

30% Remedial Design Basis of Design Report

Appendix I

Engineered Protection Design Analysis for  
Engineered Caps and Area-Specific  
Technology

---



Preliminary (30%) Remedial Design  
Basis of Design Report for  
Lower Duwamish Waterway Middle Reach

## Appendix I: Engineering Protection Analysis for Engineered Caps and Area-Specific Technology Areas

**Prepared for**  
Anchor QEA

**Prepared by**  
Blue Coast Engineering LLC

October 2025

# Table of Contents

<b>1</b>	<b>Introduction .....</b>	<b>3</b>
<b>2</b>	<b>Site Data Used in Analysis .....</b>	<b>5</b>
2.1	Bathymetry.....	5
2.2	Water Levels and Base Flood Elevation.....	5
2.3	Hydrodynamic Forces due to River Currents.....	6
2.4	Sea Level Rise Predictions.....	8
<b>3</b>	<b>Erosion Protection Design for Engineered Cap Areas.....</b>	<b>10</b>
3.1	Selection of Design Vessels.....	10
3.2	Stable Particle Size Due to Propeller Wash Forces.....	12
3.2.1	Within the Federal Navigation Channel.....	13
3.2.2	Off-channel Capping Areas .....	16
3.3	Stable Particle Size Due to Vessel Wakes .....	17
3.4	Stable Particle Size Due to River Currents.....	18
3.5	Impacts of Wind-Waves.....	19
3.6	Impacts of Climate Change .....	20
<b>4</b>	<b>Summary .....</b>	<b>21</b>
<b>5</b>	<b>References .....</b>	<b>23</b>

## TABLES

Table I-1	Tidal Datums at Seattle, Washington (NOAA Tidal Station #9447130).....	6
Table I-2	Design Vessel Information .....	11
Table I-3	Propwash Calculation Scenarios in the Federal Navigation Channel .....	15
Table I-4	Maximum Bottom Velocities and Stable Particle Sizes due to Propeller Wash in the Federal Navigation Channel.....	15
Table I-5	Wake Parameters and Associated Stable Particle Size in Priority Capping Areas (RAAs) .....	18

**FIGURES**

Figure I-1 Excess Shear Stress in LDW River (Middle Reach from RM 1.6 to 3.0) for the 100 flow/peak Ebb Tide Scenario..... 7

Figure I-2 Sea Level Rise Estimates for Middle Reach..... 9

Figure I-3 Critical Bed Shear Stress Versus Stable Particle Size ..... 19

# 1 Introduction

This appendix describes site data and engineering analyses used to complete 30% remedial design (RD) of erosion protection for engineered caps at proposed remedial action areas in the middle reach of the Lower Duwamish Waterway (LDW) between river miles (RM) 1.6 and 3.0 (Figure 2-2 in the Preliminary (30%) RD *Basis of Design Report* [BODR]). The middle reach includes all in-water areas of the LDW, including the federal navigation channel (FNC) and adjacent intertidal and shoreline/riverbank areas up to the mean higher high water (MHHW) elevation. The reach also includes four side-channel areas identified as the inlet at RM 2.2W and Slips 2, 3, and 4. The FNC within the middle reach has variable authorized depths, ranging downstream to upstream from -30 to -15 feet mean lower low water (MLLW; Figure 2-7 in the Preliminary [30%] RD BODR).

Within the middle reach, engineered capping is a technology that can be utilized in identified areas with deep contamination and appropriate final surface elevations, in accordance with the LDW Record of Decision (ROD; EPA 2014). Engineered caps have a dual function: stabilizing the underlying contaminated sediments and making the cap itself resistant to erosion (Palermo et al. 1988). Design methods for stabilizing the underlying contaminated sediments are described in Appendix H of the BODR, entitled *Engineered Cap Chemical Isolation Design Analysis*. This appendix focuses on data and methods for design of the cap erosion protection layer (armor) that will protect the underlying contaminated sediments and chemical isolation layer from erosion due to hydrodynamic forces in the middle reach. Potential hydrodynamic processes that may act on the sediment cap within the middle reach of the LDW include the following:

- Localized propeller wash (propwash) from vessels
- Waves generated by passing vessels (wakes)
- Wind-generated waves due to storm events (waves)
- River currents in the LDW due to variable tides, river flows, and other upstream sources of freshwater input (currents)
- Sea level rise (SLR) impacts on each of these processes

Each of these potential erosion processes was evaluated to determine the associated stable particle size for general cap erosion protection components. This general information was used to evaluate stable particle size in the FNC and representative off-channel capping areas (see Figure 5-2 in the Preliminary [30%] RD BODR). Additional capping areas may be considered in 60% and 90% RD and will be evaluated in those phases of design.

The requirements for the cap erosion protection layer were then determined from these results to withstand erosion under the range of anticipated conditions. General methods for these analyses were taken from Appendix A of Palermo et al. (1998), entitled *Guidance for In-Situ Subaqueous*

*Capping of Contaminated Sediments. Assessment and Remediation of Contaminated Sediments (ARCS) Program.* This appendix also presents the results of this design analysis.

## 2 Site Data Used in Analysis

Available site data that were used to complete the engineering design analysis for the cap erosion protection layer are summarized in this section and include bathymetry (i.e., water depths); water levels, including SLR estimates; and river currents for the middle reach of the LDW.

### 2.1 Bathymetry

Bathymetry and topography data for the middle reach and adjacent shoreline areas were developed from multiple datasets as described in Section 2.5.1 in the BODR. The FNC runs down the center of the middle reach and dictates the bed elevations in this area. The FNC has variable authorized bed elevations, increasing in elevation upstream from RM 1.6 to RM 3.0 as summarized as follows and shown in Figure 2-7 of the BODR:

- RM 1.6 to 2.0, -30 feet MLLW
- RM 2.0 to 2.8, -20 feet MLLW
- RM 2.8 to 3.0, -15 feet MLLW

Maximum bed elevations in Slips 2 (RM 1.7), 3 (RM 2.0), and 4 (RM 2.8), which generally follow the authorized navigation depth in the channel adjacent, are approximately -30, -20, and -15, feet MLLW respectively.

Bed elevations in areas outside the FNC within the middle reach generally range from -20 feet to +4 feet MLLW, with shoreline areas sloping up to MHHW and above at the landward boundaries of the waterway.

### 2.2 Water Levels and Base Flood Elevation

The middle reach of the LDW is an estuary where freshwater flows from the Green River and other upstream sources mix with incoming salt water from Puget Sound. The upstream boundary of salt water inundation, referred to as the saltwater wedge, is generally located within the middle reach near RM 2.8 but can extend upstream to RM 10.2 during low river flow conditions (WRIA 9 2021).

Water surface elevations in the middle reach are tidally dominated and not significantly influenced by river flows (QEA 2008; FEMA 2020a). Tidal datums for the middle reach were taken from the National Oceanic and Atmospheric Administration (NOAA) tide gage at Seattle and are provided in Table I-1

The 100-year base flood elevation defined by the Federal Emergency Management Agency (FEMA) for the middle reach (FEMA 2020b) is based on flooding due to coastal processes (high tides) and is the same elevation throughout the middle reach and further downstream to Elliott Bay. The FEMA base flood elevation is 12.0 feet relative to the North American Vertical Datum 1988 (NAVD88), which

is 14.3 feet relative to MLLW datum. This water level is also equivalent to the highest observed tide at the NOAA tidal station at Seattle, which is in Elliott Bay (Table I-1).

**Table I-1  
Tidal Datums at Seattle, Washington (NOAA Tidal Station #9447130)**

Tidal Datum	Elevation (feet relative to MLLW)	Elevation (feet relative to NAVD88)
Highest Observed Tide (HOT) (1/27/1983)	14.4	12.1
Highest Astronomical Tide (HAT)	13.3	11.0
Mean Higher High Water (MHHW)	11.3	9.1
Mean High Water (MHW)	10.5	8.2
Mean Sea Level (MSL)	6.6	4.3
Mean Low Water (MLW)	2.8	0.5
North American Vertical Datum (NAVD88)	2.3	0
Mean Lower Low Water (MLLW)	0	-2.3

## 2.3 Hydrodynamic Forces due to River Currents

Current velocities in the middle reach due to river currents and variable tidal conditions have the potential to erode material on the channel bed, intertidal, and shoreline areas. Estimates of current velocities and excess shear stress due to a combination of the 100-year flow in the LDW and peak ebb tide conditions were developed by QEA using a three-dimensional hydrodynamic and sediment transport model documented in the *Lower Duwamish Waterway Sediment Transport Modeling Report* (QEA 2008).

Shear stress is a measure of the force exerted laterally on the river bed due to hydrodynamic forces, including river currents (Ippen 1966). The critical shear stress is the value at which the sediment on the bed will begin to erode, and excess shear stress is a measure of shear stress above the critical shear stress for the sediment bed as shown in Equation I-1:

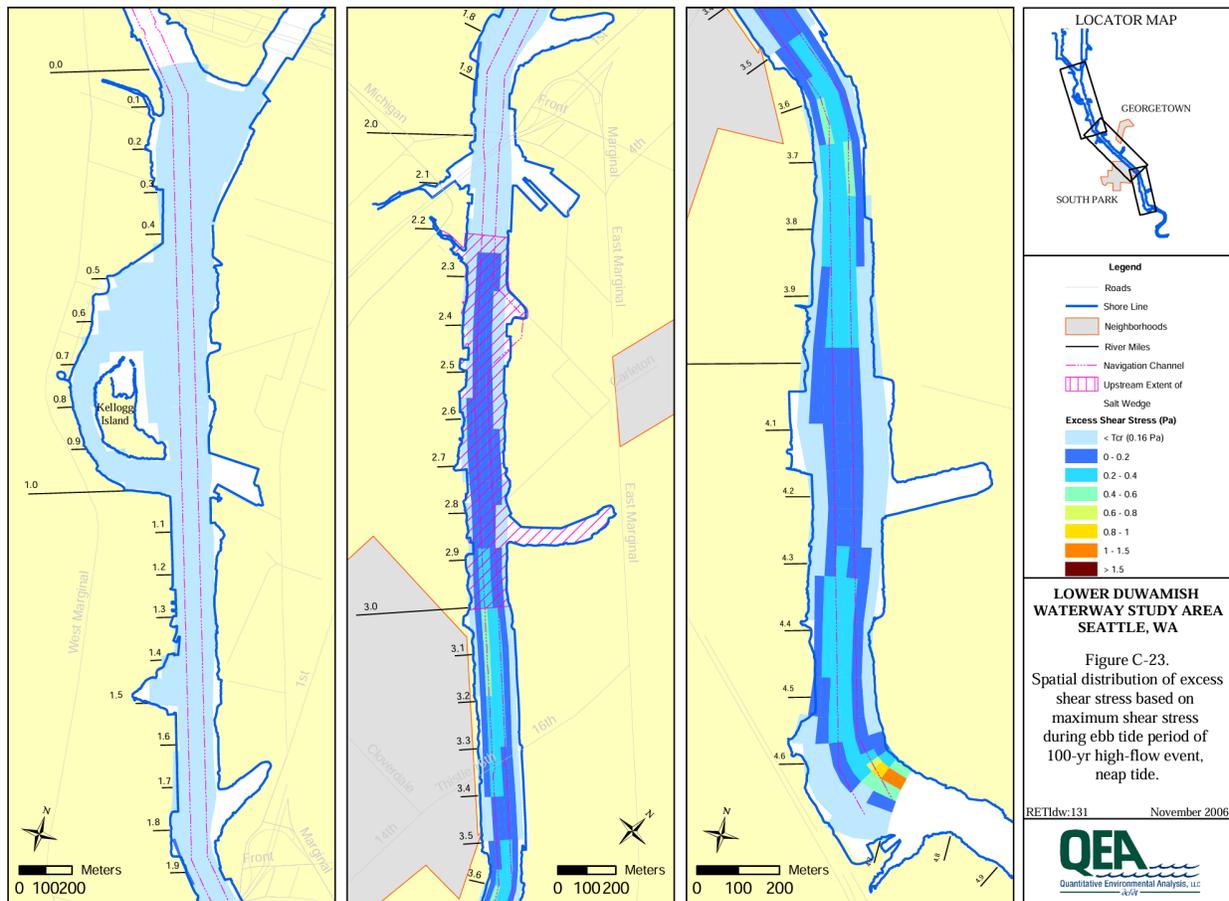
$$\tau_{ex} = \tau - \tau_{cr} \quad \text{Equation I-1}$$

where  $\tau_{ex}$  is the excess shear stress,  $\tau$  is the shear stress exerted on the sediment bed by river and tidal currents, and  $\tau_{cr}$  is the critical shear stress of the sediment bed.

The excess shear stress was estimated from sediment transport modeling completed for the LDW for the 100-year flow at peak flood and peak ebb tide, with higher values of excess shear stress occurring during peak ebb tide (QEA 2008). Figure I-1 (taken from Figure 3-16, QEA [2008]) shows model predicted excess shear stress values for the 100-year flow at peak ebb tide with the middle reach shown in the center panel of the figure.

Critical bed shear stress ( $\tau_{cr}$ ) for the LDW was estimated from Sedflume core data to be 1.6 pascal (QEA 2008). Therefore, the shear stress exerted on the sediment bed ( $\tau$ ) during the 100-year/peak ebb tide event can be determined by adding this critical shear stress value to the value of excess shear stress ( $\tau_{ex}$ ) shown in Figure I-1 (see Equation I-1). Predicted excess shear stress in the middle reach for the 100-year/peak ebb tide event ranges from approximately 0.2 to 0.6 pascal. This corresponds to shear stress values ranging from 1.8 to 2.2 pascals. This shear stress information can be used to estimate the size of sediment particles that would be stable during the 100-year/peak ebb tide scenario. This is discussed in Section 3.5 of this report.

**Figure I-1  
Excess Shear Stress in LDW River (Middle Reach from RM 1.6 to 3.0) for the 100 flow/peak Ebb Tide Scenario**



Source: Figure C-23 of QEA (2008)

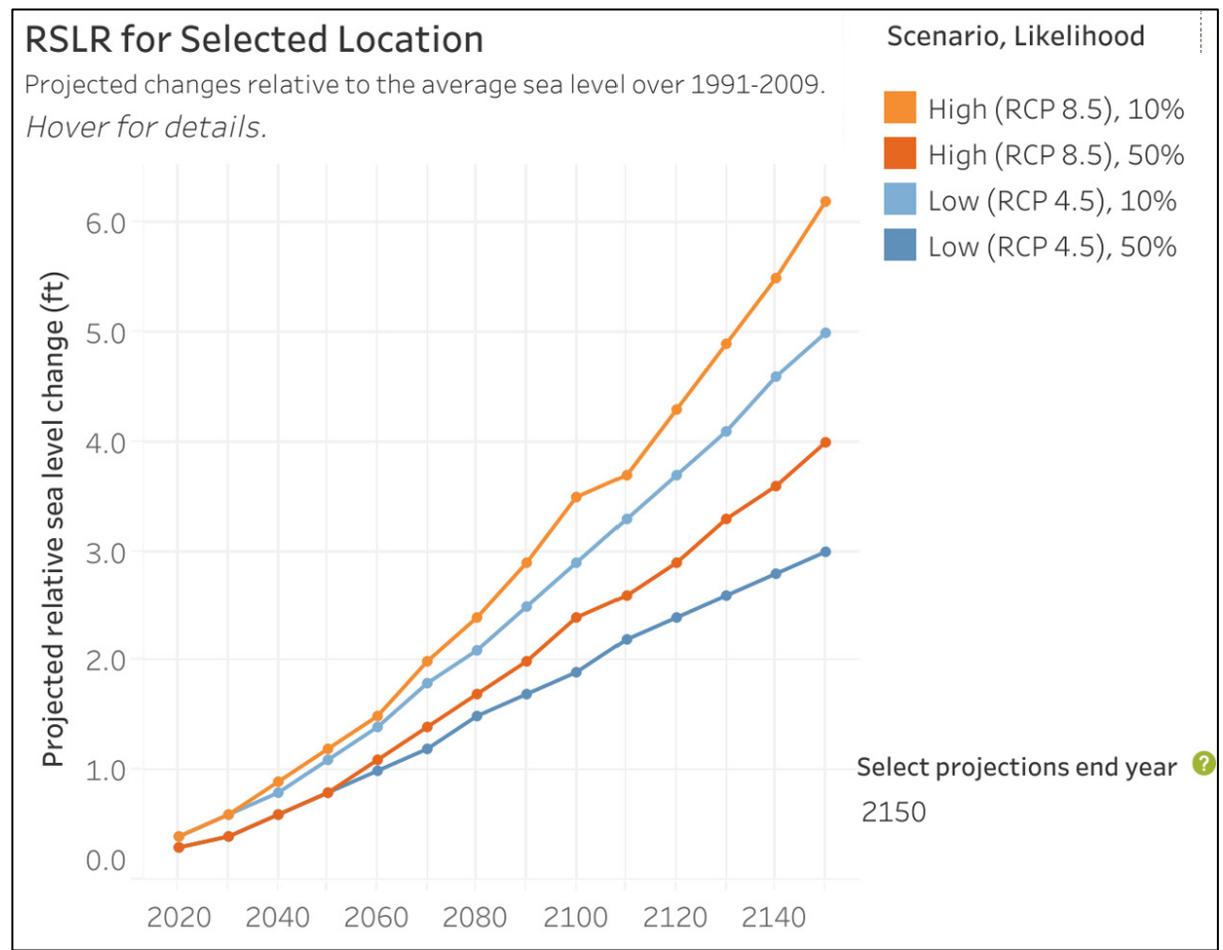
## 2.4 Sea Level Rise Predictions

SLR estimates for the middle reach were taken from *Projected Sea Level Rise for Washington State – A 2018 Assessment* (Miller et al. 2018), published by the Washington Coastal Resilience Project. The SLR predictions provided in this study have been compiled into an online visualization tool available at: <https://cig.uw.edu/projects/interactive-sea-level-rise-data-visualizations/>. SLR predictions are available based on future year of interest through 2150, probability of occurrence, and for two Representative Concentration Pathways (RCPs), which are a measure of emissions that drive global changes in temperature and subsequent SLR. RCP 4.5 represents a moderate emissions scenario with future reductions, and RCP 8.5 represents a scenario where emissions continue to rise into the future.

Guidance on selection of SLR scenarios for use in risk evaluation and design for remediation projects is available in the U.S. Environmental Protection Agency (EPA) Engineering Forum Issue Paper titled *Conducting Climate Vulnerability Assessments at Superfund Sites* (EPA 2023). This reference suggests that a scenario-based evaluation should be completed (include a range of SLR values in the analysis) with the range defined as the RCP 4.5, 50% likelihood of occurrence value as the low bound, and RCP 8.5, 10% probability of occurrence as an upper bound for SLR.

SLR predictions for the middle reach for RCPs 4.5 and 8.5 for the 50% and 10% exceedance probabilities between years 2020 and 2150 are provided in Figure I-2, which is taken from the visualization tool developed from Miller et. al. (2018) and available at the hyperlink above. Using the scenario selection guidance in EPA (2023), estimated values of SLR for the year 2100 used for this evaluation range from 1.9 feet (RCP 4.5, 50% likelihood of occurrence) to 3.5 feet (RCP 8.5, 10% likelihood of occurrence).

**Figure I-2**  
**Sea Level Rise Estimates for Middle Reach**



Developed from the visualization tool from Miller et al. (2018), available at: <https://cig.uw.edu/projects/interactive-sea-level-rise-data-visualizations/>.

## 3 Erosion Protection Design for Engineered Cap Areas

The following subsections present the methodologies used in the design of erosion protection for proposed engineered cap areas. Included in this section are the following:

- Selection of design vessels
- Empirical estimates of erosion protection design materials when exposed to the following:
  - Propwash
  - Vessel wakes
  - Wind-waves
  - River currents
- Impacts of SLR

### 3.1 Selection of Design Vessels

Local scour caused by propwash and the erosive effects of vessel wakes are dependent on vessel characteristics including size, speed, distance from shore, and propeller characteristics, such as propeller type, distance from bottom, and depth below water line. These parameters are used in a number of empirical formulas that ultimately return the approximate material size and geometry of erosion protection measures.

Vessel track data within the middle reach project site boundary were used to identify the vessel types that frequent the LDW. Vessel automatic information system (AIS) data, which provide vessel characteristics (length, draft, and breadth), speed, course, and location, were obtained from Marine Cadastre (available at: <https://marinecadastre.gov>) from 2019 through 2024. These 5 years of data were analyzed to identify vessels that are expected to produce the highest propwash velocities and produce the largest wakes in the middle reach based on vessel properties and documented speed of travel. The focus of the AIS data evaluation was on larger vessels transiting the main navigation channel expected to produce the largest propwash velocities on the sediment bed in the middle reach.

At future phases of design, additional information regarding vessel maneuvering and berthing operations within and adjacent to specific capping areas outside the FNC will be required to develop refined estimates of stable sediment sizes in those areas. Those evaluations will likely include design vessels and operations in addition to what is discussed in this report. Therefore, stable sediment sizes provided for priority capping areas outside the FNC provided in this report (30% RD level) should be considered preliminary and subject to change.

Based on this AIS data evaluation, the following two vessels were selected due to their type, size, or frequency of travel within the middle reach:

- *Garth Foss* (tractor tug): Selected because it was the largest tug, although not the most frequent, that traveled through the middle reach in the 5-year period of record
- *Clayton Arthur* (tug): Selected because it was the third most frequent tug that traveled through the middle reach in the 5-year period of record and was significantly larger than the first and second most frequently operated tugs in the middle reach

Specific vessel information for both tugs is provided in Table I-2.

**Table I-2  
Design Vessel Information**

Characteristic	<i>Garth Foss</i>	<i>Clayton Arthur</i>
Vessel Type	Enhanced Tractor Tug	Tug
Length Over All, feet	155	135
Maximum Breadth, feet	48	40
Maximum Draft, feet <sup>1</sup>	20	15
Propeller Type	5-Blade Voith Cycloidal (two) (non-ducted)	Fixed Pitch Propeller (two) (non-ducted)
Propeller Diameter, feet	9.8	7.7
Engine Power, hp	8,000	3,334

Notes:

1. Maximum draft is defined as the distance between water surface elevation and the lowest point along keel under fully loaded conditions.

hp: horsepower

The extent of travel within the middle reach for both tugs was also examined using the AIS data over the same time period. The larger tug, the *Garth Foss*, did not travel south of RM 2.6, while the *Clayton Arthur* traveled the entire length of the middle reach. For this reason, the *Garth Foss* is the design vessel to RM 2.6, and south of that location, the *Clayton Arthur* is the design vessel for the stability calculations due to propwash in the FNC and due to wake in specific capping areas outside the FNC.

Stable sediment size in specific capping areas outside the FNC and along shorelines due to propwash was not explicitly calculated as part of this study due to aforementioned data gaps associated with vessel maneuvering and docking in these areas. For the 30% RD work summarized in this report, typical stable sediment size estimated from other studies completed in the LDW and nearby East Waterway were used to estimate preliminary stable sediment sizes (see Section 3.2.2). These values

will be updated in later phases of design once more information on specific vessel operations in the specific capping areas is known.

### 3.2 Stable Particle Size Due to Propeller Wash Forces

As a vessel moves through the water, the propeller produces an underwater high-velocity jet that can resuspend and/or erode adjacent riverbed sediments. The velocity distributions in the propwash jet are turbulent and complex, and the velocity plume can extend several boat lengths behind and to the sides of the vessel, depending on vessel operations. The magnitude and spatial extent of the velocity plume can depend on the water depth, propeller draft (distance from the water line to the propeller shaft), size and type of propeller, rotational speed of the propeller (e.g., horsepower [hp] applied to the engine), and type of movement of the vessel (i.e., transiting through a channel or berthing).

Potential effects on the design of the erosion protection for proposed cap areas were evaluated in accordance with Appendix A of Palermo et al. (1998) cap armor layer design guidance.

The propwash velocity was calculated using an empirical method developed by Blaauw and van de Kaa (1978). The stable particle size under these velocities was calculated based on an empirical method by Blaauw et al. (1984) and additional research by Maynard (1988); both methods are presented in Appendix A (Armor Layer Design) of Palermo et al. (1998). These methods consider physical vessel characteristics (e.g., propeller diameter and propeller draft) and operational and site conditions (e.g., applied hp and water depth) to estimate the maximum propeller-induced bottom velocity due to vessels transiting the FNC. As part of the 30% design, maximum propeller-induced velocities on the bed ( $V_{b(max)}$ ) and stable particle sizes ( $D_{50}$ ) in line with the direction of vessel travel were calculated using Equations I-2 and I-3 from Blaauw and van de Kaa (1978) and Equation I-4 from Blaauw and van de Kaa (1984):

$$V_{b(max)} = \frac{C_1 U_o D_p}{H_p} \quad \text{Equation I-2}$$

where  $C_1$  is a coefficient set to 0.22 for non-ducted propellers,  $U_o$  is the jet velocity exiting the propeller,  $D_p$  is the propeller diameter, and  $H_p$  is the distance from the propeller shaft to the channel bottom;

$$U_o = C_2 \left( \frac{P_d}{D_p^2} \right)^{\frac{1}{3}} \quad \text{Equation I-3}$$

where  $C_2$  is a coefficient set to 9.72 for non-ducted propellers,  $P_d$  is the applied engine power in horsepower (hp), and  $D_p$  is the propeller diameter;

$$D_{50} = \frac{V_{b(\max)}^2}{C_3} \frac{1}{g \left( \frac{a_s - a_w}{a_w} \right)}$$

**Equation I-4**

where  $C_3$  is a coefficient set to 0.7 for channel protection based on infrequent impact,  $V_{b(\max)}$  is maximum bed velocity (Equation H-2),  $g$  is acceleration due to gravity,  $a_s$  is the unit weight of rock, and  $a_w$  is unit weight of water.

Proposed capping areas located outside the FNC boundaries (i.e., laterally offset from the direction of vessel travel) or within slip areas were not considered as part of this analysis. If use of capping or other remedial technologies within these areas are proposed as part of 60% or 90% RD, additional propwash evaluation will be completed based on location of capping areas relative to direction of vessel travel, specific vessel berthing operations and potentially additional design vessels.

### 3.2.1 *Within the Federal Navigation Channel*

Equations I-2 through I-4 were used to predict maximum bed velocities and corresponding stable particle sizes on the riverbed within the FNC when subjected to steady state propwash (i.e., the vessel is essentially stationary or maneuvering at a very low speed) from the *Garth Foss* tug (Table I-2). The *Garth Foss* is expected to produce higher propwash velocities due to its larger vessel size and smaller propeller draft compared to the *Clayton Author*. Therefore, the *Garth Foss* tug was used to calculate stable sediment sizes due to propwash within the middle reach where it was shown to operate in AIS data and based on minimum required keel clearances discussed below. In areas where the *Garth Foss* is not likely to operate (i.e., upstream of RM 2.6), the *Clayton Aurthur* was the design vessel used for the propwash calculations.

To evaluate propwash velocities on the riverbed and associated stable particle sizes, operational assumptions for the design vessel within the middle reach were established. There are no specific requirements for engine operation and under-keel draft for tug vessels operation within the LDW, so available guidance documents were used to develop operational assumptions used in the evaluation as described in the following:

- Applied hp while transiting the middle reach: PIANC (2015) suggests using 5% to 15% of the installed power for the main propellers for transiting vessels. Therefore, for this analysis, 15% applied power was conservatively used to calculate the propwash velocities.
- Under-keel clearance:
  - General guidelines for vessel operations developed by the Puget Sound Pilots (2025) require all vessels greater than 400 feet in length to maintain a minimum under-keel clearance of 3 feet or 10% of draft, whichever is greater. While both design vessels for the middle reach are smaller than 400 feet in length, this standard was used as a reasonable assumption for the *Garth Foss* and *Clayton Author* tugs.

- The ROD (EPA 2014) requires any engineered cap within the FNC to be at least 4 feet below the authorized depth. For the propwash evaluation, the minimum under-keel clearance estimated from the Puget Sound Pilots (2021) general guidelines presented in the preceding bullet was increased by 4 feet.

The maximum draft of the *Garth Foss* tug (Table I-2) is 20 feet, which is defined as the distance between the water line (e.g., water surface elevation) and the lowest part of the keel. For the purposes of propwash velocity calculations, the maximum draft is also assumed to be the distance between the water line and the bottom of the propeller. If available, this information will be confirmed at 60% RD. The propellers on the *Garth Foss* tug are 9.8 feet in diameter; so the distance between the water line and the shaft of the propeller<sup>1</sup> (propeller draft) is assumed to be 15.1 feet. For the *Clayton Arthur*, the propeller draft is 11.2 feet. Using guidance from the Puget Sound Pilots (2025), 10% of the maximum draft (2 feet) is less than the standard 3 feet of minimum clearance. Therefore, 3 feet was used as the minimum clearance above the FNC-authorized elevation for the propwash velocity and stable particle size calculations. Because the ROD (EPA 2014) requires 4 feet below the FNC-authorized depth in capped areas, the minimum water depth under the propeller for the calculations was set to 7 feet. A similar analysis was completed for the *Clayton Arthur* for the middle reach upstream of RM 2.6 (where the *Garth Foss* has not been documented to operate). Minimum under-keel clearance used in these calculations will be verified with pilots of design vessels as part of 60% RD.

Calculation scenarios were developed based on the range of tidal elevations in middle reach (Table I-1), the allowed minimum water depth under the propeller for both tugs (7 feet), and other operational assumptions discussed above. Calculations scenarios are listed in Table I-3, and results of the evaluation (maximum bottom velocity and stable particle size) for each calculation scenario are provided in Table I-4.

---

<sup>1</sup> Shaft of propeller is assumed to be located in the center of the propeller.  
Appendix I: Engineering Protection Analysis for Engineered Caps and  
Area-Specific Technology  
October 2025

**Table I-3  
Propwash Calculation Scenarios in the Federal Navigation Channel**

Calculation Scenario No.	Design Vessel	Applied Engine Power <sup>1</sup> (hp)	FNC-Authorized Elevation <sup>2</sup> (feet, MLLW)	Tidal Phase <sup>3</sup> (feet, MLLW)	Water Depth Under Propeller Shaft <sup>4</sup> (feet)
1	Garth Foss	15% of available, 1,200 hp	-30 (RM 1.6 to 2)	MHHW (11.3)	30.2
2				MSL (6.6)	25.5
3				MLLW (0)	18.9
4				Lowest Observed Tide (-3)	15.9
5			-20 (RM 2 to 2.6)	MHHW (11.3)	20.2
6				MSL (6.6)	15.5
7				Lowest allowable <sup>5</sup> (3)	11.9
8	Clayton Arthur	15% of available, 585 hp	-20 (RM 2.6 to 2.8)	MHHW (11.3)	24.1
9				MSL (6.6)	19.4
10				Lowest allowable <sup>5</sup> (-2)	10.8
11			-15 (RM 2.8 to 3)	MHHW (11.3)	19.1
12				Lowest allowable <sup>5</sup> (3)	10.8

Notes:

1. Based on suggested guidance in PIANC (2015). Available power on *Garth Foss* tug is 8,000 hp and on *Clayton Arthur* is 3,900 hp.
2. For propwash calculations, these water depths were increased by an additional 4 feet due to ROD (EPA 2014) requirements in capped areas within the FNC.
3. Tidal datums are provided in Table I-1.
4. See Table I-2 and text in Section 3.2.1.
5. Lowest allowable water surface elevation is based on minimum 7 feet of water depth under the bottom of the propeller.

**Table I-4  
Maximum Bottom Velocities and Stable Particle Sizes due to Propeller Wash in the Federal Navigation Channel**

Calculation Scenario No.	FNC-Authorized Elevation <sup>1</sup> (feet, MLLW)	Maximum Bottom Velocity <sup>2</sup> (ft/s)	Stable Particle Size <sup>1</sup> (inches)
1	-30 (RM 1.6 to 2)	1.6	1.2
2		1.9	1.7
3		2.6	3.1
4		3.1	4.4

Calculation Scenario No.	FNC-Authorized Elevation <sup>1</sup> (feet, MLLW)	Maximum Bottom Velocity <sup>2</sup> (ft/s)	Stable Particle Size <sup>1</sup> (inches)
5	-20 (RM 2 to 2.6)	2.4	2.7
6		3.2	4.7
7		4.1	7.8
8	-20 (RM 2.6 to 2.8)	1.5	1.0
9		1.8	1.5
10		3.3	4.9
11	-15 (RM 2.8 to 3)	1.8	1.6
12		3.3	4.9

Notes:

1. See Equation H-4; associated with maximum riverbed velocity
  2. See Equation H-2; maximum riverbed velocities in line with vessel travel direction within the FNC
- ft/s: foot per second

The largest predicted stable sediment  $D_{50}$  for the FNC between RM 2.0 and 3.0 is 7.8 inches based on minimum allowable water depth for tug operations. The *Garth Foss* and *Clayton Aurthur* tugs may not operate at the minimum allowable water depth defined in this study; so this may be an unrealistic result. As part of 60% RD, operational assumptions of design vessels should be verified.

Under all other calculation scenarios evaluated (see Table I-4), the largest predicted stable sediment  $D_{50}$  for the FNC between RM 1.6 and RM 3.0 in the middle reach is 4.9 inches.

### 3.2.2 Off-channel Capping Areas

Stable sediment sizes due to propwash were also evaluated for four representative off-channel capping areas (referred to as remedial action areas [RAAs]) are shown in Figure 5-2 of the Preliminary (30%) RD BODR as follows:

- RAA 5B: Steep shoreline area that will be armored and adjacent inter- and subtidal areas where modified cap is proposed
- RAA 9K: Area will be dredged shallower than surrounding channel due to utility crossing in this area. Finished cover elevation will be the same as the FNC-authorized depth at this location instead of 4 feet below that depth.
- RAA 20C: Inter- and subtidal areas where a modified cap is proposed

Stable sediment size for RAA 9K was taken from evaluation of propwash in the FNC because RAA 9K is within and just adjacent to the FNC. Because this area will be dredged shallower than the adjacent FNC, the top of cap will be at higher elevation than considered in the propwash scenarios listed in Tables I-3 and I-4. The bed elevation in RAA will be -20 feet MLLW, which is the authorized

navigation depth for that area. Based on operations of the *Clayton Arthur* tug in this area (see Table I-3), the stable particle size in RAA 9K will be 7 inches.

RAAs 5B and 20C are shoreline and inter- and subtidal areas adjacent to lateral docks where vessel operations are unknown. Because of these data gaps, propwash was not explicitly calculated as part of this study. From review of other similar propwash evaluations in the LDW and East Waterway, preliminary stable sediment size in these RAAs is approximately 1 to 2 inches below the elevation of approximately +4 feet MLLW (Anchor QEA 2022). These values should be considered preliminary and subject to change. These values will be updated in later phases of design once more information on specific vessel operations in the specific capping areas is known.

### 3.3 Stable Particle Size Due to Vessel Wakes

Vessels transiting north and south along the LDW have the potential to create wakes with enough energy to mobilize sediments within inter- and subtidal and shoreline (riverbank) areas of the middle reach. The size of the wake depends on many factors including proximity of vessel line of travel to area of interest, vessel dimensions, vessel speed, and water depth. The design vessels identified for the middle reach (both tugs) are expected to produce the largest wakes based on vessel specifications (Table I-2) and speed of travel identified from the AIS data (see Section 3.1).

Stable sediment sizes due to vessel wake were calculated for the shoreline and in inter- and subtidal areas within three capping areas identified in Section 3.2.2 based on RAA-specific bathymetry and distance from the FNC (line of travel). During future phases of design, additional identified RAAs with engineered caps will be specifically evaluated for vessel wake impact.

Wake characteristics were estimated using an empirical method developed by Kriebel and Seelig (2005), which improves upon the original methodology developed by Sorensen and Weggel (1984). The speed of travel of the vessels for wake calculations was limited to the documented speed limit in the FNC within the middle reach, which is 7 knots (Seattle Municipal Code Section 16.20.130I).

The stable particle size due to vessel wake was calculated using the estimated wake parameters by applying the stability formula developed by Boeters et. al. (1993) included in the CIRIA Rock Manual (2007). This method was specifically developed to estimate stable particle size due to vessel wakes (as opposed to wind-waves or other type of wave form).

Stable sediment sizes due to vessel wake were evaluated for two off-channel capping areas: RAA 5B and RAA 20C. These areas are shoreline and inter- and subtidal areas where the bed could be influenced by boat wake from the top of bank down to approximately -2 feet MLLW. The lowest elevation where vessel wake will influence the stable particle size is assumed to be three times the wake (wave) height per guidance in the *Coastal Engineering Manual* (USACE 2008).

The design vessels and methodology used for calculation of stable particle size for the general shoreline conditions (Section 3.2.1) were also used for the priority capping/RAA areas described in Section 3.2.2 and are listed in Table I-5. These calculations and estimated stable sediment sizes due to vessel wake are summarized in Table I-5.

**Table I-5  
Wake Parameters and Associated Stable Particle Size in Priority Capping Areas (RAAs)**

RAA	Design Vessel	Distance from Shore <sup>1</sup>	Speed of Travel Over Ground (knots) <sup>2</sup>	Shoreline Slope (H:V) <sup>3</sup>	Wake Height <sup>4</sup> (feet)	Wake Period <sup>4</sup> (second)	Stable Particle Size, <sup>5</sup> D <sub>50</sub> (inches)
5B	<i>Clayton Arthur</i>	175	7	1.5:1	0.6	1.9	2
20C	<i>Clayton Arthur</i> <sup>6</sup>	300		3:1	0.3	1.9	2

Notes:

1. Distance from line of travel of vessel to shoreline based on AIS data (see Section 3.1)
2. Maximum allowable speed in FNC
3. Shoreline slope represents the steepest existing slope within the RAA area based on review of bathymetry/topography data
4. Kriebel and Seelig (2005)
5. Boeters et al. (1993) valid down to an elevation of -2 feet MLLW. Below that elevation, stable particle size is determined by propeller wash (see Section 3.2.2).
6. The *Garth Foss* operates in the navigation channel adjacent to this area but cannot operate at lower tides compared to the *Clayton Arthur*.

H:V: horizontal to vertical (ratio)

### 3.4 Stable Particle Size Due to River Currents

Stable particle sizes to resist hydrodynamic flows (i.e., river currents) were generally assessed for the middle reach using LDW shear stress model results from QEA (2008), summarized in Section 2.3. Although the hydrodynamic model used to provide the shear stress predictions was developed in 2008, it is considered valid and conservative for the purpose of design for the cap erosion protection design. The bathymetry used in the hydrodynamic model represents a shallower condition than the proposed dredged and cap surface, resulting in the velocities being more conservative. Similarly, although SLR was not modeled, it is expected that any SLR added to the simulation would result in lower velocities than currently used in the protection layer analysis. Additionally, simulations with higher flows due to potential climate change were not performed because the flows are controlled by the Howard Hanson Dam. Therefore, the hydrodynamic model results are considered conservative for the cap protection design.

Predicted bed shear stress within the middle reach ranges from 1.8 to 2.2 pascal for the 100-year flow in the Lower Duwamish at peak ebb tide conditions (see Figure I-1). The U.S. Geological Survey

(USGS) developed a summary table of critical bed shear stress and corresponding particle (rock) size (USGS 2008), provided as Figure I-3. For the modeled range of bed shear stress, the corresponding stable particle (rock) size ranges from 2 to 4 millimeters (roughly 0.1 to 0.2 inches; very fine gravel).

This is in agreement with identification of most of the middle reach as net erosional, because the predicted bed shear stress in the middle reach exceeds the critical shear stress of fine sediments and sand which are predominantly present in bed sediments in the Lower Duwamish River (QEA 2008).

**Figure I-3**  
**Critical Bed Shear Stress Versus Stable Particle Size**

Particle classification name	Ranges of particle diameters		Shields parameter (dimensionless)	Critical bed shear stress ( $\tau_c$ ) (N/m <sup>2</sup> )
	$\phi$	mm		
Coarse cobble	-7 – -8	128 – 256	0.054 – 0.054	112 – 223
Fine cobble	-6 – -7	64 – 128	0.052 – 0.054	53.8 – 112
Very coarse gravel	-5 – -6	32 – 64	0.05 – 0.052	25.9 – 53.8
Coarse gravel	-4 – -5	16 – 32	0.047 – 0.05	12.2 – 25.9
Medium gravel	-3 – -4	8 – 16	0.044 – 0.047	5.7 – 12.2
Fine gravel	-2 – -3	4 – 8	0.042 – 0.044	2.7 – 5.7
Very fine gravel	-1 – -2	2 – 4	0.039 – 0.042	1.3 – 2.7
Very coarse sand	0 – -1	1 – 2	0.029 – 0.039	0.47 – 1.3
Coarse sand	1 – 0	0.5 – 1	0.033 – 0.029	0.27 – 0.47
Medium sand	2 – 1	0.25 – 0.5	0.048 – 0.033	0.194 – 0.27
Fine sand	3 – 2	0.125 – 0.25	0.072 – 0.048	0.145 – 0.194
Very fine sand	4 – 3	0.0625 – 0.125	0.109 – 0.072	0.110 – 0.145
Coarse silt	5 – 4	0.0310 – 0.0625	0.165 – 0.109	0.0826 – 0.110
Medium silt	6 – 5	0.0156 – 0.0310	0.25 – 0.165	0.0630 – 0.0826
Fine silt	7 – 6	0.0078 – 0.0156	0.3 – 0.25	0.0378 – 0.0630

Source: Table 7 in USGS (2008)

### 3.5 Impacts of Wind-Waves

Wind-generated wave parameters are generally a function of sustained wind speed and fetch. Fetch is the open-water distance over which wind can blow without obstruction. The LDW is a narrow waterway with minimal fetch distance in directions that would create wind-waves that would impact shoreline (riverbank) areas. In addition, the waterway has a low length-to-width ratio, meaning wind-waves produced along a stretch of the LDW will be smaller than waves produced over the same

length in an open sea for the same fetch distance. Therefore, wind-waves are not expected to be the dominant force for defining stable particle size in the middle reach compared to propwash and vessel wake.

A wind-wave evaluation was completed for 30% RD for the upper reach of the LDW (Anchor QEA 2022), which is applicable to the middle reach because both reaches have similar width and general wind exposure. Based on the wind-wave analysis completed for the upper reach, calculated 100-year wave heights were approximately 0.5 foot. These are similar in size to the maximum vessel wakes calculated for the middle reach described in Section 3.3 and provided in Table I-5 (0.6 foot). Thus, as expected, wind-waves will not govern the stable particle size for the middle reach.

### **3.6 Impacts of Climate Change**

A future climate change impact that should be considered in estimating stable particle size in the middle reach for future conditions is SLR (see Section 2.4).

Future SLR conditions are not expected to increase the required stable particle size in the middle reach based on propwash, river currents, or vessel wakes. The stable particle size due to these hydrodynamic forces is inversely proportional to water depth. Therefore, the stable particle size will decrease with increasing water depth caused by future SLR. Stable particle sizes calculated for existing water levels, as outlined in this report, will be conservatively large for future with SLR conditions.

## 4 Summary

Stable particle sizes for cap layers placed within the FNC and off-channel cap areas were estimated over a range of typical hydrodynamic forces including propwash, vessel wakes, river/tidal currents, and wind wakes.

Stable particle sizes are determined by propwash in the FNC and vessel wakes along the shoreline/riverbanks within RAAs where engineered caps will be placed. Stable particle sizes in intertidal and subtidal capping RAAs between the FNC and the shoreline could be dominated by either propwash or vessel wakes, depending on the bed elevations and specific vessel operations within and adjacent to each area.

This evaluation was based on limited vessel operations information, especially in capping RAAs and are subject to change at 60% design once additional specific vessel operations in and adjacent to capping areas are known. Additional capping RAAs may also be evaluated at 60% or 90% RD.

Calculated maximum stable particle sizes ( $D_{50}$ ) within the FNC throughout the middle reach (regardless of authorized navigation depth) is 4.9 inches for moderately conservative propwash assumptions (see Section 3.2.1).

Stable particle size was estimated for off-channel capping and utility crossing cover RAAs based on propwash and vessel wake, which were determined to dominate potential for sediment movement in these areas. Stable particle sizes and bed elevations where these values should be applied are summarized for each capping RAA as follows:

- RAA 5B (off-channel cap):
  - Stable particle size of 1 to 2 inches below -2 feet MLLW due to potential propwash (preliminary, see Section 3.2.2)
  - Stable particle size of 2 inches above -2 feet MLLW due to vessel wake (see Section 3.3)
- RAA 9K (utility crossing cover):
  - Stable particle size of 7 inches due to propwash (see Section 3.2.2)
- RAA 20C (off-channel cap):
  - Stable particle size of 1 to 2 inches below -2 feet MLLW due to potential propwash (preliminary, see Section 3.2.2)
  - Stable particle size of 2 inches above -2 feet MLLW due to vessel wake (see Section 3.3)

Calculated stable particle sizes based on river currents and wind-waves in the FNC and in capping RAAs are smaller than those determined by propwash and vessel wake.

The materials and geometry of proposed capping areas will depend on the site-specific conditions of each capping area, including underlying sediment conditions. In general, erosion control for capping

areas will consist of a 1-foot layer of armor rock based on the stable particle sizes calculated for the area and an additional 0.5-foot layer of filter rock sized based on both the armor rock size and underlying sediment size (Van Der Meer, 1987). The filter rock layer is required to prevent winnowing of underlying sediments through the erosion protection layer (armor rock). Specifics of erosion protection in each proposed capping area will be completed at 60% RD.

## 5 References

- Anchor QEA, 2022. *30% Remedial Design Basis of Design Report, LDW Upper Reach*. Appendix H, Engineered Cap Erosion Design Analysis. August 2022.
- Blaauw, H.G., and E.J. van de Kaa, 1978. *Erosion of Bottom and Banks Caused by the Screw Race of Maneuvering Ships*. Publication No. 202, Delft Hydraulics Laboratory, Delft, The Netherlands, presented at the Seventh International Harbor Congress, Antwerp, May 22 to 26.
- Blaauw, H.G., F.C.M. van der Knaap, M.T. de Groot, M.T., K.W. and Pilarczyk, 1984. *Design of Bank Protection of Inland Navigation Fairways*. Publication No. 320, Delft Hydraulics Laboratory, Delft, The Netherlands.
- Boeters, R.E.A.M, F.C.M Van der Knaap, H.J. and Verheij, 1993. "Behaviour of Armour Layers of Riprap Bank Protections Along Navigation Channels." In: Proc int riprap workshop, Fort Collins, Colorado, July. Also in: Thorne, C.R., S.R. Abt, F.B. Barends, S.T. Maynard, and R.W. Pilarczyk, editors, 1995. *River, Coastal and Shoreline Protection: Erosion Control Using Riprap and Armourstone*. New York: John Wiley & Sons.
- CIRIA ROCK Manual: CIRIA; CUR; CETMEF, 2007. *The Rock Manual*. The Use of Rock in Hydraulic Engineering (second edition), C683. London.
- EPA (Environmental Protection Agency), 2014. *Record of Decision*. Lower Duwamish Waterway Superfund Site. U.S. Environmental Protection Agency Region 10. November 2014.
- EPA, 2023. *Conducting Climate Vulnerability Assessments at Superfund Sites*. Engineering Forum Issue Paper, EPA 542-R-23-002. November 2023.
- FEMA, 2020a. Flood Insurance Study, King County, Washington, and Incorporated Areas. Flood Insurance Study Number 53033CV001B. December 2020.
- FEMA, 2020b. Flood Insurance Rate Map, King County, Washington, and Incorporated Areas. Map Number 53033C0640G, Panel 640 of 1725. August 2020.
- Ippen, A. 1966. *Estuary and Coastline Hydrodynamics*. McGraw-Hill Book Company, Inc. New York, 1963.
- Kriebel, D. L. and W.N. Seelig, 2005. "An Empirical Model for ship-Generated Waves." Proceedings of the 5th International Symposium on Ocean Wave Measurement and Analysis. 2005.
- Maynard, S.T. 1988. *Stable Riprap Size for Open Channel Flows*. U.S. Army Corps of Engineers Waterways Experiment Station, Technical Report HL-88-4.

- Miller, I.M., H. Morgan, G. Mauger, T. Newton, R. Weldon, D. Schmidt, M. Welch, and E. Grossman, 2018. *Projected Sea Level Rise for Washington State – A 2018 Assessment*. A collaboration of Washington Sea Grant, University of Washington Climate Impacts Group, University of Oregon, University of Washington, and US Geological Survey. Prepared for the Washington Coastal Resilience Project. updated 07/2019.
- Puget Sound Pilots, 2025. *General Guidelines for Vessels Transiting Restricted Waterways or Ports*. Revised May 13, 2025.
- Palermo, M.R., J. Miller, S. Maynard, and D.D. Reible, 1998. *Guidance for In-Situ Subaqueous Capping of Contaminated Sediments. Assessment and Remediation of Contaminated Sediments (ARCS) Program*. Prepared for the Great Lakes National Program Office, U.S. Environmental Protection Agency, Chicago, Illinois. EPA 905-B-96-004. September 1998.
- PIANC, 2015. *Guidelines for Protecting Berthing Structures from Scour Caused by Ships*. Report of Working Group 48, The World Association for Waterborne Transport Infrastructure, Brussels.
- QEA, 2008. *Lower Duwamish Waterway Sediment Transport Model Report*. Final. Prepared for EPA, Region 10, and Washington State Department of Ecology, Northwest Regional Office. October 2008.
- Sorenson, R. and Weggel, R. 1984. *Development of Ship Wave Design Information*. Conference Proceedings, Coastal Engineering, January 1984.
- USACE (U.S. Army Corps of Engineers), 2008. *Coastal Engineering Manual*. EM 1110-2-1100. April 2022; revised 2008.
- USGS, 2008. *Simulation of Flow, Sediment Transport, and Sediment Mobility of the Lower Coeur d'Alene River, Idaho*. Scientific Investigations Report 2008–5093. 2008.
- Van der Meer, J. 1987. *Stability of Breakwater Armour Layers – Design Formulae*. Coastal Engineering, Volume 11, Issue 3, September 1987.
- WRIA 9, 2021. *Water Resource Inventory Area 9 Green/Duwamish and Central Puget Sound Watershed Salmon Habitat Plan 2021 Update. Making Our Watershed Fit for a King*. Approved by the Watershed Ecosystem Forum February 11, 2021.