IES-MW05	483	574	0	534	577
IES-MW04	530	563	0	522	491
COI-MW05	377	731	646	855	307
IES-MW07	530	120	2	253	3
COI-MW03	160	272	215	421	65
COI-PW5	29	0	0	0	0
COI-PW4	376	244	214	367	50
COI-MW02	ND	0	0	0	0

Table 2
Observed and Simulated PFAS Concentrations
Groundwater Flow and PFAS Transport Modeling Report

Well ID	Concentrations (ng/L)				
	Observed	Base Model	Sensitivity Analysis Simulations		
			1	2	3
Perfluorohexanesulfonic acid (PFHxS)					
COI-MW07	5	0	0	0	0
NWN-MW08	105	2	3	11	46
NWN-MW09	154	40	43	89	216
NDS-MW01	470	62	65	216	1
COI-MW06	506	260	271	213	400
NDS-MW02	140	275	276	354	3
IES-MW01	69	28	0	64	84
IES-MW06	6	311	298	280	14
DF-MW02	175	230	0	212	248
IES-MW05	193	239	0	216	240
IES-MW04	260	235	0	212	205
COI-MW05	149	170	138	192	125
IES-MW07	210	49	0	91	1
COI-MW03	107	72	41	96	23
COI-PW5	18	0	0	0	0
COI-PW4	149	59	38	81	17
COI-MW02	5	0	0	0	0
Perfluorohexanoic acid (PFHxA)					
COI-MW07	6	0	0	0	0
NWN-MW08	140	1	1	6	27
NWN-MW09	199	22	23	49	118
NDS-MW01	145	34	36	118	0
COI-MW06	248	142	148	116	218
NDS-MW02	24	151	151	193	2
IES-MW01	24	3	0	15	8
IES-MW06	0	170	163	153	8
DF-MW02	12	23	0	24	25
IES-MW05	48	24	0	25	24
IES-MW04	100	23	0	24	20
COI-MW05	46	82	77	100	15
IES-MW07	84	5	0	18	0
COI-MW03	27	27	27	55	3
COI-PW5	ND	0	0	0	1
COI-PW4	ND	28	30	53	5
COI-MW02	5	0	0	0	0

Table 2
Observed and Simulated PFAS Concentrations
Groundwater Flow and PFAS Transport Modeling Report

Well ID	Concentrations (ng/L)				
	Observed	Base Model	Sensitivity Analysis Simulations		
			1	2	3
Perfluorobutanesulfonic acid (PFBS)					
COI-MW07	2	0	0	0	0
NWN-MW08	26	0	0	2	8
NWN-MW09	36	7	7	15	37
NDS-MW01	77	11	11	37	0
COI-MW06	107	44	46	36	68
NDS-MW02	40	47	47	61	0
IES-MW01	20	3	0	8	8
IES-MW06	5	53	51	48	3
DF-MW02	18	23	0	22	25
IES-MW05	31	24	0	22	24
IES-MW04	55	23	0	22	20
COI-MW05	51	28	24	33	13
IES-MW07	66	5	0	11	0
COI-MW03	45	11	9	19	3
COI-PW5	6	0	0	0	0
COI-PW4	48	11	9	18	3
COI-MW02	7	0	0	0	0
Perfluoropentanoic acid (PFPeA)					
COI-MW07	0	0	0	0	0
NWN-MW08	150	1	2	7	32
NWN-MW09	278	26	28	58	141
NDS-MW01	170	40	43	141	1
COI-MW06	368	169	176	138	260
NDS-MW02	32	179	180	230	2
IES-MW01	26	4	0	19	12
IES-MW06	3	202	194	182	10
DF-MW02	6	32	0	33	35
IES-MW05	46	33	0	34	34
IES-MW04	92	33	0	33	29
COI-MW05	47	98	92	120	20
IES-MW07	88	7	0	23	0
COI-MW03	27	33	33	66	5
COI-PW5	ND	0	0	0	1
COI-PW4	ND	34	35	63	6
COI-MW02	ND	0	0	0	0

ND = non-detect

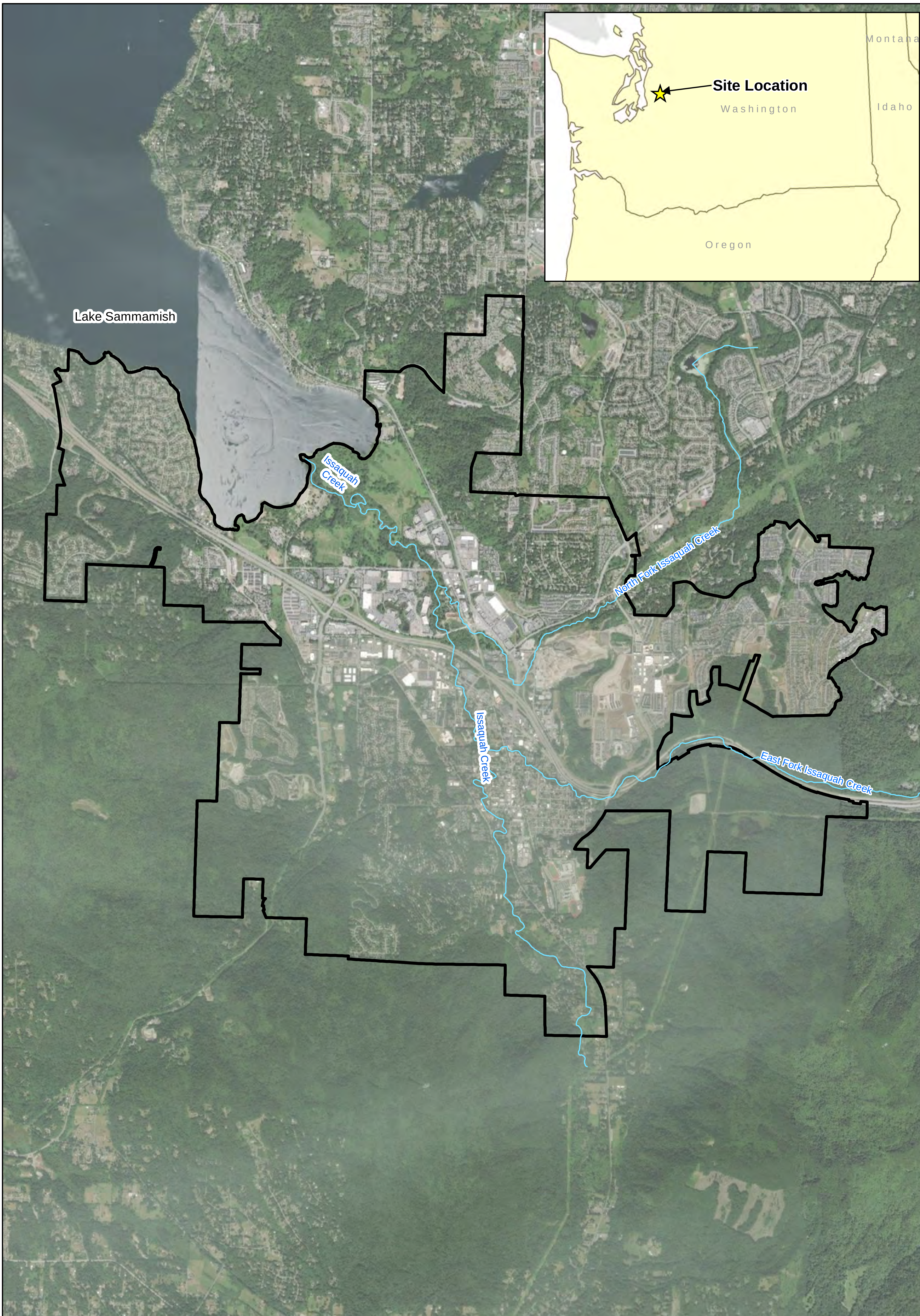
Sensitivity Analysis:

1 - Removal of School Source Zone

2 - Increase of Longitudinal Dispersivity and Hydraulic Conductivity in A Sand Aquifer

3 - Decrease of Longitudinal Dispersivity and Hydraulic Conductivity in A Sand Aquifer

FIGURES



Legend

Issaquah Creek

City Limits

Notes:
1. Aerial image from 2012.

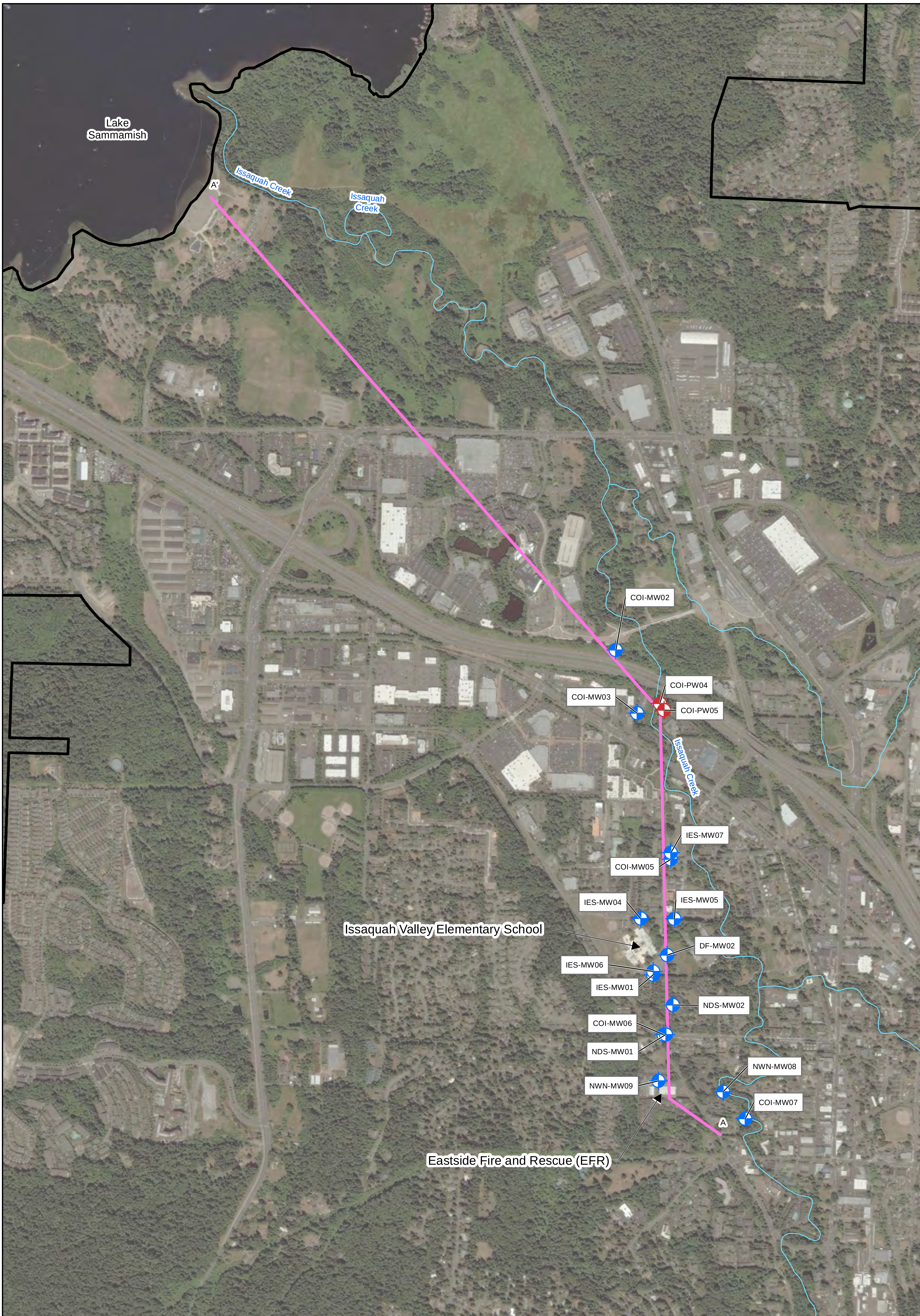
Site Location
Issaquah, Washington

Geosyntec consultants

Seattle, Washington | January 2021

Figure 1

C:\Users\beckhardt\OneDrive - Geosyntec\Documents\ArcGIS\Packages\Figure 1_Site Location_259B2AE9-25E1-4674-ADFC-50BFE533BEDF\v108\Figure 1_Site Location.mxd 1/4/2021 12:37:39 PM



Legend

- Monitoring Well
- Production Well
- Cross Section
- Issaquah Creek
- City Limits

Notes:
1. Aerial image from 2012.

N

1 inch = 1000 feet

0 — 2,000 Feet

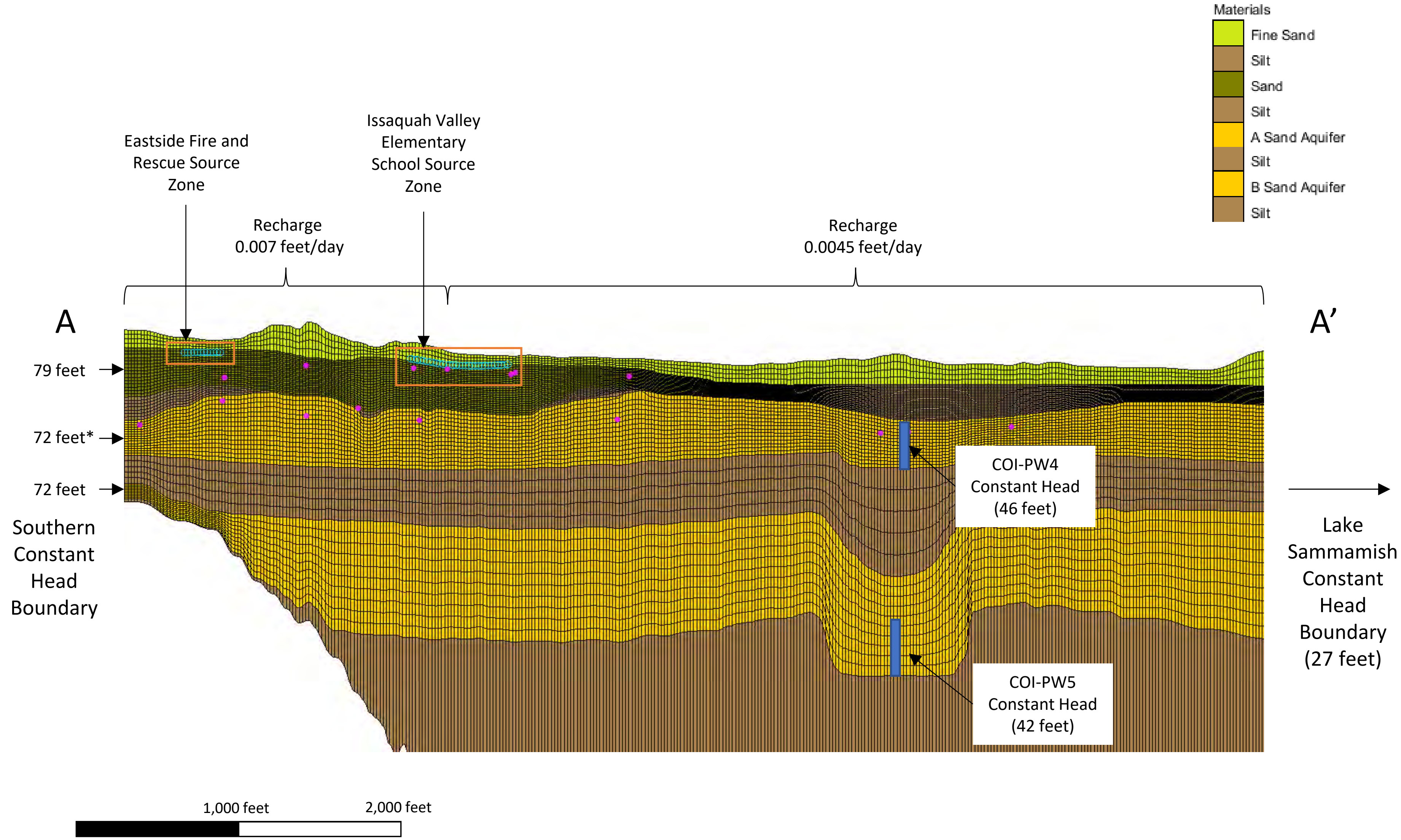
Site Map and Cross-Section Location
Issaquah, Washington

Geosyntec consultants

Seattle, Washington | January 2021

Figure 2

P:\DEPT 3040 - Anchorage\Users\BEckhardt\18 Temporary GIS\Issaquah\Figure 2_Site Map and Cross Section-2.mxd 1/6/2021 11:22:17 AM



Notes:

- Midpoint of monitoring well screen
- Constant PFAS Concentration

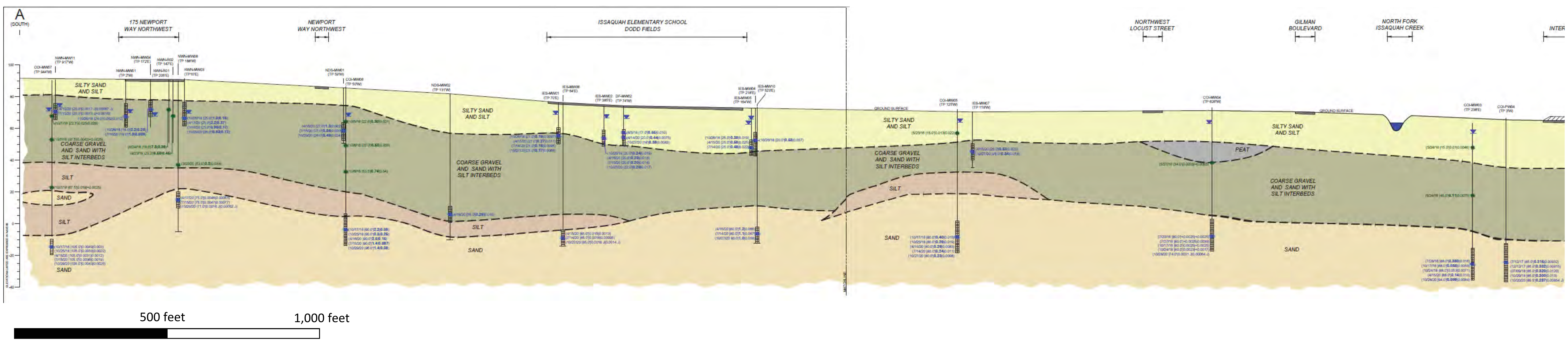
* For Mitigation Scenario 3, the constant head boundary in A Sand Aquifer is set to 77 feet.
Vertical Exaggeration: 5

Model Domain, Layering, Boundaries, and Stresses
Issaquah, Washington

Geosyntec consultants

Seattle, Washington | December 2020

Figure 3a



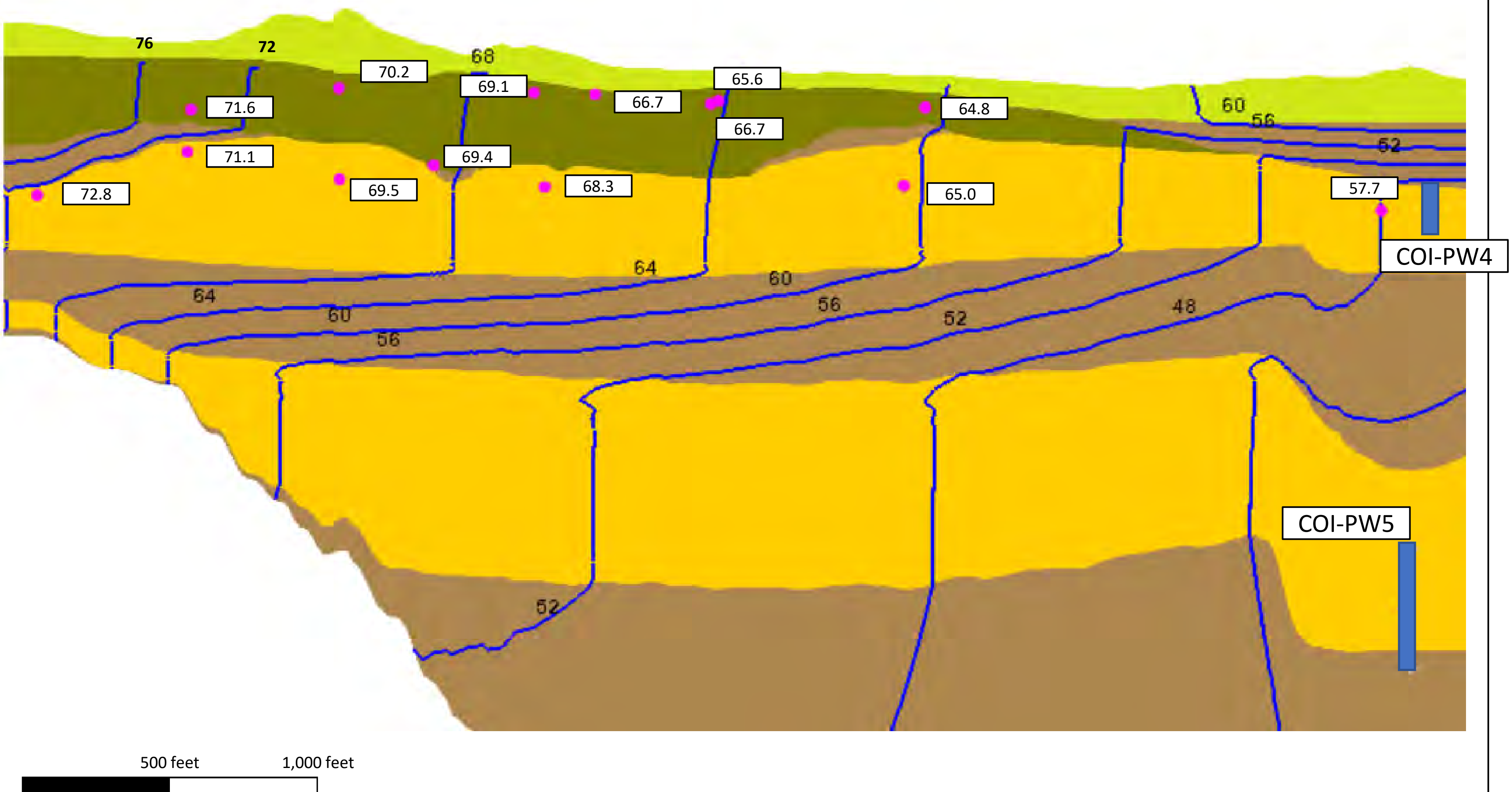
Notes:
Cross-section A-A' from Farallon (2021)

Vertical exaggeration: 5

Model Hydrostratigraphy
Issaquah, Washington

Seattle, Washington | January 2021

Figure 3b



Notes:

● Midpoint of monitoring well screen

72.8 Average of available groundwater elevation measurements between August 2018 and April 2020 (in feet NAVD88).

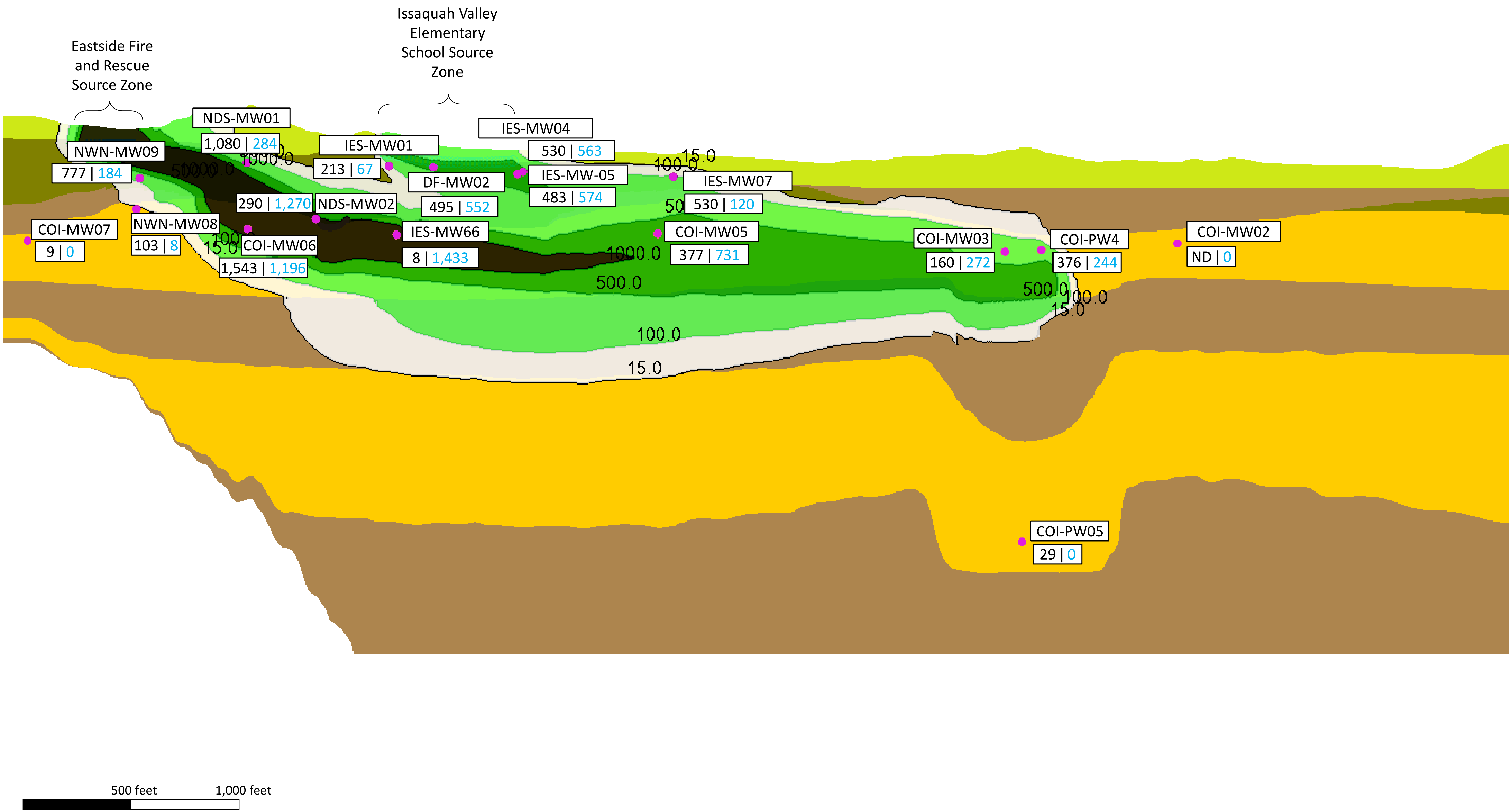
Vertical Exaggeration: 5

Groundwater Flow Model Head Contours
Issaquah, Washington

Geosyntec consultants

Seattle, Washington | December 2020

Figure 4



Notes:

- Midpoint of monitoring well screen

72 | 85 Average measured (black) PFOS concentrations
Modeled (blue) PFOS concentrations in 2020 (ng/L)

Vertical exaggeration: 5

Abbreviations:
PFAS – per- and poly- fluoroalkyl substances
PFOS – perfluorooctanesulfonic acid

Simulated PFAS Concentration Contours (ng/L)

15.0	100.0	
100.0	500.0	
500.0	1000.0	
1000.0	5000.0	

Simulated PFAS Plumes – PFOS
Issaquah, Washington

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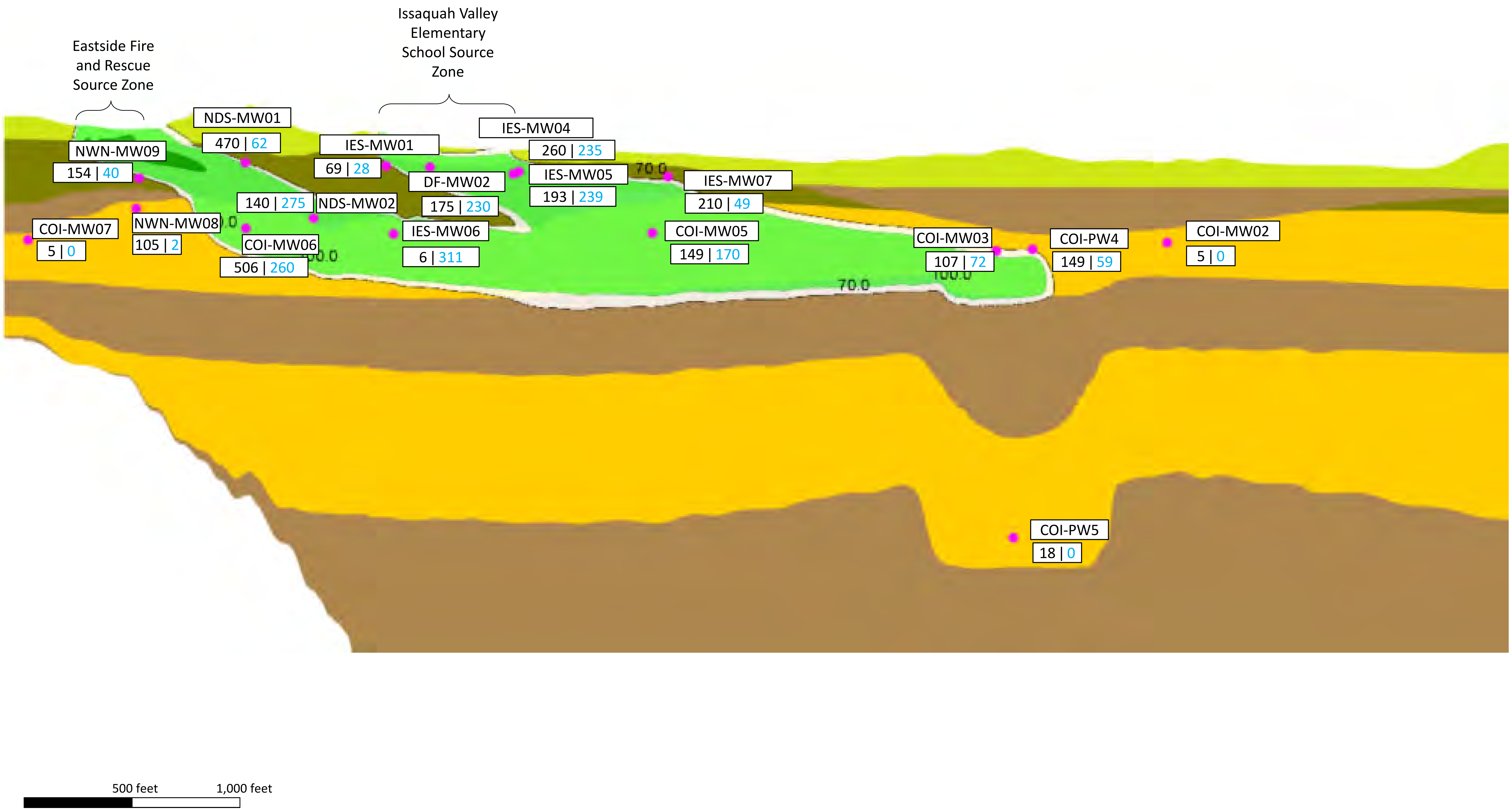
Seattle, Washington | January 2021

Figure 5a



Notes:
- Midpoint of monitoring well screen

72 | 85 Average measured (black) PFHxS concentrations
Modeled (blue) PFHxS concentrations in 2020 (ng/L)

Vertical exaggeration: 5

Abbreviations:
PFAS – per- and poly- fluoroalkyl substances
PFHxS – perfluorohexanesulfonic acid

Simulated PFHxS Concentration Contours (ng/L)

70.0	100.0	
100.0	500.0	
500.0	1000.0	
1000.0	5000.0	

Simulated PFAS Plumes – PFHxS
Issaquah, Washington

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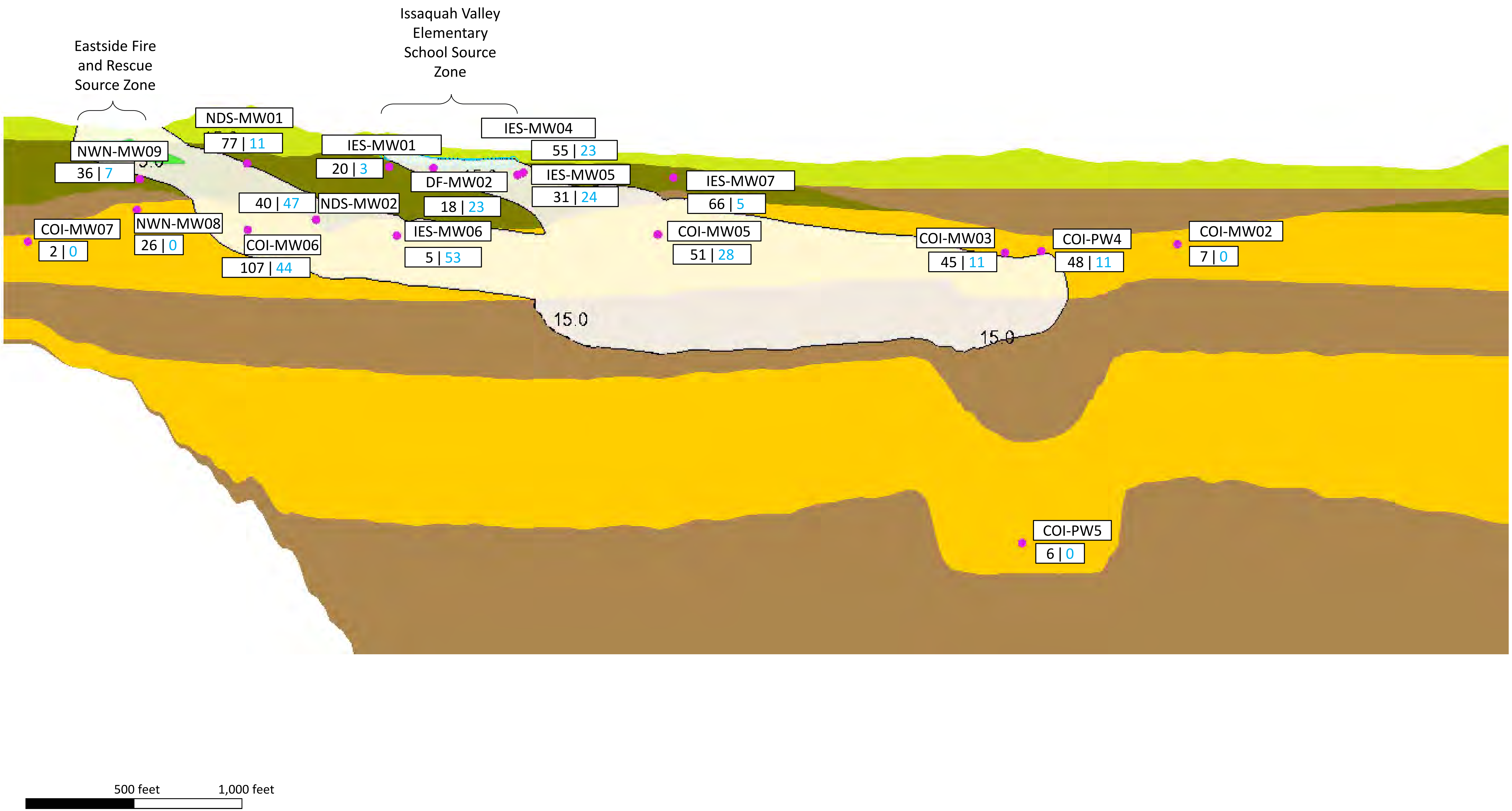
Figure 5b



Notes:

- Midpoint of monitoring well screen

72 | 85 Average measured (black) PFBS concentrations
Modeled (blue) PFBS concentrations in 2020 (ng/L)

Vertical exaggeration: 5

Abbreviations:
PFAS – per- and poly- fluoroalkyl substances
PFBS – perfluorobutanesulfonic acid

Simulated PFBS Concentration Contours (ng/L)

15.0	100.0	
100.0	500.0	
500.0	1000.0	
1000.0	5000.0	

Simulated PFAS Plumes – PFBS
Issaquah, Washington

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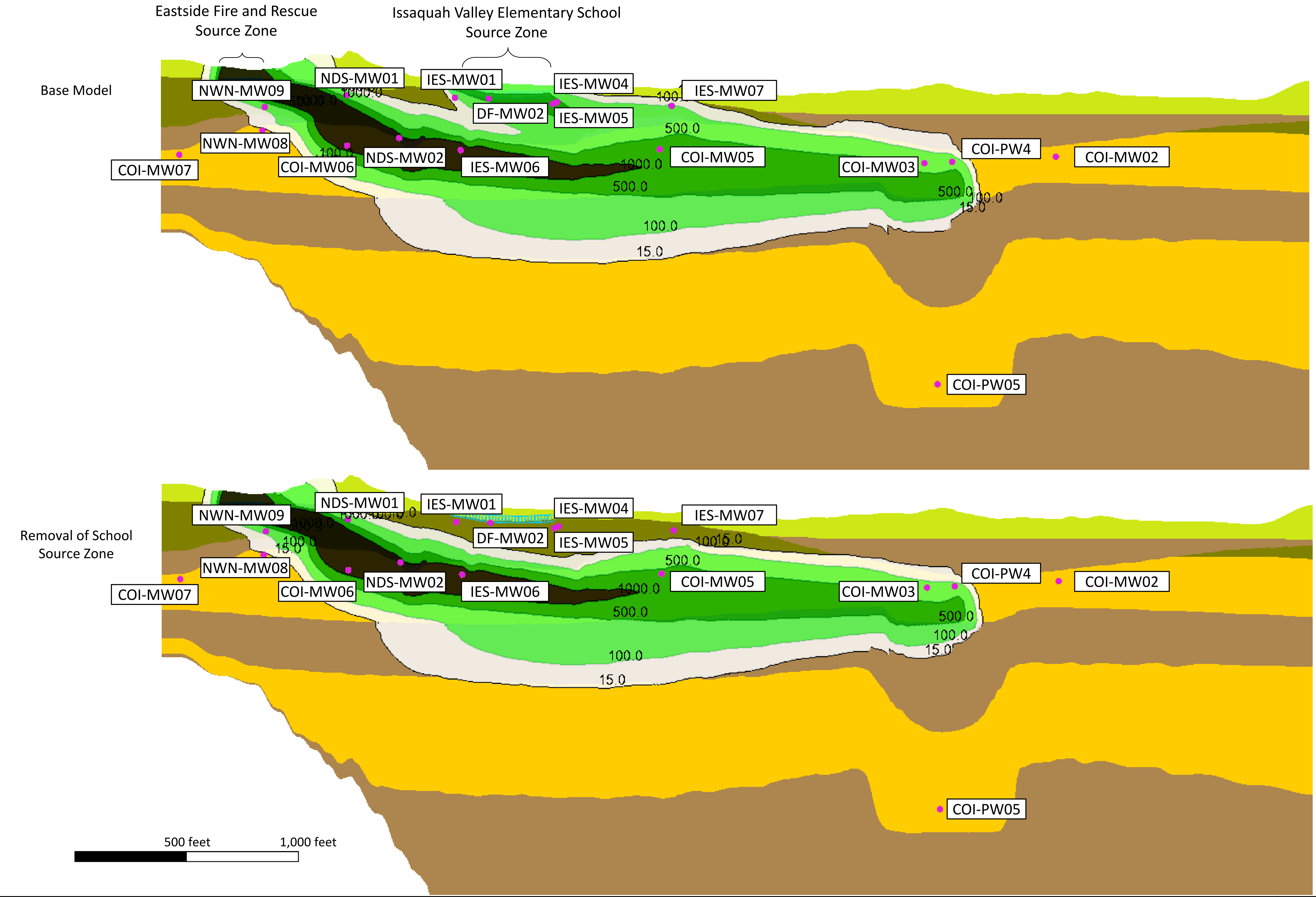
Seattle, Washington | January 2021

Figure 5c



Simulated PFOS Concentration (ng/L)		
Well ID	**Base Case**	**Simulation 1**
COI-MW07	0	0
NWN-MW08	8	12
NWN-MW09	184	197
NDS-MW01	284	302
COI-MW06	1196	1249
NDS-MW02	1270	1274
IES-MW01	67	1
IES-MW06	1433	1375
DF-MW02	552	0
IES-MW05	574	0
IES-MW04	563	0
COI-MW05	731	646
IES-MW07	120	2
COI-MW03	272	215
COI-PW5	0	0
COI-PW4	244	214
COI-MW02	0	0

Notes:
- Midpoint of monitoring well screen

Vertical Exaggeration: 5

Abbreviations:
PFOS – perfluorooctanesulfonic acid

Simulated PFOS Concentration Contours (ng/L)

15.0	100.0	
100.0	500.0	
500.0	1000.0	
1000.0	5000.0	

Simulated PFOS Plume – Sensitivity Analysis
Simulation 1
Issaquah, Washington

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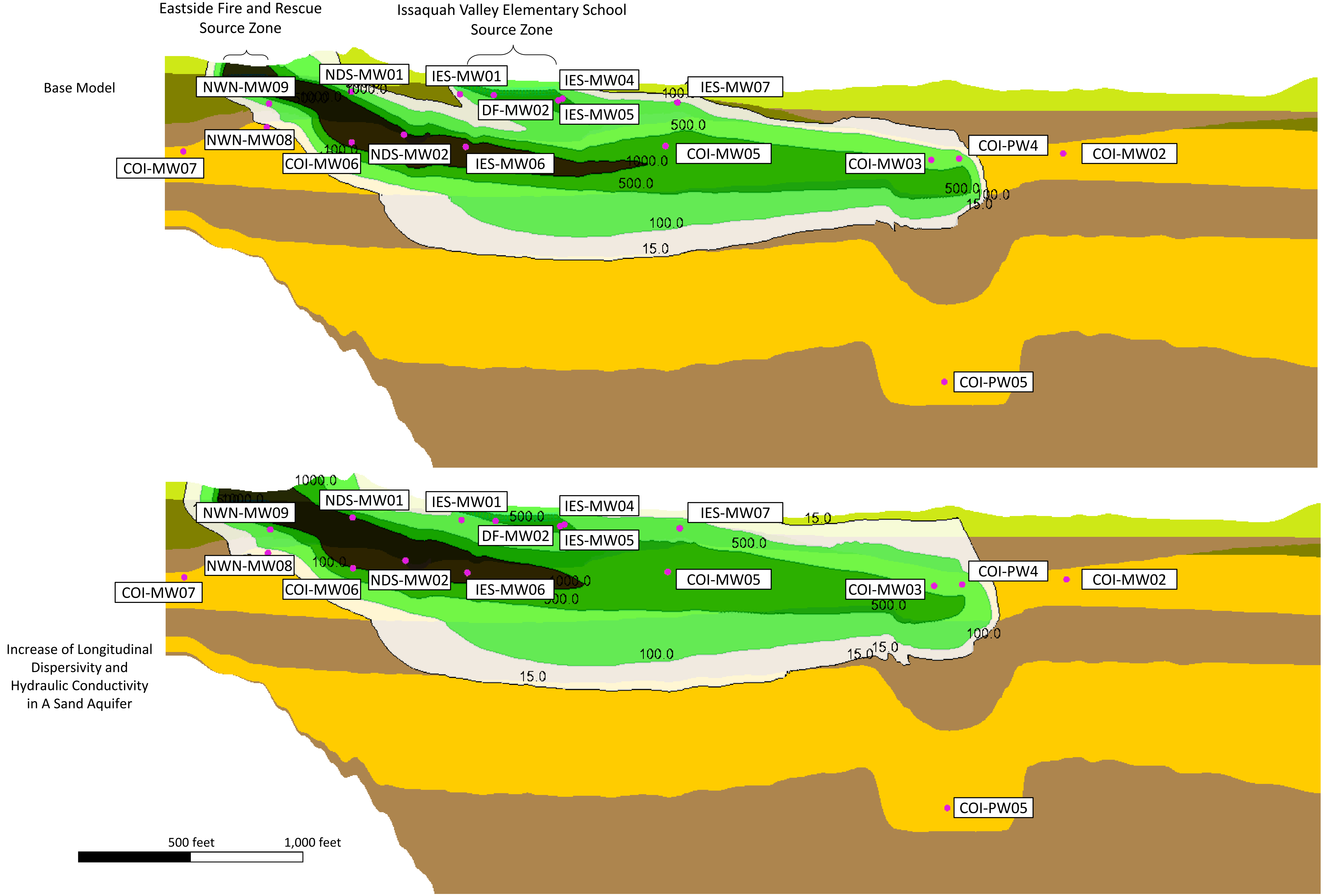
Figure 6a

Seattle, Washington | January 2021



Simulated PFOS Concentration (ng/L)		
Well ID	**Base Case**	**Simulation 2**
COI-MW07	0	0
NWN-MW08	8	49
NWN-MW09	184	410
NDS-MW01	284	997
COI-MW06	1196	981
NDS-MW02	1270	1631
IES-MW01	67	197
IES-MW06	1433	1291
DF-MW02	552	521
IES-MW05	574	534
IES-MW04	563	522
COI-MW05	731	855
IES-MW07	120	253
COI-MW03	272	421
COI-PW5	0	0
COI-PW4	244	367
COI-MW02	0	0

Notes:
- Midpoint of monitoring well screen

Vertical Exaggeration: 5

Abbreviations:
PFOS – perfluorooctanesulfonic acid

Simulated PFOS Concentration Contours (ng/L)

15.0	100.0	
100.0	500.0	
500.0	1000.0	
1000.0	5000.0	

Simulated PFOS Plume – Sensitivity Analysis Simulation 2
Issaquah, Washington

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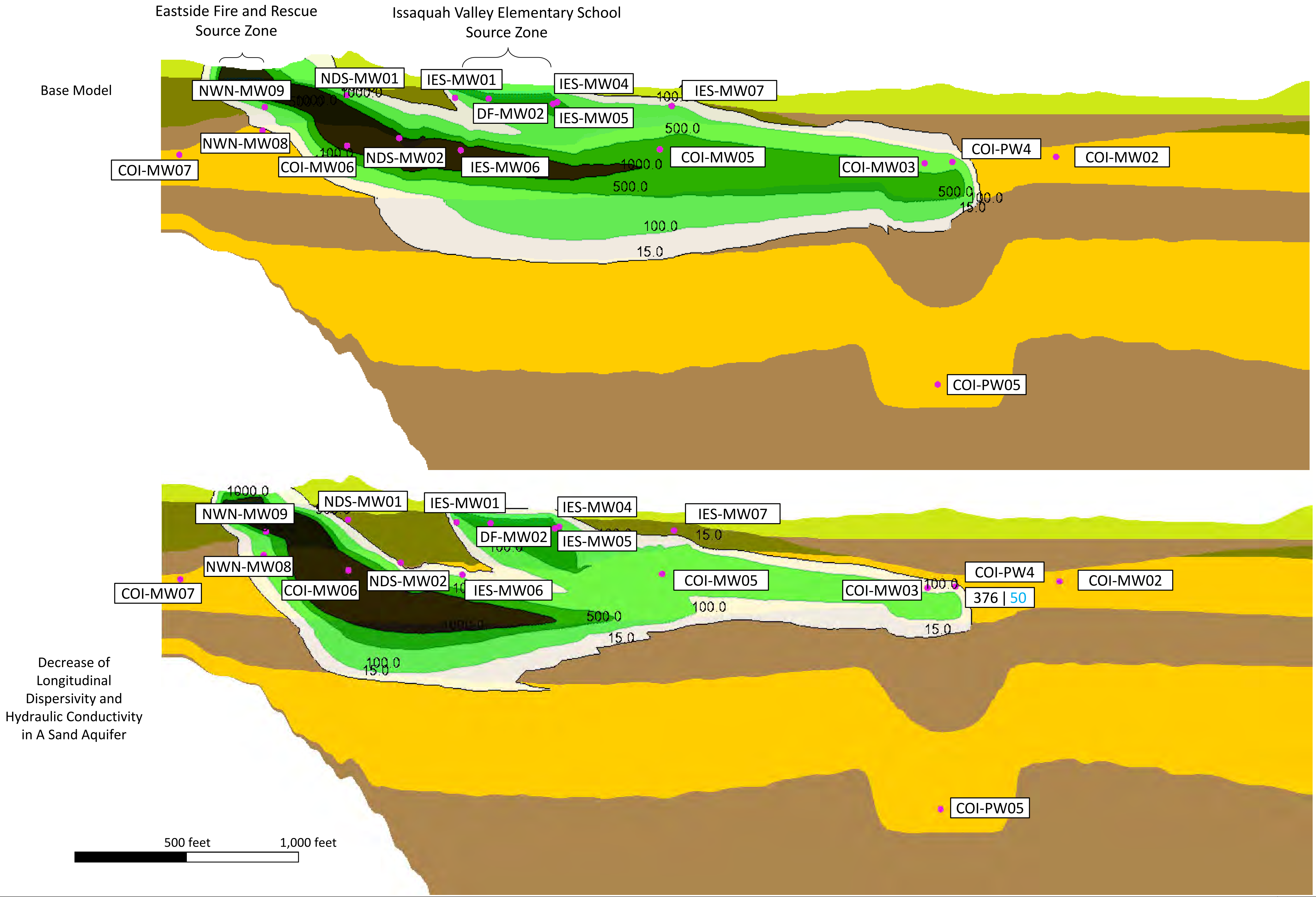
Figure 6b



Simulated PFOS Concentration (ng/L)		
Well ID	Base Case	Simulation 3
COI-MW07	0	0
NWN-MW08	8	217
NWN-MW09	184	996
NDS-MW01	284	4
COI-MW06	1196	1844
NDS-MW02	1270	12
IES-MW01	67	201
IES-MW06	1433	69
DF-MW02	552	596
IES-MW05	574	577
IES-MW04	563	491
COI-MW05	731	307
IES-MW07	120	3
COI-MW03	272	65
COI-PW5	0	0
COI-PW4	244	50
COI-MW02	0	0

Notes:
- Midpoint of monitoring well screen

Vertical Exaggeration: 5

Abbreviations:
PFOS – perfluorooctanesulfonic acid

Simulated PFOS Concentration Contours (ng/L)

15.0	100.0	
100.0	500.0	
500.0	1000.0	
1000.0	5000.0	

Simulated PFOS Plume – Sensitivity Analysis
Simulation 3
Issaquah, Washington

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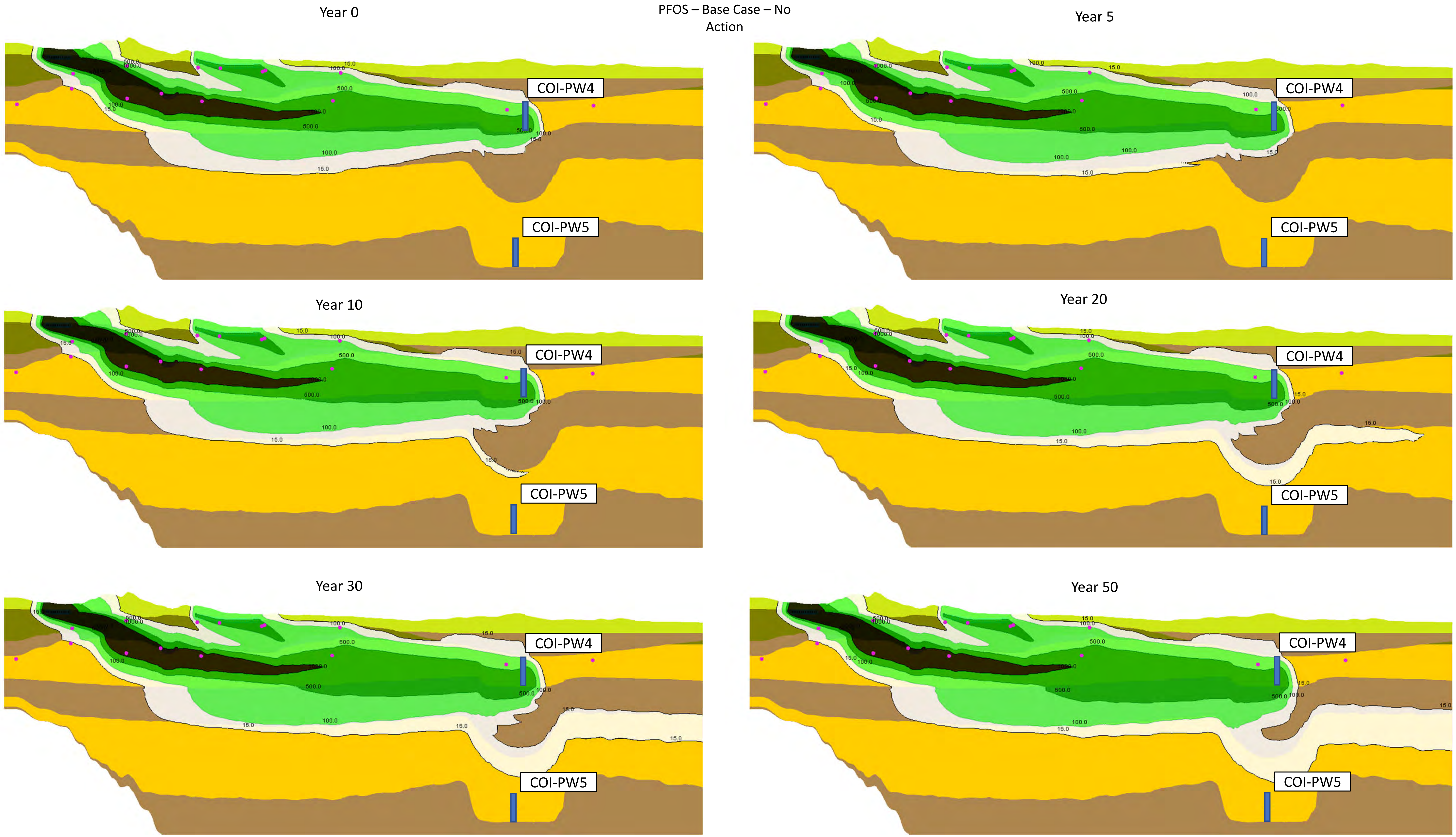
Figure 6c



Notes:
- Midpoint of monitoring well screen

Vertical Exaggeration: 5

1,000 feet 2,000 feet

Abbreviations:
PFOS – perfluorooctanesulfonic acid

Simulated PFAS Concentration Contours (ng/L)

15.0	100.0	
100.0	500.0	
500.0	1000.0	
1000.0	5000.0	

Base Case - Simulated PFOS Plumes
Issaquah, Washington

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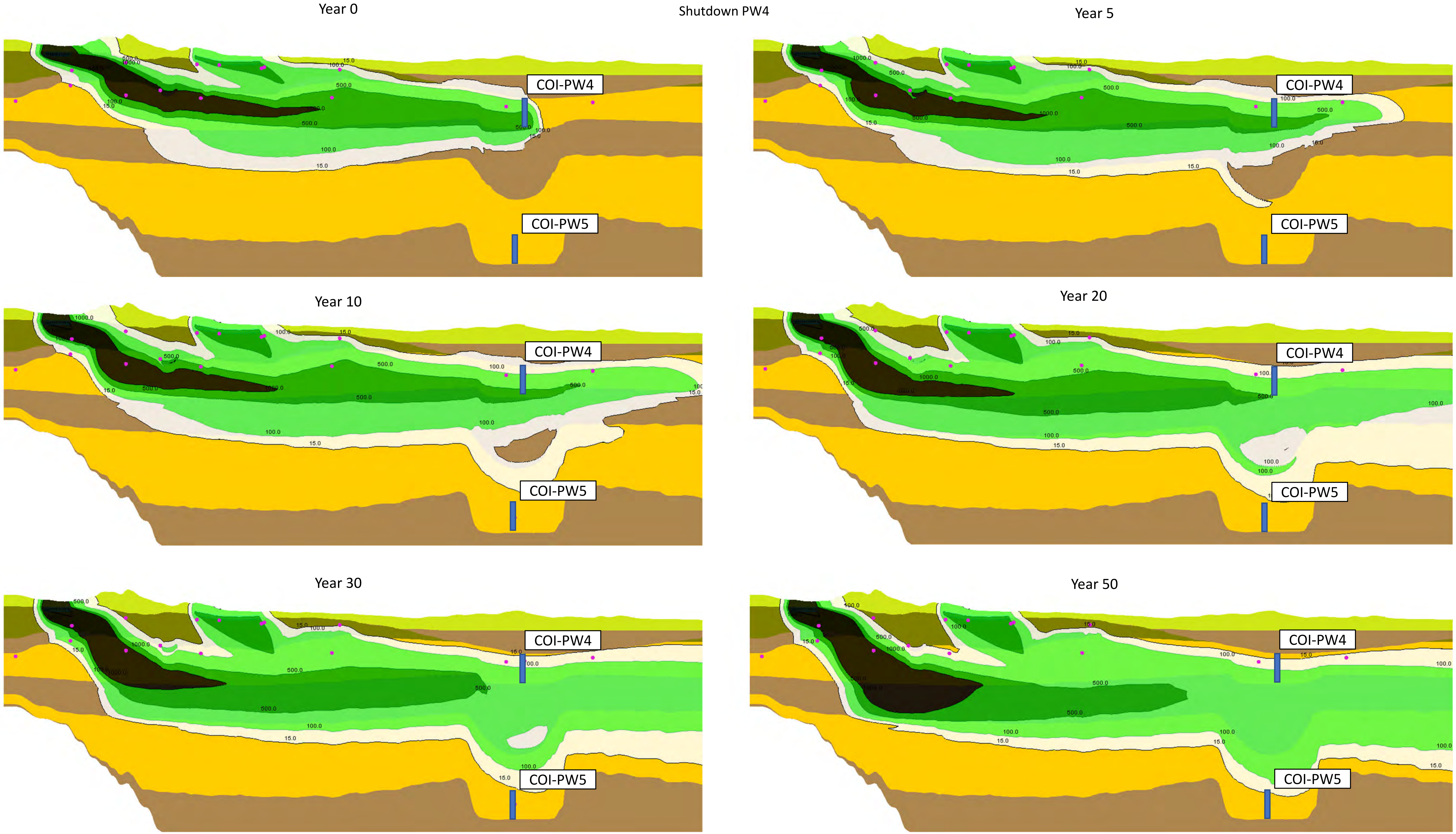
Figure 7

PFOS – Scenario 1
Shutdown PW4



Notes:
- Midpoint of monitoring well screen

Vertical Exaggeration: 5

1,000 feet 2,000 feet

Abbreviations:
PFOS – perfluorooctanesulfonic acid

Simulated PFAS Concentration Contours (ng/L)

15.0	100.0	
100.0	500.0	
500.0	1000.0	
1000.0	5000.0	

Scenario 1 - Simulated PFOS Plumes
Issaquah, Washington

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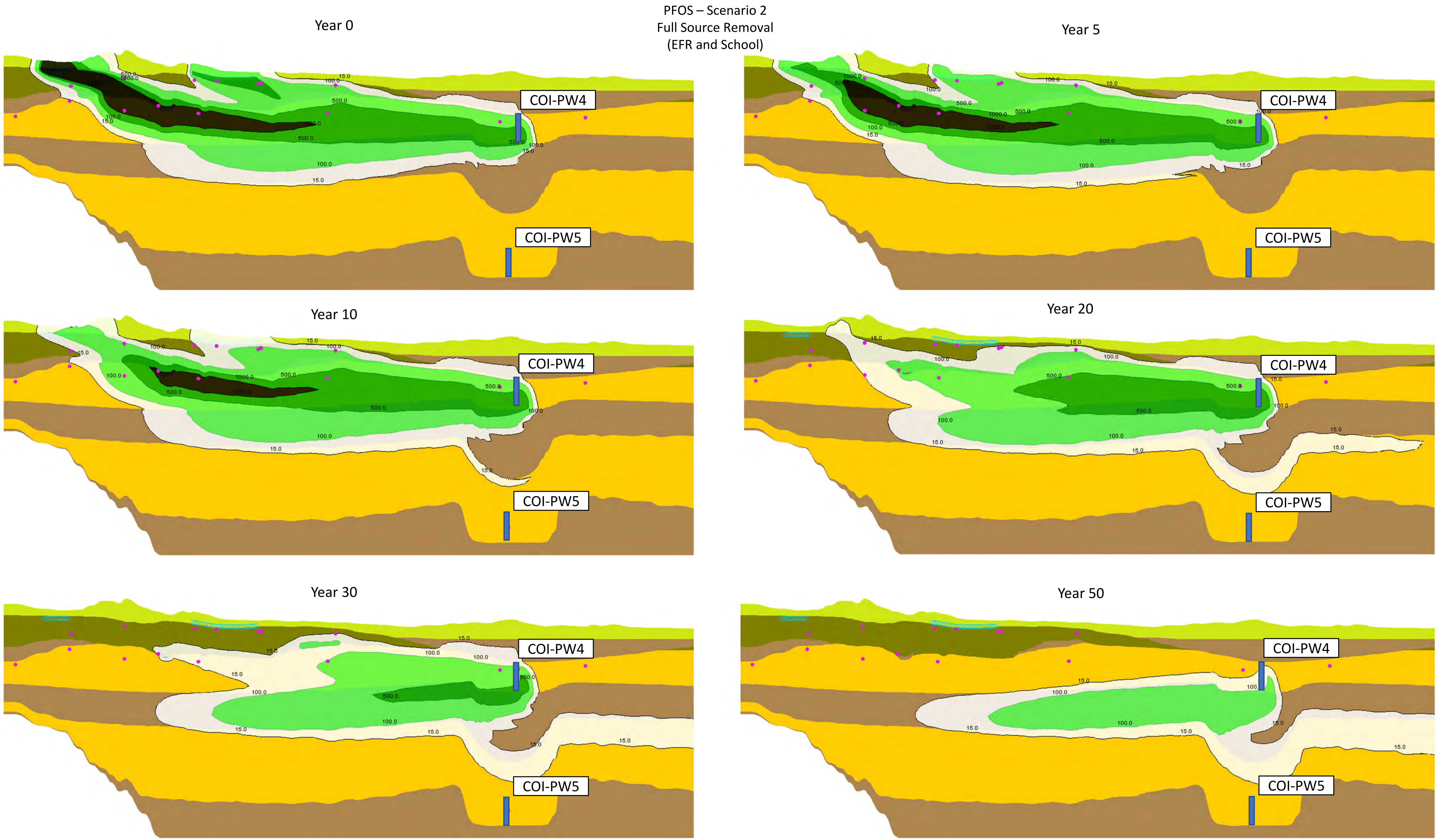
Figure 8



Notes:
● Midpoint of monitoring well screen

Vertical Exaggeration: 5

1,000 feet 2,000 feet

Abbreviations:
PFOS – perfluorooctanesulfonic acid

Simulated PFAS Concentration Contours (ng/L)

15.0	100.0	
100.0	500.0	
500.0	1000.0	
1000.0	5000.0	

Scenario 2 - Simulated PFOS Plumes
Issaquah, Washington

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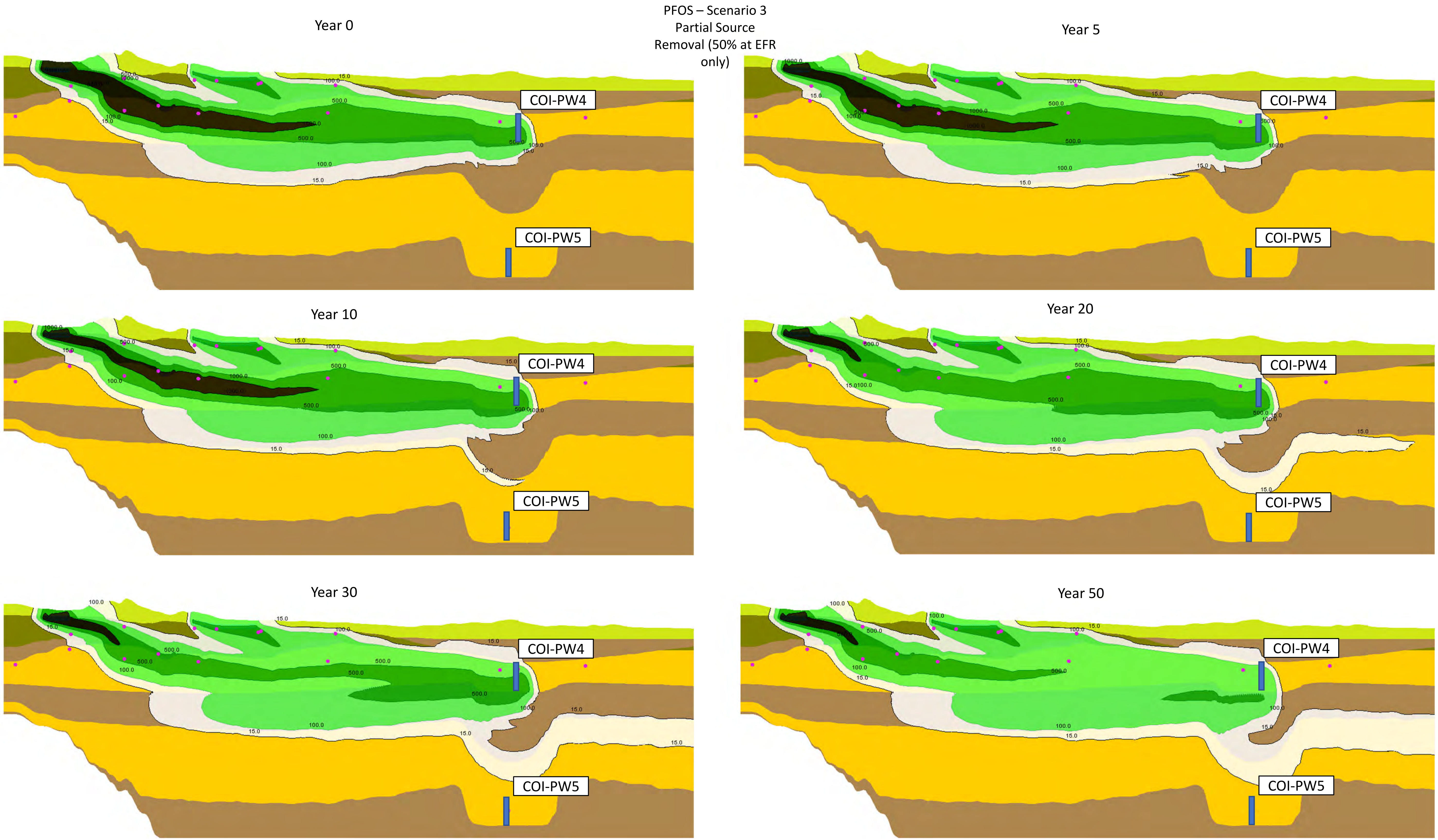
Figure 9



Notes:
- Midpoint of monitoring well screen

Vertical Exaggeration: 5

1,000 feet 2,000 feet

Abbreviations:
PFOS – perfluorooctanesulfonic acid

Simulated PFAS Concentration Contours (ng/L)

15.0	100.0	
100.0	500.0	
500.0	1000.0	
1000.0	5000.0	

Scenario 3 - Simulated PFOS Plumes
Issaquah, Washington

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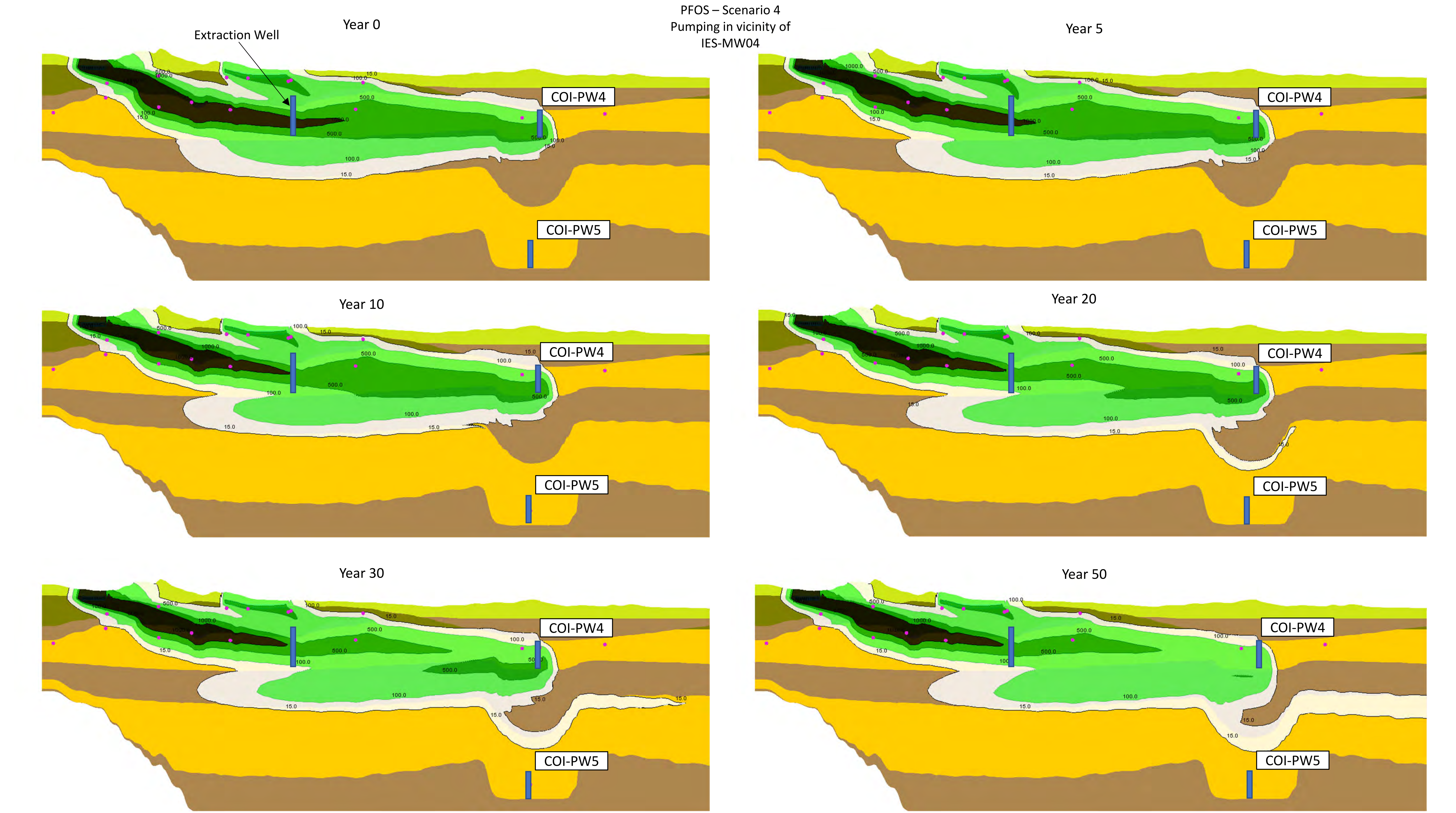
Figure 10



Notes:
- Midpoint of monitoring well screen

Vertical Exaggeration: 5

1,000 feet 2,000 feet

Abbreviations:
PFOS – perfluorooctanesulfonic acid

Simulated PFAS Concentration Contours (ng/L)

15.0	100.0	
100.0	500.0	
500.0	1000.0	
1000.0	5000.0	

Scenario 4 - Simulated PFOS Plumes
Issaquah, Washington

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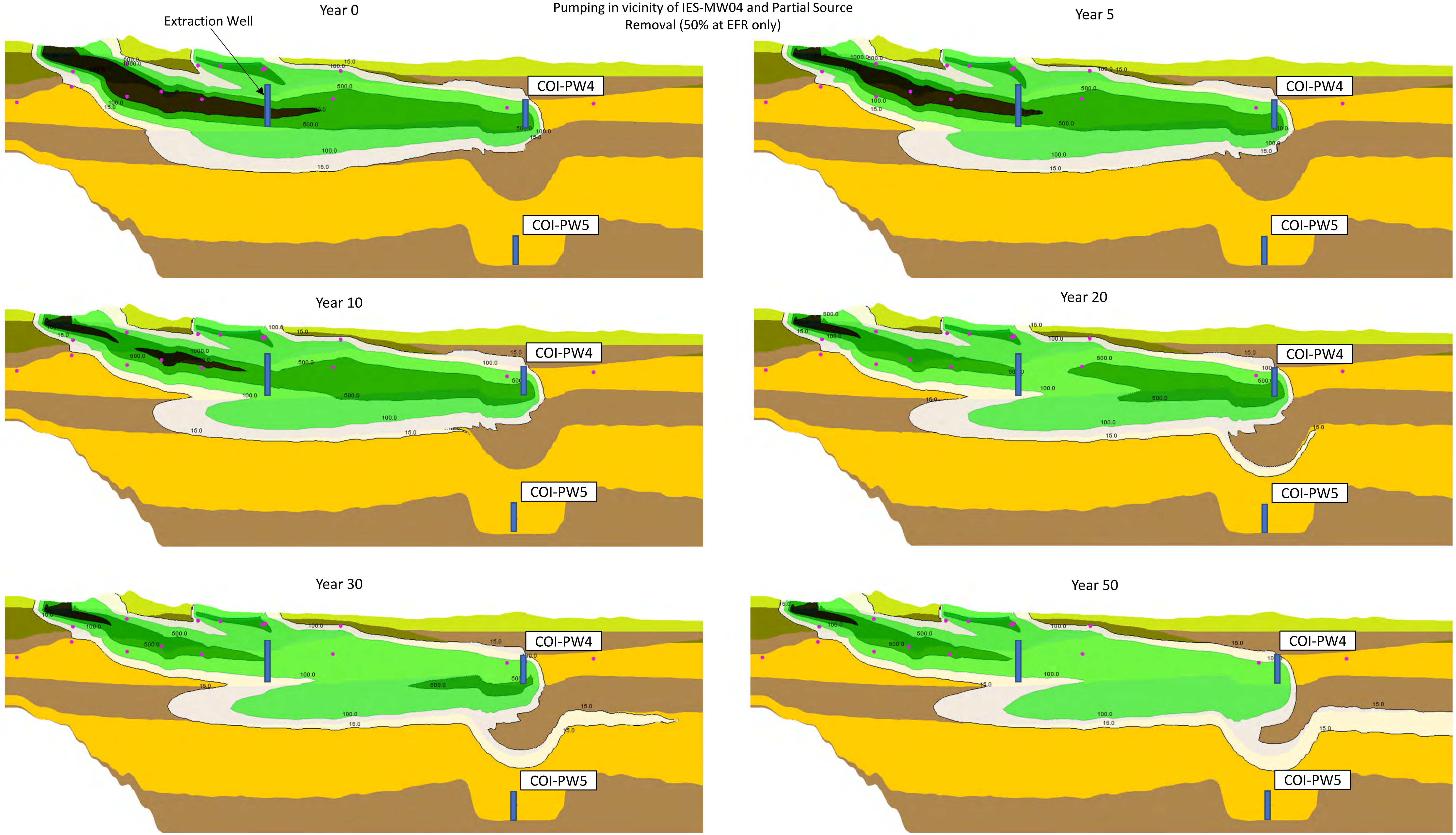
Figure 11

PFOS – Scenario 5
Pumping in vicinity of IES-MW04 and Partial Source Removal (50% at EFR only)



Notes:
- Midpoint of monitoring well screen

Vertical Exaggeration: 5

1,000 feet 2,000 feet

Abbreviations:
PFOS – perfluorooctanesulfonic acid

Simulated PFAS Concentration Contours (ng/L)

15.0	100.0	
100.0	500.0	
500.0	1000.0	
1000.0	5000.0	

Scenario 5 - Simulated PFOS Plumes
Issaquah, Washington

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Figure 12

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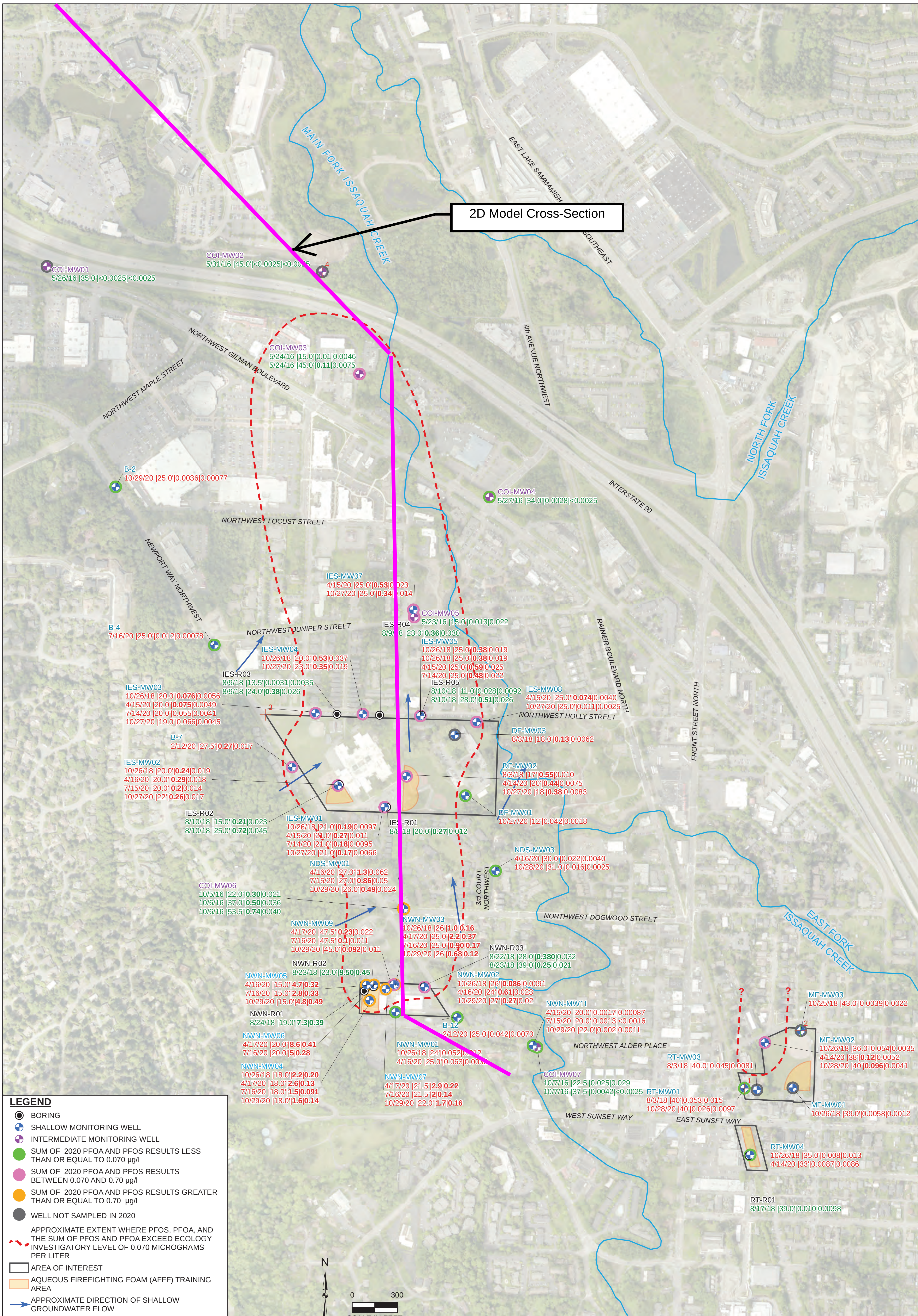
ATTACHMENT A

Cross-Section Location



NOTES:

NWN-MW02 = SHALLOW MONITORING WELL
SAMPLE RESULTS HIGHLIGHTED IN GREEN REPRESENT RECONNAISSANCE BORING TEMPORARY WELL GROUNDWATER RESULTS
SAMPLE RESULTS HIGHLIGHTED IN RED REPRESENT MONITORING WELL GROUNDWATER RESULTS
COLOR CODE ASSIGNMENT FOR EACH WELL IS BASED ON HIGHEST SUM OF PFOA AND PFOS RESULTS OBTAINED DURING ALL 2020 MONITORING EVENTS
STANDARD PRODUCT NAMES ARE PROVIDED FOR PFOS AND PFOA. BOTH COMPOUNDS WILL BE IN THEIR ANIONIC FORM WHEN ENCOUNTERED IN THE ENVIRONMENT.
DEPTH AND CONCENTRATIONS REPORTED AS:
GROUNDWATER SAMPLE DATE | SAMPLE DEPTH IN FEET BGS | PFOS | PFOA
ANALYTICAL RESULTS IN MICROGRAMS PER LITER (µg/l)
PFAS = PER- AND POLY- FLUOROALKYL SUBSTANCES
PFOA = PERFLUOROOCTANOIC ACID
PFOS = PERFLUOROOCTANE SULFONIC ACID
BOLD = DENOTES CONCENTRATIONS EXCEEDING THE APPLICABLE WASHINGTON STATE DEPARTMENT OF ECOLOGY INVESTIGATORY LEVEL OF 0.070 MICROGRAMS PER LITER
BGS = BELOW GROUND SURFACE

ALL LOCATIONS ARE APPROXIMATE.
FIGURES WERE PRODUCED IN COLOR. GRAYSCALE COPIES MAY NOT REPRODUCE ALL ORIGINAL INFORMATION.

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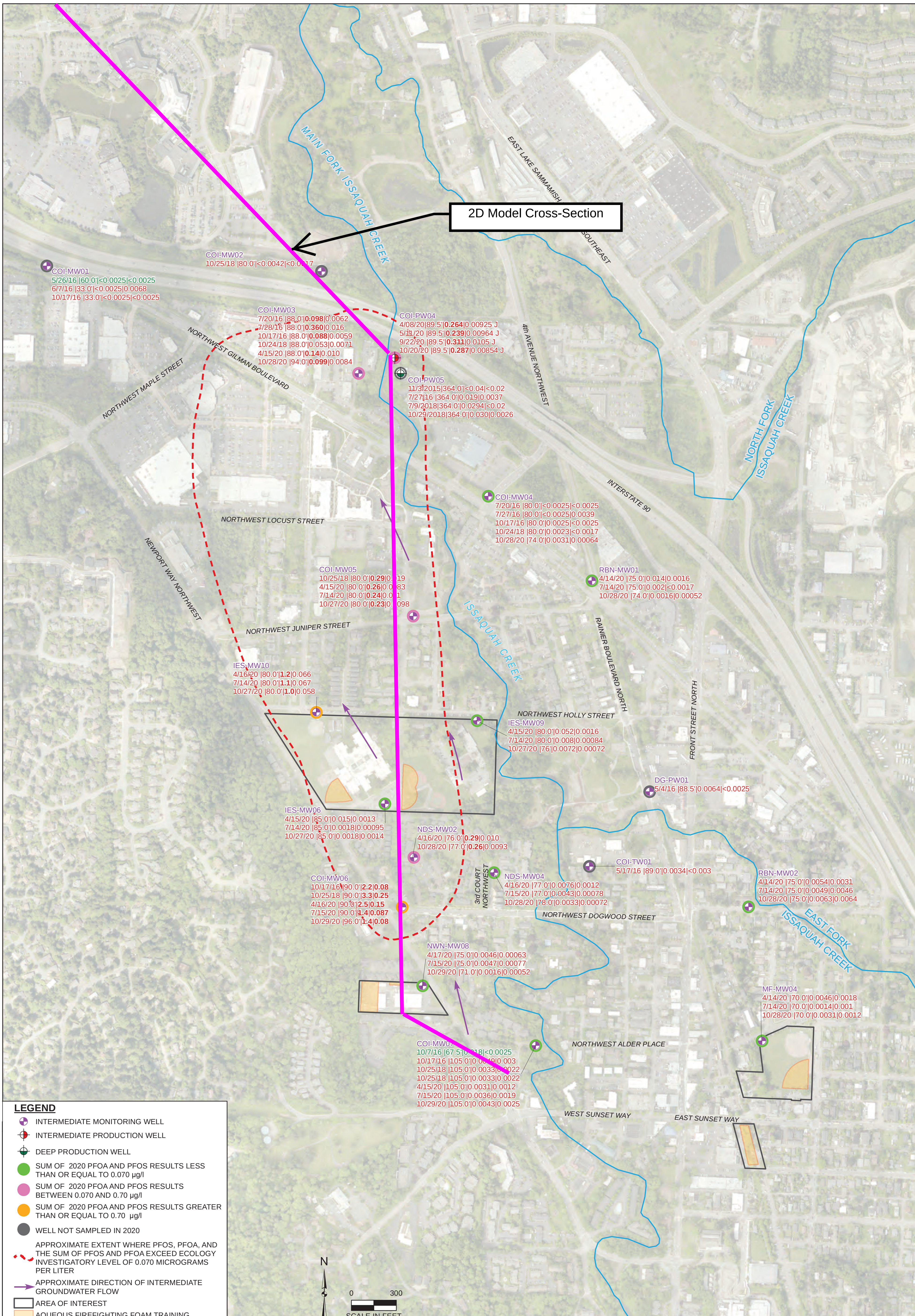
FIGURE 1

SHALLOW GROUNDWATER ANALYTICAL RESULTS
PFAS ADDITIONAL CHARACTERIZATION STUDY
SUMMARY REPORT
LOWER ISSAQUAH VALLEY
ISSAQUAH, WASHINGTON

FARALLON PN: 1754-004

Drawn By: jjones | Checked By: EB | Date: 7/13/2021 | Disc Reference:

Document Path: \\edgefs02\GIS\Projects\1754 EastsideFireRescue\1754-004 2019 Biennium PFAS Invest\007_DataComp\Mapfiles\DataCompilation_CR_202012\Figure-01_GW_Analytical_ValleyWide_Shallow-w-Plume.mxd



SAMPLE RESULTS HIGHLIGHTED IN GREEN REPRESENT RECONNAISSANCE BORING TEMPORARY WELL GROUNDWATER RESULTS

SAMPLE RESULTS HIGHLIGHTED IN RED REPRESENT MONITORING WELL GROUNDWATER RESULTS

COLOR CODE ASSIGNMENT FOR EACH WELL IS BASED ON HIGHEST SUM OF PFOA AND PFOS RESULTS OBTAINED DURING ALL 2020 MONITORING EVENTS

STANDARD PRODUCT NAMES ARE PROVIDED FOR PFOS AND PFOA. BOTH COMPOUNDS WILL BE IN THEIR ANIONIC FORM WHEN ENCOUNTERED IN THE ENVIRONMENT.

DEPTH AND CONCENTRATIONS REPORTED AS:
GROUNDWATER SAMPLE DATE | SAMPLE DEPTH IN FEET BGS | PFOS | PFOA
ANALYTICAL RESULTS IN MICROGRAMS PER LITER (µg/l)

PFAS = PER- AND POLY- FLUOROALKYL SUBSTANCES
PFOA = PERFLUOROOCTANOIC ACID
PFOS = PERFLUOROOCTANE SULFONIC ACID
BOLD = DENOTES CONCENTRATIONS EXCEEDING THE APPLICABLE WASHINGTON STATE DEPARTMENT OF ECOLOGY INVESTIGATORY LEVEL OF 0.070 MICROGRAMS PER LITER
BGS = BELOW GROUND SURFACE

ALL LOCATIONS ARE APPROXIMATE.
FIGURES WERE PRODUCED IN COLOR. GRAYSCALE COPIES MAY NOT REPRODUCE ALL ORIGINAL INFORMATION.

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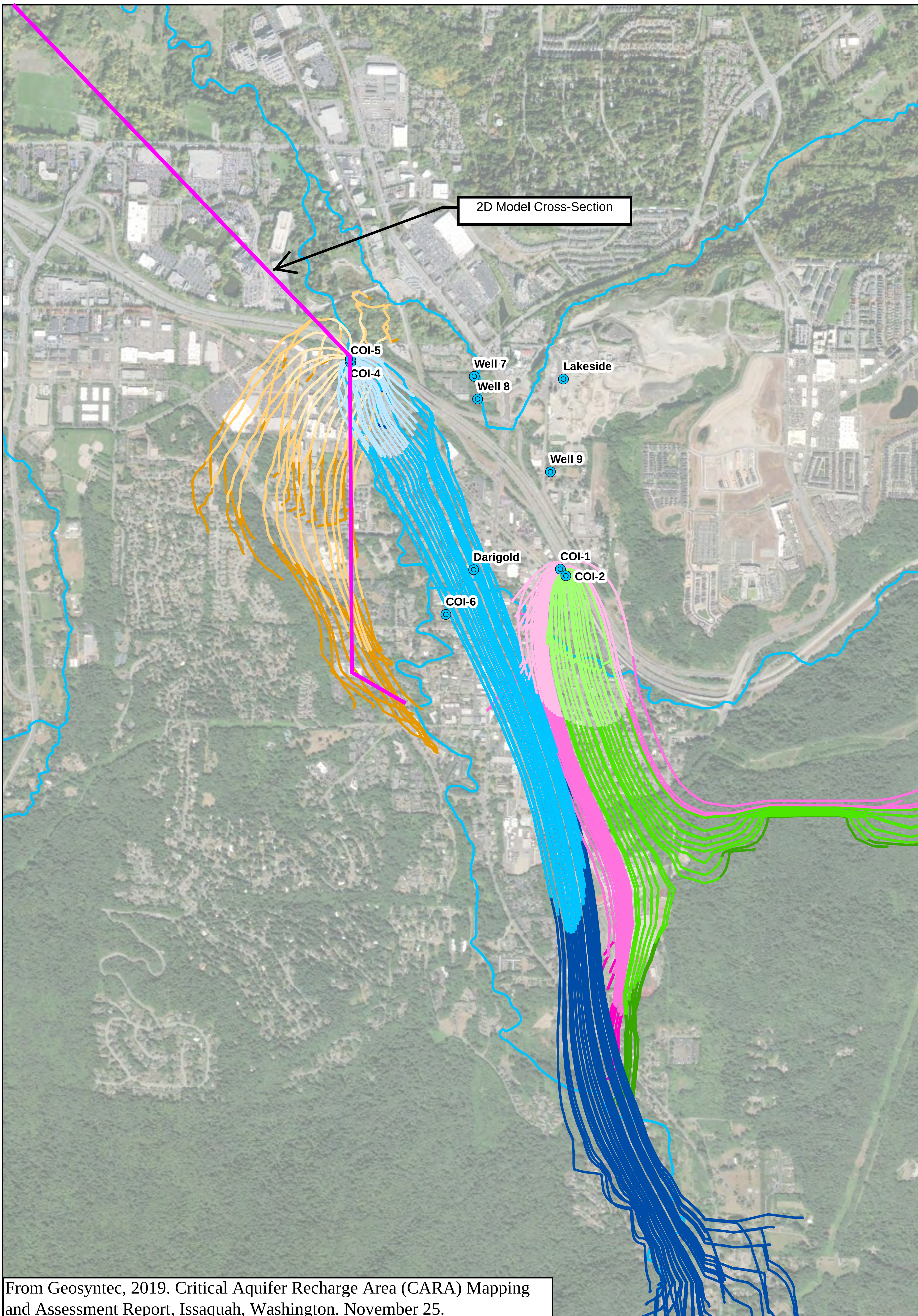
FIGURE 2

INTERMEDIATE GROUNDWATER ANALYTICAL RESULTS
PFAS ADDITIONAL CHARACTERIZATION STUDY
SUMMARY REPORT
LOWER ISSAQUAH VALLEY
ISSAQUAH, WASHINGTON

FARALLON PN: 1754-004

Drawn By: jjones | Checked By: EB | Date: 7/13/2021 | Disc Reference:

Document Path: \\edgefs02\GIS\Projects\1754 EastsideFireRescue\1754-004 2019 Biennium PFAS Invest\007_DataComp\Mapfiles\DataCompilation_CR_202012\Figure-02_GW_Analytical_ValleyWide_Intermediate_w_Plume.mxd



From Geosyntec, 2019. Critical Aquifer Recharge Area (CARA) Mapping and Assessment Report, Issaquah, Washington. November 25.

Legend

- Production Wells
- River

Capture Zone (10, 5 and 1 years)

- COI1
- COI2
- COI4
- COI5

Notes:
1. Aerial image from 2012.
2. COI-6 drilled and constructed as a production well, but is currently not used for production.

N

0 — 2,000 Feet

Particle Tracking Results
10-year total travel time
Issaquah, Washington

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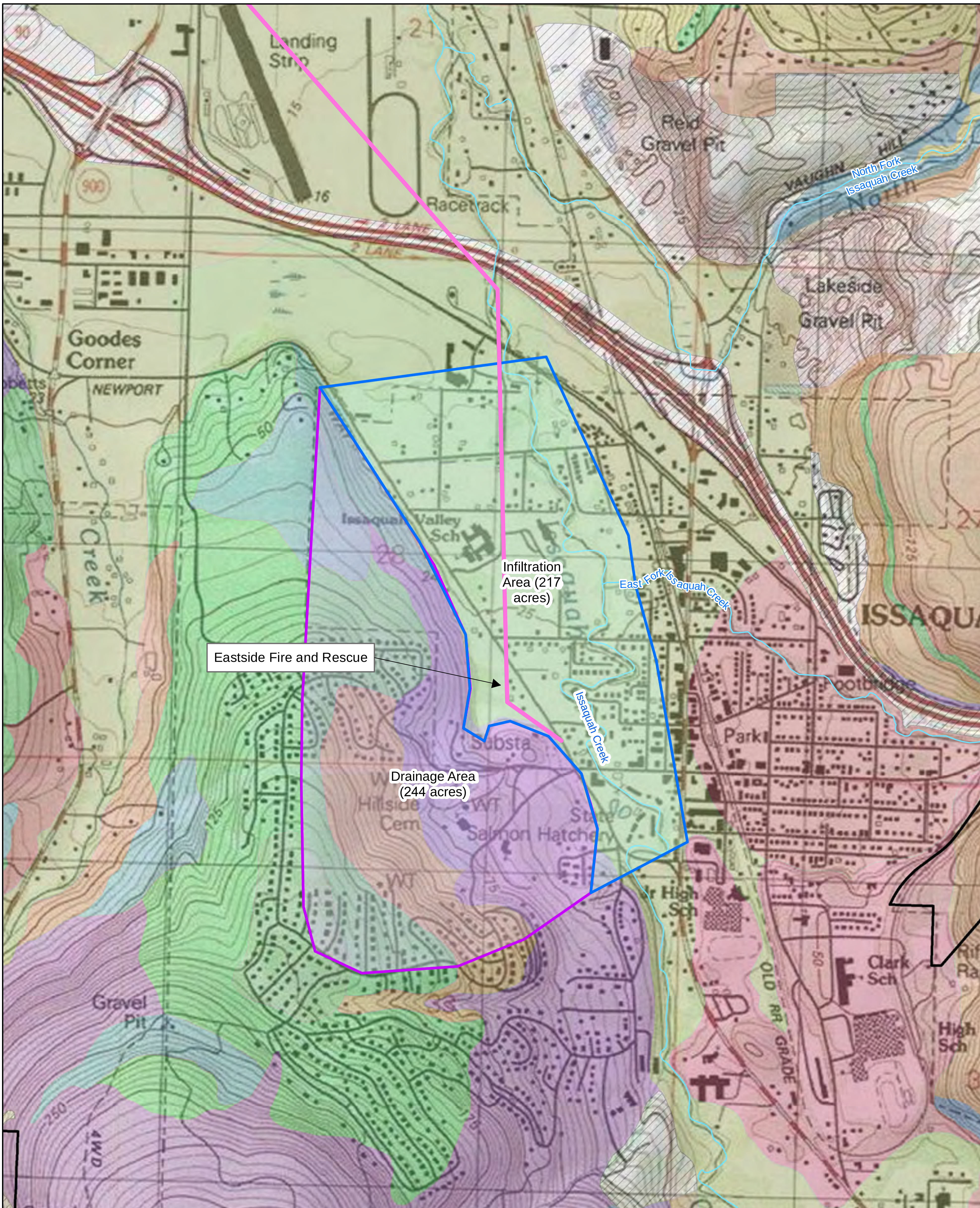
Seattle, Washington | September 2019

Figure A-3

P:\GIS\Issaquah\Projects\CARA\Fig7_Particle_Tracking_Backward.mxd 9/13/2019 5:48:57 PM

ATTACHMENT B
Drainage Calculations



Legend

- Drainage Area
- Infiltration Area
- City Limits
- Cross Section
- Issaquah Creek

UNIT

- Qal-Alluvium (Holocene)
- Qf-Fan Deposit (Holocene)
- Qg-Glacial till
- Qgl(v)-Glacial lacustrine (Vashon)
- Qmw-Mass-wastage deposits (Holocene)
- Qoal-Older alluvium (Holocene and Pleistocene)
- Qob-Olympia beds of Minard and Booth (1989)
- Qpf-Undifferentiated sedimentary deposits
- Qpog-Glacial deposits
- Qva-Advance outwash deposits
- Qvi-Ice contact deposits
- Qvi(1)-Ice-contact deposits - Stage 1
- Qvi(2)-Ice-contact deposits - Stage 2
- Qvr(1)-Recessional outwash deposits -Stage 1
- Qvr(2)-Recessional outwash deposits -Stage 2
- Qvr(3)-Recessional outwash deposits -Stage 3
- Qvr(4)-Recessional outwash deposits -Stage 4
- Qvr(5)-Recessional outwash deposits -Stage 5
- Qvt-Till
- Qw-Wetland deposits (Holocene)
- Tb-Blakely Formation of Weaver (1912) (Tertiary)
- Ti-Intrusive rock (Tertiary)
- Tpr-Renton Formation (Tertiary)
- Tpt-Tukwila Formation (Tertiary)
- Tsc-Sandstone and conglomerate (Tertiary)
- Tv-Volcanic rock (Tertiary)
- m-Modified land (Holocene)
- wtr-Water

Issaquah Quadrangle (2 maps):
Booth, D.B., and Minard, J.P., 1992, Geologic map of the Issaquah 7.5' quadrangle, King County, Washington: U.S. Geological Survey Miscellaneous Field Studies Map MF-2116, scale 1:24,000.
Booth, D.B., Walsh, T.J., Troost, K.G., and Shimel, S.A., 2012, Geologic map of the East Half of the Bellevue South 7.5' x 15' quadrangle, Issaquah Area, King County, Washington: U.S. Geological Survey Scientific Investigations Map 3211, scale 1:24,000.
Quadrangle south of Issaquah:
Booth, D.B., 1995, Surficial geologic map of the Maple Valley quadrangle, King County, Washington: U.S. Geological Survey Miscellaneous Field Studies Map MF-2297, scale 1:24,000.
Quadrangle east of Issaquah:
Dragovich, J.D., Anderson, M.L., Walsh, T.J., Johnson, B.L., and Adams, T.L., 2007, Geologic map of the Fall City 7.5-minute quadrangle, King County, Washington: Washinton Division of Geology and Earth Resources Geologic Map GM-67, scale 1:24,000.

Notes:
1. Aerial image from 2012.

N

1 inch = 1,000 feet
0 1,000 Feet

Drainage Area Calculation
Issaquah, Washington

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Figure B-1

\\10.174.20.5\data\DEPT 3040 - Anchorage\Users\BEckhardt\18 Temporary GIS\Issaquah\Figure A-1 Drainage Area.mxd 1/19/2021 5:21:22 PM

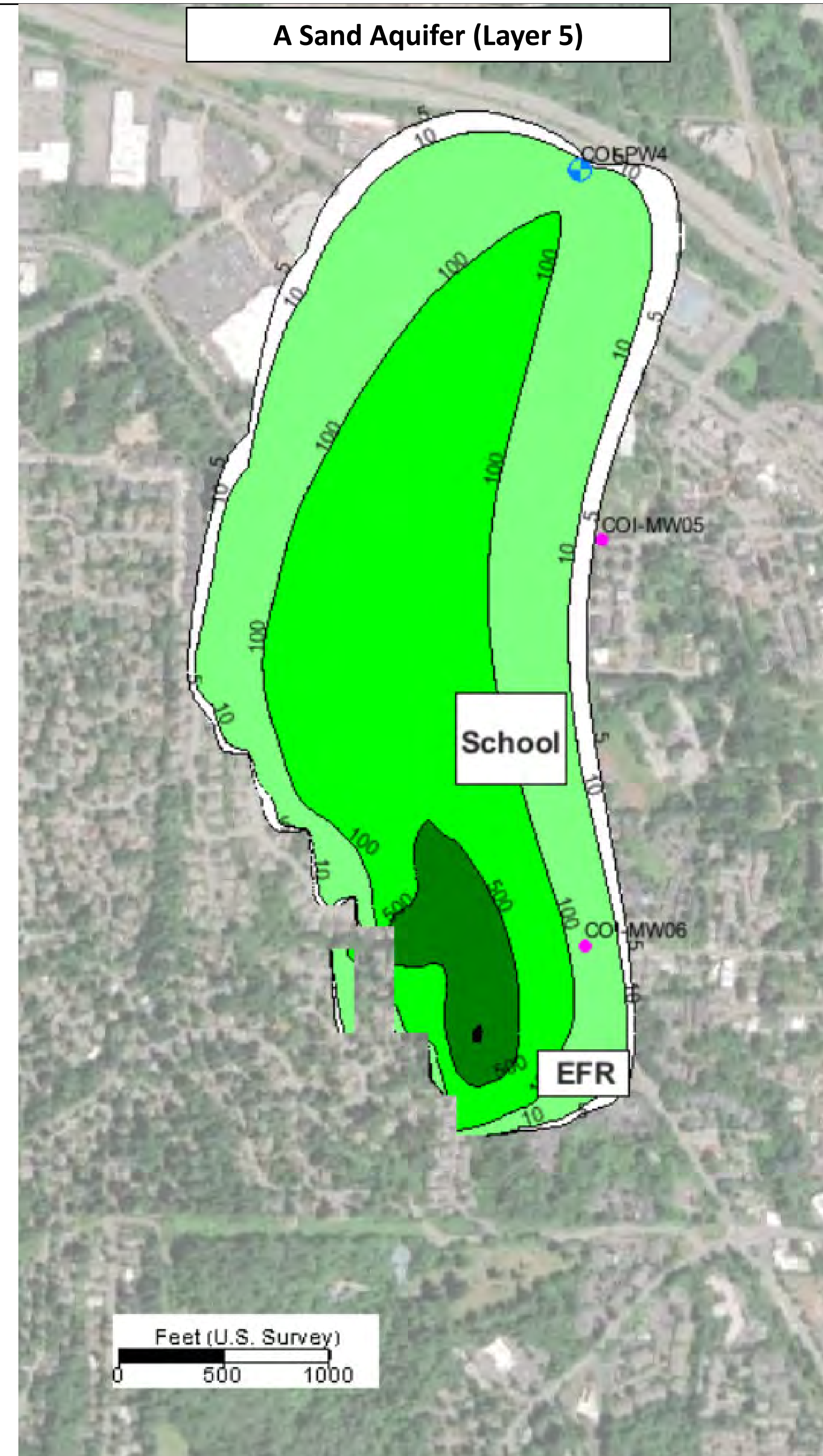
Table B-1
Drainage Area Calculation

Drainage Area (see Figure A-1)	
244	acres
Mean Annual Precipitation	
54	inches/year
Volume of Precipitation	
1,096	acre-feet per year
Runoff Coefficient	
15% - 25%	
Volume of Runoff	
164 - 274	acre-feet per year
Infiltration Area (see Figure A-1)	
217	acres
Potential Additional Recharge from Hillside Runoff	
9 - 15	in/year

Drainage area delineated based on topography (See Figure A-1)
Mean annual precipitation from https://streamstats.usgs.gov
Volume of Precipitation = Mean Annual Precipitation * Drainage Area
Runoff coefficient - range based on land use, soil, canopy cover, and slope
Volume of Runoff = Volume of Precipitation * Runoff Coefficient
Infiltration area delineated based on topography (See Figure A-1)
Potential Additional Recharge from Hillside Runoff = Volume of Runoff / Infiltration Area

ATTACHMENT C

PFOS Transport Simulation with 3D CARA MODFLOW Model



Notes:
Simulation results provided for illustration only. Additional refinement of the 3D CARA MODFLOW model is required prior to using for fate and transport simulations.

Abbreviations:
PFOS – perfluorooctanesulfonic acid

Simulated PFOS Concentration Contours (ng/L)

15.0	100.0	
100.0	500.0	
500.0	1000.0	
1000.0	5000.0	

Simulated PFOS Plume – 3D CARA MODFLOW Model
Issaquah, Washington

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Figure C-1