

**APPENDIX 6A**  
**Contaminant Fate and Transport**

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## **APPENDIX 6A CONTAMINANT FATE AND TRANSPORT**

### **1.0 INTRODUCTION**

Section 6 of the Remedial Investigation (RI) report addresses past and potential mechanisms that affect the fate and transport of contaminants, including: mobile nonaqueous phase liquid (NAPL) and tar transport; erosion and entrainment; deposition and burial; and partitioning and groundwater transport. Appendix 5F provides additional detail on mobile NAPL and tar transport mechanisms. This appendix provides supplemental technical discussion of partitioning and groundwater transport mechanisms to support conclusions presented in Section 6 of the RI. The conceptual site model for the area of investigation (AOI) includes aqueous transport of dissolved contaminants to sediment and surface water as an active transport pathway.

This appendix focuses on the fate and transport of dissolved contaminants, particularly the potential for upland groundwater and offshore groundwater (i.e., groundwater within subsurface sediment) to impact surface sediment and surface water. Figure 6A-1 presents a conceptual cross sectional view of aqueous phase transport in the AOI. Given the potential for dissolved contaminant transport from upland and subsurface sediment to surface sediment and surface water, detailed analysis is warranted. However, due to the slow groundwater flow, limited footprint of groundwater discharge to Lake Union, and attenuation, aqueous phase transport of contaminants from upland groundwater is not expected to adversely impact surface sediment or surface water and is relatively insignificant compared to other transport mechanisms such as erosion and deposition.

This appendix is structured as two parts: Section 2 explains how the original contaminant sources, and not aqueous phase transport, resulted in the current distribution of contaminants in sediment; Section 3 discusses the current conditions that affect future contaminant transport and the mechanisms that are active or not for transport of contaminants to surface sediment and surface water, particularly from sources remaining in the upland.

### **2.0 SOURCES AND MECHANISMS RESULTING IN CURRENT CONDITIONS**

This section describes the historical sources of AOI contamination and the historical migration of source material (e.g., NAPL), resulting in current conditions. The contaminant groups addressed in this section include organic contaminants primarily associated with NAPL sources, and arsenic primarily associated with the former Thylox process.

#### **2.1. Historic Sources and Transport of PAHs and Benzene**

NAPL, tar, and black carbon are the primary sources of polycyclic aromatic hydrocarbons (PAHs) in the AOI, and NAPL (both light NAPL [LNAPL] and dense NAPL [DNAPL]) is the primary source of benzene in the AOI. Higher total polycyclic aromatic hydrocarbons (TPAH) concentrations coincide with NAPL, tar, and black carbon and higher benzene concentrations are found near NAPL. The distribution of NAPL, tar, and black carbon (i.e., source materials for PAHs and benzene) in soil and sediment informs the current distribution of PAHs and benzene in the AOI. Appendix 5F addresses the original and remaining sources of NAPL and tar and provides additional detail on NAPL transport mechanisms. The sections below discuss the sources and transport mechanisms that have resulted in the current distribution of PAHs and benzene.

### 2.1.1. PAHs

The vertical distribution of sediment TPAH concentrations provides insight into potential sources and historical transport mechanisms. Figure 6A-2 shows the lateral distribution of TPAH in soil and sediment. The highest concentrations are found where TPAH is present over the entire depth interval above the till. Figure 6A-2 also shows cross section alignments paralleling the shoreline at multiple distances offshore. The cross sections associated with these alignments are shown on Figures 6A-3 and 6A-4, presenting the vertical distribution of TPAH in sediment at various distances from the shoreline. TPAH concentrations in surface soil and sediment are presented in RI Figures 5-19A and 5-19B.

An examination of the current distribution of PAHs in sediment informs the relative importance of historical transport mechanisms which in turn provide insight into current and future aqueous phase transport. Higher concentrations of PAHs in soil and sediment are discontinuous, indicating separate sources. In some portions of the AOI (far west, southeast, and northeast; see Figure 6A-2), soil and sediment areas impacted by TPAHs are separated, indicating that subsurface transport from the upland is not the source of sediment impacts; rather, most sediment impacts are the result of over-water releases. TPAH distribution in the sediment portion of the AOI correlates with source material (e.g., NAPL and black carbon) and does not reflect groundwater transport from the upland.

Detailed analysis of NAPL and PAH distribution indicate that subsurface PAHs are primarily associated with shoreline and overwater spills and subsequent lateral migration as DNAPL, not aqueous phase transport. Together TPAH (Figures 6A-3 and 6A-4) and NAPL cross sections demonstrate that most areas of continuous PAH impacts in sediment reflect the distribution of DNAPL. NAPL maps and cross sections (Appendix 5F) show the distribution of DNAPL. Lateral DNAPL migration is responsible for subsurface PAH distribution in most areas. In two areas, just east of Harbor Patrol (Figure 5F-15) and east of the Play Area (Figure 5F-20), DNAPL is continuous from the upland to sediment due to historical DNAPL migration. In other areas, DNAPL in sediment is isolated from the upland and has resulted in continuous subsurface PAH impacts along DNAPL migration pathways (see examples in Figure 6A-3).

Former manufactured gas plant (MGP) materials management (e.g., lampblack) is also responsible for PAH-impacted soil and sediment. As described in RI Section 5.3.5, black carbon (e.g., lampblack, pitch, coke, and coal) is scattered throughout the older portion of the fill in the upland and is present in sediment, especially south and east of the upland (RI Figure 5-27). The distribution of black carbon in sediment both within the fill and upper portion of recent lacustrine deposit is responsible for the higher PAH concentrations.

PAHs in subsurface sediment in the lakeshore and lake slope zones are primarily associated with DNAPL and black carbon sources. Several lines of evidence suggest higher PAH concentrations in subsurface sediment in these zones are the result of lateral NAPL migration and not aqueous phase transport of PAHs from the upland:

- PAH concentrations in some areas of the lakeshore zone are higher in subsurface sediment than in surface sediment in areas of subsurface DNAPL impacts (Figure 6A-3).
- Low solubility, low vapor pressure and high octanol-water partition coefficient ( $K_{ow}$ ) generally result in PAH partitioning to soil and sediment with very little partitioning to the water phase, indicating the potential for dissolved phase transport of high molecular weight PAHs from upland to subsurface sediment is very limited.

- Leachability testing performed for the upland Focused Feasibility Study (FS) completed in 1998 by Parametrix and Key Environmental (1998) determined that leaching from upland soil generated relatively low dissolved concentrations of high molecular weight PAHs such that flux of these PAHs are not high enough to explain concentrations observed in sediment.
- The estimated PAH (i.e., benzo(a)pyrene, chrysene, and naphthalene) travel times from upland groundwater to sediment porewater are very long and respective groundwater half-lives are relatively short. This relationship significantly limits the potential for dissolved-phase PAH migration from upland to subsurface sediment. This is described more completely in Section 3.1.1.
- Higher naphthalene concentrations in sediment are limited to subsurface NAPL-impacted areas.

PAHs in lake bottom near-surface sediment are primarily associated with overwater top-down sources. In the lake bottom, the degree of near-surface sediment impacts is greater than subsurface sediment impacts (Figure 6A-4). This relationship suggests that upland-to-sediment subsurface transport pathways (i.e., aqueous phase transport and NAPL migration) are not the primary cause of near-surface sediment impacts in the lake bottom. Migration from the upland would have resulted in greater impacts in deeper sediment than observed. In addition, groundwater primarily discharges nearshore (lakeshore and lake slope) and not through lake bottom sediment.

Shoreline monitoring well data show that dissolved PAHs are associated with residual DNAPL. Figure 6A-5 shows the alignment of a cross-section along the shoreline monitoring wells. Figure 6A-6 shows the naphthalene concentrations in groundwater and mass flux (i.e., discharge of dissolved naphthalene from the upland) along this cross section. Exceedances of the surface water screening level for naphthalene, the most soluble PAH, is limited to the Harbor Patrol Area, one well pair east of the Play Area, and one well in the northeast corner of the AOI upland—all areas with residual NAPL (see RI Figure 5-26B). The limited shoreline distribution of dissolved naphthalene is inconsistent with dissolved migration being the source of more widespread naphthalene in sediment.

In conclusion, other transport mechanisms (i.e., upland to sediment NAPL migration, overwater releases and subsequent top down migration, distribution of black carbon, and/or erosion of shoreline bank soil and lakeshore sediment and deposition) and not aqueous phase transport are responsible for the current distribution of PAHs in sediment.

### **2.1.2. Benzene**

Benzene is associated with NAPL in several areas of the AOI (see RI Figure 5-26B): benzol-rich LNAPL in the upland along the southeast shoreline of the park (NAPL Area 12), LNAPL east of the Play Area (NAPL Area 15), naphthalene-rich DNAPL in sediment off the western shoreline (NAPL Areas 3 and 5), and in NAPL-impacted sediment off the eastern shoreline (NAPL Areas 14 and 15).

The cross sections shown on Figure 6A-7 present dissolved benzene concentrations along the shoreline, as well as calculated benzene mass flux. The highest concentrations of dissolved benzene and benzene flux are associated with shoreline NAPL in the vicinity of Harbor Patrol (NAPL Areas 4 and 5A) and east of the Play Area (NAPL Areas 13 and 15). Historical aqueous phase transport of benzene from upland NAPL areas has not affected surface sediment. Benzene was not detected in most sediment samples in the AOI and is primarily associated with co-located NAPL (i.e., NAPL Areas 3, 5B, 14, and 15). In areas where benzene is present in subsurface sediment, benzene concentrations decrease rapidly toward the mudline and are not detected in surface sediment except where co-located with NAPL in surface sediment (e.g., surface sediment benzene concentrations are elevated in NAPL Area 14).

Historical NAPL releases and migration are responsible for the current distribution of benzene in sediment. The association of benzene and NAPL, combined with evidence of dissolved phase benzene attenuation described in RI Section 5.2.2.1.3 and in Section 3.1.1.2 below, suggests that dissolved benzene transport from the upland does not appear to have been an important transport mechanism for benzene in sediment.

## 2.2. Historic Sources and Transport of Arsenic

Arsenic is present in the upland and in-water portions of the AOI as a result of sources unique to each area. Arsenic in the eastern portion of the AOI upland is generally associated with the former Thylox process area where arsenic was used to remove hydrogen sulfide gas from the manufactured gas stream. Leaks and spills of sodium thioarsenate solution (i.e., Thylox solution) impacted subsurface soil and groundwater (shallow soil was excavated across most of the source area). Arsenic speciation analyses performed for the arsenic geochemical evaluation (Appendix 2B, Attachment 2B-2) indicates that dissolved arsenic in upland groundwater in the vicinity of the Play Area still contains thioarsenate in areas where alkaline conditions associated with the Thylox solution remains. Thioarsenate, which is the original form of arsenic assumed to have been released from the Thylox process area, is relatively stable under alkaline conditions, but disassociates into arsenic, sulfur, and sodium more readily under neutral or mildly acidic conditions. This finding suggests that arsenic in upland groundwater is not primarily associated with releases from impacted soil but is present in dissolved phase as a result of the original releases of Thylox solution.

The conceptual site model presented in Section 7 of the RI presents a release and transport scenario for post-operation as well as current conditions at the former Thylox process area. The release of Thylox solution, which is denser than water, appears to have acted similar to a DNAPL, migrating downward through the fill unit from the original source. The silt unit present below upgradient portions of Play Area fill soil served as a barrier to downward migration beyond the fill unit. However, this silt unit ends in the downgradient portion of the Play Area (i.e., toward the shoreline of Lake Union). This silt unit also appears to have been breached during construction of facilities, including below-grade tanks, for the Thylox process. The discontinuity of the silt layer immediately below, and complete absence immediately downgradient of, the Thylox process area allowed the dense Thylox solution to migrate downward into the outwash unit. The migration of Thylox solution explains the presence of thioarsenate species and alkaline conditions that remain in groundwater at the bottom of the outwash unit, as well as within a zone of weathered till underlying outwash. Figures 6A-8 and 6A-9 present cross sectional views of the conceptual site model for the historical migration of Thylox solution and current arsenic conditions at the Play Area.

The current dissolved arsenic conditions downgradient of the Play Area, closer to the shoreline, confirms the model described above; shallow-fill upland groundwater near the shoreline has low concentrations of dissolved arsenic and neutral to mildly acidic conditions, while deep groundwater in outwash/weathered till has the highest observed dissolved arsenic concentrations, including a high fraction of remaining thioarsenates, and alkaline conditions. Figure 6A-9 shows the conceptual current distribution of Thylox solution, dispersed lower concentration dissolved arsenic, and precipitated/adsorbed arsenic in the soil matrix. Figure 6A-10 presents dissolved arsenic conditions in the upland along the shoreline of the GWPS.

Over time, particularly in the mildly acidic conditions of the shallow-fill groundwater in the upland, thioarsenates degraded to arsenite and sulfide. Arsenite and sulfide, as well as iron, have subsequently precipitated as stable and relatively insoluble iron oxyhydroxides and arsenic sulfides. Lower concentrations of arsenic have also adsorbed onto iron oxides present in soil. The highest concentrations of arsenic in soil occurs in subsurface fill unit soil, specifically in deeper fill below the Thylox process area

that Thylox solution passed through as it migrated. Attachment 2B-2 of Appendix 2B presents the geochemical evaluation conducted for the Play Area. Relatively high arsenic concentrations in fill soil (greater than 10,000 milligrams per kilogram [mg/kg] - Appendix 2B, Attachment 2B-2, Figure 3) is the result of precipitation and adsorption of arsenite under the moderately acidic conditions of the fill unit, combined with the presence of iron in soil. The transition from the historic conditions following release to the current conditions following precipitation and adsorption of arsenic in fill soil and remediation of dissolved arsenic beneath the Play Area is represented in Figures 6A-8 and 6A-9.

Precipitated and adsorbed arsenic is present at much lower concentrations in outwash soil below the Play Area where alkaline conditions and thioarsenates associated with the Thylox solution remain in the form in which it was originally released. The low concentration of arsenic observed in outwash soil (less than 50 mg/kg - Appendix 2B, Attachment 2B-2) in the presence of the highest dissolved arsenic concentrations, is the result of alkaline conditions that have preserved the thioarsenate form of arsenic originally used in the Thylox process and have prevented precipitation and adsorption. Appendix 2B, Attachment 2B-2 addresses the geochemistry of arsenic precipitation and adsorption for the Play Area more completely.

In most areas, sediment arsenic concentrations are either lower than or similar to ambient lake concentrations, with the exception of the area east of the Play Area and the far west area of the Gas Works Park Site (GWPS) adjacent to the shipyard. This indicates that widespread arsenic impacts to the sediments are not associated with the historical industrial activities in the AOI upland.

The most probable source of arsenic in shallow sediment is historical over-water releases or direct discharges from the Thylox process area during operations rather than as a result of dissolved arsenic transport from the upland. Analysis of upland groundwater flow paths and fate and transport modeling does not support a complete pathway for arsenic to migrate from upland groundwater to surface sediment. This hypothesis is supported by the vertical distribution of arsenic in the sediment east of the Play Area. Arsenic concentrations tend to be the highest in the upper sediment column and decline with increasing depth below the mudline east of the Play Area (RI Figures 5-3A and 5-3B) indicating the presence of historical top-down sources of offshore arsenic releases directly to sediment rather than the precipitation of dissolved arsenic being transported by discharging groundwater. In addition, the area where surface sediment has the highest arsenic concentration is outside (down slope or farther offshore) of the primary area of groundwater discharge and offset to the north of the upland arsenic plume.

### **3.0 CURRENT FATE AND TRANSPORT OF DISSOLVED CONTAMINANTS**

Aqueous transport of dissolved contaminants to sediment and surface water is one of the active transport pathways in the AOI. This pathway includes both upland groundwater-to-sediment and sediment-to-surface water transport. The sections below discuss the current conditions affecting transport and the potential for future transport of contaminants to impact surface sediment and surface water.

#### **3.1. Current Partitioning and Attenuation Behavior Affecting Fate and Transport**

This section discusses partitioning and attenuation mechanisms that affect the fate and transport of GWPS chemicals of concern (COCs). Discussion is focused on PAHs and benzene as the primary individual organic contaminants, and arsenic associated with releases at the former Thylox process as the primary inorganic constituent.

### **3.1.1. Current Organic Contaminant Fate and Transport**

Because 60 to over 100 years has elapsed since contaminant release, PAH and benzene sources (e.g., NAPL areas) have likely stabilized and are in equilibrium within the soil and groundwater. Upland studies show that plumes of more mobile contaminants (i.e., benzene and naphthalene) are shrinking or stable (see RI Figures 5-6 and 5-8 and RI Section 6.5.2.1) and are unlikely to reach the lake. Current processes controlling the fate and transport of PAHs and benzene are aqueous phase partitioning and attenuation. Attenuation of these organic contaminants is dictated largely by the chemical and physical properties of the contaminants including aqueous solubility, vapor pressure, chemical partitioning coefficient, and contaminant half-life. A summary of key physical and chemical factors that are likely to affect the fate and transport of dissolved contaminants in the AOI is presented in Table 6A-1. A comparison of site-specific partitioning coefficients ( $K_d$  values) determined by Purdue (Appendix 2C, Attachment 2C-1) and Stanford (Appendix 2D, Attachment 2D-7) is presented in Table 6A-2.

As a preliminary assessment of the potential for upland groundwater to impact surface water, measured upland groundwater concentrations were compared to measured and calculated offshore groundwater concentrations. Offshore groundwater concentrations were calculated from the maximum measured concentrations of key COCs in sediment and site-specific  $K_d$  values (where available). The estimated concentrations are shown in Table 6A-3 along with the maximum measured concentrations for offshore groundwater and upland groundwater in shoreline wells. The estimated PAH and benzene offshore concentrations are much higher than the measured shoreline groundwater concentrations, which indicates that sediment is much more likely to impact surface water than upland groundwater (i.e., groundwater discharging through sediment is being re-contaminated—see RI Figure 6-3). This simplified analysis suggests that impacted sediment and not upland sources is the primary source of mass flux of PAHs and benzene to surface water.

#### **3.1.1.1. PAH-Specific Partitioning and Attenuation**

NAPL and, to a lesser degree, tar are the main sources of dissolved PAHs in groundwater and porewater. Dissolved PAHs are present at higher concentrations near NAPL-impacted source areas. However, NAPL and tar are diminishing sources of PAHs because of volatilization and dissolution of lighter fractions over time. Heavier fractions are less soluble and do not readily dissolve in groundwater. This weathering limits the amount of PAHs present as an aqueous phase. Dissolved PAHs are further reduced due to their high affinity for binding to organic material and low solubilities. The high total organic carbon (TOC) content of AOI sediment, including the contribution of black carbon, tends to make PAHs less mobile and bioavailable and inhibits aqueous-phase migration. In aqueous equilibrium testing (Appendix 2D, Attachment 2D-7), site-specific PAH partitioning coefficients between sediment solids and water (i.e.,  $K_d$  values) were higher than using the conventional approach of calculating  $K_d$  from  $K_{ow}$  and fraction of organic carbon, meaning that PAHs in offshore groundwater in the AOI have a tendency to sorb to AOI sediment more readily and are more strongly bound to sediment than typical sediment with a similar fraction of organic carbon. This is likely due to the different types of carbon that are available to bind to.

AOI sediment exhibits three distinct partitioning behaviors, differentiated by the primary source of organic carbon: modified fraction organic carbon partitioning, soot-carbon-controlled partitioning, and oil/tar partitioning. Equilibrium testing samples exhibited different partitioning behaviors depending on the predominance of either NAPL (i.e., “oil”) and tar or black carbon. In samples with lower black carbon content and relatively higher PAH concentration, oil/tar partitioning behavior best predicted aqueous concentrations (i.e., aqueous phase concentrations were driven by partitioning from NAPL). By contrast, in

samples with higher black carbon content, fraction organic carbon partitioning or soot-carbon-controlled partitioning best predicted aqueous phase PAH concentrations. Hong and Luthy postulated (Appendix 2D, Attachment 2D-7) that these phenomena can be explained based on physiochemical characteristics of the black carbon solid matrix and sorptive nature of PAHs.

Partitioning, mobility, and bioavailability of PAHs in AOI sediment are strongly influenced by the presence of black carbon. PAH  $K_d$  values are 1.5 to 2 orders of magnitude higher for samples containing black carbon than  $K_d$  values derived using the conventional organic carbon model. In other words, for a given concentration of PAHs in sediment, concentrations of PAHs in offshore groundwater or porewater in the AOI are lower than expected using the conventional approach. Elevated solid-water partitioning coefficients compared to those predicted using conventional organic carbon partitioning models suggest that AOI PAHs are sequestered and less bioavailable than they would be at a site with similar amounts of carbon from natural organic matter. These results are corroborated by the bioassay findings in the AOI where testing indicated limited toxicity below about 300 mg/kg TPAH (Appendix 4B). At a typical site without black carbon, benthic toxicity is predicted at TPAH concentrations an order of magnitude lower based on the freshwater Sediment Management Standards for Washington State (Washington Administrative Code [WAC] 173-204-100).

Elevated TOC levels in soil and subsurface lake sediment result in strong partitioning of naphthalene to solids and an incomplete pathway from upland groundwater to surface water for naphthalene. This conclusion is consistent with prior studies (see Appendix 2C, Attachment C-1), which demonstrate that upland naphthalene concentrations decrease rapidly with distance downgradient from NAPL sources and predict that naphthalene concentrations would decrease to below Washington State surface water criteria at the groundwater conditional point of compliance (i.e., sediment mudline) established under the 1999 Consent Decree.

The presence and nature of black carbon, site-specific partitioning coefficients, and evidence of attenuation suggest that elevated PAH concentrations in offshore groundwater are associated with PAH-impacted sediment—and not a more distant source (e.g., upland groundwater).

PAHs are also capable of attenuation by natural biodegradation, particularly through aerobic processes. Higher molecular weight PAHs degrade very slowly, but naphthalene is capable of significant degradation, similar to benzene described below. The biodegradation half-lives for PAHs are presented in Table 6A-1 and are used to evaluate potential for transport of PAHs in groundwater to surface water in Section 3.2 below.

In sediment, PAH concentrations are consistently higher in deeper offshore groundwater than in porewater (naphthalene was not detected in four of five porewater samples). Comparison of offshore groundwater and porewater data at two locations (NLU63 and NLU69, shown on RI Figure 5-10) support the rapid attenuation of naphthalene above subsurface DNAPL-impacted sediment, as shown by the sharp decrease in concentrations between collocated offshore groundwater and porewater.

#### **3.1.1.2. Benzene-Specific Partitioning and Attenuation**

Relative to PAHs, benzene partitions from soil to groundwater, as well as to soil vapor, to a greater degree and is generally more mobile. However, benzene naturally degrades at a much higher rate than most PAHs, which limits overall mobility and has resulted in stable or shrinking plumes in the AOI upland. For example, benzene concentrations decrease to below the screening level downgradient of NAPL impacts in the northeast corner (i.e., MW-39 and MW-40; RI Figure 5-7).

As a result of source depletion and degradation, upland sources of benzene are a diminishing source of upland to sediment aqueous phase transport. Upland benzene sources have been remediated or depleted resulting in diminished flux from source areas. As a result of diminished sources and natural attenuation, upland benzene groundwater plumes are shrinking with time (RI Figure 5-8). The vertical distribution of remaining benzene suggests that benzene is unlikely to impact surface water unless the source (NAPL) is in contact with surface water. Where benzene is present in shoreline areas, concentrations are higher in deep wells than in shallow wells. Similarly, benzene concentrations are higher in offshore groundwater than collocated overlying porewater. Both situations indicate attenuation above subsurface source material (i.e., NAPL) and significant degradation of dissolved benzene. Continued attenuation of benzene in groundwater downgradient of NAPL source areas will prevent future migration of benzene from the upland to surface water. The estimated travel time and biodegradation half-life for benzene are used to evaluate potential aqueous phase benzene transport from the upland to surface water in Section 3.2 below.

Similar mechanisms are limiting transport of benzene from subsurface sediment to surface water. Although the offshore groundwater and porewater data are limited, available data support attenuation. As described in Section 2.1, benzene concentrations in sediment decrease rapidly toward the mudline and benzene was not detected in surface sediment except where there was NAPL, indicating that benzene attenuates prior to impacting surface sediment. Likewise, benzene in offshore groundwater attenuates prior to impacting porewater. Benzene was not detected (concentrations less than the 1 microgram per liter [ $\mu\text{g/L}$ ] reporting limit) in all six<sup>1</sup> porewater samples. Although recontamination of groundwater may occur as groundwater passes through NAPL-impacted sediment, benzene attenuates as offshore groundwater approaches and passes through near-surface high TOC sediment, as evidenced by decreased concentrations in porewater and reflected in greatly diminished surface sediment concentrations. Benzene appears to exist only in surface sediment where NAPL is also present.

### 3.1.2. Arsenic Fate and Transport

As an inorganic element, arsenic behaves very differently than PAHs or benzene and is affected by a wide variety of conditions and attenuation mechanisms associated with both the source of arsenic and the conditions in soil and groundwater impacted by arsenic. Two processes are largely responsible for the fate and transport of arsenic in groundwater systems: sorption/desorption and precipitation/dissolution. Both processes are affected by geochemistry. At the Play Area, changes in pH, the abundance of iron in soil, presence of dissolved sulfide, and the species of arsenic present control the fate and transport of dissolved arsenic.

The geochemical evaluation of arsenic in soil and groundwater at the Play Area indicate that dissolved arsenic in groundwater is largely in the form of aqueous thioarsenate, the original solution released from the Thylox Process Area. In areas affected by this thioarsenate solution, groundwater conditions differ from (are more alkaline) the more prevailing conditions (groundwater is mildly acidic). The alkaline groundwater in the Play Area tends to preserve thioarsenate in solution; outside of the Play Area acidic conditions cause thioarsenate to break down into arsenite and sulfide. Where acidic groundwater is present, precipitation and adsorption processes control the fate and transport of dissolved arsenic. Evidence of dissolved arsenic attenuation due to precipitation or adsorption is readily apparent in the fill unit. In the fill unit, soil concentrations are highest along the pathway that Thylox solution migrated, indicating precipitation and/or adsorption, and downgradient dissolved arsenic concentrations are significantly lower than the

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<sup>1</sup> Includes NLU70-PW-S1 collected from 0 to 1.2 feet below mudline that is classified as an offshore groundwater sample.

concentrations in the vicinity of the presumed releases. This suggests that, within the fill unit, conditions outside the immediate geochemical influence of the alkaline Thylox solution are favorable for attenuation of dissolved arsenic by precipitation or adsorption prior to reaching Lake Union.

Geochemical modeling suggests that the change in groundwater geochemistry from alkaline to mildly acidic observed outside the immediate influence of thioarsenate solution causes the arsenite and sulfide, resulting from the breakdown of thioarsenate, to precipitate as stable and insoluble arsenic sulfides. The neutral to mildly acidic conditions in fill unit soil are favorable for the transformation of thioarsenate into arsenite and sulfide. Where the highest concentrations of dissolved arsenic occur, remaining alkaline conditions have slowed disassociation of thioarsenate and a high fraction of the original thioarsenate species remains. As described above, the released Thylox solution migrated similarly to a DNAPL and remains in isolated zones that continue to affect local geochemistry, while slowly dispersing to surrounding groundwater. Where thioarsenate has been diluted and disassociated and neutral groundwater conditions have returned, the presence of sulfide from the disassociation of thioarsenate, as well as iron present in the soil matrix, has resulted in the precipitation and adsorption of arsenic within the soil matrix. Testing conducted as part of the geochemistry evaluation (Appendix 2B, Attachment 2B-2) found evidence of precipitated arsenic in fill soil where concentrations are greater than 10,000 mg/kg, whereas concentrations are comparatively low (less than 50 mg/kg) in outwash soil where high pH and thioarsenate solution remain in groundwater.

Once in precipitated form, arsenic appears very stable and highly unlikely to re-solubilize under existing conditions. This is documented in the geochemistry evaluation presented in Appendix 2B, Attachment 2B-2. Most of the precipitated arsenic is incorporated in very stable iron oxyhydroxides and arsenic sulfides, the latter resulting from the precipitation of arsenite and sulfide under the slightly acidic conditions present outside the influence of alkaline thioarsenate solution. Arsenic extraction tests conducted during the arsenic geochemistry evaluation indicate that the iron oxyhydroxide and arsenic sulfide precipitates require acid digestion for extraction, indicating highly stable in situ conditions. The solubility of the arsenic sulfides is primarily a function of pH. Neutral to slightly acidic upgradient groundwater conditions are expected to preserve the stability of solid phase arsenic in the soil matrix. Geochemical modeling discussed in Appendix 2B, Attachment 2B-2 supports the relative insolubility of arsenic solid phases and limited partitioning of arsenic from solid to dissolved phases.

Arsenic is also subject to partitioning from groundwater to soil. The presence of high quantities of iron oxides and oxyhydroxides in soils is also expected to strongly attenuate dissolved arsenic by surface adsorption. Outside of areas where higher arsenite and sulfide concentrations lead to precipitation, dissolved arsenic concentrations are controlled by surface adsorption and by incorporation into (absorption within) iron oxides and oxyhydroxides. The arsenic geochemical evaluation described in Appendix 2B, Attachment 2B-2 concluded that  $K_d$  values are 2,800 liters per kilogram (L/kg) for the fill unit and 460 L/kg for the outwash unit. Combined with precipitation, these mechanisms are expected to continue to attenuate dissolved arsenic, resulting in limited transport of dissolved arsenic beyond the thioarsenate source area.

### **3.2. Potential for Upland to Surface Water Transport**

This section evaluates potential future aqueous phase transport of PAHs, benzene, and arsenic to surface sediment and surface water. The partitioning and attenuation mechanisms described in Section 3.1 above demonstrate that the migration of these contaminants is inhibited by site conditions, including high TOC, and contaminant properties such as high  $K_{oc}$  and degradation rates (PAHs and benzene) and high  $K_d$  and high tendency to precipitate with co-located iron and sulfide (dissolved arsenic).

### 3.2.1. PAHs and Benzene Travel Time Analysis

For PAHs and benzene, an important consideration is whether these COCs can migrate to surface water prior to degrading to below screening levels (i.e., whether there is a complete pathway). To evaluate the upland to surface water transport pathway, the relationship between degradation half-life and travel time for dissolved COCs is examined. Transit times for the movement of PAHs [using naphthalene, chrysene, and benzo(a)pyrene as surrogates] and benzene in groundwater between the shoreline and the point of discharge to Lake Union is presented in Table 6A-4.

The evaluation presented in Table 6A-4 used groundwater discharge rate information developed by groundwater modeling (Appendix 3F) as well as mass flux data calculated using groundwater discharge rates and upland contaminant concentration data. Figures 6A-6 and 6A-7 present a cross sectional representation of contaminant concentration and calculated contaminant mass flux for naphthalene and benzene, respectively. The assumptions for the analysis include the following:

- Groundwater velocity: For a conservative evaluation of upland to surface water contaminant travel time, the groundwater discharge rate at the points of highest calculated contaminant mass flux at the shoreline, approximately 20 feet upland of the ordinary high water mark (OHWM), was used to evaluate the clean groundwater velocity. Specifically, the highest mass flux area shown on the cross sections, located in the upper outwash unit/lower fill unit in the vicinity of the Play Area (red areas near the northeast end of flux cross sections shown in Figures 6A-6 and 6A-7), was used to calculate the average linear groundwater velocity.
- Retardation factor: Site specific values for porosity and contaminant specific  $K_d$  values were used to calculate retardation factors that allow estimation of COC travel time relative to the travel time of clean groundwater.
- Contaminant travel distance: The zone of highest groundwater flux at the Play Area, as shown on Figure 6A-7, was used to estimate the travel distance. Modeling indicated that groundwater from the high flux zone shown on Figure 6A-7 discharges at least 40 feet offshore. Allowing for 10 feet of vertical travel along the flow path, a total travel distance of used 50 feet was used. This is a conservative estimate as it does not account for travel through the upland from monitoring well to the OHWM.

These assumptions were used to estimate the travel time for contaminants to migrate from the upland to surface water. The results of this analysis are presented in Table 6A-4 and show that for PAHs, travel times as high as over a million years would be required to overcome the factors that inhibit groundwater transport of contaminants in the AOI. The most mobile contaminant evaluated, benzene, travels significantly faster than PAHs, taking 59 years to travel from the upland to surface water. However, because benzene is highly degradable, with a half-life of only 1 year, benzene degrades by 59 half-lives within that 59-year transport period, which would result in concentrations that are many orders of magnitude below the surface water cleanup level, even assuming starting concentrations as high as the solubility limit listed in Table 6A-4.

The analysis summarized in Table 6A-4 demonstrates the upland groundwater to surface pathway is incomplete for PAHs and benzene. This analysis does not account for recontamination as groundwater passes through subsurface sediment contamination. RI Figure 6-3 presents active chemical transport mechanisms, including groundwater becoming re-contaminated as it flows through contaminant source material in subsurface sediment. Given partitioning and attenuation mechanisms described in Section 3.1.1 and the extent of contaminant source material (e.g., NAPL areas) along groundwater flow paths in the lakeshore and lake slope, it is very likely that both natural attenuation and recontamination of offshore groundwater are under way.

### 3.2.2. Arsenic

Arsenic was not included in the evaluation of travel time because it does not biologically degrade like PAHs and benzene. Arsenic transport is driven by attenuation factors beyond partitioning and retardation. As an inorganic contaminant, arsenic fate and transport processes are nondestructive, with attenuation mechanisms resulting in transformation of arsenic to immobile or less toxic states rather than removal from the environment. As described below, transport of arsenic is governed by hydrogeologic conditions and other attenuation mechanisms.

The Play Area plume in deep outwash groundwater at the shoreline is not expected to reach Lake Union sediment or surface water due hydrogeologic conditions as well as the characteristics of fill soil and recent deposits overlaying the outwash that are amenable to precipitation and adsorption of dissolved arsenic. Figure 6A-9 presents a cross sectional view of the current conditions conceptual site model for the Play Area, showing the assumed current conditions for arsenic in the vicinity of the former Thylox process area.

Deep thioarsenate-impacted groundwater at the shoreline appears to be stable given its persistence over the past 60 plus years due to hydrogeologic conditions. Thioarsenate found in weathered till and outwash unit groundwater east of the Play Area is assumed to have migrated downward from the fill unit, as shown on Figure 6A-8. The persistence of deep thioarsenate-impacted groundwater in the outwash and weathered till indicates very slow groundwater flow and limited dispersion of the Thylox solution, which is expected considering the relatively low conductivity of these units and groundwater flow patterns near the shoreline<sup>2</sup>. Furthermore, the flow path and travel time is long and groundwater flows through the fill unit prior to discharging to Lake Union.

Attenuation of dissolved arsenic beyond the thioarsenate “source” in deeper outwash and upper weathered till is expected to be similar to that observed in shallower fill groundwater; as described in Section 3.1.2, dissolved arsenic concentrations in fill unit groundwater reduce significantly in the area immediately downgradient of the Play Area as a result of precipitation and adsorption.

Conditions outside the immediate geochemical influence of the alkaline Thylox solution are favorable for attenuation of dissolved arsenic prior to reaching Lake Union. Groundwater containing elevated concentrations of arsenic moving from the upland to subsurface sediment would flow through the fill unit where geochemical conditions would result in precipitation and adsorption of dissolved arsenic before it reaches surface sediment and surface water of Lake Union. The results of the geochemical evaluation indicate that even where partitioning of arsenic is based on adsorption, partition coefficients for arsenic in the outwash and fill will significantly attenuate dissolved arsenic prior to reaching surface sediment.

## 4.0 REFERENCES

Hong, Lei, and Richard G Luthy. 2005. Draft Final Report II - Identification of Black Carbon Material in Sediments from Lake Union. Stanford, California: Stanford University, Department of Civil and Environmental Engineering.

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<sup>2</sup> Most groundwater flows through the fill and outwash units. Groundwater flow paths turn upward in the vicinity of the shoreline prior to discharging to Lake Union partially bypassing the lower outwash and upper till. Groundwater flow modeling results indicate decreased groundwater discharge in the lower outwash and very low discharge through the till (see area between MW-36D and PAI-10 in Figure 3F-16, Appendix 3F).

Howard, PH, RS Boethling, WF Jarvis, WM, Meylan, EM Michaelenko. 1991. Handbook of Environmental Degradation Rates.

Lide, David R. 1992. CRC Handbook of Chemistry and Physics.

Parametrix and Key Environmental. 1998. Draft Gas Works Park Environmental Cleanup, Focused Feasibility Study Report Volumes 1 and 2.

Washington Department of Ecology (Ecology). 2022. Natural Background Groundwater Arsenic Concentrations in Washington State, Study Results. Publication No. 14-09-044. January 2022.

Washington State Department of Ecology. 2019. CLARC Master Data Table.

**Table 6A-1**  
**Physical and Chemical Parameters for COCs and Impacted Media**  
 Gas Works Park Site  
 Seattle, Washington

Chemical	Molecular Weight <sup>a</sup> (g/mol)	K <sub>d</sub> (L/kg)	Aqueous Solubility (mg/L)	Vapor Pressure (mm Hg)	Henry's Law Constant (atm-m <sup>3</sup> /mol)	K <sub>oc</sub> (L/kg)	Log K <sub>ow</sub>	Soil Half-life (yrs)	Groundwater Half-life (yrs)
Benzene	78.11	22 to 97 <sup>b</sup>	1,790 <sup>e</sup>	95 <sup>e</sup>	0.0056 <sup>e</sup>	100 to 449 <sup>e</sup>	2.13 <sup>e</sup>	0.03 <sup>h</sup>	1.0 <sup>h</sup>
Naphthalene	128.18	500 to 1,820 <sup>b</sup>	31 <sup>e</sup>	0.085 <sup>e</sup>	0.00044 <sup>e</sup>	2,000 to 8,430 <sup>e</sup>	3.30 <sup>e</sup>	0.09 <sup>h</sup>	0.37 <sup>h</sup>
Benzo(a)pyrene	252.32	761,000 to 2,180,000 <sup>b</sup>	0.0016 <sup>e</sup>	Negligible	0.00000046 <sup>e</sup>	3,520,000 to 10,100,000 <sup>e</sup>	6.13 <sup>e</sup>	0.79 <sup>h</sup>	3.2 <sup>h</sup>
Chrysene	228.29	112,000 to 338,000 <sup>b</sup>	0.002 to 0.00345 <sup>e</sup>	Negligible	0.0000052 <sup>e</sup>	519,000 to 1,560,000 <sup>e</sup>	5.81 <sup>e</sup>	1.9 <sup>h</sup>	7.5 <sup>h</sup>
Carbazole	167.21	732 <sup>f</sup>	1.8 <sup>e</sup>	0.00000075 <sup>e</sup>	0.00000012 <sup>e</sup>	3,390 <sup>j</sup>	3.72 <sup>e</sup>	- <sup>h</sup>	- <sup>h</sup>
Dibenzofuran	168.19	501 <sup>f</sup>	3.1 <sup>e</sup>	0.0025 <sup>e</sup>	0.00021 <sup>e</sup>	2,320 <sup>k</sup>	4.12 <sup>e</sup>	0.048 <sup>h</sup>	0.059 <sup>h</sup>
Arsenic	74.92	464 to 2,820 <sup>c</sup>	Variable <sup>d</sup>	Negligible	Negligible	n/a	n/a	n/a	n/a
Nickel	58.69	65 <sup>l</sup>	Variable <sup>i</sup>	Negligible	Negligible	n/a	n/a	n/a	n/a

**Notes:**

<sup>a</sup> Lide 1992 (CRC Handbook of Chemistry and Physics) (assumed arsenic acid for arsenic molecular weight).

<sup>b</sup> For site-specific values per geologic unit see Table 6A-2 (PAHs) and Table 6A-3 (benzene).

<sup>c</sup> Site-specific arsenic K<sub>d</sub> values for fill (2,821 L/kg) and outwash (464 L/kg) geologic units are described in Appendix 2B-2. The site-specific arsenic K<sub>d</sub> value for recent deposits (1,654 L/kg) is the mean value of calculated K<sub>d</sub> values from co-located sediment and porewater sample results for arsenic.

<sup>d</sup> Arsenic chemical and physical information - <http://www.atsdr.cdc.gov/toxprofiles/tp2-c4.pdf>. Aqueous solubility values include: Arsenic (insoluble) arsenic acid (302,000 mg/L at 12.5 deg C), arsenic pentoxide (2,300,000 mg/L at 20 deg C), and arsenic trioxide (17,000 mg/L at 16 deg C).

<sup>e</sup> EPI Suite - Estimation Program Interface Version 4.00. U.S. EPA and Syracuse Research Corporation.

<sup>f</sup> Calculated K<sub>d</sub> values based on published K<sub>oc</sub> value and average fraction organic carbon (foc) of 0.216 reported in PAH Partitioning in Black Carbon-Impacted Sediments from Lake Union (Appendix 2D). K<sub>d</sub> = foc\*K<sub>oc</sub>

<sup>g</sup> Back-calculated K<sub>oc</sub> values are based on site-specific K<sub>d</sub> values and average foc of 0.216 reported in PAH Partitioning in Black Carbon-Impacted Sediments from Lake Union (Appendix 2D). K<sub>oc</sub> = K<sub>d</sub>/foc

<sup>h</sup> Howard et al. 1991 (Handbook of Environmental Degradation Rates). Assumes anaerobic conditions for groundwater half-lives for benzo(a)pyrene and chrysene.

<sup>i</sup> Nickel chemical and physical information - <http://www.atsdr.cdc.gov/toxprofiles/tp15.pdf>. Aqueous solubility values include: Nickel (1.13 mg/L at 37 deg C), nickel acetate (170,000 mg/L at 68 deg C), nickel ammonium sulfate (104,000 mg/L at 20 deg C), and nickel carbonate (93 mg/L at 25 deg C).

<sup>j</sup> CLARC Master Data Table (Ecology 2019)

<sup>k</sup> PubChem Database (<https://pubchem.ncbi.nlm.nih.gov>).

<sup>l</sup> <https://semspub.epa.gov/work/HQ/175235.pdf>

-- = not available

n/a = not applicable

mm Hg = millimeters mercury

atm-m<sup>3</sup>/mol = atmosphere-cubic meters per mole

See text for full acronym and abbreviation list.

**Table 6A-2**  
**Site-Specific PAH  $K_d$  Values**  
 Gas Works Park Site  
 Seattle, Washington

Chemical	$K_d$ (L/kg)		$K_d$ (L/kg)
	Offshore Fill <sup>a</sup>	Offshore Recent Deposits <sup>a</sup>	Upland Soil <sup>b</sup>
<b>LPAH</b>			
Acenaphthene	655	1,860	633
Anthracene	6,330	23,200	8,680
Fluorene	1,390	3,520	1,390
Naphthalene	500	1,820	466
Phenanthrene	5,230	17,100	3,580
<b>HPAH</b>			
Benzo(a)anthracene	120,000	507,000	370,100
Benzo(a)pyrene	761,000	2,180,000	1,610,000
Benzo(b)fluoranthene	688,000	2,608,626	not measured
Benzo(k)fluoranthene	355,000	1,770,000	not measured
Chrysene	112,000	338,000	545,000
Fluoranthene	18,400	70,100	21,700
Pyrene	23,100	79,000	93,000

**Notes:**

<sup>a</sup> Distribution coefficient ( $K_d$ ) values calculated based on Stanford data (calculated site-specific data) (Appendix 2D, Attachment 2D-7). Average  $K_d$  values for fill and recent deposits calculated according to sample rationale described in the NLU Groundwater Modeling Memorandum (Appendix 3F, Attachment 3F-1).

<sup>b</sup> Purdue University work (Appendix 2C, Attachment 2C1).

HPAH = high molecular weight polycyclic aromatic hydrocarbon

L/kg = liters per kilogram

LPAH = low molecular weight polycyclic aromatic hydrocarbon

Gray shading = highest site-specific  $K_d$  value

**Table 6A-3**  
**Estimated Offshore Groundwater Concentrations**  
 Gas Works Park Site  
 Seattle, Washington

Chemical	Physical and Chemical Parameters		Maximum Sediment Concentration (mg/kg)	Maximum Calculated Offshore Groundwater Concentration, Dissolved (Cd) (µg/L) <sup>d</sup>		Maximum Measured Offshore Groundwater Concentration (µg/L)	Maximum Shoreline Groundwater Filtered Concentration, from Most Recent <sup>e</sup> Sampling Event (µg/L)
	K <sub>d</sub> (L/kg)			Fill	Soft Sediment		
	Fill	Recent Deposits					
Naphthalene <sup>a</sup>	500	1,820	20,000	40,000	11,000	7,400	7,000
Benzo(a)pyrene <sup>a</sup>	761,000	2,180,000	2,200	2.9	1.0	9	ND (1.0)
Benzene <sup>b</sup>	22	97	3,500	160,000	40,000	640	NA
Arsenic <sup>c</sup>	2,820		2,400	850		580	314,000

**Notes:**

<sup>a</sup> Distribution coefficient (K<sub>d</sub>) values for PAHs based on site-specific empirical data from Stanford study (Appendix 2D, Attachment 2D-7). K<sub>d</sub> values for fill and recent deposits are average values excluding outliers. Rationale described in the NLU Groundwater Modeling Memorandum (Appendix 3F, Attachment 3F-1).

<sup>b</sup> Benzene K<sub>d</sub> values for fill and recent deposits are derived from site-specific naphthalene K<sub>d</sub> values developed in the Stanford study by correlating to respective K<sub>ow</sub> values.

<sup>c</sup> Arsenic K<sub>d</sub> value for fill and recent deposits is the average K<sub>d</sub> values developed in the as part of the Former Thylox Process Area Geochemical Evaluation (RI Appendix 2B-2).

<sup>d</sup> Dissolved concentration (Cd) calculated as =

$$\frac{\text{sorbed concentration (max sediment concentration in mg/kg)}}{\text{distribution coefficient (K}_d \text{ in L/kg)}} \times \frac{1,000 \mu\text{g}}{1 \text{ mg}}$$

<sup>e</sup> Most recent sampling event was October 2013 for organic contaminants and December 2020 for arsenic.

Gray shading indicates that concentration is higher than site-specific solubility concentration as determined from leaching study conducted by Purdue University (Appendix 2C, Attachment 2C-1).

NA = not analyzed

ND = not detected

**Table 6A-4**  
**Estimated Upland to Surface Water Travel Times**  
**Gas Works Park Site**  
**Seattle, Washington**

<b>COC</b>	<b>Solubility Limit (mg/L)</b>	<b>Groundwater Half-life<sup>a</sup> (yr)</b>	<b>Clean Water Transit Time<sup>b</sup> (yr)</b>	<b>Contaminant Retardation Factor<sup>c</sup></b>	<b>Contaminant Transit Time<sup>d</sup> (yr)</b>	<b>Number of Half-Lives</b>	<b>Estimated Mudline Concentration<sup>e</sup> (ug/L)</b>
Benzo(a)pyrene	0.0016 <sup>f</sup>	3.2	0.44	4,570,000	2,000,000	630,000	negligible
Chrysene	0.0016 <sup>g</sup>	7.5	0.44	660,000	290,000	38,700	negligible
Naphthalene	31 <sup>f</sup>	0.37	0.44	3,000	1,320	3,570	negligible
Benzene	1,790 <sup>f</sup>	1.0	0.44	133	59	59	4E-12

**Notes:**

<sup>a</sup> Groundwater half-life values are from Howard et al. 1991 (Handbook of Environmental Degradation Rates) and assume anaerobic conditions.

<sup>b</sup> Assumes an average linear velocity of 0.31 feet/day based on a shoreline groundwater flux value of 0.1 feet per day and an outwash unit effective porosity value of 0.32 (Appendix 3F). An estimated travel distance of 50 feet from the shoreline to the mudline for Lakeshore zone sediment.

<sup>c</sup> Calculated assuming the linear sorption isotherm, a bulk density of 1.80 g/cc, and porosity of 0.30, and site-specific Fill unit Kd values from Table 6A-3.

Formula for calculating Retardation Factor (Contaminant Retardation Factor =  $1 + (\text{Bulk Density} * K_d) / \text{Porosity}$ ) is here: <http://www3.epa.gov/ceampubl/learn2model/part-two/onsite/retard.html>.

<sup>d</sup> Contaminant transit times calculated by multiplying clean water transit times by associated retardation factors.

<sup>e</sup> Estimated mudline concentration using a starting concentration of the respective solubility limit and following degradation by the number of half-lives elapsed during travel from the upland to the mudline.

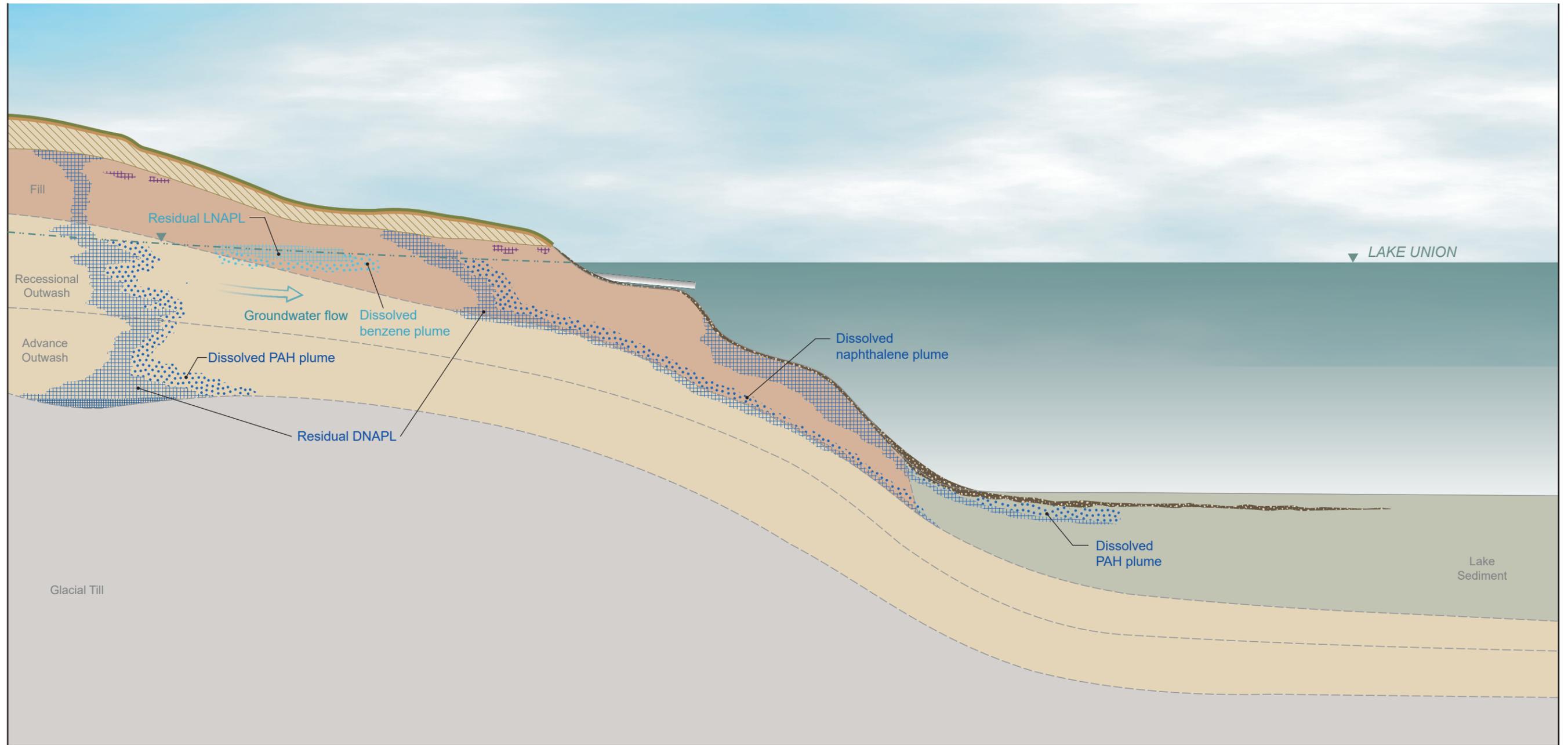
The mudline concentration was calculated using the equation  $A = A(0) * (1/2)^n$ , where A(0) equals the initial concentration, and n equals the number of half-lives elapsed.

<sup>f</sup> [http://www.epa.gov/oppt/rsei/pubs/technical\\_appendix\\_b\\_physicochemical\\_properties\\_v2.3.1.pdf](http://www.epa.gov/oppt/rsei/pubs/technical_appendix_b_physicochemical_properties_v2.3.1.pdf)

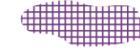
<sup>g</sup> [http://www.epa.gov/superfund/health/conmedia/soil/pdfs/part\\_5.pdf](http://www.epa.gov/superfund/health/conmedia/soil/pdfs/part_5.pdf)

North

South



**Legend:**

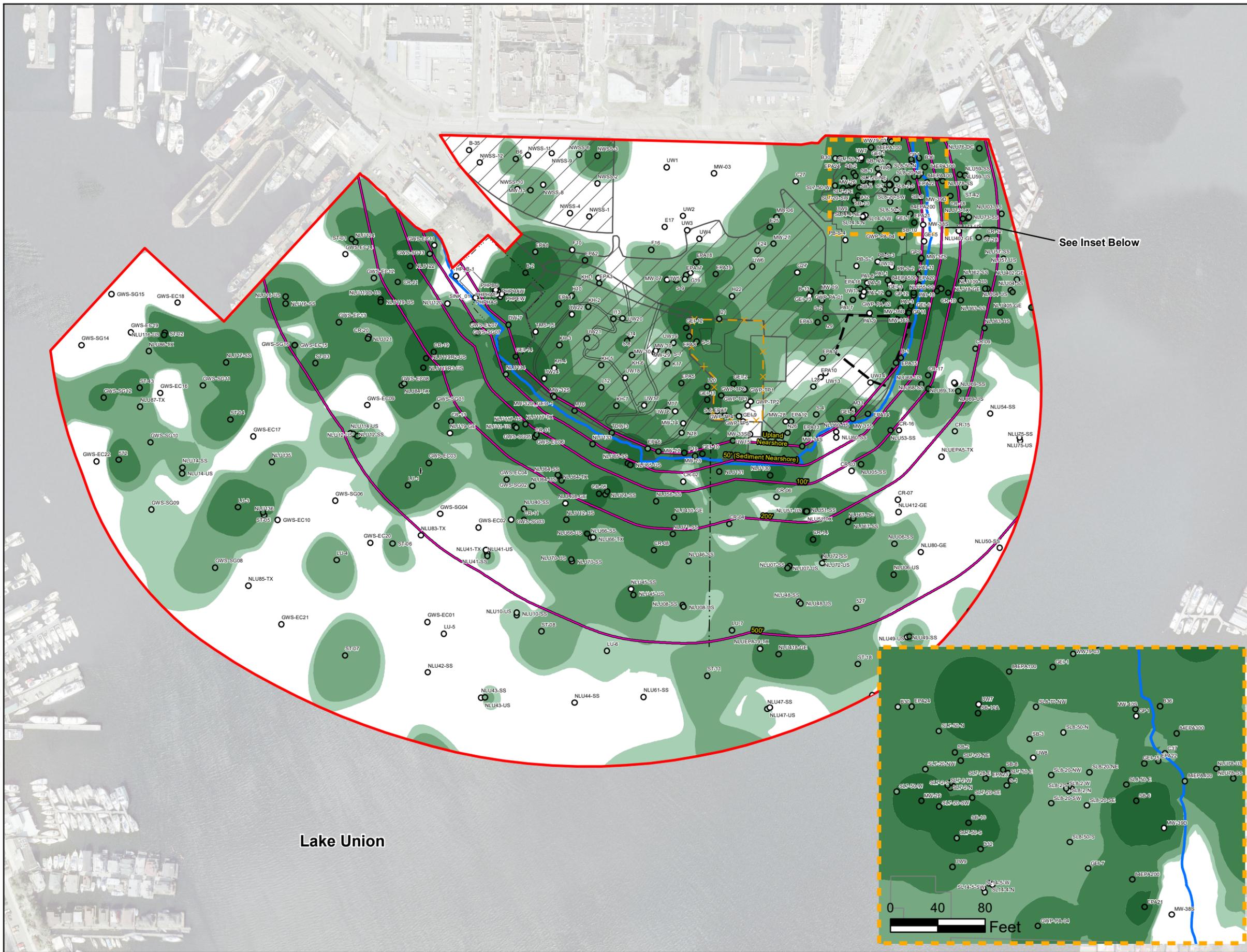
-  Mobile DNAPL
-  Residual LNAPL
-  Residual DNAPL
-  Dissolved LNAPL Constituents
-  Dissolved DNAPL Constituents
-  Tar
-  Source Material (e.g., Black Carbon)

**Conceptual Site Model of Aqueous Phase Transport**

Gas Works Park Site  
Seattle, Washington



**Figure 6A-1**



**Legend**

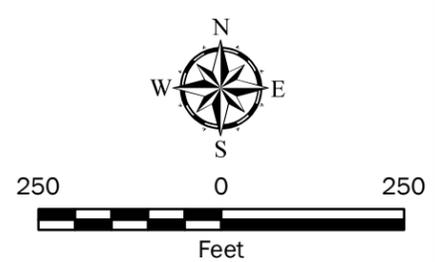
- Area of Investigation
- Shoreline (OHWM)
- 2001-2006: Air Sparging Area
- Areas with Clean Soil Caps
- Cracking Towers Security Fence
- Sample Location
- Cross Section Alignment (See Figure 5-19C and 5-19D)
- - - Cross Section Reference Line

**Maximum TPAH Concentration (mg/kg)**

- ≤ 17 (SCO)
- > 17 to ≤ 30 (CSL)
- > 30 to ≤ 170
- > 170 to ≤ 2,000
- >2,000

- Notes:**
1. TPAH is not a COC for soil. TPAH sediment screening levels = 17 mg/kg (SCO) and 30 mg/kg (CSL).
  2. † U-1 location is uncertain.
  3. For non-detects, 1/2 the reporting limit is used for interpolations. Interpolations include detects and non-detects.
  4. Concentration contours do not represent surface conditions.
  5. Concentration contours generated using CTech's Earth Volumetric Studio IDW (Shepard) interpolation method. Reach = 500, Power = 6, Anisotropy = 10. Contoured interval may differ from actual data shown due to influence of neighboring values.
  6. Basemap 2005 USGS aerial photograph. Does not show current conditions.
  7. Projection: NAD 1983 State Plane Washington North FIPS 4601 Feet.

DISCLAIMER: This drawing is for information purposes. It is intended to assist in showing features discussed in an attached document. The locations of all features are approximate. GeoEngineers, Inc. cannot guarantee the accuracy and content of electronic files. The master file is stored by GeoEngineers, Inc. and will serve as the official record of this communication.

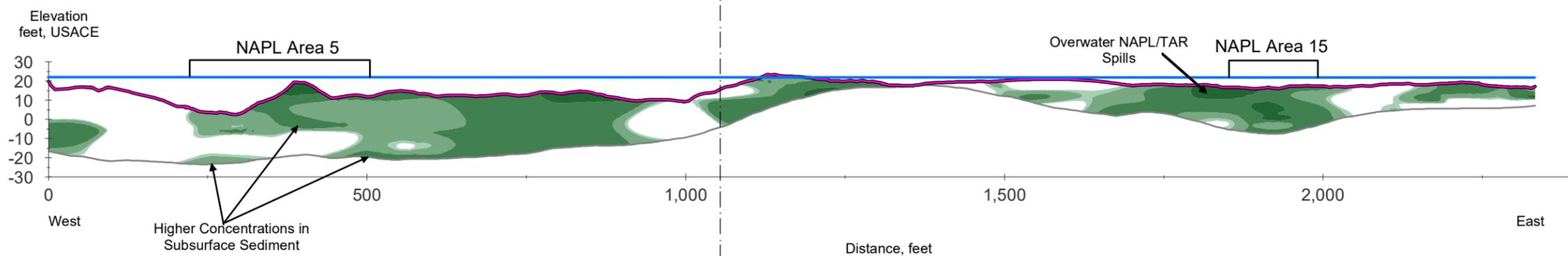


**TPAH Concentrations in Soil and Sediment - Surface and Subsurface**

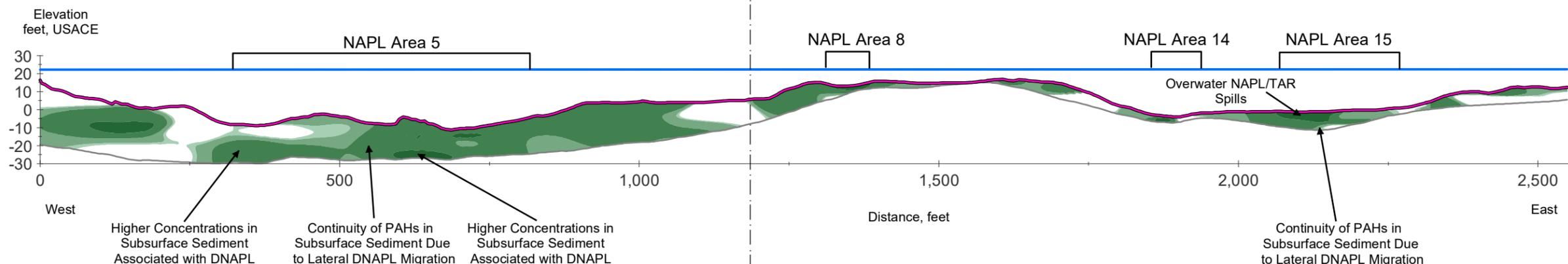
**Gas Works Park Site  
Seattle, Washington**

Path: P:\010186846\GIS\SEI\TPAH\MDX\018684601\_R1\_Rev\_TPAH\_Soil\_Sediment\_SubSurface\_CrossSections\_Fig6A-3 Map Revised: 07 December 2021 glohnmeyer

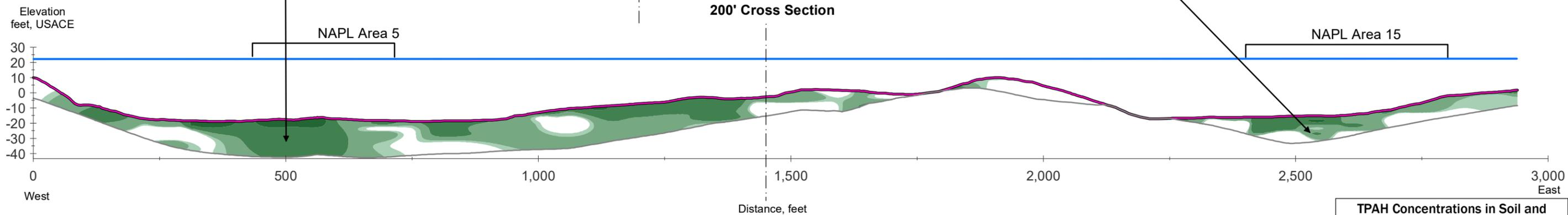
### 50' Cross Section (Nearshore Sediment)



### 100' Cross Section



### 200' Cross Section



**Legend**

- - - Cross Section Reference Line
- OHHW (22 feet, USACE)
- Existing Ground Surface or Mudline
- Top of Till

**Maximum TPAH Concentration (mg/kg)**

- ≤ 17 (SCO)
- > 17 to ≤ 30 (CSL)
- > 30 to ≤ 170
- > 170 to ≤ 2,000
- > 2,000

**Notes:**

1. TPAH is not a COC for soil. TPAH sediment screening levels = 17 mg/kg and 30 mg/kg.
2. Vertical exaggeration is 3:1 for all cross sections.
3. Concentration contours do not represent surface conditions.
4. For non-detects, 1/2 the reporting limit is used for interpolations. Interpolations include detects and non-detects.
5. Concentration contours generated using CTech's Earth Volumetric Studio IDW (Shepard) interpolation method. Reach = 500, Power = 6, Anisotropy = 10. Contoured interval may differ from actual data shown due to influence of neighboring values.

**DISCLAIMER:** This drawing is for information purposes. It is intended to assist in showing features discussed in an attached document. The locations of all features are approximate. GeoEngineers, Inc. cannot guarantee the accuracy and content of electronic files. The master file is stored by GeoEngineers, Inc. and will serve as the official record of this communication.



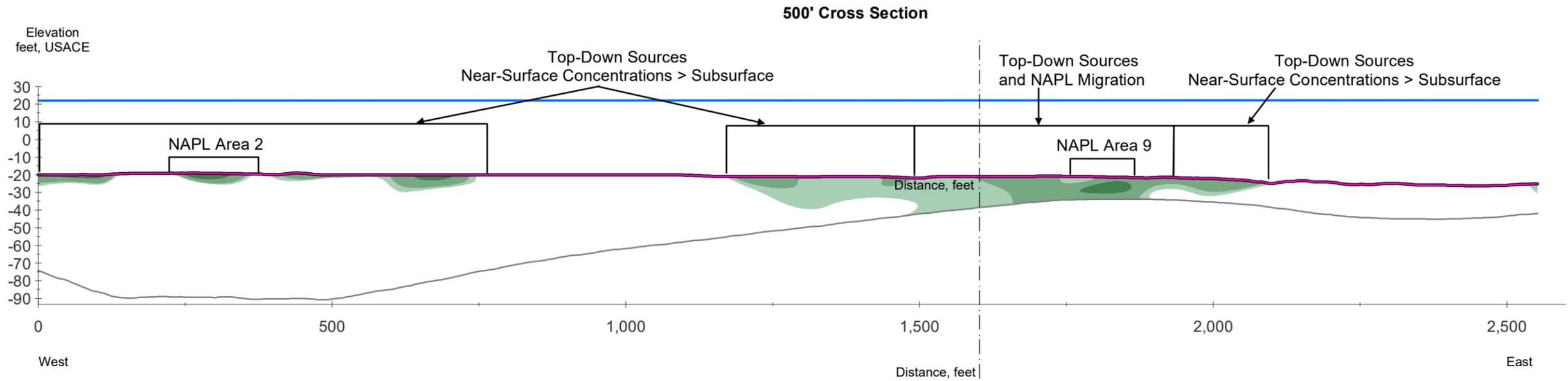
Vertical Exaggeration 3:1

**TPAH Concentrations in Soil and Sediment - Surface and Subsurface Cross Sections**

Gas Works Park Site  
Seattle, Washington

**GEOENGINEERS**  **Figure 6A-3**

Path: P:\010186846\GIS\SE\TPAH\MD\018684601\_R1\_Rev\_TPAH\_Soil\_Sediment\_SubSurface\_CrossSections\_Fig6A-4 Map Revised: 07 December 2021 glohnmeyer



**Notes:**

1. TPAH is not a COC for soil. TPAH sediment screening levels = 17 mg/kg and 30 mg/kg.
2. Vertical exaggeration is 3:1 for all cross sections.
3. Concentration contours do not represent surface conditions.
4. For non-detects, 1/2 the reporting limit is used for interpolations. Interpolations include detects and non-detects.
5. Concentration contours generated using CTech's Earth Volumetric Studio IDW (Shepard) interpolation method. Reach = 500, Power = 6, Anisotropy = 10. Contoured interval may differ from actual data shown due to influence of neighboring values.

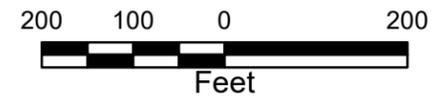
DISCLAIMER: This drawing is for information purposes. It is intended to assist in showing features discussed in an attached document. The locations of all features are approximate. GeoEngineers, Inc. cannot guarantee the accuracy and content of electronic files. The master file is stored by GeoEngineers, Inc. and will serve as the official record of this communication.

**Legend**

- OHHW (22 feet, USACE)
- - - Cross Section Reference Line
- Top of Till
- Existing Ground Surface or Mudline

**Maximum TPAH Concentration (mg/kg)**

- ≤ 17 (SCO)
- > 17 to ≤ 30 (CSL)
- > 30 to ≤ 170
- > 170 to ≤ 2,000
- > 2,000



Vertical Exaggeration 3:1

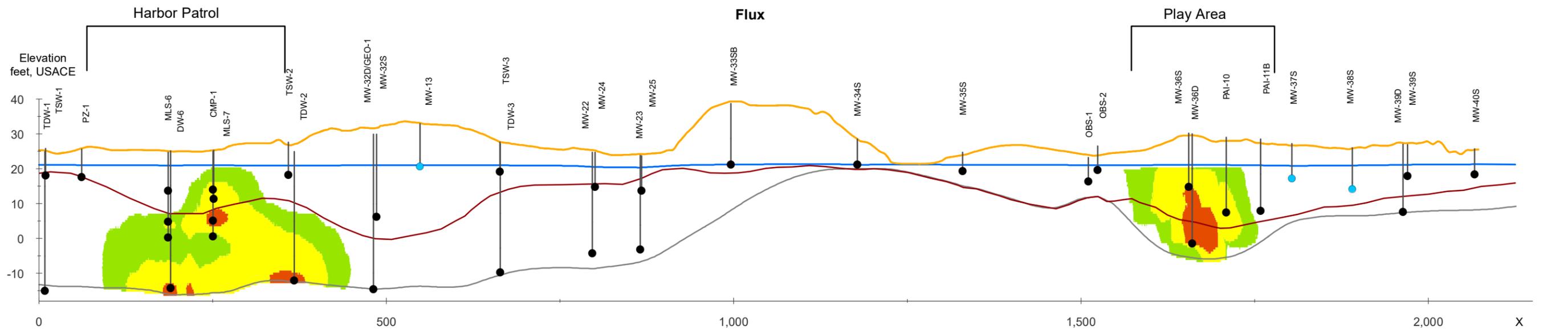
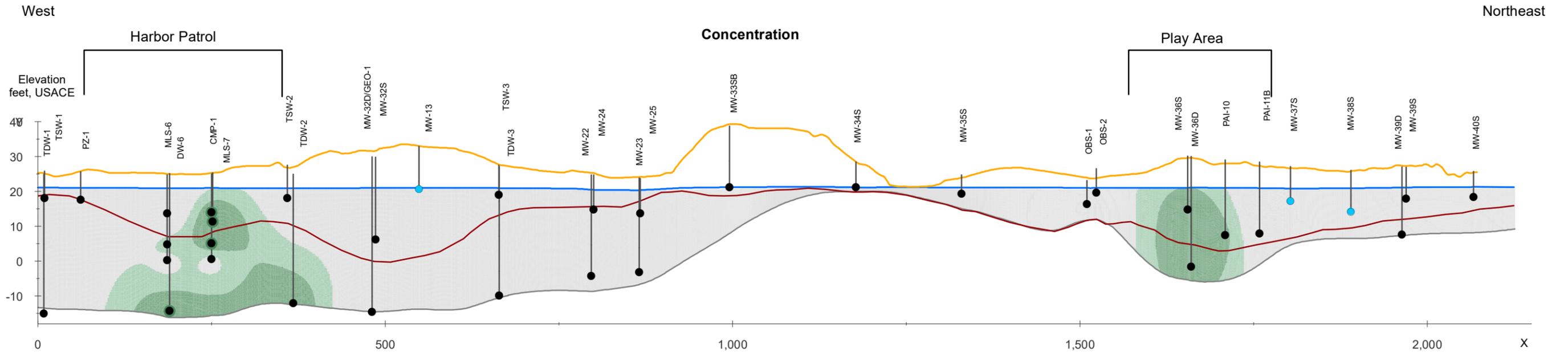
**TPAH Concentrations in Sediment - Surface and Subsurface Cross Sections**

Gas Works Park Site  
Seattle, Washington



**Figure 6A-4**





**Notes:**

1. Concentration contours generated using CTech's EVS Kriging interpolation method. Reach=1000, Anisotropy=5, Nugget=0.
2. April 2013 groundwater results were chosen for mapping instead of the October 2013. The rationale is threefold:
  - (1) the suite of wells included all wells
  - (2) reporting limits tended to be more elevated in October and
  - (3) concentrations of COCs in groundwater were generally higher in April than in October.
3. December 2014 results are MW-36D, MW-36S, PAI-2B, PAI-10, PAI-11B and PAI-12
4. Non-detects are assumed to have concentrations of half the reporting limit (RL), for contouring purposes. Map posts non-detects as < 1/2RL
5. Areas not shaded in the shoreline cross section are interpreted to have naphthalene concentrations below the screening level.
6. Naphthalene upland groundwater screening level = 9,880 µg/L
7. Wells MW-41S through MW-52D are not shown because they were installed in 2017, several years after the sampling events presented in this figure. The new wells were installed for the arsenic groundwater treatment interim action and have not been sampled for naphthalene.
8. Projection: NAD 1983 StatePlane Washington North FIPS 4601 Feet

**Legend**

- Detected Concentration
- Non-Detect Concentration, 1/2 Reporting Limit
- Ground Surface Elevation
- April 14, 2013 Groundwater Elevation (21.6 ft)
- Fill/Outwash Contact
- Top of Till

**Maximum Naphthalene Concentration (µg/L)**

- ≤ 160
- > 160 to ≤ 1,000
- > 1,000 to ≤ 9,880
- > 9,880

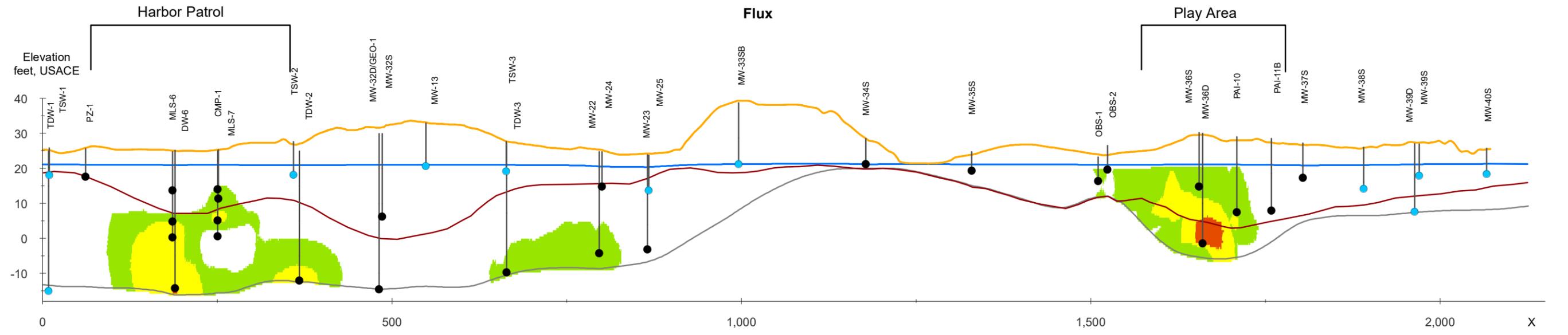
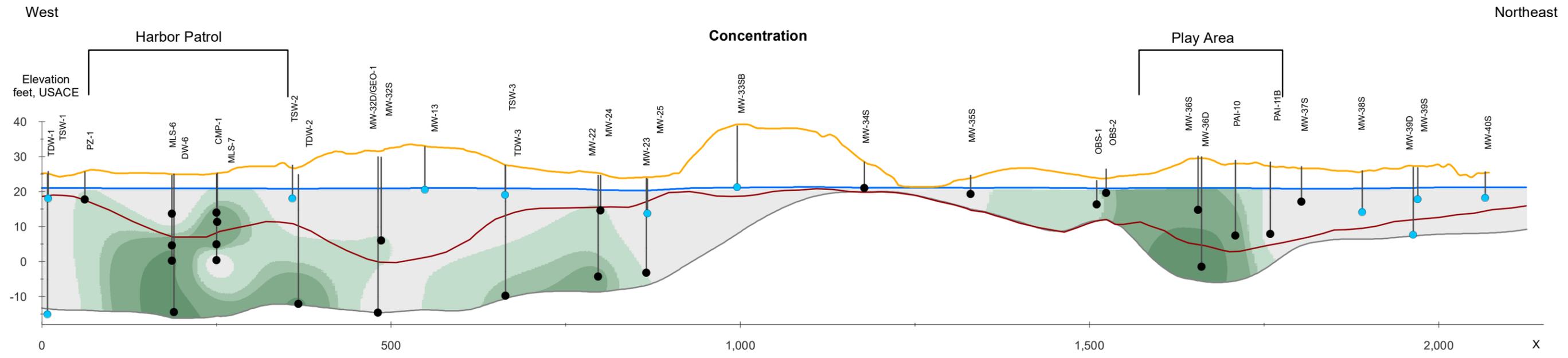
**Naphthalene Flux (mg/ft<sup>2</sup> per day)**

- 0 to 0.01
- 0.011 to 0.1
- 0.101 to 1
- > 1



<b>Shoreline Groundwater Naphthalene Concentrations and Flux</b>	
Gas Works Park Site Seattle, Washington	
GEOENGINEERS	<b>Figure 6A-6</b>

Path: P:\010186846\GIS\IE\VS\TPA\HMD\018684601\_F6A-7\_Shoreline\_BenzeneConcentrationsFlux Map Revised: 04 June 2020 glhmmeyer \ 12/6/21 spride



- Notes:**
1. Concentration contours generated using CTech's EVS Kriging interpolation method.  
Reach=1000, Anisotropy=5, Nugget=0.
  2. April 2013 groundwater results were chosen for mapping instead of the October 2013. The rationale is threefold:
    - (1) the suite of wells included all wells
    - (2) reporting limits tended to be more elevated in October and
    - (3) concentrations of COCs in groundwater were generally higher in April than in October.
  3. December 2014 results are MW-36D, MW-36S, PAI-2B, PAI-10, PAI-11B and PAI-12
  4. Non-detects are assumed to have concentrations of half the reporting limit (RL), for contouring purposes. Map posts non-detects as < 1/2RL.
  5. Areas not shaded in the shoreline cross section are interpreted to have benzene concentrations below the screening level.
  6. Benzene upland groundwater screening level = 43 ug/L
  7. Wells MW-41S through MW-52D are not shown because they were installed in 2017, several years after the sampling events presented in this figure. The new wells were installed for the arsenic groundwater treatment interim action and have not been sampled for benzene.
  8. Projection: NAD 1983 StatePlane Washington North FIPS 4601 Feet

- Legend**
- Detected Concentration
  - Non-Detect Concentration, 1/2 Reporting Limit
  - Ground Surface Elevation
  - April 14, 2013 Groundwater Elevation (21.6 ft)
  - Fill/Outwash Contact
  - Top of Till

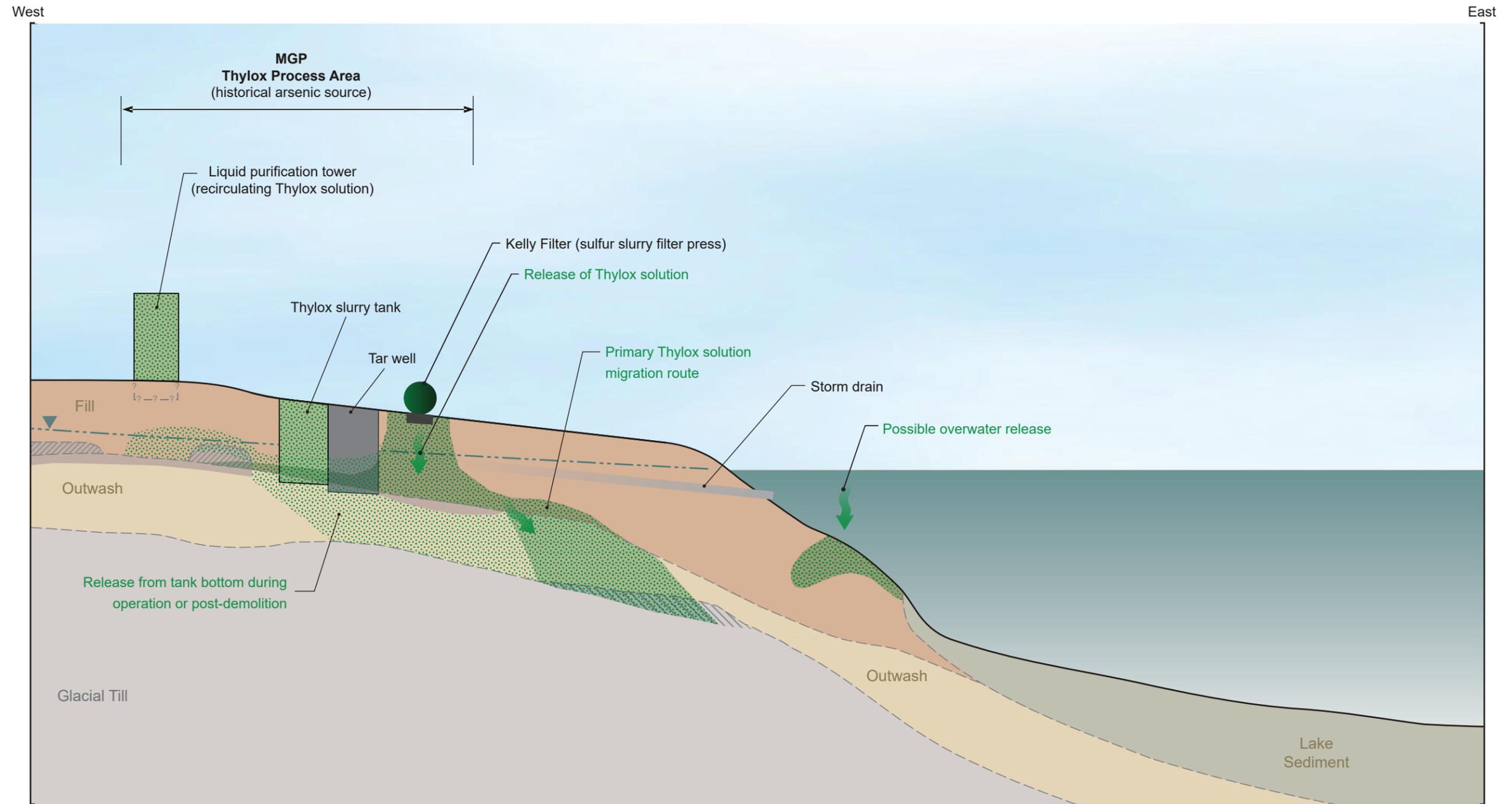
- Maximum Benzene Concentration (µg/L)**
- < 5
  - 5 - 43
  - 43 - 100
  - 100 - 1,000
  - > 1,000
- Benzene Flux (mg/ft<sup>2</sup> per day)**
- 0 to 0.01
  - 0.011 to 0.1
  - 0.101 to 1
  - > 1



**Shoreline Groundwater Benzene Concentrations and Flux**

Gas Works Park Site  
Seattle, Washington

GEOENGINEERS **Figure 6A-7**



**Legend**

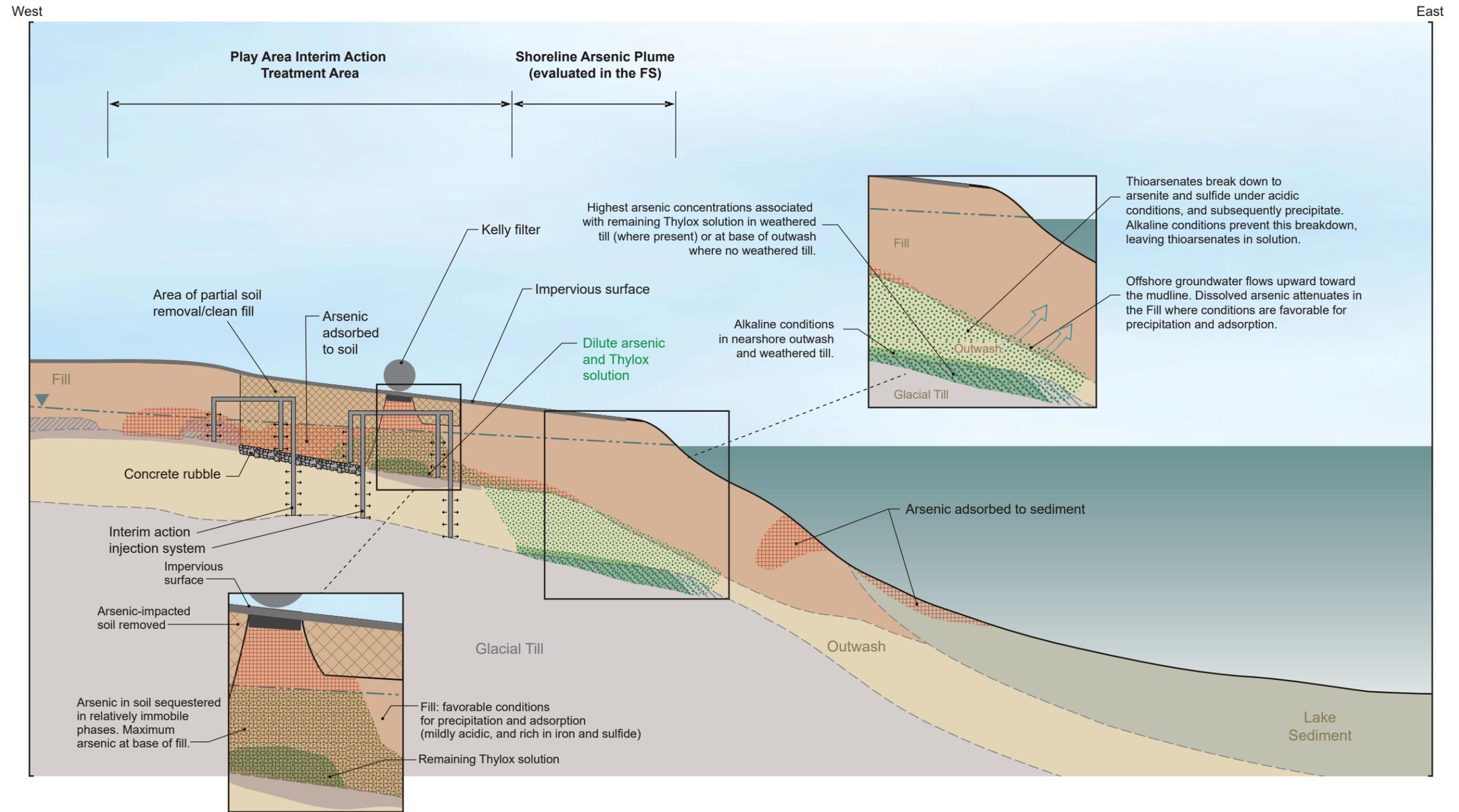
- |  |                   |  |                    |  |                        |
|--|-------------------|--|--------------------|--|------------------------|
|  | Thylox Solution   |  | Native Clay/Silt   |  | Glacial Till           |
|  | Dissolved Arsenic |  | Reworked Clay/Silt |  | Weathered Glacial Till |

**Historical CSM -  
Arsenic Release and Transport  
Mechanisms and Pathways**

Gas Works Park Site  
Seattle, Washington



**Figure 6A-8**



**Legend**

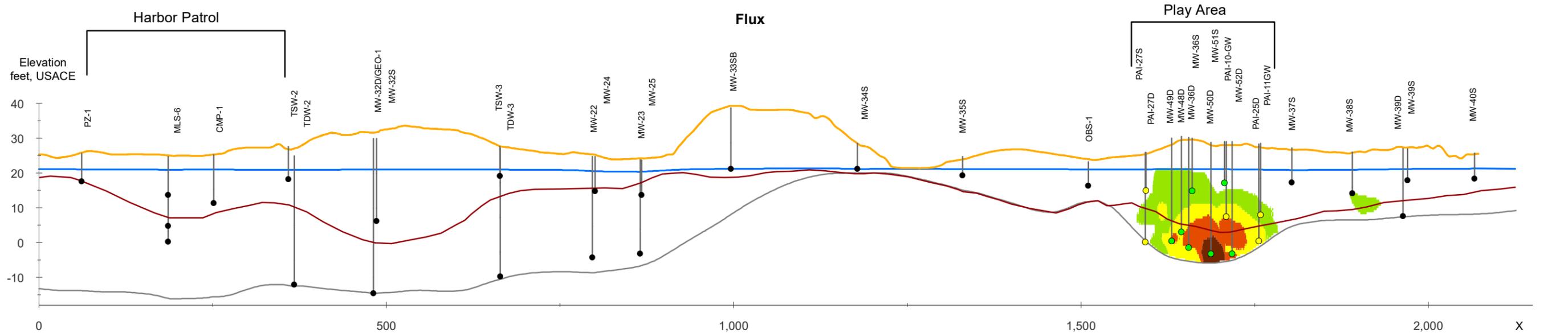
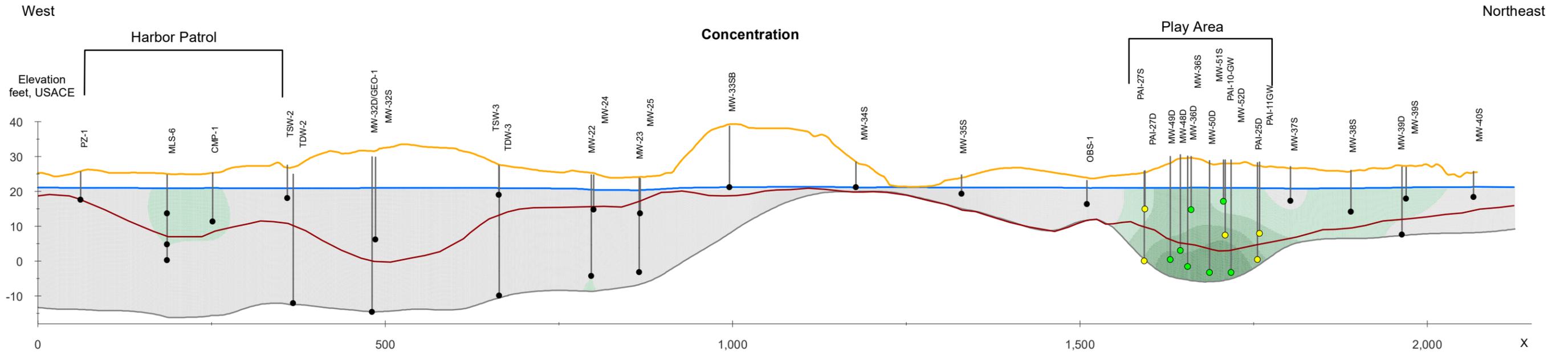
-  Remaining Thylox Solution
-  Native Clay/Silt
-  Glacial Till
-  Dissolved Arsenic
-  Reworked Clay/Silt
-  Weathered Glacial Till
-  Arsenic in Soil/Sediment

**Current CSM -  
Arsenic Release and Transport  
Mechanisms and Pathways**

Gas Works Park Site  
Seattle, Washington



**Figure 6A-9**



Path: P:\010186846\GIS\VIEW\MXD\018684601\_F6A-10\_Shoreline\_ArsenicConcentrationsFlux Map Revised: 11 June 2020 glhmmeyer | 9/21/2022 spride

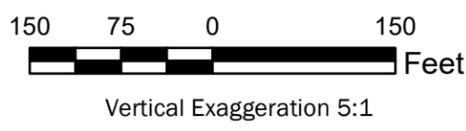
**Notes:**

- 1.\*8 ug/L = Natural background groundwater concentration for the Puget Sound Basin (Ecology 2022)
2. Concentration contours reflect dissolved concentrations.
3. Concentration contours generated using CTech's Earth Volumetric Studio Kriging interpolation method. Reach=1000, Anisotropy=5, Nugget=0.
4. Groundwater results from October 2013, December 2014, September/October 2016 and February 2018 were chosen for mapping. 2018 samples analyzed by method SW6010C lab filtered non-preserved. Previous samples analyzed by method SW6010C field filtered preserved with HNO3. See Section 5 for a discussion of why these data sets were selected.
5. Areas not shaded in the shoreline cross section are interpreted to have arsenic concentrations below the screening level.
6. Although arsenic is not a groundwater contaminant of concern, concentrations were screened against 8 mg/L.
7. Projection: NAD 1983 StatePlane Washington North FIPS 4601 Feet

DISCLAIMER: This drawing is for information purposes. It is intended to assist in showing features discussed in an attached document. GeoEngineers, Inc. can not guarantee the accuracy and content of electronic files. The master file is stored by GeoEngineers, Inc. and will serve as the official record of the communication.

- Legend**
- Monitoring Well
  - Interim Action Performance Monitoring Well
  - Temporary Well
  - Ground Surface Elevation
  - April 14, 2013 Groundwater Elevation (21.6 ft)
  - Fill/Outwash Contact
  - Top of Till

- Maximum Arsenic Concentration (µg/L)**
- ≤ 8\*
  - > 8 to ≤ 50
  - > 50 to ≤ 500
  - > 500 to ≤ 5,000
  - > 5,000
- Arsenic Flux (mg/ft² per day)**
- 0 to 0.01
  - 0.011 to 0.1
  - 0.101 to 1
  - 1.01 to 10
  - > 10



**Shoreline Groundwater Arsenic Concentrations and Flux**

Gas Works Park Site  
Seattle, Washington

GEOENGINEERS **Figure 6A-10**