November 24, 2021

Confidential

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Subject: **Potential Changes to Large Woody Debris Prevalence in the Lower Squamish River Estuary Following the Central Estuary Restoration Project**

WSP ref.: 201-02747-00

INTRODUCTION

The Squamish River Watershed Society (SRWS) is undertaking the Central Estuary Restoration Project (CERP) to restore salmon habitat in the lower Squamish River Estuary. The overall Project entails the removal of approximately 900 m of the Squamish River Training Berm (Berm) south of 49.694850° N, -123.180733° W (Yellow Gate) and retention of the current tip of the Berm (Island) south of 49.687127° N, -123.178385° W. The first phase of the CERP, to be completed in Fall 2021 and Winter 2022, will remove approximately the lower 300 m of Berm north of the Island (49.687127° N, -123.178385° W). The finished elevation of the removal section is proposed as -1.0 m CGVD28, preserving a weir-like structure that is occasionally above still water. Figure 1 presents an overview of the study area and oblique views of the removal section.

WSP Canada Inc. (WSP) is pleased to present this technical memo summarizing potential changes to the distribution of large woody debris (LWD) in the lower Squamish River estuary that may be attributable to first phase of the CERP. The aim of the analysis is to estimate potential changes to LWD prevalence in the Central Estuary and at Squamish Terminals' (SQT) west berth (Berth). Potential impact forces on the fendering system of the Berth have been estimated.

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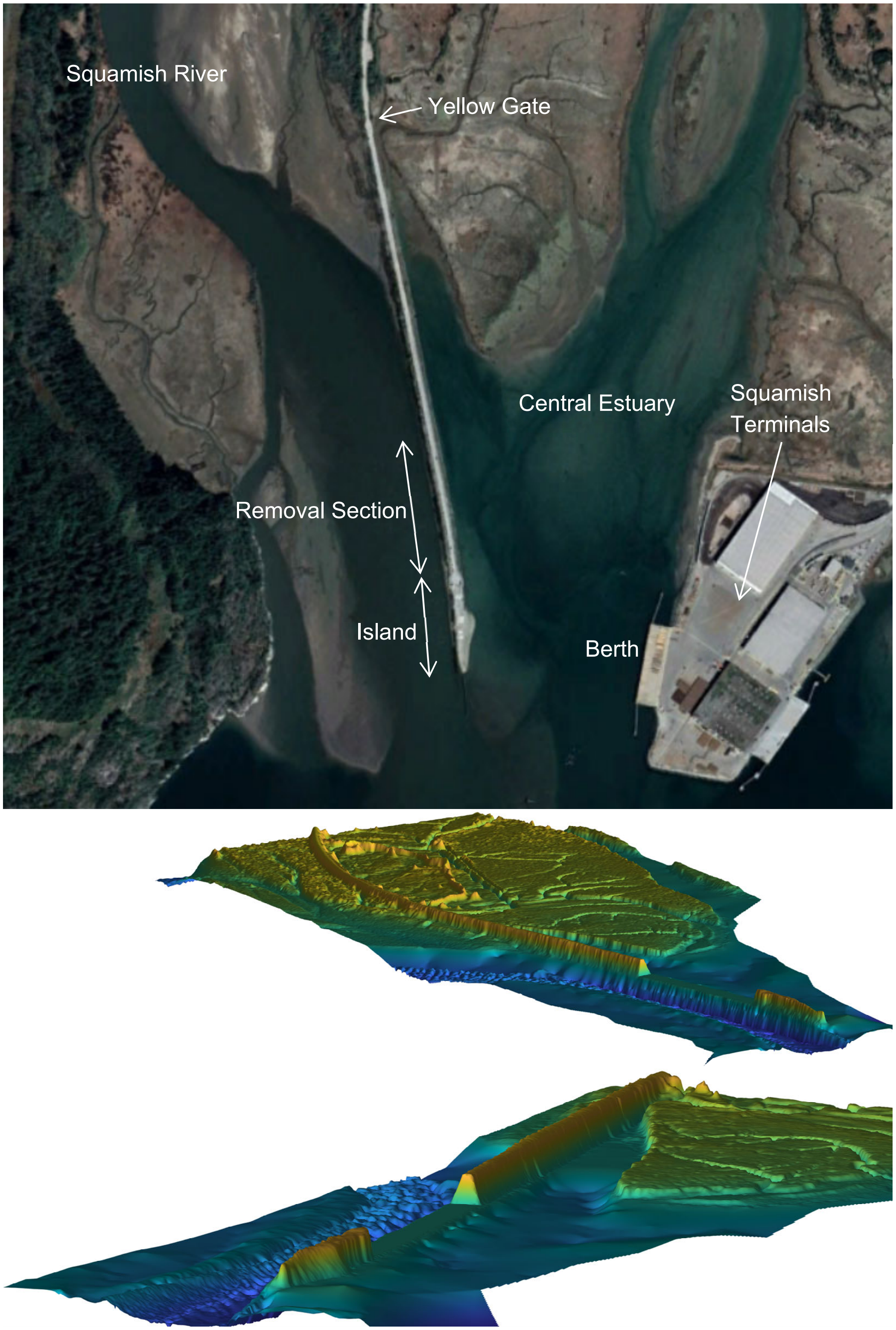

Figure 1: Top Panel, study site plan and nomenclature, Google Earth V 7.3.4.8248. (Nov 2021). Middle Panel, oblique view looking east of the removal section. Bottom Panel, oblique view looking west of the removal section.

METHODOLOGY

LWD, consisting of trees, branches and logs, are produced upriver from the project site and are transported downstream by the Squamish River. As this debris travels downstream, portions of it become stranded or otherwise trapped along the banks and flats of the river, with some proportion of the LWD ultimate transported through the battery limits of the CERP and into Howe Sound where wind and wave driven transport governs the ultimate fate of the LWD.

Under present-day conditions, LWD are transported by river flows and ebb tides into Howe Sound. The primary mechanism by which LWD are transported into the Central Estuary is a combination of flood tides, inflow, wind and waves driving LWD from Howe Sound northwards into the Central Estuary. Therefore, the CERP will only induce changes in LWD behaviour during period of high river discharge (e.g. flood events) and ebb tide conditions while there is sufficient water depth above the removal section to permit the passage of LWD. Under most conditions, the CERP should serve to mitigate LWD presence by providing a net-seaward current in the Central Estuary to clear accumulations of LWD.

The following methodology has been applied to quantify changes to the distribution of LWD in the Central Estuary:

- Debris Characterization: The dimensions and characteristics of LWD have been quantified from historical aerial imagery of the lower Squamish River estuary. LWD stranded on the banks and shoreline of the river and Berm have been digitized to estimate the population of LWD in the river. As only the largest LWD will become stranded, this represents a conservative estimation of debris size in the lower Squamish River estuary.
- Debris Passage, Tidal Conditions: The removal section of the Berm has been set to an elevation of -1.0 m CGVD28, which provides limited freeboard for the passage of LWD and often completely prevents debris from entering the Central Estuary from the river. Changes to the population of LWD between the river and Central Estuary have been estimated based on the freeboard of the removal section and streamline tracing.
- Debris Passage, Flood Conditions: During flood events, the prevalence and, likely, size of LWD increases. Therefore, storm conditions have been analyzed separately to derive both a ‘design’ LWD to quantify potential impact forces on the fendering system of the Berth and the prevalence of LWD during flood events. Streamline tracing has been applied to estimate the likelihood of a given LWD traversing the removal section and passing near the Berth.

DEBRIS CHARACTERIZATION

In order to quantify the population of LWD in the lower Squamish River estuary, the size and characteristics of LWD has been estimated using historical imagery available in Google Earth. The resolution of historical imagery in April 2009, May 2019 and April 2021 were high enough to clearly identify logs, trees, root balls and branches. In total, 66 sample of logs and trees were digitized and measured for length, thickness, root ball diameter and branch extent. Figure 2 provides an overview of the lower Squamish River estuary and exposed banks. Figure 3 provides several examples of digitized LWD.

Figure 2: Google Earth V 7.3.4.8248. (April 2009) showing the lower Squamish River estuary and exposed banks with LWD.

Figure 3: Examples of logs and trees digitized to quantify the population of LWD

Based on the dimensions of the LWD, the volume and mass of each sample data was calculated assuming cylindrical cross section and saturated wood density of 870 kg/m^3. Saturated wood density was calculated based on the dry density of 550 kg/m^3, specific gravity of 0.37 and 100% moisture content, (Simpson, 1993). Table 1 below shows a summary of the LWD population, while Figure 4, Figure 5 and Figure 6 compare the typical lengths of LWD to their thickness (trunk diameter), root ball diameter and mass. In general, LWD length is a relatively poor predictor of other aspects of LWD, however, as shown on Figure 7 the thickness of LWD is an excellent predictor of LWD mass and the ability of LWD to pass over the removal section itself.

Table 1: Summary of digitized LWD based on 66 samples

Variable	Minimum	Average	Maximum
Length (m)	3.1	13.6	43.1
Thickness (m)	0.4	0.7	1.7
Volume (m^3)	0.8	6.4	21.2
Mass (kg)	679	5,564	18,457

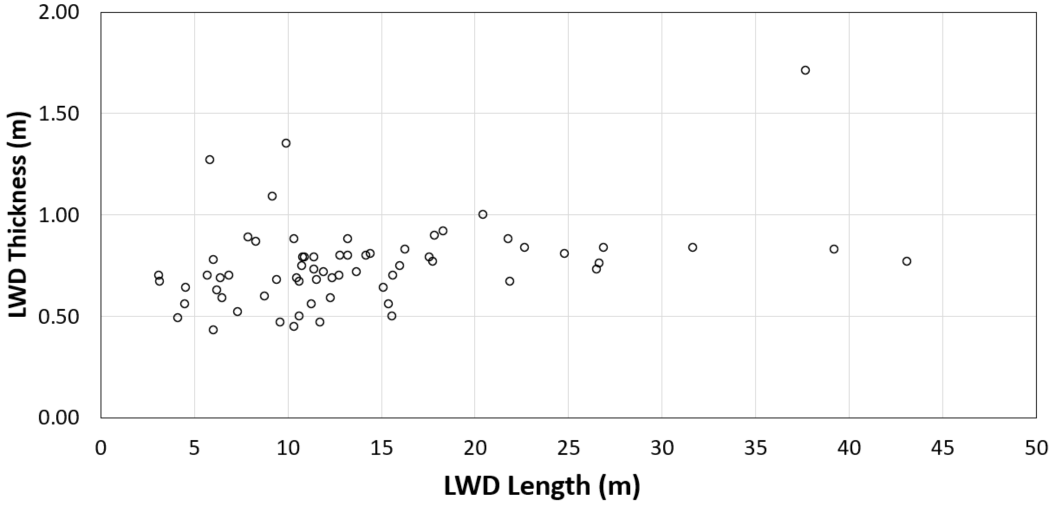

Figure 4: LWD length versus thickness

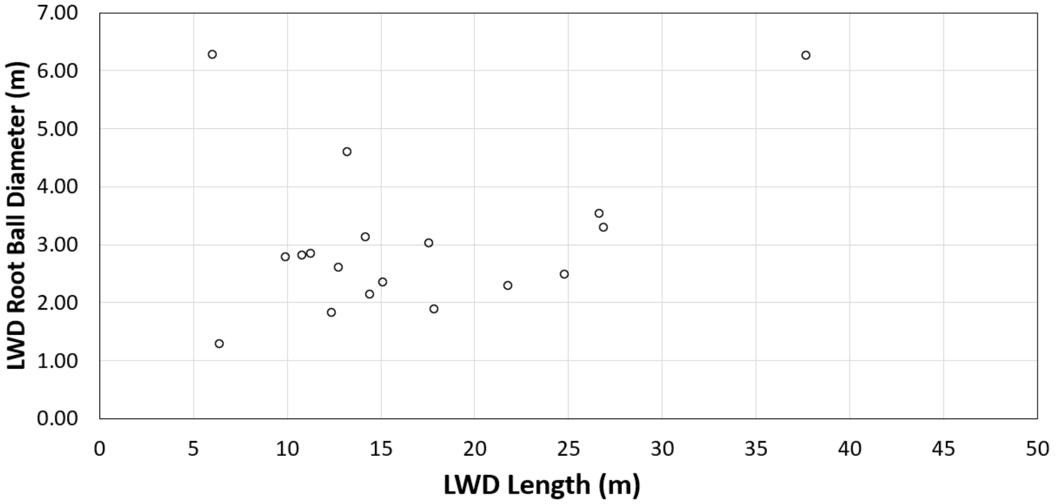

Figure 5: LWD length versus root ball diameter

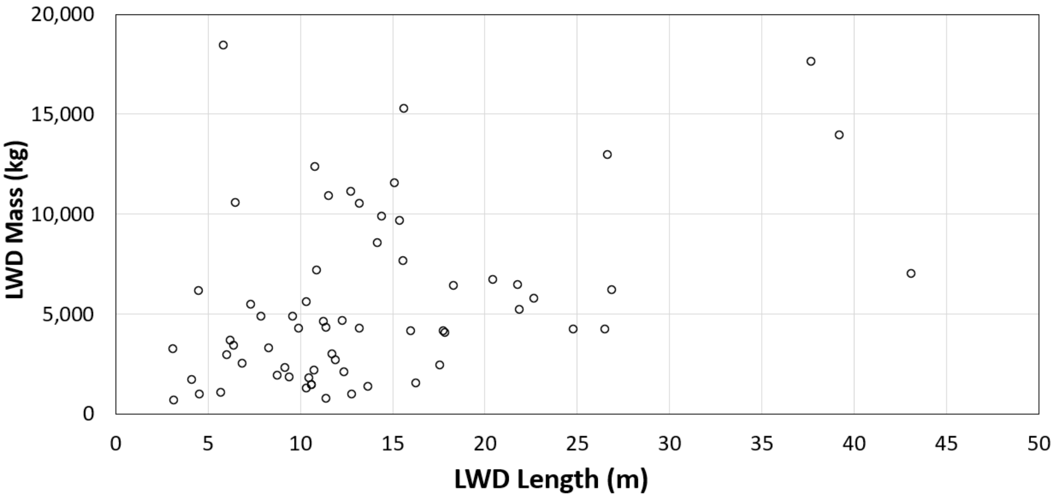

Figure 6: LWD length versus mass

To derive an impact force, an estimate of LWD mass is required. Using the population of digitized LWD, a regression curve has been fit to estimate the mass associated with a given LWD diameter and, hence, freeboard above the removal section. Figure 7 presents the regression curve derived for the measured LWD samples, resulting in Eq. (1):

$$m = 10529 * \ln(D) + 10021;\ D > 0.45\ m \qquad (1)$$

Where m = the estimated mass of the LWD in kg; D = the diameter of LWD in meters. For LWD smaller than the lower bound of the sample population a piecewise regression has been applied using Eq. (2) for LWD with diameters smaller than 0.45 m:

$$m = 9684.4 * D^{2.2318}\ D \leq 0.45\ m \qquad (2)$$

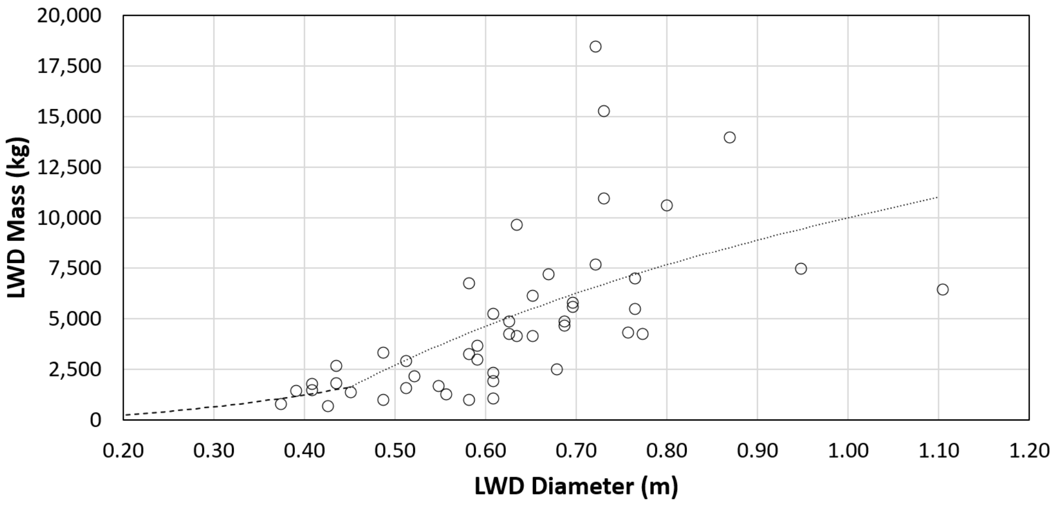

Figure 7: Regression of LWD diameter and mass

DEBRIS PASSSAGE: TIDAL CONDITIONS

Tidal conditions have been established as spring and neap tides over the winter low flow period. Fluvial discharge over a 24-hour simulation period was established as 26 m^3/s, with a 3.9 m spring tide range and a 2.6 m neap tide range. The currents in the lower Squamish River estuary have been simulated using a three-dimensional numerical model developed by Tetra Tech Canada Inc. (Tetra Tech 2017, A. Leung pers. comm. 2021).

Using surface currents produced by the numerical model, potential LWD trajectories have been established using a combination of the water depth above the removal section and streamline tracing of current patterns. An ensemble of 1,000 pieces of LWD were seeded uniformly across the Squamish River upstream of the CERP battery limit. For every hour over the 24-hour simulation the trajectory of these 1,000 LWD were tracked to establish their final fate and position. Each LWD was assigned the full diameter population of the digitized LWD samples to determine which proportion of the population could pass over the berm for a given set of hydraulic conditions. If the LWD passed within the dredge pocket of the Berth, then this was flagged as a “near miss”, while if the LWD passed within 25 m of the Berth then this was flagged as a “potential contact”. The depth of water over the removal section governs the size of CERP-related LWD that can pass into the Central Estuary and LWD transported is assumed to be prevented when the depth of water over removal section is less than 0.3 m.

Table 2 and Table 3 summarize the percent of LWD present in the river that could traverse the removal section and is a candidate for either a near miss or potential contact for spring and neap tide conditions, respectively. Overall, 0.30% to 0.37% of LWD in the river under typical tidal conditions has potential to contact the Berth, while 0.30% to 0.77% could pass within the dredge pocket. This means that, should log be present in the river, then there is a 0.30% to 0.37% chance (1:270 to 1:330) chance that this log could contact the Berth and approximately 875 logs over a 24 hour period would be required to result in a 95% probability of Berth contact.

Table 2: Summary of LWD passage over the berm removal section during spring tide, low flow conditions

Hour	Tide	Water Surface Elevation (m, CGVD28)	Maximum LWD Diameter (m)	Potential Contact Rate	Overall Contact and Near Miss Rate
1	Flood	-1.53	-	0.00%	0.00%
2	Flood	-0.84	-	0.00%	0.00%
3	Flood	0.00	0.87	0.00%	0.00%
4	Flood	0.78	1.76	0.00%	0.00%
5	Flood	1.40	2.47	0.00%	0.00%
6	Ebb	1.72	2.84	0.00%	0.00%
7	Ebb	1.69	2.80	0.00%	0.00%
8	Ebb	1.42	2.49	1.07%	1.07%
9	Ebb	1.03	2.04	0.00%	0.00%
10	Ebb	0.57	1.52	0.00%	0.00%
11	Ebb	0.24	1.13	0.00%	0.00%
12	Flood	0.10	0.98	0.00%	0.00%
13	Flood	0.25	1.15	4.45%	4.45%
14	Flood	0.56	1.51	0.09%	0.09%

15	Flood	0.93	1.93	0.00%	0.00%
16	Flood	1.28	2.33	0.00%	0.00%
17	Flood	1.41	2.48	1.56%	1.56%
18	Ebb	1.24	2.29	0.00%	0.00%
19	Ebb	0.77	1.74	0.00%	0.00%
20	Ebb	0.12	1.00	0.00%	0.00%
21	Ebb	-0.66	0.10	0.00%	0.00%
22	Ebb	-1.42	-	0.00%	0.00%
23	Ebb	-1.99	-	0.00%	0.00%
24	Ebb	-2.22	-	0.00%	0.00%
		Overall	**1.39**	**0.30%**	**0.30%**

Table 3: Summary of LWD passage over the berm removal section during neap tide, low flow conditions

Hour	**Tide**	**Surface Elevation (m, CGVD28)**	**Maximum LWD Draft (m)**	**Potential Contact Rate**	**Overall Contact and Near Miss Rate**
1	Ebb	0.35	1.26	0.00%	2.49%
2	Ebb	0.20	1.09	2.03%	4.65%
3	Ebb	0.05	0.92	6.89%	11.44%
4	Ebb	-0.03	0.83	0.00%	0.00%
5	Flood	0.04	0.91	0.00%	0.00%
6	Flood	0.23	1.13	0.00%	0.00%
7	Flood	0.50	1.44	0.00%	0.00%
8	Flood	0.79	1.77	0.00%	0.00%
9	Flood	1.04	2.06	0.00%	0.00%
10	Flood	1.16	2.20	0.00%	0.00%
11	Ebb	1.08	2.10	0.00%	0.00%
12	Ebb	0.80	1.78	0.00%	0.00%
13	Ebb	0.38	1.30	0.00%	0.00%
14	Ebb	-0.12	0.72	0.00%	0.00%
15	Ebb	-0.63	0.14	0.00%	0.00%
16	Ebb	-1.07	-	0.00%	0.00%
17	Ebb	-1.35	-	0.00%	0.00%
18	Ebb	-1.41	-	0.00%	0.00%
19	Flood	-1.26	-	0.00%	0.00%
20	Flood	-0.94	-	0.00%	0.00%
21	Flood	-0.55	0.23	0.00%	0.00%
22	Flood	-0.14	0.70	0.00%	0.00%
23	Flood	0.20	1.09	0.00%	0.00%
24	Flood	0.41	1.33	0.00%	0.00%
		Overall	**0.96**	**0.37%**	**0.77%**

DEBRIS PASSSAGE: FLOOD CONDITIONS

Flood conditions have been established based on a joint probability extreme value analysis of storm surge (Point Atkinson, 7795) and river discharge (Brackendale, 08GA022) to derive the worst-case combination of discharge and surge that comprises a 100-year return period event in the lower Squamish River estuary. Several discharge and storm surge combinations were simulated over a 24-hour period in a three-dimensional numerical model and the design condition has been selected as a combination of a 2,000 m^3/s discharge and 0.77 m storm surge (A. Leung pers. comm. 2021).

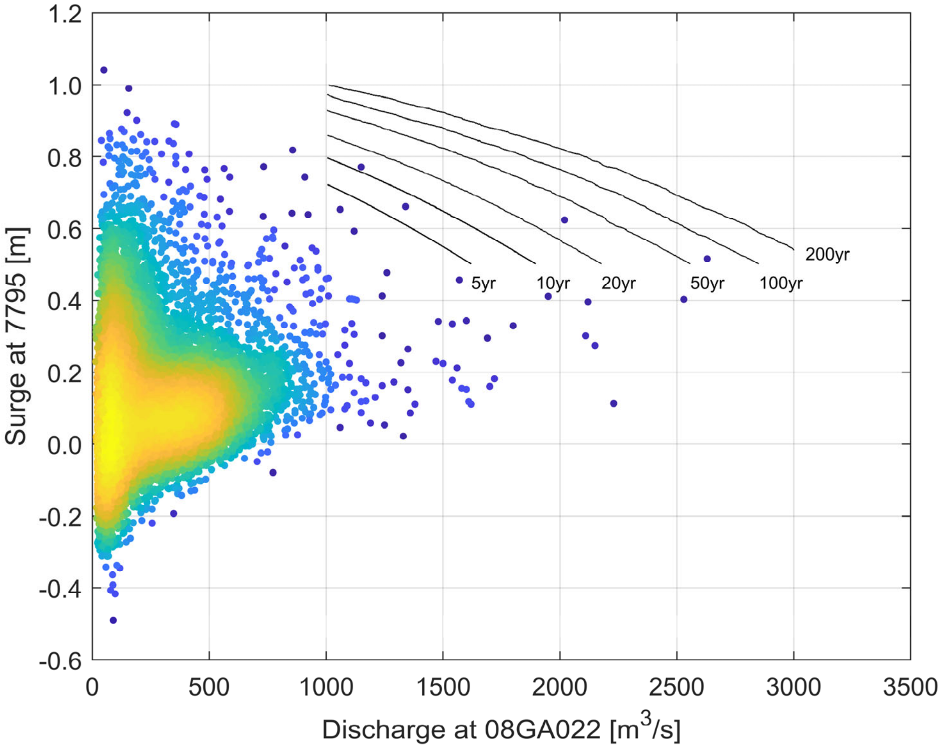

Figure 8: Bivariate extreme value contours of surge and discharge in the lower Squamish River estuary

Figure 9 presents the results of the previously described streamline tracing procedure for ebb tide (left panel) and flood tide (right panel). LWD that does not pass near the berth as plotted as white streamlines, near miss LWD as plotted as gray streamlines while potential contact LWD are plotted as red streamlines.

Table 4 summarizes the percent of LWD present in the river that could traverse the removal section and either a candidate for either a near miss or potential contact. Overall, 0.15% (1:670) of LWD in the river during a design flood event has potential to contact the berth, while 1.41% (1:71) could pass within the dredge pocket. Overall, the design storm event tends to reduce the likelihood of LWD encountering the berth by 2.0 to 2.5 times as compared to tidal conditions while the likelihood of LWD within the dredge pocket is increased by a factor of 1.8 to 3.2. This indicates that large storm events may increase relative prevenance of LWD in the vicinity of the berth as compared to tidal conditions, but the incidence of berth contact are relatively reduced. Tidal conditions following the storm event are expected to flush LWD from the Central Estuary due to the net-seaward flow and modest likelihood of further LWD influx. In all cases the prevalence of LWD is expected to be extremely low: 2,050 logs passing down the river in a 24-hour period would be required to results in a 95% probability of Berth contact.

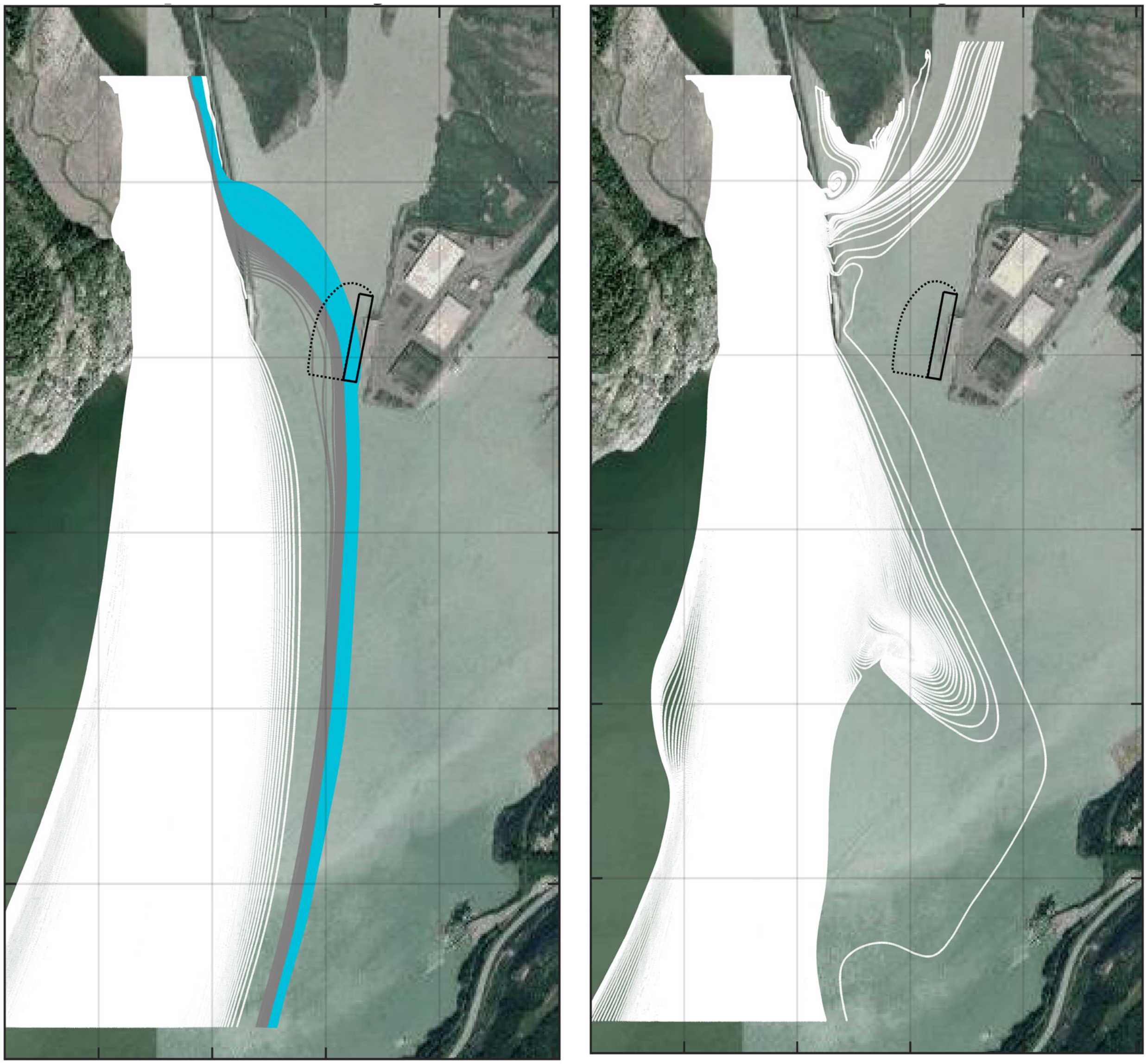

Figure 9: Left Panel, potential impacts (red), near misses (grey) and misses (white) during ebb tide. Right Panel, LWD trajectories during flood tide. Dotted black outline delineates "near miss" polygon consisting of the Berth dredge pocket, solid black outside delineates "potential impact" polygon consisting of a 25 m buffer around the Berth.

Table 4: Summary of LWD passage over the berm removal section during a 100-year flood event

Hour	Tide	Surface Elevation (m, CGVD28)	Maximum LWD Draft (m)	Potential Contact Rate	Overall Contact and Near Miss Rate
1	Slack	0.34	1.09	0.00%	4.70%
2	Flood	0.35	1.10	0.00%	5.51%
3	Flood	0.54	1.29	0.00%	5.19%
4	Flood	0.84	1.59	0.00%	2.59%
5	Flood	1.13	1.88	0.00%	1.35%
6	Flood	1.29	2.04	0.00%	0.00%
7	Slack	1.19	1.94	0.00%	0.00%
8	Ebb	0.82	1.57	0.00%	0.00%
9	Ebb	0.23	0.98	0.00%	4.51%
10	Ebb	-0.45	0.30	0.00%	0.00%
11	Ebb	-0.71	0.04	0.00%	0.00%
12	Ebb	-0.70	0.05	0.00%	0.00%
13	Ebb	-0.70	0.05	0.00%	0.00%
14	Slack	-0.69	0.06	0.00%	0.00%
15	Flood	-0.70	0.05	0.00%	0.00%
16	Flood	-0.70	0.05	0.00%	0.00%
17	Flood	-0.55	0.20	0.00%	0.00%
18	Flood	0.21	0.96	3.64%	6.95%
19	Flood	1.01	1.76	0.00%	3.08%
20	Flood	1.55	2.30	0.00%	0.00%
21	Slack	1.75	2.50	0.00%	0.00%
22	Ebb	1.66	2.41	0.00%	0.00%
23	Ebb	1.37	2.12	0.00%	0.00%
24	Ebb	0.98	1.73	0.00%	0.00%
		Overall	**1.17**	**0.15%**	**1.41%**

POTENTIAL IMPACT FORCES

CALCULATION METHODOLOGY

There are three distinct theoretically equivalent approaches for estimating the maximum impact force. Each of these approaches estimates the maximum impact force based on the debris velocity and mass. All of the approaches are based on a one-degree-of-freedom system and only the mass of the debris is considered in the calculation of forces. The contact stiffness approach is based on a one-degree-of-freedom spring-mass system where the stiffness of the interaction between the debris and the structure is required, Eq. (3):

$$F_{i,max} = u_1\sqrt{k(m_1 + Cm_f)} \qquad (3)$$

Where u_1 = log velocity; m_1= mass of the log; C = added mass coefficient; m_f= mass of the displaced fluid; and k = effective contact stiffness of the collision.

The American Association of State Highway Transportation Officials (AASHTO 1998) LRFD Bridge Design Specifications uses this approach to estimate the loads resulting from ship collisions with bridge piers.

The impulse-momentum approach equates the momentum of the debris and the time history of force, or impulse, imparted on the structure, Eq. (4).

$$F_{i,max} = \frac{\pi}{2} \frac{u_1 m_1}{t_i} \qquad (4)$$

Where t_i = the time history of applied force.

In this approach the stopping time of the debris and the shape of the force function with time must be assumed. This approach is used in the flood-proofing guidance provided by the Federal Emergency Management Agency (FEMA 1995) and the U.S. Army Corps of Engineers (1995).

The work-energy approach equates the energy of the debris with the work done on the structure, Eq. (5).

$$F_{i,max} = \frac{m_1 u_1^2}{2\Delta x} \qquad (5)$$

This approach requires an estimate of the stopping distance of the debris (Δx) as the distance the debris moves from the time of the initial contact until the debris is fully stopped ($u_1 = 0$). The National Association of Australian State Road Authorities (NAASRA 1990) Highway Bridge Design Specification guidance on designing bridges for debris impacts uses this approach. NAASRA recommends a range of stopping distances based on the bridge design for a log with a minimum mass of 2 metric tons. The stopping distances used in the NAASRA guidance vary with pier stiffness only, with shorter stopping distances for stiffer piers (Table 5).

Table 5: LWD stopping distance by pier material type

Bridge pier material	**Stopping distance, mm**
Timber	300
Hollow concrete	150
Solid Concrete	75

The aim of each approach is to estimate the maximum impact force based on the velocity and mass of the woody debris. Each requires an additional, generally unknown, parameter: an impulse-momentum calculation requires the stopping time; a work-energy calculation requires the stopping distance; and a contact stiffness calculation requires the effective contact stiffness. Haehnel and Daly (2004) have shown that all three approaches can be derived from a single-degree-of-freedom model of the collision and are equivalent. They show that neither stopping time, in the case of impulse momentum, nor stopping distance, in the case of work energy, is an independent parameter. Stopping time depends on the effective contact stiffness and the debris mass; stopping distance depends on the effective contact stiffness, the debris mass, and the debris velocity. They reported that it is problematic to select a single value for stopping time or stopping distance that can be applied over a wide range of debris mass and impact velocity. They improve the ability of the impulse-momentum and work-energy approaches to reproduce the laboratory results by making the stopping time or stopping distance variable rather than constants.

They found that the peak impact force is associated with the log striking the target on its end with the long axis of the log parallel to the flow direction and normal to the target face. Eccentric and oblique impacts systematically reduce the maximum impact force as each is increased. Based on the laboratory data they suggested Eq. (6) for the maximum impact forces.

$$F_{i,max} = 1550\, u\sqrt{m} \qquad (6)$$

Where u = LWD velocity (m/s) and m = mass including the fluid added mass (kg). The maximum impact force, F_{max}, is in Newtons.

Eq. (6) is particularly useful for the present analysis both for its ease of application and the assumption of a mean structure stiffness of 2.4 MN/m, which is close to the approximately 3MN/m typical for fendering systems. Therefore, Eq. (6) has been applied in this analysis.

IMPACT FORCES

Table 6 below summarizes the potential impact forces associated with a LWD impact during a 100-year return period flood event. 66% of the time, there is no CERP-related risk of LWD impact due to either at-berth currents preventing a potential contact or near miss or flood tide conditions which are not impacted by the CERP.

The maximum impact force is estimated to be 73.8 KN, which is associated with a direct perpendicular impact from the largest possible LWD that can pass over the removal section. This impact force is approximately an order of magnitude lower than the typical 1,000 KN maximum reaction force for fendering systems. Given that currents along the berth face are oblique, this impact force could be reduced to the force component perpendicular to the berth face. Conservatively assuming a 62.5° angle between the currents and berth face (the currents will be nearly parallel), the maximum impact force reduces to 34.1 KN.

In terms of overall probability, there is a 0.0200% probability of a maximum force exceeding 47.0 KN and an overall probability of 0.0019% of a force exceeding 73.8 KN during the 100-year flood event. These forces reduce to 21.7 KN and 34.1 KN, respectively, when the angle of approach is accounted for.

Therefore, the impact of LWD is both well within the capacity (i.e., maximum reaction force) of a typical fendering system and the occurrence of an impact maximum is extremely unlikely.

Table 6: Maximum LWD impact force during a 100-year flood event

Hour	Potential Contact or Near Miss	Maximum LWD Diameter (m)	Associated LWD Mass (kg)	At Berth Surface Current (m/s)	Maximum Impact Force (KN)
1	Yes	1.25	12,359	0.32	55.5
2	Yes	1.26	12,461	0.40	68.7
3	Yes	1.49	14,185	0.39	72.0
4	Yes	1.83	16,399	0.37	72.6
5	Yes	2.17	18,162	0.32	66.1
6	No	2.35	19,017	0.29	-
7	No	2.23	18,488	0.29	-

8	No	1.81	16,259	0.26	-
9	Yes	1.13	11,273	0.32	52.6
10	No	0.34	896	0.44	-
11	No	0.05	10	0.27	-
12	No	0.06	16	0.17	-
13	No	0.05	14	0.14	-
14	No	0.07	22	0.08	-
15	No	0.05	14	0.05	-
16	No	0.05	15	0.15	-
17	No	0.23	376	0.45	-
18	Yes	1.10	11,059	0.29	47.0
19	Yes	2.02	17,415	0.36	73.8
20	No	2.65	20,276	0.38	-
21	No	2.88	21,147	0.29	-
22	No	2.77	20,737	0.25	-
23	No	2.44	19,412	0.21	-
24	No	1.98	17,229	0.18	-

CONCLUSIONS

Using a combination of aerial photography and three-dimensional numerical modelling, potential LWD presence in the Central Estuary has been assessed following the CERP. Under tidal conditions, there is a 0.30% to 0.37% chance that a given LWD will contact the Berth, with a 0.30% to 0.77% chance that a given LWD will pass through the dredge cut of the Berth. During flood conditions, there is a 0.15% probability of a given LWD contacting the Berth, with a 1.41% likelihood of a given LWD passing through the dredge pocket. In all cases, several hundred logs to several thousand LWD per day would be required in the river before the likelihood of CERP-related LWD contacting the Berth exceeds 95%.

Should LWD contact the Berth, the estimated impact loading to the fendering system is an order of magnitude below its likely maximum reaction force.

CLOSURE

We appreciate the opportunity to present this technical memo. We trust that the information presented in this document meets your immediate requirements. Should you have any questions or require additional information or clarification, please contact the undersigned.

Best regards,

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