APPENDIX 11A

Integral Dredgeability Evaluation Tech Memo

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DRAFT MEMORANDUM

To:	Dan Baker, Chris Bailey
From:	Integral Consulting Inc.
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Subject:	Gas Works Park Soft Sediment Dredgeability Assessment
Project No.:	C1454

This memorandum presents an assessment of the potential presence of fluid mud and very soft sediments and related feasibility considerations for dredging within the Gas Works Park site (Site). To support this assessment, this memorandum begins with an introduction of the properties of fluid mud and very soft sediment, discusses the dredgeability of these materials with conventional mechanical equipment, and provides a focused analysis of relevant site-specific data provided by GeoEngineers.

PROPERTIES OF FLUID MUD AND VERY SOFT SEDIMENT

Similar to geotechnical description of soil, the relative consistency of cohesive sediment may be described according to degree of firmness, by the terms “fluid”, “very soft”, “soft”, “medium”, “stiff”, “very stiff”, and “hard”.

Fluid sediment, referred to herein as fluid mud, describes the condition where cohesive sediment has immeasurably low shear strength and will not stand without lateral confining pressure, exhibiting a fluid-like behavior (USACE 2015). Fluid mud is a high concentration aqueous suspension of fine-grained sediment in which settling is substantially hindered by the proximity of sediment grains and flocs, but which has not formed an interconnected matrix of bonds strong enough to eliminate the potential for mobility, leading to a persistent suspension (McAnalley et al. 2007). Key general characteristics of fluid mud are summarized in Table 1. These characteristics include low *in situ* density, moisture content well above the liquid limit, low to high plasticity, high organic content, very low to extremely low undrained shear strength (S_u), and unmeasurable unconfined compressive strength (USACE 2015).

Very soft cohesive sediments can also be characterized based on standard penetration test (SPT) data and undrained shear strength (Table 2). Typical saturated unit weights for a variety of silts and clays and organic silts and clays are presented in Table 3.

Common techniques for identification of fluid and very soft sediment conditions include a variety of physical measurements to evaluate sediment density including acoustic speed and attenuation, electrical resistivity, electromagnetic, optical, and nuclear methods (McAnalley et al. 2007). Acoustic methods are commonly employed to investigate fluid mud in channels during nautical depth surveys (Buchanan 2005).

DREDGEABILITY OF FLUID MUD AND VERY SOFT SEDIMENT

The U.S. Army Corps of Engineers (USACE) provides guidance and associated software ("DREDGABL") to aid preliminary evaluations of sediment dredgeability. USACE considers the following excavation properties in evaluating dredgeability with mechanical dredges (Spigolon 1993):

- **Cuttability**: the relative ease with which sediment can be excavated by shearing with a blade, knife, or plow. This property is a direct function of the *in situ* shear strength of the material, which, in turn, is directly affected by *in situ* density, degree of saturation, grain size distribution, clay content, and clay mineral type (reflected in the Atterberg limits). This property is also affected by surrounding conditions, hydrostatic pressures, and friction with the cutting surface.
- **Flowability**: the underwater slope stability. This property is a function of sediment particle cohesion and can be used to predict whether the material will experience slope failure and potentially be mobilized (i.e., flow into the excavated area) during dredge cuts.
- **Scoopability**: the ability to dislodge the sediment with a cutting edge. Scoopability is governed by *in situ* shear strength, grain size distribution, percent fines, plasticity, and adhesion to the cutter.
- **Scourability**: the erodibility of the material. Scourability is governed by *in situ* shear strength, particle cohesion, and plasticity. A relatively loose fine-grained material free of cohesive fines can be easily scoured.

The USACE DREDGABL assessment of mechanical dredgeability based on the above properties reveals that a clamshell dredge is not suitable for use with fluid mud. Because of its fluid-like properties, fluid mud will either be displaced by the pressure wave induced by the motion of the bucket, or will otherwise not retain its shape in the bucket and will overflow and spill out. The challenge presented by dredging amorphous sediment could potentially be reduced using a closing environmental clamshell, although environmental clamshells have not been proven to be effective for fluid mud conditions and are not exempt from concerns regarding pressure wave displacement of sediment. For very soft sediment having low plasticity (Table 2), a clamshell dredge may be suitable for cutting; however, it would be subject to the potential problems further discussed below including wash-out and residuals. Table 4 presents the detailed results from the USACE DREDGABL software.

Although mechanical clamshells may be suitable for cutting and scooping very soft material, there are subsequent issues that may present significant challenges in the remediation of contaminated very soft sediments. Very soft sediment fines may wash or run out of the bucket because of their fluid-like properties and generate residuals (Spigolon 1993). If an environmental (closing) bucket is used, this phenomenon is particularly problematic in the presence of debris, which could prevent the bucket from completely closing and allowing fines to run out of the bottom. Similar to fluid mud conditions, very soft sediments may be disturbed and re-suspended simply due to the raising and lowering of the bucket. Sediment resuspension and redistribution within, and possibly beyond the removal limits, would further exacerbate water quality and ecological impacts.

Another potential concern is slope instability and the sloughing of surrounding soft sediments into the dredge prism during dredging activities. This problem is exemplified by experience at United Heckathorn Superfund site in Richmond, California (CH2M Hill 2015). During remedy implementation at this site, soft sediment beneath adjacent piers sloughed into the dredged portions of the channel (Kohn 1998). Subsequent reinvestigation of the channel indicated that recontamination of sediments was likely due to soft sediment residuals generated during dredging (CH2M Hill 2015).

HANDLING AND TRANSPORT

In addition to affecting the feasibility of dredging, very soft or fluid-like material will present significant challenges to handling and transport of contaminated material that must be considered in the feasibility evaluation of remedial technologies. Typical ancillary technologies used with dredging include dewatering, stabilization, and truck or rail transport for offsite disposal.

If there is a high water content entrained in the contaminated dredged material, the material may be handled slowly (i.e., by removing the material from barge scows) or require specialized equipment (e.g., hydraulic slurry pumps.) Sediment would likely require dewatering (e.g., mechanical filter press, geotubes, etc.) and/or stabilization (flyash, cement, or other additives) to remove free water to a consistency that is acceptable for truck or rail transport. A treatability study may be required during remedial design to fully evaluate material management techniques for very soft sediments.

SITE-SPECIFIC EVALUATION

To support the feasibility evaluation of dredging within the Site, available geotechnical data was compared against the criteria summarized above (Tables 1 and 6) to identify conditions indicative of very soft sediment and fluid mud.

Data Sources

To facilitate this evaluation, site-specific data from multiple remedial investigation studies conducted at the Site were provided by GeoEngineers. Key data reports include the Site-Wide Remedial Investigation Report, Appendix H "Geotechnical Engineering" (GeoEngineers 2014) and the Gas Works Sediment Western Study Area Data Report (FSC 2005). In addition, pertinent SPT data were evaluated from Figures 2, 4, and 6 of the Eastern Study Area Remedial Investigation/Feasibility Study (RI/FS) (RETEC 2006).

The supplied geotechnical engineering data included grain size distributions, moisture content, Atterberg limits, organic content, consolidation tests results (including void ratio), and density or unit weight. For this evaluation, *in situ* density, or unit weight, is referred to as saturated unit weight.

Undrained shear strength data were provided for both the Eastern and Western study areas, including unconfined, undrained triaxial (UU) tests cone penetrometer test (CPT) and vane shear test (VST) measurements. CPT and VST report undrained shear strength on an effective stress basis, whereas UU tests represent undrained shear strength on a total stress basis. Because of the extremely low undrained shear strength values, UU test data were directly compared with the CPT and VST undrained shear strength data.

SPT data were available at selected locations and depths in the Western Study Area and are also summarized in terms of relative consistency. SPT data are useful in determining relative density of sediments as well as their relative consistency. For the Eastern Study Area samples, available SPT blow counts were generalized for the entire boring and were reported as one of three categories: 5 blows/ft, 20 blows/ft, or < 60 blows/ft (RETEC 2006).

This evaluation focused on locations where CPT, VST, SPT, and UU tests were conducted. These test locations typically included other geotechnical index properties. Available index properties from neighboring borings in near proximity to CPT, VST, SPT, and UU test locations were also considered.

In addition, supporting *in situ* measurements and observations included soft sediment probing results (RETEC 2006; Figures 3-7 and Figure 4-8). These data (soft sediment probe penetration depths) were used in a rough correlation of probe penetration with evidence of fluid mud or very soft sediment conditions in the geotechnical data. Associated video footage showing divers at the bottom of Lake Union were reviewed to develop a general sense of the sediment consistency. Particular attention was given to video segments where divers manually sampled sediment.

Results

Boring locations having suspected fluid mud and/or very soft sediment (Table 5) were identified based on a comparison between available geotechnical data and the criteria summarized in Tables 1 and 6. The available grain size distribution data indicate the sediments with properties indicative of fluid mud and/or very soft sediment consist of silts and clays and are located within a unit classified geologically as recently deposited lacustrine sediments (RETEC 2006).

Atterberg Limits

Atterberg limit tests indicate that the sediment from the selected samples range from non-plastic to highly plastic. Four Atterberg limit tests were available from the Eastern Study Area, in which sediments ranged from non-plastic to highly plastic. These sediments were classified as highly plastic organic silts (OH) according to the Unified Soil Classification System (USCS). Nineteen Atterberg limit tests were available from the Western Study Area. These results indicate sediments ranging from low plasticity to high plasticity clays and organic clays and silts. The vast majority of the samples presented in Table 5 yielded liquid limits >50, indicating potential presence of fluid mud or very soft sediment according to the criteria presented in Table 1.

Moisture Content

Moisture content is extremely high to depths up to 30 ft below the mud line (BML); decreasing with increasing depth in both Eastern and Western study area sediments. The RETEC investigation (RETEC 2006) indicated that the moisture content of the samples appears to range from 41 to 880 percent. The average moisture content for all samples evaluated was 436 percent and ranged from 9.2 to 881 percent. Moisture content exceeding 800 percent was noted for only two of the 53 samples evaluated. Measured moisture content was at least two times greater than the measured liquid limit for all but six samples where Atterberg limits were tested, indicative of fluid mud conditions (USACE 2015; Table

1). Samples where moisture content was less than two times greater than the liquid limit were obtained from sediment at relatively greater depth, ranging from 6 to 65 ft BML.

Unit Weight

The saturated unit weight of the sediment samples is very low, albeit somewhat variable, for both the Eastern and Western study Areas (Table 5). Typical unit weights for fluid mud vary from approximately 72 to 75 lb/ft^3 (McAnally et al. 2007; Table 1), while the unit weight of very soft clay can approach 130 lb/ft^3 (Table 3). The minimum, maximum, and average saturated unit weights at the Site are 11, 132, and 69 lb/ft^3, respectively. There were only two instances where both the saturated and dry unit weights exceeded 100 lb/ft^3. The minimum, maximum, and average dry unit weights were 6, 114, and 27 lb/ft^3, respectively. These extremely low unit weights are only slightly greater than that of water, 62.4 lb/ft^3, another indicator of fluid mud or a fluid mud-like material.

Organic Content

Organic content for sediments is considered to be high when greater than 20 percent (ISO 2002) and is another characterization criterion for fluid mud (Table 1). For the samples exhibiting potential characteristics of fluid mud and/or very soft sediment, organic content ranged 14 to 45 percent (Table 5). There does not appear to be a trend between the organic content and depth, at least for the locations analyzed.

Undrained Shear Strength

The CPT, VST, and UU test data reveal perhaps the most significant findings in this evaluation in that there appears to be extremely low undrained shear strength, S_u, in the majority of the uppermost sediments for the locations analyzed in both the Eastern and Western study areas. Table 5 summarizes the CPT, VST, and UU test data evaluated. For comparison purposes, Table 6 presents undrained shear strength data for soft clays.

In general, the undrained shear strength increases with increasing depth. For instance, in the Eastern Study Area, sampling location NLU407 appears to have an undrained shear strength that varies from 0 to 490 lb/ft^2 from 0 to 7 ft and 490 to 8,000 lb/ft^2 from 14.7 to 17.8 ft BML. Similarly, GWS-VS-04 in the Western Study Area reveals an undrained shear strength of 62 lb/ft^2 at 1 ft BML to 178 lb/ft^2 at 13 ft BML. Similar patterns are seen in all of the CPT, VST, and UU test data for both the Eastern and Western study areas.

Also, it appears that the undrained shear strength increases at shallower depths in areas closer to the shoreline. For instance, in the Eastern Study Area, NLU400 shows a change in undrained shear strength from 40 to 3,200 lb/ft^2 between 2.5 and 4.9 ft BML. Similarly, in the Western Study Area, GWS-GC02 shows undrained shear strength of 350 lb/ft^2 at only 1 ft BML. It appears that the lowest undrained shear strengths were recorded at locations corresponding to the areas of deep water where soft sediment thicknesses were greater than 12 ft in prior studies and where other *in situ* tests (i.e., disc probing) did not indicate a competent sediment–water interface (NLU415, NLU420, NLU416, NLU419, NLU407, GWS-GC/VS/CPT-04, GWS-GC/VS/CPT05).

The SPT data correlate with the CPT and VST measurements in the Eastern Study Area. In regions of suspected fluid mud and very soft sediment observations and thicknesses, "no blow counts are available for this unit as the sampler free fell through the sediment" (RETEC 2006). Blow counts also increase with increasing depth from the mudline. Figure 2 (RETEC 2006) shows that the depth to an SPT blow count of 5 blows/ft occurs at depths of 16 and 20.64 ft BML for locations NLU402 and NLU420, respectively. These depths BML correlate to higher undrained shear strength > 1,000 lb/ft^2 with CPT data measured in these depth ranges. However in some study areas, including the Eastern Study Area where disc probe penetration was >12 ft, blow counts remain low throughout the top 10 ft or so of the sediment column, indicating soft sediment or fluid mud thickness increases with increasing distance from the shoreline.

The SPT data indicate that blow counts decrease significantly with increasing distance from the shoreline. For example, in the Eastern Study Area, a blow count of only 5 occurs from approximately 2 to 8 ft BML in a sample collected within the slope area, and in generally shallow water depth. In the Western Study Area, a relatively low blow count of 19 was measured in a shallow water depth sample at 4 ft BML, and blow counts remained low through 51 ft BML in this sample. Blow counts from regions closest to the shore indicate denser sediments.

The majority of the undrained shear strength measurements reveal extremely low undrained shear strength. The undrained shear strength result of < 209 lb/ft^2 is the most common characterization of strength in the data set and is also one of the criteria for fluid mud (Table 1).

In Situ Testing—Sediment Probes and Diver Videos

A disc probe may be used to determine the sediment–water interface in highly organic, soft material where typical conical probe points may not provide enough surface area to generate adequate force for the prober to feel the interface (Cooke et al. 1986). The soft sediment disc probing at the Site may reveal important observations of fluid-like material and roughly correlates with undrained shear strength, as discussed above. Figures 3-7 and Figure 4-8 (RETEC 2006) indicate that a rod with a 6 in. circular plate was pushed into the sediments by the diver until refusal. Results indicate that the probe was able to be pushed to a depth ranging from 0 ft to greater than 12 ft. The probe penetration exceeding its entire probe length of 12 ft is shown in the "Soft Sediment > 12 ft Thick" in Figure 4-8 (RETEC 2006). The ability of the diver to push the disc probe to its entire length likely indicates fluid, or very soft sediment conditions. In this evaluation, the ability to easily push the disc probe to significant depth roughly correlates with extremely low strength in Eastern Study Area samples and may be indicative of fluid mud.

In addition, diver videos appear to show soft sediments that the diver can easily reach his entire hand into without any apparent resistance. As the diver releases the sediments, the majority of the sediments remain in suspension in the water making the water turbid and having the appearance of fluid mud.

Conclusions and Recommendations

Geotechnical index properties presented in Table 5 reveal characteristics of fluid mud and very soft sediments. Soils were observed to have extremely high moisture content, far greater than the liquid limit. In addition, sediment appeared to have a low density and high total organic carbon where the average saturated unit weight was 69 lb/ft^3. This average unit weight is similar to the fluid mud range of 72–75 lb/ft^3 (Table 1), is similar to the unit weight of water, and indicates fluid mud or fluid mud-like material. Lastly, Atterberg limits revealed sediments to be non-plastic to highly plastic, which is another fluid mud criterion used in this evaluation.

The CPT and VST data indicate clay sediment types that display either very soft sediment or possibly fluid mud characteristics. As previously noted, the CPT and VST data reveal undrained shear strength much lower than the defined criterion for very soft sediment (Table 1) from approximately 4.5 ft BML in the slope area to 20 ft BML in the deeper, flat areas.

Field measurements and observations such as low to zero resistance from the sediment probe and the inability to record SPT are also good indicators of fluid mud or very soft sediments.

The geotechnical engineering data appear to support the observation that very soft sediments and likely fluid mud appear to exist in the lacustrine sediments at Lake Union. Deeper water, flat areas appear to have the greatest thickness of very soft sediments or fluid mud; potentially up to 20 ft in certain areas. The available evidence indicates potential deposits of very-soft sediments or fluid mud in shallower water slope areas, albeit at lesser thickness than deeper areas. The region closest to the shoreline adjacent to the Site appears to have firmer sediments (Figure 1).

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FIGURE

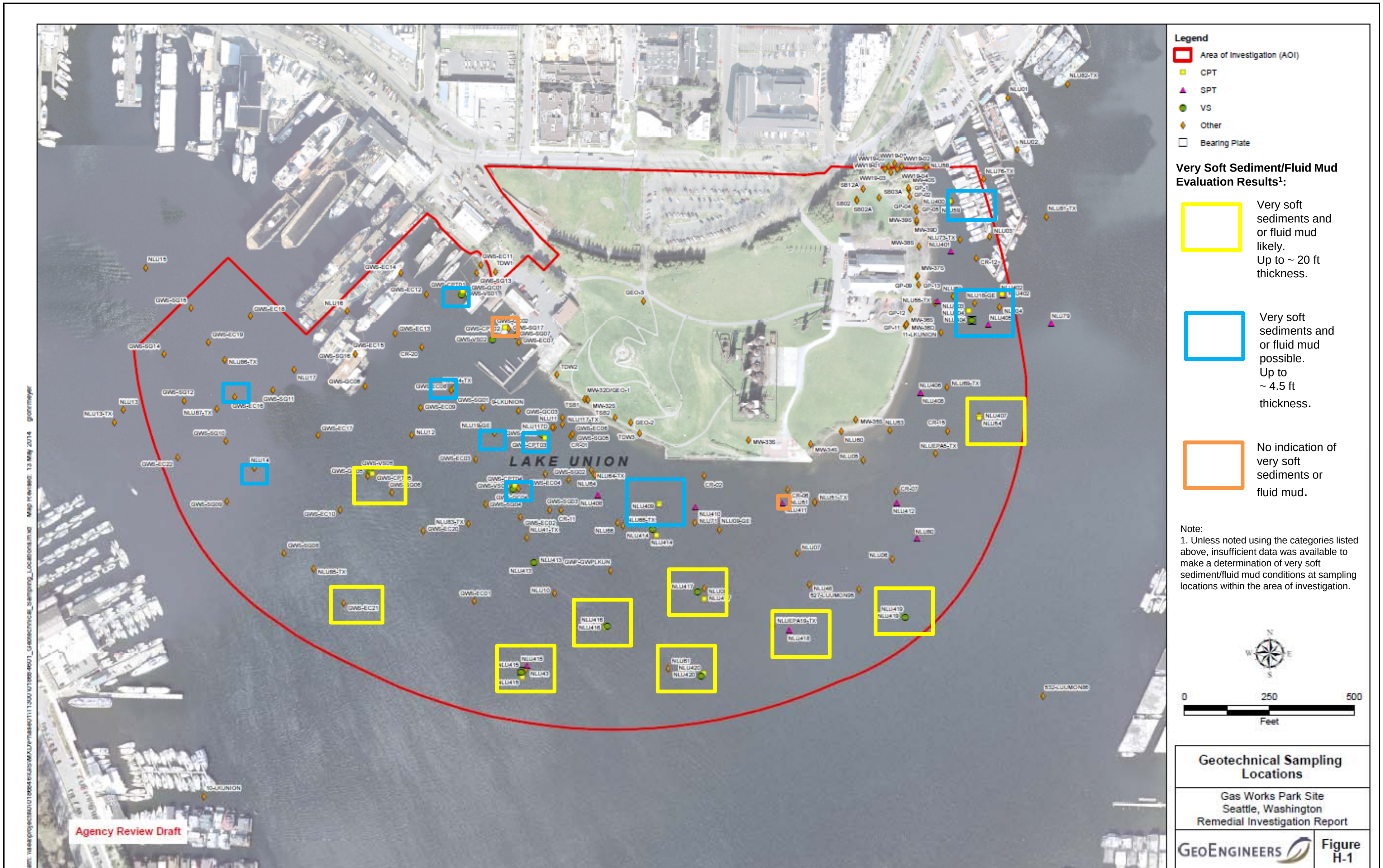

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Figure 1.
Potential Locations of Very Soft Sediment and/or Fluid Mud

TABLES

Table 1. Fluid Mud Characteristics

Parameter	Comment	Value
Density / Unit Weight	Low in-situ density/unit weight.	72 - 75 lb/ft^3 [a]
Moisture Content, *w* (%)	Very high moisture content well above the liquid limit, *LL.*	*w* >> *LL*
Atterberg Limits	Low to high plasticity	*LL* : [b] < 30 to > 50
Organic Content, Soils (% of dry mass)	High organic content	> 20 % [c]
Undrained Shear Strength, S_u	Very low to extremely low S_u	209 - 417 lb/ft^2 [c] to < 209 lb/ft^2
Unconfined Compressive Strength (lb/ft^2)	Unmeasurable	--

Notes:

[a] McAnalley et al. (2007)

[b] Terzaghi and Peck (1948)

[c] ISO (2002)

[d] USACE (2015)

Table 2. Geotechnical Test Data and Relative Consistency

Relative Consistency	SPT Data: (blow count: blows/ft) with Varying Plasticity[a] Avg. Plasticity (LL ≈ 40)	Low Plasticity (LL < 30)	Medium Plasticity (30 ≤ LL ≤ 50)	High Plasticity (LL > 50)	Undrained Shear Strength, S_u [b] (lb/ft^2)
Very soft	0 - 2	0 - 3	0 - 2	0 - 1	< 250
Soft	2 - 4	3 - 7	2 - 3	1 - 2	250 - 500
Medium	4 - 8	7 - 13	3 - 7	2 - 4	500 - 1000
Stiff	8 - 15	13 - 27	7 - 13	4 - 8	1000 - 2000
Very stiff	15 - 30	27 - 53	13 - 27	8 - 16	2000 - 4000
Hard	> 30	> 53	> 27	> 16	> 4000

Notes:

LL = liquid limit

SPT = standard penetration test

[a] Terzaghi and Peck (1948)

[b] Coduto (2001)

Table 3. Unit Weights of Clays

	Unified Soil Classification System (USCS)	Typical Unit Weights (Saturated) lb/ft^3 [a]
Low plasticity silts	ML	80 - 130
High plasticity silts	MH	75 - 130
Low plasticity clays	CL	75 - 130
High plasticity clays	CH	70 - 125
Organic silts	OH	87 - 131
Organic clays	OH	81 - 125

Notes:
CL = Inorganic clays of low to medium plasticity, gravelly, sandy, and silty clays.
CH = Inorganic clays of high plasticity, fat clays and sandy clays.
MH = Inorganic silts, micaceous or diatomaceous silty soils, elastic silts.
ML = Inorganic silts, clayey silts of low to medium plasticity.
OH = Organic silts and clays of high plasticity, sandy organic silts and clays.

[a] Coduto (2001)

Table 4. USACE DREDGABL Software Detailed Output: Mechanical Clamshell with Fluid Mud and Very Soft Sediment

Relative Consistency Term	Suitability of Mechanical Clamshell Dredge	Cuttability	Flowability	Scoopability	Scourability
Fluid mud	NOT SUITABLE: fluid will overflow bucket.	Not applicable: extremely low shear strength.	Not applicable: behaves like fluid; flows easily.	Not applicable: Behaves like fluid; very easy scooping.	Not applicable: extremely low shear strength.
Very soft sediment[a]	Easy digging; fines may wash out	Very high: easy cutting; low cohesive strength	High: small height if extremely soft or fluid	Very high: some suction; possible loss of fines	Medium to high: optimum size; depends on consistency

Notes:

USACE = U.S. Army Corps of Engineers

[a] Very soft sediment properties defined by USACE: low strength (zero to 0.25 tons/SF) organic silt with sand or gravel with low plasticity (index less than 22).

Table 5. Geotechnical Test Data Results for Selected Sediment Samples

Boring No.	Water Depth (ft)	Total Measured Depth (ft)	Measured Sediment Thickness (ft)	Depth BML (ft) From	Depth BML (ft) To	Unit Weight, $\gamma(\rho)$ (lb/ft^3) Saturated	Unit Weight, $\gamma(\rho)$ (lb/ft^3) Dry	Moisture Content (%)	Void Ratio, e Initial	Void Ratio, e Final	Organic Matter (%)	Atterberg Limits LL (%)	Atterberg Limits PL (%)	Atterberg Limits PI (%)	Atterberg Limits USCS Soil Type	Atterberg Limits Plasticity	SPT Blows / ft	Relative Consistency from SPT Data	Undrained Shear Strength, S_u (lb/ft^2) CPT From	CPT To	VST Peak	VST Residual	UU	Strength Range	Geotechnical Engineering Properties Indicative of Very Soft Sediments and/or Fluid Mud
Eastern Study Area																									
NLU400	9.5	14.4	4.9	0.0	1.5														5.6	10.8				Extremely low	Extremely low S_u (<< 209 lb/ft^2) from 0 to 4.9 ft BML
				2.5	4.9														40.0	3200.0				Extremely low	
NLU402	37.8	51.4	13.6	0.0	2.0														0.1	8.0				Extremely low	Extremely low S_u (<< 209 lb/ft^2) from 0 to 10 ft BML.
				2.0	3.0			265.4				79.0	69.4	9.6	OH	High			31.0	60.0				Extremely low	Very high moisture content, low sat. unit weight, and
				3.0	5.0	68.2	17.8	238.1	7.8	5.0	19.9	-	-	-	-				60.0	71.0				Extremely low	high organic matter from 0 to 10 ft BML.
				8.0	10.0	66.1	8.3	700.0			31.5								151.2	1446.0				Extremely low	Moisture content >> LL from 2 to 3 ft BML.
				10.0	13.6														1446.0	1190.0					
				16.0	17.0												5 (16 ft BML)								
NLU18-GE				0.0	2.0	67.1	13.6	393.6	7.4	5.1		NA	NA	NA	NP	-							13.5	Extremely low	Extremely low S_u (<< 209 lb/ft^2) and very high moisture
				2.0	3.0	89.8	20.0	349.0	7.1	5.6		79.0	69.4	9.6	OH	High									content, low sat. unit weight, and high void ratio from 0
				3.0	4.0	128.2	105.7	21.3, 292	5.0	4.0		NA	NA	NA	NP	-							11.3	Extremely low	to 3 ft BML.
				4.0	5.0	131.9	114.3	15.4, 16	0.5	0.5							5 (10 ft BML)						46.0	Extremely low	
NLU404	35.5	42.5	7.0	0.0	0.5														18.2	19.8	16.0	5.0		Extremely low	Extremely low S_u (<< 209 lb/ft^2) from 0 to 4.5 ft BML
				0.5	2.5														19.8	67.6	50.0	20.0		Extremely low	
				2.5	3.0							79.0	69.4	9.6	OH	High			67.6	21.0				Extremely low	
				3.0	4.5														21.0	625.0				Extremely low	
				4.5	5.7												5 (7 ft BML)		625.0	2367.0					
NLU405	-	-	-	1.0	2.5			382.1																	Very high moisture content and high organic matter
				2.5	3.0			471.1																	from 0 to 5 ft BML.
				3.0	5.0			548.5			27.9						5 (3 ft BML)								
NLU409	24.9	31.7	6.8	0.0	0.5														0.0	1.8				Extremely low	Extremely low S_u (<< 209 lb/ft^2) from 0 to 6.8 ft BML.
				0.5	2.6														1.8	4.9				Extremely low	
				2.6	2.8														4.9	257.7				Extremely low	
				2.8	6.8												5 (4 ft BML)		257.7	18263.0					
NLU407	40.3	17.8	22.4	0.0	1.5														0.0	16.0				Extremely low	Extremely low S_u (<< 209 lb/ft^2) from 0 to 14.7 ft BML.
				1.5	7.0														16.0	44.0				Extremely low	
				7.0	14.7														44.0	490.0				Extremely low	
				14.7	17.8												5 (18 ft BML)		490.0	8000.0					
NLU414	-	-	-																		40.0	10.0			Extremely low S_u (<< 209 lb/ft^2)
NLU413	40.1	50.2	10.1	0.0	0.9														0.0	10.9	15.0	6.0		Extremely low	Extremely low S_u (<< 209 lb/ft^2) from 0 to 8.9 ft BML.
				0.9	2.9														10.9	46.7	35.0	13.0		Extremely low	
				2.9	4.9														46.7	64.8	50.0	20.0		Extremely low	
				4.9	6.9														64.8	92.0	56.0	22.0		Extremely low	
				6.9	8.9														92.0	109.0	65.0	30.0		Extremely low	
				8.9	20.8												5 (21 ft BML)		109.0	334.0					
NLU418-GE	-	-	-	3.0	5.0	56.2	6.0	837.0	23.4	13.2	34.9														Very high moisture content, high void ratio, and low
				6.5	8.5			699.8			32.5						5 (10 ft BML)								density from 3 to 8.5 ft BML.
NLU417	40.8	50.2	9.4	0.0	1.2														0.0	3.2	16.0	8.0		Extremely low	Extremely low S_u (<< 209 lb/ft^2) from 0 to 8.7 ft BML.
				1.2	3.2														3.2	41.2	30.0	10.0		Extremely low	
				3.2	5.2														41.2	60.0	35.0	16.0		Extremely low	
				8.0	8.7														181.0	534.0				Extremely low	
				8.7	9.0												5 (10 ft BML)		534.0	1559.0					
NLU419	39.5	63.3	23.8	0.0	0.5						45.5								0.0	4.5	15.0	8.0		Extremely low	Very high organic matter from 0 to 0.5 ft BGL.
				0.5	2.5														14.6	35.5	27.0	12.0		Extremely low	Extremely low S_u (<< 209 lb/ft^2) from 0 to 16.3 ft BML.
				2.5	4.5														35.0	96.0	45.0	20.0		Extremely low	
				4.5	6.5														96.0	116.8	65.0	25.0		Extremely low	
				6.5	8.5														116.8	101.8	70.0	25.0		Extremely low	
				8.5	16.3												5 (14 ft BML)		101.8	1553.0					
NLU415	39.5	62.2	22.7	0.0	0.5	80.3	31.0	159.0	4.0	2.7	14.0								3.6	4.5	9.0	4.0		Extremely low	Low sat. unit weight and high void ratio from 0 to 0.5 ft
				0.5	2.5						14.0								4.5	15.9	30.0	10.0		Extremely low	BML.
				2.5	4.5			778.7			33.0								15.9	57.5	45.0	20.0		Extremely low	Very high organic matter from 0 to 4.5 ft BGL.
				4.5	5.5			706.5											57.5	77.7				Extremely low	Extremely low S_u (<< 209 lb/ft^2) from 0 to 22.7 ft BML.
				5.5	6.5			704.9											77.7	74.2	42.0	22.0		Extremely low	Very high moisture content from 0 to 22.7 ft BML.
				6.5	8.5														74.2	87.3	75.0	28.0		Extremely low	
				8.5	10.0			706.5											87.3	82.5				Extremely low	
				10.0	22.7			577.8									5 (>15 ft BML)		82.5	116.0				Extremely low	

Table 5. Geotechnical Test Data Results for Selected Sediment Samples

Boring No.	Water Depth (ft)	Total Measured Depth (ft)	Measured Sediment Thickness (ft)	Depth BML (ft) From	Depth BML (ft) To	Unit Weight, $\gamma(\rho)$ (lb/ft^3) Saturated	Unit Weight, $\gamma(\rho)$ (lb/ft^3) Dry	Moisture Content (%)	Void Ratio, e Initial	Void Ratio, e Final	Organic Matter (%)	Atterberg Limits LL (%)	Atterberg Limits PL (%)	Atterberg Limits PI (%)	Atterberg Limits USCS Soil Type	Atterberg Limits Plasticity	SPT Blows / ft	Relative Consistency from SPT Data	Undrained Shear Strength, S_u (lb/ft^2) CPT From	CPT To	VST Peak	VST Residual	UU	Strength Range	Geotechnical Engineering Properties Indicative of Very Soft Sediments and/or Fluid Mud
Eastern Study Area (continued)																									
NLU416	40.7	59.2	18.5	0.0	1.3														0.0	4.7	18.0	6.0		Extremely low	Extremely low S_u (<< 209 lb/ft^2) from 0 to 18.5 ft BML.
				1.3	3.3														4.7	34.9	34.0	11.0		Extremely low	
				3.3	5.3														34.9	60.0	46.0	19.0		Extremely low	
				5.3	7.3														60.0	100.0	58.0	24.0		Extremely low	
				7.3	9.3														100.0	67.6	68.0	30.0		Extremely low	
				9.3	18.5												5 (19 ft BML)		67.6	74.2				Extremely low	
NLU420	42.0	62.2	20.2	0.0	1.0														0.0	10.5	11.0	6.0		Extremely low	Extremely low S_u (<< 209 lb/ft^2) from 0 ot 20.0 ft BML.
				1.0	3.0														10.5	21.7	33.0	13.0		Extremely low	
				3.0	5.0														21.7	71.2	42.0	20.0		Extremely low	
				5.0	7.0														71.2	92.0	58.0	25.0		Extremely low	
				7.0	9.0														92.0	98.0	70.0	28.0		Extremely low	
				9.0	20.0												5 (21 ft BML)		98.0	1045.0					
Western Study Area																									
NLU80	-	-	-	1.5	3.5			456.1			17.3	NA	NA	NA	NP	-									Very high moisture content from 1.5 to 3.5 ft BML.
GWS-EC21-0050				-	-			569.5			23.5														Very high moisture content and organic matter. Unknown depth BML.
GWS-EC21-0177				-	-			506.7			17.0														
NLU19-GE	-	-	-	0.0	1.0	65.5	11.6	472.0	9.0	5.4		NA	NA	NA	NP	-									Very high moisture content and void ratio, low sat. unit weight from 0 to 4 ft BML. Moisture content >> LL from 0 to 4 ft BML. Extremely low Su (<< 209 lb/ft2) from 2.0 to 4.0 ft BML.
				1.0	2.0	55.3	15.5	528.0	9.2	8.4		100.1	81.7	18.4	OH	High									
				2.0	3.0	69.4	9.2	655.5	13.1	9.9		179.8	111.3	68.6	OH	High							3.6	Extremely low	
				3.0	4.0	60.9	6.2	881.2	14.4	11.2		241.6	205.1	36.5	OH	High							3.6	Extremely low	
GWS-EC16-0066	-	-	-	-	-			603.7			25.4														Very high moisture content and organic matter. Unknown depth BML.
GWS-EC-16-0173				-	-			517.2			16.3														
GWS-E16-0050				-	-			569.5			23.5														
GWS-EC21-0177				-	-			506.7			17.0														
GWS-CPT-01 / GWS-VS-01 / GWS-GC01	29.0	21.3		0.0	2.0																				
				2.0	3.0												[a]	Very soft			47.0	0.0		Extremely Low	Extremely low S_u (<< 209 lb/ft^2) and no SPT
				3.0	4.0			18.2									19	Very hard							
				4.0	5.5																				
				10.0	11.0			14.5									50/3	Very hard							
				15.0	16.0			17.2									50/10	Very hard							
				20.0	21.0			38.0									50/5	Very hard							
GWS-CPT-02 / GWS-GC02	26.5	18.3		0.0	1.0	125.1,102	105.6,108	18.9	0.7	0.6		NA	NA	NA			[a]						350.0	Very low	
				2.0	5.0																				
				8.0	9.0			17.3									50/6	Very hard							
				12.5	13.5			19.4									50/2	Very hard							
				17.0	18.0	11.0	13.0	20.4									50/2	Very hard							
	3.8	*18.3*		1.0	2.0																259.0	29.0		Very low	
GWS-VS-02				3.0	4.0																37.0	9.0		Extremely low	
GWS-C03	10.8	14.4		0.0	2.0												[a]	Very soft							
				5.0	6.0			9.7									17	Very hard							
				10.0	11.0			11.0									15	Hard							
				13.0	14.0			28.3									50/6	Very Hard							
	39.8	14.4		0.5	1.5																37.0	9.0		Extremely low	Extremely low S_u (<< 209 lb/ft^2) from 0 - 5.5 ft BML.
GWS-CPT-03 / GWS-VS-03				2.5	3.5																75.0	22.0		Extremely low	
				4.5	5.5																47.0	18.0		Extremely low	
				7.0	7.5																				

Table 5. Geotechnical Test Data Results for Selected Sediment Samples

Boring No.	Water Depth (ft)	Total Measured Depth (ft)	Measured Sediment Thickness (ft)	Depth BML (ft) From	Depth BML (ft) To	Unit Weight, $\gamma(\rho)$ (lb/ft^3) Saturated	Unit Weight, $\gamma(\rho)$ (lb/ft^3) Dry	Moisture Content (%)	Void Ratio, e Initial	Void Ratio, e Final	Organic Matter (%)	Atterberg Limits LL (%)	Atterberg Limits PL (%)	Atterberg Limits PI (%)	Atterberg Limits USCS Soil Type	Atterberg Limits Plasticity	SPT Blows / ft	Relative Consistency from SPT Data	Undrained Shear Strength, S_u (lb/ft^2) CPT From	CPT To	VST Peak	VST Residual	UU	Strength Range	Geotechnical Engineering Properties Indicative of Very Soft Sediments and/or Fluid Mud
Western Study Area (continued)																									
GWS-CPT-04 / GWS-VS-04 / GWS-GC04	41.8	32.3		0.0	1.0																62.0	26.0		Extremely low	Extremely low S_u (<< 209 lb/ft^2) from 0 to 5.5 ft BML.
				2.0	3.0																50.0	21.0		Extremely low	Extremely high moisture content from 4 to 20 ft BML.
				4.0	5.0			703.2				N/A	N/A	N/A		-	1	Very soft			74.0	21.0		Extremely low	Very low SPT blow count, 4 to 17 ft BML.
				6.0	7.0																101.0	38.0		Extremely low	Extremely low unit weight from 16 to 17 ft BML.
				8.0	9.0			408.9				N/A	N/A	N/A		-	1	Very soft			108.0	37.0		Extremely low	Extremely high void ratio, 16 to 17 ft BML.
				10.0	11.0																142.0	19.0		Extremely low	
				12.0	13.0																178.0	36.0		Extremely low	
				16.0	17.0	11.0	13.0	500.0	13.3	10.9		472.0	287.0	185.0	OH	High	[a]	Very soft							
				19.0	20.0			436.7																	
				20.0	21.0			9.2									25	Hard							
				27.0	28.0			15.1									55	Hard							
				28.0	29.0																				
				31.0	32.0			13.7									50/4	Hard							
GWS-CPT-05 / GWS-VS-05 / GWS-GC05	*41.0*	*56.3*		0.0	1.0												[a]				14.0	3.0		Extremely low	Extremely low S_u (<< 209 lb/ft^2) from 0 to 13 ft BML.
				2.0	3.0			289.2				112.7	63.0	49.7	OH	High	[a]	Very soft			30.0	18.0		Extremely low	Extremely high moisture content from 2 to 39 ft BML.
				4.0	5.0												[a]				62.0	11.0		Extremely low	Very low SPT blow count from 2 to 43 ft BML.
				6.0	7.0	12.0	16.0	740.6,426	9.1	6.8		624.3	307.4	315.8	OH	High	[a]	Very soft			74.0	20.0		Extremely low	Extremely high void ratio from 6 to 7 ft BML.
				8.0	9.0												[a]				104.0	26.0		Extremely low	Extremely low unit weight from 6 to 7 ft BML.
				10.0	11.0												[a]				129.0	37.0		Extremely low	
				12.0	13.0												[a]				142.0	31.0		Extremely low	
				38.0	39.0			304.2				N/A	N/A	N/A	NP	-	2								
				42.0	43.0			87.9				N/A	N/A	N/A	NP	-	3								
				50.0	51.0			78.5									20								
				55.0	56.0			73.3				50.0	27.2	22.8	CL-CH	Medium	2	Very soft							
GWS-GC06	19.7	76.0		0.0	2.0												[a]								Extremely low S_u (<< 209 lb/ft^2) from 6 to 7 ft BML.
				2.0	3.0			523.0				N/A	N/A	N/A		-	[a]								Very low S_u (< 250 lb/ft^2) from 35 to 56 ft BL.
				4.0	5.0			731.3									[a]								SPT blow count not measurable until 75 ft BML.
				6.0	7.0	65.9,8	8.5,9	732.0	13.8	12.4		645.2	309.0	336.1	OH	High	[a]	Very soft					70.0	Extremely low	Extremely high moisture content from 2 to 51 ft BML.
				20.0	21.0			520.3									[a]								Extremely high void ratio from 6 to 36 ft BML.
				25.0	26.0			637.1				N/A	N/A	N/A			[a]								
				30.0	31.0			548.7									[a]								
				35.0	36.0	66.2,10	10.5,12	546/528.9	11.7	9.9		405.5	307.8	97.7	OH	High	[a]	Very soft					227.5	Very low	
				40.0	41.0			358.9									[a]								
				45.0	46.0			390.7				N/A	N/A	N/A			[a]								
				50.0	51.0			129.4									[a]								
				55.0	56.0	93.6,44	48.7,56	93.7	3.0	2.1		71.8	30.4	41.4	OH	High	[a]	Very soft					167.5	Extremely low	
				60.0	61.0			88.0									[a]								
				65.0	66.0	98.5,55	59.6,64	51.7/65.2	2.1	1.7		47.0	28.8	18.1	OL	Medium	[a]	Very soft					250.0	Very low	
				70.0	71.0			70.6									[a]								
				75.0	76.0			32.0									50	Hard							

Notes:

Saturated unit weight = *in situ* density/unit weight

BGL = below ground level
BML = below mud line
CPT = cone penetrometer test
CL-CH = low plasticity to high plasticity clays
LL = liquid limit
N/A = not applicable
NP = non-plastic
OH = highly plastic organic clays
OL = organic silts and clays, low plasticity
PI = index of plasticity
PL = plastic limit
SPT = standard penetration test
S_u = undrained shear strength
USCS = unified soil classification system
UU = unconsolidated, undrained triaxial test
VST = vane shear test

[a] SPT sampler was pushed, not driven

Table 6. Undrained Shear Strength Parameters for Selected Soft Clays

								Depth (m)		Depth (ft)						
Site	Soil Description	Liquid Limit, LL (%)	Plastic Limit, PL (%)	Index of Plasticity, IP (%)	Moisture Content, w (%)	Total Unit Weight (lb/ft^3)	Sensitivity	From	To	From	To	OCR	Undrained Shear Strength S_u^{a} (lb/ft^2)	Strength Ratio: Uncon-solidated Undrained to S_u^{a} (UU)/S_u^{a}	Strength Ratio: Undrained Shear Strength to initial effective stress S_u^{a}/σ'_0	Reference
Rio de Janeiro - Guanabara bay	Soft gray clay	135	50	85	170	84.1	2.6	4	6	13.1	19.7	2	169.2	0.73	0.1	Bardet (1997)
		110	45	65	125	84.1	2.6	6	8	19.7	26.2	1.7	281.9	0.69	0.46	
		90	35	55	110	84.1	2.6	8	10	26.2	32.8	1.7	275.7	0.65	0.44	
		57	26	31	29	84.1	2.6	6	12	19.7	39.4	1.2	1798.2	0.61	0.6	
San Francisco Bay Mud	Soft gray clay (new Bay mud)	88	43	45	92	89.2	-	6	10	19.7	32.8	1.4	563.9	0.77	0.43	Bardet (1997)
		90	45	45	95	93.7	-	10	15	32.8	49.2	1.3	731.0	0.77	0.44	
Hamilton	Firm to stiff gray silty clay	32	18	14	30	-	-	3	6	9.8	19.7	3.2	1048.4	0.93	0.73	Bardet (1997)
		44	24	20	31	-	-	6	9	19.7	29.5	2.2	1647.8	0.55	0.78	
		39	22	17	33	-	-	11	11	36.1	36.1	1.2	1198.8	0.84	1.48	
TxDOT, Site 4	Soft gray clay	-	-	52	-	-	-	-	-	3.5	3.5	-	150	-	-	Varathungarajan (2008)
		-	-	52	-	-	-	-	-	6.5	6.5	-	318	-	-	
		-	-	52	-	-	-	-	-	9.5	9.5	-	226	-	-	
		-	-	60	-	-	-	-	-	12.5	12.5	-	195	-	-	
		-	-	60	-	-	-	-	-	16	16	-	210	-	-	

Notes:
UU = unconsolidated, undrained triaxial test - total stress analysis
CU = consolidated, undrained triaxial test - effective stress analysis
S_u^{a} - undrained shear strength, determined from CU tests
- = no available data.
OCR = over-consolidation ratio

APPENDIX 11B
PanGeo Geotechnical Review

PanGEO
INCORPORATED
Geotechnical & Earthquake
Engineering Consultants

May 11, 2007
File No. 06-091-3060

Ms. Kate Snider
Floyd Snider
601 Union Street # 600
Seattle WA 98101-2341

Re: Geotechnical Review
Gas Works Sediment Western Study Area RIFS
Seattle, Washington

Dear Kate,

This letter summarizes our review of the geotechnical aspects of proposed environmental remediation measures that may be used for the Gas Works Sediment Western Study Area RIFS where Floyd Snider is the lead consultant. The intent of our review is to discuss geotechnical constraints or construction limitations of the various remediation measures that are being considered for the site. Broadly, the active environmental measures being considered for the site cleanup include excavation/dredging, capping with a sand blanket or impermeable barrier (i.e., grout mat, HDPE liner, clay amendment etc.), or a combination of these measures. The following summarizes our conclusions on the geotechnical viability of these measures. This appendix also contains our engineering calculations that were used to develop our geotechnical recommendations for the construction of the site remediation.

SITE ZONES

For the purposes of discussion, we have divided the offshore area into 4 distinct zones in which bathymetric features and hydrodynamic conditions and subsurface conditions may influence the selection and construction of the remediation alternatives. These zones are consistent with the geographic zones described in the Feasibility Study. Their pertinent characteristics are described below:

Bank Zone

- Zone located near existing water surface of Lake Union (Elev. ~ 20')
- Generally between elevations +25 and +15 feet (USACE datum)
- Surface Slopes of about 2(H):1(V)
- Surface (at water's edge) underlain by rip rap overlying medium dense granular fill
- Existing slopes appear to be generally stable

Shoreline Slope Zone

- Zone located between elevations +15 and -10 feet (USACE datum)
- Surface Slopes of about 2(H):1(V) to 3(H):1(V)
- Surface underlain by granular fill overlying medium dense to very dense native granular soils
- Existing slopes appear to be generally stable

Transition Zone

- Zone which transitions between the steep shoreline slope and the flat lake bottom sediments
- Generally located between elevations -10 and -20 feet (USACE datum)
- Surface Slopes of about 5(H):1(V) or flatter
- Surface underlain by approximately 0 to 6 feet of soft sediments overlying a thin granular fill and/or medium dense to very dense native granular soils

Lake Bottom Zone

- Relatively flat lake bottom located at approximate elevation -20 feet (USACE datum)
- Surface underlain by about 4 to as much as 70 feet of soft, unconsolidated sediments overlying medium dense to dense, native, granular soils (i.e. stratified drift)

- Surface sediments are very weak (peak shear strengths of 10 psf at the surface) compressible sediments with water contents of 100 to 700%

GEOTECHNICAL CONSTRAINTS

The broad diversity of bathymetric, hydrodynamic and subsurface conditions present some rather unique challenges with the implementation of the various remedial technologies. That is, remedial technologies applicable and effective in one zone may have constraints in other zones. Accordingly, the following sections briefly discuss the geotechnical constraints of the various remedial technologies with respect to the different geotechnical zones.

EXCAVATION / DREDGING

The major geotechnical concerns for excavation (dredging) relate to slope stability, particularly in the soft sediments in the transition and lake bottom zones. Furthermore, the nature of the sediments in the different geotechnical zones will likely require the use of different dredging techniques, as discussed below:

Bank – The presence of rip rap, obstructions, and dense soils will require conventional clamshell buckets or land based trackhoe excavators to complete dredging in the near shore bank zone area. The presence of the obstructions will generally preclude the effective use of environmental buckets. The coarse grained soils in this region should provide relatively stable excavation slopes of 2(H):1(V).

Shoreline Slope – Conventional clamshell buckets and environmental buckets may be applicable for dredging in the shoreline slope zone. Environmental buckets would be preferred, to reduce redepositon, but are frequently ineffective on sloped surfaces. Conventional clamshell buckets may be needed to remove debris and obstructions. The coarse grained soils in this region should provide relatively stable excavation slopes of 2(H):1(V).

Transition - The thin zone (0 to 6 feet) of soft sediments at the surface in the transition zone are most suitably removed with an environmental bucket or a suction dredge, although both dredging techniques are problematic on slopes and areas with significant debris. The extremely weak surficial sediments will have a significant risk of re-suspension and residual deposition from the dredging operations. Hydrodynamic forces from the dredging operations, whether current velocities from a hydraulic dredge or the turbulence associated with the removal of a dredging bucket, will exceed the low (4 to 10 psf) residual strength of the weak near surface sediments resulting in the flow of the sediments into the excavation. We estimate that the excavation slopes for the fine grained soft sediments may be about 5(H):1(V) or flatter.

Lake Bottom – Similar to the transition zone, dredging of the weak sediments at the lake bottom would require an environmental bucket or a hydraulic dredge, both of which will likely resuspend sediments and result in potential recontamination. The high water-content, fine grained soft sediments will likely slough into the work area and result in excavation slopes of about 5(H):1(V) or flatter.

In summary, different dredging techniques may be required depending upon obstructions and the nature of the dredged soils. The fill soils underlying the shoreline and slope zones are relatively stable and can support cut slopes of 2(H):1(V) whereas dredging the soft sediments in the transition and lake bottom zones would likely result in cut slopes of 5(H):1(V) or flatter, and significant contaminant redistribution.

CAPPING

An approximate 3 foot thick sand cap may be needed for containment of contaminated sediment within all offshore areas of the site. Such a cap may require wave protection in the bank and shoreline slope zones. This wave protection could be provided with native materials, such as quarry spalls or manufactured materials, such as a grout mat. The following describes geotechnical considerations for cap design and placement in the different geotechnical zones.

Bank, Shoreline Slope and Transition Zones. The bank, shoreline slope and transition zones are inter-related regarding cap construction because of the need to create a stable platform at the toe of the slope (i.e. transition zone) to support a cap on the slope as well as any slope armoring. Specifically, the soft sediments in the transition zone will be displaced during construction of the toe buttress on the underlying native granular soil. Soft sediment displacement should be controlled through use of silt curtains and no capping activities should be completed until the toe buttress construction is complete. In general, the toe buttress can be constructed on the slightly sloping surface (i.e. 5(H):1(V) or flatter) of the transition zone. The bench for the toe buttress should have a minimum width of 6 feet to provide adequate support for the sand cap and armoring that will be constructed on the bank and shoreline slope. Specific approaches regarding construction of the toe buttress will be completed during the design phase of the project.

The sand cap in the bank and shoreline slope zone should be protected from waves and currents with slope armoring consisting of a 2 foot thick layer of quarry spalls (WSDOT 9-13.6 (WSDOT, 2006)) that extends from at least elevation 22 feet to at least elevation 10 feet, or as determined from the results of hydraulic modeling to be performed for the design study. If needed, the quarry spalls may be covered with habitat mix. Below about elevation 10 feet, the sand cap material may be placed on the slope down to the toe buttress.

Materials placed in the above configuration would provide adequate stability for the slope. Because of the granular nature of the soils underlying the slope, the most critical surface for slope stability is a near surface wedge or layer of soil. With the maximum slope of 2(H):1(V) of the bank and shoreline slope and an estimated minimum angle of internal friction of 32 degrees for the cap material and underlying slope material, the cap would have a minimum static factor of safety of 1.25 to resist shallow sliding The cap, however, would be marginally stable under a 100 year design earthquake, a minimum requirement of the City of Seattle (1993) and the cap may experience a down slope movement of about 9 inches under a rare 2,475 year earthquake as defined by the 2006 International Building Code (International Code Council, 2006). The seismic displacement of 9 inches was based on Newmark (1965) sliding block analysis with a peak design ground surface acceleration of 0.36g.

Potential earthquake induced ground movements are expected to result in a bulge of the cap at the toe of the slope and a subsidence of the cap at the shoreline. The subsidence of the cap at the shoreline can be easily addressed, if needed, with the placement of additional cap material. The soils underlying the cap are not expected to experience any significant movement or consolidation as a result of the placement of the cap or the performance of the slope in a future earthquake.

Finally, the shoreline above the lake surface within the bank zone adjacent to Gas Works Park may need to be modified including construction of a retaining wall to provide grade separation and a barrier between the park walkway and the lake shoreline area. Depending upon the height requirements for this separation, various wall types may be constructed along the shoreline. Applicable wall types would include rockeries, concrete block walls, and mechanically stabilized earth (MSE) walls. Details for wall design will be provided as appropriate during the design phase of the project.

Lake Bottom Zone. The low strength of the soft lake bottom sediments will restrict the amount of material and the rate of material placement for the cap. That is, the soft sediments will restrict the initial layer placement thickness for the cap to approximately 6 inches and this layer will need to remain in place for a period of about 1 to 3 weeks to allow the underlying sediments to consolidate and gain strength before placing additional cap material. The maximum thickness of the second lift should be limited to 18 inches to avoid creating a mud wave. However, assuming that the cap will have a total thickness of 3 feet, the second layer should be specified as having a thickness of 12 inches, which should remain in place for about 1 to 3 weeks to allow the underlying materials to consolidate and gain strength before placing a third and final lift.

We anticipate that the 3 foot thick cap will result in 6 to 12 inches of settlement in the transition zone and 30 to 40 inches of settlement in the lake bottom zone. Approximately 70% of the estimated settlement will occur within about 15 months of the cap placement and about 90% of the settlement will occur within about 4 to 5 years. This magnitude of settlement is expected to produce relative gradual deflections of the cap, without surface breaks or ruptures.

The construction and performance of the cap may be enhanced by placing a geotextile at the base of the cap. The geotextile would act as a separator to reduce resuspension of fines from the cap placement. The geotextile would also provide a means to confirm the integrity (thickness) of the cap during subsequent project monitoring. The geotextile barrier, however, would not necessarily permit the complete placement of the cap in a single lift.

IMPERMEABLE BARRIER

An impermeable barrier may be used in lieu of a sand cap or possibly in conjunction with partial sand cap to provide containment of underlying contamination. Impermeable barriers can be constructed using a variety of technologies and may include grout mats, HDPE liners, clay amendments etc. This geotechnical appendix focuses on grout mats to be used as impermeable barriers within the Western Study Area. The final decision regarding selection of impermeable barrier technologies will be made during the design phase of the project.

Grout mats are constructed by filling a geotextile pillow or form with cement grout to essentially form a rigid surface. Grout mats have typical thickness ranging from 3 inches to 8 inches. Because of the rigid nature of the cured concrete in the grout mat, grout mats are typically restricted to use on slopes or surfaces that are not susceptible to settlement. However, articulated grout mats, which are composed of separate grout filled pillows that are interconnected with high strength cables, may be used over irregular terrain or ground that is susceptible to settlement without impairing the integrity of the grout. Alternatively, it is possible to construct a hybrid grout mat using a bentonite based grout that doesn't cure and gain strength to provide the benefits of low permeability as well as flexibility. The following discusses the potential uses of grout mats in the different geotechnical zones.

Bank, Shoreline Slope and Transition Zones. The bank, shoreline slope and transition zones are inter-related regarding construction of a grout mat because of potential irregularities in the offshore slope and the potential for settlement of the mat from consolidation of the soft sediments in the transition zone. According, we believe that an articulated grout mat, similar to the Armor Form Articulating Block Mat, would provide the best service within all three zones.

Specifically, the grout mat would be anchored at the top of the slope, where the high strength cables would be embedded to provide support for the entire length of the mat. The mat would then be placed over the dredged surface of the slope, without the need of an underlying sand cap. Compared to a sand cap, the articulated block mat, which is anchored at the top of the slope would avoid the need to construct a soil buttress at the toe of the slope and it would not be susceptible to earthquake induced ground instability or movement. Furthermore, the articulated block mat provides protection from waves and currents and would not require slope armoring.

A potential disadvantage of the articulated block mat is from the potential decomposition of the geotextile covering of the mat in the splash zone. Should the covering deteriorate, the underlying high strength cables would still prove support to the discrete grout pillows in the mat.

While the mat may experience up to about 10 inches of settlement at the far (offshore) edge of the transition zone where the underlying soft sediments may be as thick as 6 feet, the articulated nature of the mat would readily accommodate the differential settlement without impairing the integrity of the mat.

To enhance aquatic life, the geotextile fabric forming the exposed surface of the mat may be modified to include pockets that would allow the placement of a thin layer of habitat mix on the surface of the mat.

Lake Bottom Zone. Although grout mats may also be used in the lake bottom zone, the low strength and high compressibility of the soft lake bottom sediments will restrict not only the type of mat that may be used in this area but also the techniques that are used to construct or place the mats. Specifically, articulated grout mats and/or grout mats constructed with a bentonite based grout would be needed in the lake bottom zone to accommodate the large, long term settlements that will occur in this are with the consolidation of the soft sediments. Additionally, there is a high likelihood that unrestricted placement of the mats may create a mud wave in the underlying soft sediments. However, construction success would be increased by constructing the mats on a 6 inch thick sand blanket and requiring use of a frame to place the mat that supports the mat by at least 12 points.

We estimate that a 6 inch thick grout mat and a 6 inch thick sand bedding layer would experience total settlement in the range of 10 to 15 inches. Approximately 70% of the estimated settlement will occur within about 15 months of the mat placement and about 90% of the settlement will occur within about 4 to 5 years.

In summary, we believe that dredging and capping with a conventional sand blanket or a grout mat are all viable techniques that may be employed with certain restrictions, as outlined in this letter, to provide environmental remediation of the near and offshore areas at Gasworks Park.

Please call if there are any questions on this letter.

Sincerely,

W. Paul Grant, P.E.
Principal Geotechnical Engineer

Encl: Engineering Calculations

REFERENCES

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APPENDIX 11C
Natural Recovery and Monitored Natural Recovery

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LIST OF FIGURES

1.0 NATURAL RECOVERY AND MONITORED NATURAL RECOVERY

The purpose of this appendix is to present lines of evidence that demonstrate that natural recovery of sediments is taking place within the sediment portion of the Gas Works Park Site (GWPS), which is referred to in the FS as the sediment cleanup unit (SCU). This appendix also includes analyses to support the use of monitored natural recovery (MNR) as a feasible sediment remediation technology. .

The key evaluation demonstrations for sediment natural recovery at the GWPS are as follows:

- Section 2 of this appendix uses carcinogenic polycyclic aromatic hydrocarbons (cPAHs) and total PAHs (TPAHs) sediment results to show that natural recovery is occurring in the SCU.
- Section 3 of this appendix shows that conditions within the SCU are favorable for the use of MNR as a sediment remediation technology.

This appendix uses the following terms (see Figure 11C-1):

- SCU – the sediment portion of the AOI.
- Lake Shore – the relatively shallow nearshore zone of the SCU.
- Lake Slope – the steep sloped portion of the SCU adjacent to the Lake Shore zone.
- Lake Bottom – the slightly sloping portion of the SCU that extends towards the center of the lake from the lake slope zone.
- SMA-14 – a sediment management area (SMA) delineated in the SCU. SMA-14 is a subset of the lake bottom zone and is same area as the natural recovery area identified in Section 6.6 of the RI.

Based on the evaluation presented in this appendix, it is reasonable to assume that GWPS and ambient Lake Union (ALU) contaminants of concern (COCs) are naturally recovering. As noted in Section 3.3 (Summary and Conclusions), additional data will be collected during remedial design to determine the final boundary of the natural recovery area and to further refine estimates of natural recovery rates.

2.0 NATURAL RECOVERY

Natural recovery of sediment refers to physical, chemical, and biological processes that reduce contaminant concentrations in surface sediment over time. Processes that contribute to natural recovery include burial by deposition of sediment transported within the watershed, dilution from mixing caused by bioturbation (organisms reworking the top layer of sediment) or other physical processes, dispersion (e.g., partitioning to other media, diffusion, hydraulic transport of resuspended material), and chemical and biological degradation. In most systems, burial by cleaner sediment is the dominant natural recovery process for surface sediment.

2.1. Lines of Evidence Supporting Natural Recovery

Evidence that natural recovery in sediment is occurring is primarily established by documenting changes in chemical concentrations or spatial distribution over time. Data that provide this evidence include differences in the vertical and lateral extent of contaminants in surface and subsurface sediment and reductions in sediment chemical concentrations over time. Characteristics of the physical environment (e.g., hydrology, energy regime, sediment inputs) are also used to demonstrate the potential for natural recovery.

The lines of evidence that demonstrate that natural recovery is occurring in SMA-14 are discussed in the following sections based on temporal trends and spatial distributions of cPAHs and TPAHs, which are two of three primary GPWS COCs. The physical characteristics of the lake bottom zone, including SMA -14, that make it favorable for natural recovery are also discussed. In addition, the sediment deposition rates discussed in Section 3.2.4 provide further evidence that natural recovery is occurring.

2.1.1. Temporal Trends in Contaminants of Concern

Changes in surface sediment chemical concentrations of TPAHs were evaluated in the RI for the area of the central and eastern portion of the SCU that has been repeatedly sampled over time. An areal, rather than point-by-point, approach was used to look at temporal changes because historical sample locations were not accurately documented. These areas were sampled during two U.S. Environmental Protection Agency (EPA) surveys conducted in 1984 and 1995 and again by Puget Sound Energy (PSE) and the City of Seattle in 2004 and 2005. Changes in chemical concentrations are represented as surface-area-weighted average concentrations (SWACs) using geographic information system (GIS) interpolation and averaging methods[1]. Changes in TPAH concentrations over time are included as a line of evidence to show that natural recovery processes are occurring in the SCU. The evaluation is not specific to SMA-14.

As shown on Figure 11C-2, the concentrations of TPAHs located close to shore have remained elevated since 1984, but the TPAH concentrations in SMA-14 have decreased since 1984.

The reductions in the TPAH SWAC for the portion of the SCU shown on Figure 11C-2 are significant and represent an 84 percent reduction in TPAH concentrations between 1984 and 2005.

Survey Date	Total PAH SWAC (mg/kg)	Number of Sample Locations	Percent Reduction Since Previous Period	Average Annual Reduction Percent
1984/1985	2,870	21		
1995	776	27	73	11
2004/2005	450	42	42	5
Overall reduction between 1984 to 2005			84	8

The temporal trends in cPAH TEQ[2] concentrations were evaluated within SMA-14 area using GIS interpolation and averaging methods (samples and area evaluated are depicted in Figure 11C-3). The cPAH TEQ data from samples obtained primarily in 1984, 1995, 1999, 2002 and 2004/2005 were used to calculate cPAH TEQ SWACs for each sampling period to estimate the percent reduction in cPAH TEQ concentrations in surface sediment in SMA-14. The GIS interpolation of cPAH TEQ surface sediment concentrations in SMA-14 for these five periods is shown on Figure 11C-4.

[1] GIS interpolation and the calculation of SWACs is discussed in Appendix 5A.

[2] The cPAH TEQ (toxicity equivalent) is a normalized concentration of a group of high-molecular-weight PAHs based on their toxicity relative to benzo(a)pyrene.

Period	cPAH TEQ SWAC (mg/kg)	Percent Reduction Since Previous Period	Average Annual Reduction Percent
1984/1985	156[a]		
1995	29	81	14
1999	23	21	6
2002	10	57	24
2004/2005	3.3	67	31
Overall reduction between 1984 and 2005		98	17

[a] Based on limited data points.

The differences in the average annual rates of decline for TPAHs and cPAHs are partially a function of the area evaluated. The average annual rate of decline (8 percent) for TPAH between 1984 and 2005 was derived using data from the lakeshore, lake slope and lake bottom zones, including those areas closest to the historical contaminant sources. The average rate of decline for cPAHs (17 percent) considers only the SMA-14 portion of the lake bottom zone, which is located further from the historical contaminant sources. The distribution of contaminants within the SCU is discussed below. In addition to the historical sources, other factors influencing the rates of decline are differences in the geochemical nature of the contaminants, rates of new sediment deposition and the chemical quality of the new sediment settling within the lake bottom zone, including SMA-14.

2.1.2. Trends in Vertical Distribution of Contaminants of Concern

A general model of occurrence and type of contamination below the mudline and improving sediment conditions near the surface is depicted in Figure 11C-5. The type and levels of contamination in SMA-14 change with depth below mudline and reflect the history of industrial activities and timing of releases.

Deeper sediment reflects discharges, accidental spills, and releases during the operation of the manufactured gas plant (MGP). The gray marker bed (discussed further in Section 3.2.4.2) helps date sediment impacted by industrial activities after about 1916. In the lake bottom zone near the toe of the slope, the source(s) of slight to moderate sheens and odor in subsurface sediment likely date back to early years of MGP operation (1907 to about 1937). Sooty layers observed in overlying sediment likely represent lamp black releases including stormwater transport from storage areas during later years of MGP operations (post-1937) and episodic erosion of fill material along the shoreline.

Sediment quality improves in sediment closer to the mudline. Results of each successive surface sediment sampling event had lower concentrations of cPAHs (see previous table and Figure 11C-5). Based on sediment core and grab samples, sediment petrology, and sediment transport and deposition patterns, specific contaminant layers are less distinguishable farther offshore in the lake bottom zone (see RI Figure 7-1D). The primary source of sediment in the lake bottom zone is suspended solids from shoreline/lakeshore erosion, stormwater runoff and transport from Lake Washington, Portage and Union Bays, and plankton or plant material deposited from the water column.

The concentration of cPAHs in surface and subsurface sediment was evaluated for vertical trends based on cores collected in the lake bottom zone (Figure 11C-6). The relative percent difference between the top 10 centimeters (cm) (surface interval) and the first interval of a co-located core (shallow subsurface interval; typically, within the first three feet below the mudline) was calculated. These two intervals occur within the loose sediment[3] that has been deposited on the lake bottom. On average, the surface interval was 11 percent of the concentration of the shallow subsurface interval (that is, the surface sediment cPAH TEQ concentrations are, on average, 89 percent lower than the co-located shallow subsurface concentrations). The change in chemical concentration demonstrates that the more recent sediments that are being deposited have lower cPAH TEQ concentrations. The differences in cPAH TEQ concentrations between the surface sediment and shallow subsurface are likely a result of the cessation of the MGP operations in North Lake Union, cleanup of the upland portion of GWPS, and non-GWPS source control activities throughout the lake.

The sample locations used in the comparison of surface and shallow subsurface concentrations are shown on Figure 11C-6 and the associated relative percent differences are shown in the following table.

Location	cPAH Carcinogenic PAH (TEQ) (mg/kg)		Relative Difference
	Surface (0-0.33 feet below mudline)	Shallow Subsurface (~0-3 feet below mudline)	
NLU04	4.2	22	81%
NLU12	6.8	65	90%
NLU41	1.8	9.8	82%
NLU43	0.8	17	95%
NLU48	2.4	22	89%
NLU49	1.2	31	96%
NLU70	1.0	24	96%
NLU-121	23	136	83%
		Average	**89%**

2.1.3. Patterns in Spatial Distribution of Contaminants of Concern

The distribution of cPAH and TPAH concentrations generally tend to be highest in the shoreline and lakeshore zones, in the vicinity of historical contaminant releases and lowest in SMA-14 in the lake bottom zone. The spatial distributions are shown in Figure 11C-7. The relationship of lower concentrations with distance from the shoreline is evident in areas adjacent to the park except the western portion of the SCU, which has been influenced by multiple historical and ongoing sources of PAHs over time (e.g., shipyard activities, bulk petroleum storage and other local and regional sources).

Surface sediment concentrations in SMA-14 contain the lowest concentrations of contaminants within the SCU, including concentrations of PAHs that are similar to concentrations found throughout the main basin of Lake Union (ambient Lake Union). Concentrations of cPAHs and TPAHs in surface sediment are depicted in Figure 11C-7.

[3] Loose sediment is also referred to in the RI as soft sediment or fluid mud.

The average lake bottom concentration of cPAHs in ambient Lake Union outside of the SCU[4] was 5.4 milligrams per kilogram (mg/kg) (RI Table 3-1) based on samples collected from the mid-1980s to about 2005. cPAH concentrations in samples collected in SMA-14 were either lower or were of a similar order of magnitude, averaging 3.3 mg/kg based on 2004/2005 data. TPAHs showed a similar pattern—the ambient Lake Union average concentration was 47 mg/kg, while the average TPAH concentration in SMA-14 was 22 mg/kg.

2.1.4. Physical Characteristics

The data describing the chemical distribution and magnitude are the primary lines of evidence that natural recovery is occurring in the lake bottom zone, including SMA-14. There are also physical processes affecting natural recovery in the lake bottom including the source of material that settles out on the bottom, current speeds near the bottom, and frequency and magnitude of waves or vessel prop wash. Figure 11C-8 depicts a site-specific conceptual model of processes that may affect natural recovery.

The lake bottom of Lake Union is generally depositional due to the low energy environment and ongoing supply of sediment (see Section 6.6.2 of the RI). The lake bottom zone starts at elevations of about -15 to -18 feet U.S. Army Corps of Engineers (USACE) and gently slopes towards the center of Lake Union and the channels leading from Portage Bay to the east and towards Fremont in the west. Surface sediment in the lake bottom is very fine-grained, which is indicative of a low energy environment where suspended sediment settles. Soft sediment forms a thick layer on the lake bottom; sediment probing conducted as part of previous investigations estimated thicknesses of 20 feet or more of the fine-grained deposits (see Appendix 3H); geological investigations suggest this layer may be as thick as 50 feet (see Appendix 3B). Rates of suspended sediment deposition are discussed as part of the analysis in Section 3.

Sediment in the lake bottom zone has both a mineral and biogenic component. Mineral particles are sourced from suspended solids transported from Lake Washington, Portage and Union Bays, discharges from storm drains and combined-sewer overflows, erosion of the shorelines surrounding Lake Union and resuspended sediment from the lakeshore and lake slope zones. Dead plankton, including diatoms with silica frustules, and decomposing aquatic and terrestrial plant material compose the biogenic component. A study of the sediment petrology conducted by Stanford (Appendix 2E of the RI) quantified the relative proportions of mineral, diatomaceous and plant fractions of sediment from cores collected within the SCU. For those cores collected in the lake bottom zone, approximately 35 percent of the sediment was biogenic in origin and about 65 percent was mineral in origin. Diatoms and decaying plant material contribute to the characteristics of the soft sediment and provide a relatively clean source of sediment for continued natural recovery.

Currents in Lake Union are also relatively slow and contribute to the depositional nature of the lake bottom. Currents in North Lake Union tend to flow from Lake Washington to Puget Sound due to the controls at the Hiram M. Chittenden Locks. The rate of discharge is controlled by the Locks and circulation of the lake system is further restricted by the configuration of the lake basin, bottom features, and seawater intrusion. A sill (a shallow rise in bathymetry) near the beginning of the Fremont Canal inhibits the circulation of deeper lake water and enhances sedimentation. Repeated openings of the Locks for recreational and commercial

[4] The area used to calculate average ambient Lake Union conditions outside of the SCU did not include potential lakeshore source areas (specifically, samples with 300 feet of the shoreline were not included in the average).

boat traffic in the summer allows intrusion of salt water, which also affects lake circulation over the longer term and contributes to flocculation and sedimentation within the lake basin.

3.0 MONITORED NATURAL RECOVERY

When applied as a remedial technology for sediment cleanup, the goal of natural recovery is to achieve cleanup levels within a reasonable timeframe (10 years under the Sediment Management Standards) through natural sedimentation processes. The rate of natural recovery and success of the remedy is documented by monitoring surface sediment over the target recovery period.

The success of MNR depends largely on physical, chemical, and biological factors affecting surface sediment quality as well as the timing and effectiveness of source controls within a watershed. Surface sediment equilibrates to regional or ambient conditions through inputs of suspended material.

3.1. Conditions Favorable to the Use of Monitored Natural Recovery

Monitored natural recovery is generally effective in sediment areas where the following characteristics are present (Ecology, 2021; EPA, 2005; ITRC, 2014):

- Physically stable environment.
- Limited erosion potential of sediment bed (slow current/wave forces or prop wash).
- Limited groundwater discharge (i.e., advection is not a dominant contaminant transport mechanism).
- Moderate chemical concentrations, such that dilution and mixing can contribute to achieving cleanup goals over time.
- Depositional environment with a source of cleaner material contributing to surface sediment.
- Rate of deposition sufficient to meet “reasonable timeframe” requirements (typically 10-years).
- Source controls are sufficient to prevent recontamination.

3.2. Evaluation of the Potential Use of MNR in the Remediation of the GWPS SCU

Previous sediment investigations provide data that support MNR as a feasible remedial technology that can be included in the remedy. Existing data used in this evaluation include:

Conditions Favorable to Use of MNR	Site-Specific Lines of Evidence
Stable sediment/low erosion potential	▪ Bathymetry (e.g., water depth) ▪ Bottom slope ▪ Grain size characteristics ▪ Geotechnical properties ▪ Current flow measurements ▪ Hydrodynamic evaluation
Limited groundwater discharge	▪ Hydrogeologic setting. ▪ Upland groundwater gradients and physical characteristics of soil and sediment ▪ Modeled rates of discharge

Conditions Favorable to Use of MNR	Site-Specific Lines of Evidence
Moderate surface sediment chemical concentrations	▪ Magnitude of COCs
Sufficient sediment deposition	▪ Sediment dating (multiple approaches) ▪ Sediment profiles
Source controls are sufficient to prevent recontamination	▪ Remedy design elements that address existing outfalls, stabilize shoreline and isolate remaining sediment source areas ▪ Compliance with stormwater permit requirements including the City Business Inspection Program ▪ City of Seattle/King County Ship Canal Water Quality project (scheduled to be completed and operational in 2025)

Multiple lines of evidence were evaluated for MNR in SMA-14 and MNR is predicted to be successful. These lines of evidence are discussed below.

3.2.1. Stable Sediment/Minimal Erosion

Sediment in the lake bottom zone is characterized as very fine-grained silts and clays with high water and organic material content. These soft sediments reflect both inorganic and biogenic particles that have settled to form the lake bottom including suspended sediment transported from upstream embayments (Portage Bay, Union Bay) and Lake Washington, eroded soil from the banks along the Lake Washington Ship Canal, sediment resuspended from lakeshore and lake slope areas within Lake Union, particles transported by stormwater and discharged to the lake system, decaying plant biomass and material associated with diatoms and other plankton in Lake Union. Once settled, these particles remain in place due to the quiescent environment and low slope associated with the lake bottom zone.

Near-bottom current speeds in the lake bottom zone (but above the sediment-water interface) averaged 4 to 7 centimeters per second (cm/sec) during an investigation of lake hydrodynamics in 2005 (see Appendix 3G). Spikes in current speeds were detected at depths greater than -18 feet USACE and were associated with vessel traffic. However, current spikes were rare and of very short duration (high spikes comprised less than 0.005 percent of the readings collected over three different periods). Storm-generated wave forces were also modeled. Wave forces were predicted to attenuate rapidly at depths greater than 8 feet USACE (the upper lake slope region) based on the model results. These current measurements and modeling confirm the generally quiescent conditions near the bottom of the lake.

Due to the water depth and low bottom current speeds, the lake bottom zone is a depositional area with a low potential for physical disturbance from currents, wind- or storm-induced waves or prop wash. These attributes contribute to the feasibility of MNR as effective technology for GWPS sediment.

3.2.2. Limited Groundwater Flow

Groundwater flow to the lake from the uplands is limited due to existing hydrogeologic characteristics. Till is the dominant geologic stratum and has a low hydraulic conductivity that limits recharge to localized precipitation. As a result, groundwater flow from the uplands to the lake is limited. While the park portion of the uplands is irrigated, the amount of water applied is adjusted to the amount of moisture in the soil, limiting the contribution of irrigation water to groundwater. Rainwater percolates through the overlying Fill unit where permeable surfaces are present, and either discharges through the Fill along the shoreline or enters the underlying outwash discharging near the shore along the lake slope region (see RI Figure 3-14). The hydrogeologic model, supported by groundwater flow modeling, predicts a primary zone of discharge from the uplands to be within 300 feet of the shoreline with flow attenuating with distance from the shore. Figure 11C-9 depicts mudline groundwater discharge volumes from the uplands to Lake Union. Groundwater discharge is very low (negligible) in the lake bottom zone; thus, advection is not a mechanism for contaminant transport to lake bottom surface sediment. Minimal groundwater advection is another key factor in successful implementation of MNR as part of a remedy.

3.2.3. Sediment Chemistry at the Lake Bottom

SMA-14, which is considered for MNR, represents the lowest surface sediment contaminant concentrations within the SCU. The area-weighted average cPAH (the most wide-spread COC) concentration in SMA-14 is 3.3 mg/kg based on data from the 2004/2005 sediment quality investigation. TPAHs, another widespread COC, averaged 22 mg/kg based on this same SMA-14 data set. In addition, this area is similar in concentration to the lake bottom in greater Lake Union, which represents the ambient condition in the lake. Given the concentration reduction factors discussed in Section 2.1.1 above the concentration of contaminants is expected to be lower now than in 2004/2005.

3.2.4. Adequate Sediment Deposition Rates

3.2.4.1. Sediment Dating

Sediment deposition rates were estimated as part of several studies conducted in Lake Union in the 1970s and 2000s (Barnes et al. 1978, Tomlinson et al. 1977, Mattingly 2003 and RETEC 2004). Based on these studies, sedimentation rates ranged from 0.1 to 1.7 centimeters per year (cm/year), depending on location in the lake. The rates were estimated by measuring sediment core radioisotope activity (lead-210 and cesium-137). The lowest deposition rates were found in the center of Lake Union (0.1 to 0.2 cm/year) and higher sedimentation rates were measured in northern part of Lake Union (0.8 to 1.0 cm/year) outside of the SCU.

Sediment dating was also performed on several cores within the SCU, which showed evidence of net deposition. Lakeshore and lake slope zones within the SCU were shown to have deposition rates ranging from 0.2 to 0.6 cm/year and the lake bottom zone within the SCU was shown to have deposition rates ranging from 0.9 to 1.7 cm/year. The median deposition rate within the lake bottom zone is approximately 1.0 cm/year.

3.2.4.2. Sediment Profiles Documenting Rates of Deposition

Sediment profiles were also used to evaluate sediment deposition rates over time. In 1916, during the construction of the Lake Washington Ship Canal, the temporary dam at the Montlake Cut was breached. The massive lowering of Lake Washington carried a large amount of fine-grained sediment into Lake Union, which is evident today as a thin subsurface layer of light gray clay (referred to as the “gray marker bed” in Figure 11C-5). Field logs from cores collected from the SCU were reviewed and the depths below mudline of the gray marker bed were compiled (see Figure 11C-6 for core locations) to determine sediment deposition rates since the 1916 event. The depth of the gray marker bed ranged from 1.3 to 3.8 feet (40 to 116 cm) below the mudline. The sediment deposition rate since 1916 was estimated at each location by dividing the depth below mudline (cm) by the number of years of accumulation since 1916 to the time of sample collection. By this method, the deposition estimates within the SCU ranged from 0.5 to 1.3 cm/year and on average is 0.8 cm/year.

Sediment Core Location	Year Collected	Depth Below Mudline of 1916 Marker Layer (cm)	Accumulation Per year (cm/year)
CR-13	1999	55	0.7
CR-21	1999	85	1.0
GWS-EC04	2005	49	0.5
NLU08-US	2002	64	0.7
NLU10-US	2002	64	0.7
NLU16-US	2002	55	0.6
NLU41-US	2004	40	0.5
NLU43-US	2004	46	0.5
NLU45-DC	2005	49	0.5
NLU45-US	2004	67	0.8
NLU47-US	2004	49	0.6
NLU48-US	2004	101	1.1
NLU49-US	2004	85	1.0
NLU52-US	2004	88	1.0
NLU70-US	2004	73	0.8
NLU75-US	2004	116	1.3
Mean			**0.8**
95% Confidence Interval			**0.7-0.9**

The deposition rates based on the sediment profile in the lake bottom zone of the SCU are generally within the range estimated using sediment dating techniques (0.9 to 1.7 cm/year).

3.2.5. Implementation of Source Controls

Source control plays an important role in reaching and maintaining cleanup goals in sediment. Sources of GWPS COCs within the lakeshore and lake slope zones will be controlled once a remedy is in place. Areas of shoreline erosion and active sediment transport will be controlled, eliminating impacted lakeshore and lake slope sediment as a source to the lake bottom. On-site stormwater infrastructure has been inspected and will be modified, as necessary, to minimize infiltration of groundwater and subsurface contaminant leachate to storm drains. Some of the stormwater infrastructure improvements occurred as part of the Play Area renovation conducted by the Seattle Parks Department in 2018 or as part of other planned maintenance; the remainder will occur prior to, or as part of the implementation of the cleanup action for the SCU[5].

Regional stormwater and combined sewer discharges have been a long-term and are an on-going source to Lake Union and the Ship Canal. Both the City and King County have implemented major sewer-separation/combined-sewer overflow (CSO) reduction projects that have reduced contaminant discharges to Lake Union. In addition, these two agencies began a joint project in 2020 to construct a combined sewage storage tunnel between Wallingford and Ballard to further reduce CSO events in the Ship Canal,

[5] In addition, two buried perforated pipes associated with storm drains at the park have already been plugged to minimize infiltration of contaminated soil or groundwater into the storm drains.

which will reduce the input of contaminated particulate material to the lake. The City of Seattle/King County Ship Canal Water Quality project is scheduled to be completed in 2025 and operational by the end of 2025.

The City will continue to enforce its stormwater code including the performance of the business inspection program in the Wallingford neighborhood that surrounds the GWPS to reduce sources to stormwater over time.

Further details on source control are presented in Appendices 12A and 12B.

3.3. Summary and Conclusions

SMA-14, which is located in the lake bottom Zone has characteristics that support natural recovery of sediment. SMA-14 is a relatively flat, quiescent environment with minimal physical disturbance. Sediment deposition is occurring and has contributed to the reduction of chemical concentrations in sediment over time. There is no known active transport of contaminants via groundwater advection to surface sediment in SMA-14 and data are sufficient to conclude that GWPS and co-located ALU COCs are naturally recovering. Therefore, MNR is a viable remedial technology for SMA-14. Additional data will be collected during remedial design to determine the final boundary of the natural recovery area and to further refine estimates of natural recovery rates.

4.0 REFERENCES

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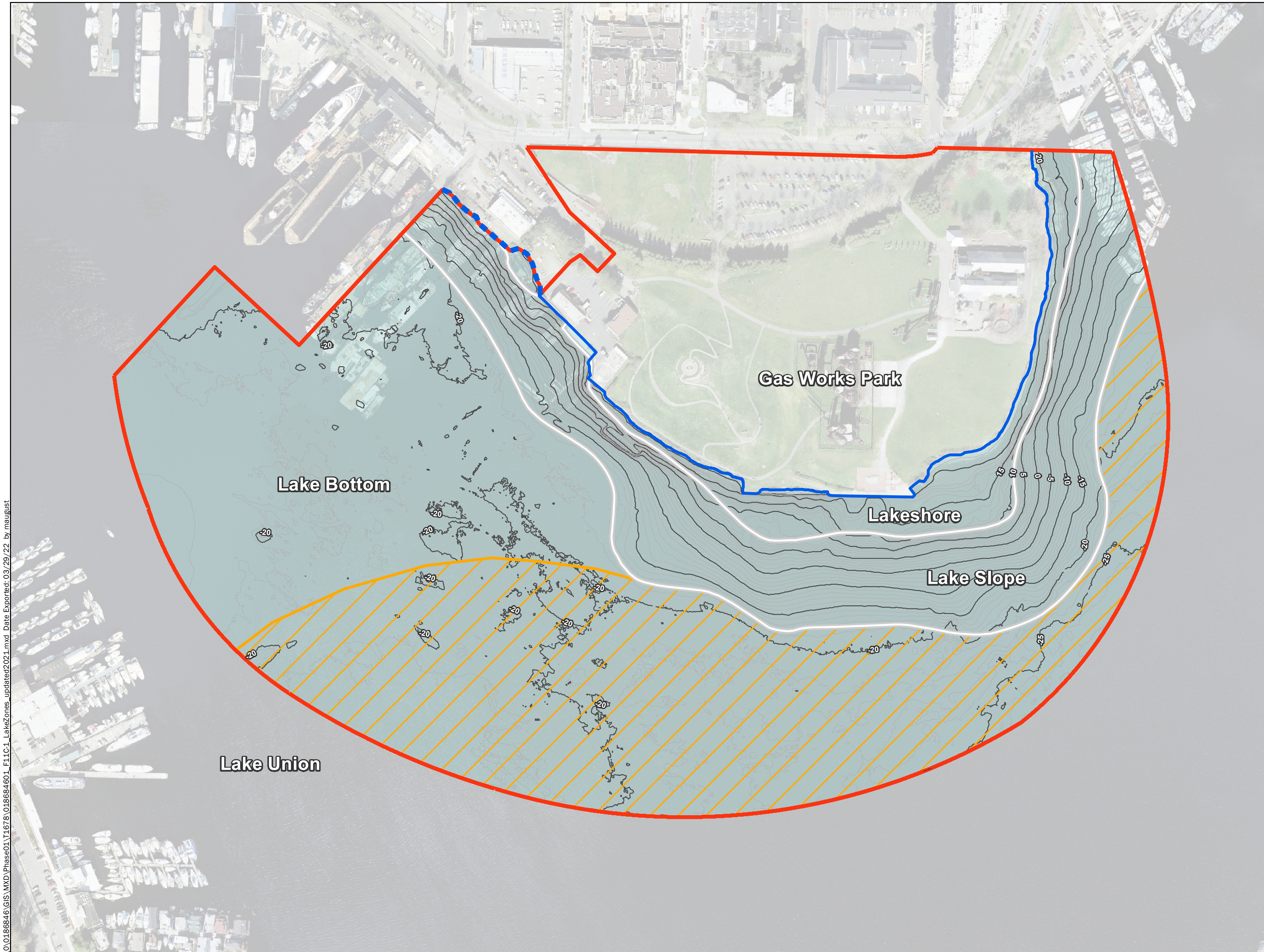

Legend

- Area of Investigation
- Shoreline (OHWM)

Bathymetric Contour in Feet (USACE Locks Datum)

- 1' Contour Interval
- 5' Contour Interval
- SMA-14
- Sediment Cleanup Unit (SCU)

Notes:

1. Data Source: Upland topography is based on AECOM 2010 topographic base map supplemented with True North Land Surveying, Inc., Gas Works Park, Kite Hill Soil Cover Project, drawing J14-80.00, August 20, 2015; and Northwest Corner topography from City of Seattle (2005). Northeast Corner topography does not reflect 2012 capping. Bathymetry generated from side-scan sonar surveys (RETEC, September 1999; City of Seattle November 2002), nearshore singlebeam bathymetry survey (RETEC, October 2002), multibeam bathymetry surveys (Parametrix, December 2002; Tetra Tech, October 2006), leadline survey (RETEC, 2005).
2. Basemap 2005 USGS aerial photograph. Does not show current conditions.
3. Projection: NAD 1983 StatePlane Washington North FIPS 4601 Feet.

Lake Zones

Gas Works Park Site
Seattle, Washington

GeoEngineers | **Figure 11C-1**

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P:\0\0186846\GIS\MXD\Phase01\T1678\018684601_F11C-2_tpah_IDW_4up2021.mxd Date Exported: 03/29/22 by maugust

Legend

TPAH Concentration (mg/kg)

- ≤17 (SCO)
- >17 to ≤30 (CSL)
- >30 to ≤170
- >170 to ≤500
- >500

- Area of Investigation
- Shoreline (OHWM)
- SMA-14
- Sample Location

N W E S

300 0 300

Feet

Notes:

1. TPAH sediment screening level = 17 mg/kg (SCO) and 30 mg/kg (CSL).
2. For mappng purposes surface sediment is defined as the top 6 inches of sediment.
3. ArcGIS Inverse Distance Weighted (IDW) interpolation settings: Power = 6, Neighbors = 8, Radius = 1,000 feet.
4. Where TPAH was not detected, 1/2 the reporting limit was used in the interpolation.
5. Basemap 2005 USGS aerial photograph. Does not show current conditions.
6. Projection: NAD 1983 StatePlane Washington North FIPS 4601 Feet.

Temporal TPAH Trends in Surface Sediment 1984-2005

Gas Works Park Site
Seattle, Washington

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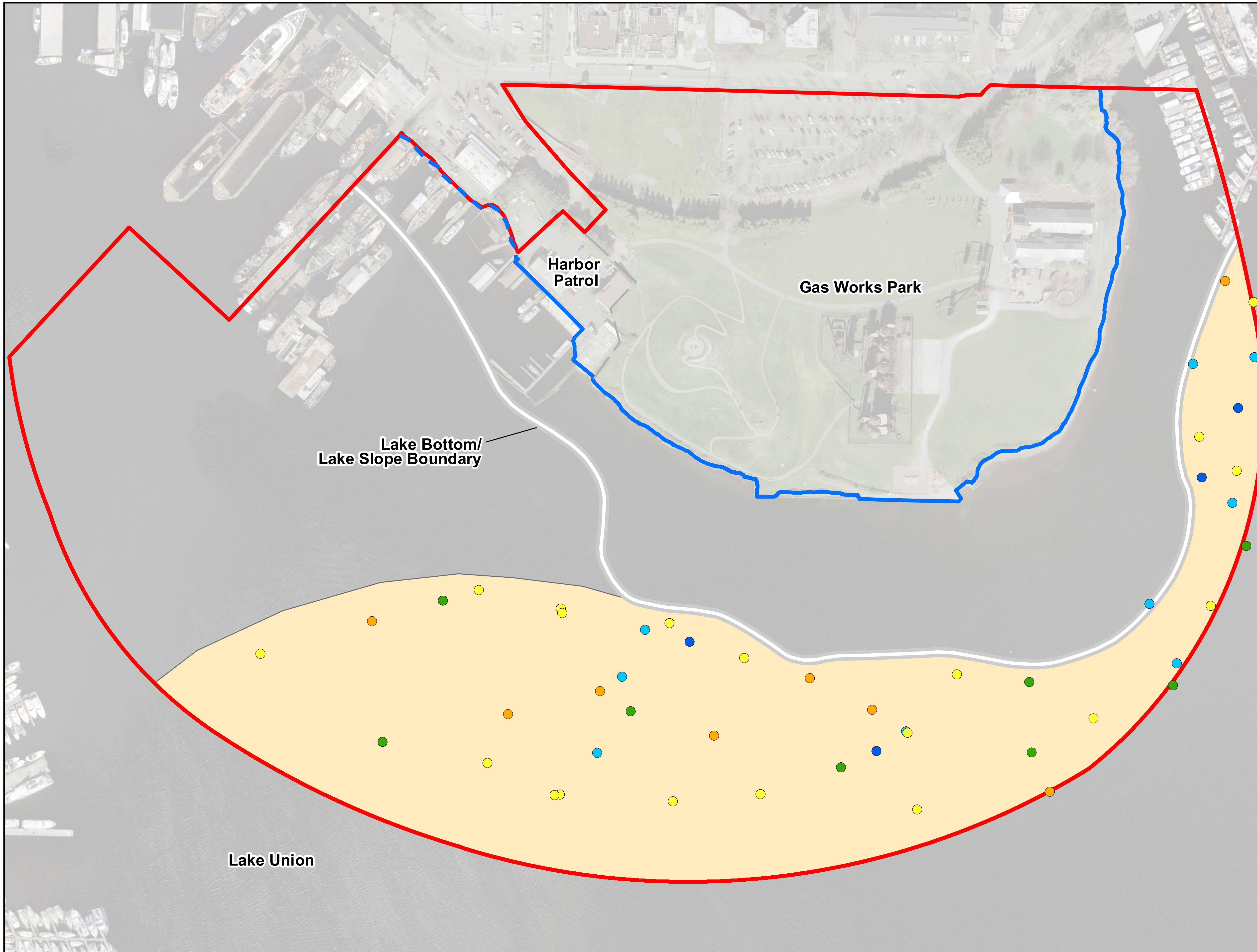
Figure 11C-2



Legend

- Area of Investigation
- Shoreline (OHWM)
- SMA-14

Samples Collected from:

- 1984 - 1985
- 1987-1998
- 1999 - 2001
- 2002 - 2003
- 2004 - 2005

Notes:

1. Basemap 2005 USGS aerial photograph. Does not show current conditions.
2. Projection: NAD 1983 StatePlane Washington North FIPS 4601 Feet.

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N W E S

200 0 200

Feet

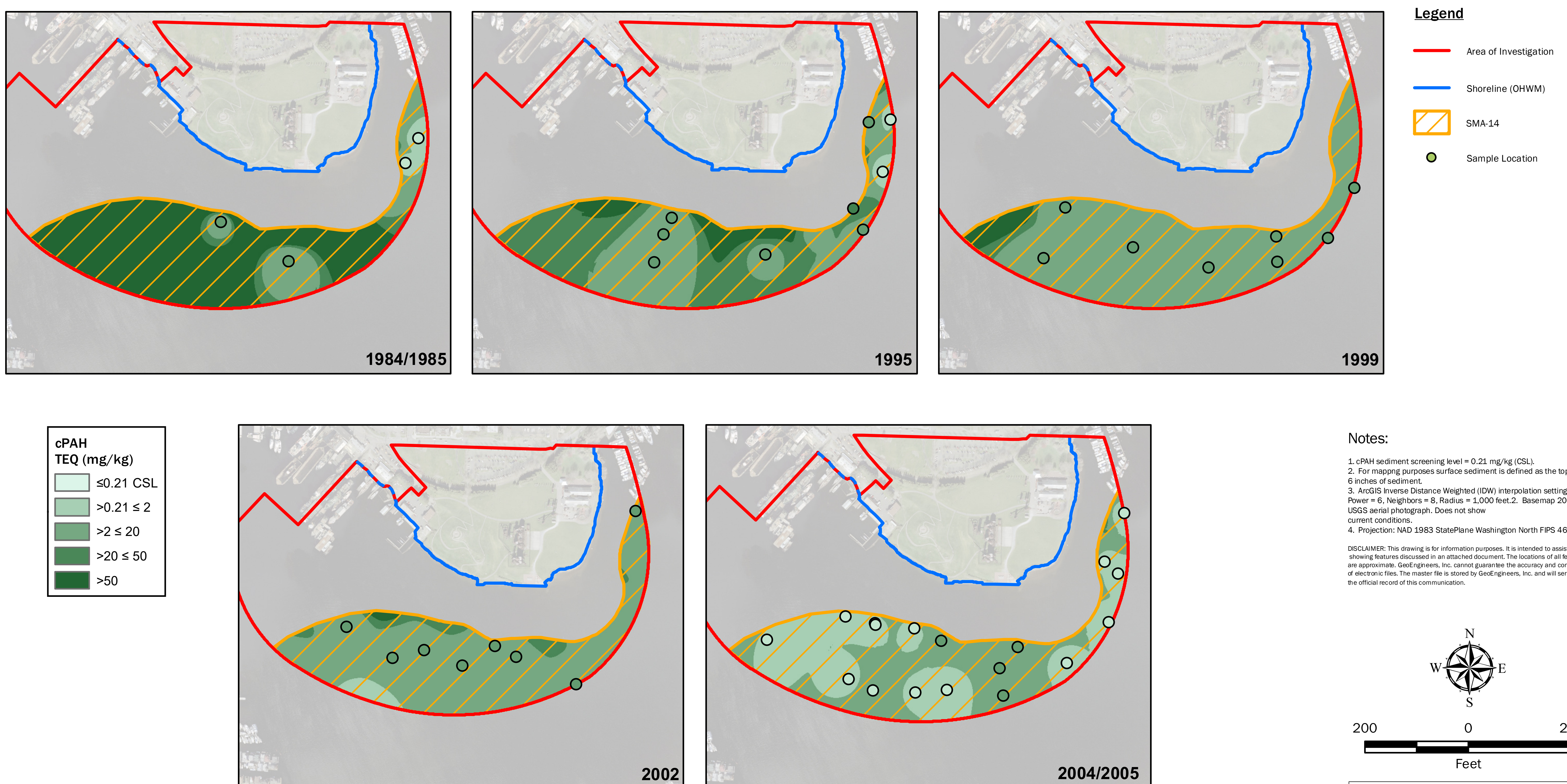
Surface Sediment Samples in SMA-14

Gas Works Park Site
Seattle, Washington

GeoEngineers

Figure 11C-3

Path: P:\0\0186846\GIS\MXD\Phase01\T1678\018684601_F11C-3_Natural_RecoveryAreaSamples2021.mxd Map Revised: 29 March 2022 maugust



Notes:

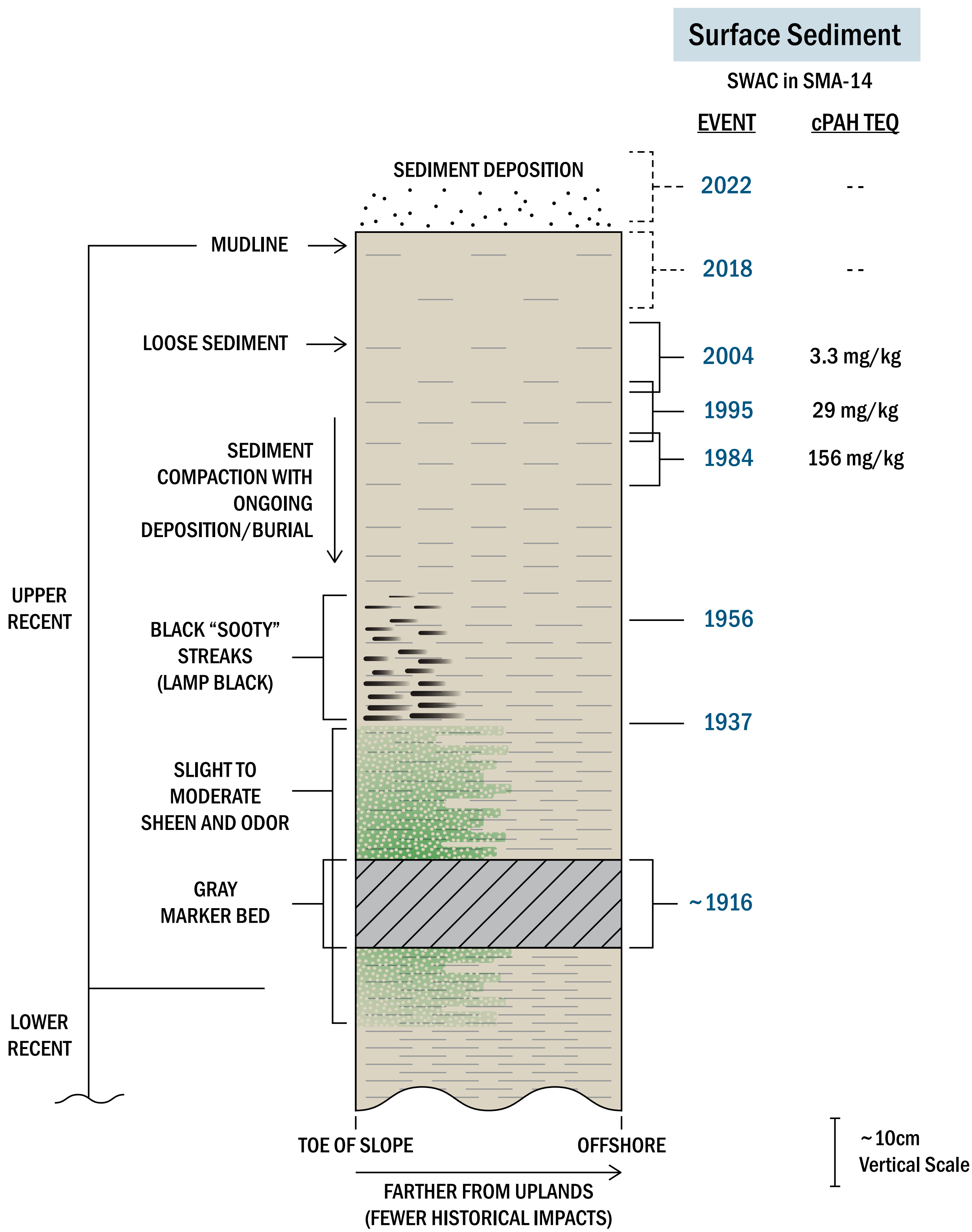
1. cPAH sediment screening level = 0.21 mg/kg (CSL).
2. For mappng purposes surface sediment is defined as the top 6 inches of sediment.
3. ArcGIS Inverse Distance Weighted (IDW) interpolation settings: Power = 6, Neighbors = 8, Radius = 1,000 feet.2. Basemap 2005 USGS aerial photograph. Does not show current conditions.
4. Projection: NAD 1983 StatePlane Washington North FIPS 4601 Feet.

Temporal cPAH TEQ Trends in SMA-14 Surface Sediment 1984-2005

Gas Works Park Site
Seattle, Washington

GeoEngineers **Figure 11C-4**

Path: P:\0\0186846\GIS\MXD\Phase01\T1678\0186846 01_F11C-4_cPAH_timeseries.mxd Map Revised: 17 May 2022 maugust



Representative Sediment Column Showing Natural Recovery in SMA-14

Gas Works Park Site
Seattle, WA

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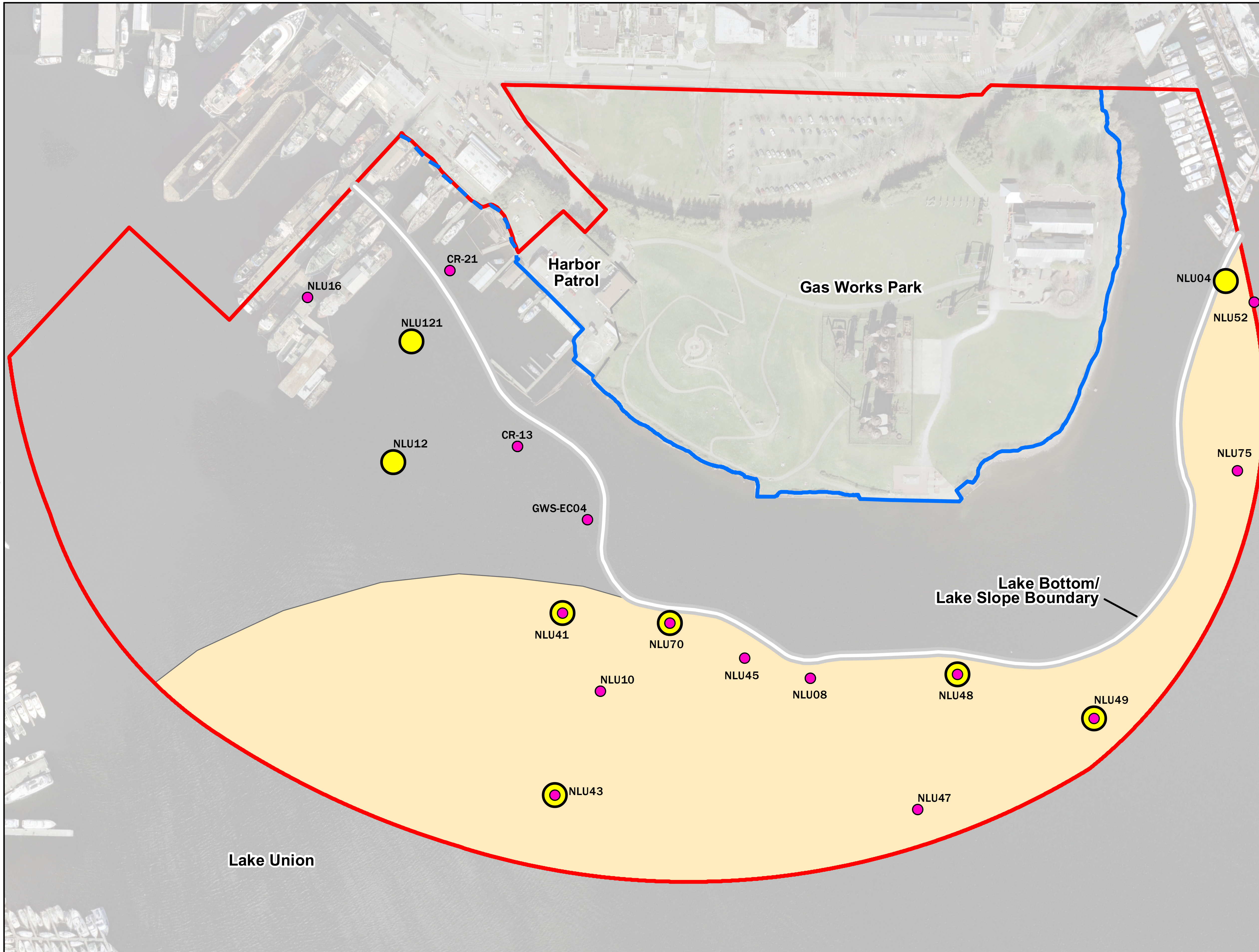
Figure 11C-5



Legend

- Area of Investigation
- Shoreline (OHWM)
- Sample Used to Estimate Deposition Rate
- Sample Used to Evaluate Vertical cPAH TEQ Concentration Trends
- SMA-14

Notes:

1. Basemap 2005 USGS aerial photograph. Does not show current conditions.
2. Projection: NAD 1983 StatePlane Washington North FIPS 4601 Feet.

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N W E S

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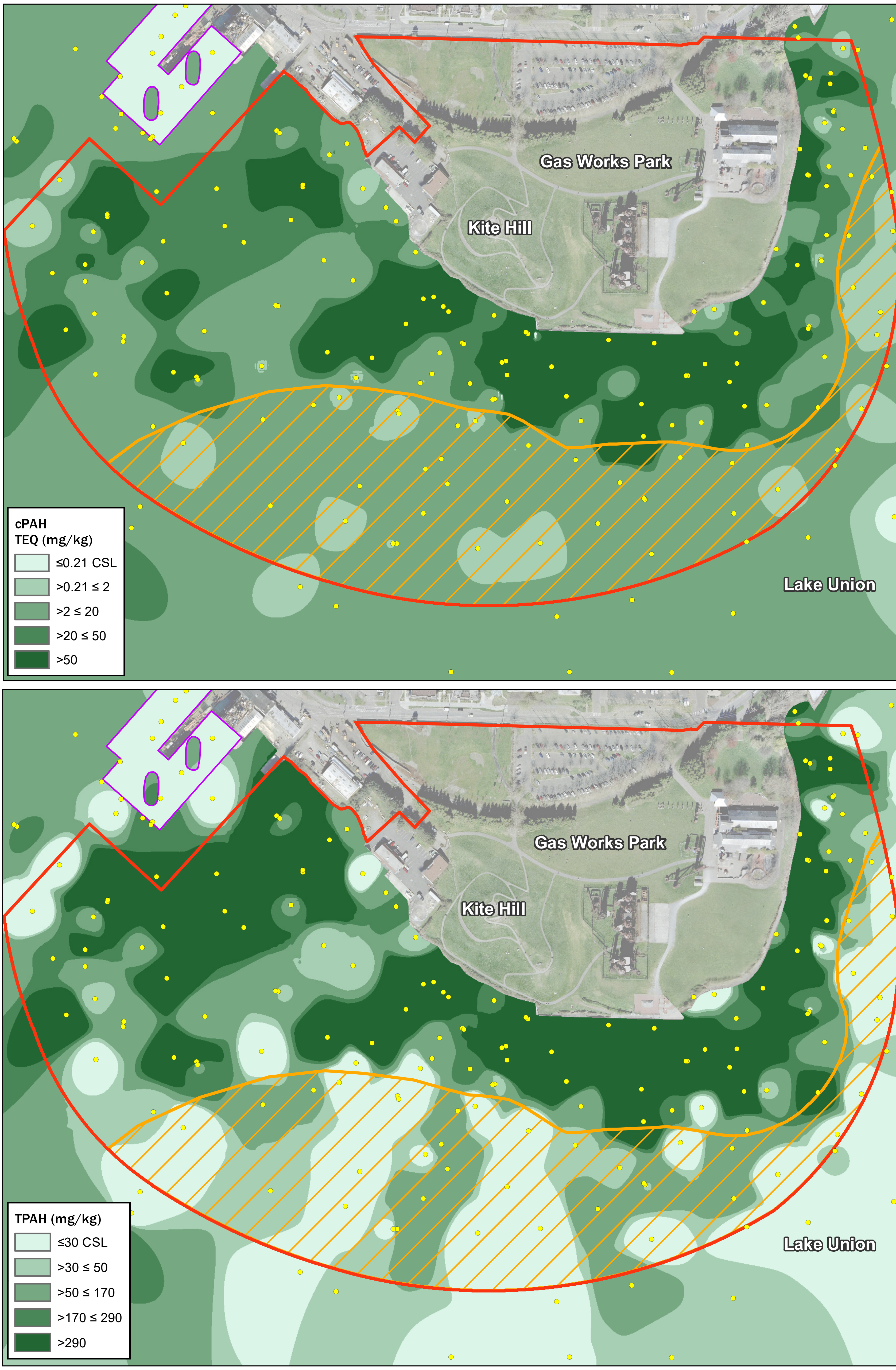
Feet

Samples Used to Estimate Deposition Rates and cPAH TEQ Vertical Trends

Gas Works Park Site
Seattle, Washington

GEOENGINEERS **Figure 11C-6**

Path: P:\0\0186846\GIS\MXD\Phase01\T1678\018684601_F11C-6_DepositionRates2021.mxd Map Revised: 29 March 2022 maugust



Legend

- Sample Location
- SMA-14
- Northlake Shipyard Dredged Area
- Area of Investigation (AOI)

Notes:

1. cPAH TEQ sediment screening level = 0.21 mg/kg CSL.
TPAH sediment screening level = 30 mg/kg CSL.
2. Interpolation settings: IDW - Power=6, Neighbors=8, Reach=1,000 ft
3. Projection: NAD 1983 StatePlane Washington North FIPS 4601 Feet
4. Basemap 2005 USGS aerial photograph. Does not show current conditions.

N
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Feet

cPAH TEQ and TPAH Concentrations in Surface Sediment Samples

Gas Works Park Site
Seattle, Washington

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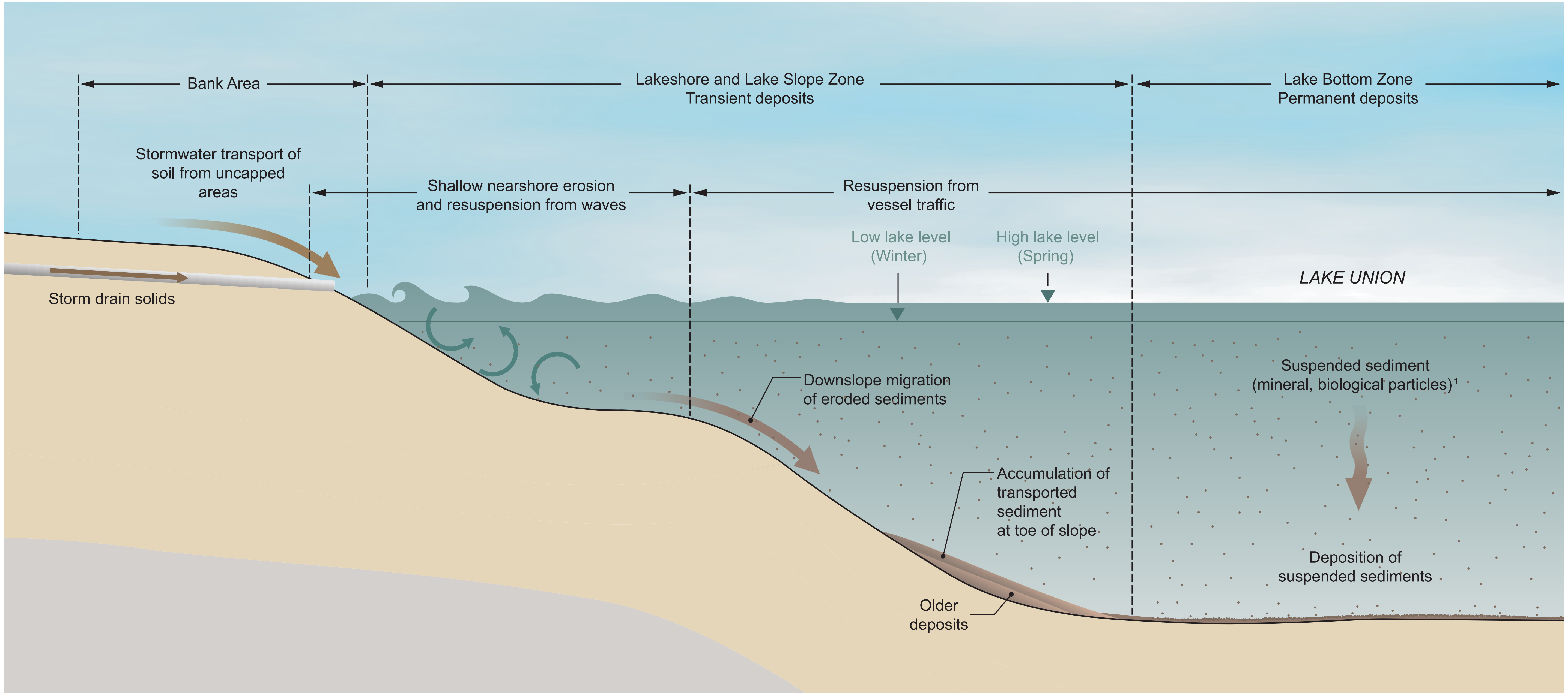
Figure 11C-7



Notes:

1. Mineral particles are sourced from suspended solids transported from Lake Washington and Union Bays, storm drain and combined sewer overflow discharges, erosion of Lake Washington shoreline, and sediment resuspended in nearshore areas. Biological particles are from plankton, diatoms and decaying terrestrial and aquatic plant material.

Physical Processes Affecting Natural Recovery

Gas Works Park Site
Seattle, Washington

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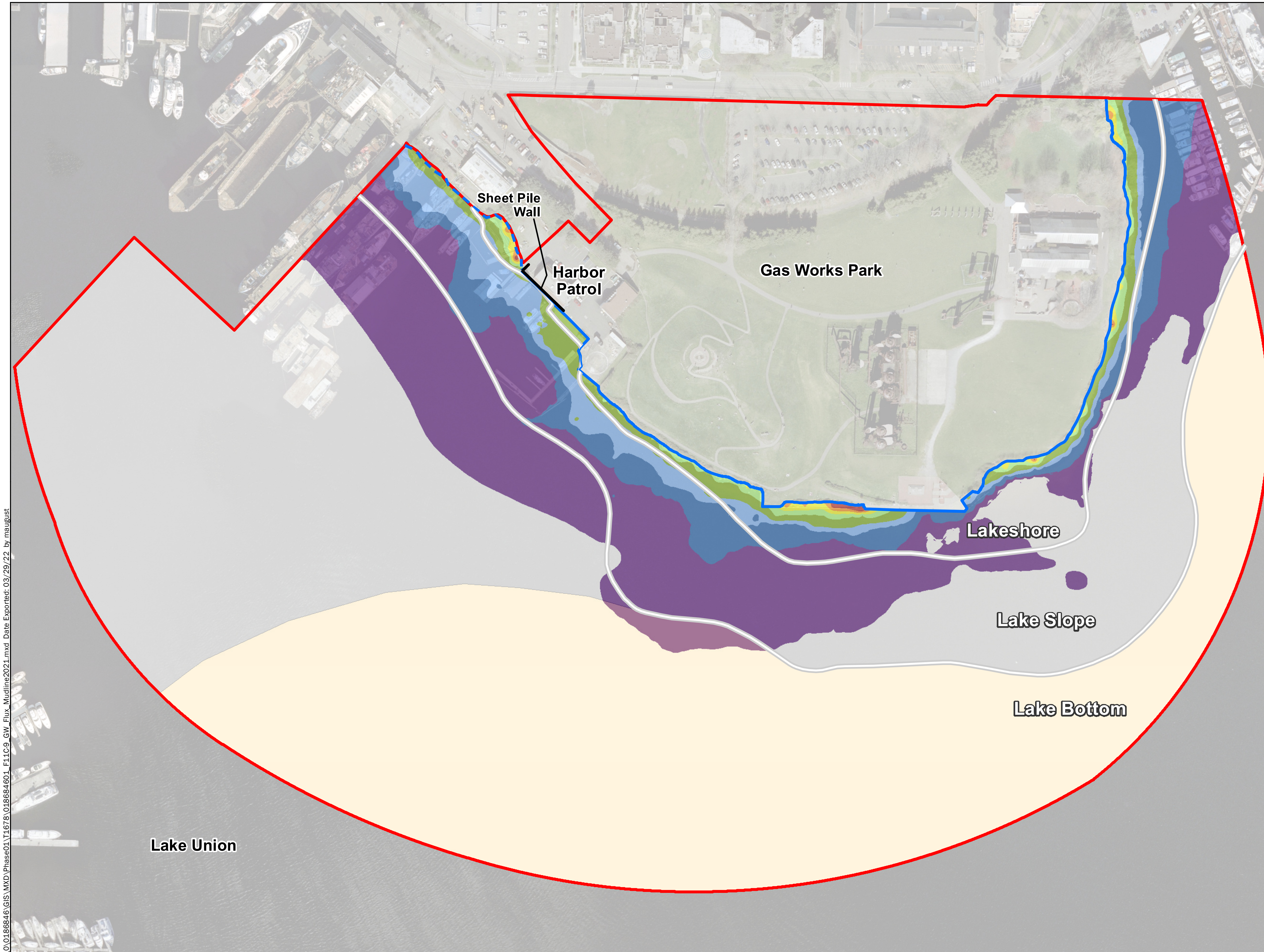
Figure 11C-8

P:\0\0186846\Graphics_Misc\Figure 6-8 - Physical Processes Affecting Natural Recovery in Lake Bottom.ai Exported 4/29/21 by spride



Legend

Area of Investigation

Shoreline (OHWM)

Mudline Discharge (feet/day)	% Total Discharge	% Cumulative Discharge
>0.05	3%	3%
0.05 - 0.04	5%	8%
0.04 - 0.03	9%	17%
0.03 - 0.02	18%	35%
0.02 - 0.01	29%	64%
0.01 - 0.005	17%	81%
0.005 - 0.001	11%	92%
0.001 - 0.0001	6%	98%
<0.0001	2%	100%

SMA-14

Notes:

1. Calculated discharge through the fill and outwash at the shoreline within the AOI is 1,660 cfd. Shoreline fill and outwash groundwater discharges to Lake Union nearshore in the area where mudline discharge is less than 0.001 ft/day (i.e., Groundwater Discharge Zone).
2. Mudline discharge data from Anchor QEA 2018.
3. Basemap 2005 USGS aerial photograph. Does not show current conditions.
4. Projection: NAD 1983 StatePlane Washington North FIPS 4601 Feet.

N
W E
S

200 0 200

Feet

Estimated Groundwater Discharge at Mudline

Gas Works Park Site
Seattle, Washington

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Figure 11C-9

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