SEATTLE HARBOR
NAVIGATION IMPROVEMENT PROJECT

APPENDIX B

Engineering

Final Integrated Feasibility Report and Environmental Assessment

US Army Corps of Engineers®
Seattle District

Port of Seattle®

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U.S. Army Corps of Engineers, Seattle District

Seattle Harbor Navigation Improvement Project

Engineering Appendix

1 Contents

1. Physical Environment

The Seattle Harbor Navigation Project is located on the Lower Duwamish River in Seattle, Washington in the in Central Puget Sound Basin. The project consists of the East, West, and Duwamish Waterways all with varying authorized depths (Table B-1). The federal navigation project includes 7.75 miles of channel. The current Seattle Harbor Navigation Improvement Project (NIP) is investigating channel deepening and widening on only the East and West Waterways (Figure B-1).

1.1 Climatology

Average annual precipitation over the Seattle area is 34 inches and is relatively low compared to the adjacent areas where moisture laden air masses are forced up the sides of the Cascade and Olympic Mountains creating over 100 inches of precipitation per year. Over half of the annual precipitation occurs in the four month period from October to January. Average annual air temperature in the region is 52° F. Summer temperatures normally range in the 60's and 70's and winter temperatures in the 40's and 50's.

1.2 Streamflow characteristics

The Green–Duwamish River flows 93 miles from the crest of the Cascade Mountains to its mouth in Puget Sound (Figure B-2). The Duwamish River is the seventh largest freshwater discharge into Puget Sound (Czuba et al. 2011). Historically, the White, Green, and Cedar Rivers flowed into the Duwamish River and drained an area of over 1,600 square miles (Kerwin and Nelson 2000). However, major alterations of the Green-Duwamish watershed have taken place over the last century resulting in many changes to the drainage area. In 1911, the White River was diverted to the Puyallup River for flood control resulting in a loss of 30% of the original watershed area. In 1916, the Black and Cedar Rivers were diverted from the Duwamish River into Lake Washington to improve navigation, resulting in a loss of 40% of its original watershed area. In 1962, Howard A. Hanson Dam was constructed at River Mile (RM) 64.5 for flood control. Currently, the Green-Duwamish River basin has a drainage area of 483 square miles. Regulated flow from Howard Hanson dam maintains a high-low discharge of 12,000 to 300 cubic feet per second on the Duwamish River.

At RM 11, the Green becomes the Duwamish River, which flows through a heavily industrialized area of Seattle and then enters Elliott Bay. The lower 11 miles of the estuary is highly stratified with a distinct salt water wedge intruding beneath a freshwater lens. The salt wedge migrates with tide and the amount of freshwater discharge from the river. The average daily discharge reported at the USGS 12113000 Green River gauge at Auburn is 1,345 ft^3/s. The peak regulated discharge of 12,400 ft^3/s was observed on February 8, 1996. At the river mouth, the flow on the Duwamish is diverted into the East and West Waterway near the head of Harbor Island. Harbor Island is a large artificial island constructed in 1919 from dredged material used to create the East and West Waterways. The majority of freshwater flow from the Duwamish River is diverted into the West Waterway as a shallow sill separates the Duwamish Waterway from the East Waterway.

Table B-1. Existing Seattle Harbor Federal Navigation Project - Channel Reach and Stationing

Channel reach	Authorized depth (feet, MLLW)	Channel Station	Within NIP
East Waterway	**-51**	**0+00 to 46+78**	**Yes**
East Waterway	**-34**	**46+78 to 72+32**	**Yes**
West Waterway	**-34**	**0+00 to 61+09**	**Yes**
Duwamish Waterway	-30	0+00 to 134+00	No
Duwamish Waterway	-20	134+00 to 176+00	No
Duwamish Waterway	-15	176+00 to 275+56	No

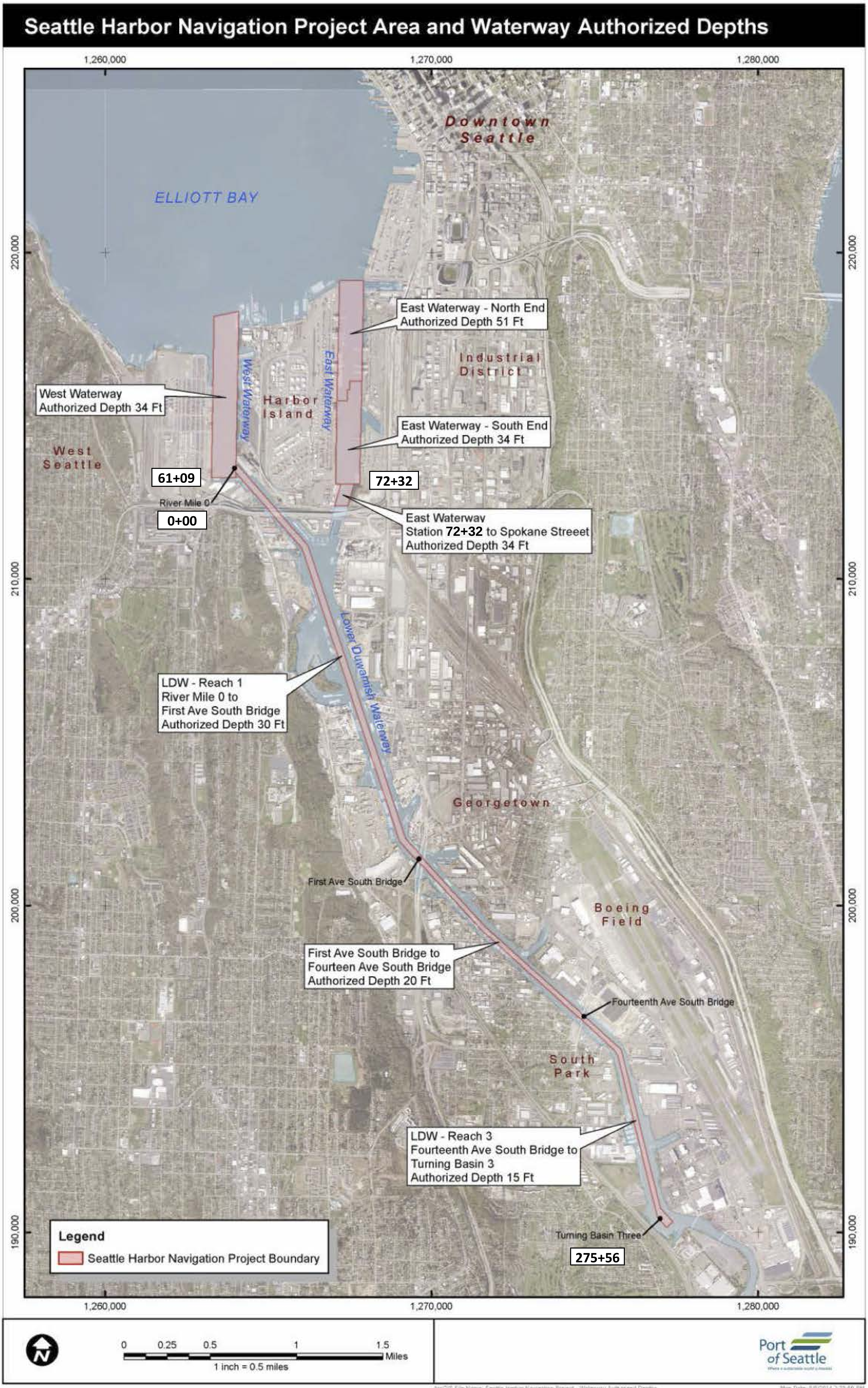

Figure B-1. Seattle Harbor – Existing Federal Navigation Project

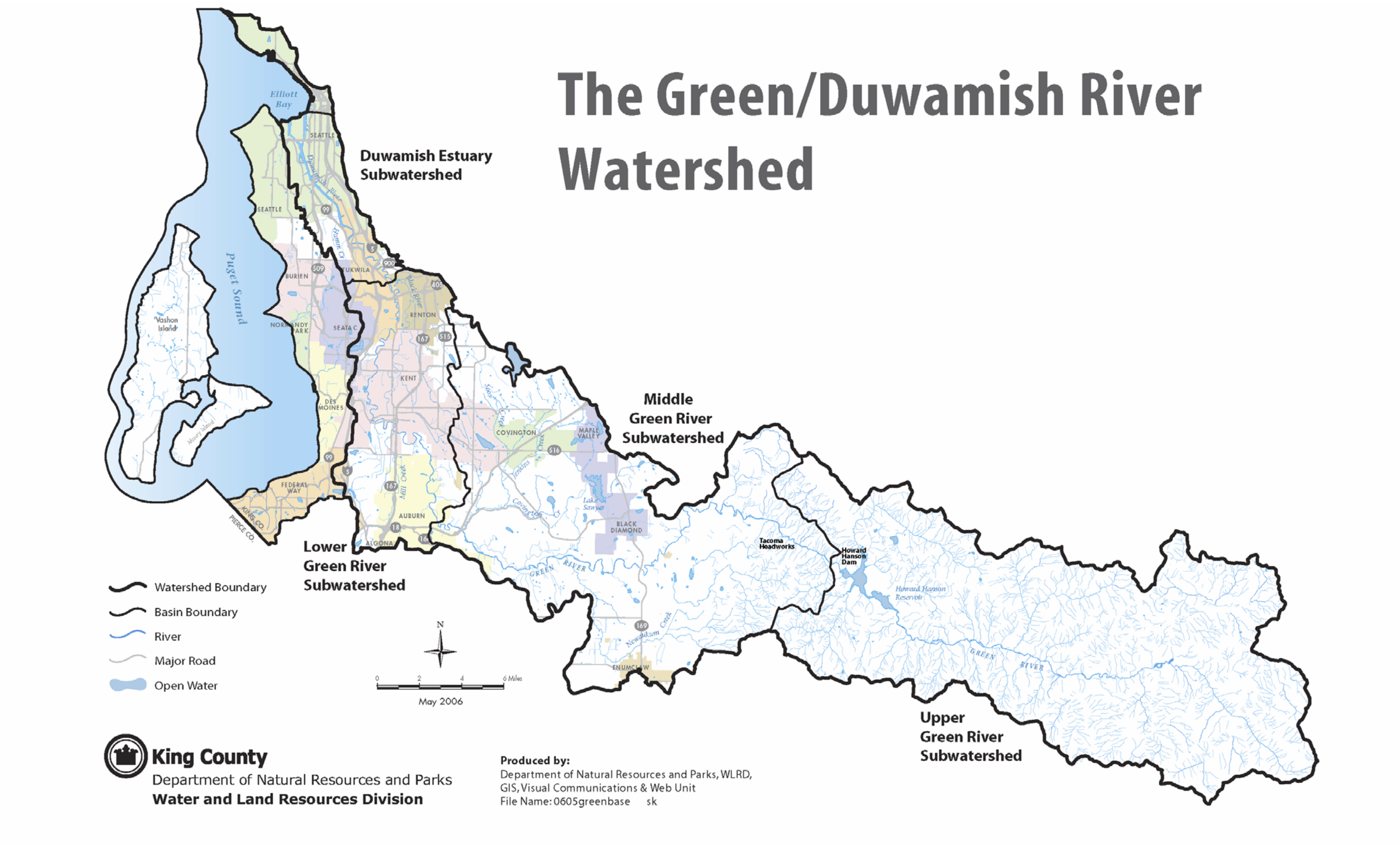

Figure B-2. Green/Duwamish River Basin

1.3 Tides

Tides in Seattle Harbor have the diurnal inequality typical of the U.S. West Coast. Tidal datums for Seattle are listed in Table B-2. The mean diurnal tidal range for Seattle published by the National Ocean Survey is 7.66 feet. The great diurnal tidal range for Seattle is 11.36 feet. Observed water levels are primarily a function of astronomical tide influences. However anomalies from the predicted astronomical tide occur due to factors including changes in atmospheric pressure, wind set-up, wave set-up, and river discharge.

Table B-2. Tidal Datum at Seattle, WA, NOS Station 9447130

Datum	Water Level
Highest Observed Water Level	14.48
Mean Higher-High Water (MHHW)	11.36
Mean High Water (MHW)	10.49
Mean Tide Level (MTL)	6.66
Mean Low Water (MLW)	2.83
North American Vertical Datum (NAVD)	2.34
Mean Lower Low Water (MLLW)	0
Lowest Observed Water Level	-5.04

1.4 Sea Level Change

Sea level change is an uncertainty, potentially increasing the frequency of extreme water levels. Planning guidance in the form of an USACE Engineering Regulation (ER), USACE ER 1100-2-8162 (USACE 2013), incorporates new information, including projections by the Intergovernmental Panel on Climate Change and National Research Council (IPCC 2007, NRC 2012). The ER requires that projects be evaluated to determine how sensitive they are to various scenarios of future sea-level change (SLC). Since predictions of future SLC have uncertainty, the risks associated with three SLC scenarios are analyzed. These scenarios are termed low, intermediate, and high and correspond to different rates of global sea level acceleration. Historically, this global (eustatic) sea level rise rate has been approximately 1.7 millimeters (mm) per year.

Locally, SLC varies geographically as it is the difference between the global SLC (1.7 mm/year according to IPCC 2007) and local vertical land movement (VLM). The accuracy of local mean sea level rates is a function of the period of record of the water level time series. ER 1100-2-8162 recommends that a National Oceanic and Atmospheric Administration (NOAA) water level station should be used with a period of record of at least 40 years. The historic sea level change observed in Seattle since 1899 is shown in Figure B-3. Table lists the predicted SLC at Seattle, Washington for the low, intermediate (Int), and high scenarios. At the end of the 50 year project life cycle, the predicted sea level rise at the project ranges from 0.55 to 3.05 feet.

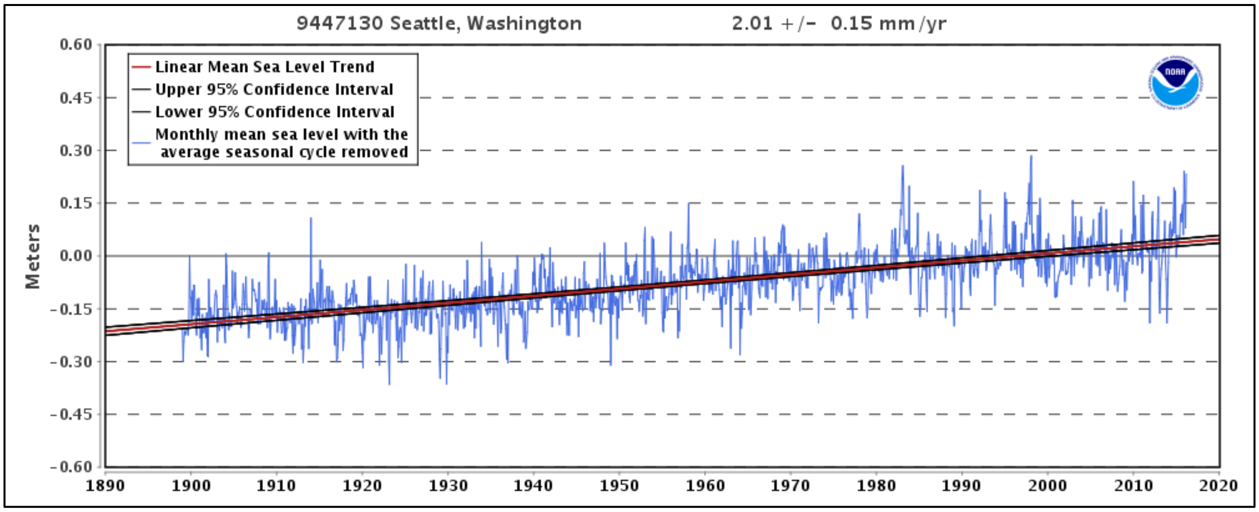

Figure B-3. Sea level change rate in Seattle, WA from 1899 to 2015 (from NOAA/NOS CO-OPS)

1.5 Currents

Figures B-4 through B-7 display velocity magnitude (color contours) and direction (vectors) during four tidal stages (peak ebb, peak flood, low water slack, and high water slack) predicted by the Environmental Fluid Dynamics Code (EFDC) depth averaged hydrodynamic model during average flow conditions (Hayter et al. 2015). In general currents in each waterway are less than 1 knot (0.5 meters per second) during all tidal phases. The currents are stronger in the West Waterway during ebb tides (Figure B-4) as the West Waterway receives the majority of freshwater flow from the Duwamish River. The currents are oriented slightly northwest toward Terminal 5 during the ebb tide. This effect has been described by the harbor pilots and requires tug assistance to counteract this westward drift.

Table B-3. Predicted sea level change (in feet) at Seattle, Washington per ER 1100-2-8162

Year	Low	Int	High	Year	Low	Int	High
2024	0.22	0.31	0.60	2074	0.55	1.15	3.05
2025	0.22	0.32	0.63	2080	0.60	1.28	3.47
2030	0.26	0.39	0.79	2085	0.63	1.40	3.84
2035	0.29	0.46	0.98	2090	0.66	1.52	4.22
2040	0.32	0.53	1.18	2095	0.70	1.64	4.63
2045	0.36	0.61	1.40	2100	0.73	1.77	5.05
2050	0.39	0.69	1.64	2105	0.76	1.90	5.50
2055	0.43	0.78	1.90	2110	0.80	2.04	5.96
2060	0.46	0.87	2.17	2115	0.83	2.18	6.44
2065	0.49	0.97	2.47	2120	0.87	2.32	6.94
2070	0.53	1.07	2.78	2124	0.89	2.44	7.35

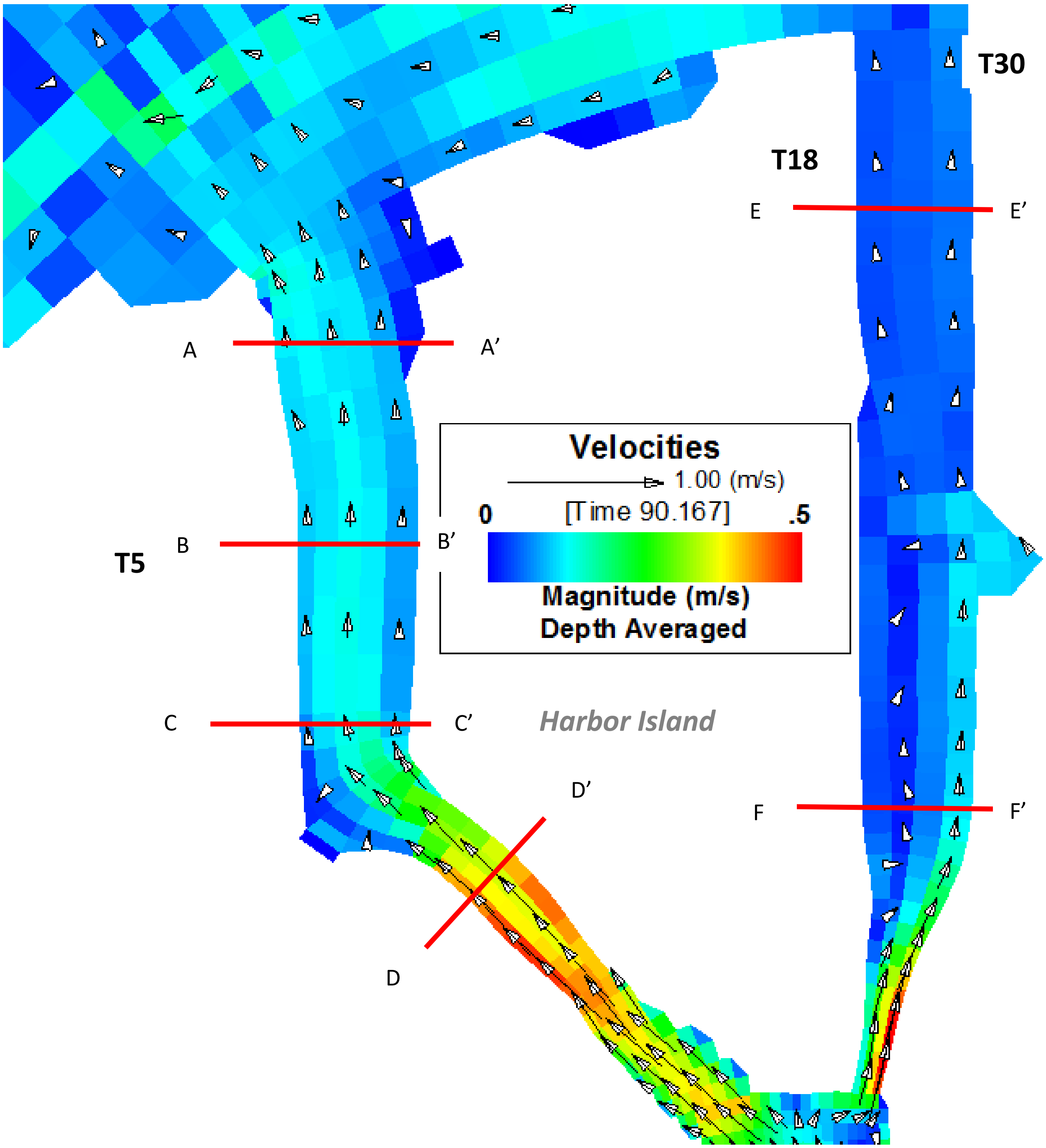

Figure B-4. EFDC depth averaged current velocities during peak ebb tidal phase

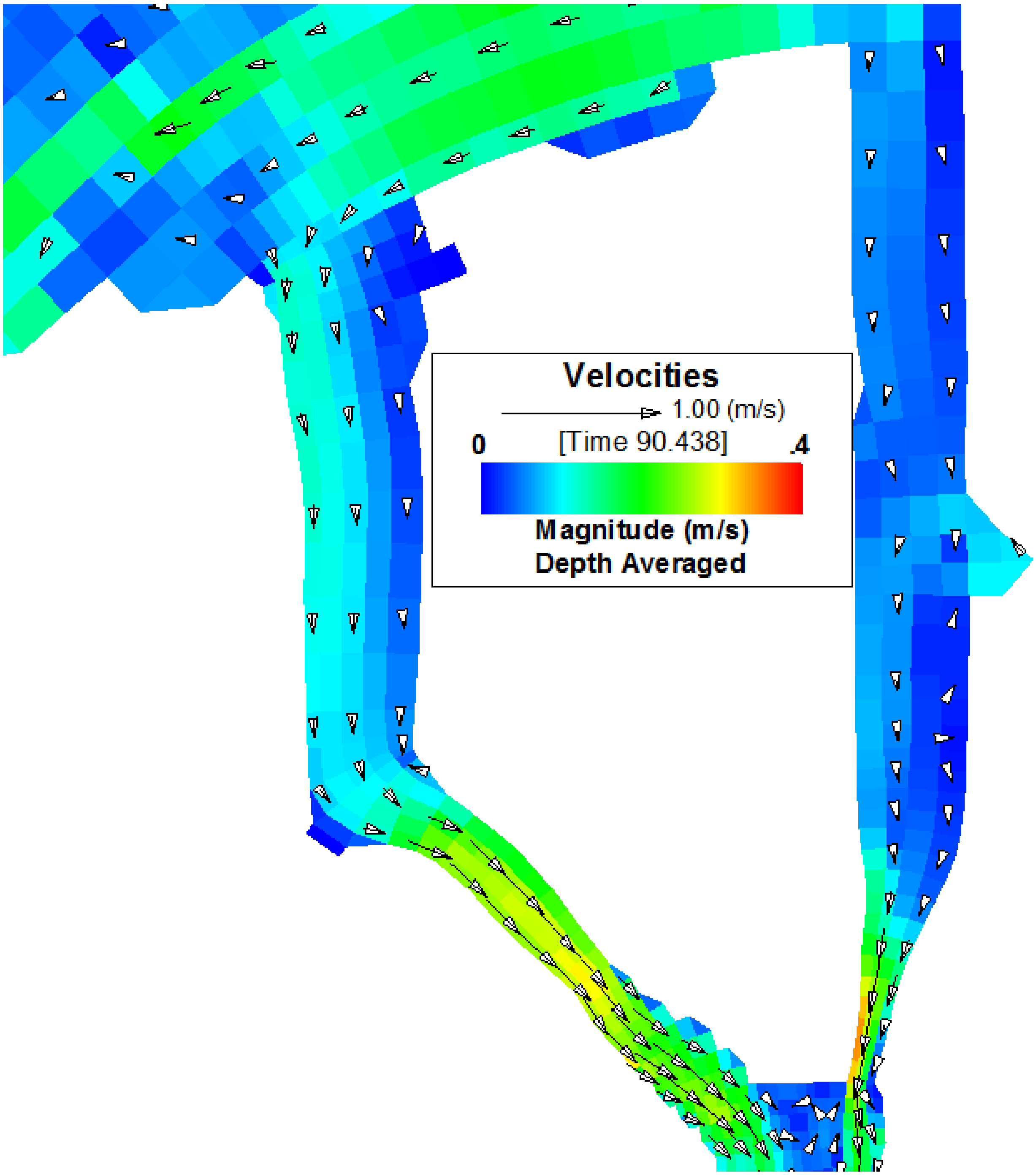

Figure B-5. EFDC depth averaged current velocities during <u>peak flood</u> tidal phase

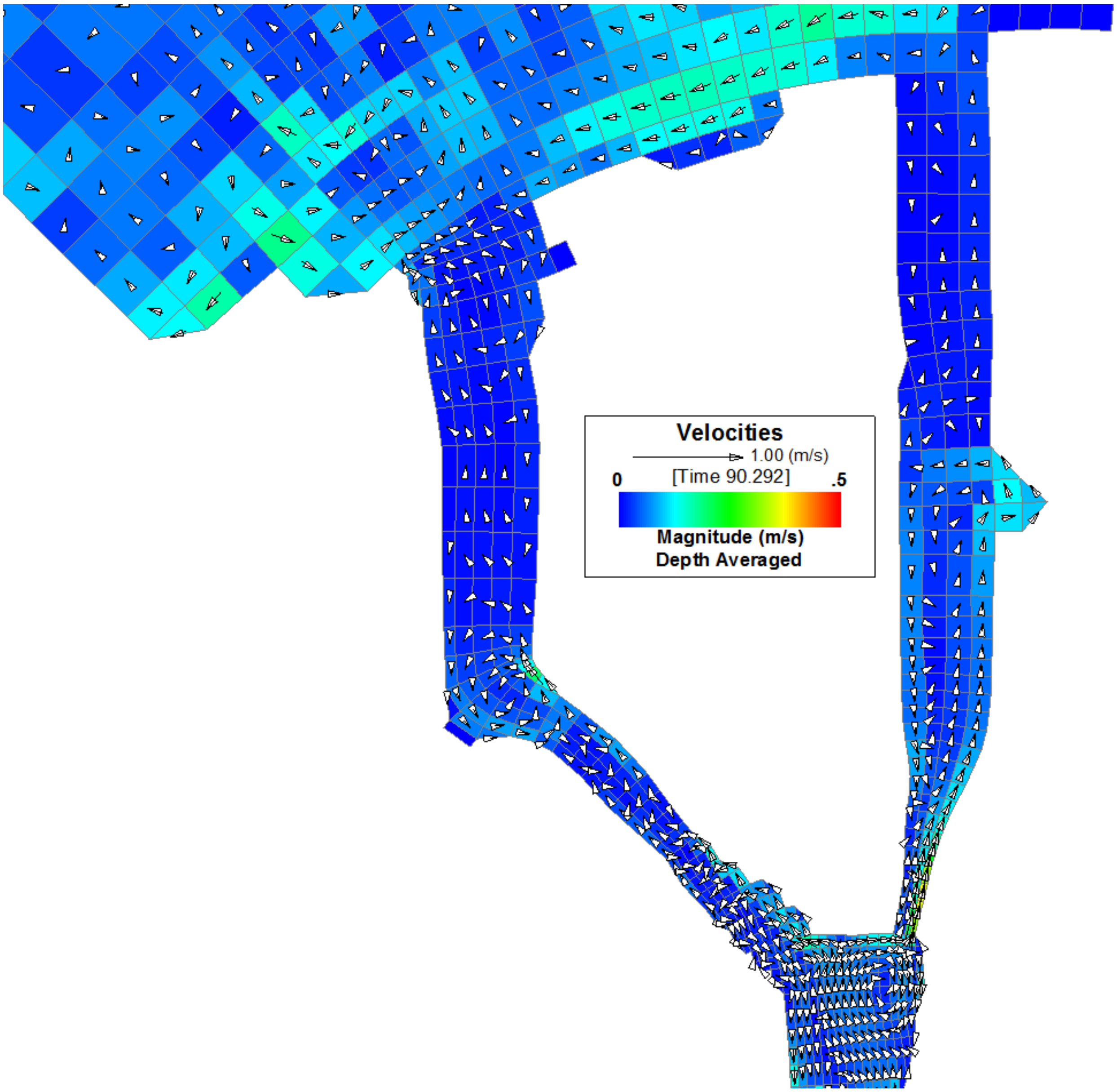

Figure B-6. EFDC depth averaged current velocities during <u>low water slack</u> tidal phase

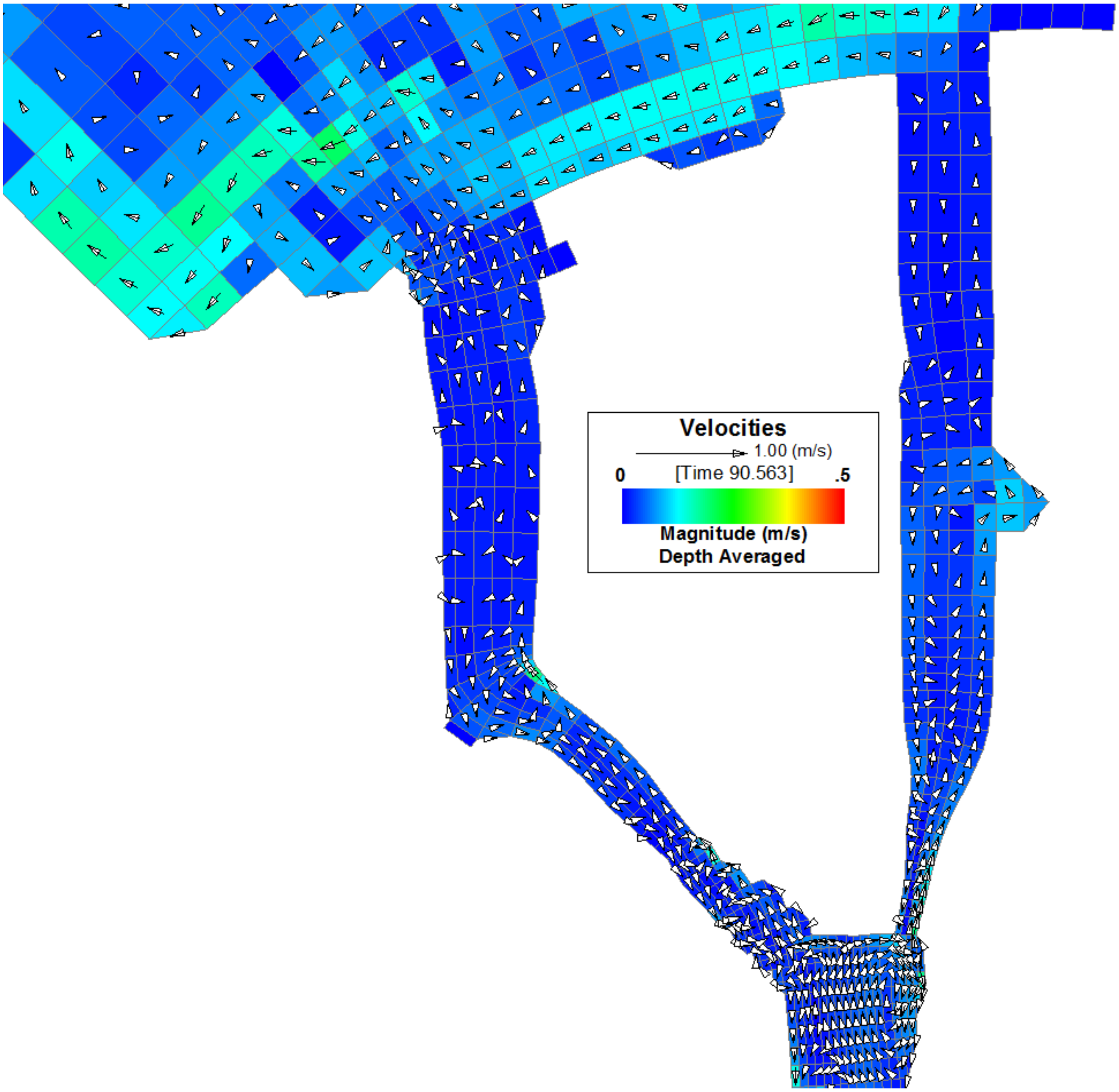

Figure B-7. EFDC depth averaged current velocities during high water slack tidal phase

1.6 Winds

The seasonal cycle of winds over the northeast Pacific Ocean is largely determined by the circulation about the North Pacific high pressure area and the Aleutian low pressure area which drives the jet stream over the North Pacific. During the summer months, the high reaches its greatest development. In July the center of highest pressure is located near latitude 35° N., longitude 150° W. During this period, the Aleutian low is almost nonexistent. This pressure distribution causes predominantly northwest and north winds over the coastal and near offshore areas of Oregon and Washington. The high weakens with the approach of the winter season and by November is usually little more than a weak belt of high pressure lying between the Aleutian low and the equatorial belt of low pressure. These traveling depressions moving eastward cause considerable day-to-day variation in pressure, particularly in the area north of latitude 40° N.

As shown in Figure B-8, in Seattle the prevailing wind direction is out of the south and north. The strongest winds originate from the southerly directions and have recorded 2 minute average wind speeds exceeding 40 feet per second (ft/s).

1.7 Waves

Waves in Puget Sound are fetch limited. The largest waves are generated from winds blowing out of the south, or the longest fetch length in in Central Puget Sound Basin. The southern shoreline of Elliott Bay and the Seattle Harbor project is sheltered from these wave events. Winds out of the west and northwest are less frequent and calmer but still result in the largest wave heights at the Entrance to the East and West Waterway (Figure B-9). Wind generated waves near the Entrance to the East and West Waterways are typically less than 2 feet in height (Figure B-10).

1.8 Sedimentation

An annual average sediment load on the Duwamish is estimated at 210,000 tons per year (Czuba et al. 2011). However, the seasonal and yearly variation can be quite large. During a field campaign from 1996 to 1998, the annual sediment load varied between 59,000 and 500,000 tons per year and approximately 65% of the sediment load occurs during the three winter months (Embrey and Frans 2003). The majority of sedimentation affecting the Seattle Harbor project occurs in the Duwamish Waterway between the Turning Basin and the First Ave. Bridge. Sedimentation in the East and West Waterways is low. Analysis of historic condition surveys from 2011 to 2016 indicate sedimentation to be approximately 2,700 cubic yards (CY) per year in the West Waterway and 3,800 CY per year in the East Waterway (Figure B-11). The region showing greatest shoaling (cool colors) occurs at the entrance of the West Waterway, where suspended sediments coming from the Duwamish River settle out in the deep water of Elliott Bay. The analysis shows areas of significant scour (hot colors) near the berthing areas at T-5, T-18, and T-46, likely caused by vessel propeller wash.

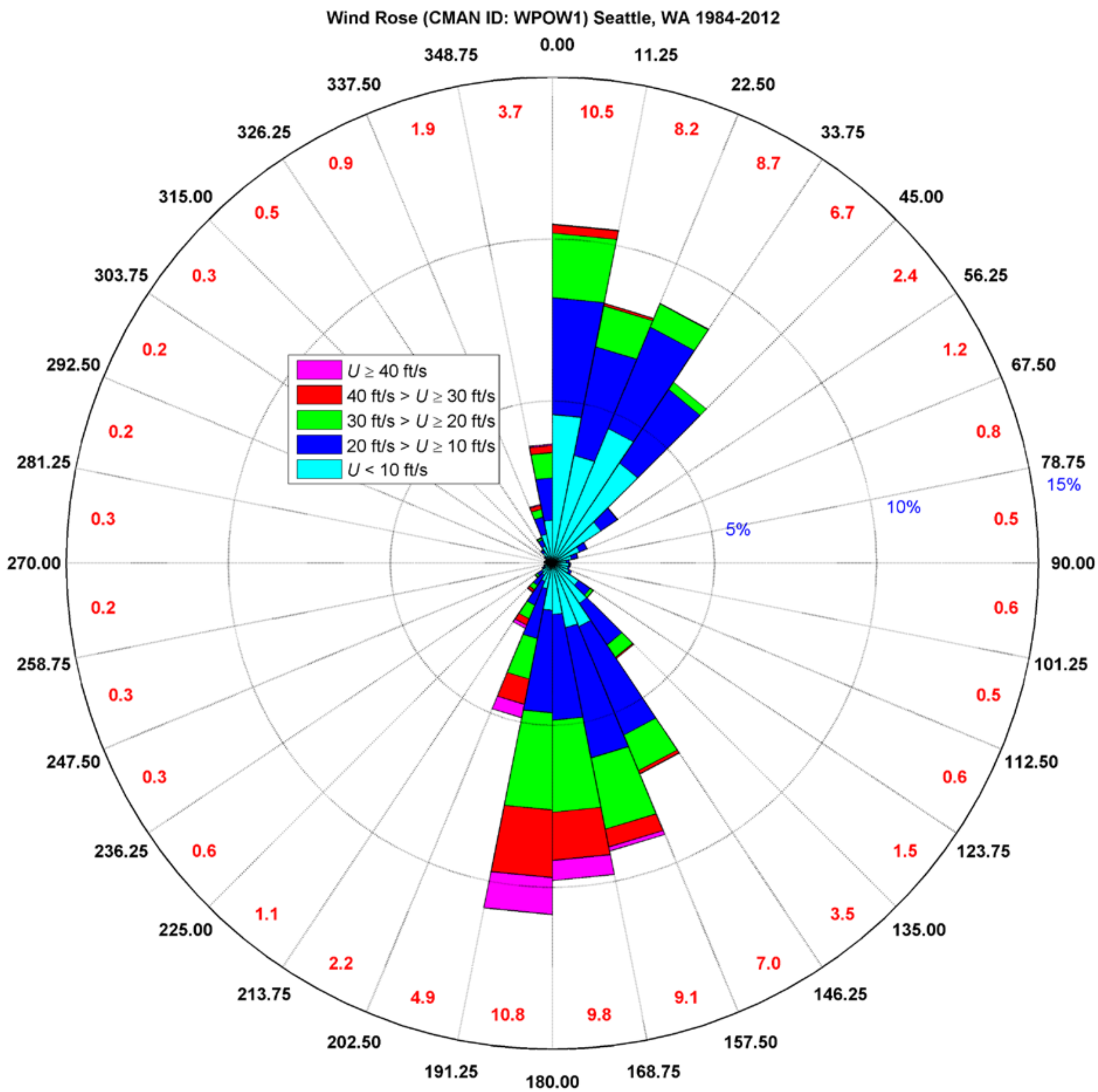

Figure B-8. Wind Rose of 2-minute average wind speeds (Seattle, WA). Circular rings denote frequency of occurrence

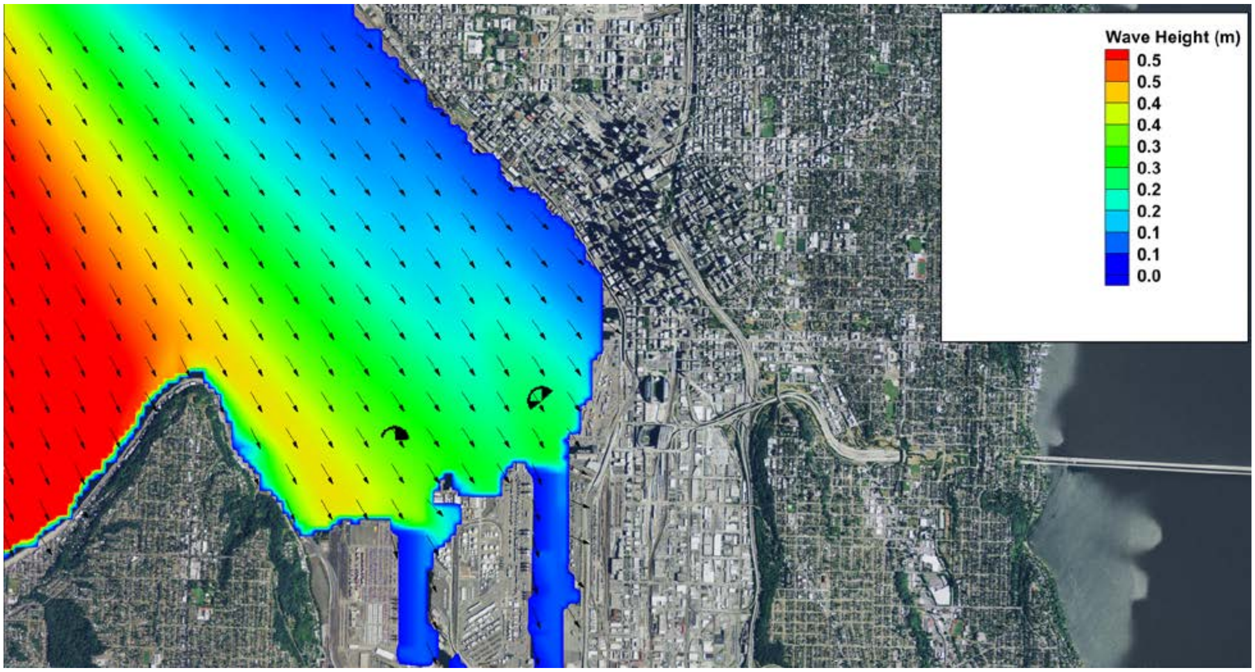

Figure B-9. CMS-WAVE modeled wave height for incident wind speed of 30 ft/s and Dir = 337.5 °.

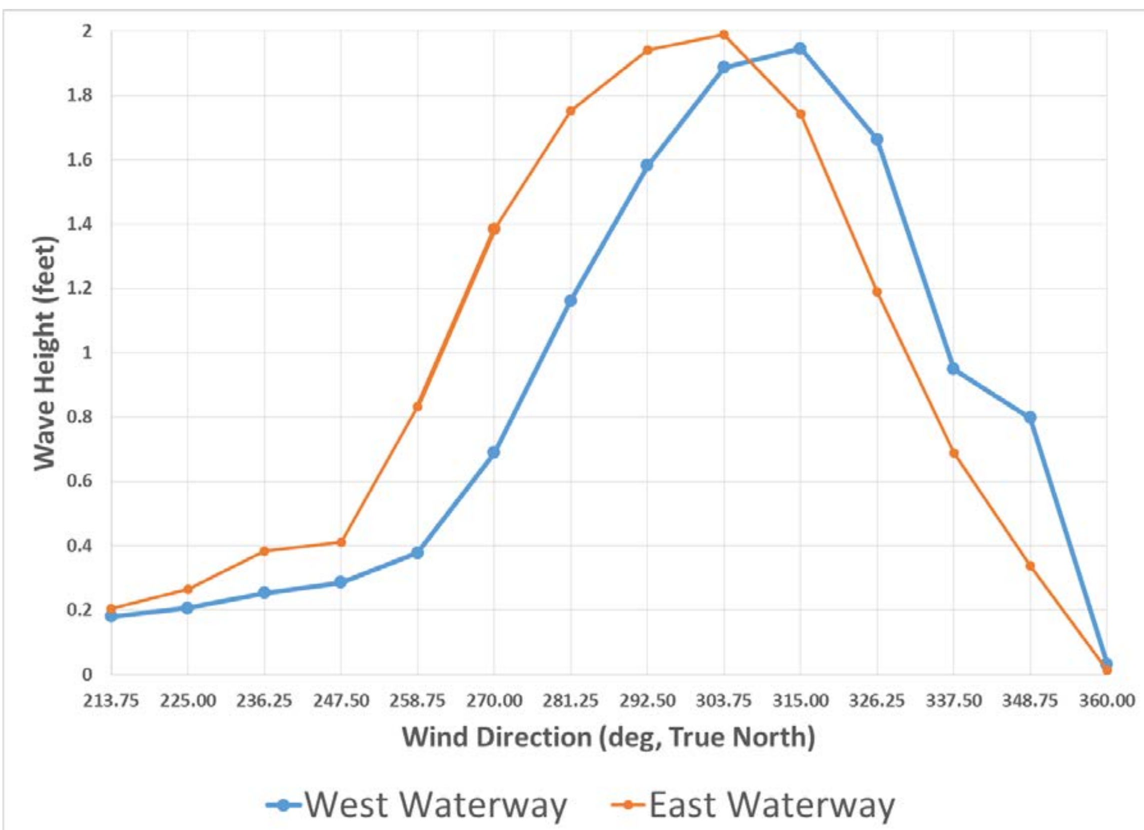

Figure B-10. CMS-WAVE computed wave height at the entrance to the East and West Waterway for a 30 ft/s wind event at various incident directions.

1.9 Geotechnical Considerations

1.9.1 Geology

The Duwamish River valley widened and deepened during the last major Pleistocene ice sheet advance (Vashon). During this period, ice scoured the valley as it advanced southward, depositing a mantle of till. The mantle forms the cap of the adjacent ridges but lies below the present valley floor. As the continental ice sheet retreated, glacial outwash (silt, sand, gravel cobbles) deposited in the lower valley. Subsequent sea level rise drowned the lower (north) end of the valley. Stream processes, largely from the White River, formed a long alluvial delta, forcing the marine environment back northward to its current position. As a result of these geological processes, the lower valley contains a mixture of fine grained, unconsolidated alluvial and marine sediments which are underlain at depth by coarser grained glacial sediments. Subsurface exploration indicates that bedrock is approximately 250 feet below sea level (USACE 1983).

1.9.2 Subsurface exploration

Recent subsurface borings have been collected for the ongoing CERCLA project on the East Waterway (Winward 2010; Anchor QEA 2012). In January 2010, 18 geochronological cores were collected by divers using a manually operated slide hammer in effort to estimate the sedimentation rate in the waterway (Figure B-12). The maximum length of these cores was 90 cm (3 feet). In March 2010, 65 cores subsurface borings (Shelby tube/split spoon) and vibracores were collected with a typical penetration depth of 14 feet below the mudline (Figure B-13). Recovery of the vibracores ranged from 70 to 100%.

In February 2015, 23 vibracores were collected in the West Waterway by the Port of Seattle in effort to determine the suitability of material for open water disposal at the Elliott Bay site for this project (USACE 2015a; Anchor QEA 2015). Typical penetration depths were 12 feet below the mudline. Recovery of the vibracores ranged from 75 to 100% (Figure B-14).

Surface sediments in each waterway are predominantly sands and silts, with smaller fractions of gravels and clays. Native sediments are predominantly a sand matrix (95% and non-silty) with laminated and stratified beds of slightly silty to silty sand, and silt. The sand matrix consisted of multicolored grains of red, beige, black, white, and gray. Layers of undecomposed wood and shells were often present in the matrix. The native sand unit typically graded to stiff, inorganic silt as depth increased (Winward 2010). The median grain size measured in the East Waterway samples ranged from 0.012 to 0.055 millimeters (mm), or fine silt. In general the grain size increases from south to north in the East Waterway. In the West Waterway the median grain size ranges from 0.047 to 0.375 mm, or coarse silt to medium sand. On the West Waterway, sediments become stiffer with depth, but penetration in excess of 10 feet was commonly found during the vibracore field collection. This indicates dredging production may slow with depth, but a clamshell bucket should be sufficient for dredging to the required depth. Wet bulk density measured in samples in the East Waterway ranged from 1.16 to 2.00 grams per cubic centimeter (g/cm^3).

New subsurface samples will be conducted in the Pre-Construction Engineering and Design phase (PED) to ensure the dredge area is sufficiently characterized. A strategic risk-based decision was made to delay collection of new subsurface cores for this project to the PED phase as Dredged Material Management Program (DMMP) recency rules only allow subsurface cores to be utilized to characterize material for open water disposal suitability for 3 years following collection. The earliest potential construction year for this project is estimated at 2024 which would negate any new subsurface cores collected in the feasibility stage for use during the construction phase.

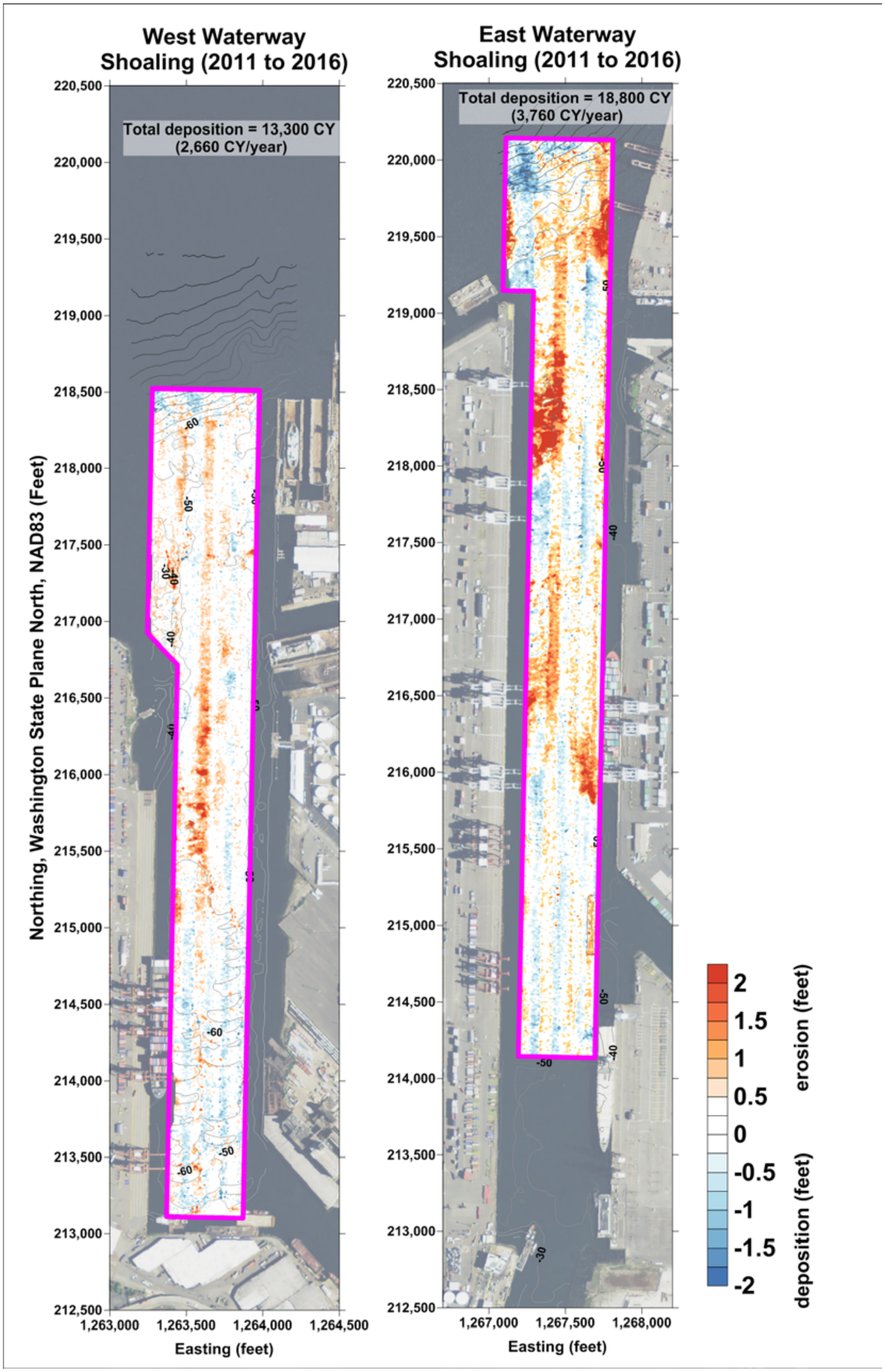

Figure B-11. Shoaling patterns in the West and East Waterway from 2011 to 2016.

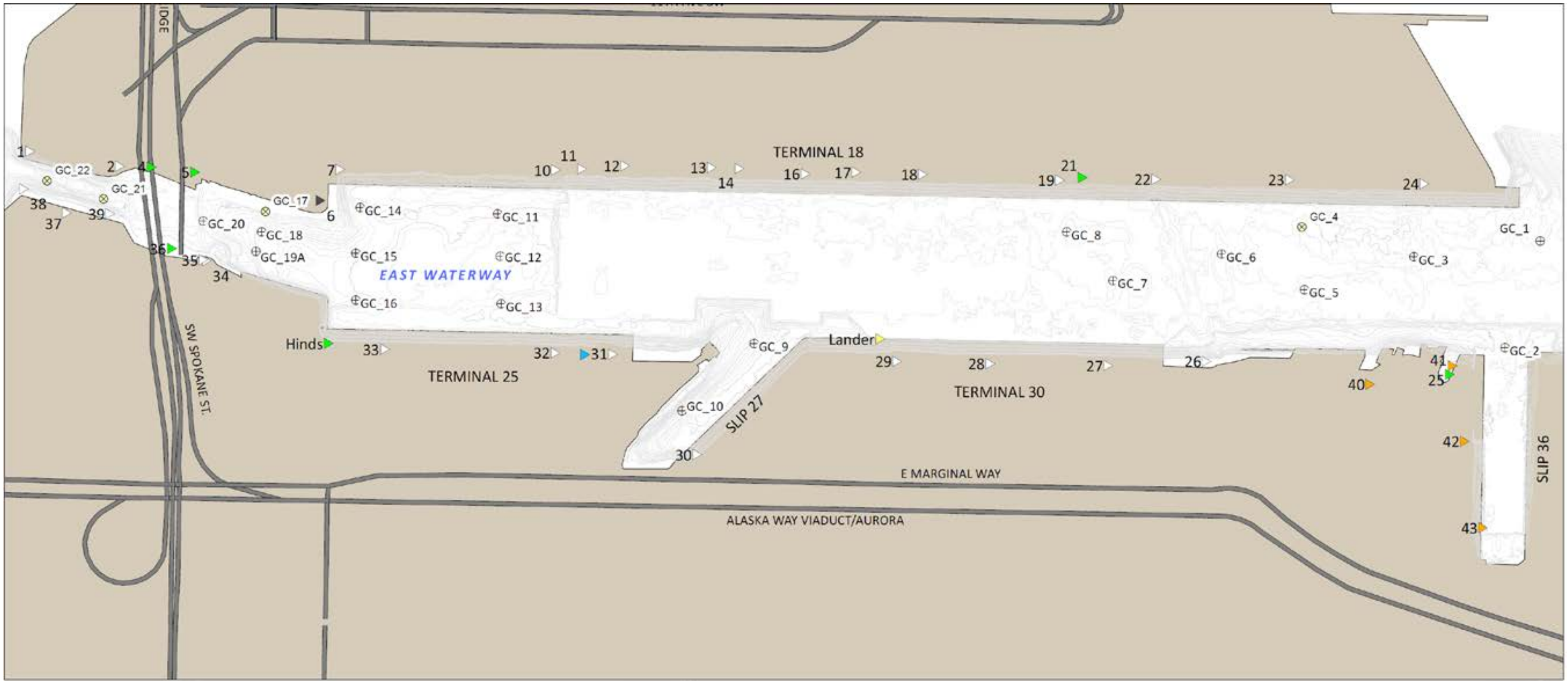

Figure B-12. Geochronological cores collected in the East Waterway in January 2010 (Anchor QEA 2012)

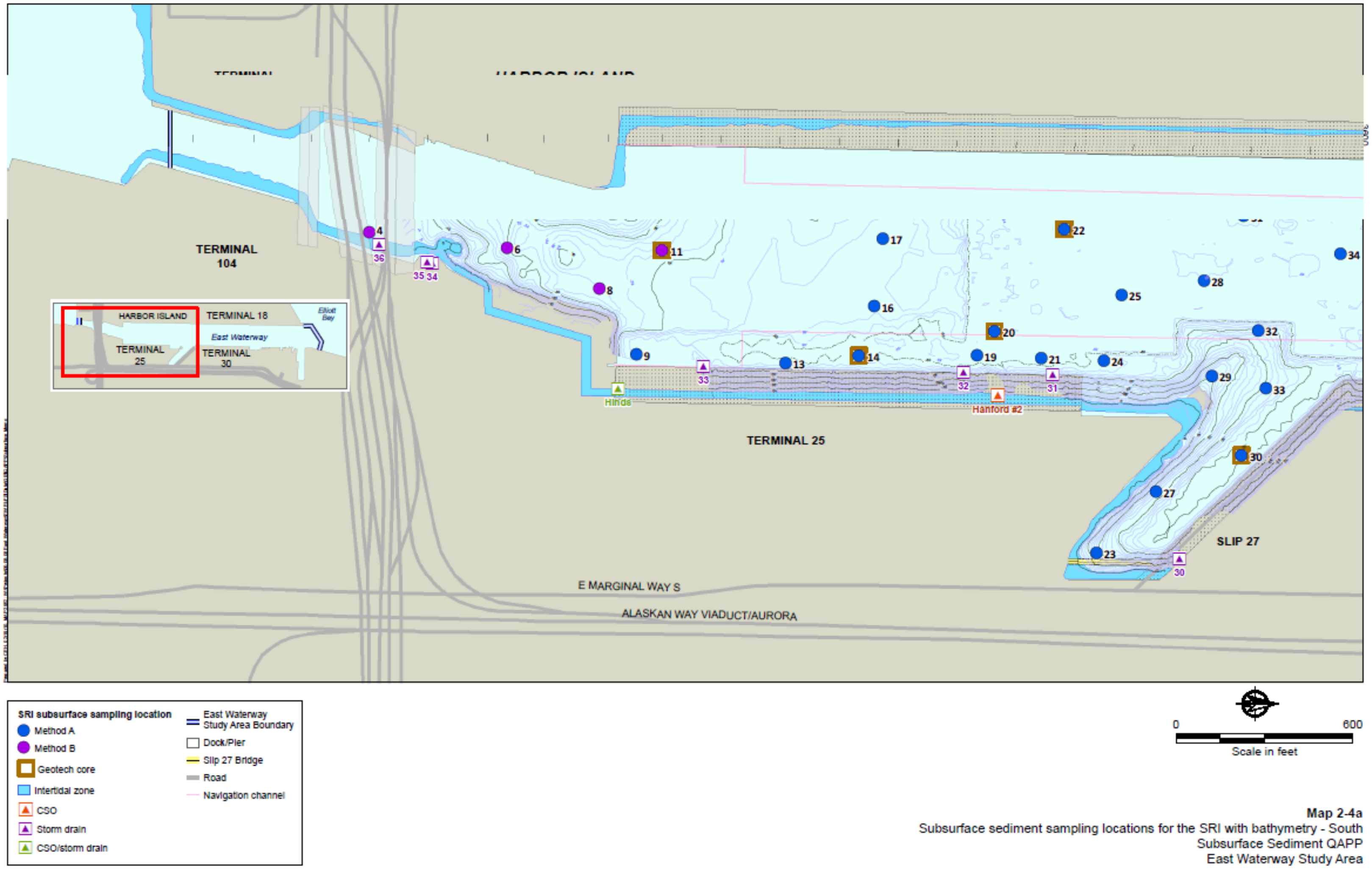

Figure B-13a. Subsurface borings collected in the East Waterway in March 2010 (Winward 2010)

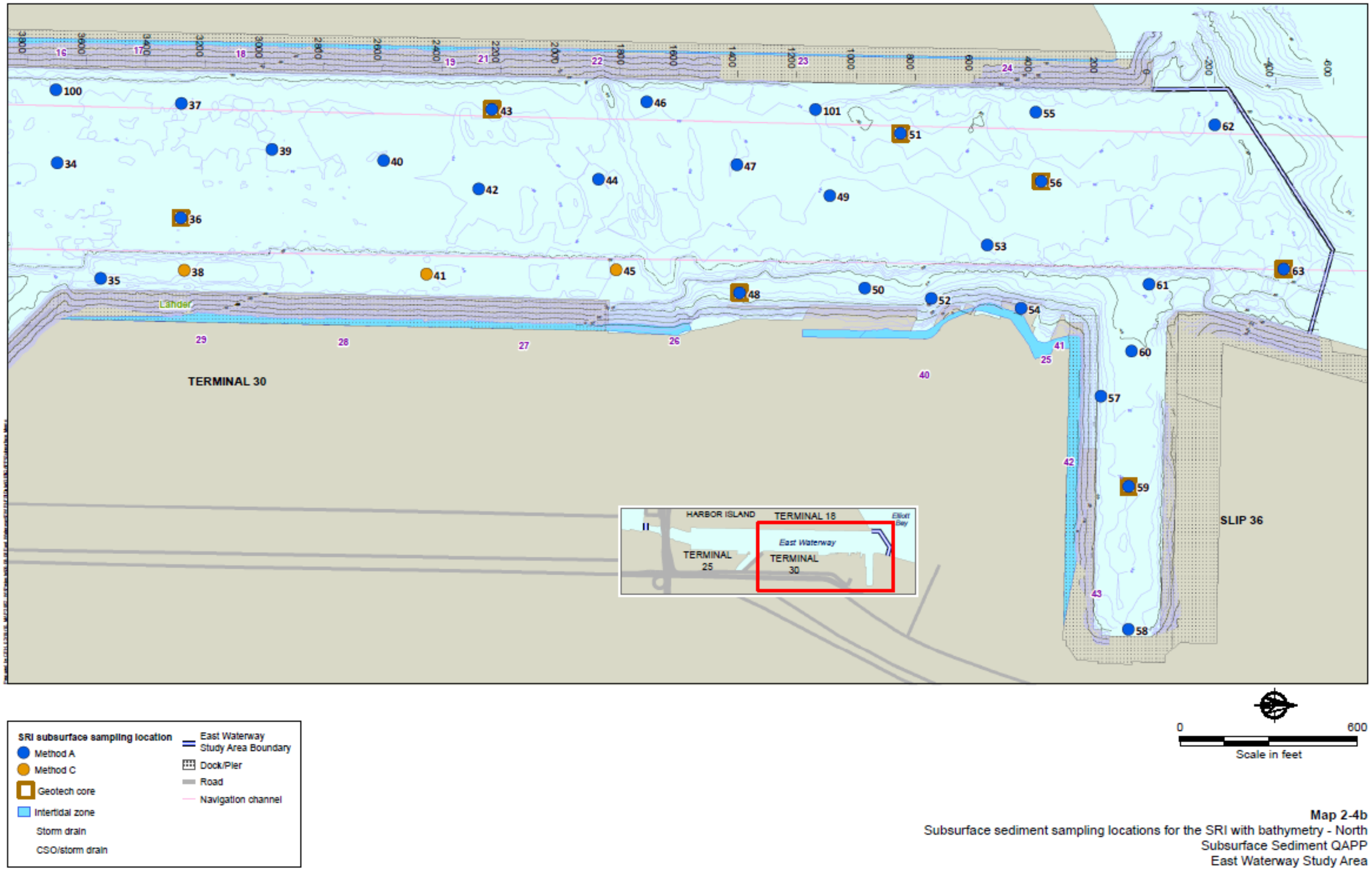

Figure B-13b. Subsurface borings collected in the East Waterway in March 2010 (Winward 2010)

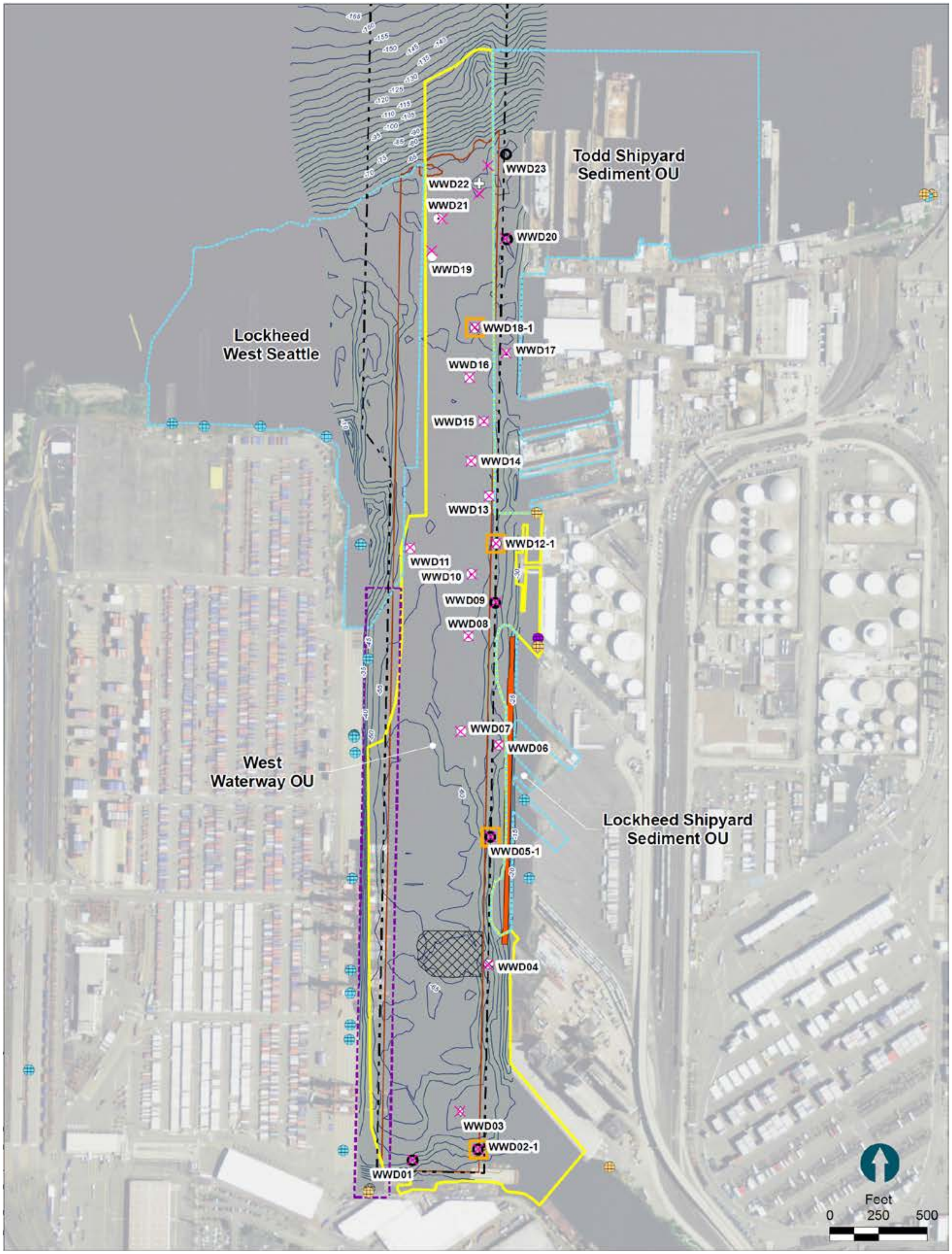

Figure B-14. Vibracores collected in the West Waterway in February 2015 (Anchor QEA 2015)

2 Design Considerations

2.1 Vessel Traffic

Data on vessels calling port since 2010 have been compiled from preliminary data supplied from the Port of Seattle pilots. Vessels serving the East and West Waterways include containers, tankers, and breakbulk cargo ships. A total of 2,570 vessels arrived and 2,496 departed port from January 2010 to November 2014. Vessels with the largest beam of approximately 150 feet utilized Terminals T-5 and T-18. Up until early 2016, the largest vessel calling the Port of Seattle was the ZIM ROTTERDAM. The vessel dimensions are: Length (LOA) = 1145', Beam (B) = 149.6', Design Draft = 49.2', Dead Weight Tonnage (DWT) = 116,500 metric tons. Tables B-4 and B-5 list the average, median, and maximum vessel dimension for vessels arriving and departing port by terminal. Vessels typically enter the waterway at 3 knots and use 2-3 tug assists depending on the pilot and the conditions. The current operating guidance used by the pilots is to have an underkeel clearance of 10% of the draft.

Table B-4. Port of Seattle (Arrival Vessel Statistics 2010-2014)

Vessel Dimension[1]		T-5	T-18	T-30	All
N		978	1,165	281	2,570
Median (B)	ft	131.2	130.9	105.6	106.0
Max (B)	ft	150.3	150.0	140.6	150.3
Median (D)	ft	36.1	36.0	36.1	35.1
Max (D)	ft	47.0	49.0	45.1	49.0
Median (DD)	ft	45.0	44.0	42.0	44.0
Max (DD)	ft	48.0	49.0	48.0	49.0
Median (DWT)	metric tons	66,644	69,192	51,570	66,694
Max (DWT)	metric tons	99,123	116,499	102,453	116,499

Table B-5. Port of Seattle (Departures Vessel Statistics 2010-2014)

Vessel Dimension		T-5	T-18	T-30	All
N		981	1,174	281	2,496
Median B	ft	131.2	130.9	105.6	106.0
Max B	ft	150.3	150.0	140.6	150.3
Median D	ft	38.0	35.1	37.1	37.0
Max D	ft	47.1	49.1	46.0	49.1
Median DD	ft	38.0	44.0	42.0	44.0
Max DD	ft	47.1	49.0	48.0	49.0
Median DWT	metric tons	66,644	69,107	51,570	66,771
Max DWT	metric tons	99,123	116,499	102,453	116,499

[1] B = Beam Width; D = Operation Draft; DD = Design Draft; DWT = Dead Weight Tonnage; N = Number of Vessels

2.2 Design Vessel

Vessels are progressively getting larger and future vessel fleet forecasts continue show this trend. Trade between the U.S. West Coast and Asia is not constrained by beam restrictions imposed by the Panama Canal thus could hypothetically could receive wider beam vessels. Terminal 18 on the East Waterways currently has a crane outreach capacity of 210 feet (or 25 container wide vessels) and Plans to upgrade Terminal 5 on the West Waterway will include similar cranes (Figure B-14). The Port of Seattle currently has a contract with Maersk Shipping Company. Maersk operates the largest container ship Triple E-Class vessels. The Triple E Class type vessels have a beam of 194 feet and have primarily served the Europe to Asia Trade route through the Suez Canal. The forecasted maximum vessel is a Generation IV E-Class container ship with a capacity of up to 15,000 twenty-foot equivalent units (TEU), or approximately 157,000 dead weight tons (DWT). The *Emma Maersk* represents a typical vessel in this fleet. These dimensions include:

- Beam (B) = 184 feet
- Length (L) = 1,302 feet
- Draft (D) = 51 feet
- Dead Weight Tonnage (DWT) = 156,907 metric tons

2.3 Channel Design

The USACE Engineering Manual for deep draft navigation projects recommends a design channel width of three (3) times the design beam width for one-way ship traffic for a canal type channel and current speeds between 0.5 and 1.5 knots (USACE 2006). Thus the navigation channel would require a width of 3.0*(184 feet) = 552 feet. Thus the existing authorized channel width of 500 feet would need to be widened approximately 50 feet to 550 feet to serve this design vessel. In the approaches to each channel an additional width factor is advisable when cross winds are present. An additional 150 feet of channel width is included at the approach to each waterway, as shown in Table B-6 (PIANC 1995). Thus a 700 foot approach channel width to each Waterway is recommended. The footprint of the recommended federal navigation channel is shown in Figure B-15. A feasibility level ship simulation study was conducted in May 2017 by ERDC-CHL in Vicksburg, MS to determine the minimum channel width for the design vessel in each Waterway. From the analysis it was determined the existing authorized channel width in the inner reaches of 500 feet was sufficient, for the varying berthing configurations and environmental conditions simulated. However, it was found the full 700 feet approach width at the entrance of each waterway was needed in order to safely navigate strong cross winds and obstructions on either side of the Waterway (USACE 2017).

Channel depth required for the design vessels must account for the design vessel draft, minimum safe clearance, freshwater sinkage, trim, squat, and tidal effects.

<u>Design Draft</u>. The design vessel for the East and West Waterways has a loaded draft of 51 feet.

<u>Minimum safe clearance</u>. A minimum of two additional feet in depth is required under the keel after all other requirements for depth have been met. This is needed to avoid damage to ships propellers from sunken timbers and debris, to avoid fouling of pumps and condensers by bottom material, reduce

propeller wash effects, provide allowance for spot shoals, and offset poor steerage effects caused by underkeel clearance close to the seabed.

Freshwater Sinkage. Passing from seawater with a specific gravity of 1.026 in Puget Sound into a freshwater system with a specific gravity of 1.0, a vessels displacement will increase approximately 3%. However, due to high salinity in the East and West Waterways fresh water sinkage is anticipated to have a negligible effect on vessel displacement.

Trim. The difference between the vessel draft at midship and the bow or stern is termed trim. It is often complex and expensive to keep a ship at even keel and a nose down vessel does not maneuver well, so a vessel is often loaded to keep the stern lower than the bow. Observations of vessel loading practices in the East and West Waterways show the stern drafts are commonly 1.5 feet greater than at midship (USACE 1983; PSP 2014). Hence, an additional 1.5 feet was added to the required depth.

Squat. A moving ship causes a drawdown of the water surface causing the vessel to ride lower relative to a fixed datum. Squat is dependent upon many variables including vessel speed through the water, water depth, and vessel to channel blockage ratio. Vessel speed in the Waterways is generally limited to less than 4 knots. Computation using the empirical formula (Eryuzlu et al 1994) indicate squat would be approximately 0.5 feet in each waterway.

Tidal effects. The reference datum, 0.0 foot, for the project area is mean lower low water (MLLW). A tidal analysis shows that on the average, over a period of one year, the tide is below the reference 4% of the time. Similarly, the tide is below the elevation -2.0 feet MLLW, approximately 0.4% of the year. The economic analysis (Appendix A) takes into account both the design and sailing draft of each vessel class and the availability of tide when each vessel calls using NOAA tide stations that are included in the HarborSym model. The transiting costs are based on the calls at each project depth and by evaluating how the calls would differ under each scenario. "Riding the tide" is a common practice in multiple ports and the Corps economic analysis takes that into account to determine if an additional foot of channel depth is more efficient than allowing a certain number of vessels to wait for the tide when their sailing draft requires it. The underkeel clearance requirement used in the analysis is based on existing practices for the current fleet. Those practices, along with pilot interviews, were used to estimate the additional underkeel clearance required for vessels larger than the current fleet that are anticipated to call during the period of analysis. The recommended plan is based on taking into account the reduction in total transiting costs, which includes any delays for tide, for the forecasted fleet during the period of analysis and the total project cost for each alternative.

Table B-7 summarizes the channel depth critical allowances leading to the recommended plan of authorized depths of -57 feet MLLW in the East and West Waterways. In addition to these authorized depths, initial dredging would include an overdepth tolerance of 2 feet. All channel width design assumptions will be confirmed through use of a ship simulation as required by ER 1110-2-1403 (USACE 1998) in the Preconstruction, Engineering, and Design phase (USACE 2015b).

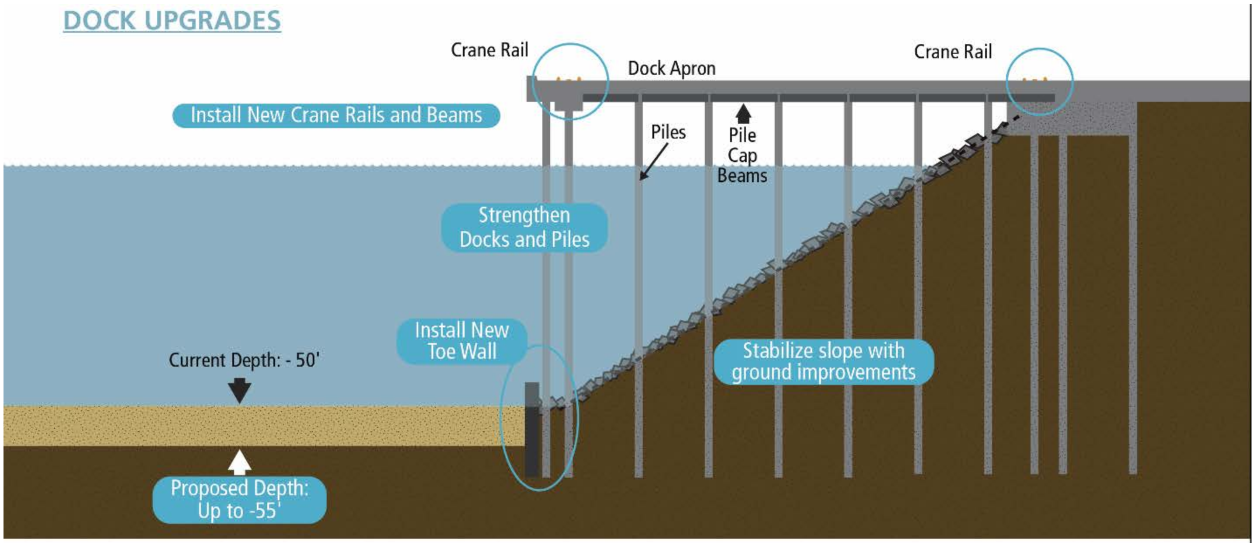

Figure B-14. Proposed upgrades on Terminal 5 (from NWSPA)

2.4 Berthing Areas

The berthing areas at Terminal 5 on the West Waterway and Terminals 18 and 30 in the East Waterway will need to increase in width to accommodate the new design vessel. Due to the restricted width in each waterway, a portion of the berthing areas will overlap with the federal channel. At T-5 and T-18 the berthing width is 190 feet. At T-30 the berthing width is 175 feet. In the West Water way this results in a 65 foot overlap on the west side of the Federal Channel between Sta. 33+5-0 to 61+09. In the East Waterway this results in a 65 foot overlap on the west side of the Federal Channel between Sta. 15+00 and 60+00 and a 50 foot overlap on the east side of the Federal Channel between Sta. 29+00 to 44+50 (Figure B-15). The local sponsor will be responsible for all O&M related dredging in the berthing areas including the portions which overlap with the Federal Channel. This has been coordinated through the vertical team and confirmed as a feasible solution from a navigation safety perspective through scenarios investigated in the ship simulation study

In the May 2017 ship simulation study, multiple scenarios were modeled to evaluate different transit configurations of the design vessel as well as berthed vessel configurations. The critical scenario evaluated the transit of the design vessel as it backed into the southernmost berth (i.e., berth 2) at T-18 on the East Waterway. This scenario included a Generation IV vessel (beam width of 190 feet) berthed at the northern berth (i.e., berth 1) at T-18 and a Generation III vessel (beam width of 170 feet) berthed at T-30 on the opposite side of the waterway. This resulted in a staggered configuration of berthed vessels on either side of the waterway which allowed an inbound/outbound vessel to snake between the berthed vessels. The Pilots employed a T-squared tug package (2 – 50 ton tugs) on the stern of the inbound vessel and 1 – 75 ton tug on the bow quarter in order to narrow the swept path of the vessel while passing the berthed vessels. The scenario was tested for multiple environmental wind conditions (15 knot south, 15 knot south-southwest, 15 knot northwest, and 25 knot northwest winds). This was a successful configuration that provided enough horizontal clearance between the transiting and berthed vessels. The minimum horizontal distance between the berthed and transiting vessel never exceeded 130 feet during the simulations. This indicated that berthing areas overlapping the Federal Channel are feasible from an operational standpoint.

2.5 Utilities

A communication cable crosses the East Waterway. Based on available information, the cable is located between Station 27+00 and Station 30+00 (between Terminal 18 and the northern portion of Terminal 30). The cable was originally buried in 1972 at approximately -64 feet MLLW in an armored trench. During PED, an underwater channel survey will confirm the size, depth, and extent of armoring of the communication cable. Based on the results of the channel survey, it is uncertain whether the armoring should be replaced or relocated. The Corps conservatively assumes the utility will be relocated at the expense of the non-Federal sponsor; therefore an estimated relocation cost was included in the baseline real estate cost estimate.

Table B-6. Additional width factors for straight channel sections (per PIANC 1995)

Width factor variable	Inner Channel (protected water)
(a) Vessel Speed (knots) -slow	0.0 B
(b) Cross wind (knots) - moderate > 15 -33	0.5 B
(c) Prevailing Cross current (knots) - low	0.0 B
(d) Prevailing longitudinal current (knots) -low	0.0 B
(e) Significant wave height -Low (Hs < 1m)	0.0 B
(f) Aids to Navigation - good	0.0 B
(g) Bottom surface -smooth and soft	0.1 B
(h) Depth of Waterway < 1.25 T (Ship draught)	0.2 B
(i) Cargo hazard level - Low	0.0 B
Σ	**0.8 B**

Table B-7. Depth factors considered for minimum required underkeel clearance

Depth factor	feet
Design ship draft	51.0
Minimum safe clearance	2.0
Freshwater sinkage	0.0
Trim	1.5
Squat	0.5
Low Tide	2.0
TOTAL	57.0

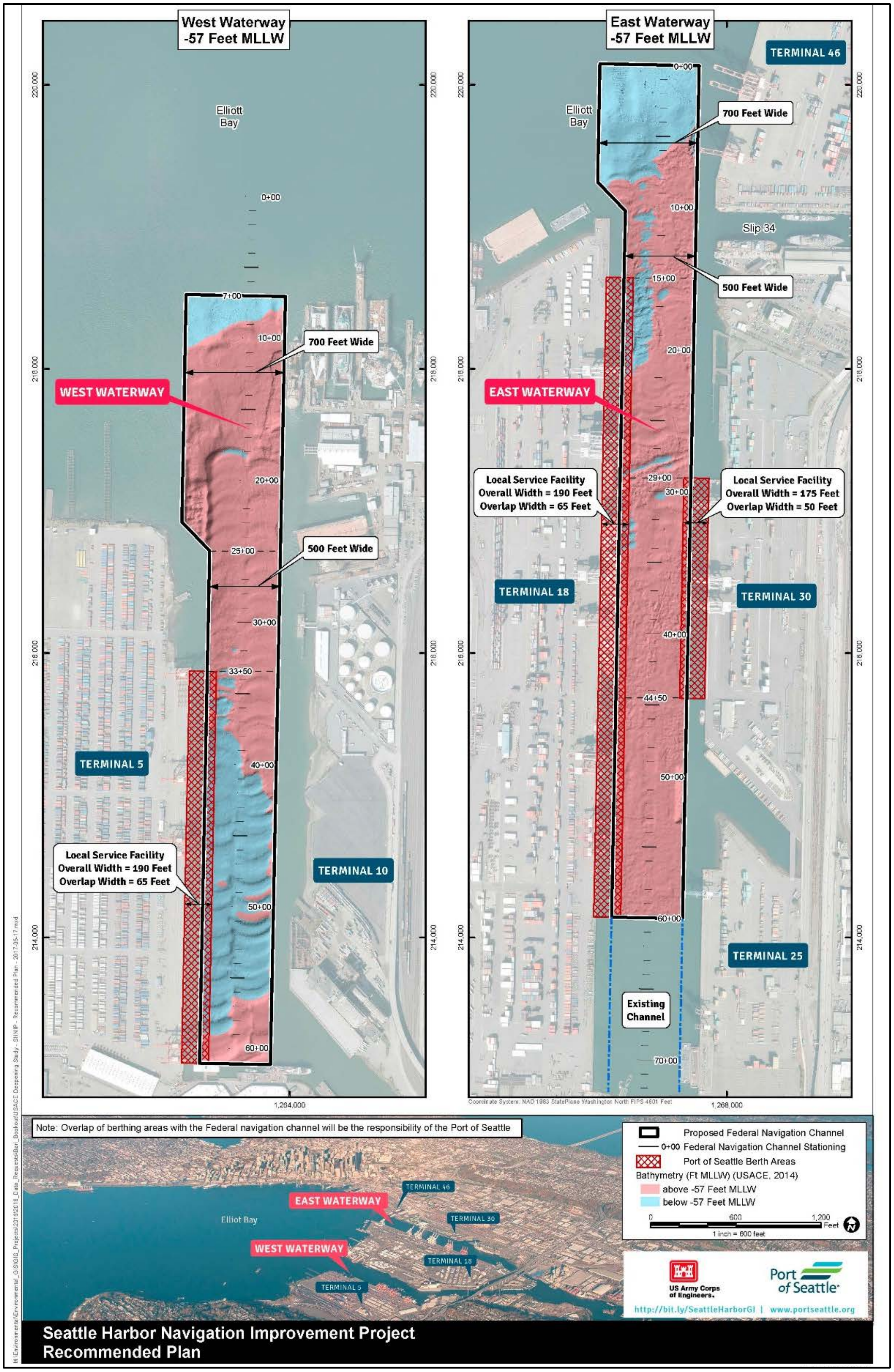

Figure B-15. Seattle Harbor Navigation Improvement Project – Channel Design and Berthing Areas

2.6 Slope stability

The recommended channel width of 550 feet is less than the pier head to pier head width of 750 feet in each waterway. The recommended sideslope for the federal channel is 1 vertical on 2 horizontal. Near Terminal 5 and Terminal 18, the berthing areas are maintained by the Port of Seattle and effectively deepen the federal channel beyond the required depth. In order to ensure sideslope stability the Port has constructed bulkheads to support the wharf and local service facilities. Terminal 5 is currently undergoing modernization repairs consists of installation of a new king-pile toe wall and soil improvement (Figure B-14) to reinforce the wharf structure to ensure the berths can be deepened to the required depth (NWSPA 2015). The Port of Seattle also plans to perform similar dock upgrades on the East Waterway near Terminal 18.

Under static conditions, it appears that the wharf is and has been stable, as evidenced by its past and current use. The driving factor in many designs in the Puget Sound region is seismic stability. The southern end of the project is within the northern portion of the Seattle Fault Zone and the vast majority of submerged soils within 80 feet of the ground surface are susceptible to liquefaction in the Maximum Considered Earthquake (MCE) event. Currently many of the existing wharf piles could see settlement because they do not all extend to the bearing layer. This could lead to significant differential settlement within the wharf structure and between the structure and surrounding ground surface.

The Terminal 5 modernization project will install new crane rail piles, a new submerged king-pile toe wall near the waterside edge of the terminal, and slope stabilizing pinch poles to improve sideslope stability. The king-pile toe wall will be installed near -90 feet MLLW and allow an increase in the design berth depths by 8 to 13 feet over existing conditions. This will allow berthing areas and the Federal Navigation Channel to be deepened to the fully authorized depth including an allowable overdepth tolerance up to 3 feet. The pinch piles specified are 60 foot long, 14 inch diameter timber piles with a 1 inch taper every 10 feet to minimize king-pile system displacement. A global stability analysis has been completed for this design using the PLAXIS finite element numerical model and SLOPE/W model to analyze structural deformations and slope stability for a range of loading conditions. The analysis indicates the proposed design ensures the measures meet or exceed the required factors of safety (Hart Crowser 2016).

Additional sideslope stability improvements may be necessary near the southern end of Terminal 46 of the East Waterway and the southern end of the West Waterway. Sideslope stability requirements will be further analyzed and addressed in PED phase when ship simulation confirms the final channel alignment and width.

2.7 Dredging and placement of dredged materials

Three alternatives are considered in the Feasibility Report.

- Alternative 1: No Action – maintain current project depth of -34 to -51 feet MLLW
- Alternative 2: National Economic Development (NED), Deepen project depth to -56 feet MLLW
- Alternative 3: Locally Preferred Plan (LPP), Deepen project depth to -57 feet MLLW

The maximum allowable dredging depth for each alternative includes 2 foot of overdredging tolerance beyond the project depth to account for inaccuracies during dredging operations. However, based on historical evidence, only about half of this material is removed by the contractor, as any material that exceeds the overdepth tolerance is unpaid. For each alternative it is assumed the channel would be dredged to its project depth plus 1 foot overdepth and to its full width. The suitability of dredged material has been characterized by the Port of Seattle (USACE 2015a) in the West Waterway and by USEPA for the East Waterway Operating Unit of the CERCLA project (Anchor QEA 2014) which overlaps with the dredging footprint for the channel improvement project.

2.7.1 Dredged material quantities

Table B-9 lists dredged volumes to obtain the project depth plus 1-foot of overdredge allowance. A contingency of 10% is added to the neatline volume to account for additional sedimentation between the survey year (2016) and project implementation year (2024). Quantities were computed through surface to surface calculations in MicroStation InRoads. A Digital terrain model (DTM) was developed from XYZ triplet data set surveyed by the Navigation Section Hydrosurvey Unit in June 2016. The Waterways were surveyed using a Reson 712 Multibeam, 140° swath, 400 kHz transducer in HYPACK, Inc. HYSWEEP® software. Tidal corrections were performed using RTK. Delaney triangulation was used to create the DTM surface. The “Generate Sloped Surface” command in InRoads is used to project the channel sideslopes of 1 vertical on 2 horizontal (1:2) from the channel bottom up to the point of intersection with the condition survey DTM. Assumptions and methodology for computing dredged material volumes are described in more detail in (USACE 2015c).

2.7.2 Dredging schedule and production

To meet a two year completion schedule it is assumed one clamshell and two bottom dump scow barges will be utilized. It is likely each waterway would be dredged in separate years to avoid adverse impacts to Port operations. Historical O&M dredging production during the 2000 East Waterway deepening averaged 3,000 cubic yards per day. The environmental dredging window in the project area is 16 July to 14 February. Based on the production rate, the West Waterway would take two dredge seasons to complete, while the East Waterway could be completed in one dredging season.

2.7.3 Placement of dredged materials

Placement of dredged material suitable for open water disposal will be hauled by a bottom dump scow barge approximately 1.5 nautical miles north of the project area to the Elliott Bay PSDDA disposal site. The disposal site is managed through the Dredged Material Management Program which consists of the U.S. Army Corps of Engineers, U.S. Environmental Protection Agency - Region 10, Washington State Department of Natural Resources, and Washington State Department of Ecology (DMMP 2016). The disposal site ranges between 300 to 360 feet in depth, and the disposal zone is a 1,800 foot diameter circle (Figures B-15 and B-16).

2.7.3.1 Open water disposal site capacity

The Corps’ Engineering Regulation ER 1105-2-100 mandates that all Corps District develop a Dredged Material Management Plan for all federal harbor projects where there is an indication of insufficient placement capacity to accommodate maintenance dredging for the next 20 years. Given the naturally deep waters in the Elliott Bay disposal site and low sedimentation rates, O&M dredging in the East and West Waterways is anticipated 2 times in the 20 years following construction. O&M dredging on the Duwamish Waterway upstream of the project is the only other significant source of sediment placed in the Elliott Bay disposal site. O&M dredging on the Duwamish Waterway does not exceed 100,000 cubic yards a year, or a maximum of 2,000,000 cubic yards over the next 20 years.

Placing approximately 753,600 CY of dredged material estimated for the LPP alternative (Table B-9 and B-10) would produce a mound less than 10 feet above the seabed, assuming no dispersion of material beyond the limits of the disposal zone. A detailed disposal plan will be created prior to construction to minimizing mounding in the disposal site. Sufficient capacity will remain in the PSDDA site following implementation of the project for O&M related dredging in the Seattle Harbor project.

2.7.3.2 Upland disposal considerations

Upland disposal is required for all sediments which do not meet the chemical criteria required for open water disposal (DMMP 2016). It is assumed unsuitable material will be transloaded to one of the existing facilities located on the Lower Duwamish Waterway and disposed by rail at an authorized landfill. For preliminary cost estimates it is assumed the dredged material will be transported to the Roosevelt landfill in Eastern Washington. It is assumed that remedial actions implemented by the CERCLA projects will address the majority of unsuitable material in the waterways.

Based on a feasibility level advisory suitability determination, a percentage was assigned to each dredged material management unit's (DMMU) likelihood of meeting open water disposal criteria. In the West Waterway this included four (4) DMMU's in the surface layer stratum of 0 to 4 feet below the mudline, and two (2) DMMU's from 4 feet to the required dredging depth. (USACE 2015a; Anchor QEA 2014). The required dredging cut was computed in MicroStation InRoads by generating an isopach surface of the required neatline dredging depth relative to the June 2016 condition survey surface Digital Terrain Model (DTM). The percentages from the DMMU's in the advisory suitability determination (Table B-8) were then applied to compute the volume of dredged material suitable for open water and upland disposal (Table B-9). In the West Waterway 147,400 CY of upland disposal and 546,200 CY of open water disposal is calculated.

In the East Waterway, dredged material not meeting the open water disposal criteria will be small following implementation of the CERCLA remedy. However, there is some risk that residual contamination may be present due to inaccuracies in dredging and construction of the remedy. As a result the PDT estimated approximately 10% of the volume remaining following the CERCLA action would require upland disposal (Table B-10). The East Waterway is estimated to require 23,100 CY of upland disposal and 207,400 CY of open water disposal following implementation of the CERCLA remedy.

The disposal requirements for each waterway for the NED and LPP plan are summarized in Table B-11

Table B-8. West Waterway – Total dredged material and percentage of material suitable for open water disposal in each DMMU

	0-4 foot stratum[1] (open water suitability %)						4 foot to depth stratum (open water suitability %)						Total
Project Depth/DMMU	**Polygon 1 (30%)**	**Polygon 2 (90%)**	**Polygon 3 (30%)**	**Polygon 4 (0%)**	**Lockheed backfill (100%)**	**Berthing Area (100%)**	**Polygon 1 (100%)**	**Polygon 2 (100%)**	**Polygon 3 (100%)**	**Polygon 4 (70%)**	**Lockheed backfill (100%)**	**Berthing Area (100%)**	
(ft, MLLW)	**CY**	**CY**	**CY**	**CY**	**CY**	**CY**	**CY**	**CY**	**CY**	**CY**	**CY**	**CY**	**CY**
-55	18,429	112,195	42,943	44,327	102,072	1,986	4,031	10,555	3,191	42,657	129,618	288	512,293
-56	**20,972**	**137,749**	**53,720**	**48,799**	**106,416**	**2,579**	**6,501**	**19,138**	**7,111**	**50,002**	**147,638**	**438**	**601,063**
-57	**22,998**	**156,733**	**63,301**	**53,912**	**109,125**	**3,339**	**9,611**	**34,598**	**13,581**	**58,135**	**167,548**	**705**	**693,586**
-58	24,503	167,574	71,618	60,913	111,177	4,369	13,385	58,506	22,146	67,237	188,473	1,120	791,020

Table B-9 – West Waterway – Dredged Material disposal requirements for various project depths

Project Depth	Open water	Upland	Total
-55	400,989	111,304	512,293
-56	**471,204**	**129,859**	**601,063**
-57	**546,151**	**147,435**	**693,586**
-58	625,895	165,125	791,020

Table B-10 – East Waterway – Dredged Material disposal requirements for various project depths

Project Depth	Open water	Upland	Total
-55	82,130	9,126	91,255
-56	**137,387**	**15,265**	**152,652**
-57	**207,370**	**23,041**	**230,411**
-58	289,213	32,135	321,348

Table B-11. Required dredging volumes for recommended channel depths for NED and LPP alternatives

		NED	**LPP**
Channel Reach	**Stationing**	**-56' MLLW[1] (Volume, CY)**	**-57' MLLW[1] (Volume, CY)**
West Waterway			
Approach	7+00 to 25+00	369,800	417,500
Inner	25+00 to 61+09	231,300	276,100
Total		**601,100**	**693,600**
East Waterway			
Approach	0+00 to 10+00	12,500	19,900
Inner	10+00 to 60+00	140,200	210,600
Total		**152,700**	**230,500**

[1] Neatline volumes based on June 2016 condition survey and include 1-foot of overdepth and a 10% contingency to account for shoaling prior to implementation

2.8 Impacts to Salinity from channel deepening

Channel deepening will increase the tidal prism into the Lower Duwamish estuary. In order to investigate the impact of deepening on salinity concentration and estuarine habitat, a three-dimensional numerical tidal circulation model was developed (Hayter et al 2015). The model includes tidal and freshwater input and analyzes the position of the salt water wedge various fresh water discharge scenarios. The impacts associated with the intermediate sea level change at project year 50 are also investigated.

Results indicate minor differences that never exceed +/- 5 practical salinity units (5 PSU); the change would be that the deepened channels would allow the salt wedge to propagate slightly farther upstream during flood tides. This study, conducted specifically for this project, indicated that SLC would have a greater effect on the saltwater wedge extent than would deepening both channels to -57 MLLW. With such a minor change of up to a half mile of the upstream extent of the saltwater wedge, this alternative would not have a significant impact on environmental resources. The full report is included in the Engineering Appendix Annex for more information.

2.9 Impacts to Currents from channel deepening

The circulation model was also used to compare current velocities for a deepened channel relative to the existing condition. Multiple current velocity transects in the West Waterway and East waterway were compared at different tidal cycles. In general the deepened channel smooths out sharp transitions in currents over the waterway as a result of the more uniform depth, particularly near the entrance of the West Waterway where there is presently a depth constriction. During a flood tide the current velocities in the deepened waterways are found to slow down. During an ebb tide, there is slight increase in velocity in the connection between the Duwamish Waterway and the West Waterway. Table B-12 lists the changes at each transect for the existing and deepened channel.

Table B-12. Change in current velocity over each transect for deepened channel, (+) increase (-) decrease

Transect (see Figure B-4)	Average change – flood (cm/s)	Average change – ebb (cm/s)
A-A’	-2.0	-1.0
B-B’	-1.0	2.0
C-C’	-1.0	2.0
D-D’	-2.0	7.0
E-E’	0.0	-1.0
F-F’	0.0	-1.0

2.10 Impacts from sea level change

The project footprint includes only the East and West Waterways, thus there are no bridge clearance concerns associated with the project. The biggest potential risk associated with SLC is inundation to the local service facilities (LSF), including the piers, sea cranes, and utilities serving the berthing areas.

Impacts to the LSF are assessed using statistics from historical water levels combined with the predicted SLC scenarios. The 99% annual exceedance probability (AEP; or 1-year return period) of the measured total water level (TWL) at the Seattle tide gauge is added to each SLC scenario. If SLC coupled with the 99% AEP total water level exceeds the deck height of the terminals on the waterways, it is assumed to be in a condition that would require significant structural modifications. The deck height of the terminals are presently high enough to avoid inundation for all scenarios with the exception of the 2124 High SLC scenario (Table B-13). This indicates there is a low overall risk to the LSF at the project over the 50-year project life cycle.

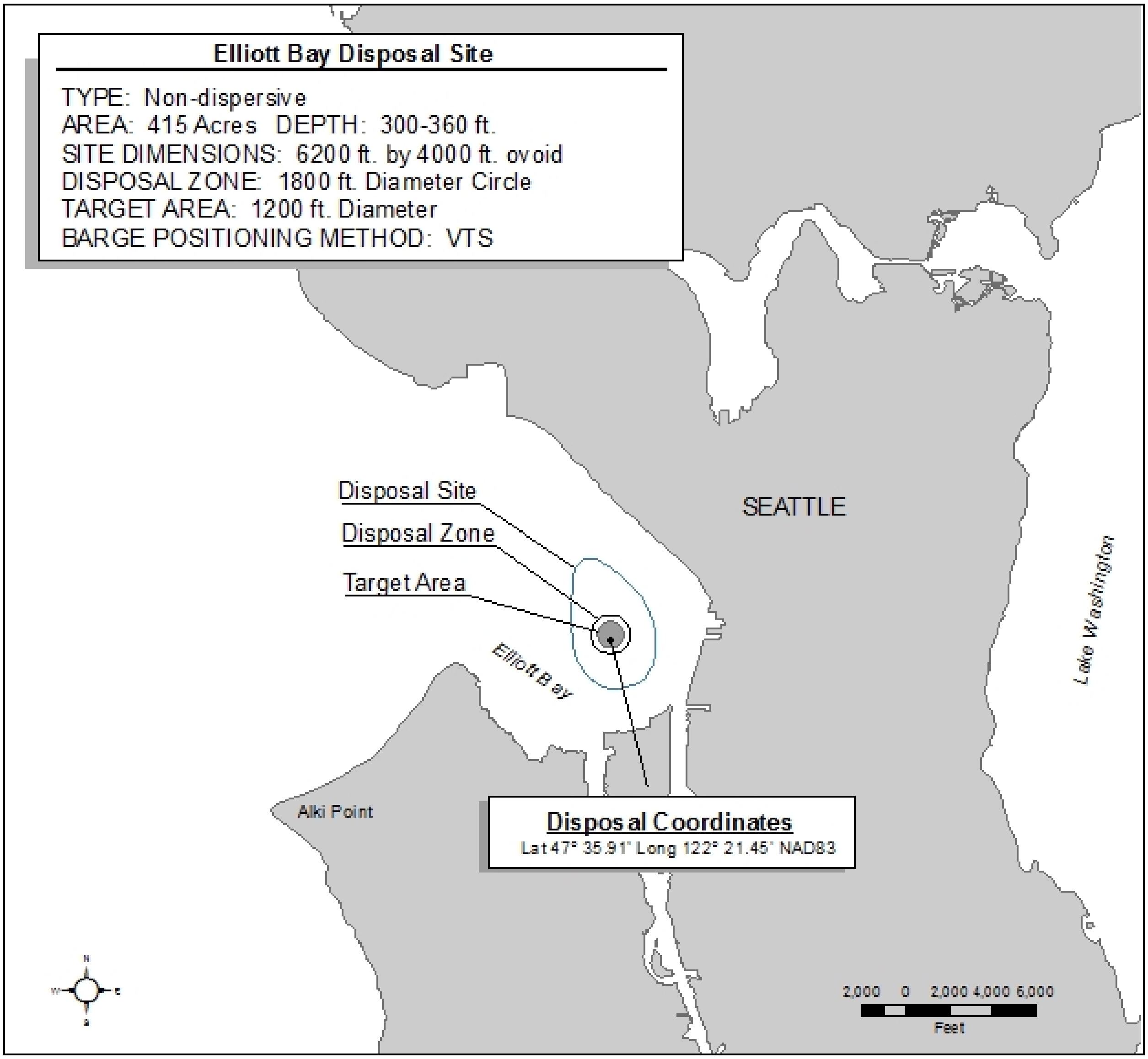

Figure B-17. Elliott Bay PSDA open water disposal site. Located north of the Seattle Harbor project.

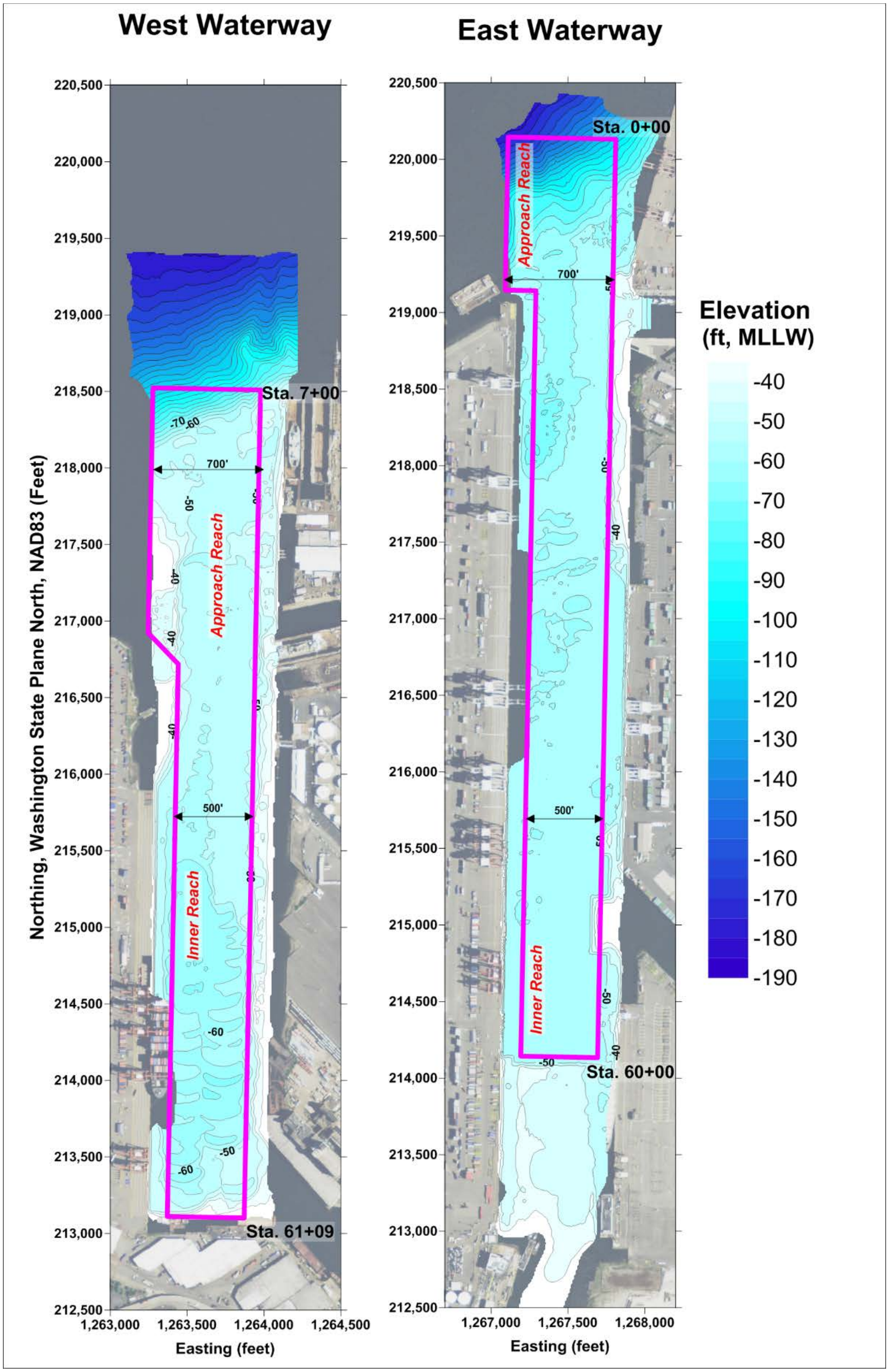

Figure B-16. Current conditions in the East and West Waterway (June 2016 condition survey)

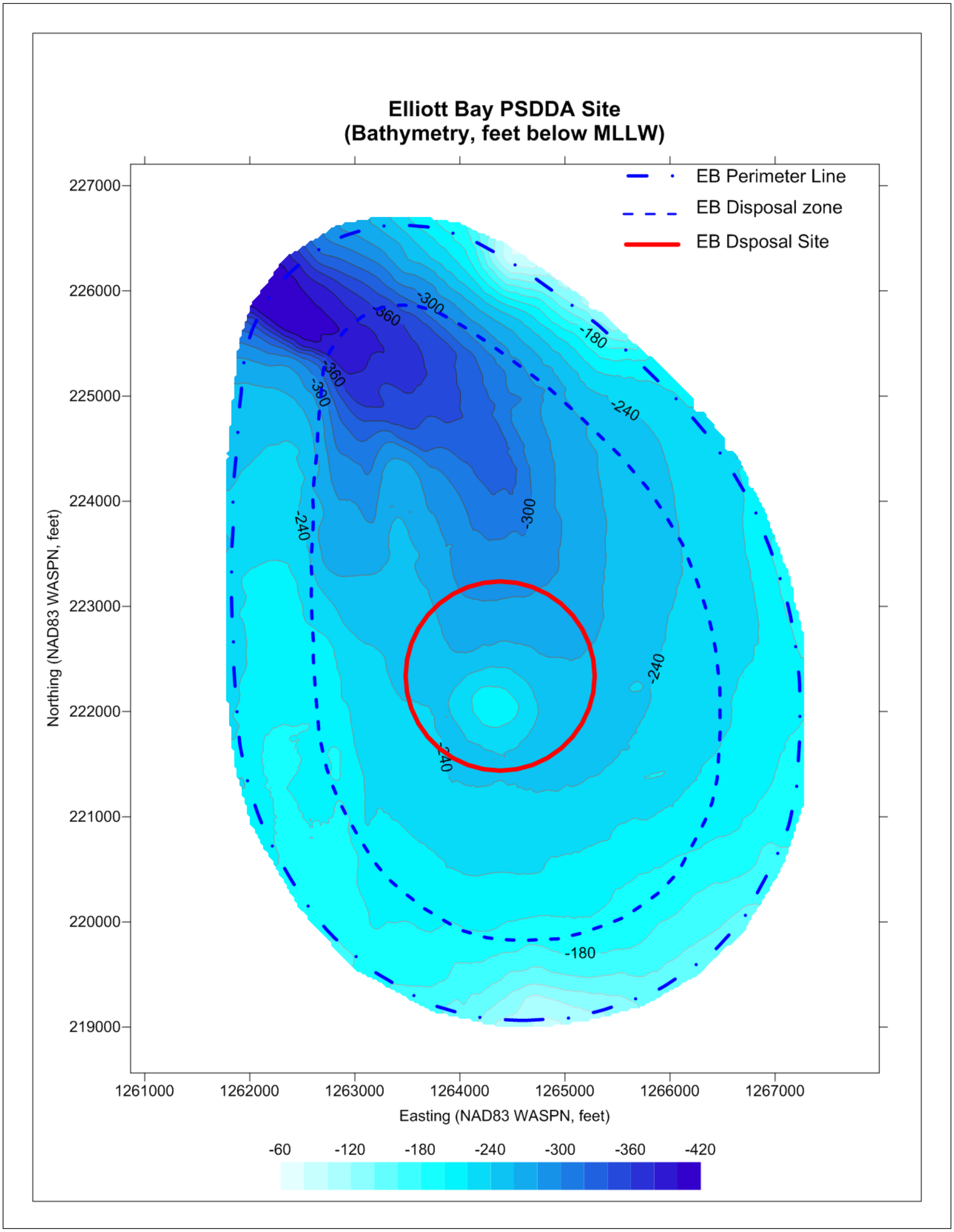

Figure B-18. Bathymetric in the Elliott Bay PSDDA open water disposal site (July 2013 condition).

Table B-13. Deck height of each Terminal at Seattle Harbor and predicted SLC scenarios

Terminal	Deck Height (feet, MLLW)	2074 Low/High + 1-year TWL[1]	2124 Low/High SLC + 1-year TWL[1]
T-5	18.5	13.4 / 15.9	13.7 / 20.2
T-18	18.5		
T-30	18.5		
T-46	18.0		

[1] 1-year TWL (99% Annual Exceedance Probability) is 12.82 feet MLLW (NOAA 2015);

3 Operations and Maintenance

Historically channel deepening and widening projects result in a net increase in O&M dredging requirements. This has been well documented over multiple historic deepening and widening projects (Rosati 2005). The Seattle Harbor project was historically dredged beyond its authorized depth, thus O&M dredging has not been required since 1941, however average sedimentation in the proposed channel footprint in each waterway still occurs at a rate of 2,660 and 3,760 CY/year in the West and East Waterways respectively (Figure B-11). Due to the relatively low sedimentation rate in each Waterway, the depth in the federal channel has never shoaled in above the authorized depth, and thus has not required O&M dredging. Still following implementation of the SHNIP project, the authorized depth will be deepened leaving much smaller of a buffer between the seabed and the required project depth. As a result sedimentation will result in the need for O&M dredging at the recommended depth over the project life. Shoaling rates are computed using the empirical method using historic survey data separated by distinct points in time (Vincente and Uva 1984). The empirical formula assumes that the shoaling rate is proportional to the relative bottom elevation in the channel. The proportionality is expressed by

$$\frac{dC}{dt} = K(C_e - C) \tag{1}$$

where C is a variable that represents the different bottom elevations at time t; C_e is a constant that represents the bottom natural equilibrium elevation in the channel; and K is a constant sedimentation coefficient that expresses the proportionality between shoaling rate and bottom elevation. By integrating equation (1), one obtains

$$C_2 = C_1 + (C_e - C_1) \cdot (1 - e^{-K \cdot (t2 - t1)}) \tag{2}$$

where C_1 is the initial depth at time t_1 and C_2 is the future depth at time t_2.

The shoaling analysis was completed for each waterway using multibeam surveys from 2011 and 2016, or a time interval of 5 years. The shoaling rates were completed only within the Federal Channel boundaries. For the without project condition it is computed to require O&M at 25 year intervals to maintain the authorized depth in each waterway. The analysis predicts O&M dredging would be approximately 35,000 CY in the East Waterway and 500 CY in the West Waterway every 25 years. The future federal O&M dredging for the LPP Alternative (e.g. -57' MLLW – 1' overdepth) is anticipated every 10 years with a quantity of approximately 34,000 CY in the East Waterway and 23,000 CY in the West Waterway (USACE

2016). Based on a production rate of approximately 3,000 CY per day, this work would take approximately 19 days to achieve the recommended project depth.

Table B-14. Required disposal volumes for NED and LPP alternatives

	NED	**LPP**
Disposal Volumes	**-56' MLLW[1] (Volume, CY)**	**-57' MLLW[1] (Volume, CY)**
West Waterway		
Open Water	**471,200**	**546,200**
Upland	**129,900**	**147,400**
East Waterway		
Open Water	**137,400**	**207,400**
Upland	**15,300**	**23,100**

4 References

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5 Engineering Appendix – Annex

- West Waterway Suitability determination (USACE 2015a)
- Volume calculation MFR (USACE 2015c)
- O&M Volumes Calculation MFR (USACE 2016)
- Ship Simulation decision MFR (USACE 2015b)
- EFDC Salinity modeling Letter Report (Hayter et al. 2016)
- Terminal 5 Deepening and Crane Rail Upgrade (Hart Crowser 2016)
- Seattle Harbor Feasibility Level Ship Simulation Study Report