



Hood Canal Bridge Ecosystem Impact Assessment: Phase 1 Report

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Executive Summary

Hood Canal is a long, narrow fjord that forms the western lobe of Puget Sound. Coined “the wild side of Washington”, many tourists and locals visit or move to the Hood Canal region to experience nature. While Hood Canal’s natural ecosystem is more intact than many other regions of Puget Sound, vital elements are at risk. Abundances of wild Chinook salmon, chum salmon and steelhead native to Hood Canal are low and all three species are listed as threatened under the Endangered Species Act (ESA). Also, fish kills from low dissolved oxygen events occur periodically and ocean acidification threatens commercially important shellfish beds in Hood Canal more so than the rest of Puget Sound.

The Hood Canal Bridge carries traffic across the northern outlet of Hood Canal, connecting the Olympic and Kitsap peninsulas and supporting tourism and other economic activities. As a 1.5-mile long floating bridge, its pontoons span over 80% the width of Hood Canal and extend 15 feet underwater. Because of its location, all salmon and steelhead must navigate around or underneath the Hood Canal Bridge on their migration to and from the Pacific Ocean. In 2015, federal, state, tribal, and nonprofit partners convened to develop the Hood Canal Bridge Ecosystem Impact Assessment Plan. The plan was designed to pinpoint how the bridge affects ESA-listed juvenile steelhead survival; determine whether other salmon may also be affected; and determine whether, and if so, to what extent the bridge impacts the health of the Hood Canal ecosystem. Phase 1 of the Assessment Plan consisted of two years of intensive data collection, analysis, and modeling to characterize physical and biological dynamics near the bridge and identify impacts to juvenile steelhead and salmon, predator assemblages, and water quality parameters.

This document describes the research conducted during the first phase of the assessment and the resulting outcomes and recommendations. Phase 1 research addressed these primary questions:

I. How is the bridge acting as a barrier to juvenile steelhead migration and leading to increased mortality? How does the bridge influence other fish, including salmon?

Researchers studied juvenile steelhead migration behavior and mortality, surveyed predator abundances and collected observational data on predator behavior, and investigated light, shade, and noise impacts from the bridge. These datasets were used to determine what species are most likely preying upon steelhead and how the bridge functionally leads to increased predation.

II. Is the bridge impacting the entire Hood Canal ecosystem?

Because species throughout Hood Canal respond to changes in water quality, any effects of the bridge on ecosystem processes may ripple throughout the food web in unknown ways. Phase 1 research included collecting field data and refining circulation models to characterize the extent of bridge impacts on water quality.

During this first phase of the assessment, the project’s Assessment Team performed these activities:

- **Track steelhead migration and mortality** – Juvenile steelhead were acoustically tagged and their migration pattern tracked past the bridge to determine where mortality is occurring and most likely causes of mortality.
- **Map fish densities** – The distribution and density of epipelagic biomass in the area were assessed near the bridge to characterize density patterns along the bridge.

- **Identify predators and map their densities** – Potential steelhead and salmon predators were identified and their distribution and abundance mapped along the bridge to identify hotspots of predation risk.
- **Assess light/shade and noise near the bridge** – Pilot studies of light and noise levels at and near the bridge were carried out to determine whether further investigation on potential impacts is warranted.
- **Evaluate the impact of pools and eddies caused by pools at the center of the bridge** – Open pools into which the bridge's center drawspan retracts to let ships pass form open-bottom enclosures. Pools were investigated to determine whether this infrastructure aggregates plankton, thus attracting planktivorous salmon and steelhead (or other prey fish species like herring) and increasing their susceptibility to predation.
- **Collect and model oceanographic data near the bridge** – Devices were placed in proximity to the bridge to precisely measure impacts to water circulation. These data were used to refine models simulating the extent of this impact to the overall circulation and flushing of Hood Canal, and to what extent dissolved oxygen, temperature, acidity, and nutrient dynamics are affected.

Research efforts were conducted throughout steelhead outmigration periods (April-June) of 2017 and 2018 and spanned a range of conditions that could affect the extent of bridge impacts: tidal cycles, day versus night, and periods of time during which the center drawspan of the bridge (used to allow large ships to pass) was both open and closed.

Results from Phase 1 of the Hood Canal Bridge Ecosystem Impact Assessment include:

1. The Hood Canal Bridge significantly contributes to early marine mortality of juvenile Hood Canal steelhead by impeding fish passage and facilitating predation.
2. The bridge impacts other fish species such as juvenile Chinook and chum.
3. The bridge significantly impacts water quality parameters (temperature, salinity, currents) in its vicinity. Although bridge effects on water quality dissipate with increasing distance from the bridge and do not appear to propagate throughout Hood Canal, these near-bridge changes in circulation and flow may be linked to impacts on juvenile salmon and steelhead behavior and mortality.
4. Avian and mammalian predators were documented near the bridge. Harbor seal predation on juvenile steelhead was the most frequent source of mortality based on tagged juvenile steelhead mortality patterns.

With this information, the Hood Canal Bridge Assessment Team, Engineer Team, and Management Committee members participated in workshops and exercises to develop solutions to test during Phase 2, and to identify the research needed beyond the scope of Phase 1 to address bridge impacts on other juvenile salmon species, potential bridge impacts on returning adult salmon, and predator deterrence options. With the guidance of the Assessment Team, engineers at R2 Resource Consultants completed initial scoping and design recommendations for Phase 2 solutions. Solutions were prioritized into three categories: 1) management actions recommended for early implementation, 2) management actions that were high-ranking but need additional research, and 3) management actions ranked lower. Solutions in category 1 are being proposed for installation, effectiveness testing, and further investigation in Phase 2. This category includes installing fillet and eddy reduction structures to reduce

or restrict fish access to existing pontoon corners of the infrastructure, as well as pilot testing longer-duration bridge drawspan openings timed on strong ebb tides to encourage fish passage and investigating modifications to luminaries to reduce overwater light spillover. Phase 2 may also provide an opportunity to conduct the research necessary to move towards implementing solutions in category 2: bridge re-design and replacement/modifications and pinniped deterrence activities such as restricting haul-out and bridge access.

Background and Overview

The Hood Canal Bridge is the longest floating bridge in a saltwater tidal basin in the world, and the third-longest floating bridge overall. It is an important regional transportation asset in western Washington, providing a vital connection between the Olympic and Kitsap peninsulas with over 18,000 trips per day¹ by local commuters and commercial vehicles. During the tourist season, the bridge helps drive the economy by bringing visitors to the Olympic Peninsula to recreate on land and water. Locals and visitors alike expect Hood Canal to be a healthy, vibrant ecosystem, teeming with life including salmon and steelhead that define their home and the purpose of their visit.

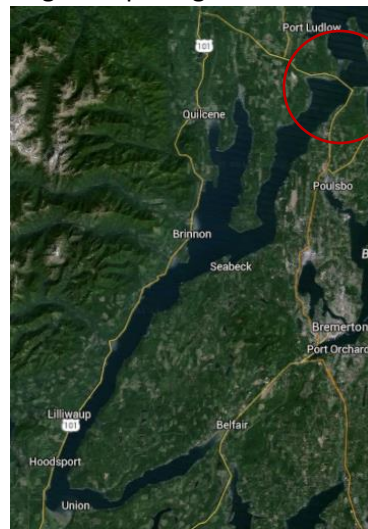


Figure 1. Hood Canal Bridge is located at the north end of Hood Canal near its entrance to Puget Sound. Image from Google Maps.

All salmon originating from Hood Canal rivers must pass the Hood Canal Bridge as juveniles on their way out to the Strait of Juan de Fuca and the Pacific Ocean (Figure 1). They must pass through the bridge again as adults on their return trip to spawn in their natal streams. Three species of Hood Canal salmon and steelhead are listed as *Threatened* under the Endangered Species Act (ESA): Puget Sound Chinook, Hood Canal Summer Chum, and Puget Sound steelhead. Millions of dollars have been spent on efforts to restore and protect these fish and their habitat throughout Hood Canal. The Hood Canal Bridge carries State Route 104 across the northern outlet of Hood Canal in Puget Sound. As a 1.5-mile long floating bridge, its pontoons span over 80% of the width of Hood Canal and extend 15 feet underwater (Figure 2). Slower migration times, higher mortality rates in the vicinity of the bridge relative to other areas on their migration route, and unique behavior and mortality patterns at the bridge suggest the bridge impedes steelhead

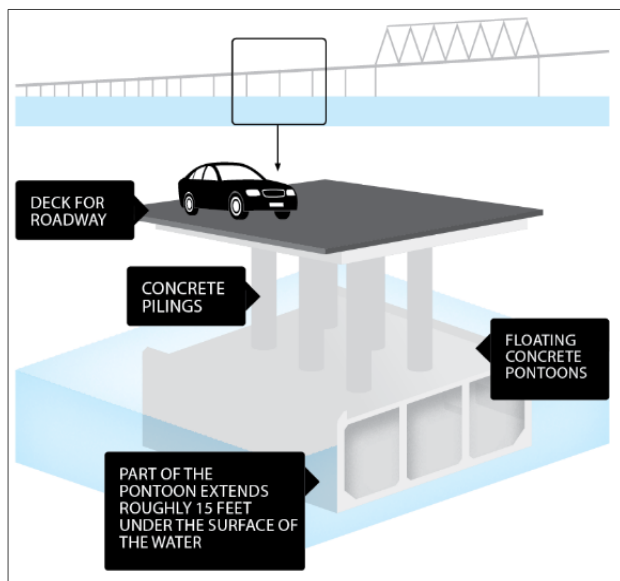


Figure 2. The Hood Canal Bridge floats on pontoons that span much of the width of Hood Canal and extend roughly 15 feet underwater. Image property of Long Live the Kings.

¹ <https://www.wsdot.wa.gov/Traffic/API/PermanentTrafficRecorder/?sitelId=R085>, data from April-June 2017-2018

migration and facilitates predation². The bridge may also disrupt Hood Canal circulation and water quality³.

In 2015, federal, state, tribal, and nonprofit partners convened to develop the Hood Canal Bridge Ecosystem Impact Assessment Plan, designed to pinpoint how the bridge is negatively affecting ESA-listed juvenile steelhead survival; determine whether other salmon may also be affected; and determine whether, and if so, to what extent the bridge is impacting the health of the Hood Canal ecosystem. This effort was driven by increasing recognition of the evidence and need for understanding and mitigating bridge impacts in the context of salmon and steelhead recovery.

Puget Sound steelhead populations (including Hood Canal) have declined to under 10% of historic run sizes over the past three decades and many wild populations now face possible extinction⁴. Juvenile mortality in the marine environment is a major cause of population declines, and the Phase 1 research conducted during the Hood Canal Bridge Ecosystem Impact Assessment shows that the Hood Canal Bridge significantly contributes to early marine mortality of steelhead populations native to Hood Canal: approximately half of the

juvenile steelhead that arrive at the bridge die there. The bridge serves as a physical barrier to steelhead fish passage, slowing migration by 1-2 days on average, and facilitates predation (Figure 3). Of the predator species observed at the bridge, harbor seals are a likely candidate for a majority of observed juvenile steelhead mortality.

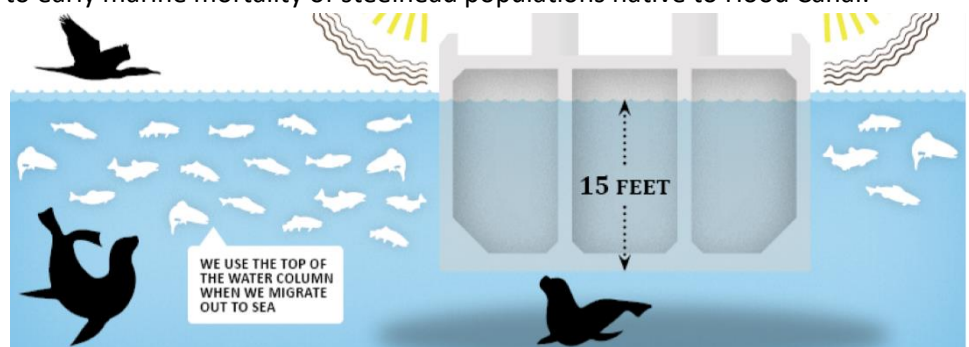


Figure 3. The bridge pontoons are a physical barrier for surface-oriented juvenile steelhead, slowing migration and increasing vulnerability to predation. Image property of LLTK.

The bridge also affects other fish, including ESA-listed Chinook and Hood Canal chum. All juvenile salmon must pass the Hood Canal Bridge while outmigrating, and Phase 1 research findings indicate that large numbers of juvenile chum and chinook aggregate around bridge infrastructure during the spring outmigration season, spanning across the full width of the bridge. Some evidence supports the “reef effect” hypothesis, which posits that the bridge’s unique infrastructure has created low-complexity artificial habitat for plankton, fish, and predator species: zooplankton sampling suggests community differences near the bridge vs. away from the bridge in Hood Canal waters, smaller species of salmon appear to school along the length of the bridge infrastructure and exhibit milling and feeding behaviors in certain areas, and predator species interact with the bridge structure as artificial shoreline. Specific features of the bridge appear to elicit different behavior than others, such as corners made from pontoons oriented perpendicular to the road deck and partially enclosed pools that allow retraction of the bridge drawspan during bridge openings (Figure 4). Observations on the bridge suggest that certain

² Moore et al. 2013. A floating bridge disrupts seaward migration and increases mortality of steelhead smolts in Hood Canal, Washington State. <https://doi.org/10.1371/journal.pone.0073427>

³ Khangaonkar & Wang 2013. Potential alteration of fjordal circulation due to a large floating structure – numerical investigation with application to Hood Canal basin in Puget Sound. <https://doi.org/10.1016/j.apor.2012.11.003>

⁴ Federal Registry Notice: 72 FR 26722

species of predators, like harbor seals, exploit these features to capture prey in areas where fish are aggregated with little refuge. It is noteworthy that most steelhead mortalities occurred in close proximity to the bridge structure, and in several cases where tagged steelhead were consumed by predators and the tag data began reflecting predator movement, that those predators remained in proximity to the bridge.

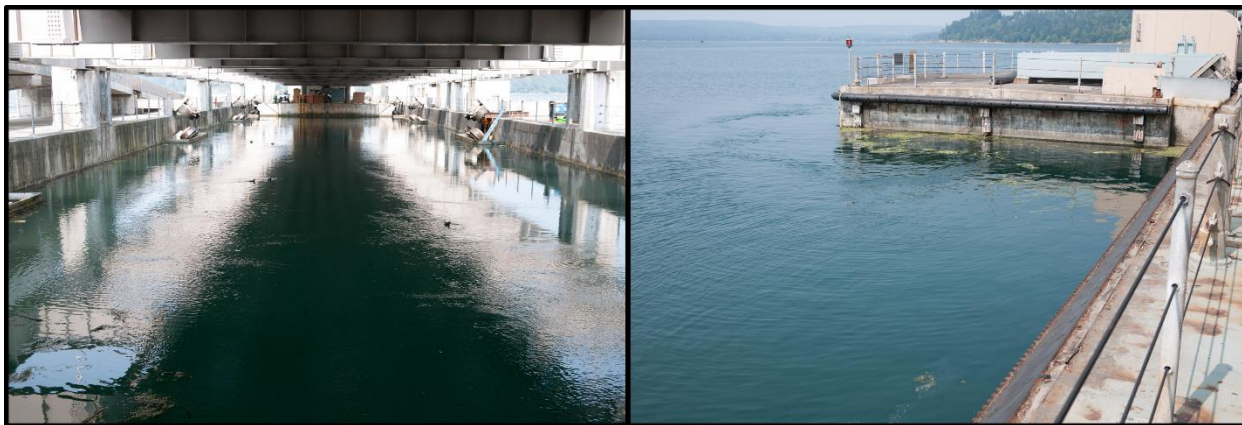


Figure 4. On left, the east bridge pool area, looking towards the closed center drawspan. On right, one of the corner areas created by cross-pontoons that jut out from the bridge structure. Photos courtesy of LLTK.

Light and noise/sound levels are increased at the bridge relative to surrounding waters. Observed noise levels during the steelhead outmigration period did not rise to a level of immediate concern based on previous studies of noise and pressure sensitivity in salmonids. However, observed nighttime light levels from artificial lights installed on the bridge deck spilling over to surface waters were within a range that previous studies have reported to affect salmon behavior. Increased nighttime light levels may either attract or deter juvenile salmon from lit areas, may alter feeding behavior of fish and predators, and may affect a fish's vulnerability to predation. However, no relationships between tagged steelhead behavior and noise levels varying between daytime and nighttime periods were apparent in the telemetry data.

The natural ecosystem in Hood Canal is controlled by deep narrow estuarine circulation with classic fjord-like features where mean circulation and mixing is dominated by the influence of freshwater runoff. This balance of surface outflow of buoyant freshwater and the corresponding inward-bound deep saltwater compensation current is essential to sustaining the water quality and overall health of fjord-like waterbodies such as Hood Canal. Unimpeded outflow of brackish water from typical fjords through the shallow surface layers is responsible for setting up stratification, salinity gradients, and resulting exchange flow and flushing of the basin needed for maintenance of water quality.

Preliminary modeling studies which formed the basis of development for Phase 1 research suggested localized and wide-ranging impacts of the bridge on water quality. During Phase 1, models were validated and refined with oceanographic data collected at the bridge, near the bridge, and away

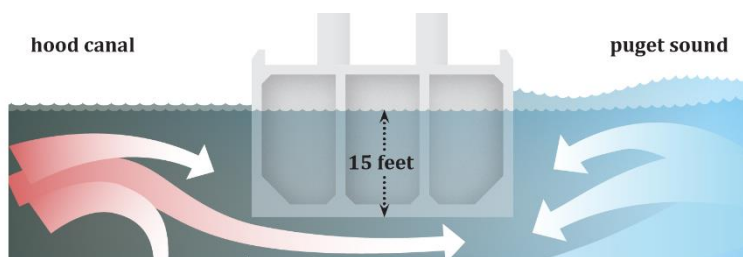


Figure 5. The bridge pontoons extend into the surface layer of the water column, impacting temperature, salinity, and currents and causing increased mixing near the bridge. Image property of Long Live the Kings.

from the bridge during the juvenile steelhead outmigration season. Results from these improved modeling studies confirmed that the floating bridge has localized impacts on water quality, obstructing the brackish outflow surface layer, and thereby causing increased mixing near the bridge, pooling of up-current water, and shadow/sheltering of down-current water across the tidal cycle (Figure 5).

Impacts on currents, salinity, and temperature are highest at the bridge and extend about 20 m below the water's surface and up to 5 km away from the bridge before dissipating to within a 10% deviation from ambient conditions. Model results did not predict significant bridge impacts to Hood Canal-wide circulation/flushing or water quality.

Individual Assessment Components: Brief Methods and Outcomes

The Hood Canal Bridge Ecosystem Impact Assessment was structured following an adaptive management approach: an iterative process where work occurred in phases, building from the information described in the Hood Canal Bridge Ecosystem Impact Assessment Plan⁵. Studies conducted during Phase 1 of the assessment were under the purview of the Assessment Team members listed at the beginning of this document. The Assessment Team worked with a Management Committee to evaluate Phase 1 progress and develop recommendations for Phase 2 actions and effectiveness testing. External reviewers and contributors were engaged as needed along the way to ensure Phase 1 results and recommendations are broadly accepted.

Phase 1 of the assessment was structured around a multi-question framework described in full in the Hood Canal Bridge Ecosystem Impact Assessment Plan. Briefly, Phase 1 consisted of investigating two main questions: 1) how does the bridge impact juvenile steelhead migration and mortality and potentially other fish species (including salmon) and 2) what are the bridge's effects on water quality and do those effects impact the entire Hood Canal ecosystem? These questions and associated sub-questions served to define assessment components that were addressed in a stepwise process through multiple Phase 1 studies and subsequent synthesis across studies.

The following provides a brief summary of the methods and outcomes of each assessment component included in Phase 1 research. Extended methods and results for each assessment component, as well as technical reports and peer-reviewed publications associated with select assessment components, are provided in full in [Appendices A-F](#). Assessment components are ordered and numbered consistently with the framework developed in the Hood Canal Bridge Impact Assessment Plan for cross-reference across sections and documents. **Due to the complex interconnected nature of this assessment, the component numbers do not reflect order or priority.** The key questions, sub-questions, associated hypotheses and affiliated assessment components, along with Principal Investigators, are all mapped in [Appendix G. Hood Canal Bridge Impact Assessment Matrix](#).

⁵ Hood Canal Bridge Assessment Team. 2016. Hood Canal Bridge Ecosystem Impact Assessment Plan: Framework and Phase 1 Details. Long Live the Kings, Seattle, WA.

- I. How is the bridge acting as a barrier to juvenile steelhead migration and leading to increased mortality? How does the bridge influence other fish, including salmon?
 - A. What are fish migration behavior and fish distribution patterns at versus away⁶ from the bridge? For steelhead, what defines a successful migration past the bridge versus one that results in mortality?

Juvenile steelhead acoustic telemetry provided the core data of the Phase 1 investigation of bridge impacts on fish migration and mortality. Prior telemetry research (Moore et al. 2013) indicated the Hood Canal Bridge might delay migration of steelhead smolts and contribute to disproportionately high mortality at this location compared to the rest of the freshwater-to-ocean migration. During Phase 1, the telemetry receiver array at the bridge was expanded beyond previously established array designs to enable triangulation of tags and map individual migration paths and mortality locations of tagged fish. Hydroacoustic surveys in North Hood Canal provided context on broader fish distribution patterns during the outmigration season.

1. Track steelhead migration behavior at bridge and steelhead mortality before, at, and after bridge

Megan Moore and Barry Berejikian, NOAA Northwest Fisheries Science Center

For detailed methods and results, see [Appendix A](#).

Wild steelhead smolts were collected from the South Fork Skokomish River and Big Beef Creek during April-May 2017 and 2018. Each smolt was surgically implanted with an acoustic transmitter. Different types of transmitters were used throughout the study period: some tag groups were implanted with basic transmitters, some were implanted with transmitters that contained pressure sensors, and some were implanted with transmitters that contained temperature sensors. One additional group was implanted with transmitters programmed to be silent for a portion of the migration to test the “dinner bell” hypothesis, which suggests that pinnipeds may hear and target actively-pinging transmitters; no evidence was found for differential mortality between steelhead implanted with silent transmitters versus actively-pinging transmitters.

Acoustic receivers were deployed at various locations along the steelhead outmigration route from Hood Canal rivers to the Pacific Ocean, including a network of receivers at the bridge placed closely together such that individual transmitter positions could be calculated as tagged steelhead moved through the receiver array (Figure 6). After the outmigration season, a boat-based receiver was deployed to compare locations of stationary transmitters (mortalities) at fixed stations situated both near and far from the bridge.

⁶ Within this document, the terms “at the bridge”, “near the bridge”, and “within the bridge zone of influence” refer to the yet established geographic area around the bridge that is impacted by the various causal agents being investigated, whereas “away from the bridge” refers to the area beyond impact zone of the bridge.

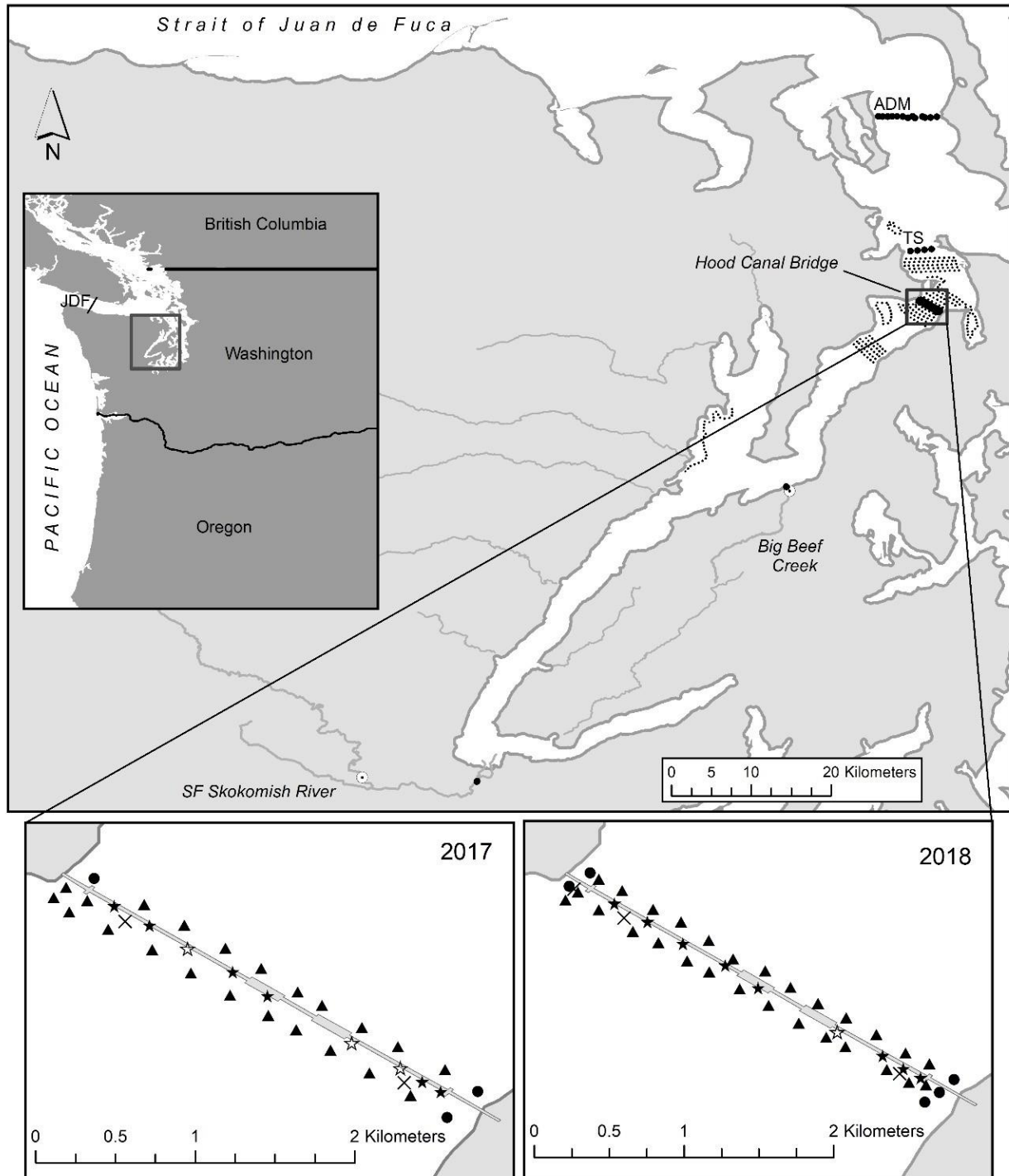


Figure 6. Receiver locations (black dots) at the mouths of Big Beef Creek and the Skokomish River downstream of in-river release locations for tagged steelhead (white dots), the Hood Canal Bridge, Twin Spits (TS), Admiralty Inlet (ADM), and the Strait of Juan de Fuca (JDF, black line). Boat-based survey locations are shown as tiny black dots. Lower insets show the receiver array installed at the bridge in 2017 and 2018 (various shapes denote types of receiver deployments; see [Appendix A](#)).

On average, the bridge delayed surviving tagged steelhead by 1-2 days, which means fish spent roughly 6-10% of their total migration time on a distance representing 0.5% of their total journey. About half of the tagged steelhead that encountered the Hood Canal Bridge died there; survival probabilities for the 7 km migration segment including the bridge were 49-57% across the two years of study. Survival probability was not related to smolt size, the location at which smolts first approached the bridge, tidal stage, current velocity at time of first approach, or time (day vs. night) of first approach. However, survival probabilities did vary by week during the outmigration period, with later-arriving fish having higher probability of survival (Figure 7).

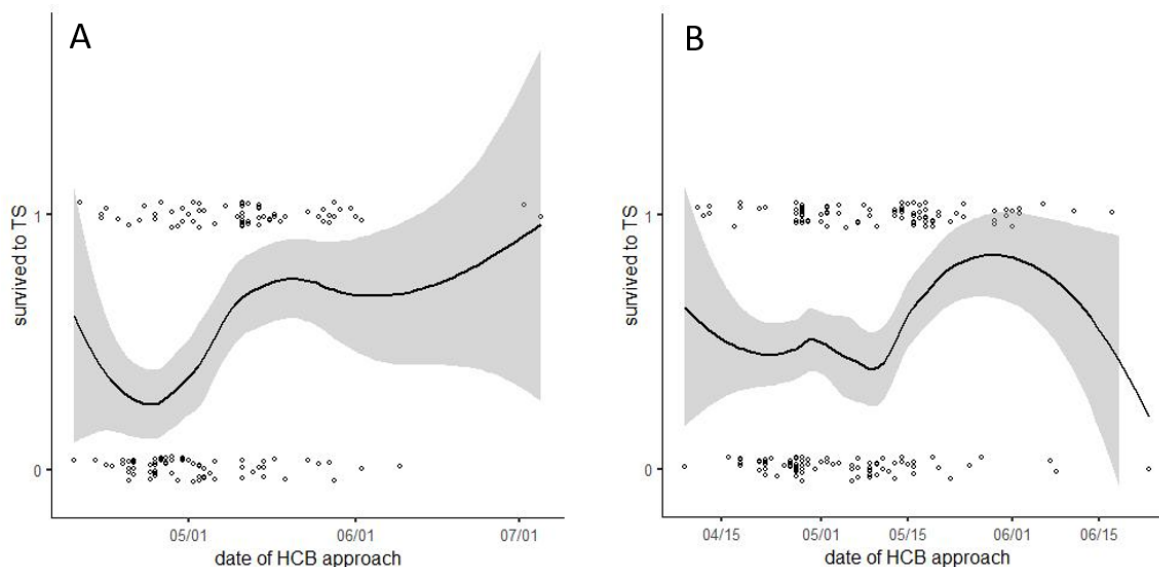


Figure 7. Logistic regression showing the relationship (black line = moving average of odds of survival) between survival probability (1 = survived, 0 = did not survive) past the Hood Canal Bridge (HCB) to the Twin Spits (TS) receiver array and the date of first approach at the HCB in 2017 (panel A) and 2018 (panel B).

Density patterns of surviving steelhead smolts were consistent across years, with high densities observed in corner locations formed by pontoons that extend perpendicularly out into the water from the bridge's deck (Figure 8 A, B). Density patterns of non-surviving tagged fish (presumed mortalities) were also consistent across years. Similar to survivors, mortalities were concentrated along the south side of the bridge and in corner locations (Figure 8 C, D). However, survivors were more frequently located near the center drawspan and on the east side of the bridge than mortalities. Stationary tags (see [Appendix A, Figure A6](#)) were less likely to be found further away from the bridge structure, although a few were identified in nearby Port Gamble Bay and along the route from the Hood Canal Bridge to Port Gamble Bay.

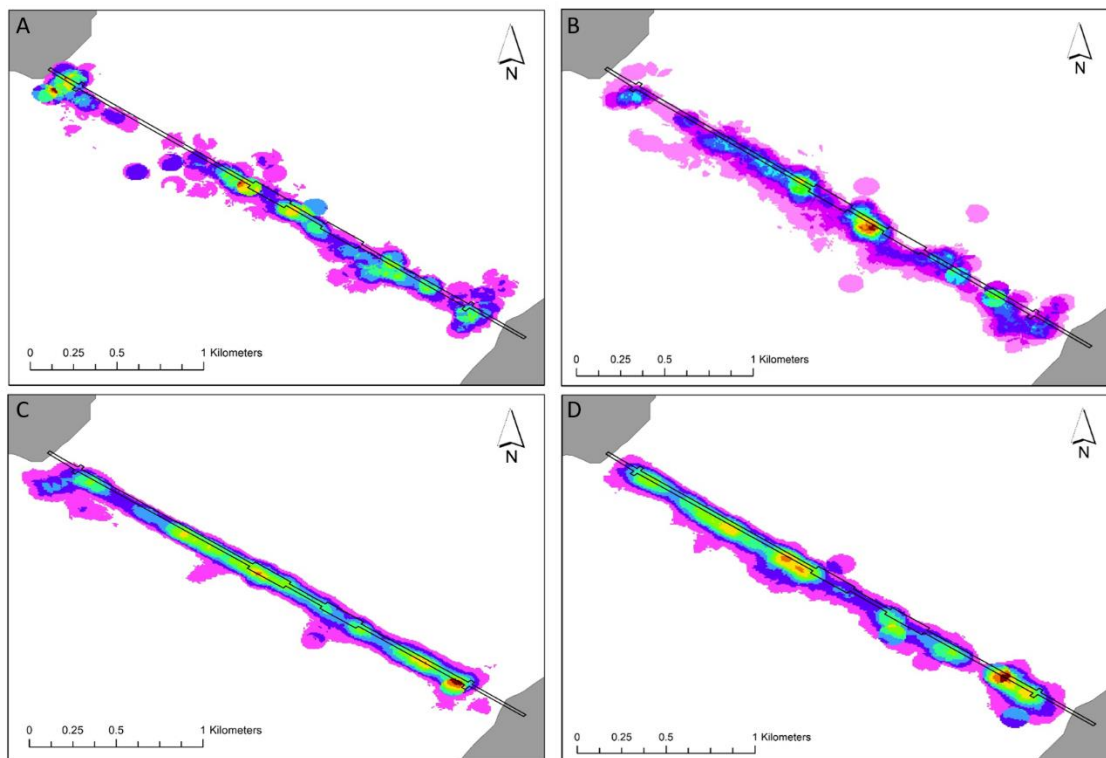


Figure 8. Density of tagged steelhead encountering the HCB that survived past the bridge in 2017 (A) and 2018 (B) compared to density of tagged steelhead that did not survive past the bridge in 2017 (C) and 2018 (D). Dark red indicates highest densities, blue/green represent intermediate densities, and pink/purple represent lowest densities. Density values differ between figures and scale with sample size.

Steelhead that successfully crossed the bridge did so by crossing through open east and west spans (2017: 49%, 2018: 23%) that are not obstructed by bridge pontoons or by diving underneath the bridge pontoons (2017: 51%, 2018: 77%). Crossing locations were distributed fairly evenly along the length of the bridge (Figure 9). Most (84%) crossings took place during daylight hours, and crossing was much more likely to occur during ebb tides. Except for the brief dive period of those fish that crossed underneath bridge pontoons, tagged steelhead were strongly surface-oriented and traveled in the upper 1 meter of the water column.

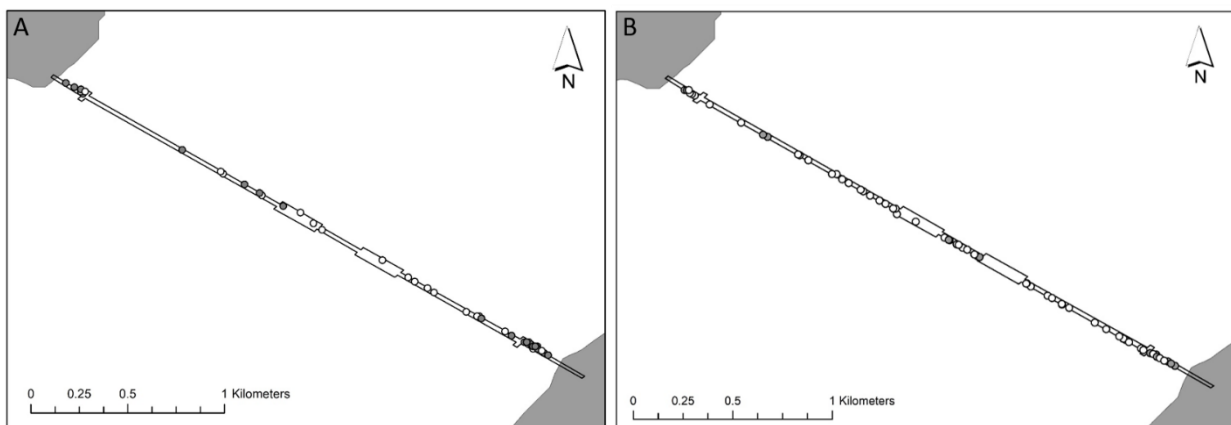


Figure 9. Locations where tagged steelhead crossed the HCB in 2017 (A) and 2018 (B). Open circles represent day crossings; filled circles represent night crossings.

2. Map fish densities and distribution at vs. away from bridge

Hans Daubenberger, Port Gamble S'Klallam Tribe and Emily Bishop, Westward Ecology

For detailed methods and results, see [Appendix B](#).

Fish abundance and distribution in the upper 10 meters of the water column near the bridge were mapped weekly using a split-beam hydroacoustic transducer deployed from a boat running along predetermined transect lines both perpendicular (2017) and parallel (2018) to the bridge infrastructure (Figure 10). Data were filtered to exclude bridge infrastructure and isolate acoustic returns corresponding to juvenile salmonid-sized fish. Visual observations from the bridge deck (further described in [Assessment Component 14](#)) suggest that fish aggregate at some portions of bridge infrastructure; those patterns are not apparent in this particular dataset as the methods used were insufficient to characterize the 15m adjacent to bridge infrastructure.

No significant trend in fish density was observed with distance from the bridge (excluding the 15 m directly adjacent to the structure), and the probability of high/low fish density did not differ among areas 15-200 meters away from the bridge and areas 200 meters to 2 km from the bridge. Fish density along the length of the bridge was similarly stochastic. Areas of both high and low densities appeared across both survey

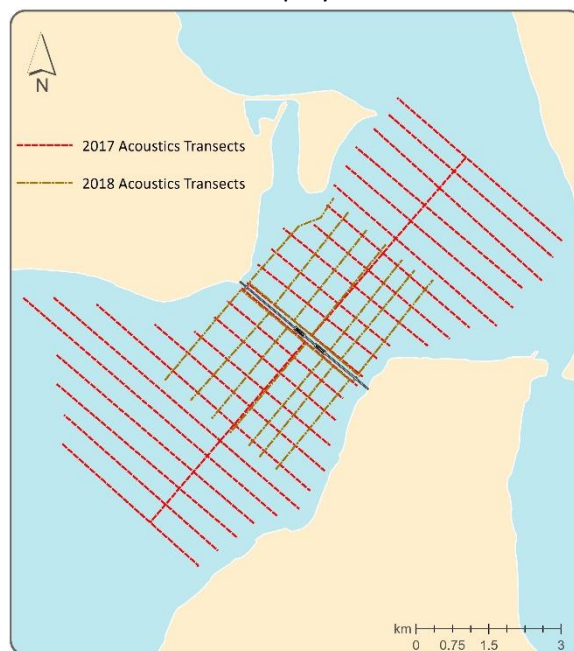


Figure 10. Transect lines surveyed in 2017 (red) and 2018 (yellow). The long center transect perpendicular to the bridge was sampled across both years.

seasons, but no consistent spatial or temporal patterns in densities were observed. When averaged across all weeks, the center transect perpendicular to the bridge structure showed a slight increase in density with increasing proximity to the south side of the bridge, but this correlation was not consistent across individual weeks.

An initial alignment of fish detection data with the zooplankton data described in [Assessment Component 14](#) suggests a positive relationship between plankton density and fish density, which may be indicative of fish response to plankton patterns near the bridge.

B. Are steelhead and other fish at the bridge more susceptible to predation (vs away from the bridge)? If so, who are the primary culprits?

Migration delays described in [Assessment Component 1](#) increase the density of migrating smolts on the south side of the bridge and channel migrating smolts through more densely concentrated routes, potentially attracting predators and facilitating predation. Additionally, pontoons extending from the bridge deck create corner areas which aggregate fish and may reduce their ability to evade predators.

3. Map predator (marine mammal and seabird) densities

Jessica Stocking and Scott Pearson, Washington Department of Fish and Wildlife

Hans Daubenberger, Port Gamble S'Klallam Tribe and Emily Bishop, Westward Ecology

For detailed methods and results on boat-based predator surveys, see [Appendix C](#) and bridge-based surveys, see [Appendix B](#).

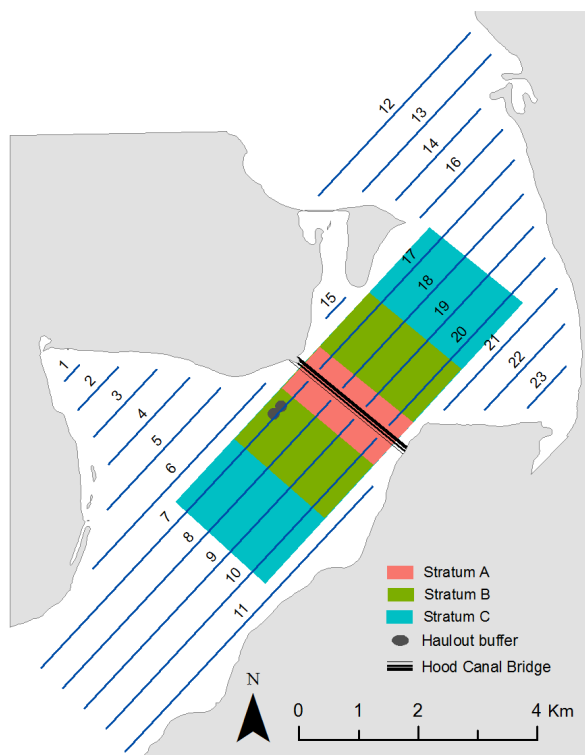


Figure 11. Predator survey transects used to survey potential steelhead predators near vs. far from the bridge (bold blue lines) and within three distance strata from the bridge (A = 0-300 m, B = 301-1500 m, C = 1501-3000 m).

Boat-based visual predator surveys were conducted weekly along transects running perpendicular to the bridge (Figure 11). Only in-water/on-water predators were counted; flying birds were not included in the count unless they were observed landing or foraging within the survey area or unless they were an aerial hunting species (bald eagles, osprey, terns). All harbor seals and cormorants within 100 m of the Sisters Rock seal haulout site southwest of the bridge were removed from analysis since they were not actively foraging.

The density of predators in pool areas of the bridge infrastructure (further described in [Assessment Component 14](#)) was quantified using a survey method intended to produce comparable density estimates to boat-based surveys. Observers recorded predator presence within the pools for 40 seconds, based on the estimated time it would take to

observe the same area during a boat-based survey.

Boat-based surveys recorded over 13,000 individual observations of predators, including 22 piscivorous avian species and three marine mammal species. We note only a few species here; all are detailed in [Appendix C](#). Pigeon guillemots were the most numerous predator species observed throughout the study, with highest distributions along shorelines and at the bridge. Pigeon guillemots are unlikely to be a major source of juvenile steelhead mortality as there is little overlap in the prey sizes guillemots consume and the size distribution of outmigrating juvenile steelhead. However, juvenile Chinook, coho, and chum all fall within the preferred prey length of pigeon guillemots and observers on the bridge deck noted guillemots feeding on chum and Chinook.

Harbor seals and harbor porpoises were observed in generally low densities throughout the study area, although boat-based surveys may not have fully captured the area directly alongside the bridge due to restrictions on vessel distance from the bridge infrastructure. Seals and porpoises were typically observed as single animals rather than foraging in groups (Figure 12). Both species were observed at higher densities near the bridge than away from the bridge in 2017; that pattern was not apparent in 2018, when densities were similar across the entire survey region. In-pool densities of harbor seals were slightly lower but not significantly different than out-of-pool densities (see [Appendix C, Figure C17](#)). Harbor seals are a known predator of juvenile steelhead in other regions of Puget Sound, although no diet information for harbor seals at the bridge was collected through this study.

While not considered to be potential major predators on juvenile steelhead, distribution patterns for two other avian species are of note: rhinoceros auklets were observed almost exclusively north of the bridge and marbled murrelets were more abundant to the south. These surprising distribution patterns raise questions about whether the bridge may influence the movement of bird populations into or out of Hood Canal.

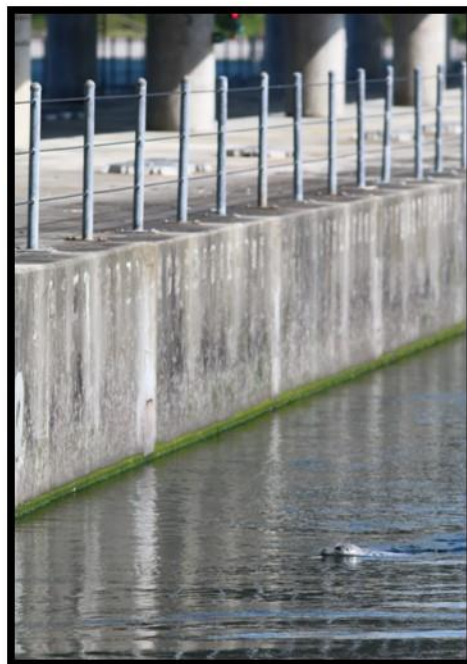


Figure 12. Harbor seal in the water next to one of the bridge pontoons. Photo courtesy of Port Gamble S’Klallam Tribe.

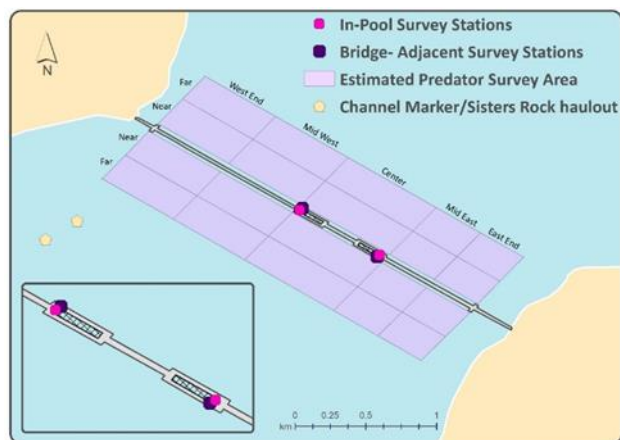


Figure 13. Observers stood on the upper bridge deck at locations marked with purple dots to survey the pale purple area. Pink dots represent observer locations on the lower bridge deck for pool surveys described in [Assessment Component 14](#).

Bridge-adjacent predator surveys took place on the upper bridge deck. During these surveys, one observer visually swept surface waters with binoculars identifying and enumerating every predator observed in the gridded survey region (Figure 13), while another observer recorded data and assisted in identifying species as needed. Seabirds in flight were not counted, nor were birds perched on the bridge. Predators were only recorded at first detection to avoid recounting if an individual moved across survey regions.

Predators were observed in the vicinity of the bridge during every bridge-adjacent visual survey. Weather appeared to affect predator location: southerly winds were associated with higher abundances of avian predators on the north side of the bridge while northerly winds were associated with avian predator observations on the south side of the bridge. In light wind conditions, predators were always observed on both sides. Observers reported that predators did not appear deterred by bridge-associated noise and, while they avoided the center span during bridge openings, boat traffic did not cause them to leave the general area. For some predators, the bridge appeared to function as a shoreline. Pigeon guillemots were observed flying into open ledges on the bridge structure and seals were observed hauling out onto bridge floats at night. WSDOT workers reported pigeon guillemots breeding on the bridge. No nests were confirmed during predator surveys in April/May; however, during this time pigeon guillemots would be incubating eggs on the nests, so nesting activity may have gone unobserved.

Data collected from juvenile steelhead implanted with pressure-sensitive and temperature-sensitive transmitters (described in [Assessment Component 1](#); detailed methods and results in [Appendix A](#)) allowed insight into which of the predator species described above was responsible for juvenile steelhead mortality. Of the steelhead smolts implanted with pressure-sensitive transmitters, all survivors exhibited strong surface orientation whereas 83-85% of mortalities approached the bridge near the surface then suddenly changed behavior and began exhibiting frequent deep dives, a subset of which eventually became stationary (Figure 14). Time between first detection at the bridge and the behavioral change indicating a predation event averaged 17 hours in 2017 and 1.6 hours in 2018; nearly all (90%) predation events occurred within two days of bridge encounter.

Dive behavior of the predated tags was compared with literature values for dive behaviors of several different candidate predators (see [Appendix C2](#)). Of the candidate predators, avian species at the bridge are capable of diving to > 37 m deep but do not typically do so on a regular basis (pers comm Scott Pearson). The avian predators common at the bridge primarily forage in water shallower than 40 m. Less information was available on harbor porpoise behavior; observations at the bridge suggest they do not spend extended periods of time at the bridge but rather migrate through the area on a regular basis. Despite indications that porpoise behavior does not match with observed predation patterns at the bridge, they cannot be ruled out as a candidate predator. Harbor seals are likely to regularly dive to depths > 40 m, and are regarded as the most likely candidate predator that would cause the observed tag dive patterns.

Of the steelhead implanted with temperature-sensitive tags, 69% of mortalities exhibited elevated temperatures consistent with the internal body temperature of a marine mammal or bird, with temperature increases occurring an average of 18 hours after tagged steelhead arrived at the bridge. Nearly 40% of mortality sensors with elevated temperature were detected within range of Sisters Rock, a known harbor seal haulout 750 meters south of the

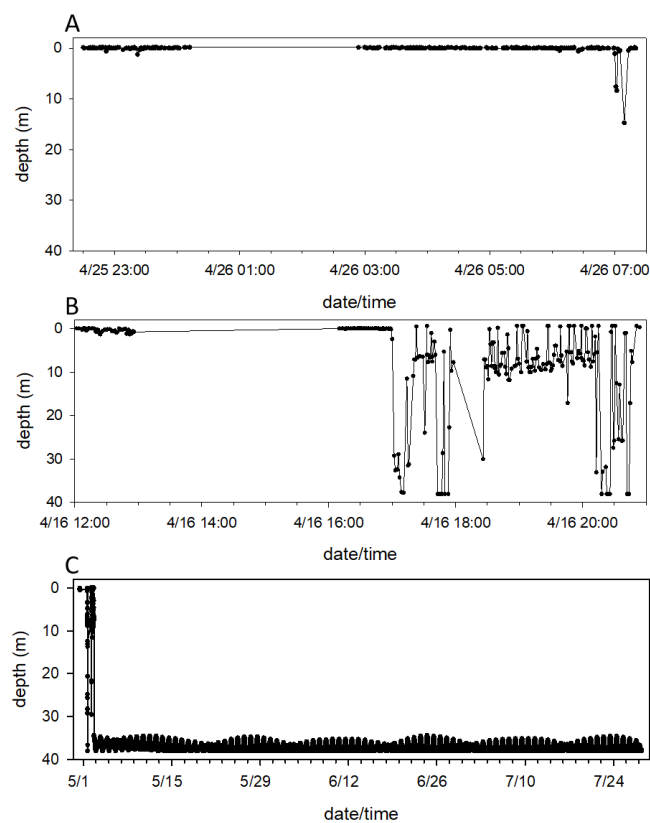


Figure 14. Depth profiles of tagged steelhead exhibiting behavior typical of a surviving smolt (A), a non-surviving smolt that was eaten by a deep and frequently-diving predator (B), and a non-surviving smolt that was eaten then excreted by the predator and became stationary on the seafloor, continually pinging until the transmitter battery expired. The maximum depth detectable by the tag sensors was 38 m.

bridge. As noted in [Assessment Component 1](#), a few mortalities were associated with the nearby Port Gamble Bay site, where harbor seal haulouts have also been documented⁷.

Locations of predation events as defined by behavioral change or temperature increase tended to be close to the bridge and dispersed along the length of the bridge, with a slightly western bias. Several (40%) of predation events occurred in close proximity to the corners formed by cross-pontoons extending from the main bridge infrastructure (Figure 15).

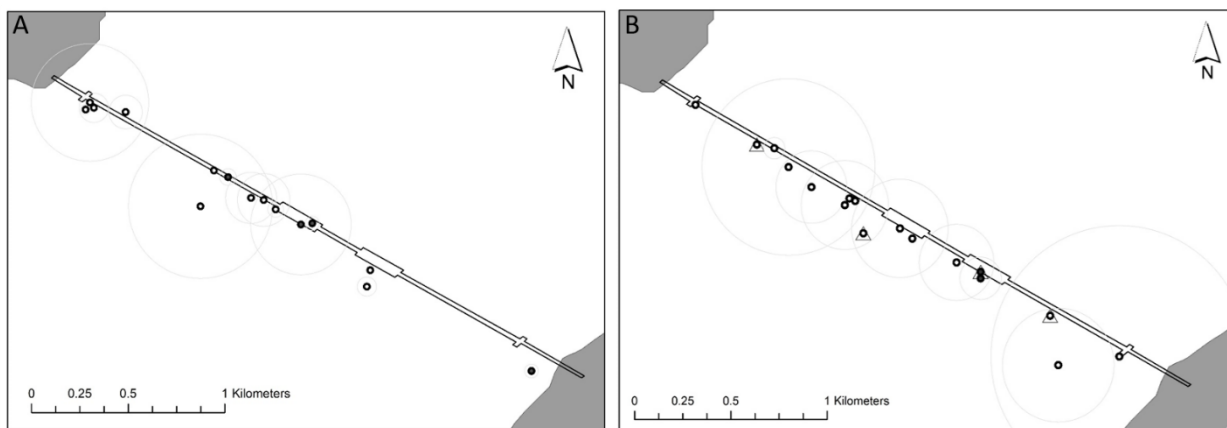


Figure 15. Locations of identified predation events in 2017 (A) and 2018 (B). Open circles represent predation events that occurred during daylight hours while filled circles represent events that occurred during nighttime hours. Gray circles represent the error radius in meters (some are so small they are obscured by the event symbol), with gray triangles marking locations where data were not available for error calculation.

4 & 5. [Potential] Assessing harbor seal-related steelhead (and other salmon) mortality

These components were not funded for Phase 1, and consequently, the Phase 1 remaining research needs and solutions prioritizations reflect this lack of data.

C. What is the influence of the bridge on the surrounding physical environment, at vs away from the bridge?

There are numerous pathways through which the bridge can lead to fish mortality. The data collected indicate that the most likely pathways include the bridge pontoons acting as a physical barrier for fish and/or altering water circulation and other water properties such that fish are deterred. This delay then increases fish densities in nearby areas, subsequently increasing susceptibility to predation. Other factors like noise or light may intensify or exacerbate these impacts. Vehicle traffic across the bridge generates sound and vibrations into the surrounding waters. The bridge's design includes light posts along the length of the southern side of the upper bridge deck, additional lighting around the east and west control towers, and a navigation light on the center drawspan. Light spillover from the bridge lighting into surface water at night (Figure 16) may impact juvenile salmon, steelhead, and their predators.

⁷ Jeffries et al. 2003. Trends and status of harbor seals in Washington state: 1978-1999. *Journal of Wildlife Management* 67(1): 207-218.

6. Measure light and shade impacts to fish and predator behavior

Hans Daubenberger, Port Gamble S’Klallam Tribe and Emily Bishop, Westward Ecology

For detailed methods and results, see [Appendix B](#).

A LiCor sensor attached to an extendable pole was held over the lower deck’s railing, about one meter horizontally away from the bridge and three meters vertically over the water’s surface, and walked around the perimeter of the lower bridge deck during a full moon with partial to no cloud cover and a new moon under heavy cloud cover. Lux values (illuminance) were highest on the south side of the bridge and the pool areas described in [Assessment Component 14](#), exceeding the typical value for a full moon at mid-latitudes.



Figure 16. The Hood Canal Bridge viewed from the water at night. Photo courtesy of Port Gamble S’Klallam Tribe.

All but one of the nighttime mortality locations were near the well-lit pool areas. Turning bridge lights off at night was not possible during Phase 1 and we therefore cannot speculate whether tagged steelhead behavior would have changed if bridge lighting was not present. Light levels observed along the bridge at night are within a range that may affect juvenile chum and Chinook salmon behavior. Preliminary data from within the well-lit pool and at a section of the bridge with less artificial light indicate harbor seals foraged in both areas across day and night hours, but in the less well-lit area seal activity was lower at nighttime than daytime whereas in the well-lit pool seal activity was relatively consistent across day/night hours. Additional work would be necessary to understand and quantify light effects across bridge infrastructure on smaller salmonids and on predator behavior; the growing body of literature regarding artificial light impacts on salmon passage and predation dynamics and precedent from other bridges in the region raise the importance of continued consideration of potential light impacts at the Hood Canal Bridge.

7. Measure noise impacts to fish behavior

Daniel Deng, Xiaoqin Zang, Jayson Martinez, Jun Lu, Scott Titzler, Pacific Northwest National Laboratory

For detailed methods and results, see [Appendix D](#).

A pilot study was conducted to characterize noise propagation from the bridge and determine whether sound (pressure and particle motion) was in a range that could negatively impact juvenile salmon and steelhead behavior. Three sets of sound and vibration monitoring systems which included hydrophones and accelerometers were installed along the bridge near the metal section of the roadway which produces loud

sounds when vehicles cross. Traffic volume data were provided by the Washington State Department of Transportation. Wind speed could affect measurements of sound pressure levels and particle speed accelerations; wind data were collected from a nearby buoy to evaluate the relationship between wind and noise. Background noise levels were measured with a hydrophone deployed while drifting a boat with the motor off about 70 m away from the bridge. To evaluate sound attenuation with distance from the bridge, a sound broadcasting test was conducted by deploying an underwater speaker from the bridge and measuring sound levels with the boat positioned 60, 80, and 120 m away from the bridge.

Vehicle crossing noise was easily identified in audio files collected by the sound and vibration monitoring systems. There was strong diurnal variation in sound pressure levels and particle speed accelerations – quiet and low acceleration during the night versus loud and high acceleration during the day – which was not unexpected given typical traffic patterns. Observed measurements correlated closely with observed traffic volumes, especially when accounting for type of vehicle (motorcycles/cars, single-unit trucks, double-unit trucks, triple-unit trucks). Wind speed was also weakly correlated with sound pressure levels and particle speed accelerations.

NOAA Fisheries and US Fish and Wildlife Service have suggested 150 dB re 1 μ Pa rms as the threshold for behavioral effects to fish species that are listed as being threatened or endangered, although the specific threshold for salmon response to sound levels in saltwater has not been well-defined. Salmon are believed to be more sensitive to particle motion than sound pressure, and based on a literature synthesis of juvenile salmon avoidance responses to sound, the threshold for adverse impacts to juvenile salmon and steelhead was set at 0.01 m/s² in the 5-10 Hz band. Observed sound pressure levels and particle speed acceleration at the bridge were mostly below these thresholds of adverse effects, and sound pressure levels 70+ m away from the bridge were always below the adverse effects threshold.

There were no differences observed in tagged steelhead migration behavior or mortality over day (high traffic volumes, high sound pressure and particle acceleration) versus night (low traffic volumes, low sound pressure and particle acceleration), and observers on the bridge reported no obvious changes in either fish or predator behavior associated with noise.

D. What are the impacts of pools and eddies created by bridge pontoons adjacent the center drawspan?

The bridge infrastructure design includes cross-pontoons that jut out perpendicularly from the bridge deck into the surrounding waters, forming 90° corners in several spots along the bridge. Additionally, large open sections are cut into the sub-deck of the bridge. When the bridge opens to allow vessel traffic the drawspan retracts into these sections; when the bridge is closed, these sections create large pools of water that can aggregate debris and plankton. These corner areas and bridge pools affect water flow and fine-scale circulation, potentially impacting plankton, fish, and predator behavior.

Zooplankton abundance and species composition were important considerations as indicators of bridge effects. Altered circulation caused by water moving past the bridge could clump plankton into dense patches or force plankton away from their typical positions within the water column.

14. [Comparative assessment of fish, predator, zooplankton densities in pools and eddies vs away from them](#)

Hans Daubenberger, Port Gamble S’Klallam Tribe and Emily Bishop, Westward Ecology

For detailed methods and results, see [Appendix B](#).

Zooplankton and water quality parameters (including temperature, salinity, pH, dissolved oxygen, chlorophyll, and blue-green algae) were sampled at locations spanning areas both north and south of the bridge as well as within bridge pools (Figure 17). Water quality was measured over the top 50 meters of the water column. Zooplankton samples followed protocols developed through the Salish Sea Marine Survival Project⁸, except that sampling was restricted to the surface 0-5 meters of the water column.

Within three of the seven weeks sampled, differences in surface water temperature and dissolved oxygen at the surface between north and south sampling stations were measurable and significant based on Washington State water quality standards⁹. These results align with the model output and conclusions described in [Assessment Component 9](#).

Although limited by small sample sizes, zooplankton density appeared slightly higher within bridge pools than at stations north/south of the bridge infrastructure, and slightly higher south of the bridge than north of the bridge. The vertical tow sampling method and small net mesh size used in this sampling design likely did not accurately reflect the abundance of fast-moving, larger plankton taxa. Visual observations showed dense aggregations of these large plankton taxa (euphausiids/krill, larval crab) within bridge pools which were not well-captured in zooplankton samples (Figure 18).

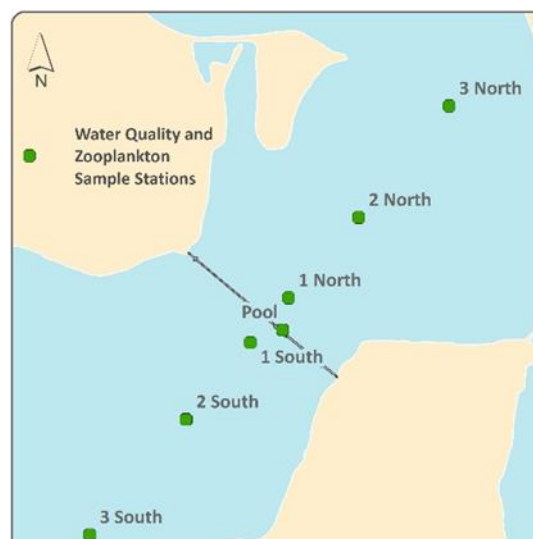


Figure 17. Stations sampled April-May 2017; stations labeled “2 North” and “2 South” were also sampled weekly April-May 2018.



Figure 18. Juvenile chum salmon swimming in a cloud of larval crab within one of the bridge pools. Photo courtesy of Port Gamble S’Klallam Tribe.

⁸ Keister and Winans 2015. SSMSPP Zooplankton Sampling Protocol. [Full protocol linked here](#).

⁹ WAC 173-201A-320, Ecology. [Full legislative text linked here](#).

Tagged steelhead were rarely observed in pools, however they were disproportionately observed in corner areas of the bridge. To determine steelhead associations with bridge corners, unique steelhead transmitters were quantified within a 150 m along-bridge x 100 m perpendicular-to-bridge area adjacent to all corners formed by bridge pontoons. Only surviving fish were included in this analysis, because it was not possible to determine whether a non-surviving transmitter was in a steelhead or a predator at the time of position triangulation within the corner. Therefore, this analysis represents a minimum estimate of the number of fish affected by corner structures and does not take into account steelhead that may have died as a result of being eaten in a corner area. In 2017, approximately 60% of surviving fish encountered a corner area on the bridge; in 2018, 73% of survivors were detected in corner areas.

Surface predator surveys within bridge pools were designed to complement the boat surveys described in [Assessment Component 3](#) to compare in-pool/out-of-pool predator presence. Surveyors observed the 90mx20m body of water and recorded the number of each predator species present. Predators were observed in 45% of the bridge pool surveys. Pigeon guillemots were the most frequently seen predator species within the pools, with as many as three individuals recorded during a 40-second survey period. No predators other than pigeon guillemots were recorded in the east pool, despite frequent observations of seals made by surveyors before and after the official survey period. Seals were observed twice in the west pool; three on 5/9/17 and two on 5/31/18. No other predator species were observed in bridge pools during surveys.

As described in Assessment Components [1](#) and [3](#), corner areas created by cross-pontoons were associated with higher densities of tagged steelhead (Figure 8) and with predation events on tagged steelhead (Figure 15). A BlueView imaging sonar unit was deployed in three locations to capture underwater predator presence: 1) within the bridge pool, 2) outside of the pool facing away from the bridge structure, and 3) in one of the corner areas created by a cross-pontoon (Figure 19).

Seals were observed in the pool area at all hours of the day and night, spending an average of 39 seconds every hour within 30 m of the BlueView device in 2017 (Figure 20) and a maximum time of 9 minutes 17 seconds in a single hour. Seal presence was slightly higher during daylight hours versus nighttime hours. Comparison of in-pool and out-of-pool data in 2018 did not show large differences in seal presence or behavior in these two areas (Figure 21).

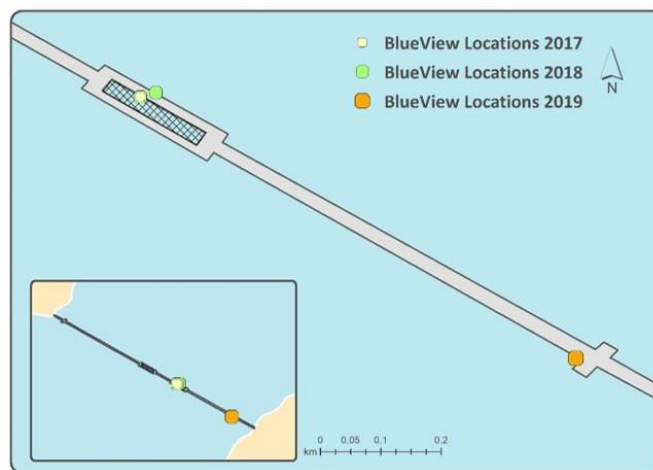


Figure 19. BlueView imaging sonar deployments in 2017 (deployed in east pool April 12-June 2, recording intermittently), 2018 (deployed in eastpool for 2 days, deployed on bridge structure facing away from bridge for 2 days), and 2019 (deployed in southeast corner for 20 days).

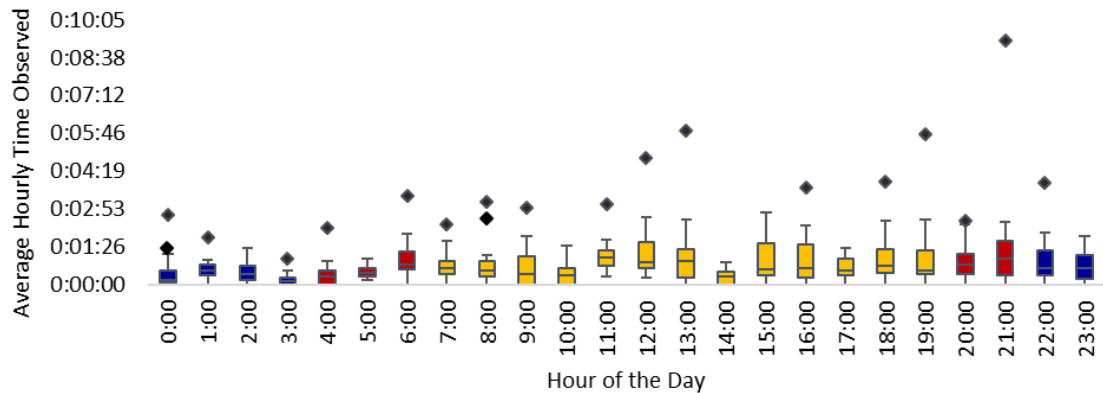


Figure 20. Hourly time observed (a summation of time seals were observed within 30 m of the BlueView unit over the course of one hour) averaged for each hour of the day across 20 days of BlueView placement within the east bridge pool in 2017. Blue bars represent nighttime hours, red represent dawn and dusk, and yellow represent daylight hours.

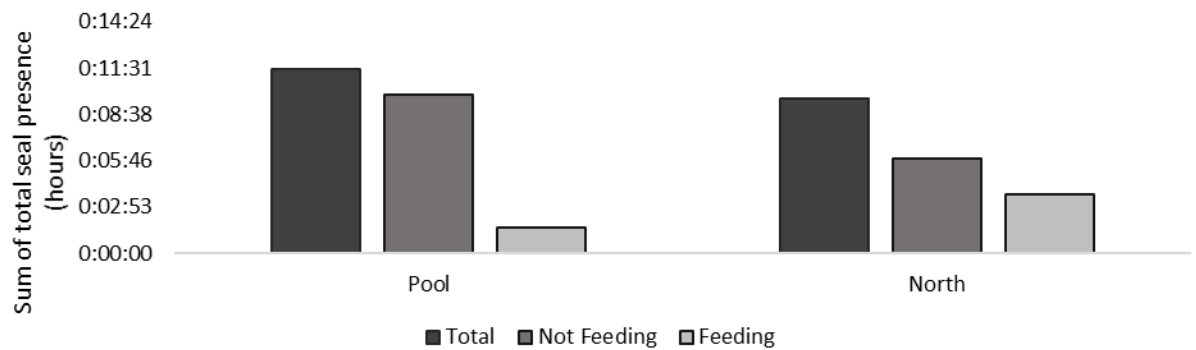


Figure 21. Sum of seal presence over 24 hours within 30 m of the BlueView unit deployed inside the east bridge pool (June 5, 2018) and on the north side of the bridge outside the east pool (June 7, 2018) looking away from the structure. The light gray and intermediate gray bars reflect time spent feeding and not feeding, respectively, and the dark gray bar represents the sum of the two behavior categories.

Seal presence was higher in a southeast corner area created by a cross-pontoon; seals spent an average of 111 seconds every hour within 30 m of the BlueView device (Figure 22) with a maximum time of 18 minutes 28 seconds in a single hour. Seal presence in the corner was significantly higher during daylight hours (155 seconds/hour) than during nighttime hours (51 seconds/hour).

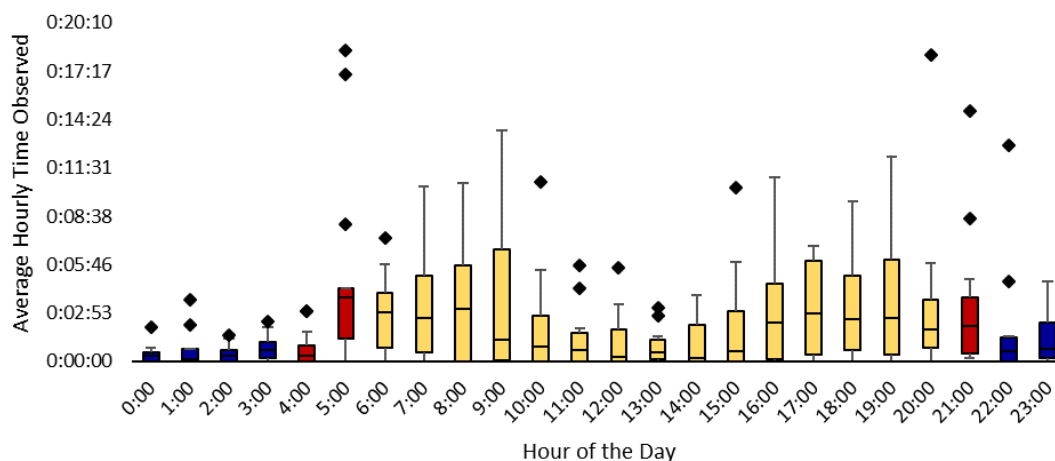


Figure 22. Hourly time observed (a summation of time seals were observed within 30 m of the BlueView unit over the course of one hour) averaged for each hour of the day across 20 days of BlueView placement within a southeast corner area in 2019. Blue bars represent nighttime hours, red represent dawn and dusk, and yellow represent daylight hours.

- E. What influences steelhead migration/mortality and fish distribution patterns near the bridge? What are the spatial-temporal relationships between steelhead migration and mortality patterns, fish densities, predator densities and how the bridge is impacting the surrounding physical environment?

13. Synthesize patterns of steelhead migration behavior and mortality and fish distribution with predation densities and distribution, and the physical impacts of the bridge (physical barrier, water circulation, water quality, light and noise)

The Assessment Team spent a considerable amount of time reviewing data and results of each assessment component and synthesizing across components both qualitatively and quantitatively. Tagged steelhead migration behavior and mortality data were considered in combination with predator survey data, hatchery salmon release data, rainfall data, day/night, bridge opening data, near-bridge fish biomass, and water characteristics (e.g., tide, turbidity). Maps of fish biomass and predator density were compared visually to assess patterns. Some of these comparisons (e.g., noise/light effects on tagged steelhead behavior and mortality) are described in preceding individual assessment components; this section focuses on data comparisons and analyses that exceeded the scope of other individual components.

Increasing survival probabilities across the outmigration season associated with hatchery releases and higher turbidity

Survival of tagged steelhead smolts was related to the date the fish approached the bridge, with higher probabilities of survival after early-to-mid May each year. Two factors co-varied with steelhead mortality probability across the outmigration season: turbidity and hatchery salmon releases. Higher turbidity was correlated with higher survival probabilities, although the mechanism underlying this relationship is not yet understood. Three hatcheries (Quilcene, Cushman, and George Adams) release several million salmon into Hood Canal each spring. Releases include coho, chinook, and steelhead, and typically are performed over April and May. A preliminary pairing of known release timing, estimated travel time of hatchery fish from release to bridge, and observed fish species at the bridge suggests that the arrival of hatchery releases at the bridge roughly aligns with an increase in survival probability for tagged steelhead (Figure 23). This may be due to a buffering effect where the large number of hatchery fish present at the bridge temporarily alleviates the predation pressure experienced by the relatively few steelhead at the bridge.

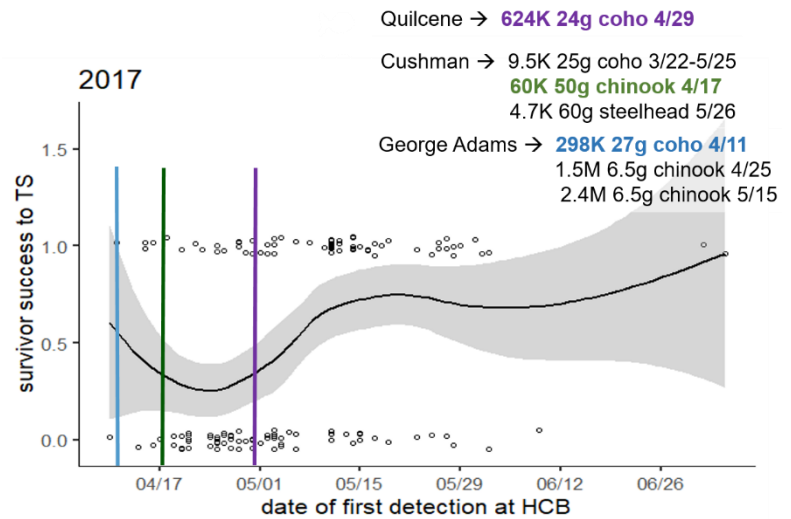


Figure 23. Survival probability over the outmigration season, overlaid with timing of Quilcene coho (purple line), Cushman Chinook (green line), and George Adams coho (blue line) hatchery releases.

Time to event analysis

To understand whether the length of delay in migration caused by the bridge influenced the rate of predation we compared passage rate and predation rate. We were able to determine the time of predation for smolts tagged with depth sensors, and the time of passage for fish that were detected on both sides of the bridge, so we developed Kaplan-Meier curves for a subset of 32 steelhead

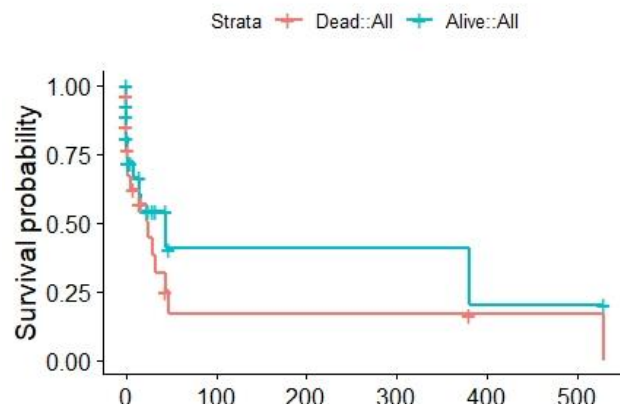


Figure 24. Time to passage versus time to predation upon tagged steelhead first encountering the bridge.

smolts in 2017 (Figure 24). Smolts pass the bridge (blue line) at the same rate they are being eaten (red line) during the first two days of encounter (after that sample sizes are too low to make a reliable comparison). This analysis shows that smolts spending more time at the bridge are not necessarily more susceptible to predation than those taking less time to pass. Rather, both passage events and predation events are occurring fairly quickly upon arrival at the bridge. Therefore, resolving issues of predation and delay are equally important.

Predator versus fish abundance and density patterns

Pigeon guillemots were the only predator species detected commonly enough to generate a weekly abundance estimate; no relationship was apparent between steelhead mortalities and pigeon guillemot presence/abundance over time. In four weeks of the assessment, data were sufficient to map harbor seal counts ([Assessment Component 3](#)) alongside fish biomass densities ([Assessment Component 2](#)); however, there appeared to be little consistency and no detectable correlation between the two, likely due to the stochastic nature of both fish density patterns and observed harbor seal in-water locations (Figure 25).

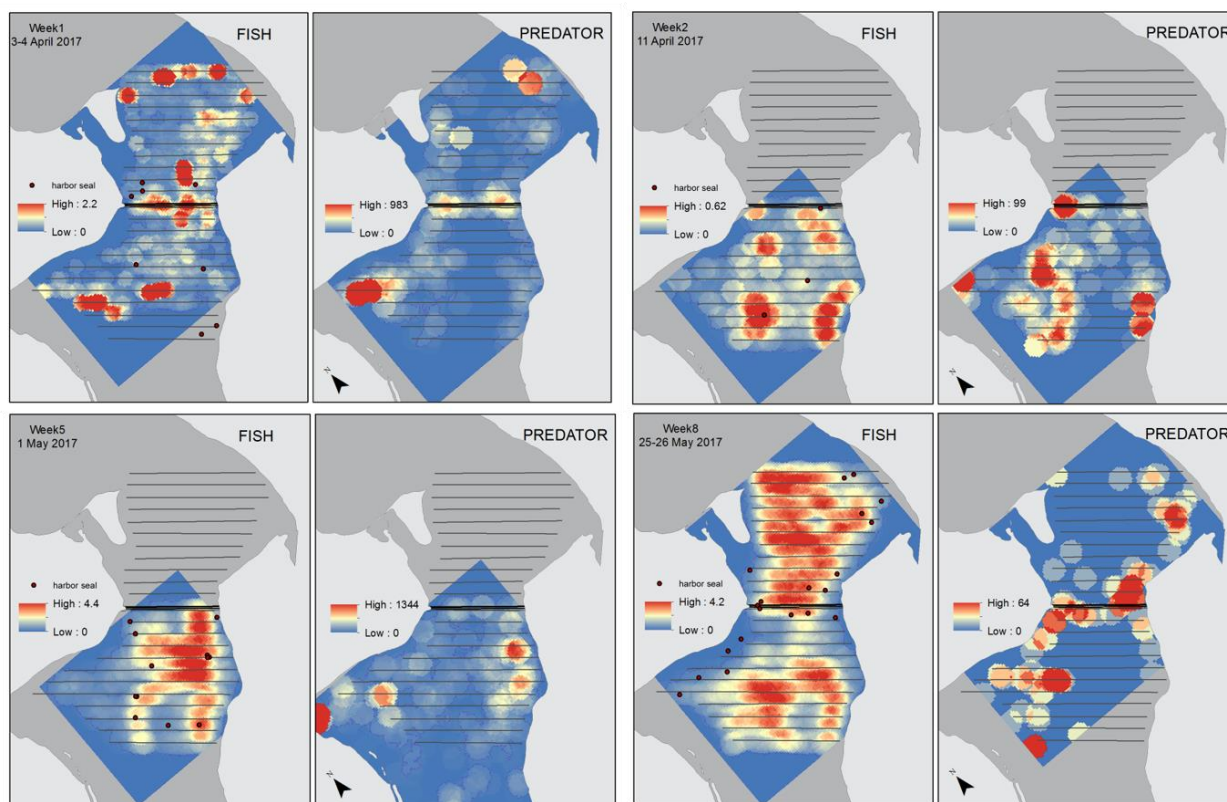


Figure 25. Side-by-side density maps of fish biomass (left panel in each week) overlaid with single harbor seal observations and harbor seal densities (right panel in each week) over four weeks of the 2017 outmigration season. Red colors indicate higher densities. Density values differ among panels.

Successful steelhead passage at the bridge associated with ebbing tidal currents

Tidal currents at the bridge had a strong effect on tagged steelhead passage. Almost all tagged steelhead migrated past the bridge on an ebbing current as water drains from Hood Canal towards the ocean. Steelhead that migrated through the open spans at the side of the bridge were less dependent on the tidal cycle; most steelhead that dove underneath the bridge only did so during high velocity ebb currents (Figure 26).

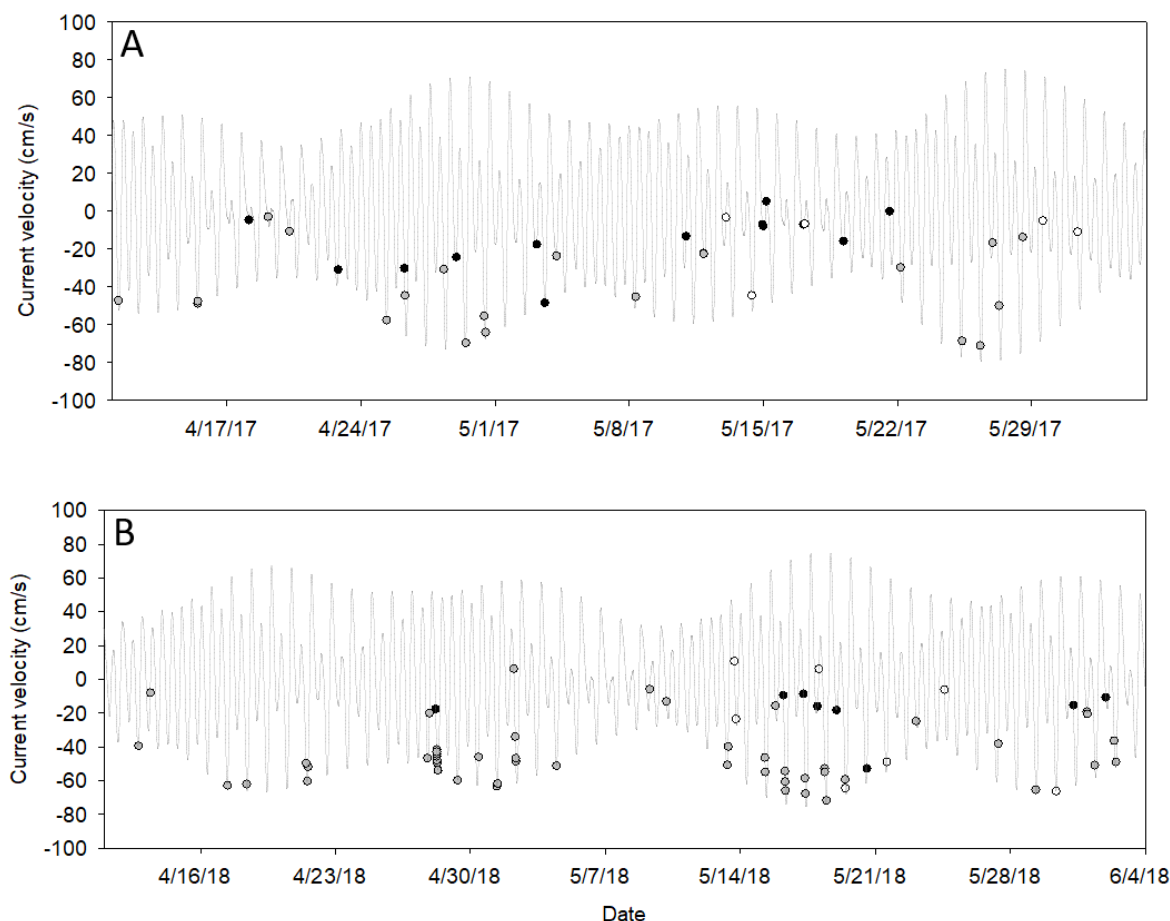


Figure 26. Crossing location times of smolts that crossed under (light gray circles), around through the east drawspan (black circles), or around through the west drawspan (open circles) in 2017 (A) and 2018 (B) in relation to current velocity (predictions at NOAA current station PUG1603, https://tidesandcurrents.noaa.gov/noaacurrents/Predictions?id=PUG1603_20).

Drawspan openings and tagged steelhead passage

The bridge's center drawspan is retractable to allow for vessel traffic and maintenance operations. Data on timing and duration of bridge openings were paired with tagged steelhead behavior to determine whether steelhead crossed through the open center when the option was available. Over the 2017 and 2018 outmigration periods, the center drawspan was opened partially or fully a total of 55 times in 2017 and 101 times in 2018, generally remaining open for approximately 15-20 minutes. Only two tagged steelhead each

year were within 200 m of the center span during the time periods when the bridge was open. Distance from center span was calculated between the location of the tagged fish and the closest point of the drawspan. One 2017 crossing occurred during a full bridge opening; the other three crossings occurred during partial openings. In 2017, one of the two tagged steelhead was detected within 100 m of the center for the first seven minutes of bridge opening but subsequently moved away from the center span despite a strong ebb tide; the other steelhead moved within 25 m of the center span and remained there for five minutes but did not pass through. In 2018, one of the two tagged steelhead within 200 meters during a drawspan opening moved through on a strong ebb tide, while the other steelhead moved back and forth parallel to and 30-60 m from the drawspan before moving away without crossing during a moderate ebb tide.

Since more frequent and longer duration center span openings were one proposed solution to facilitate steelhead passage, an additional analysis was conducted to determine how many tagged fish were in proximity (within 100 m) of the center span at any point during the steelhead outmigration season and, of the fish that entered that area, how long they remained there. Of the surviving tagged steelhead smolts, about 30% were detected near the center span at some point during their migration. On average, fish spent 29 ± 9 (2017) and 12 ± 3 (2018) continuous minutes within 100 m of the center span. Of the fish that were detected within 100 m of the center span, nearly all were detected in this area during ebbing currents. Upon further investigation, surviving tagged steelhead smolts were located much closer to the bridge infrastructure during ebb currents and moved further away from the structure (but still within a detectable range) during slack and flood currents (Figure 27).

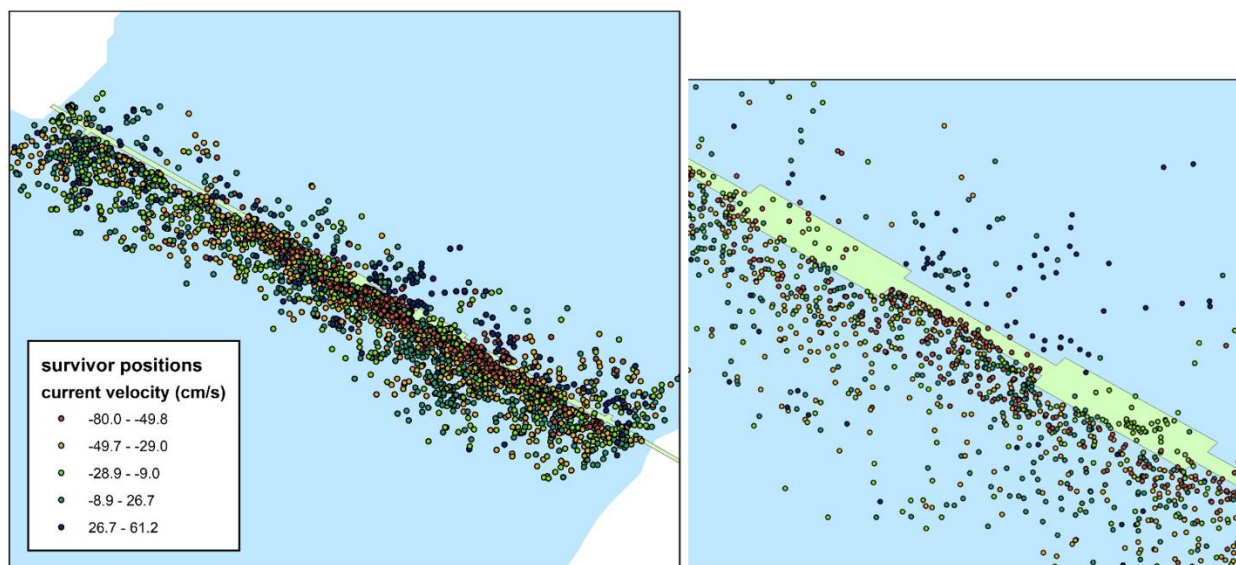


Figure 27. Positions of tagged steelhead in 2017 along the entire bridge (left) and within 100 m of the center span (right). Position dots are colored to reflect current velocity at the time of position, where redder dots indicate stronger ebb currents.

Stormwater impacts at the bridge

Rainfall patterns were investigated using data from nearby NOAA stations and stations monitored by citizen scientists to determine whether there was any signal of stormwater impacts on tagged steelhead mortality. Timing and level of precipitation did not appear related to steelhead mortality patterns across the migration season.

II. Is the bridge impacting the entire Hood Canal ecosystem?**A. Does the bridge obstruct ebb - flood currents & impact flushing of brackish outflow water?**

Previous circulation models suggested the bridge had the potential to impede flushing of Hood Canal. However, at the time no field data in the vicinity of the bridge was available to validate model results. During Phase 1, researchers collected *in situ* oceanographic data near the bridge structure, increased model resolution and accuracy, and used the improved model to investigate circulation and water quality parameters near the bridge and throughout Hood Canal. These studies defined the bridge's zone of influence: the distance from the bridge where relative difference induced by bridge infrastructure on water quality parameters reduces to < 10% of the maximum deviation.

8. Collect oceanographic data at Bridge (current, salinity, and temperature profiles)

Tarang Khangoankar, Adi Nugraha, Taiping Wang, Pacific Northwest National Laboratory

For detailed methods and results, see [Appendix E](#).

Three *in situ* current and conductivity, temperature, and depth sensors were deployed at the bridge, 500 m upstream of the bridge, and 500 m downstream of the bridge. A water level station placed just north of the bridge measured water surface elevation. These instruments collected data throughout the 2017 steelhead outmigration period. Additional conductivity, temperature, and depth data were collected from vessels during sensor deployment and retrieval. These observed data were then compared with model-predicted water surface elevations, currents, salinities, and temperatures to validate the model described in Assessment Component 9.

9. Characterize the bridge zone of influence – Hydrodynamic Modeling

Tarang Khangoankar, Adi Nugraha, Taiping Wang, Pacific Northwest National Laboratory

For detailed methods and results, see [Appendix E](#).

To quantify the spatial extent of the bridge's effect on hydrodynamic parameters, the Salish Sea model – an externally coupled three-dimensional hydrodynamic and biogeochemical model – was validated and refined to embed the Hood Canal floating bridge in high resolution. Several techniques were explored:

1. Implementation of a velocity block, wherein the bridge was embedded as an impermeable surface block,

2. Implementation of momentum sink at the bridge using form drag, wherein the bridge was represented in the model as densely-packed hypothetical cylinders which resulted in blockage of nearly ~95% of surface currents. This scenario represents a leaking bridge but allows effects on continuity and momentum.
3. Free surface pressure modification with a bottom drag, wherein the pressure boundary condition is manipulated to cause a model response of surface depression down to the extent that the bridge sits in the water. This method also employs drag formulation for the water layer immediately under the modified pressure boundary, inducing reduction in flow velocity.

Results using each of these modeling techniques were tested against the observed data collected in Assessment Component 8, and all methods performed similarly in terms of near-field impacts of the bridge. Model predictions compared favorably to observed water surface elevations, currents, salinities, and temperatures, and implementation of the bridge module in the Salish Sea model was successful in reproducing the observed reduction in velocity near the bridge. Sensitivity tests were performed by running additional model scenarios with the bridge module removed from the model, representing Hood Canal conditions without the bridge, and with the bridge module altered to leave the center span open, representing bridge openings due to, e.g., vessel traffic. Predictions across all model scenarios were compared to define the bridge's zone of influence.

The model results confirm that the Hood Canal Bridge obstructs the brackish outflow surface layer of water, inducing increased local mixing near the bridge and causing pooling of up-current water and shadow/sheltering of down-current water (Figure 28). In addition, surface layers of water are forced underneath the bridge, creating warmer, fresher waters at depth. The effect on currents, salinity, and temperature is highest at the bridge and reduces with increasing distance from the bridge. The bridge's zone of influence extends ~20 m below the surface and varies from 2-3 km for currents, from 2-4 km for salinity, and from 2-5 km for temperature before effects diminish to <10% relative to simulated conditions without the bridge.

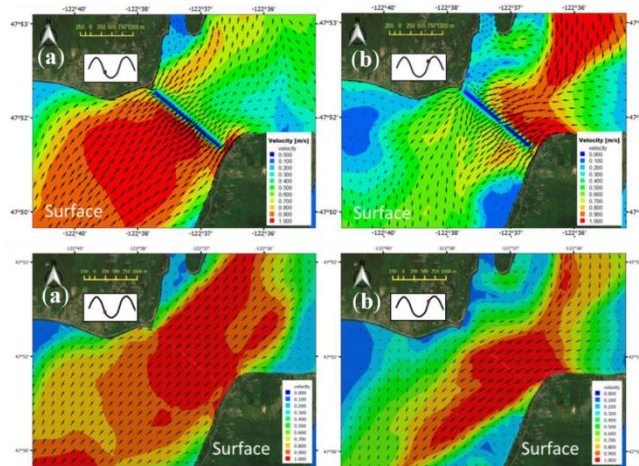


Figure 28. Upper panels: model-predicted horizontal velocity contour and vector plots with the HCB present for (a) ebb and (b) flood currents in the surface layer. Lower panels: model-predicted horizontal velocity contour and vector plots with no HCB for (a) ebb and (b) flood currents in the surface layer. Both upper and lower panel scenarios represent a typical spring tide (April 27, 2017).

B. What is the impact of Hood Canal Bridge on basin wide circulation and water quality?

Previous modeling studies suggested the Hood Canal Bridge may have a subtle but persistent and cumulative effect on the residence and flushing of the Hood Canal basin. While low DO

levels, nutrients, pollutants and pH in Hood Canal have received much attention, potential effects of the Hood Canal Bridge on these issues had not been examined prior to Phase 1 of the Hood Canal Bridge Ecosystem Impact Assessment. Phase 1 work included a coarse analysis using the refined model developed through assessment component 9 to determine whether proceeding with a more extensive investigation of potential bridge impacts to the Hood Canal ecosystem was warranted.

10. Model the bridge's effect on flushing, biogeochemistry, dissolved oxygen, and pH of Hood Canal

Tarang Khangankar and Adi Nugraha, Pacific Northwest National Laboratory

For detailed methods and results, see [Appendix F](#).

This modeling effort investigated the bridge's effects on Hood Canal-wide circulation, determining whether the presence of the floating bridge significantly impacted basin circulation/flushing by blocking the surface brackish layer. The Hood Canal Bridge module was embedded within the Salish Sea model using the velocity block method as described in Assessment Component 9, and was then validated throughout Hood Canal using observational data collected by the Washington Department of Ecology. Model validations including tests of water quality parameters, nutrients, phytoplankton, and dissolved oxygen. The model was able to replicate a prior version of the Salish Sea model without a bridge block and also performed well in comparisons to observed data.

The validated model was then used to simulate the entire Salish Sea domain for one year under three scenarios: 1) Hood Canal Bridge present, 2) no Hood Canal Bridge, and 3) Hood Canal bridge present but with center span always open. These scenarios were compared to determine the bridge's effect on circulation/flushing and exchange flows, and predict impacts on water quality parameters like temperature, salinity, dissolved oxygen, and

pH. Results suggested that the bridge does not cause a large-scale impact on circulation: predicted parameters in simulations without the bridge were nearly identical to simulations with the bridge. Southern Hood Canal (Lynch Cove) was expected to show the strongest response since this region has the longest flushing time; however, comparisons of predicted parameters in simulations with and without the bridge as well as comparisons to observed data showed no differences large enough to be of practical significance (Figure 29). Additional sensitivity tests (double precision, variations in bridge block formulation layering schemes, etc.) were conducted to ensure that these results were not simulation error.

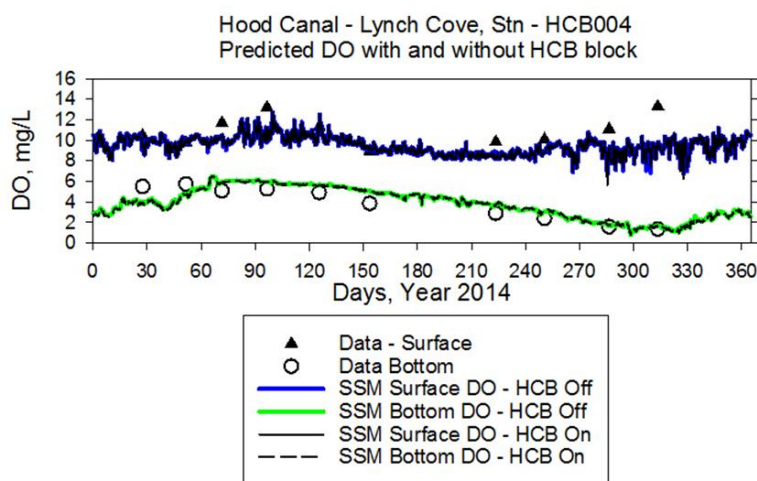


Figure 29. Model predictions for dissolved oxygen (DO) levels at Lynch Cove with and without the presence of the Hood Canal Bridge in the model.

A final set of flushing time tests were performed using a numerical dye tracer. To evaluate relative change in flushing time due to the bridge, focus was again placed on southern Hood Canal (Lynch Cove), a region with a flushing time that exceeds 200 days, although all Hood Canal regions were subjected to bridge/no-bridge simulation comparisons. Simulations were run without the Hood Canal Bridge and with the Hood Canal Bridge using two different approaches to represent the bridge's surface layer blockage. All three of these simulation tests resulted in flushing times of 229 days at Lynch Cove (Figure 30). These results suggest that, while the bridge does significantly affect currents, temperature, and salinity within its zone of influence as defined in [Assessment Component 9](#), this effect is restricted to the zone of influence and is not strong enough to impact Hood Canal-wide circulation/flushing and water quality. These findings contrast with prior model research; in reviewing the prior model's methods and results, authors believe that the previous model produced a false positive based on inadequately specified ocean boundary conditions. Further investigation, while beyond the scope of this Phase 1 Assessment, should consider scenarios reflecting climate change and population growth in the Hood Canal region as these factors may exacerbate known Hood Canal water quality issues. Since fish and other biota can be sensitive to even small fluctuations in water quality parameters, additional investigation into potential impacts at specific locations within Hood Canal may be warranted.

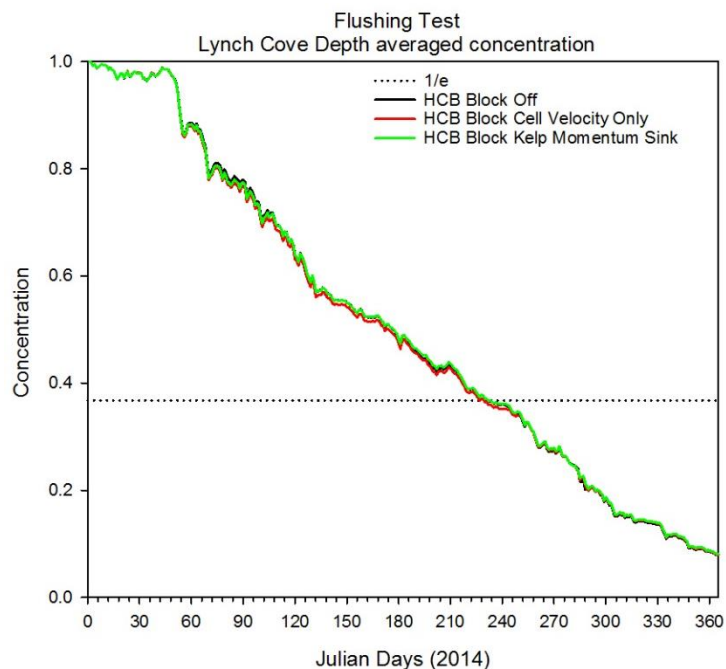


Figure 30. Time histories showing depth-averaged dye concentrations at Lynch Cove modeled without Hood Canal Bridge (black line), with HCB represented in the model with a velocity block (red line), and with HCB represented with a momentum sink (green line).

Conclusions

Results from Phase 1 of the Hood Canal Bridge Ecosystem Impact Assessment indicate that the Hood Canal Bridge significantly contributes to early marine mortality of juvenile Hood Canal steelhead by impeding fish passage and facilitating predation, resulting in mortality of about half the smolts that encounter the bridge. The structure also affects other fish species such as juvenile Chinook and chum, although the extent of bridge effects on smaller salmonids are not yet quantified, and significantly impacts water quality parameters (temperature, salinity, currents) in its vicinity. Specific portions of the bridge infrastructure cause problems beyond the initial deterrence of the bridge's pontoon structure (15 vertical feet of continuous underwater concrete): corner areas created by cross-pontoons that extend perpendicularly from the bridge structure are associated with high densities of fish, predator presence, and predation events. Although bridge effects on water quality dissipate with distance from the bridge and do not appear to propagate throughout Hood Canal, these near-bridge changes in circulation and

flow may be linked to impacts on juvenile salmon and steelhead behavior and mortality. Tidal currents were closely linked to steelhead passage. No day/night effects or noise effects on tagged steelhead behavior and mortality were observed, but artificial light at night remains a concern in the vicinity of the bridge. Observational data supported the artificial reef effect hypothesis, where the bridge infrastructure aggregates plankton, fish, and predators; researchers observed higher zooplankton densities, large schools of juvenile salmon, and consistent predator presence at the bridge. However, quantifying the effects of this potential dynamic on salmon species was beyond the scope of the assessment Phase 1. A suite of avian and mammalian predators was associated with the bridge; based on tagged steelhead mortality patterns and predator behavior, harbor seals are the strongest candidate predator responsible for juvenile steelhead mortality at the bridge. Improving juvenile steelhead survival through this migration segment requires reducing the amount of time juvenile steelhead are delayed by the bridge's physical obstruction and minimizing the predation pressure that juvenile steelhead experience at the bridge.

Recommendations, Remaining Data Gaps, and Limitations

Based upon the findings reported above, the Hood Canal Bridge Assessment Team, Engineer Team, and Management Committee members participated in workshops and exercises to develop solutions to test during Phase 2, and to identify the research needed beyond the scope of Phase 1 to address bridge impacts on other juvenile salmon species, potential bridge impacts on returning adult salmon, and predator deterrence options. With the guidance of the Assessment Team, engineers at R2 Resource Consultants completed initial scoping and design recommendations for Phase 2 solutions. Solutions were prioritized into three categories: 1) management actions recommended for early implementation, 2) management actions that were high-ranking but need additional research, and 3) management actions ranked lower.

Solutions in category 1 are being proposed for installation and effectiveness testing in Phase 2. This category includes installing fillet and eddy reduction structures to reduce or restrict fish access to existing pontoon corners of the infrastructure, as well as pilot testing longer-duration bridge drawspan openings timed on strong ebb tides to encourage fish passage and investigating modifications to luminaries to reduce overwater light spillover. Phase 2 may also provide an opportunity to conduct the research necessary to move towards implementing solutions in category 2: bridge re-design and replacement/modifications and pinniped deterrence activities such as restricting haulout and bridge access and exploring targeted acoustic startle technology which has shown initial success at deterring pinnipeds in other areas of Puget Sound.

See appendices H, I, and J for details on the Assessment Team's process of identifying remaining research priorities and developing Phase 2 solutions as well as the full R2 Resource Consultants report on scoping and design of Phase 2 solutions. The Assessment Team recommends that Category 1 solutions undergo a more substantial feasibility and design process before they are installed and assessed during Phase 2 studies. To assess solution effectiveness while accounting for observed inter- and intra-annual survival variation across the steelhead outmigration period, Assessment Team members strongly recommend a series of replicated control (no solutions)/treatment (solutions installed) tests spanning two outmigration seasons.

Phase 1 studies addressed central questions of bridge effects, yet several research priorities remain. The most pressing priorities, and recommendations on addressing each, include:

- How do juvenile Chinook and chum interact with the bridge and do they experience increased mortality because of the bridge?

During the Phase 1 assessment, on-bridge and near-bridge visual and acoustic surveys found schools of small Chinook and chum salmon aggregated within and around bridge infrastructure. These data also suggested a potential increase in milling behavior near corners in the bridge infrastructure. Quantifying juvenile Chinook and chum behavior and mortality at the bridge was beyond the scope of Phase 1, but the Assessment Team and Management Committee recommend this as needed research to support Hood Canal Chinook and chum population recovery efforts and to further inform or refine bridge solutions. Studies recommended for consideration in Phase 2 would quantify schooling/milling behavior along bridge infrastructure. Additional studies suggested but not recommended within the Phase 2 scope include tagging juvenile Chinook with small acoustic tags or a paired predator-fish PIT-tag study to directly measure consumption rates of juvenile Chinook by seals.

- How do returning adult salmon interact with the bridge and do they experience migration delays or increased mortality because of the bridge?

No data were collected on adult salmon during the Phase 1 assessment. Anecdotal information from state and tribal representatives suggest potential bridge impacts to returning adult chum. The Assessment Team and Management Committee recommend a small, investigative tagging study on returning adult chum that takes advantage of the acoustic array that will be deployed at the Hood Canal Bridge during Phase 2. This research would determine whether the bridge impacts returning adult salmon and may further inform or refine bridge solutions.

- Is predation by harbor seals and other predators on juvenile Chinook and chum greater near to vs. away from the bridge?

Juvenile Chinook and chum are susceptible to a wider array of potential predators than larger steelhead smolts. Understanding how predators near the bridge contribute to Chinook and chum mortality, and whether mortality at the bridge is disproportionately higher than in areas away from the bridge, is important information; however, it is not currently prioritized in Phase 2 given the lack of quantitative data on juvenile Chinook and chum behavior and mortality at the bridge.

- Which seals forage at the bridge, and what behavior patterns do seals employ while foraging at the bridge?

Assessing the array of potential steelhead predators and predator density near to versus away from the bridge was an important component in the Phase 1 assessment. Studies of predator behavior and diet were not possible in Phase 1 but are recommended for consideration in Phase 2. The Assessment Team prioritizes research to identify which seals forage at the bridge – is

bridge foraging a specialized behavior in which only a few repeat offenders engage? Or do all seals near the bridge engage in this behavior? – and what behaviors seals foraging at the bridge employ. Studies on seal behavior at and near the bridge may further inform and refine bridge solutions.

Recommended solution concepts for Phase 2, and what each concept will do:

Category 1 Management Actions, Recommended for Early Implementation	Bridge Corner Fillet Structures	Reduce or restrict access to the existing pontoon corners
	Eddy Reduction Structures at Corners	Eliminate or reduce the size of eddies formed at existing pontoon corners
	Open Bridge Span More Often for Fish Passage	Expedite fish passage through the bridge
	Lighting at Bridge	Modify luminaries to provide bridge deck lighting while reducing overwater light spill
Category 2 Management Actions, High Ranking but Need Research	Bridge Re-Design and Replacement/Modifications	Replace the bridge or bridge sections with a more fish-friendly design
	Pinniped Deterrence (excluding lethal removal)	Deter pinnipeds via haulout restriction and/or prevent pinniped access to the bridge
Category 3 Management Actions, Considered but Not Supported or Recommended	Behavioral Guidance System	Guide fish to existing passageways through bridge side spans
	Pumping Water to Signal Fish Passage	Guide fish to existing passageways through bridge side spans
	Guide Fish with Bubble Curtains	Guide fish to existing passageways through bridge side spans
	Noise Reduction	Reduce bridge noise in surrounding waters

Marine Growth
Removal/Control

Remove/control marine growth
on the bridge structure

Induced Turbidity

Increase turbidity to impede
predator foraging efficacy near
bridge

Additional detail on Category 1 Management Actions, Recommended for Early Implementation

Bridge Corner Fillet Structures

Existing corners created by bridge pontoons jutting perpendicularly out from the bridge deck are hypothesized to delay juvenile steelhead migration and aggregate smaller fish species by creating back-eddies or water velocity anomalies. Mammalian predators may corral fish in a corner as a foraging strategy. Telemetry data suggest elevated density in corner areas. To address this situation, flexible bridge corner fillet structures (Figure 31) will be placed at inside corners of east and west abutments,

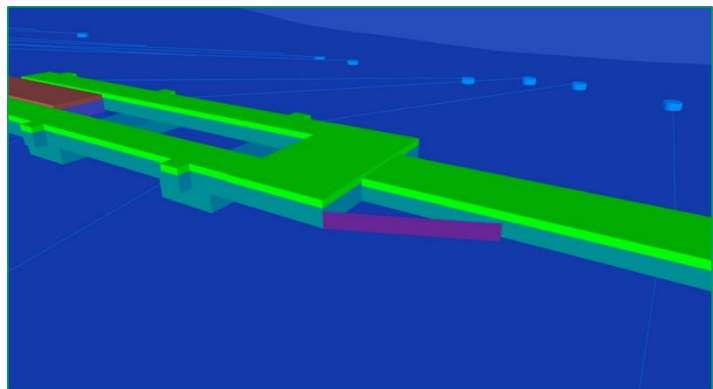


Figure 31. Conceptual full bridge depth corner fillet structure. Image courtesy of R2 Resource Consultants.

where they will reduce or restrict fish access and guide fish around these corner areas. Fillets will be either full bridge depth (15 ft) or half bridge depth (8 ft) and will be constructed of high density polyethylene (HDPE) pipe, synthetic netting, or fabric that is weighted with a continuous steel chain at the bottom. An HDPE plate will be welded to the top of the pipe to deter pinnipeds from hauling out onto the structure. The attachment to the bridge structure will include an elastic-type connection to absorb energy and limit forces on the fillet and the bridge during turbulent water conditions. The assembly is anticipated to be similar to fish guidance systems and debris booms that have been shown to be effective at several hydroelectric projects in the Pacific Northwest. The design of the fillet structures requires close coordination with WSDOT engineers to ensure suitable design load criteria, model fillet performance under varying conditions, and develop a system for fastening the structure to the bridge.

Eddy Reduction Structures at Corners

Eddy reduction structures at pontoon corners (Figure 32) will eliminate or reduce the size of the eddies described above to reduce predation in corners and expedite fish passage by creating more laminar flow around corners. A half-round or bull-nose eddy reduction structure will be constructed out of flexible HDPE pipe and plates attached to the corner of the bridge pontoon and extending 15 ft deep (full bridge depth). Eddy reduction structures will be designed for maximum benefit at peak flood and ebb tides. The assembly will be designed to be neutrally buoyant when deployed, and will require close coordination with WSDOT engineers throughout design, construction, and deployment of the structure.

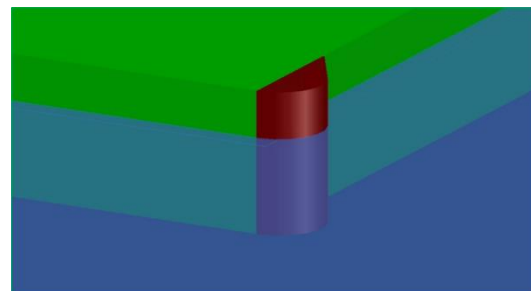


Figure 32. Conceptual full bridge depth eddy reduction structure. Image courtesy of R2 Resource Consultants.

Open Bridge Span More for Fish Passage

During the Phase 1 assessment, approximately a third of the tagged juvenile steelhead that survived bridge passage were detected in proximity to the bridge's center span during their outmigration, spending an average of 12 to 30 minutes in the vicinity. Tagged steelhead were consistently closest to the bridge infrastructure on ebb tides, and most steelhead passage occurred on ebb tides.

Opening the bridge's center draw span during ebb tides is a relatively low-risk alternative to expedite fish passage and is a simple way to gain information on potential



Figure 33. Vessels passing through the open Hood Canal Bridge drawspan. Image courtesy WSDOT.

bridge design solutions currently ranked in Category 2: would additional fixed openings along the bridge structure increase fish passage? While existing Phase 1 data does not provide clarity on the optimum duration of bridge openings, the Assessment Team recommends testing openings of one hour during ebb tides, and prioritizing the strongest ebb tides. No further design work is needed to implement this solution, as the current bridge design readily allows openings (Figure 33). However, longer bridge opening durations would need approval from a number of relevant actors and an intensive public awareness and outreach campaign will be necessary to mitigate disruptions in traffic.

Lighting at Bridge

Light levels at night around certain portions of the bridge structure are within the range expected to impact juvenile salmon behavior and migration. Additionally, anecdotal evidence suggests an association between the zooplankton aggregations and juvenile salmon behavior at certain areas of the bridge. The Hood Canal Bridge has more overhead lighting than other floating bridges because there is no separated bicycle path and interspersed bicycle and car/truck traffic requires more lighting for safety. Currently, luminaries are placed at 120 ft intervals along the bridge's lift deck and double luminaries light the pontoon and work decks of the bridge (Figure 34). Lights are high pressure 150-watt sodium bulbs producing 13,000-16,000 lumens. Luminaries could be modified to produce more lighting on the bridge deck while reducing the amount of light radiated into the water, or adapted to minimize blue-rich lighting and use "warm" color temperature or filtered light sources, while still maintaining the safety standards required of mixed-vehicle bridge decks. This solution has more uncertainties than the other Category 1 solutions; however, the growing body of literature regarding artificial light impacts on salmon passage and predation dynamics and precedent from other bridges in the region raise the importance of continued consideration of lighting options at the Hood Canal Bridge. Therefore, the Assessment Team recommended investigating the feasibility of lighting changes during phase 2, as this may be considered "best practice" to reduce impacts on salmonids.

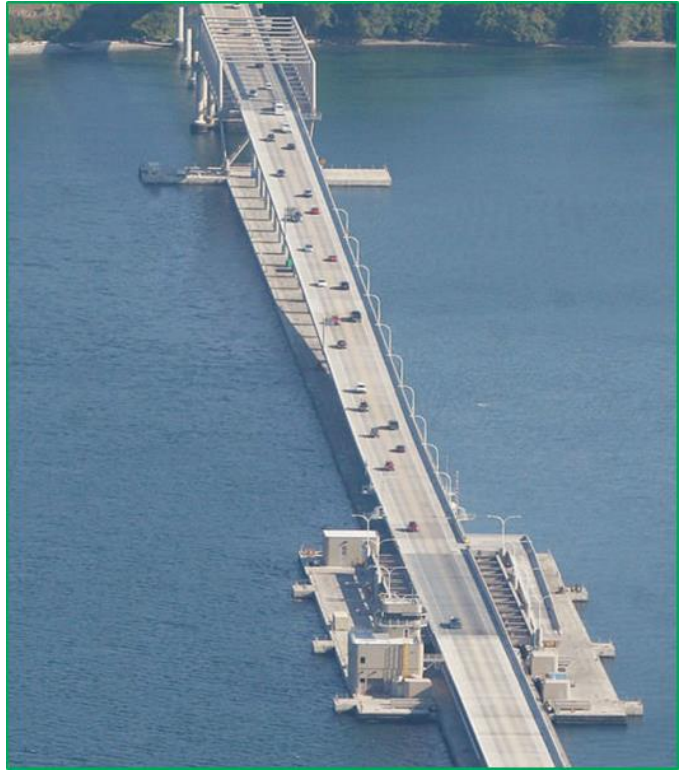


Figure 34. Light luminaries on the east half of the Hood Canal Bridge. Image courtesy WSDOT.

List of Appendices

- A. [Moore & Berejikian 2019 Acoustic telemetry investigation of altered migration behavior and mortality of steelhead smolts at the Hood Canal Bridge, Puget Sound WA. Unpublished methods and results.](#)
- B. [Daubenberger & Bishop 2019 Components of the Hood Canal Bridge Ecosystem Impact Assessment addressed by the Port Gamble S’Klallam Tribe: Split-beam acoustic surveys, water quality and zooplankton, predator surveys, visual acoustic surveys, and gopro and biota surveys. PGST technical briefs.](#)
- C. [Stocking & Pearson 2019 Evaluating the potential influence of the Hood Canal Bridge on piscivorous bird and mammal density. WDFW technical report.](#)
- D. [Deng et al. 2018 Hood Canal Bridge noise impact assessment: phase 1 findings. PNNL technical memorandum.](#)
- E. [Khangaonkar et al. 2018 Hydrodynamic zone of influence due to a floating structure in a fjordal estuary—Hood Canal Bridge Impact Assessment. Journal of Marine Science and Engineering, 6:119. doi:10.3390/jmse6040119](#)
- F. [Khangaonkar & Nugraha 2019 Hood Canal Bridge impact on basin-wide water quality – initial analysis. PNNL technical report.](#)
- G. [Hood Canal Bridge Impact Assessment Matrix](#)
- H. [Assessment Team and Management Committee Ranking Exercise: Phase 2 Solutions](#)
- I. [R2 Resource Consultants: Phase 2 Scoping and Recommendations](#)

Appendix A. Moore & Berejikian 2019

Acoustic telemetry investigation of altered migration behavior and mortality of steelhead smolts at the Hood Canal Bridge, Puget Sound WA

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Introduction

Threatened steelhead (*Oncorhynchus mykiss*), endangered summer chum salmon (*O. keta*), Chinook salmon (*O. tshawytscha*), and coho salmon (*O. kisutch*) originating in Hood Canal rivers must migrate past the Hood Canal Bridge (HCB) to complete their life cycle in the Pacific Ocean. However, the HCB floats on continuous concrete pontoons that extend 4.6 meters beneath the surface and occupy 90% of the width of Hood Canal. Despite openings (i.e., drawpans) that flank the east and west shoreline and comprise the remaining 10% of the canal width, migration delays at the bridge contribute to increased mortality of steelhead smolts attempting passage (Moore et al. 2013). The submerged structure also blocks brackish water outflow and disrupts natural currents, altering local salinity and temperature profiles (Khangaonkar and Wang 2013) that likely impact the movement of other salmonid species moving out of the basin. To understand the impact of the HCB on listed salmonid species' productivity, and to protect the significant investment made on salmonid habitat restoration in Hood Canal rivers, we used acoustic telemetry to conduct an intensive assessment of the HCB impact on juvenile salmon and steelhead outmigrants. Telemetry arrays set up during previous Hood Canal studies (2006-2010) were deployed to detect the presence of individual steelhead smolts at the Hood Canal Bridge, but lacked the precision to estimate exact locations of smolts encountering the bridge. The current study deployed an extensive acoustic telemetry array on either side of the HCB and along the steelhead migration route, providing the precise fish location data to (1) estimate the impact of the HCB on survival, (2) identify physical and biological factors contributing to migration delay and low survival, (3) map spatial patterns of movement and mortality, and (4) isolate potential predator species based on the behavior of transmitters retained at the HCB.

Methods

Fish Tagging

Wild steelhead smolts were collected from a rotary screw trap in the South Fork Skokomish River (river kilometer (rkm) 13.5) and a weir trap in Big Beef Creek (rkm 0.1) during April and May of 2017 and 2018 (Figure A1). Captured smolts were held in flow-through circular tanks for 1-48 (typically < 24) hours prior to tagging. Steelhead smolts were surgically implanted with one of five types of Vemco 69 kHz transmitters: (1) V8-4x (8 mm diameter x 20.5 mm length), (2) V9P-6L (9 mm x 31mm, 4.9 g, equipped with pressure sensor), (3) V7P-4H (7 mm x 24 mm, 2.0 g, equipped with pressure sensor), (4) V7T-4H (7 mm x 34 mm, 2.0 g, equipped with temperature sensor), or (5) 'delay' V8-4x (8 mm diameter x 20.5 mm length, 2.0 g in air), (<https://www.vemco.com/products/v7-to-v16-69khz/>, Table A1). All transmitters

were programmed to ping continuously at random intervals between 30 and 60 seconds. Delay V8 tags were programmed to be off for the first 8 days (time it took 75% of smolts to travel to the Hood Canal Bridge in previous telemetry studies) after release before turning on again. Recent studies have demonstrated that pinnipeds are capable of hearing the sound emitted by a 69 kHz transmitter (Cunningham et al. 2014), so delay tags were deployed to test the null hypothesis that the survival rate of tagged steelhead emitting a signal at 69kHz did not differ from the survival rate of steelhead with silent transmitters. Vemco V7 and V9 pressure sensors recorded the depth (maximum depth = 38 m but sensor continued to record max depth if deeper), and temperature sensors record the ambient temperature (range = -5 – 35 °C) of the tagged animal when within range of a hydrophone. Tagged steelhead were held for 20-30 hours after surgery then released at the location of capture.

Receiver Deployment

A network of Vemco receivers was deployed at various locations along the steelhead outmigration route to record the unique signal of each tagged smolt as it migrated from river mouths (RM) to the Pacific Ocean (Figure 1). Receiver arrays were deployed to estimate survival and provide fine-scale behavior patterns within approximately 250 meters on either side of the Hood Canal Bridge (HCB). Two VR2W receivers were installed at the river mouths (RM) of the Skokomish River and Big Beef Creek to detect tagged smolts entering the marine waters of Hood Canal. A Vemco Positioning System (VPS) comprised of 24 VR2AR and 3 VR2W hydrophones (69 kHz acoustic receivers capable of decoding the signal from Vemco acoustic transmitters <https://www.vemco.com/products/>) in 2017 (March 5 – August 1), and 28 VR2AR and 14 VR2W hydrophones in (March 6 – September 13) 2018, was configured and deployed to provide fine-scale spatial information on tagged steelhead at the HCB (Figure 1). The VPS system uses an array of receivers equipped with co-located transmitters to communicate the instrument location to other system receivers. Receivers were deployed in close proximity to each other to facilitate detection of a single transmission by multiple receivers, which enabled triangulation of each transmitter as it moved through the array. Stationary reference transmitters (5 transmitters in 2017 and 4 transmitters in 2018) were deployed within the system to test the accuracy and precision of the VPS system each year. Four additional VR2AR receivers were deployed approximately 600 meters apart at Twin Spits (TS), 7 kilometers north of the HCB, to determine whether smolts migrated successfully past the HCB. Twelve Vemco VR3 receivers spanned Admiralty Inlet (ADM), and a final line of 29 Vemco VR3 and VR4 receivers (maintained by the Ocean Tracking Network, <https://oceantrackingnetwork.org/>) span the Strait of Juan de Fuca at Pillar Point (JDF; Figure 1).

Data Processing

All receiver files were downloaded from recovered receivers or via surface modem (VR3s and VR4s) and compiled into a database. Raw data from single node receivers were used for some analyses requiring only presence/absence information, while files from VPS array receivers were sent to Vemco to generate precise transmitter positions.

Vemco processed VPS receiver detection data using hyperbolic positioning techniques (Smith 2013). Briefly, hyperbolic positioning measures differences in transmission detection times between pairs of time-synchronized receivers, then converts the time differences to distance values using the signal propagation speed, allowing for triangulation of a transmitter position. VPS analysis returned the coordinates and date/time of each tagged animal as it moved through the array, coordinates and date/time of the reference transmitters throughout the length of each deployment, as well as an

estimate of accuracy for each position that is unique to each VPS array. To calculate error, the VPS analysis software uses the known positions of the reference transmitters to measure the distance between the triangulated position and the true position (HPEm), then calculates a second error estimate (HPE) that incorporates variation based on receiver array geometry and effects of depth, temperature, and salinity on the speed of signal transmission. However, the true location is only known for reference transmitters and not for animal transmitters, so the relationship between HPEm and HPE can only be examined for reference transmitters then subsequently applied to animal positions. For both VPS arrays separately, we created bins for all HPE values and plotted them against median HPEm values. Where there was a steep increase in median HPEm we defined a threshold (same for both years), and deleted animal detections with HPE values larger than that threshold. After applying this filter, 96.2% (2017) and 87.6% (2018) of the animal positions were retained. Median HPEm values for identically filtered reference transmitter data were 4.4 m in 2017 and 5.0 m in 2018. These accuracy estimates can be applied to animal position data because HPE was calculated in the same way for both reference and animal transmitters. Processed data from all tagged animals were plotted for further analysis using ArcGIS 10.5.1.

Data Analysis

Survival estimation

Segment-specific survival of tagged steelhead smolts was estimated using separate Cormack-Jolly-Seber (CJS) mark-recapture models for 2017 and 2018 detection data (Cormack 1964, Jolly 1965, Seber 1965). The R (R Core Team 2019) package 'RMark' (Laake 2013) was used to construct and test models to jointly estimate both survival (ϕ) and detection probability (p) in concert with the program Mark (White and Burnham 1999). Presence or absence of all transmitters (except not V8 delay transmitters) at each receiver array were compiled to create encounter histories. Models were structured to estimate ϕ from release (REL) to river mouth (RM; ϕ_{REL-RM}), RM to the Hood Canal Bridge (HCB; ϕ_{RM-HCB}), HCB to Twin Spits (TS; ϕ_{HCB-TS}), TS to Admiralty Inlet (ADM; ϕ_{TS-ADM}), and ADM to the Strait of Juan de Fuca (JDF; $\phi_{ADM-JDF}$) in 2017. In 2018, our transmitters were not compatible with the ADM receiver code maps, so we combined ϕ_{TS-ADM} and $\phi_{ADM-JDF}$ to estimate ϕ_{TS-JDF} (Figure A1).

The survival probabilities from these models were compared between length-varying migration segments by distance-based Instantaneous mortality rates:

$$(-\ln \phi_s)/d_s$$

Where ϕ_s is the model-derived survival probability of migration segment s , and d is the distance in km between the initial and final detection at segment s .

We took a two-phase approach to modelling ϕ and p , using Akaike's Information Criteria for finite sample sizes (AICc) to identify the best models in each phase. Assuming separate parameters for all ϕ segments and all receiver array-specific p , the first phase compared a simple segment-varying model (ϕ (segment), p (array)) to models that incorporated additional effects of tag type (V8, V9P, V7P or V7T) on p and differences in ϕ_{REL-RM} and ϕ_{RM-HCB} by population since longer distances were covered by Skokomish smolts during these first two migration segments. Since we were primarily interested in the effect of the HCB on survival, the second round of model comparisons took the model with the lowest

AICc from the first phase and compared models with additional effects on $\phi_{\text{HCB-TS}}$. Covariates tested individually in the second phase models included smolt fork length, tag type, date of first detection at HCB (hereafter 'approach week' - binned by week and modeled as both factor and integer), HCB approach location (determined by the receiver location of the first detection, modeled as both 2-factor (side or middle) and 9-factor (250 m increments across the bridge span)), tidal stage (ebb or flow) at time of first HCB bridge detection, predicted current velocity (https://tidesandcurrents.noaa.gov/noaacurrents/Predictions?id=PUG1603_20) at time of first HCB detection, and time of day of HCB first detection (day or night based on time of sunset and sunrise).

Goodness-of-fit was assessed by computing Fletcher's c-hat (Fletcher 2012). Estimated C-hat was found to be 1.2 for the null 2017 mark-recapture model, so model comparison tables were adjusted accordingly. Models using 2018 data showed no evidence of overdispersion (c-hat ≈ 1.00), so no adjustments were made.

Survival of delay and continuous transmitters was compared by computing the proportion of each tag type found stationary (see 'Stationary Transmitters' below), as well as the proportions detected at the three final arrays along the migration route (TS, ADM, and JDF). Only detections of continuous transmitters recorded after 8 days from tagging were included in the analysis, which provided an identical and unbiased assessment of both tag types. Two-sample tests for equality of proportions, with a continuity correction, were used to determine the probability of equal proportions of delay and continuous tags detected at TS, ADM, and JDF arrays, as well as of those tags found to be stationary.

Travel/residence Times

Travel times were calculated by subtracting the date and time of a transmitter's last detection at the first receiver array along the migration route from the date and time of last detection at the subsequent receiver array. Travel distances were measured as the minimum straight line distance from the center of one receiver array to the next. Time spent at the HCB (HCB time) was calculated as the time between the first and last detection at any HCB array receiver. To calculate continuous HCB time, we subtracted all time greater than 24 hours during which a transmitter was not heard on any receivers. Travel time for the entire marine migration (RM-JDF) was calculated by summing average travel times for each migration segment (RM-HCB + HCB-HCB + HCB-TS + TS-ADM + ADM-JDF).

Stationary Transmitters

Mobile tracking at stations surrounding the HCB was performed using a Vemco VR100 and 69kHz omnidirectional hydrophone suspended approximately 3 m under the surface of the water. A set of 261 stations was designed to monitor: (1) the area immediately adjacent to the HCB, (2) areas on the migration route yet removed from the HCB, and (3) areas of predator aggregation (Figure A1). After the conclusion of the typical smolt migration period, we listened for 4 minutes at each station in both 2017 and 2018, recording any decoded transmitters during that time. Transmitters classified as stationary during mobile tracking had to be relocated on more than one occasion to ensure it had not moved, and never heard on any receivers further along the migratory route. A stationary tag was considered to be associated with the HCB if it was located at a tracking station within 3 km of the bridge structure.

To quantitatively identify stationary (or consumed) transmitters at the HCB, we fit a bivariate normal mixed model to (square-root transformed) continuous HCB time statistics for each tag detected at the

HCB to distinguish between transmitters in live steelhead and transmitters continually pinging within range of HCB receivers. The R package 'mixtools' (Benaglia et al, 2019) was used to fit the model and estimate the parameters of the two distributions (e.g., Romine et al 2013; Figure 2). Long HCB time (component 2) was indicative of a dead smolt, either consumed and detected while in a predator digestive tract or stationary. Short HCB time (component 1) indicated a live smolt, but may have included smolts (transmitters) consumed by a predator and subsequently deposited on land or at an unmonitored marine location. Using the distribution around longer continuous HCB time, we quantified the probability that each transmitter detected at the HCB behaved in a manner consistent with being consumed. Tags were classified as consumed or stationary if the probability of belonging to component 2 exceeded 0.95. Many of the transmitters identified as dead using these quantitative methods were also classified as stationary using mobile tracking methods. Data from the two independent methods both provided additional confirmation and compensated for imperfect detection ability of the alternate method.

Locations of stationary tags were resolved when more than 1000 detections were recorded repeatedly in the same place without subsequent detection elsewhere. We used the point of highest density of the spatial distribution to pinpoint the location of the stationary transmitter. When the transmitter was located using mobile tracking only, we used the location of the station with the loudest (highest dB) detections.

Density

Smolts were classified as survivors if they were detected at the Twin Spits receiver array ($p_{2017} = 0.979$, $p_{2018} = 0.938$), or at any other array further along the migration route, and were classified as non-survivors, or 'mortalities', if they were not detected after the HCB. Density plots for all survivors and all mortalities were executed with the Point Density tool in ArcMap using VPS positions (63 survivors and 68 mortalities in 2017, 86 survivors and 83 mortalities in 2018). The density tool divided the number of detections around each raster cell by the specified surrounding area (circle with radius = 50m) then plotted the values to create a density surface. To avoid pseudoreplication, position data were inversely weighted by number of detections per transmitter, so that the output density value reflected the number of fish (or predators), rather than the number of detections, per km². Stationary transmitter detections were removed from the datasets prior to density calculation.

HCB Crossing

The location and mode (around east drawspan, around west drawspan, or under pontoons) of HCB crossing was described for each surviving smolt if both a VPS location on the south side and on the north side of the HCB were observed within 20 minutes, though the time difference between locations was typically much shorter (median₂₀₁₇ = 2.5 min, median₂₀₁₈ = 3.3 min). The location of crossing was the point at which the line between south and north positions crossed the midline of the HCB. The approximate time of crossing was determined by dividing the difference between the time of south position and time of north position by two, then adding the quotient to the time of south detection. We then paired the time of crossing with NOAA current velocity data and light level (day or night based on sunrise and sunset) to investigate factors that may affect crossing success. If the crossing location was located within the open drawspan sections, we categorized the crossing strategy as 'around', and if the crossing location occurred along the length of the HCB pontoons, we assumed the smolt navigated

‘under’. To identify any smolt preference for certain velocities, current velocity at each time of crossing was compared to mean daily current velocity using a paired t-test.

Sensor Transmitters

Recorded depths from 31 V9P (2017) and 31 V7P (2018) depth sensors, and temperature profiles from 34 V7T (2018) sensors detected at the HCB were used to quantify the behavior of migrating steelhead smolts and identify predation events. For smolts with depth transmitters, we created a depth profile for each pressure sensor, then quantified the number of dives per hour, dive depth range, and max dive depth. We only quantified behavior during time segments where sequential detections were less than 10 minutes apart. A dive was defined as an increase in depth from the surface (depth < 2) to 3 m or more with a return to the surface. We identified abrupt changes in diving behavior that took place only in mortalities. Depth profiles of surviving transmitters exhibited nearly exclusive surface-oriented behavior, though sometimes with one or two short, shallow (<16 m) dives (that often corresponded with HCB crossing times), while mortality profiles featured short time periods of surface residence (while the transmitter was presumably still in a smolt) followed by frequent deep dives. For the first dive after which there were no periods of continuous surface residence (), the time of detection after a transmitter transitioned from continuous surface depth records (less than or equal to 2m) to depths greater than or equal to 3m was considered the time of a predation event. For temperature transmitters, we defined the time of predation as the first detection associated with a temperature increase that eventually rose to 35 °C (maximum sensor value), with the assumption that a temperature increase of this magnitude meant the smolt had been eaten by a warm-blooded predator. We defined the location of predation as the VPS position triangulated closest in time (21 min or less, median time = 4.7 min) to the time of predation. Spatial error around the predation location was calculated by multiplying the average speed of the tag movement within 1 hour after the putative predation event by the time between the behavioral shift or temperature increase and the closest VPS position.

Results

Survival

Steelhead smolts survival probabilities between the Hood Canal Bridge and Twin Spits were $49.4 \pm 4.6\%$ SE in 2017 and $56.5 \pm 4.4\%$ in 2018. Distance-based instantaneous mortality rates were markedly higher between the HCB and TS (2017 = 10.1%/km; 2018 = 8.2%/km) relative to migration segments before and after smolts encountered the HCB in 2017 (RM-HCB_{BBC} = 1.3%/km, RM-HCB_{Skokomish} = 0.4%/km, TS-ADM = 1.2%/km, ADM-JDF = 0.7%/km) and in 2018 (RM-HCB_{BBC} = 0.6%/km, RM-HCB_{Skokomish} = 0.9%/km, TS-JDF = 1.0%/km; Figure 3). Survival probability in freshwater was high during both years (2017 = $93.4 \pm 2.7\%$, 2018 = $98.1 \pm 1.2\%$ (BBC) and $92.3 \pm 2.7\%$ (Skokomish)).

In 2017, mark-recapture model comparison suggested no differences in ϕ_{REL-RM} or ϕ_{RM-HCB} by population ($\Delta AICc = 0.56$ and $\Delta AICc = 0.68$, respectively). The best model from phase 1 included an effect of tag type and a difference in detection probability p at each river mouth (Table A2). The only models in phase 2 with AICc less than AICc values of the null model included approach week (Table A2). The best model estimated a linear effect of approach week on ϕ_{HCB-TS} ($\beta = 0.35$; Figure A4a), while the model with the

second lowest AICc estimated separate $\phi_{\text{HCB-TS}}$ for each approach week ($\Delta\text{AICc} = 5.48$). All ϕ and p values were derived from the best model.

In 2018, model comparison results indicated a difference in survival probabilities by population for both $\phi_{\text{RM-HCB}}$ and $\phi_{\text{REL-RM}}$, and no differences in p by array or by tag (Table A3). Phase 2 model results supported an additional effect of approach week, with separate $\phi_{\text{HCB-TS}}$ for each approach week (Figure A4b). An effect of body length ($\beta = -0.02$) and a linear effect of approach week ($\beta = 0.21$) were also supported by model comparison results (Table A3). All ϕ and p values were derived from the best model, except for $\phi_{\text{HCB-TS}}$ was derived from the second best model (Table A3) to obtain a single estimate rather than separate estimates by approach week.

Smolts tagged with delay transmitters and smolts tagged with continuous transmitters survived at similar rates from release to the TS array ($\chi^2 = 0.045$, $p = 0.832$), to the ADM array ($\chi^2 = 0.236$, $p = 0.901$), and to the JDF array ($\chi^2 = 0.00015$, $p = 0.990$). The time between tagging and detection at the HCB was less than 8 days for 39 of the 46 (85%) continuous-tagged smolts detected at the HCB, so the programmed delay (8 days) was sufficient to assume that a high proportion of delay tags were silent for the entire RM-HCB migration. The last detection at the HCB occurred less than 8 days after tagging for 24 of the 46 (52%) continuous-tagged smolts. Another indicator of no difference in mortality between the delay and continuous tag groups was the similar proportion of stationary tags (mortalities) found via mobile tracking after the migration window ($\chi^2 = 0.000$, $p = 0.990$).

Travel/HCB time

Survivors spent an average of 1.9 ($\pm$ SE 0.6) days in 2017 and 0.9 ($\pm$ SE 0.2) days in 2018 within range (~ 500 m on either side) of the HCB, while only taking an average of 0.2 ($\pm$ 0.02) and 0.3 ($\pm$ 0.03) days, respectively, to travel the subsequent 7 km migration segment from HCB-TS (Figure A5). Transmitters categorized as mortalities were detected for an average of 44.2 ($\pm$ 5.2) days in 2017 and 35.3 days in 2018 within range of the HCB. The entire marine migration from RM-JDF took Big Beef Creek smolts 17.1 days in 2017 and 12.6 days in 2018, while Skokomish smolts took 15.8 days in 2017 and 14.2 days in 2018 (Figure A5).

Stationary transmitters

In 2017, we detected 35 stationary transmitters via mobile tracking, 33 of which were within 3 km of the HCB. The 2 other stationary transmitters were detected in between the HCB and Twin Spits (5.5 and 6 km north of the HCB; Figure A6A). In 2018, we detected 19 stationary transmitters, all of which were located within 3 km of the HCB except for one transmitter found in south Port Gamble Bay (Figure A6B). Several stationary transmitters identified by mobile tracking were also determined to be stationary by the fixed array at the HCB (mixed model analysis). Using both methods, 49 (37%) of the smolts detected at the HCB were found stationary in 2017, and 47 (27%) were found stationary in 2018 (Table A4).

Stationary transmitter locations were concentrated near the HCB and less likely to be found at stations farther away from the structure. Locations were distributed along the entire length of the HCB, but a higher density was observed along the western portion, especially in 2018 (Figure A6). Three stationary transmitters were found each year in Port Gamble Bay, where harbor seal haulouts have been documented (Jeffries et al. 2003), in addition to transmitters deposited on the route from HCB to Port Gamble Bay (Figure A6).

Density

Patterns of smolt density near the HCB were similar for survivors in 2017 and 2018, with more frequent occurrence on the south side of the HCB, and high densities observed near the corners formed by the pontoons and center drawspans. Survivors were also more often located on the east side of the HCB compared to the west side, and were located in the open areas under the east and west approach spans that are not covered by submerged pontoons (Figure A7A and A7B).

Density patterns of mortalities were also similar among years, and showed some areas of high density similar to survivors, but differed in other ways. Similar to survivors, mortalities were concentrated along the south side of the HCB and also tended to spend time in corner areas, but were located near the center drawspan less frequently than survivors (Figure A7). Mortalities were more uniformly distributed across the length of the HCB than survivors (Figure A7), but this could be a result of many more VPS locations of mortalities (2017: 18,492 positions; 2018: 28,795 positions (excluding detections of transmitters that became stationary)) than survivors (2017: 3,272 positions, 2018: 3,173 positions).

Crossing Locations

Out of 41 crossing events documented in 2017, thirteen (32%) smolts crossed under the east flank, seven (17%) crossed under the west flank, and 21 (51%) were assumed to have crossed under the pontoons (Figure A8). Twenty-three (56%) of the 2017 crossings occurred during the day, while 18 (44%) occurred at night. In 2018, a higher percentage of smolts crossed under the HCB than in 2017, with 52 (77%) smolts crossing under, and only nine (13%) crossing the east and seven (10%) crossing through the west flank. Fifty-seven (84%) of the 2018 crossings took place during the day, while thirteen (16%) occurred during nighttime hours. Smolts that crossed under the HCB pontoons did not appear to have a preference for certain crossing locations, rather the locations were distributed somewhat evenly along the length of the HCB. Crossing location distribution was similar between years, except that eleven smolts crossed under the center drawspan in 2018, whereas only one smolt crossed at that location in 2017 (Figure A8). Crossing events were much more likely to occur during times of negative (ebbing) current velocity ($t = 17.091$, $df = 108$, $p < 0.001$; Figure A9).

Depth Sensor

Thirty-one smolts implanted with pressure-sensing transmitters were detected at the HCB in 2017. Thirteen of those survived to TS and 18 did not. All 13 survivors exhibited a strong surface orientation. Ninety-one percent of detections indicated migration in the top 1 m of the water column, and 95% in the top 3 m; (Table A5). All 13 survivors migrated past the TS array at average depths less than 1 m. In contrast, only 38% of the depth sensor detections from mortalities (stationary tags excluded) were recorded in the top meter (45% in the top 3 meters; Table A5). Six of the eleven survivors were initially recorded at the surface, then exhibited 1-3 short shallow dives per smolt ($\bar{x} = 0.4$ per hr), before return to shallow depths < 1 m (for example, Fig A10a; Table 6). The remaining 5 survivors remained exclusively within the top 2 meters while within range of the HCB array. Fifteen of the 18 non-surviving smolts approached the HCB at depths < 1 m, then subsequently exhibited frequent dives ($\bar{x} = 4.5$ per hr, Fig A10b; Table A6). Six of those 15 mortalities were subsequently detected stationary by the HCB array (for example, Fig A10c). Fifteen of 18 mortalities dove to 38 meters at least once (Table A6). A single mortality exhibited frequent diving behavior (7.5 dives/hr) to intermediate depths (max = 25 m), then was last detected at the surface. Time between first detection at the HCB and the predation event

averaged 16.7 hrs, with 5 of the 18 events occurring in less than one hour and all events in less than 2 days.

Depth sensor data for 19 survivors and 13 mortalities detected at the HCB in 2018 revealed behavioral patterns similar to those seen in 2017. Most detections of survivors (82%) occurred at depths in the top meter of the water column (87% in the top 3 meters; Table A5). Nearly all survivors (18 of 19) in 2018 migrated past the TS array in average water depths less than 1 m. At the HCB, mortalities were located in the top meter only 30% of the time (stationary tags excluded) in 2018 (28% in the top 3 meters; Table A5). Four of the 19 survivors remained at depths less than 2 m as they migrated past the HCB, while the remaining 15 surviving smolts exhibited short dives ($\bar{x}$ = 1.1 per hr, max depth = 24.8 m) as they passed the HCB (Fig A10d). Similar to 2017, most mortalities (11 of 13) approached the bridge near the surface (≤ 2 m) and subsequently exhibited frequent ($\bar{x}$ = 4.6 per hr) deep dives, with at least one dive greater than 35 m (Table A6). Six of these 11 frequent deep divers appeared stationary following active behavior. One of the 13 mortalities exhibited a dive profile indicating shallower dives ($\bar{x}$ = 3.8, max = 17 m) occurring markedly more frequently than the other 2018 mortalities (11.5 dives/hr), and did not become stationary. Most predation events (9 of 12) occurred in less than six hours ($\bar{x}$ = 1.6) from the time of initial detection at the HCB, while the remaining three events occurred within 36 to 243 hours. One final 2018 mortality did not display a pattern of predation, but remained nearly exclusively in the top 2 meters (one detection at 3.1 m), indicating that the assumed mortality event took place outside the HCB array.

Temperature tag results

Eleven of the 16 temperature sensors in 2018 non-surviving steelhead exhibited temperature profiles consistent with being consumed by a marine mammal or bird. These 11 transmitters were all initially detected on the HCB array with ambient temperatures (9-14 °C), then recorded for a period of time (1.5-81.5 hrs) at 35 °C before either exiting receiver range or abruptly returning to ambient temperature (Table A7). Six of these mortality sensors with elevated temperature were detected within range of Sisters Rock, a known harbor seal haulout 750 m south of the HCB, and 7 of the 11 warm sensors later became stationary (Table A7). The temperature increase occurred an average of 17.9 hours after arrival at the HCB (4 of 11 events occurred in < 1 hr). The temperature sensors in the remaining 5 mortalities showed no sign of abnormal temperature increase.

We were able to establish the predation location of 15 of 16 (2017) and 7 of 12 (2018) non-surviving depth-tagged smolts, and 10 of the 11 transmitters that exhibited temperature increase (the remaining mortalities did not have a VPS location within 20 minutes of the change in diving behavior/temperature). Predation locations in both study years tended to be closer to the HCB rather than out away from the bridge, and were somewhat spread out, with a slightly western bias, along the bridge length (Figure A11). There were several predation events (13 of 32) over both years that took place in close proximity to the corners formed by the cross-pontoons and drawspan with the main bridge pontoons, and one that appears to have occurred in the west pool (Figure A11A).

Table A1. Tagged smolts

Tag type	Number tagged	Average Length (mm) $\pm$ SE	Average Weight (g) $\pm$ SE
2017			
BBC V8	61	183 $\pm$ 2	57 $\pm$ 2
BBC V8 (delay)	49	185 $\pm$ 2	61 $\pm$ 3
BBC V9P	40	223 $\pm$ 4	107 $\pm$ 7
Skokomish V8	89	175 $\pm$ 1	50 $\pm$ 1
Skokomish V9P	9	209 $\pm$ 3	86 $\pm$ 3
TOTAL	248	188 $\pm$ 2	64 $\pm$ 2
2018			
BBC V8	92	175 $\pm$ 2	51 $\pm$ 3
BBC V7P	29	185 $\pm$ 5	61 $\pm$ 6
BBC V7T	28	185 $\pm$ 5	61 $\pm$ 5
Skokomish V8	58	166 $\pm$ 2	42 $\pm$ 1
Skokomish V7P	21	187 $\pm$ 6	56 $\pm$ 4
Skokomish V7T	22	181 $\pm$ 3	55 $\pm$ 2
TOTAL	250	177 $\pm$ 1	52 $\pm$ 1

Table A2. Comparison of 2017 CJS survival (ϕ) and detection probability (p) models

Phase 1 model	number of parameters	QAICc	Δ QAICc	weight
$\phi(\sim \text{segment})p(\sim \text{array} + \text{RMarray:pop})$	11	745.64	0.00	0.28
$\phi(\sim \text{segment} + \text{REL-RM:pop})p(\sim \text{array} + \text{RMarray:pop})$	13	746.19	0.56	0.21
$\phi(\sim \text{segment} + \text{RM-HCB:pop})p(\sim \text{array} + \text{RMarray:pop})$	13	746.31	0.68	0.20
$\phi(\sim \text{segment})p(\sim \text{array} + \text{RMarray:pop} + \text{tagtype})$	12	747.66	2.02	0.10
$\phi(\sim \text{segment} + \text{REL-RM:pop})p(\sim \text{array} + \text{RMarray:pop} + \text{tagtype})$	14	748.14	2.50	0.08
$\phi(\sim \text{segment} + \text{RM-HCB:pop})p(\sim \text{array} + \text{RMarray:pop} + \text{tagtype})$	14	748.36	2.73	0.07
$\phi(\sim \text{segment} + \text{REL-RM:pop} + \text{RM-HCB:pop})p(\sim \text{array} + \text{RMarray:pop})$	15	749.49	3.86	0.04
$\phi(\sim \text{segment} + \text{REL-RM:pop} + \text{RM-HCB:pop})p(\sim \text{array} + \text{RMarray:pop} + \text{tagtype})$	16	751.50	5.86	0.01
$\phi(\sim \text{segment} + \text{REL-RM:pop})p(\sim \text{array})$	11	795.83	50.19	0.00
$\phi(\sim \text{segment} + \text{REL-RM:pop} + \text{RM-HCB:pop})p(\sim \text{array})$	13	799.53	53.90	0.00
$\phi(\sim \text{segment})p(\sim \text{array})$	9	810.45	64.81	0.00
$\phi(\sim \text{segment} + \text{RM-HCB:pop})p(\sim \text{array})$	11	814.36	68.73	0.00
Phase 2 model				
$\phi(\sim \text{segment} + \text{HCB-TS:week.numeric})p(\sim \text{array} + \text{RMarray:pop})$	12	747.97	0.00	0.92
$\phi(\sim \text{segment} + \text{HCB-TS:week.factor})p(\sim \text{array} + \text{RMarray:pop})$	20	753.22	5.25	0.07
$\phi(\sim \text{segment})p(\sim \text{array} + \text{RMarray:pop})$	11	760.10	12.13	0.00
$\phi(\sim \text{segment} + \text{HCB-TS:length})p(\sim \text{array} + \text{RMarray:pop})$	12	760.42	12.45	0.00
$\phi(\sim \text{segment} + \text{tagtype})p(\sim \text{array} + \text{RMarray:pop})$	12	760.85	12.89	0.00
$\phi(\sim \text{segment} + \text{HCB-TS:side.middle})p(\sim \text{array} + \text{RMarray:pop})$	13	761.28	13.31	0.00
$\phi(\sim \text{segment} + \text{HCB-TS:velocity})p(\sim \text{array} + \text{RMarray:pop})$	12	762.18	14.21	0.00
$\phi(\sim \text{segment} + \text{HCB-TS:day.night})p(\sim \text{array} + \text{RMarray:pop})$	13	763.18	15.21	0.00
$\phi(\sim \text{segment} + \text{HCB-TS:tide})p(\sim \text{array} + \text{RMarray:pop})$	13	764.18	16.21	0.00
$\phi(\sim \text{segment} + \text{HCB-TS:pop})p(\sim \text{array} + \text{RMarray:pop})$	13	764.28	16.31	0.00

$\phi(\sim\text{segment} + \text{HCB-TS:location.250m})p(\sim\text{array} + \text{RMarray:pop})$	20	773.32	25.35	0.00
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Table A3. Comparison of 2018 CJS survival (ϕ) and detection probability (p) models

Phase 1 model	number of parameters	AICc	DeltaAICc	weight
$\phi(\sim \text{segment} + \text{REL-RM:pop} + \text{RM-HCB:pop})p(\sim \text{array})$	11	723.70	0.00	0.23
$\phi(\sim \text{segment} + \text{RM-HCB:pop})p(\sim \text{array} + \text{RMARRAY:pop})$	11	723.82	0.12	0.21
$\phi(\sim \text{segment} + \text{RM-HCB:pop})p(\sim \text{array})$	9	724.17	0.48	0.18
$\phi(\sim \text{segment} + \text{RM-HCB:pop})p(\sim \text{array} + \text{RMARRAY:pop} + \text{tagtype})$	12	725.85	2.15	0.08
$\phi(\sim \text{segment} + \text{REL-RM:pop} + \text{RM-HCB:pop})p(\sim \text{array} + \text{RMARRAY:pop} + \text{tagtype})$	14	725.94	2.24	0.07
$\phi(\sim \text{segment} + \text{REL-RM:pop})p(\sim \text{array})$	9	753.84	30.15	0.00
$\phi(\sim \text{segment})p(\sim \text{array})$	7	754.69	30.99	0.00
$\phi(\sim \text{segment} + \text{REL-RM:pop})p(\sim \text{array} + \text{RMARRAY:pop})$	11	756.06	32.36	0.00
$\phi(\sim \text{segment})p(\sim \text{array} + \text{RMARRAY:pop})$	9	756.13	32.44	0.00
$\phi(\sim \text{segment} + \text{REL-RM:pop})p(\sim \text{array} + \text{RMARRAY:pop} + \text{tagtype})$	12	756.38	32.68	0.00
$\phi(\sim \text{segment})p(\sim \text{array} + \text{RMARRAY:pop} + \text{tagtype})$	10	756.83	33.13	0.00
Phase 2 model				
$\phi(\sim \text{segment} + \text{REL-RM:pop} + \text{RM-HCB:pop} + \text{HCB-TS:week.factor})p(\sim \text{array})$	21	712.92	0.00	0.91
$\phi(\sim \text{segment} + \text{REL-RM:pop} + \text{RM-HCB:pop} + \text{HCB-TS:length})p(\sim \text{array})$	12	718.95	6.03	0.04
$\phi(\sim \text{segment} + \text{REL-RM:pop} + \text{RM-HCB:pop} + \text{HCB-TS:week.numeric})p(\sim \text{array})$	12	719.51	6.58	0.03
$\phi(\sim \text{segment} + \text{REL-RM:pop} + \text{RM-HCB:pop})p(\sim \text{array})$	11	723.70	10.77	0.00
$\phi(\sim \text{segment} + \text{REL-RM:pop} + \text{RM-HCB:pop} + \text{HCB-TS:velocity})p(\sim \text{array})$	12	723.78	10.86	0.00
$\phi(\sim \text{segment} + \text{REL-RM:pop} + \text{RM-HCB:pop} + \text{HCB-TS:pop})p(\sim \text{array})$	13	724.23	11.31	0.00

$\phi(\sim\text{segment} + \text{REL-RM:pop} + \text{RM-HCB:pop} + \text{tagtype})p(\sim\text{array})$	12	725.73	12.81	0.00
$\phi(\sim\text{segment} + \text{REL-RM:pop} + \text{RM-HCB:pop} + \text{HCB-TS:side.middle})p(\sim\text{array})$	13	727.23	14.31	0.00
$\phi(\sim\text{segment} + \text{REL-RM:pop} + \text{RM-HCB:pop} + \text{HCB-TS:tide})p(\sim\text{array})$	13	727.56	14.64	0.00
$\phi(\sim\text{segment} + \text{REL-RM:pop} + \text{RM-HCB:pop} + \text{HCB-TS:day.night})p(\sim\text{array})$	13	727.82	14.90	0.00
$\phi(\sim\text{segment} + \text{REL-RM:pop} + \text{RM-HCB:pop} + \text{HCB-TS:location.250m})p(\sim\text{array})$	20	736.38	23.46	0.00

Table A4. Stationary tags identified by mobile tracking and mixed model analysis

	2017	2018
Number of smolts detected at HCB	134	174
Number of stationary/consumed tags at HCB identified using mixed model	36	40
Additional stationary tags at HCB identified using mobile receiver	13	7
Total stationary (% of tagged smolts)	49 (36.6)	47 (27.0)

Table A5

Depth (m)	2017		2018	
	Number of survivor detections	Number of mortality detections (proportion of mortalities)	Number of survivor detections	Number of mortality detections (proportion of mortalities)
0 - 1	3806	8007 (0.68)	3198	7944 (0.71)
2	119	644 (0.84)	158	1253 (0.89)
3	47	861 (0.95)	38	842 (0.96)
4 – 10	189	7588 (0.96)	379	11322 (0.97)
11 – 16	37	935 (0.96)	63	2197 (0.97)
16 - 34	0	1556 (1.0)	50	2244 (0.98)
35 - 38	0	1740 (1.0)	0	663 (1.0)

Table A6. Depth sensor summary

Year and fate of tag	N	Hours of behavior sampled	Number of dives per hour (average $\pm$ SE)	Dive depth maximum	Number of tags recording >37 m depth
2017 survivors	13	40	0.4 $\pm$ 0.1	16.5	0
2017 mortalities	18	104	4.5 $\pm$ 0.6	38.0*	15
2018 survivors	19	40	1.1 $\pm$ 0.2	24.8	0
2018 mortalities	13	122	4.6 $\pm$ 0.2	38.0*	11

*sensor maximum

Table A7. Temperature sensor summary

Fate of tag	N	Temperature maximum (°C)	Number of tags recording > 35°C*	Number of tags detected on Sisters Rock receiver while 35°C	Number of tags that became stationary
Survivor	18	14	0	0	0
Nonsurvivor	16	35*	11	6	7

*sensor maximum

Figure A1

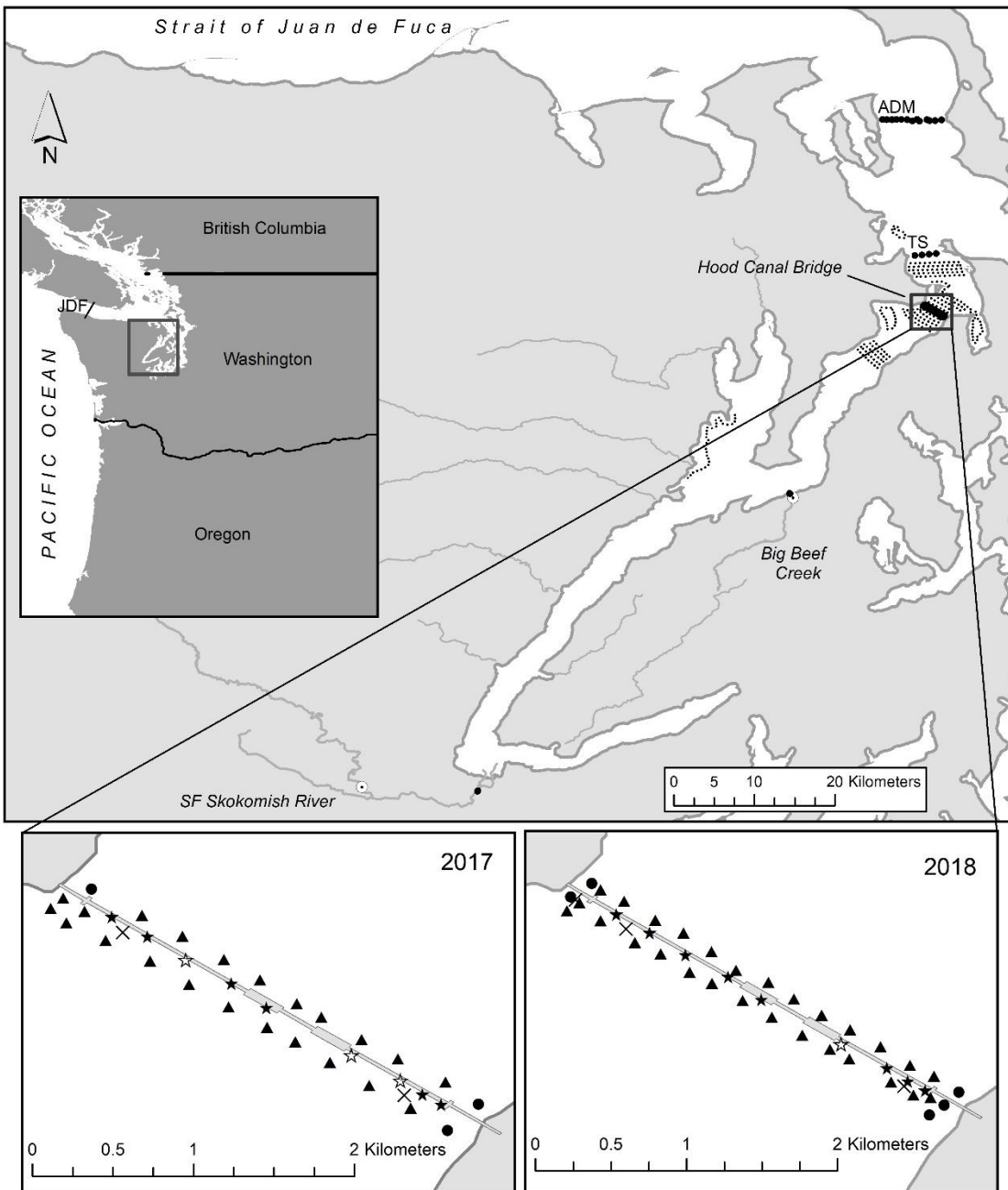
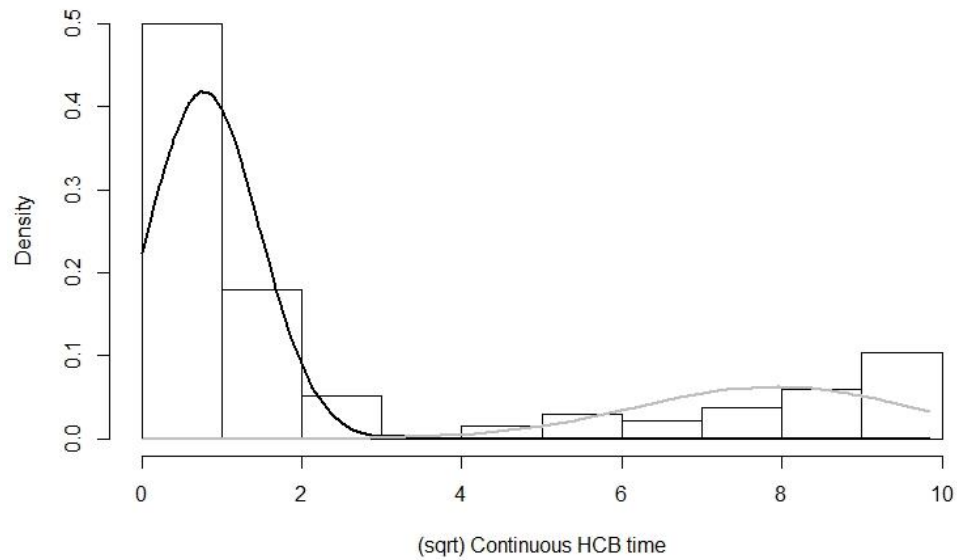


Figure A2

A



B

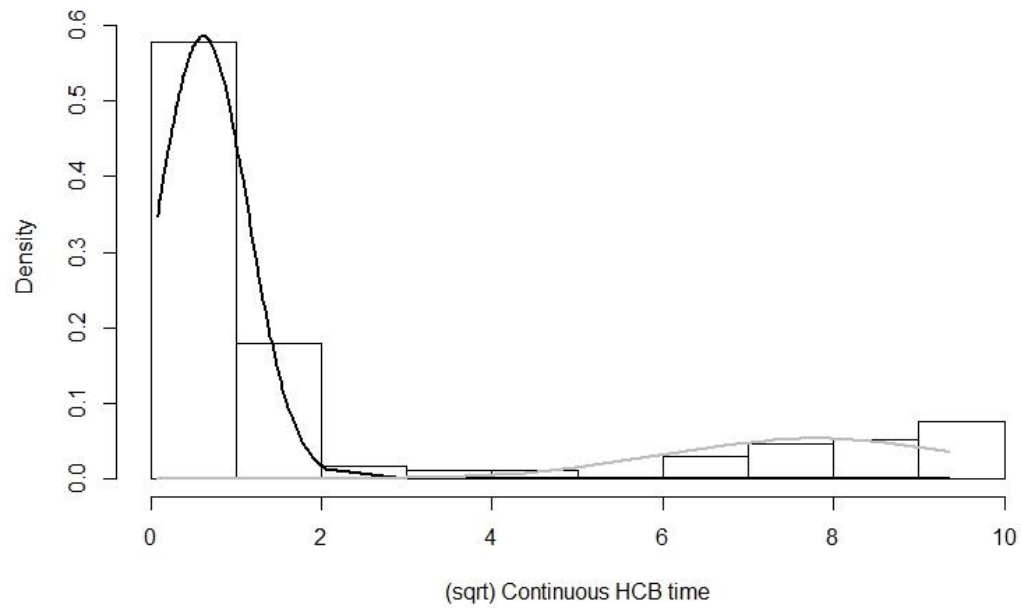


Figure A3

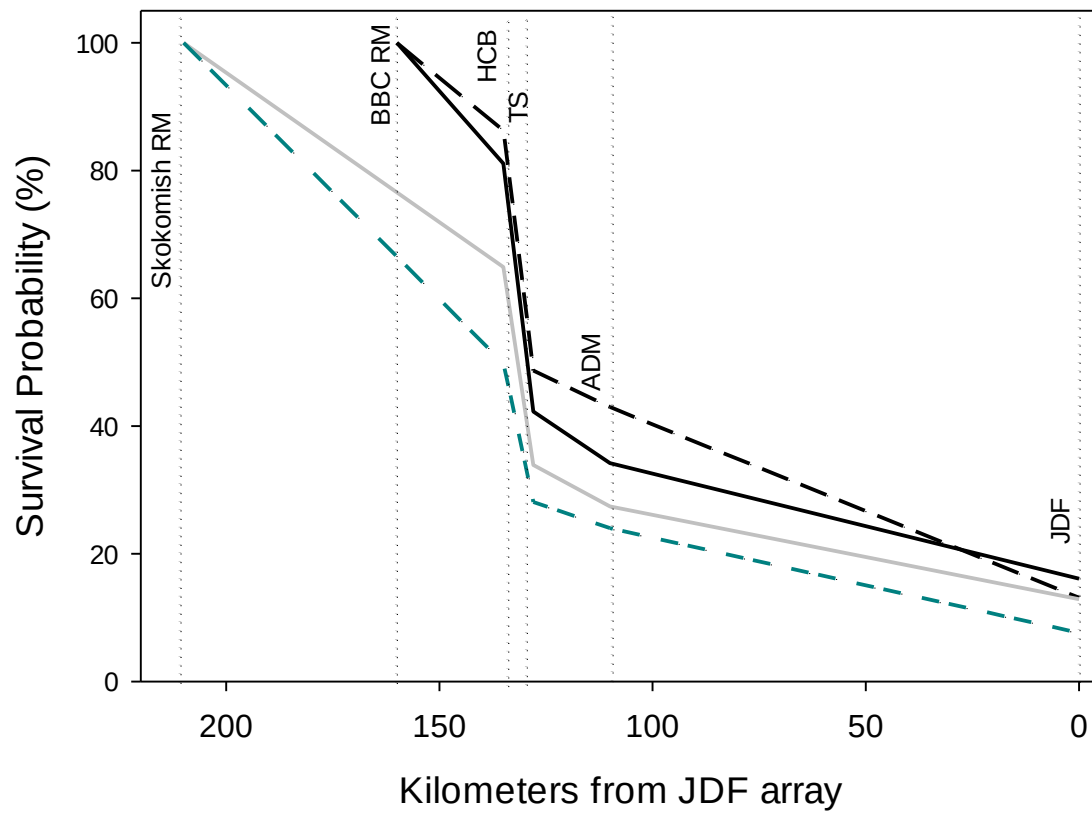
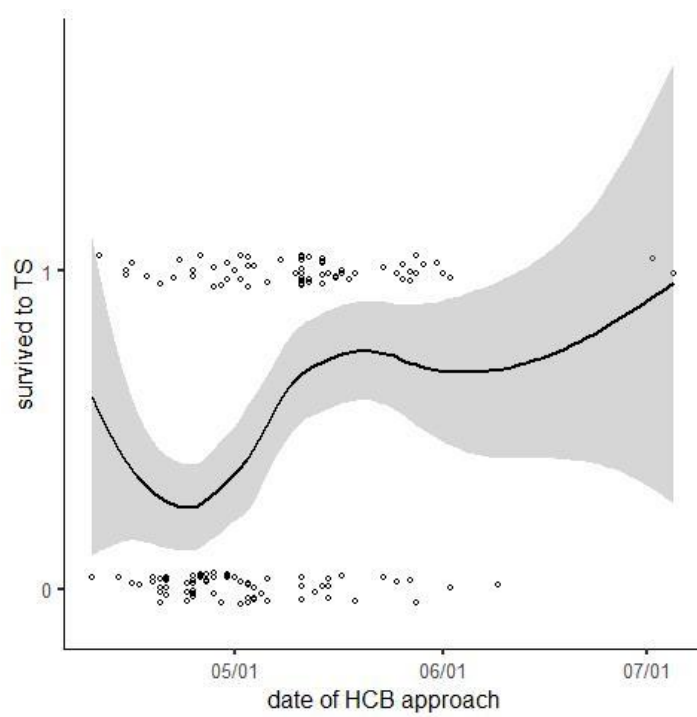


Figure A4

A



B

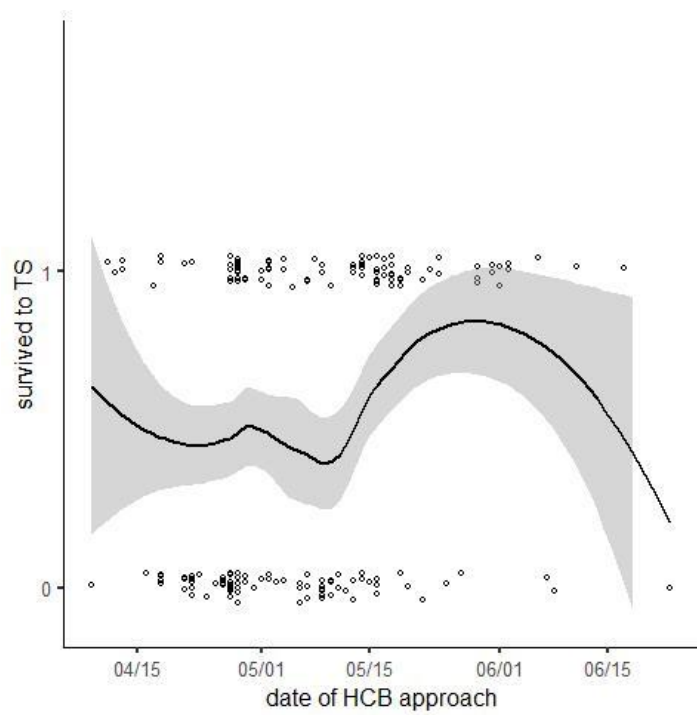


Figure A5

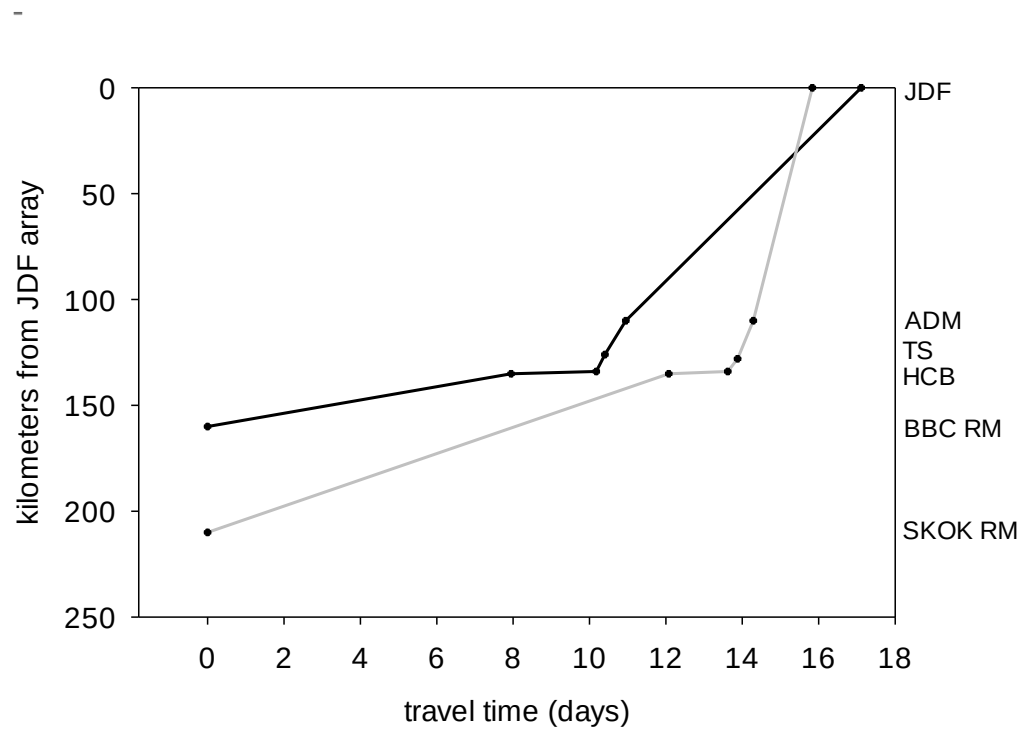
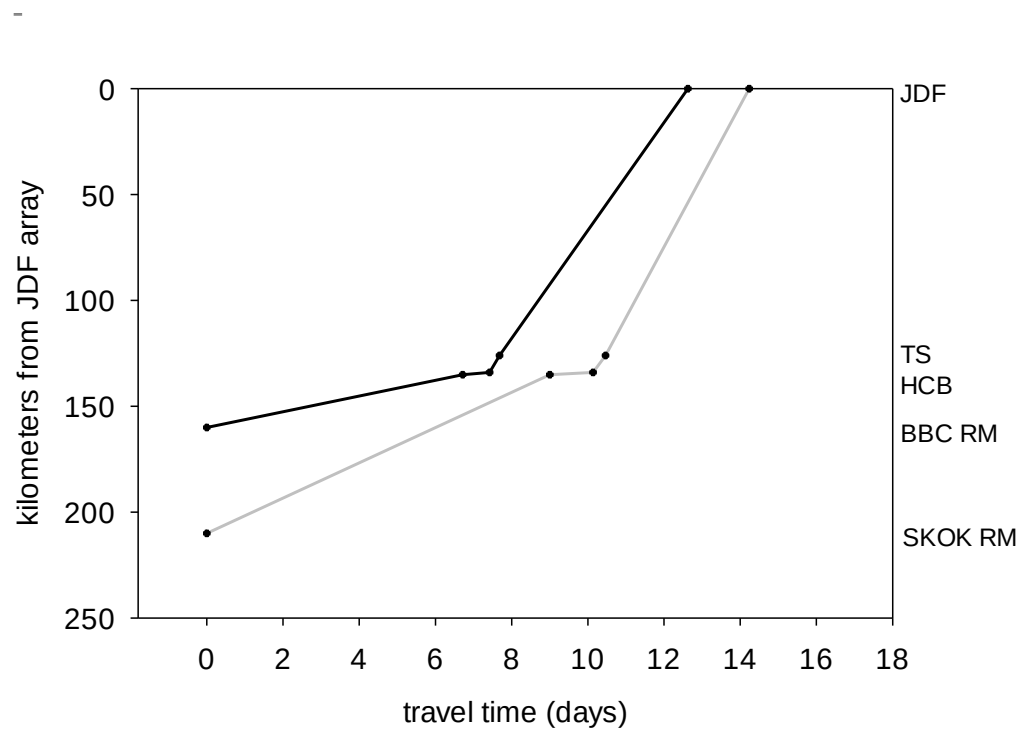
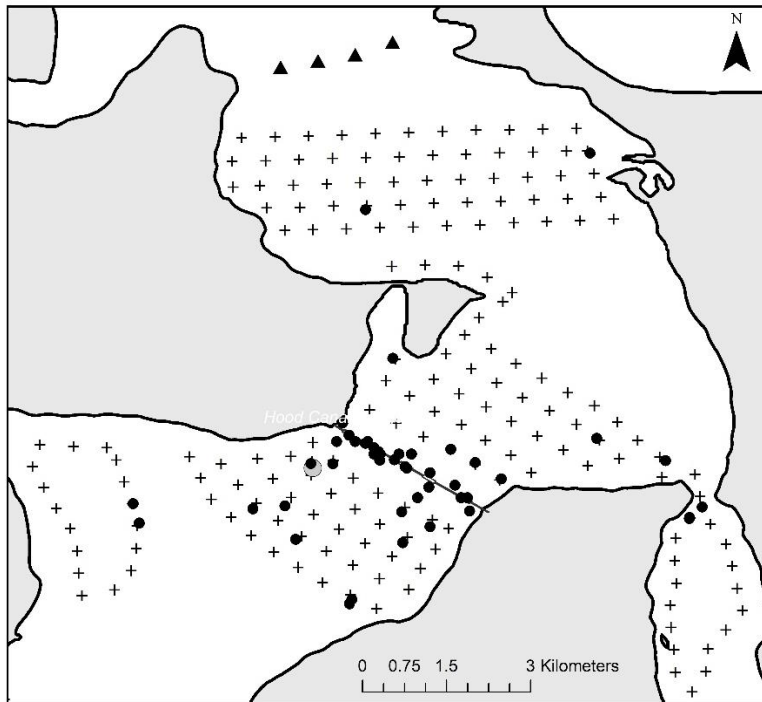
A**B**

Figure A6

A



B

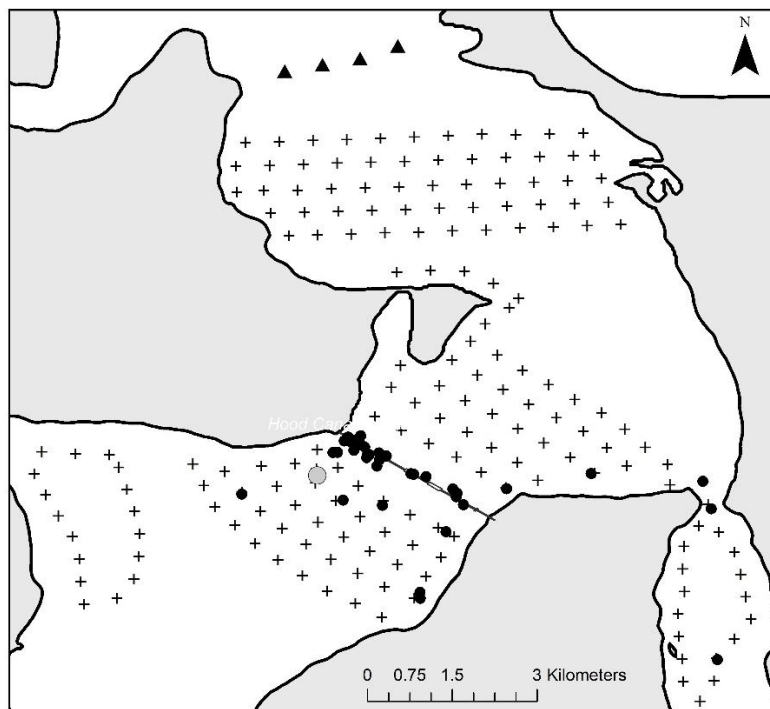
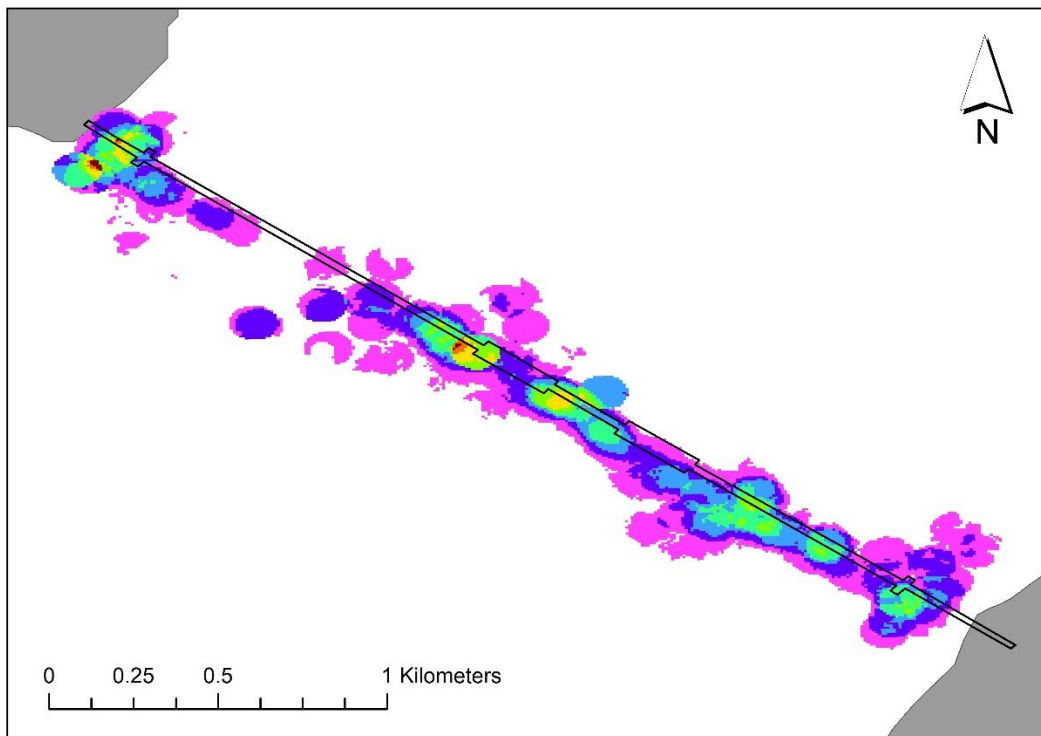
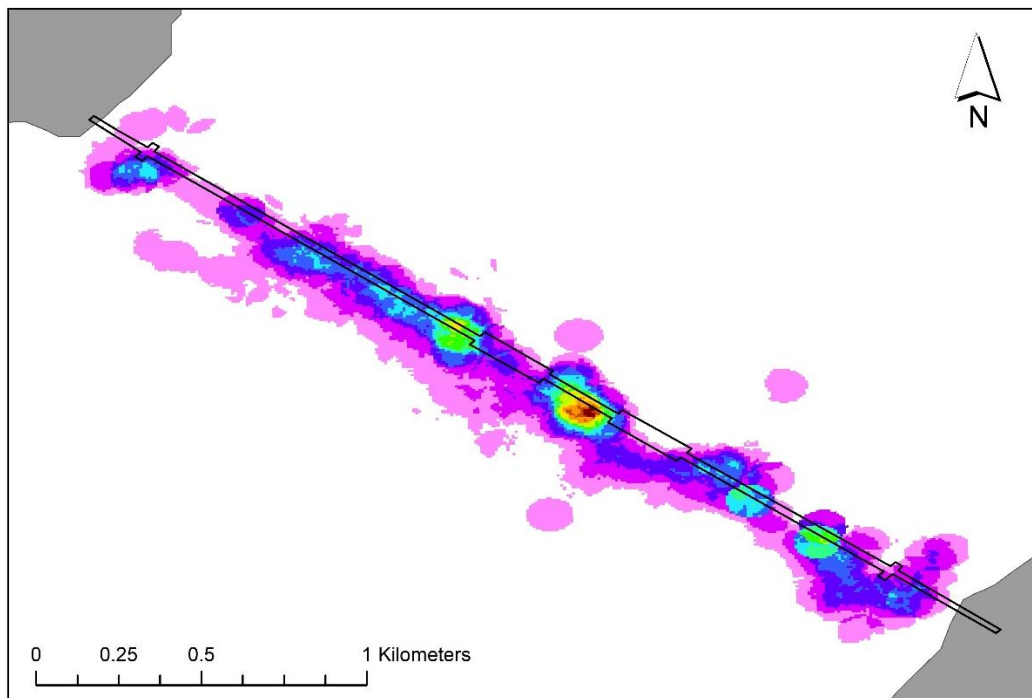


Figure A7

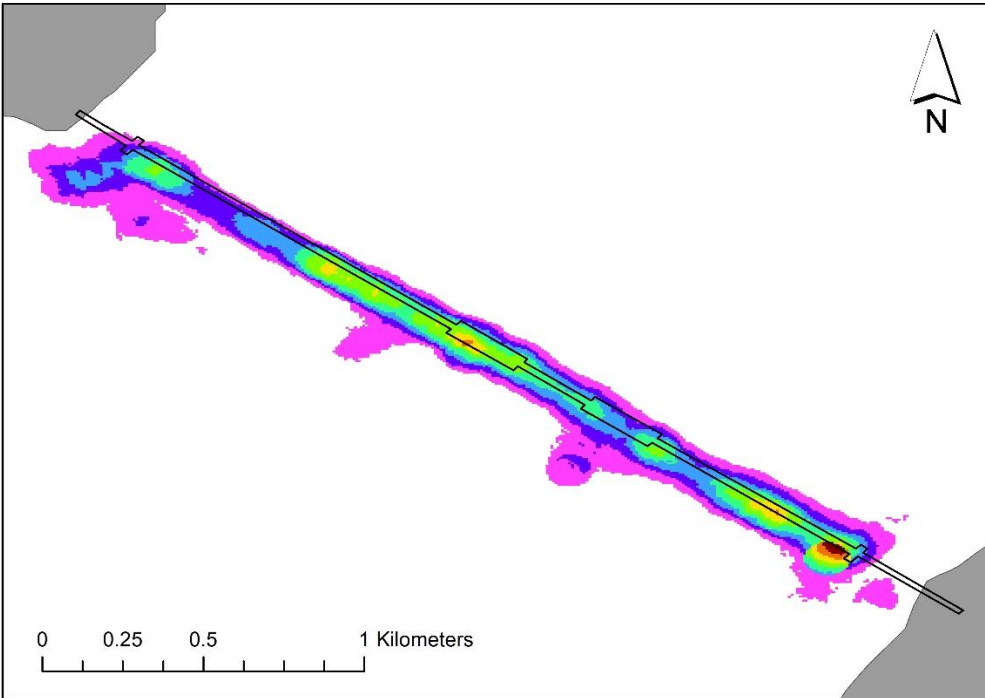
A



B



C



D

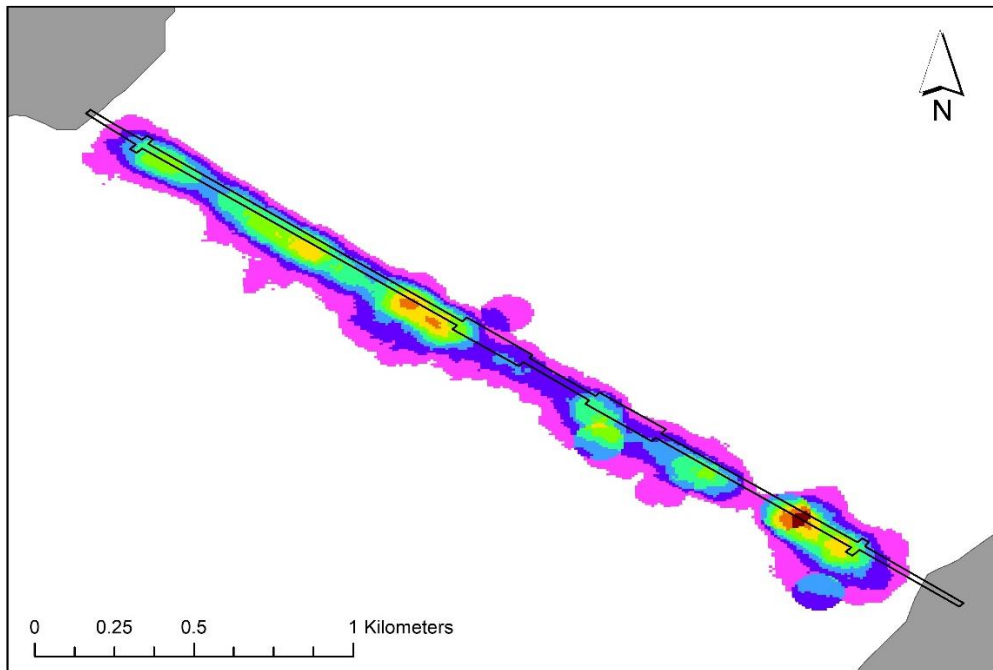
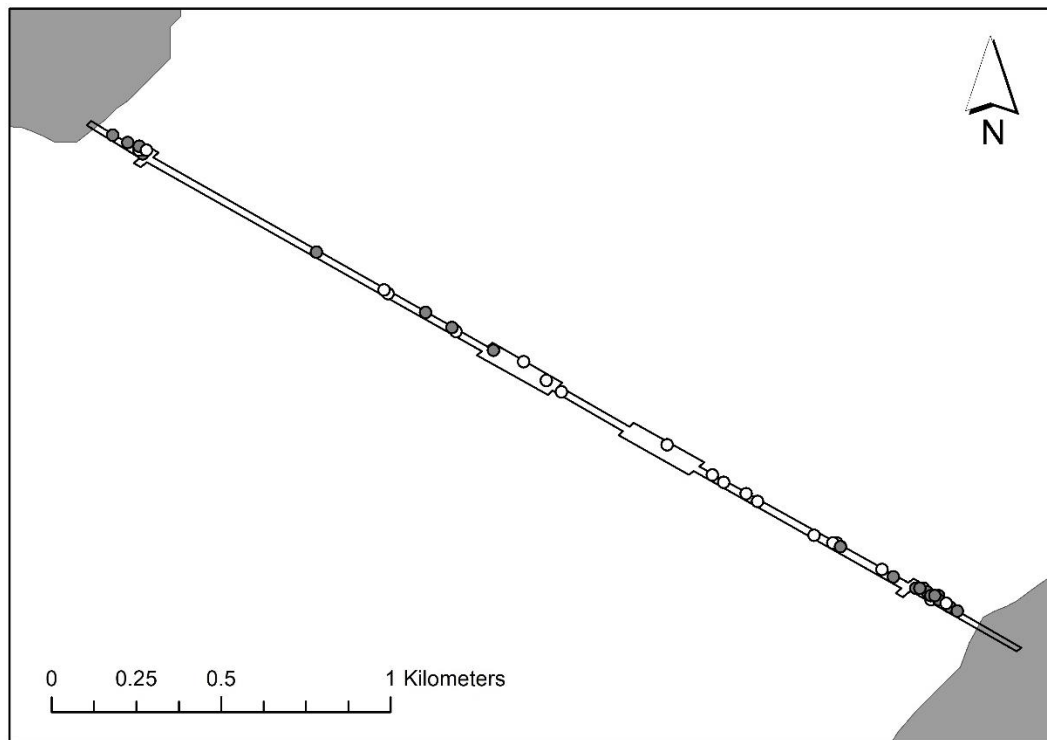


Figure A8

A



B

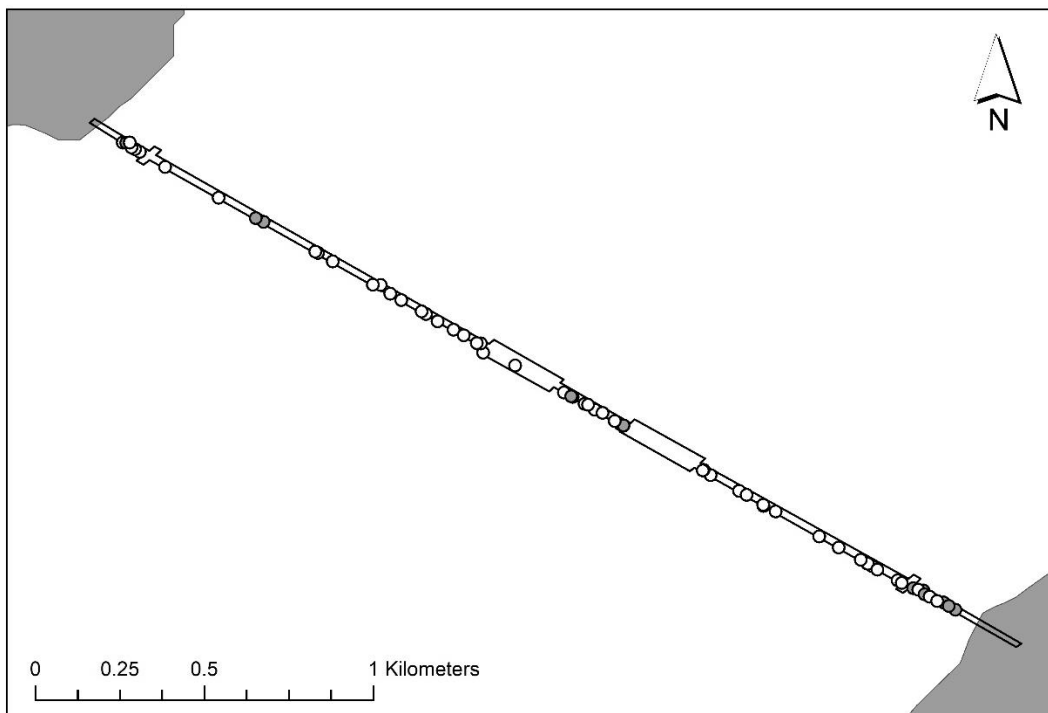
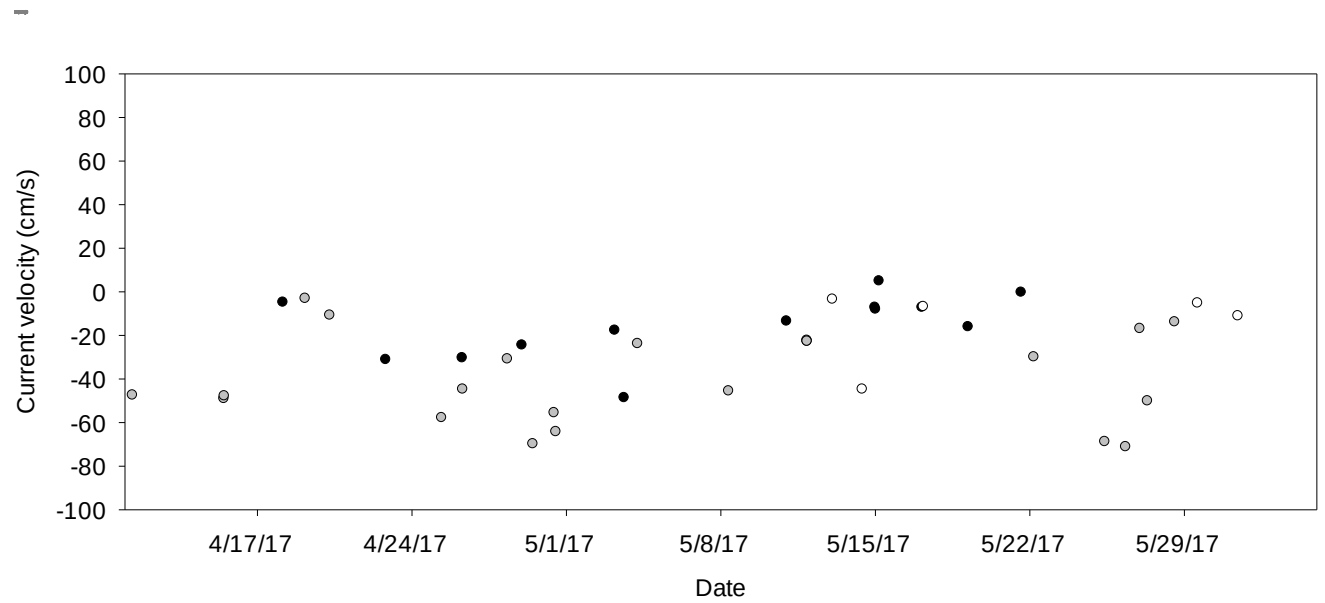


Figure A9

A



B

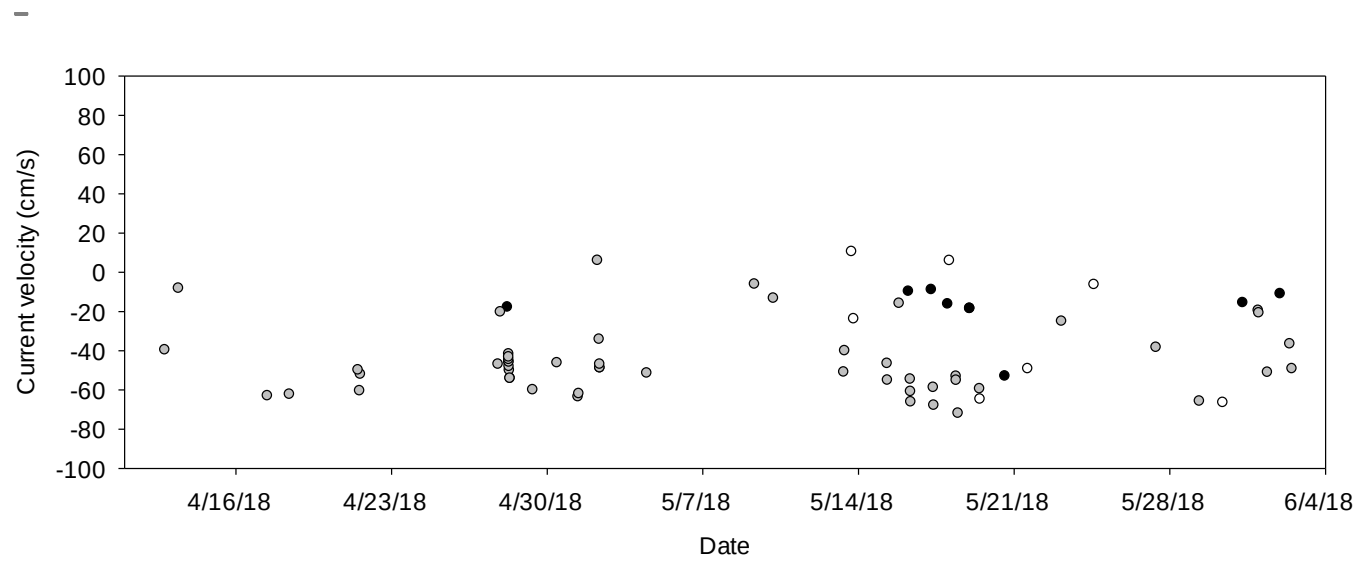
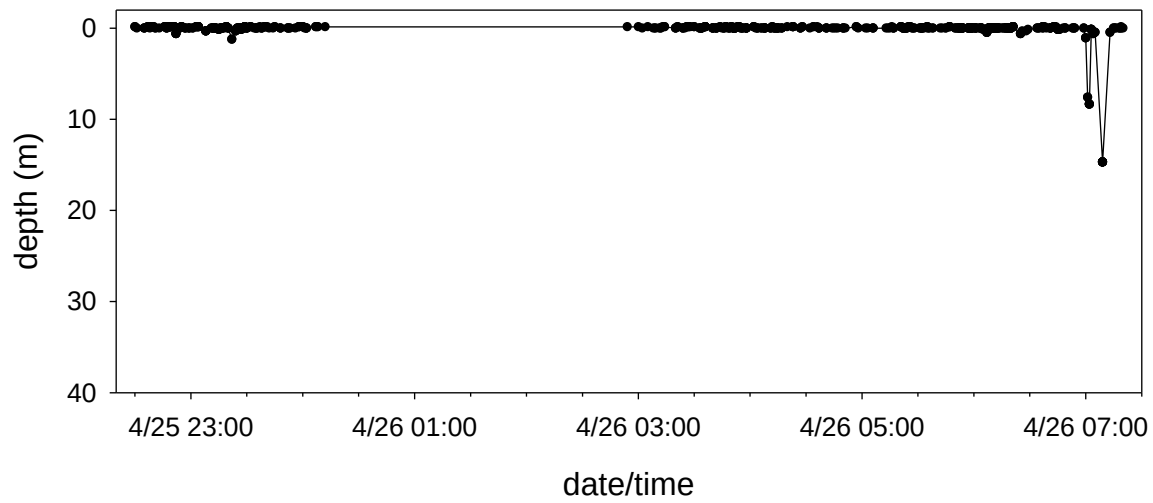
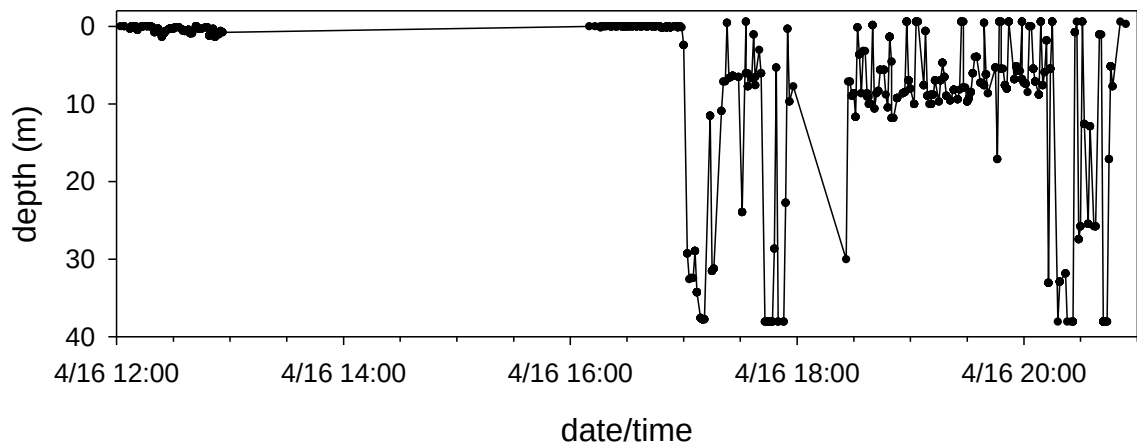


Figure A10

A



B



c

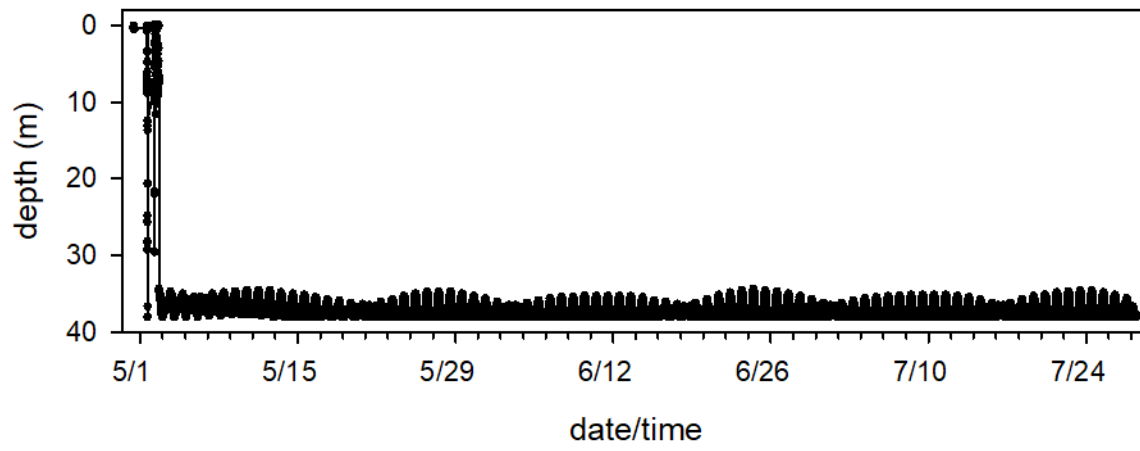
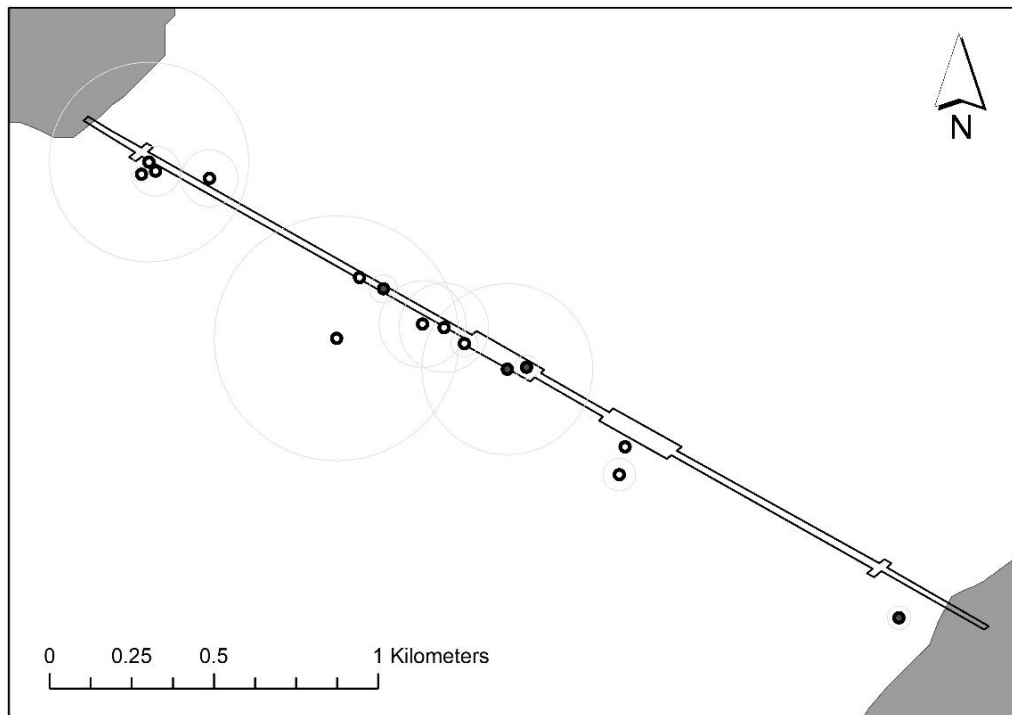


Figure A11

A



B

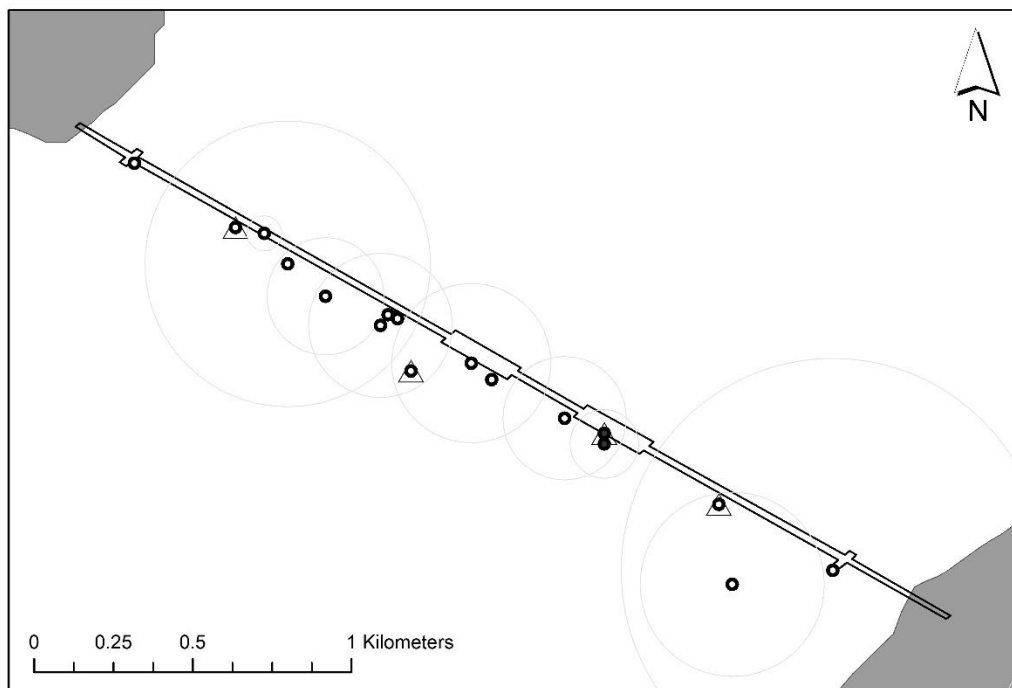


Figure captions

Figure A1. Map of the Hood Canal study area showing receiver locations (black dots) at the mouths of Big Beef Creek and the Skokomish River, the Hood Canal Bridge, at Twin Spits (TS), at Admiralty Inlet (ADM), and the Strait of Juan de Fuca (JDF, black line). Steelhead smolts were collected and released in Big Beef Creek and the South Fork Skokomish River (white circles). Mobile tracking stations are depicted as tiny black dots. Lower insets show locations of VR2AR receivers (black triangles), seabed-moored VR2W receivers (black circles), seabed-moored VR2W receivers with co-located reference transmitter (open stars), VR2W receivers hanging from the bridge railing (black stars), and seabed-moored reference transmitters (black X) that formed the Vemco positioning System (VPS) in 2017 and 2018.

Figure A2. Mixed model fit showing the bimodal distribution of square-root transformed continuous Hood Canal Bridge (HCB) time statistics for tagged steelhead smolts in 2017 (A) and 2018 (B). The black line fits the short HCB time component representing the variation in behavior typical of survivors, while the gray line fits the long HCB time component, indicative of longer variable time periods during which a predator of a tagged smolt continues to forage at the HCB and may deposit the transmitter within range of the HCB.

Figure A3. Survival probability estimated with mark-recapture models using detection data from tagged steelhead smolts from Big Beef Creek (BBC; black solid line = 2017, black dashed line = 2018) or the Skokomish River (gray solid line = 2017, gray dashed line = 2018) from river mouth (RM; km from the Strait of Juan de Fuca (JDF) = 0) to the Hood Canal Bridge (HCB; km from JDF = 135), the Twin Spits array (TS; km from JDF = 128), the Admiralty Inlet array (ADM; km from JDF = 110), to the final JDF array.

Figure A4. Logistic regression plot showing the relationship between survival probability (1 = survived, 0 = did not survive) past the Hood Canal Bridge (HCB) to the Twin Spits array (TS) and the date of HCB approach. The black line depicts the locally estimated scatterplot smoothing (LOESS) function with 95% confidence limits.

Figure A5. Average travel time of steelhead smolts detected at the Skokomish (SKOK; gray line) or Big Beef Creek (BBC; black line) river mouth (RM) to the Hood Canal Bridge (HCB), the Twin Spits array (TS), Admiralty Inlet (ADM; 2017 only) and the Strait of Juan de Fuca (JDF) in 2017 (A) and 2018 (B), plotted in relation to the distance of each population's distance to the JDF array.

Figure A6. Locations of stationary tags (black circles) identified in 2017 (A) and 2018 (B) by mobile tracking and mixed model analysis. Black crosses represent mobile tracking stations visited to listen for transmitters after the expected smolt migration window.

Figure A7. Density plots, inversely weighted by number of detections per fish, showing the density of VPS positions of tagged smolts encountering the HCB that (A) survived to the TS array or beyond in 2017, (B) survived to the TS array or beyond in 2018, (C) were not detected after the HCB in 2017, and (D) were not detected after the HCB in 2018. Dark red indicates highest densities and pink/purple represent the lowest densities, with green and blue representing intermediate densities (density values differ between figures and scale with sample size).

Figure A8. Locations of where tagged steelhead smolts crossed from the south to the north side of the HCB in 2017 (A) and 2018 (B). Open circles represent crossings that took place between sunrise and sunset (day), while filled circles represent crossings between sunset and sunrise (night).

Figure A9. Crossing location times of smolts that crossed under (light gray circles), around through the east drawspan (black circles), or around through the west drawspan (open circles) in 2017 (A) and 2018 (B) in relation to current velocity (predictions at NOAA current station PUG1603, https://tidesandcurrents.noaa.gov/noaacurrents/Predictions?id=PUG1603_20).

Figure A10. Depth profiles of steelhead smolts exhibiting behavior typical of a surviving smolt (A), a non-surviving smolt that was eaten by a deep and frequently diving predator (B), and a non-surviving smolt that was eaten then deposited by a predator to become stationary until the transmitter battery expired. The maximum value of the depth sensors was 38 m.

Figure A11. Locations of predation events inferred by changes in diving behavior or increases in transmitter temperature in 2017 (A) and 2018 (B). Filled black circles represent predation events that occurred during nighttime hours, while open circles depict events that occurred during the day. Gray circles around most symbols represent the error radius in meters (some are so small they are obscured by the symbol), with triangles surrounding points where data were not available for error calculation.

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[Appendix B. Bishop et al. 2021](#)

The Port Gamble S’Klallam Tribe research component summary is currently in progress, and will be released in early 2021. This summary covers split-beam acoustic surveys, water quality and zooplankton, predator surveys, visual acoustic surveys, light surveys, and gopro and biota surveys.

Factors impacting juvenile salmon migration at the Hood Canal Bridge

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[Appendix C. Stocking & Pearson 2019](#)**EVALUATING THE POTENTIAL INFLUENCE OF THE HOOD CANAL BRIDGE
ON PISCIVOROUS BIRD AND MAMMAL DENSITY***November 2019*Jessica J. Stocking¹ and Scott F. Pearson¹

With contributions from

K. Beach, C. Cowles, M. Lance, C. Norris, D. Schwitters, W. Simper and E. Weiss

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INTRODUCTION

Human-built structures can dramatically change predator-prey dynamics. For example, dams can act as a barrier to migrating species like salmon. Dams can either dramatically slow or halt migration, and the fish ladders that allow fish to bypass a dam concentrate fish through a single, narrow passageway where they are vulnerable to predation. The end result is a numerical and functional response by pinnipeds, unusually high hunting success, and ultimately, unusually high predation rates (Keefer et al. 2012, Schakner et al. 2017). Another example of human-built structures influencing pinniped predation rates on salmon are the bridges across the Puntledge River, British Columbia, Canada, where harbor seals (*Phoca vitulina*) regularly position themselves side-by-side, ventral side up, in the upstream shadow of two bridges near the light-shadow boundary (Yurk and Trites 2000). The seals swim against the river current and hold their position in the water using minimal movements of their hind flippers. This feeding strategy results in an almost continuous barrier for surface-migrating salmon and results in high interception of downstream drifting salmon smolts that is aided by the bridge lights that illuminate the water surface (Yurk and Trites 2000). In these examples, the seals and sea lions are the proximate cause of high predation rates but the human-built structures are ultimately responsible.

The Hood Canal Bridge is a 1.5-mile long floating bridge that carries vehicle traffic across the northern outlet of Hood Canal. Its pontoons span much of the width of Hood Canal and extend 12 feet underwater. Because of its location, all salmon and steelhead originating from Hood Canal rivers and streams must pass the Hood Canal Bridge on their migration to and from the Pacific Ocean. Recent studies indicate the bridge is a barrier to fish passage (Moore et al. 2013). Slower migration times and higher mortality rates associated with the bridge suggest it is impeding migration and reducing survival. The proximate (e.g., predation) and ultimate (e.g., the bridge structure) mechanisms responsible for reduced salmon survival have not been identified.

Recent research indicates that the bridge may disrupt water circulation (Khangaonkar and Wang 2013). Fjords, like Hood Canal, depend upon strong surface flows associated with tidal exchanges to be replenished with well oxygenated water. The surface water layer is responsible for the outflow of water from the fjord and is important for the flushing of the basin and water quality maintenance. Modeling indicates that the Hood Canal Bridge may have increased water residence times in the basin by 8-13%, which could be an important factor affecting water quality and ultimately fish passage rates.

In 2015, federal, state, tribal, and nonprofit partners convened to develop the Hood Canal Bridge Ecosystem Impact Assessment Plan (Plan). The Plan was designed to determine how the bridge is negatively affecting Endangered Species Act-listed juvenile steelhead and salmon survival and the health of the Hood Canal ecosystem, and guide actions that simultaneously address ecosystem impacts and maintain the bridge. Specifically, the Plan focuses on how the bridge acts as a barrier to juvenile steelhead and salmon migration and how the bridge impacts the entire ecosystem including water circulation, water quality, and predator assemblages and densities.

The specific objectives of this aspect of the Hood Canal Research Project were:

- 1) Estimate the density of potential steelhead smolt predators within 4 km of the Hood Canal Bridge during the outmigration period (1 April - 30 May).
- 2) Determine if potential bird and mammal steelhead smolt predators are more abundant near the Hood Canal Bridge during the outmigration period.
- 3) Provide spatial locations for all potential steelhead smolt predators within 4 km of the bridge during the outmigration period.

This work was conducted concurrent with work to quantify fish densities in the same study area, relative to the bridge. Ultimately, if predation is responsible for high juvenile salmon and steelhead mortality, we would predict that the bridge would concentrate both predators and their prey near the bridge.

METHODS

Survey area

We established transects running perpendicular to the bridge and extending 4 km northeast (bounded by shoreline) and 6 km southwest of the bridge (Fig. C1). Transect lines were spaced regularly throughout the survey area, 500 m apart and extending to 250 m off each shore. We selected these distances between transects and the shore based on previous experience and results using this same methodology in the same region. For density estimation, we discard the most distant 5% of each species detections to improve modeling of detection functions and reduce the potential undue influence of very distant detections (see below). In our experience, the resulting effective detection distances for nearly all species is less than 250 m. This assumption was well supported by our data in this study (see effective survey distances in Table C1). No observations were discarded because of distance from the boat in our distribution analysis.

Boat-based survey methods

Surveys were conducted from a 26-foot Lee Shore boat (R/V *Fog Lark*) with twin-outboard engines traveling at between eight and 12 knots. The starting transect and direction of travel were rotated systematically. The survey team consisted of one boat operator, two observers, and one data recorder; crew members regularly switched duties to avoid survey fatigue. The two observers scanned from 0° off the bow to 90° abeam of the vessel on their respective sides. Observers scanned continuously, with a complete scan of the survey area taking approximately 4-8 seconds. Slightly more effort was spent watching for predators forward of the boat, close to the transect line (within 45° of line). Observers scanned far ahead of the boat for predators that flushed or dove in response to the boat and communicated between observers to minimize missed detections or double counting. Crew members communicated via wireless headsets; data were recorded using DLOG2 software (R.G. Ford, Inc., Portland, OR) that collects real time location data at regular intervals and for each observation. For each predator detected, we collected the following data: group size, species, distance from the vessel, distance and direction from the transect line, and behavior. Additional data such as transect, sea condition, glare and observer initials were recorded manually into the DLOG2 program. Binoculars were used for species verification, but not for detecting animals. Survey effort was ended if glare obstructed the view of observers, or if Beaufort wind scale was 3 or greater for more than 200 m.

We collected the data for analysis in a distance sampling framework, to account for detection error as a function of distance from the transect line (Buckland et al. 2001). Accurate distance estimates are critical to the success of this approach. Technological methods, such as laser range finders, do not reliably read objects that are low profile (e.g. harbor seal heads) or that are only visible or stationary for a fraction of a second (e.g. diving or flushing birds). As a result, substantial time was spent practicing and visually calibrating distance estimates before surveys began, followed by weekly testing throughout the survey period. We estimated the distance from the vessel to the animal and from the transect line to the animal, then calculated the location (i.e., geographic coordinates) of each animal using the vessel's position and the time of the observation and the estimated distances and direction data (Fig. C2).

Our species selection was driven largely by a previous examination into potential juvenile steelhead and salmonid predators (Pearson et al. 2015). We erred on the side of being too conservative, including some species that do not appear to have much dietary overlap but were abundant enough in the study area to potentially have an impact (e.g. pigeon guillemot and grebes). We omitted non-piscivorous waterfowl species (Anatidae) because they do not normally eat fish. Unless we observed flying birds landing or foraging within the survey area, we assumed they were passing through and did not count them. The

exception to this rule was for aerial hunters including bald eagles, osprey, and terns. Due to small numbers of observations for some species, they were grouped for analysis with species that were closely related and have similar diets. For example, double-crested cormorant (*Phalacrocorax auritus*), pelagic cormorant (*P. pelagicus*), and Brandt's cormorant (*P. penicillatus*) were combined into the group "Cormorants." A similar approach was taken for loons, grebes, and mergansers. This approach has the added benefit of allowing inclusion of birds that were identified to genus but were not identified to species (e.g. unidentified loon).

Because we were focusing on animals that could potentially be foraging on juvenile salmon and steelhead, we removed all harbor seals and cormorants within 100 m of the Sisters "haulout site" (henceforth, haulout; see Figure C1). Most of the animals detected within 100 m of the haulout were either resting on the rocks (the size of the haulout above the water level depends on the tide height), transiting to or from the haulout, or bottom resting (in the case of harbor seals), and therefore not actively foraging.

Bridge pool surveys

Underneath the bridge are covered pools of water, approximately 90 x 20 m, which receive the retracted bridge deck during bridge openings. Biologists working for the Port Gamble S'Klallam Tribe estimated the density of predators in these pools using a survey method intended to produce comparable density estimates to our boat-based surveys. Specifically, surveyors observed the pools for 40 seconds and recorded the number of each predator species present during that survey. The 40-second survey duration was based on the estimated time it would take to observe the same area traveling in our boat at a speed of 8-12 knots as described in the methods above.

Distribution analysis.

In order to present distribution of potential steelhead predators in the study area, we generated a continuous distribution surface of estimated density for each species or species group using the Kernel Density tool in ArcMap 10.4.1 (Spatial Analyst; ESRI 2011, Redlands, CA). All transects ($n = 23$) were included in this analysis. Transects were surveyed more times in 2017 than 2018 (Appendix C2). To standardize effort across the two years, we selected the fourteen surveys in 2017 that most closely aligned with the fourteen dates surveyed in 2018. Maps thus reflect the *pooled* relative density of all animals observed over the course of the season (April 4 – June 1). Color value is broken into seven quantiles that vary for each species group; darker areas indicated greater estimated density.

Near-far comparative analysis.

We used a subset of the data for evaluating the effect of the bridge on bird and mammal distribution. We isolated the four interior transects on either side of the bridge in order to minimize the effect of the shoreline on the density of species (i.e. transects 7-10, 17-20; Fig. C1). We then divided transects into three strata: 0-300 m from the bridge (Stratum A); 301-1200 m (Stratum B); and 1201-3000 m (Stratum C). Transects extended to 50 m from the bridge, allowing the crew to observe animals at the bridge.

We used the program DISTANCE 7.3 (Thomas et al. 2010) to estimate $f(0)$, the probability density function of perpendicular detection distances evaluated from the transect line (henceforth, detection function) and the mean number of animals per group [or cluster size, $E(s)$] for each species. We compared four binning approaches for the detection function: continuous (no binning), and three, five and seven bins of equal intervals. The detection function was calculated using the entire dataset for each species and could take one of two forms: uniform or half-normal, each with the possibility of a cosine adjustment. The models were compared using AIC (Burnham and Anderson 1998), and model fit was evaluated using a Chi-squared goodness of fit (GOF) test. Due to size and behavioral differences, the effective sampling

distance differs across species. For this reason, we truncated the data to contain 95% of observations for each species based on distance (Buckland et al. 2001). Discarding detections far from the transect line can also improve modeling of detection functions (Buckland et al. 2001).

We estimated density (animals per km²) for each stratum by using the estimates and encounter rate (number of animals observed per km, ER) from DISTANCE with the following formula:

$$\hat{d} = 1000 * f(0) * \hat{E}(s) * ER/2$$

The “hats” over the letters designate estimates. DISTANCE used the mean observed cluster size as $\hat{E}(s)$ unless an internal test found evidence that detection was a function of cluster size, in which case DISTANCE applied a correction (Buckland et al. 2001). We used density estimates and 95% confidence intervals to compare densities of potential predators in the three strata for each year.

For marine mammals, detection on the line can be imperfect (i.e. $g(0) \neq 1$) due to long dive times. To address this, we applied correction factors based on published measures: $g(0) = 0.204$ for harbor seals (Laake et al. 1997) and $g(0) = 0.292$ for harbor porpoise (Wilson et al. 2014, Jefferson et al. 2016). These correction factors were also applied to the US Fish and Wildlife Service survey data for comparison.

To provide context to the densities reported in this study, we compared our densities to those derived using nearly identical survey methods and analytical approach in other areas of the Salish Sea (“US Fish and Wildlife Service (USFWS)” data points in Figs. 13-21). For details on the survey methodology please see Raphael et al. (2007) and for details on this specific survey year please see McIver et al. (2019) and Pearson and Lance (2019). Note that although the survey effort is focused on marbled murrelets, we record all other birds and mammals detected during these surveys. These surveys were conducted by the same survey crew and survey platform as used in this study and were conducted between 15 May and 30 July 2018, and therefore overlap our Hood Canal effort for about two weeks. Because of the differences in the timing of these two survey efforts, we only included comparative densities for year-round resident species and not migratory species that are likely moving through the area during the April-May period.

RESULTS

We surveyed the 23 transects over 29 days between 3 April - 2 June, 2017 and over 15 days between 4 April - 31 May, 2018. We recorded observations of 13,133 individual animals. We observed 22 piscivorous avian species and three marine mammal species (Appendix C1). Mean effective survey distance was 226 m and ranged from 174 m (marbled murrelet; *Brachyramphus marmoratus*) to 290 m (loons; Table C1), but all species were truncated to 250 m to reduce the potential of double-counting of animals. Numbers of observations for some species (e.g. loons, cormorants) were quite low, and estimates could not be derived for every stratum-year (see mergansers, Fig. C21).

For in-pool surveys, fourteen surveys were completed of the east pool and ten were completed of the west pool between the two survey years. Only two species were observed in the bridge pools (pigeon guillemots and harbor seals); results can be found in their respective sections with data points labeled “in-pool” (Figs. C13 and C17).

For four species (rhinoceros auklet, grebes, harbor seal and harbor porpoise), even the distance function with the lowest AIC value provided a poor fit to the data (Table C1), due to fewer observations on the transect line than observations in the next bin farther from the line. This could be a violation of the assumption that individuals on the line are detected perfectly. In our study, we suspect this to be evidence of evasive behavior of animals in the boat’s path before detection occurs. However, we have no reason to expect that bias differs over time or space within our study (i.e. should not vary within our data) and

maintain that the relative densities are useful for the purposes of the study. It should be noted, however, that particular caution should be exercised in comparing those densities to other studies/methodologies.

Because each species exhibited fairly unique density patterns among strata and between years, we focus on species-specific results rather than generalizable patterns among species. Pigeon guillemots (*Cepphus columba*) were the most numerous species observed throughout the study (Appendix C1). Distribution was fairly consistent during the two years, with higher densities along shores and at the bridge (Fig. C3). In the near-far analysis, the three strata were significantly different from one another, with guillemot density decreasing with distance from bridge (Fig. C13). Guillemots in the bridge pools and elsewhere in the region (USFWS) were more consistent with the stratum farthest from the bridge.

Rhinoceros auklets (*Cerorhinca monocerata*) were more abundant in the second year of the study but did not show a strong preference between strata (Fig. C14). Interestingly, they were observed almost exclusively on the northeast side of the bridge in both years (Fig. C4). Overall, rhinoceros auklets were less dense compared to other areas in the region (Fig. C14), particularly in 2017.

Horned grebes (*Podiceps auritus*) were the second most numerous species observed during the study, and all grebe species were relatively abundant (Appendix C1). Grebe species were most numerous along the shorelines and in bays (Fig. C5) and showed no preference for the bridge in either year (Fig. C15).

Marbled murrelets comprised the fourth most numerous species observed during the study (Appendix C1). Murrelets had higher relative densities in 2017 and on the southwest side of the bridge (Fig. C6). In the near-far analysis, densities were higher in 2018, and birds showed no preference for the near-bridge stratum (Stratum A) relative to the other two more distant strata. Murrelet densities in the study area were generally consistent with data from elsewhere in the region (Fig. C16).

Harbor seals (*Phoca vitulina*) and harbor porpoises (*Phocoena phocoena*) showed similar patterns. Both species had generally low densities throughout the study area (Figs. C7, C8) and were typically observed as single animals (Table C1). Seals and porpoise had higher density in Stratum A near the bridge in 2017, although there was some overlap in confidence intervals with the other strata (Figs. C17, C18). This pattern did not hold in 2018, when all strata had approximately equal density estimates. Seals appeared to have slightly lower densities in this study than elsewhere in the region (Fig. C17), while porpoise had more similar densities (Fig. C18).

Loons were composed of three species: common (*Gavia immer*), Pacific (*G. pacifica*) and red-throated (*G. stellate*; Appendix C1). Common loons were relatively abundant in the study area, and red-throated loons were infrequently observed (Appendix C1). Loons were distributed along the shorelines and in bays, with the pattern particularly evident in 2018 (Fig. C9). Loon density was lowest in Stratum C, farthest from the bridge, with non-overlapping confidence intervals in 2017 (Fig. C19).

Comorants were similarly distributed in 2017 and 2018 and appeared to be avoiding the center of the channel (Fig. C10). Density was higher near the bridge in 2017 and generally low in strata B and C, but there were no observations in Strata A in 2018 (Fig. C20). Densities were generally low (Table C1).

Three species of mergansers were observed during the study, dominated by red-breasted merganser (*Mergus serrator*; Appendix C1). In general, mergansers occurred along the shorelines (Fig. C11) and in groups of 2-3 individuals (Table C1). In 2017, merganser density was significantly higher near the bridge in 2017 when stratum C density could not be estimated, and only a single observation occurred in near-far transects in 2018 (Fig. C21).

Caspian terns (*Hydroprogne caspia*) were observed more to the northeast of the bridge (Fig. C12). There were too few observations in the near-far subset of the data to compare densities between strata.

DISCUSSION

The only species demonstrating consistently higher densities near the bridge than far from the bridge was the pigeon guillemot, and we suspect this pattern is occurring because they are nesting in suitable crevices provided by the bridge structure. Generally, pigeon guillemot diet during the nesting season is focused on nearshore species like gunnels and sculpin (Ewins 1993, Bishop et al. 2016). However, because the water is deep along the bridge, it is possible that birds nesting on cavities in the structure of the bridge are not foraging in the nearshore and, as a result, they might eat more juvenile salmon than they would normally. There is little overlap in the length of prey generally consumed by guillemots and the length of outmigrating juvenile steelhead (Ewins 1993, Pearson et al. 2015). However, juvenile Chinook, coho and chum would be within the preferred prey length of this species.

Harbor porpoise and seal both spent more time near the bridge in 2017 than in 2018. These inter-annual differences likely reflect variation in prey distribution. There is no strong numerical response by either of these species to the bridge. It is possible, however, that individuals of these two species are eating more listed salmon near than far from the bridge (a functional response), but this possibility cannot be evaluated without diet composition information.

Several species of birds and mammals show some evidence for greater density near the bridge in at least one year. However, it is difficult to evaluate the cumulative impacts of multiple predators on listed salmon and steelhead near the bridge without specific diet information for these species both near and far from the bridge. Because no species other than the guillemot is exhibiting a strong potential numeric response to the bridge, and if predators are exhibiting a top-down influence on listed salmon and steelhead at the bridge, it might be the cumulative influence of multiple predator species that is causing this effect. We only present this idea as a potential hypothesis to investigate. The distribution of some bird species (loons, mergansers and to some degree, cormorants) suggest that the bridge essentially acts as an extended shoreline out into the deep water in the middle of Hood Canal – a pattern that we don't see in other areas of Puget Sound.

A very surprising outcome of this study was pattern of two bird species being largely restricted to one side of the bridge or the other. The rhinoceros auklet was found almost exclusively north of the bridge and the marbled murrelet was more abundant to the south. These patterns raise questions about the influence of the bridge on the movement of birds into or out of Hood Canal and ultimately have large-scale influences on predator-prey dynamics and the health of both fish and predator populations. We don't know if the bridge has anything to do with this pattern. The bridge is placed near the confluence of Hood Canal and Admiralty Inlet, an area with considerable tidal exchange, strong currents, and the mixing of fresh and salt water. As a result, these patterns of bird distribution may have occurred prior to bridge construction.

ACKNOWLEDGEMENTS

A special thanks to Michael Schmidt and Iris Kemp from Long Live the Kings for supporting and coordinating this project. Megan Moore provided very helpful comments on an earlier version of this report. Hans Daubenberger and Emily Bishop with the Port Gamble S'Klallam Tribe provided the "in-pool" used density comparisons. The Northwest Forest Plan Effectiveness Monitoring Program provided the "USFWS" densities. Thank you all very much!

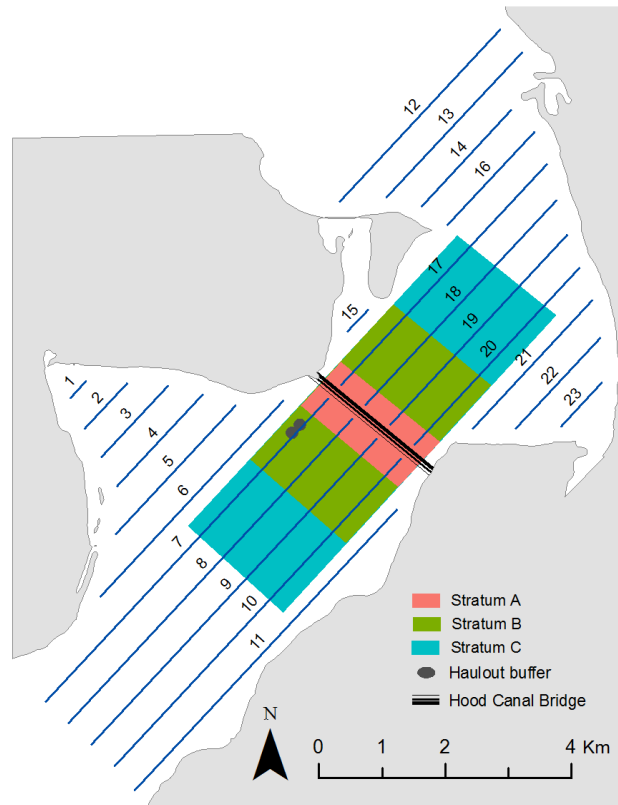


Figure C1. Study area and perpendicular transect lines for surveys of potential steelhead predators in area of Hood Canal Bridge. Bold blue lines indicate the section of transects used for the near-far analysis; color blocks indicate the three distance strata from the bridge (A=0-300 m; B=301-1500 m; C=1501-3000 m).

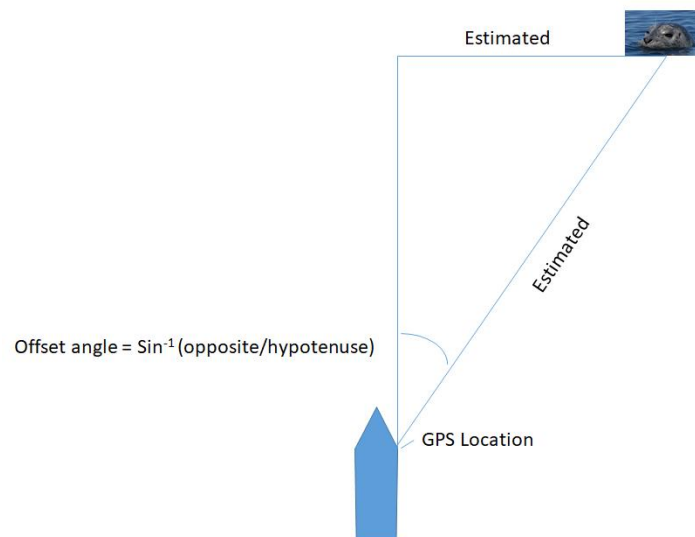


Figure C2. Illustration of technique for calculating an animal's position using estimated distances from vessel and transect line.

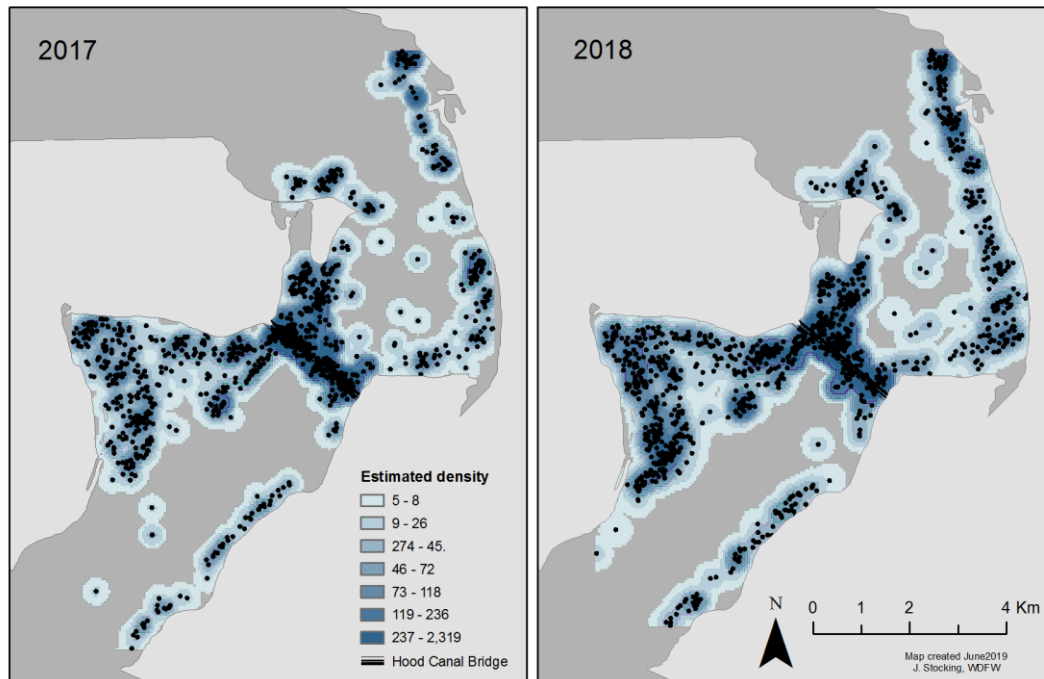


Figure C3. Relative density of pigeon guillemot (*Cephus columba*) in line transect surveys of Hood Canal bridge, WA during steelhead outmigration 2017-2018 (n=14visits/year). Points represent observations.

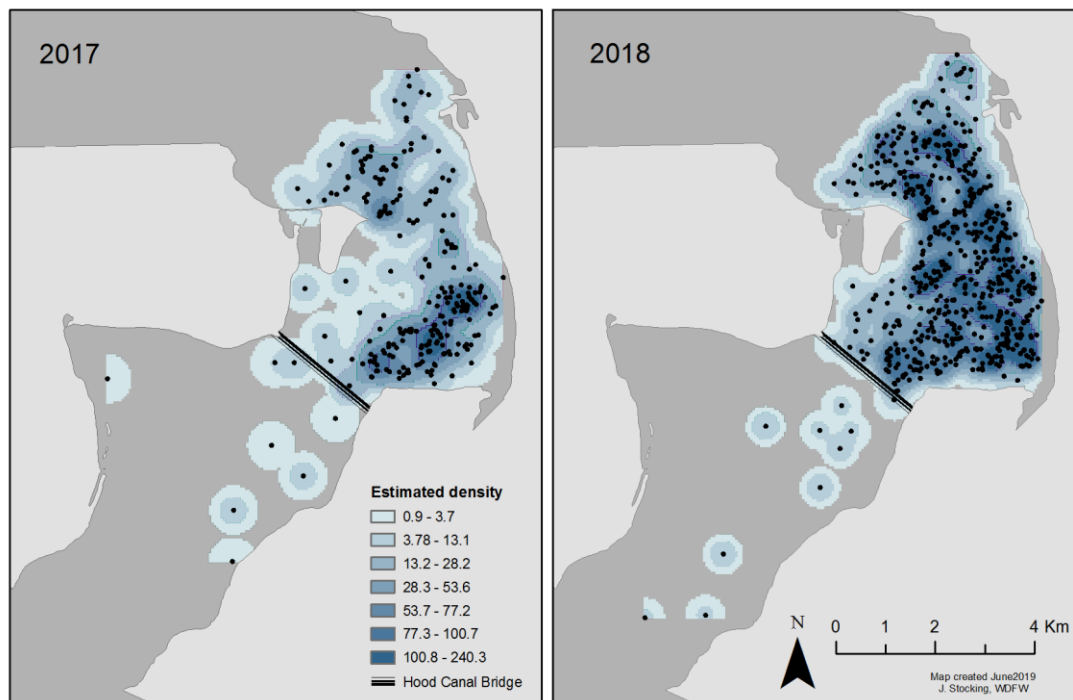


Figure C4. Relative density of rhinoceros auklet (*Cerorhinca monocerata*) in line transect surveys of Hood Canal bridge, WA during steelhead outmigration 2017-2018 (n=14visits/year). Points represent observations.

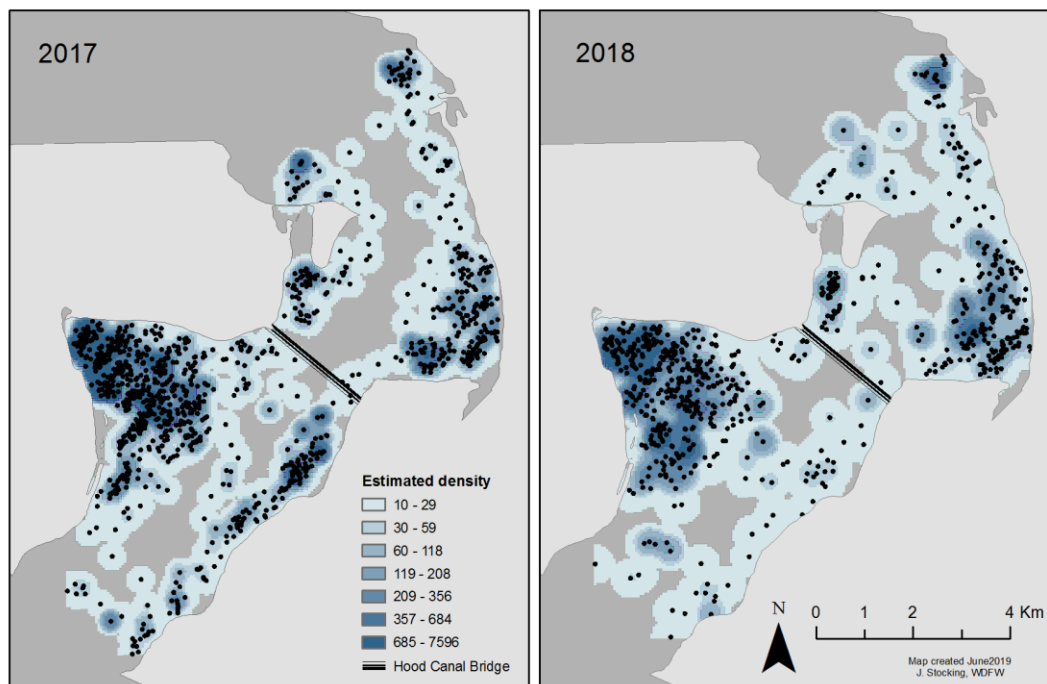


Figure C5. Relative density of grebes (Family Podicipedidae) in line transect surveys of Hood Canal bridge, WA during steelhead outmigration 2017-2018 (n=14visits/year). Points represent observations.

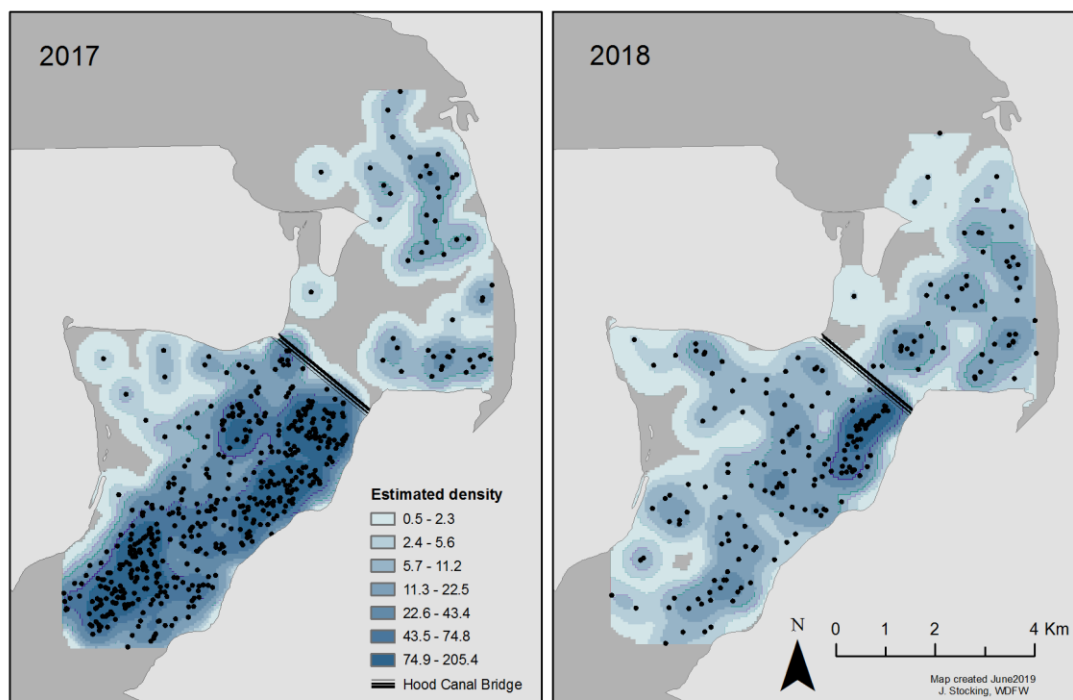


Figure C6. Relative density of marbled murrelet (*Brachyramphus marmoratus*) in line transect surveys of Hood Canal bridge, WA during steelhead outmigration 2017-2018 (n=14visits/year). Points represent observations.

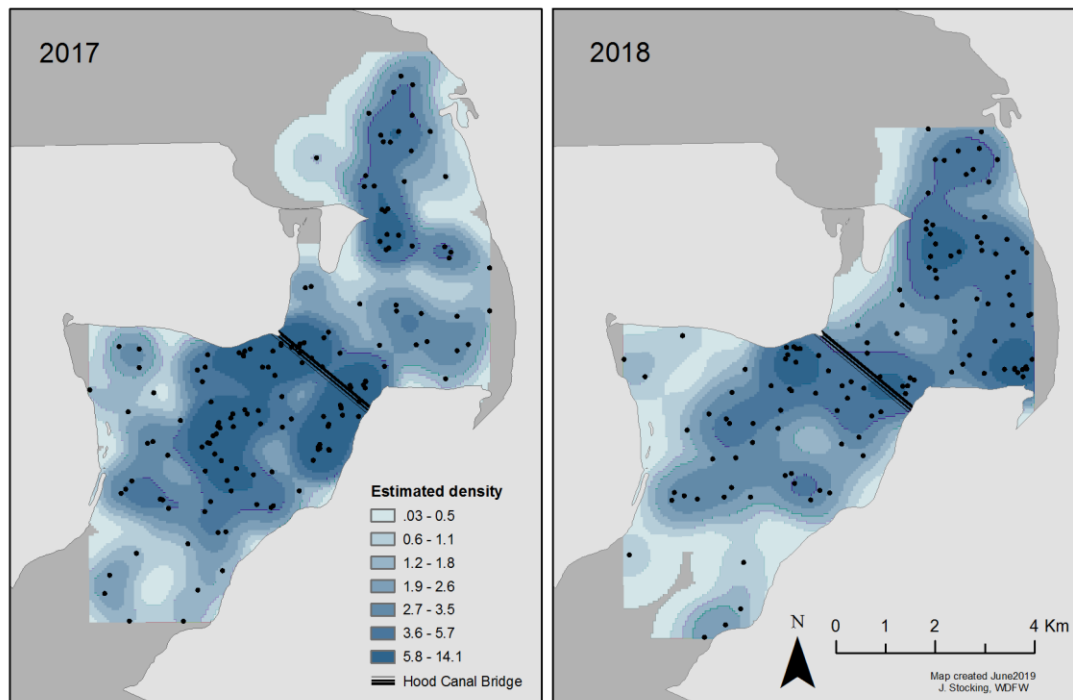


Figure C7. Relative density of harbor seal (*Phoca vitulina*) in line transect surveys of Hood Canal bridge during steelhead outmigration 2017-2018 (n=14 visits/year). Points represent observations.

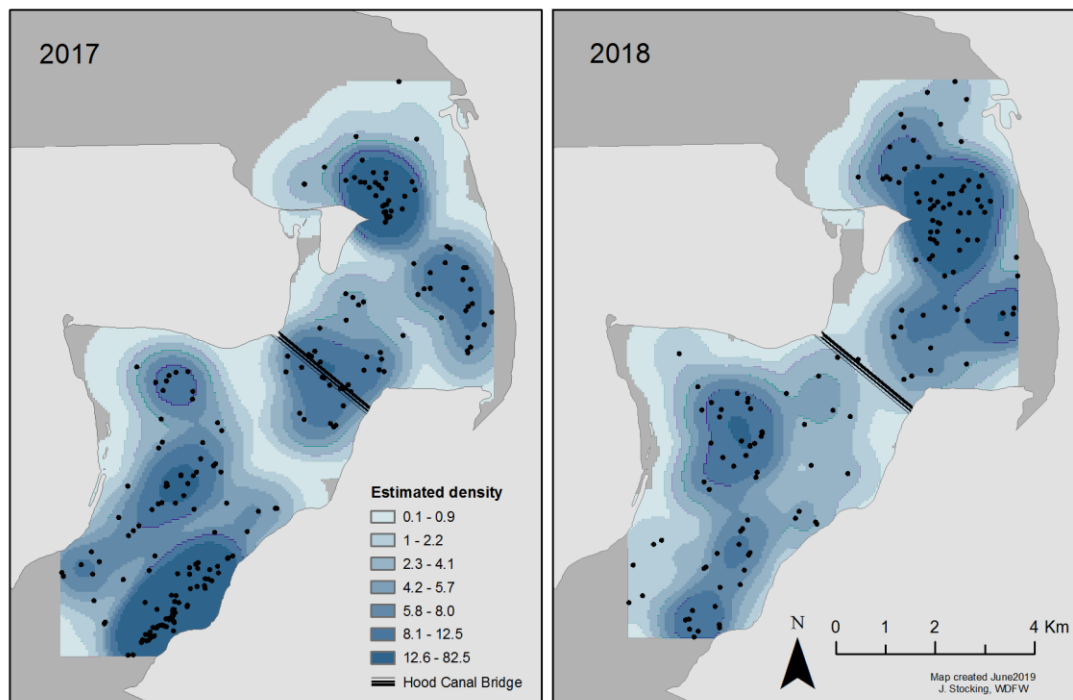


Figure C8. Relative density of harbor porpoise (*Phocoena phocoena*) in line transect surveys of Hood Canal bridge during steelhead outmigration 2017-2018 (n=14 visits/year). Points represent observations.

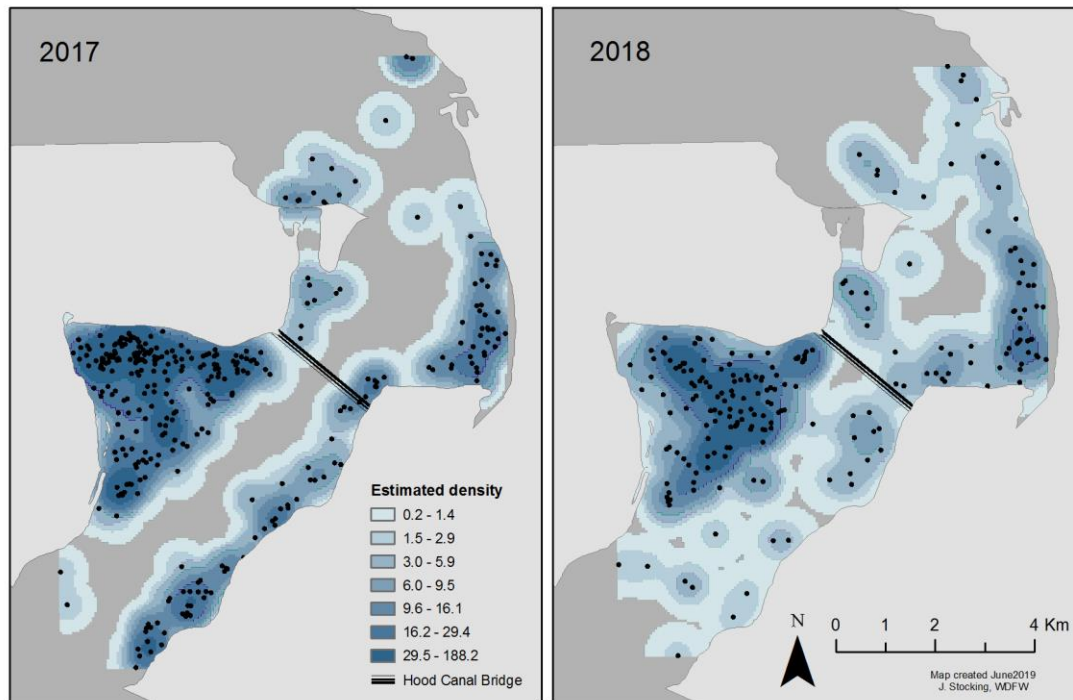


Figure C9. Relative density of loons (*Gavia spp.*) in line transect surveys of Hood Canal bridge during steelhead outmigration 2017-2018 (n=14 visits/year). Points represent observations.

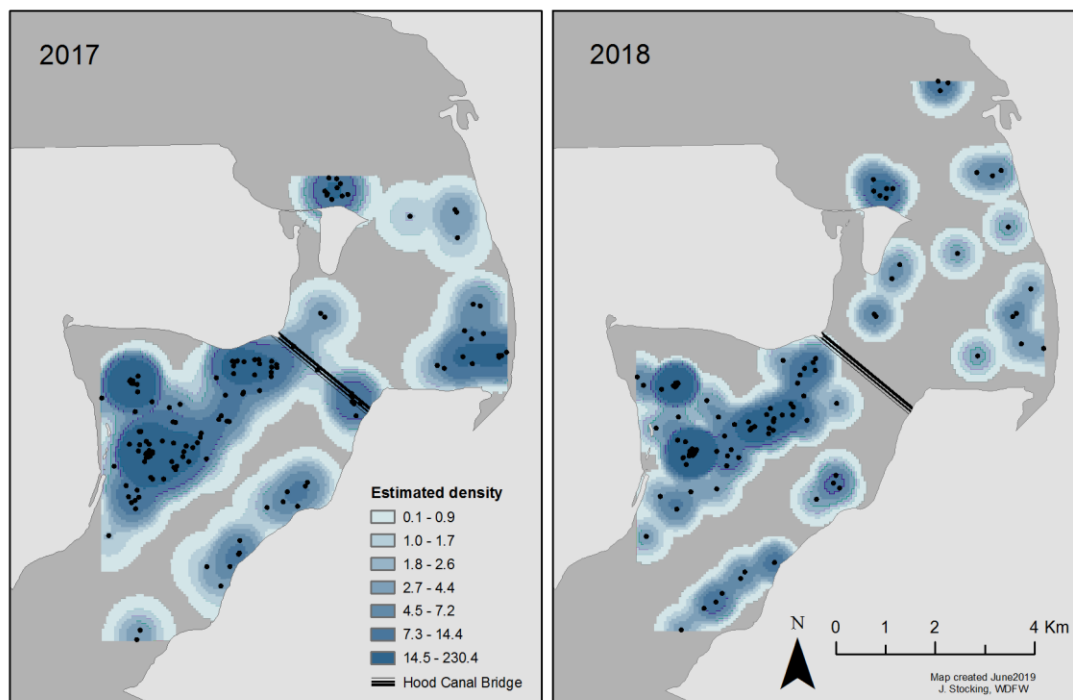


Figure C10. Relative density of cormorants (*Phalacrocorax spp.*) in line transect surveys of Hood Canal bridge during steelhead outmigration 2017-2018 (n=14visits/year). Points represent observations.

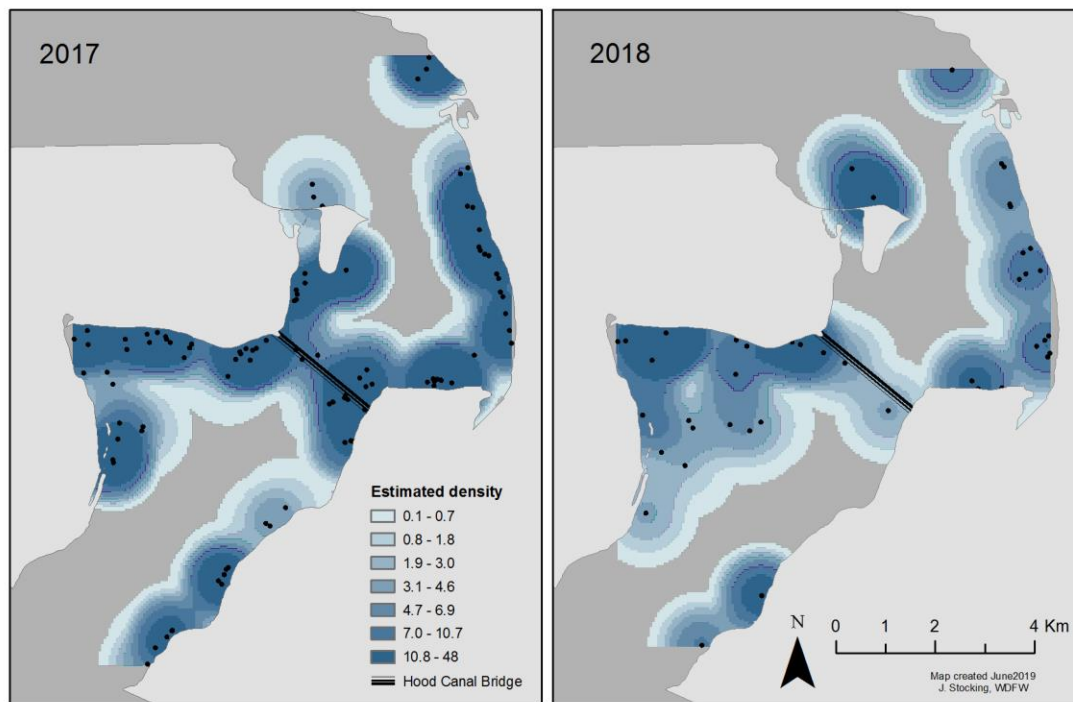


Figure C11. Relative density of mergansers (*Mergus spp*) in line transect surveys of Hood Canal bridge during steelhead outmigration 2017-2018 (n=14visits/year). Points represent observations.

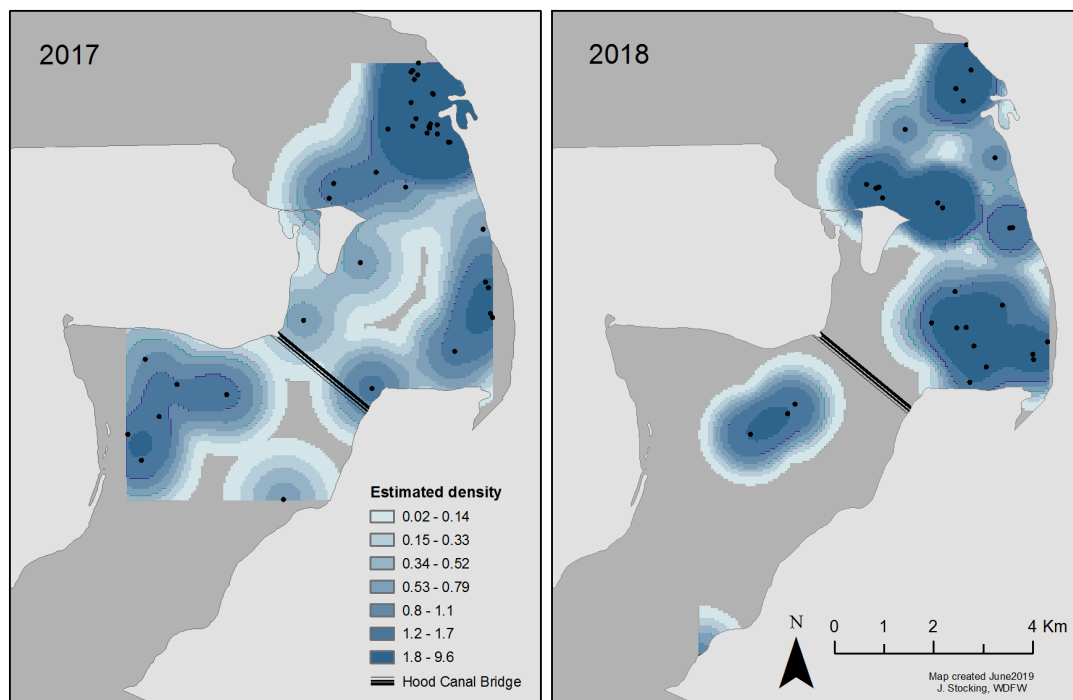


Figure C12. Relative density of Caspian tern (*Sterna caspia*) in line transect surveys of Hood Canal bridge during steelhead outmigration 2017-2018 (n=14visits/year). Points represent observations.

Table C1. Data and distance analysis summary for potential steelhead predator species near Hood Canal Bridge, WA.

Species	#obs	Effective survey distance (m) ^a	Estimated density animals (km ²)	Density Lower 95% CI	Density Upper 95% CI	Estimated abundance	Abundance Lower CI	Abundance Upper CI	Detection model	Distance bins ^b	p-value GOF	Mean cluster size
Pigeon guillemot	730	232	8.496	6.85	10.53	103	82	126	Uniform+	5	0.821	4.2
Rhinoceros auklet	290	207	2.367	1.79	3.12	28	22	37	HN	3	0.070	1.9
Grebes [†]	135	221	1.749	1.06	2.89	21	13	35	HN	5	0.087	3.6
Marbled murrelet	128	174	1.590	0.98	2.59	19	12	31	Uniform+	5	0.997	2.4
Harbor seal	89	226	1.466	1.06	2.03	18	13	24	HN	3	0.349	1.0
Harbor porpoise	82	224	1.118	0.81	1.55	2	1	5	Uniform	3	0.127	1.7
Loons ^{†‡}	32	250	0.103	0.06	0.18	1	1	2	HN	5	0.813	1.1
Cormorants [†]	29	235	0.077	0.05	0.12	1	1	1	Uniform	5	0.883	1.3
Mergansers [†]	26	226	0.144	0.09	0.24	2	1	3	Uniform	5	0.860	2.7

^a Represents distance in which 95% of observations were documented and beyond which data are truncated.

^b Number of distance bins (intervals) in detection function with lowest AIC value.

[†] Multiple species were lumped into this group.

[‡] Forced truncation at 250 m due to distance between transects.

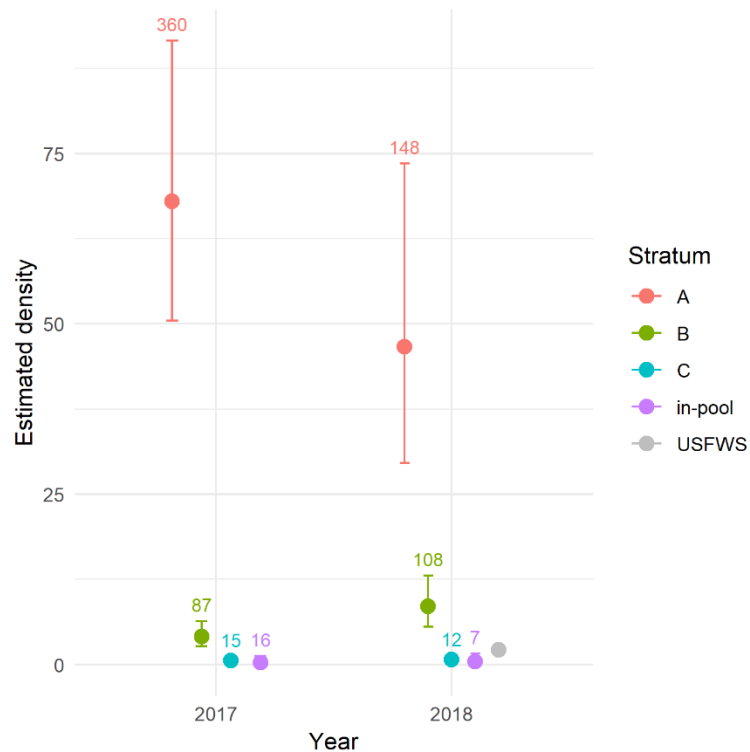


Figure C13. Density estimates (birds/km²) derived by distance sampling of pigeon guillemot (*Cepphus columba*) near Hood Canal Bridge, WA during steelhead outmigration in 2017-2018. Stratum A is 0 - 300 m from the bridge; Stratum B is 301 – 1200 m; Stratum C is 1201 – 3000 m. In-pool refers to animals observed in the two pools within the structure of the bridge; USFWS is estimated density from summer 2018 surveys in the Salish Sea for comparison (see Methods). Error bars represent 95% confidence interval; numbers above bars represent sample size.

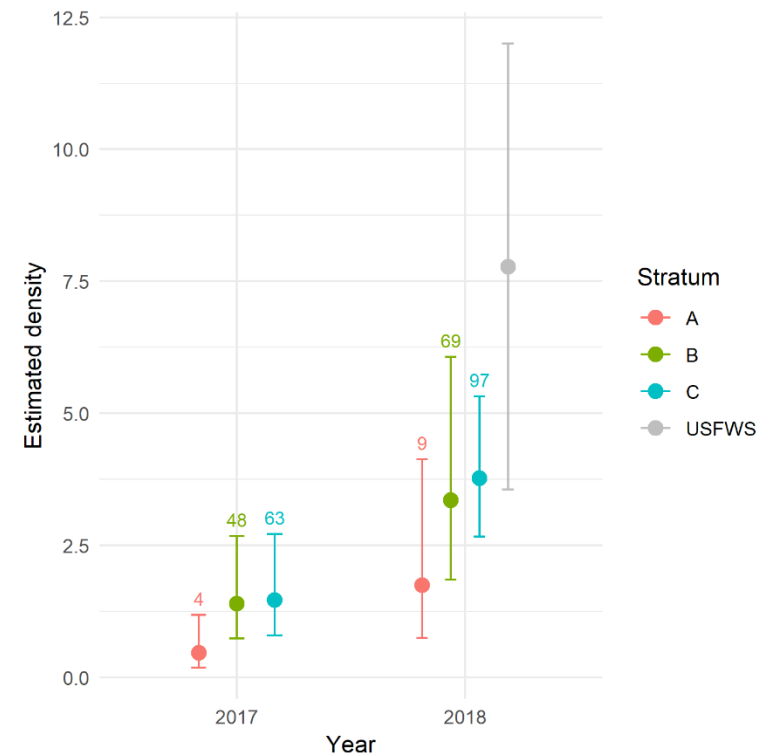


Figure C14. Density estimates (birds/km²) derived by distance sampling of rhinoceros auklet (*Cerorhinca monocerata*) near Hood Canal Bridge, WA during steelhead outmigration in 2017-2018. Stratum A is 0 - 300 m from the bridge; Stratum B is 301 – 1200 m; Stratum C is 1201 – 3000 m. USFWS is estimated density from summer 2018 surveys in the Salish Sea for comparison (see Methods). Error bars represent 95% confidence interval; numbers above bars represent sample size.

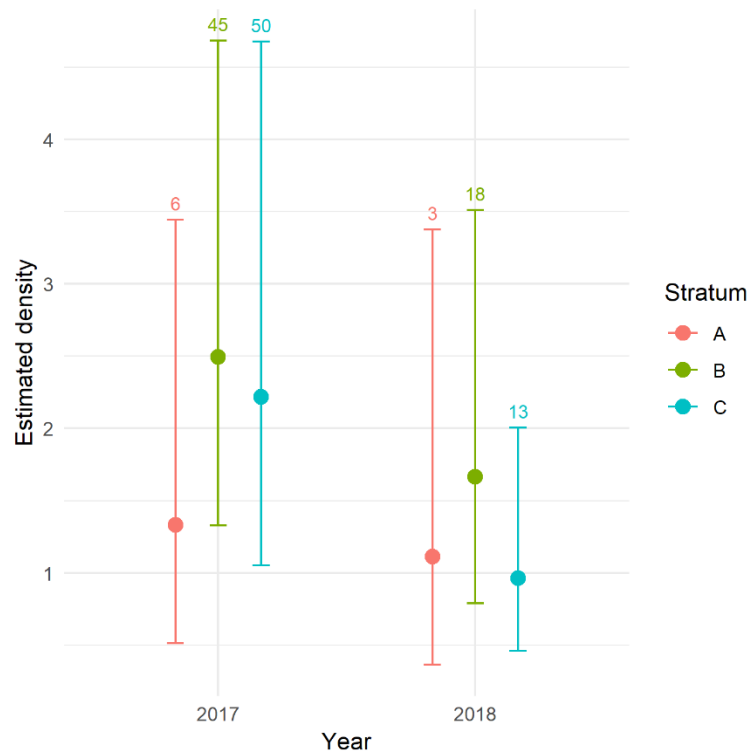


Figure C15. Density estimates (birds/km²) derived by distance sampling of grebes (Family Podicipedidae) near Hood Canal Bridge, WA during steelhead outmigration in 2017-2018. Stratum A is 0 - 300 m from the bridge; Stratum B is 301 – 1200 m; Stratum C is 1201 – 3000 m. Error bars represent 95% confidence interval; numbers above bars represent sample size.

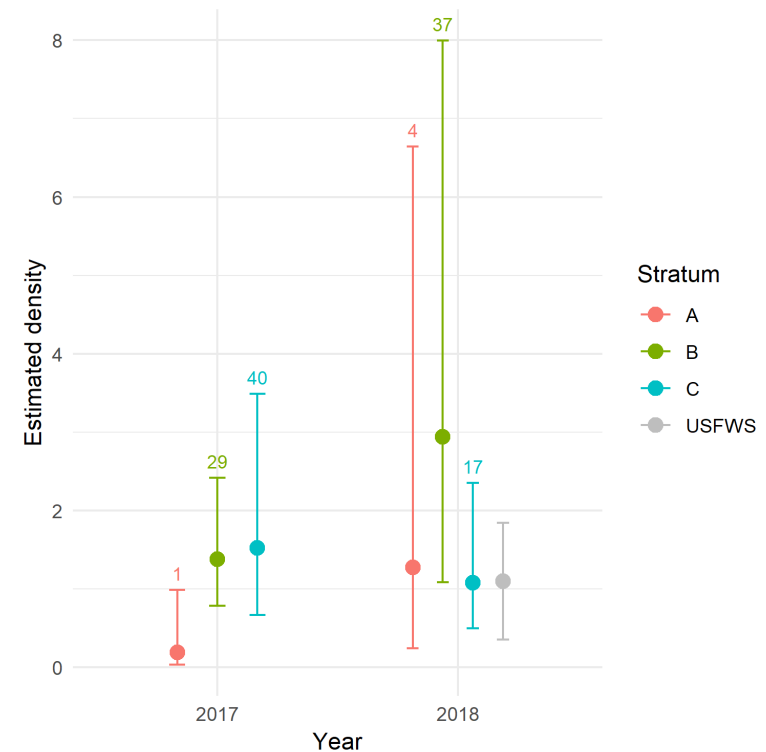


Figure C16. Density estimates (birds/km²) derived by distance sampling of marbled murrelet (*Brachyramphus marmoratus*) near Hood Canal Bridge, WA during steelhead outmigration in 2017-2018. Stratum A is 0 - 300 m from the bridge; Stratum B is 301 – 1200 m; Stratum C is 1201 – 3000 m. USFWS is estimated density from summer 2018 surveys in the Salish Sea for comparison (see Methods). Error bars represent 95% confidence interval; numbers above bars represent sample size.

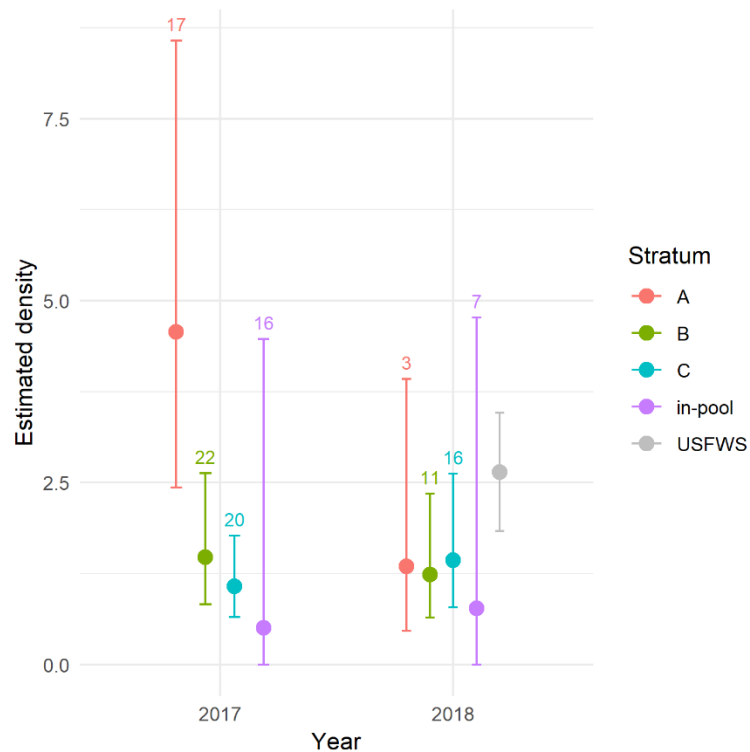


Figure C17. Density estimates (animals/km²) derived by distance sampling of harbor seal (*Phoca vitulina*) near Hood Canal Bridge, WA during steelhead outmigration in 2017-2018. Stratum A is 0 - 300 m from the bridge; Stratum B is 301 – 1200 m; Stratum C is 1201 – 3000 m. In-pool refers to animals observed in the two pools within the structure of the bridge; USFWS is estimated density from summer 2018 surveys in the Salish Sea for comparison (see Methods). Error bars represent 95% confidence interval; numbers above bars represent sample size.

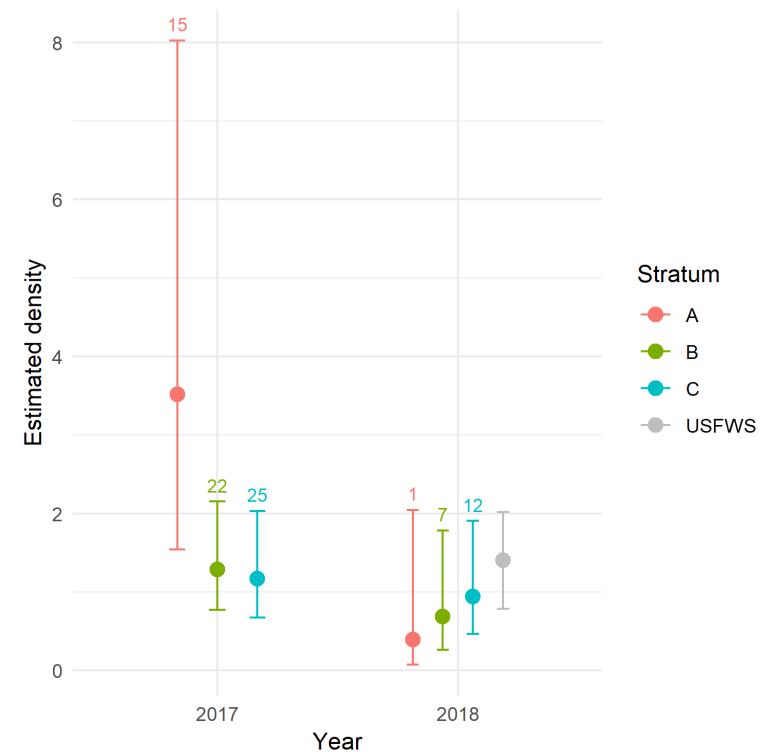


Figure C18. Density estimates (animals/km²) derived by distance sampling of harbor porpoise (*Phocoena phocoena*) near Hood Canal Bridge, WA during steelhead outmigration in 2017-2018. Stratum A is 0 - 300 m from the bridge; Stratum B is 301 – 1200 m; Stratum C is 1201 – 3000 m. USFWS is estimated density from summer 2018 surveys in the Salish Sea for comparison (see Methods). Error bars represent 95% confidence interval; numbers above bars represent sample size.

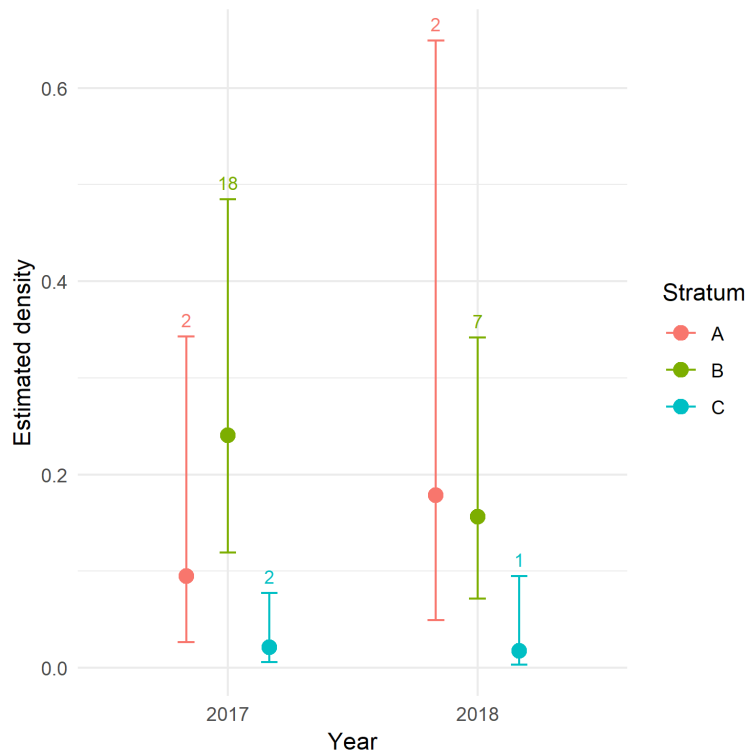


Figure C19. Density estimates (birds/km²) derived by distance sampling of loons (*Gavia spp.*) near Hood Canal Bridge, WA during steelhead outmigration in 2017-2018. Stratum A is 0 - 300 m from the bridge; Stratum B is 301 – 1200 m; Stratum C is 1201 – 3000 m. Error bars represent 95% confidence interval; numbers above bars represent sample size.

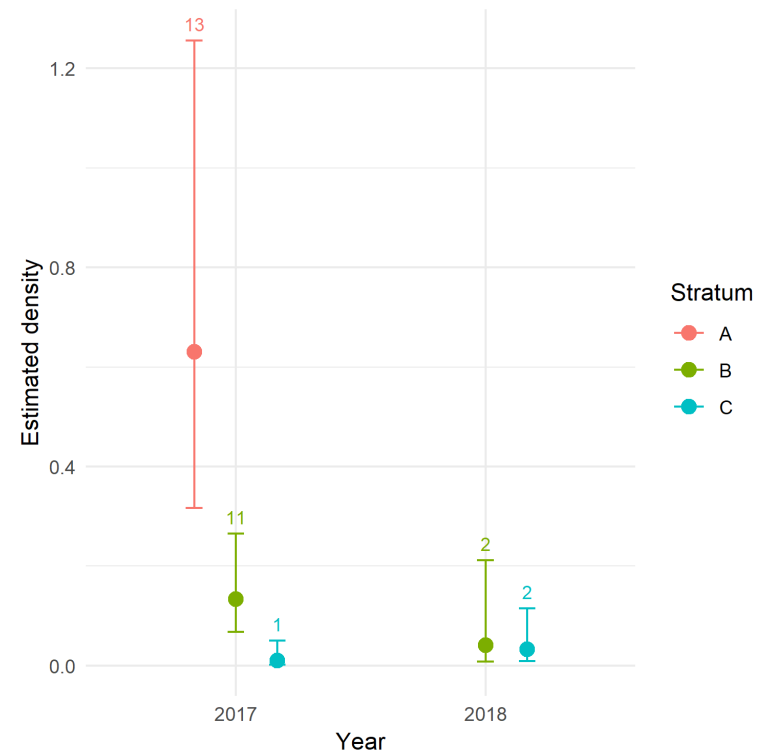


Figure C20. Density estimates (birds/km²) derived by distance sampling of cormorants (*Phalacrocorax spp.*) near Hood Canal Bridge, WA during steelhead outmigration in 2017-2018. Stratum A is 0 - 300 m from the bridge; Stratum B is 301 – 1200 m; Stratum C is 1201 – 3000 m. Error bars represent 95% confidence interval; numbers above bars represent sample size. Missing points indicate insufficient data to generate an estimate for that stratum-year.

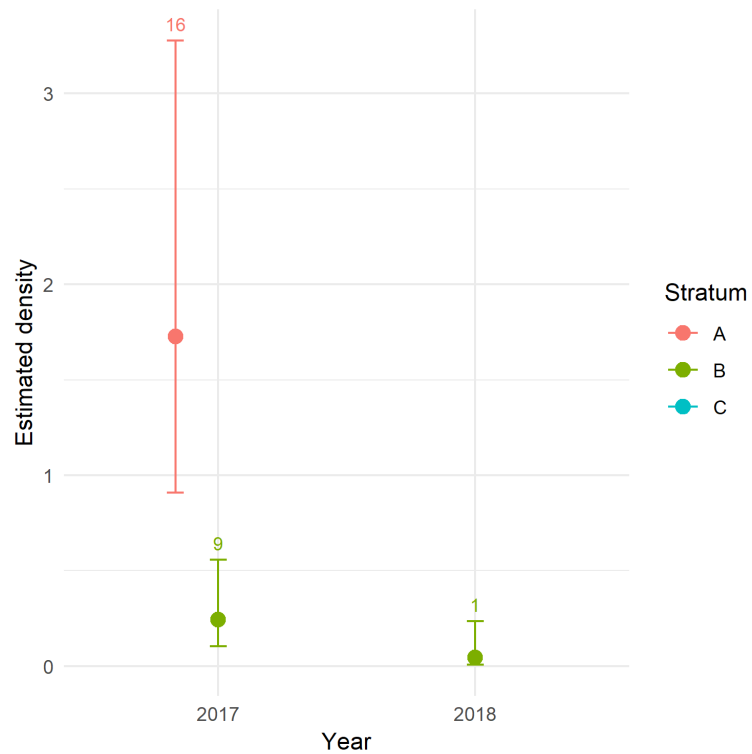


Figure C21. Density estimates (birds/km²) derived by distance sampling of mergansers (*Mergus spp.*) near Hood Canal Bridge, WA during steelhead outmigration in 2017-2018. Stratum A is 0 - 300 m from the bridge; Stratum B is 301 – 1200 m; Stratum C is 1201 – 3000 m. Error bars represent 95% confidence interval; numbers above bars represent sample size. Missing points indicate insufficient data to generate an estimate for that stratum-year.

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Appendix C1. Total observations and total observations by kilometer surveyed of birds and mammals detected during line transect surveys of Hood Canal survey area during steelhead outmigration in 2017 and 2018. Survey effort in 2017 was greater than in 2018, observations/km columns are to facilitate comparison between years (see Appendix C2).

Common name	Scientific name	Observations		Observations/km	
		2017	2018	2017	2018
Bald eagle	<i>Haliaeetus leucocephalus</i>	48	12	0.05	0.02
Belted kingfisher	<i>Megaceryle alcyon</i>	0	1	0.00	0.00
Brandt's cormorant	<i>Phalacrocorax penicillatus</i>	56	23	0.06	0.04
Caspian tern	<i>Hydroprogne caspia</i>	55	29	0.05	0.05
Common loon	<i>Gavia immer</i>	321	115	0.32	0.19
Common merganser	<i>Mergus merganser</i>	3	4	0.00	0.01
Common murre	<i>Uria aalge</i>	35	3	0.03	0.00
Double-crested cormorant	<i>Phalacrocorax auritus</i>	43	19	0.04	0.03
Great blue heron	<i>Ardea Herodias</i>	7	22	0.01	0.04
Horned grebe	<i>Podiceps auritus</i>	1211	397	1.21	0.65
Marbled murrelet	<i>Brachyramphus marmoratus</i>	665	211	0.66	0.35
Osprey	<i>Pandion haliaetus</i>	22	9	0.02	0.01
Pacific loon	<i>Gavia pacifica</i>	78	42	0.08	0.07
Pelagic cormorant	<i>Phalacrocorax pelagicus</i>	138	29	0.14	0.05
Peregrine falcon	<i>Falco peregrinus</i>	1	0	0.00	0.00
Harbor porpoise	<i>Phocoena phocoena</i>	329	141	0.33	0.23
Harbor seal	<i>Phoca vitulina</i>	277	144	0.28	0.24
Pigeon guillemot	<i>Cepphus columba</i>	1649	1265	1.64	2.07
Red-breasted merganser	<i>Mergus serrator</i>	118	16	0.12	0.03
Red-necked grebe	<i>Podiceps grisegena</i>	394	121	0.39	0.20
Red-throated loon	<i>Gavia stellate</i>	17	5	0.02	0.01
Rhinoceros auklet	<i>Cerorhinca monocerata</i>	545	606	0.54	0.99
Unidentified alcid	Alcidae	17	10	0.02	0.02
Unidentified cormorant	Phalacrocoracidae	110	63	0.11	0.10
Unidentified grebe	Podicipedidae	131	64	0.13	0.10
Unidentified loon	Gaviidae	166	46	0.17	0.08
Unidentified merganser	Anatidae	49	23	0.05	0.04
Unidentified sea lion	Otariidae	0	1	0.00	0.00
Western grebe	<i>Aechmophorus occidentalis</i>	475	169	0.47	0.28
California sea lion	<i>Zalophus californianus</i>	13	3	0.01	0.00

Appendix C2. Number of replicates for each steelhead predator survey transect included in distance sampling analysis in 2017 and 2018.

Transect	2017	2018
07	21	14
08	22	14
09	22	14
10	22	14
17	25	14
18	25	14
19	25	14
20	25	14

Appendix C3. Literature review of dive profiles of predator species observed at the Hood Canal Bridge.

Table 1. Summary table of literature sources described in Table 2.

	mean depth (m)	max depth (m)	mean duration (s)	max duration (s)	notes
cormorants	2.2 - 38.2	>100 (BRAC)	22 - 51	120	
loons	no data	no data	33 - 94	124†	‡the Birds of North America account suggests that 10-min (!) dives are very rare, but I
mergansers	<4*	6	~20	120	
common murre	13.4 - 50	180	41 - 71	212	
grebes	<6	no data	25 - 30	73	
marbled murrelet	no data	50*	20 - 44	115	
harbor porpoise	14 - 41	226	44 - 103	321	
harbor seal	50 - 60†	481†		135	†multiple papers suggest seals dive to bottom
pigeon guillemot	10 - 20	50'	30 - 87	204	'black guillemot; none found for PIGU
rhinoceros auklet	<10 - 14	57	15-53	148	
* based on single study					

Table 2. Literature sources describing dive profile characteristics of predator species.

date	author	species	location	depth mean	depth sd	max depth (m)	duration mean	duration sd	max duration (s)	notes
1911	Clay	BRAC								caught in nets at 55-70m
1990	Ainley, et al.	BRAC				>100 m				
1973	Scott, J.M.	BRAC					30.45 sec	13.2	90-100	duration closely related to water depth

1990	Ainley, et al.	BRAC					51 sec		95	
2008	Coleman, JTH	DCCO	NY			25.8	22	10		V-shaped dives
1974	Ross, R.K.	DCCO	Nova Scotia	4.7 m		7.9				
1936	Mendall, H.L.	DCCO					19.3-22 s in 3 m; 22.5-27.7 s in 4.5 m		41 s	
2009	Coleman, JTH	DCCO	NY	10-15 m?		25.8	22 s		17-34 s range	
1995	King et al.	DCCO	MS				11.9 s		45 s	shallow catfish ponds (1.4m)
1929	Lewis, H.F.	DCCO	Ontario						70 s	
2011	Kotzerka et al.	PECO	Gulf of Alaska	2.2-38.2 (median)		32.1-42.2	28-76 (median)		90-120sec (range)	corms most often either made shallow (1-6m) or deep (28-33m) dives
2011	Kotzerka et al.	PECO				42.2 m	4-120 sec range			same paper as referenced above (but different stats pulled)
1985	Hobson & Sealy	PECO					34.9 s	4.1		FOR depth 2-5m (and adults only)
1964	Dow, D.D.	PECO					45.3 s	1.35		FOR depth 1.5-6.1m
1990	Ainley, et al.	PECO					45 s		70 s	
1959	van Tets, G.F.	PECO					31.3 s			
1973	Scott, J.M.	PECO					28.8 s	7.7		
unpubl.	Vlietstra, L.S.	COLO	CA				94 s			
1988	Parker, K.E.	COLO	NY				42.6 s			
1999	Paruk, J.D.	COLO	MI, WI				33.3 s			n=8
2002	Nocera & Burgess	COLO	Canada n Maritimes				30 - 50 s, depending on chick status		124	
1999	Paruk, J.D.	COLO							>120 s (uncommon); >10min! very rare	
unpubl.	Vlietstra, L.S.	PALO	CA				77 s	25		
unpubl.	Vlietstra, L.S.	RTLO	CA				49 s			

1980	Reimchen & Douglas	RTLO	Queen Charlotte	70% of foraging in ≤ 1 m deep						
1996	Alvo, R.	COME		"prefers" < 4 m depth						
1977	Cramp & Simmons	COME					< 30 s		up to 2 min	
1972	Nilsson, L.	COME	Sweden			6 m			20-28 s range	longer in deeper (appears to be contradicted elsewhere in BNA account)
1980	Bowles, W.F. Jr.	RBME					16 s			FOR < 2 m depth
1963	Hending et al.	RBME					17 s			
1985	Piatt & Nettleship	COMU	Newfoundland	20-50 m "normal depth"		often to 70 m; occasionally 180 m				
1924	Dewar, J.M.	COMU					15 s			FOR < 2 m depth
1924	Dewar, J.M.	COMU					61 s			FOR > 8 m depth
1973	Cody, M.L.	COMU	WA				41 s		70	
1990	Ainley, et al.	COMU	CA				55 s		71	
1973	Scott, J.M.	COMU	OR				71 s		140	
2003	Tremblay et al.	COMU	Norway			37 m			119 s	
2009	Hedd et al.	COMU		30 m	0.8	152 m	64 s	1.3	212 s	
2010	Regular et al.	COMU				177 m				
2010	Thaxter, et al.	COMU	UK	13.4 (shallow), 50.4 (deep)	8.9, 7.4		46.4 (shallow), 118.4 (deep)	27.4, 17.2	175ish	
table 2 in	Boyd&Croxall	COMU					66		204	
1924	Dewar, J.M.	HOCR		< 6 m (generally)						
VARIED	VARIED	HOCR	VARIED				7-25 s (norm)		73 s	tends to feed at bottom of

										shallow waters (0-4 m
1970	Simmons	RNGR					24.8 s	0.7		FOR ~2 m depth; "capable of much longer foraging dive times"
1950	Lawrence	WEGR					30.4 s		63 s	
1989	Thoresen, A.C.	MAMU	WA			"within 50m of surface"	20-44 s		2-115 s range	vary with water depth
2003	Henkel, et al.	MAMU	CA				24.8 s	15.7		single radio-tagged bird
1999	Jodice&Collopy	MAMU	OR				26.84			
2009	Peery et al.	MAMU					23.5 s	9	~58 s	
1985	Westgate, et al.	PHPH	Bay of Fundy	14	16	226	44	37	321sec	fewer, deeper dives at night
1985	Westgate, et al.	PHPH	Bay of Fundy	41	32		103	67		individual range (with above)
2013	Linnenschmidt et al.	PHPH	Denmark			14,25, 34 (n=3 indiv)			94,138,213sec	water typically <50m deep
2007	TEILMANN, et al.	PHPH	Danish Belt seas			132m				
1999	Bowen, et al.	PHVI	Nova Scotia			59m			90 - 135sec	
1998	Lesage et al.	PHVI	St. Lawrence Estuary	5.8m			40s			V-shaped dives
1999	Lesage et al.	PHVI	St. Lawrence Estuary	to bottom (20m)						U-shaped dives
2005	Eguchi and Harvey	PHVI	Monterey Bay	5-100 (median)		481		35.25m		
1998	Tollit, et al.	PHVI	Scotland	80% of dives 20-40m; 75% of dives						multiple individuals

				50-60m						
table 2 in	Boyd&Croxall	PHVI					96		138	
multiple papers suggest that seals (PHVI) dive to the bottom										
1994	Clowater & Burger	PIGU	Vancouver Island	15-20m (mode)			87sec (37-144)		144	
1987	Duffy et al.	PIGU	SeaWorld				28.4	9.1		
1973	Scott, J.M.	PIGU		10-20 m "optimal efficiency"					10-144 s range	
1985	Piatt & Nettleship	BLGuill emot	Newfoundland			50m				
table 2 in	Boyd&Croxall	PIGU					84		204	
1993	Burger, et al.	RHAU	B.C.			30m mean deepest dive,	45sec		69sec	90% of time was spent in the top 10m, but most birds had dives to 20-60m

						n=16 (12-60 range)				
1987	Duffy et al.	RHAU	SeaWorld				15.3	6.4		
2016	[Shoji et al.] - see Kuroki paper	RHAU	table 1	14		57	53		148	
2000	Davoren, G.K.	RHAU					37	1.3		
2003	Kato, et al.	RHAU	Japan	12.1	5.5	51.6	42.7 s	17.7	131	
2003	Kuroki, et al.	RHAU	Japan	14	1.8	57	53	8	148	

[Appendix D. Deng et al. 2018](#)

Hood Canal Bridge noise impact assessment: phase 1 findings

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MEMORANDUM

Date: **January 29, 2018** Project No.: **68000**

To: **Iris Kemp; Michael Schmidt** Internal Distribution: **Tarang**
(LLTK) **Khangaonkar**

From: **Daniel Deng; Xiaoqin Zang,**
Jayson Martinez, Jun Lu,
Scott Titzler (PNNL)

Subject: **Hood Canal Bridge noise impact**
assessment: phase 1 findings

Purpose

This work is the first phase of the Hood Canal Bridge noise impact assessment to evaluate the effect of sounds and vibrations generated by the bridge on the migrating salmon. This memo summarizes the experimental method and preliminary findings of the pilot trial, including:

- Measuring the sound pressure with hydrophones lowered down the bridge into water to monitor sound pressure levels over a month
 - Measuring the acceleration with an array of three orthogonally mounted single-axis accelerometers deployed near the edge of the pontoon to monitor bridge vibration over a month
 - Identifying the correlation between measured sound & vibration and the traffic volume on the bridge
 - Recording sounds in the canal using a hydrophone deployed from a boat to evaluate sound pressure levels in the canal
 - Calculating sound pressure level attenuation with the distance from the bridge
 - Evaluating the measured sound pressure levels and acceleration magnitudes with reference to previous studies on the effect of anthropogenic sounds on salmon
-

1. Introduction

The objective of this study is to establish whether there is a relationship between steelhead smolt behavior and the anthropogenic noises associated with the Hood Canal Bridge. And, if so, does a change in behavior lead to an increased probability of mortality? This study is planned to be performed in two phases. Phase 1 was done to roughly characterize noise propagation from the bridge, and to determine whether sound (pressure and particle motion) are in a range that could be negatively impacting steelhead migration and other juvenile salmon behavior. If the results of Phase 1 suggest a more detailed representation of noise propagation is needed, then Phase 2 will be implemented. This documents the methods and preliminary findings of Phase 1.

This study was inspired by a recent research conducted by NOAA's Manchester Research Laboratory, which has provided "strong evidence of a substantial migration interference and increased mortality risk associated with the Hood Canal Bridge, and may partially explain low early marine survival rates observed in Hood Canal steelhead populations" (Moore et al. 2013). Increased probable mortalities were consistently observed at the Hood Canal Bridge during 2006-2010 study with exception of 2009, when the bridge was closed to vehicle traffic during the steelhead smolt outmigration. This observation led to the need to consider the effect of anthropogenic noise produced by the vehicle traffic on the bridge on the migrating steelhead smolts.

The behavior of salmon in response to underwater sounds is still largely unknown. It is well recognized that salmon are sensitive to particle motion rather than the fluctuations in sound pressure. In our study, both sound pressure and particle acceleration were measured and evaluated with reference to the thresholds established in previous research. For the sound pressure levels, as a conservative measure, NOAA Fisheries and U.S. Fish and Wildlife Service have suggested 150 dB re 1 μ Pa root mean square (rms) as the threshold for behavioral effects to fish species that are listed as being threatened or endangered. However, it should be noted that due to the lack of data, the specific threshold for salmon behavior in the ocean in response to continuous sound sources is still unknown. For the particle acceleration, Knudsen et al. (1994) reported that a particle acceleration of 0.01 m/s^2 at 10 Hz at 3 m deterred downstream migrating Atlantic salmon smolts in a river. In our study, we evaluated the acceleration in both the infrasound band of 5-10 Hz and the broadband of 0.5-1000 Hz with reference to the 0.01 m/s^2 threshold.

To characterize the sound and vibration produced by the bridge, we first deployed three sets of measuring systems along the bridge. Each of the measuring system was composed of a hydrophone, an array of three orthogonally mounted single-axis accelerometers, a data

acquisition system and a solar power unit. Sound pressure and acceleration data were recorded continuously for a month. Sound pressure levels and acceleration magnitudes were calculated in every second, every minute and every hour, respectively. To verify the relationship between the measured sound and the vehicle traffic on the bridge, we calculated the correlation coefficient between sound pressure levels/acceleration magnitudes and traffic volume. Because wind speed was a potential factor that could contribute to the measured sound, we also correlated sound pressure and acceleration with wind speed. The experiment on the bridge, the data processing method and results are reported in Section 2, 3 and 4. In addition to the measurement along the bridge, sound pressure levels were also measured near the bridge on a boat, as reported in Section 5.

2. Experimental Setup

Three sets of low-power, fully autonomous sound and vibration monitoring systems were installed on the Hood Canal Bridge. The signals from the hydrophones and accelerometers were sampled at 2 kilohertz (kHz), allowing for measurement in the frequency band of 5 Hz to 1 kHz for the hydrophones and 0.5 Hz to 1 kHz for the accelerometers. This range is critical for understanding the behavioral response of salmonids to sound (Popper and Carlson 1998) within the hearing threshold for juvenile Chinook salmon, which from available audiograms extends up to at least 800 Hz (Halvorsen et al. 2009).

Each system included a hydrophone, an array of three orthogonally mounted single-axis accelerometers, the signal conditioning modules for the hydrophone and accelerometers, a low power single board computer, a cellular modem, and a solar panel used to provide power and charge battery banks:

- **Hydrophones:** a RESON TC4032-1 hydrophone was installed at each measurement site. The TC4032-1 is an omni-directional low noise hydrophone with a built-in 10 dB preamplifier, receiving sensitivity of -164 dB reference to 1 volt per microPascal (μPa) and a frequency range of 5 Hz to 120 kHz (Appendix A). The hydrophones were powered by RESON EC6073 input modules.
- **Accelerometers:** three PCB Piezotronics model 393A03 single-axis accelerometers were installed in a tri-axial array configuration to measure particle motion relative to the vibration of the concrete bridge at each of the measurement sites. The PCB Piezotronics model 393A03 accelerometers are designed to measure ultra-low amplitude, low frequency vibrations. They have a frequency range of 0.5 Hz to 2 kHz (Appendix A) and a broadband resolution of 0.0001 m/s^2 .

- **Data Acquisition System:** a Develogic Subsea System OBS.Vault was used to collect the data from the hydrophones and accelerometers. This system is a low-power autonomous data collection system that can sample at up to 4 kHz. This system can simultaneously collect data from 4 channels with a 31 bit resolution and a measurement range of ± 2.5 V. This system features built-in user-selectable gain and filters, although for this deployment no gain was used and the filters were not enabled.
- **Power:** each measurement site was powered by a 100 W solar panel that was used to charge two 125 Ah AGM batteries that were connected in parallel resulting in a battery capacity of 250 Ah. This combination of solar panel and batteries was able to power each site from the time when the systems were deployed on 5/16/17 to 7/26/2017.

The sound and vibration monitoring gear was deployed on the south side of the Hood Canal Bridge on 5/16/17. Prior to deployment it was observed that the sounds of vehicles driving on the roadway was significantly louder when driving over the metal drawbridge section in the middle of the bridge relative to the concrete sections on the ends. For this reason the sites were shifted slightly closer to metal section of the roadway. Site one was located at the pier designated S1, site two was at pier J5, and site three was deployed at pier G5 (Figure 2.1)



Figure 2.1: Location of measurement sites on the Hood Canal Bridge

Prior to the deployment each of the hydrophones and accelerometers were calibrated in the laboratory. The measurement system and sensors were deployed on the HCB in the same configuration as they were tested in the laboratory (Appendix B).

The hydrophones were attached to weighted stainless steel frames (Figure 2.2). These frames had sections of garden hose attached to the back side to eliminate noise from metal on concrete. A steel anchor was first deployed on a stainless steel wire rope, which was secured to the bridge by wrapping it around the nearby support pillar. This created a “track” that the hydrophone frame can be lowered down on, allowing the hydrophone to be more easily pulled up if necessary. The hydrophones were deployed 10 ft below the water surface. Anywhere that the stainless steel cable would be in contact with the concrete a section of garden hose was placed over the cable to prevent abrasion of the concrete.



Figure 2.2: Hydrophone deployment

The accelerometers were deployed near the edge of the pontoon close to where the hydrophones were lowered down (Figure 2.3). The three accelerometers were mounted in a tri-axial array to a machined stainless steel block, to provide three axes of measurement (X, Y, and Z), and the block was glued to a prepared location on the concrete of the pontoon. The accelerometers were deployed in a right handed coordinate system where channels 1, 2, and 3 corresponded to X, Y, and Z. The X-axis was perpendicular to the bridge facing the north direction, the Y-axis was parallel to the bridge facing the west direction, and the Z-axis was vertical.



Figure 2.3: Accelerometer deployment

Prior to deploying each of the sensors portable test devices (shaker for accelerometers and pistonphone for hydrophones) were used to confirm that each channel was operational. It was discovered that site 1 was not operating correctly and the problem couldn't be identified in the field. On 5/25/2017 it was discovered that the data acquisition system for site 1 had gotten damaged during transport so it was replaced with a backup unit. After replacing the data acquisition system for site 1 all of the measurement sites were operational and allowed to collect continuous data, with the data being downloaded on a weekly basis.

All cables were routed from the side of the pontoon to the storage container, which contained all of the electronics, using cable protectors (Figure 2.4). The solar panels were placed as close to the edge of the pontoon that still allowed enough room for vehicles to drive by if necessary. Excess sensor and solar panel cables and the electronics project boxes were secured to the nearby support pillar. In addition to securing the project boxes to the support pillars the boxes were kept in place by the two batteries with a total weight of about 150 lbs.



Figure 2.4: Routing of sensor cables and position of solar panel

3. Data processing

3.1 Threshold and frequency range

For the sound pressure, raw data were processed by a 5-800 Hz bandpass filter, which was jointly determined by the lower bound of the hydrophone sensitivity (Appendix A) and the hearing threshold of juvenile Chinook salmon (Halvorsen et al. 2009). The selected threshold was 150 dB re 1 μ Pa rms, which was suggested by NOAA Fisheries and U.S. Fish and Wildlife Service for behavioral effects to fish species that are listed as being threatened or endangered.

Salmon are believed to be more sensitive to particle motion than sound pressure. Table 1 lists a literature synthesis of the avoidance response of juvenile salmon to infrasound. Knudsen et al. (1992) studied Juvenile Atlantic salmon in a pool and concluded that the particle acceleration at 5-10 Hz should be at least 0.01 m/s² to elicit an avoidance response. In a following study, they reported that a particle acceleration of 0.01 m/s² at 3 m deterred downstream migrating Atlantic salmon smolts in a river (Knudsen et al. 1994). Therefore, in our study, we selected

0.01 m/s² in the 5-10 Hz band as the threshold of acceleration magnitude, and evaluated the acceleration magnitudes calculated in each second referring to the 0.01 m/s² threshold.

Table 1: A literature synthesis of the avoidance response of juvenile salmon to infrasound (<20 Hz).

Researcher	Fish species	Test frequency	Location of study	Results
Knudsen et al. 1992	Juvenile Atlantic salmon	5, 10, 60 and 150 Hz	In a tube	The thresholds for awareness reactions were much lower at 5-10 Hz than at 150 Hz.
		10 and 150 Hz	In a pool	1. 10 Hz sound evoked avoidance response for fish within 2 m of the sound source. 2. The avoidance response threshold to 10 Hz sound was 10-15 dB above the spontaneous awareness reaction threshold. 3. At 5-10 Hz the particle acceleration should be at least 0.01 m/s ² to elicit an avoidance response. 4. The 150 Hz sound failed to evoke avoidance response.
Knudsen et al. 1994	Juvenile Atlantic salmon	10 and 150 Hz	In a small river	Avoidance response to 10 Hz sounds was seen up to 3 m from the source, where the particle acceleration was about 0.01 m/s ² .
Knudsen et al. 1997	Juvenile spring chinook salmon and rainbow trout	10 Hz	In a tank	Initial tests always resulted in a strong flight response, but after three to four tests the fish more typically simply swam away as far as possible from the source. The avoidance response did not habituate even after 20 trials.
Mueller et al. (PNNL) 1998	30-70 mm rainbow trout and chinook salmon	7-14 Hz, 150, 180, and 200 Hz	In a tank	1. Juvenile salmonids, as small as 30 mm long, have infrasound detection capability when the particle motion exceeds 10 ⁻² m/s ² at a frequency of 7-10 Hz. 2. A startle response in wild chinook salmon was observed when exposed to high-intensity (162 dB re 1 µPa), 150-Hz pure tone sound. 3. No observable effects were noted on hatchery chinook salmon or rainbow trout fry when exposed to 150, 180, or 200 Hz high-intensity sound. 4. Even for the maximum range at which acceleration measurement was made (4.2 m), the local flow acceleration exceeded the minimum required for fish reactance (10 ⁻²

				m/s ²).
Mueller et al. (PNNL) 2001	Juvenile chinook salmon, brook trout and rainbow trout	10 Hz	In a tank	1. Wild chinook salmon are much more likely to respond to 10 Hz infrasound than hatchery reared fish. 2. Rainbow trout fry showed no observable avoidance responses to infrasound, although a startle response was observed with 16% of the first five test exposures. 3. Test groups of eastern brook trout displayed the least behavior responses to the infrasound.

3.2 Sound pressure and acceleration

The acceleration data were collected by three orthogonal accelerometers deployed at the three measurement sites along the bridge near the edge of the pontoon. The accelerometers were deployed in a right handed coordinate system where channels 1, 2, and 3 corresponded to X, Y, and Z. Sound pressure data were collected by hydrophones deployed at each measurement site near the accelerometers and recorded by channel 4 of the OBS system. All data was collected with a sampling frequency of 2 kHz and was saved as waveform audio files with a range of ± 1 . Since the measuring range of OBS system is -2.5 V to 2.5 V, raw sound pressure data and acceleration data were first multiplied by 2.5, and then converted to physical units according to the calibration sheet (Appendix B). Bad data files, which had impulsive peaks of 2.5 V in all channels, were detected and excluded from data analysis. A total of eight one-minute data files were removed.

After converting to physical units, sound pressure data were filtered with a bandpass filter of 5-800 Hz, and then processed in the form of the following metrics:

- **Root mean square (RMS) sound pressure level (SPL_{rms}):** the level of the log-transformed square root of the average square pressure of the signal over a specific time interval:

$$SPL_{rms} = 20 \log_{10} \left(\frac{P_{rms}}{1 \cdot \mu Pa} \right) \quad (1)$$

where P_{rms} is RMS pressure in μPa , and SPL_{rms} is RMS sound pressure level in dB referenced to 1 μPa .

- **Peak sound pressure level (SPL_{peak}):** the level of the maximum absolute amplitude value in a signal during a specified time interval:

$$SPL_{peak} = 20 \log_{10} \left(\frac{|P_{peak}|}{1 \cdot \mu Pa} \right) \quad (2)$$

where $|P_{peak}|$ is the absolute peak pressure in μPa , and SPL_{peak} is the absolute peak sound pressure level in dB referenced to 1 μPa .

Since the hydrophones in use have an internal amplifier of 10 dB gain, the calculated RMS and peak SPLs were subtracted by 10 dB accordingly.

The X, Y, and Z components of the acceleration data (a_x , a_y , and a_z) were converted to physical units of m/s^2 respectively. Then, the magnitude of acceleration in 0.5-1000 Hz band was calculated with

$$a = \sqrt{a_x^2 + a_y^2 + a_z^2} . \quad (3)$$

To evaluate the magnitude of acceleration in the infrasound range, a_x , a_y , and a_z were each filtered using a 5-10 Hz bandpass filter. After filtering the individual acceleration components the magnitude of acceleration in the 5-10 Hz band was calculated using Equation (3). The acceleration of both the 0.5-1000 Hz and 5-10 Hz bands were processed in the following metrics:

- **Acceleration peak:** the maximum magnitude during a specified time interval, with the unit of m/s^2 ;
- **Acceleration RMS:** first take the RMS of each acceleration component over a specific time interval, and then take the square root of the sum of the squared RMS values of three components, with the unit of m/s^2 , as Equation (4) (Nedelec et. al, 2016).

$$a_{rms} = \sqrt{rms(a_x)^2 + rms(a_y)^2 + rms(a_z)^2} . \quad (4)$$

Both the sound pressure data and the acceleration data were recorded in many one-minute-long audio files. The sound pressure and acceleration metrics were first calculated within every second, and then in every minute and every hour, respectively. The results obtained in every second were to show the instantaneous variation of each measurement; the metrics calculated in every minute were to show the diurnal variation of these metrics; the hourly measurements were to be correlated with the traffic volume, which was only available on hourly basis.

3.3 Traffic volume

Traffic volume data were provided by Washington State Department of Transportation via the website http://www.wsdot.wa.gov/data/tools/geoportal/PtrSites/?Site_ID=R085.

Two measures of traffic volume data were provided: one counted the number of vehicles that passed the bridge in each hour in each bound (i.e., direction); the other specified the axle spacing type of each vehicle, including motorcycle, car, van and pickup, single-unit truck,

double-unit truck and triple-unit truck. The second measure of traffic volume data were processed by multiplying the axle number (1, 2, 3 or 4) with the corresponding number of vehicles of each axle spacing type, and then sum up all types as the traffic volume in each bound. Then, the traffic volume data in eastbound and westbound were summed up as the total traffic volume within given hours. Through comparison, the second measure of traffic volume, which added the traffic type as a weight to traffic volume, has a higher correlation coefficient with measured SPL and acceleration than the more general first measure of traffic volume.

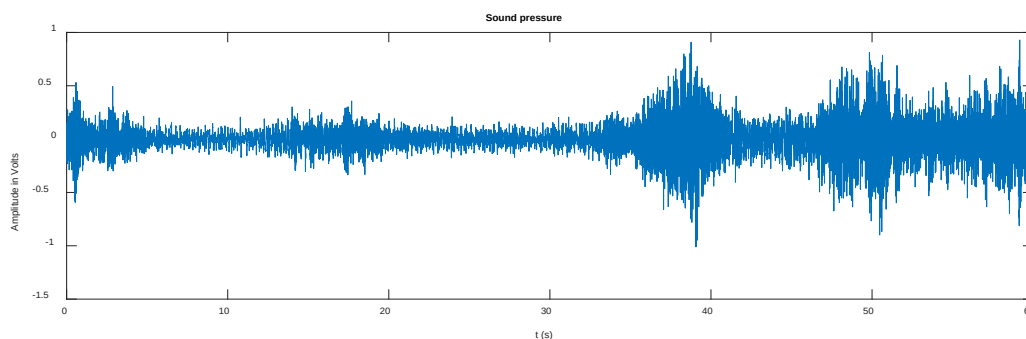
3.4 Wind speed

In addition to traffic volume, wind speed, which could affect the measured SPL and particle acceleration at the measurement sites, were also analyzed. Metrological data were obtained from a buoy located at Port Townsend, which is about 20 miles away from Hood Canal Bridge. Historical metrological data were downloaded from National Data Buoy Center, station PTWW1. Hourly mean wind speed was correlated with SPLs and accelerations to evaluate the relationship between wind and observed noise.

4 Results

4.1 Sound pressure

To show the characteristics of sounds collected in the field experiment, two representative examples were selected and compared in waveforms: one with the cars crossing the bridge during the high traffic hour in the afternoon; the other with no cars on the bridge at late night. The waveforms of the two one-minute long data files were compared in Figure 4.1. The passage of motor vehicles on the bridge caused loud wave packets in the sound pressure waveform, which could be identified by listening to the audio file. On the other hand, during the night when no vehicles were crossing the bridge, it was very quiet.



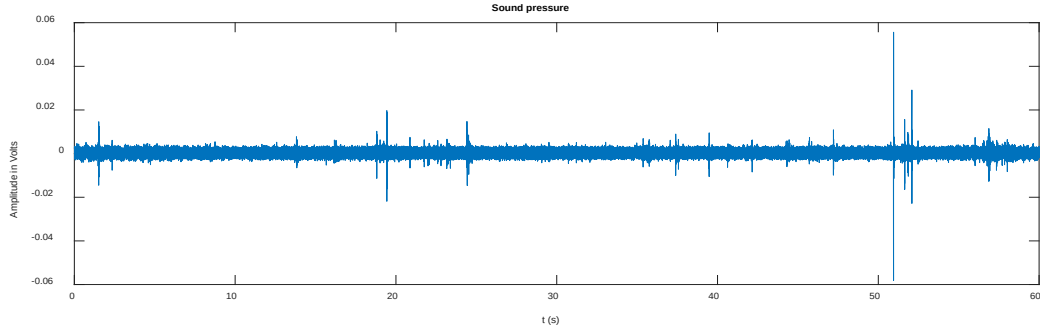


Figure 4.1 Two examples of sound pressure data files. Top panel: field data with motor vehicles crossing the bridge during high traffic hours in the afternoon. Bottom panel: field data with no cars on the bridge in the late night.

Following the data processing method given in the previous section, RMS and peak sound pressure levels (SPLs) were calculated for every one-second-long period of data. Figure 4.2, 4.3 and 4.4 show the results of the first week (from 12:38 PM, May 25th to 11:06 AM, May 30th 2017) at Site 1, 2 and 3, respectively. Diurnal variation was observed in the SPLs at all sites. It appears that the sound was quiet during the night and loud during the day. The RMS SPLs varied from 100 to 150 dB re 1 μ Pa, while the peak SPLs varied from 110 to 160 dB re 1 μ Pa. SPL_{rms} values were occasionally over the threshold of 150 dB re 1 μ Pa rms suggested by NOAA Fisheries and U.S. Fish and Wildlife Service, denoted by the red line in each figure.

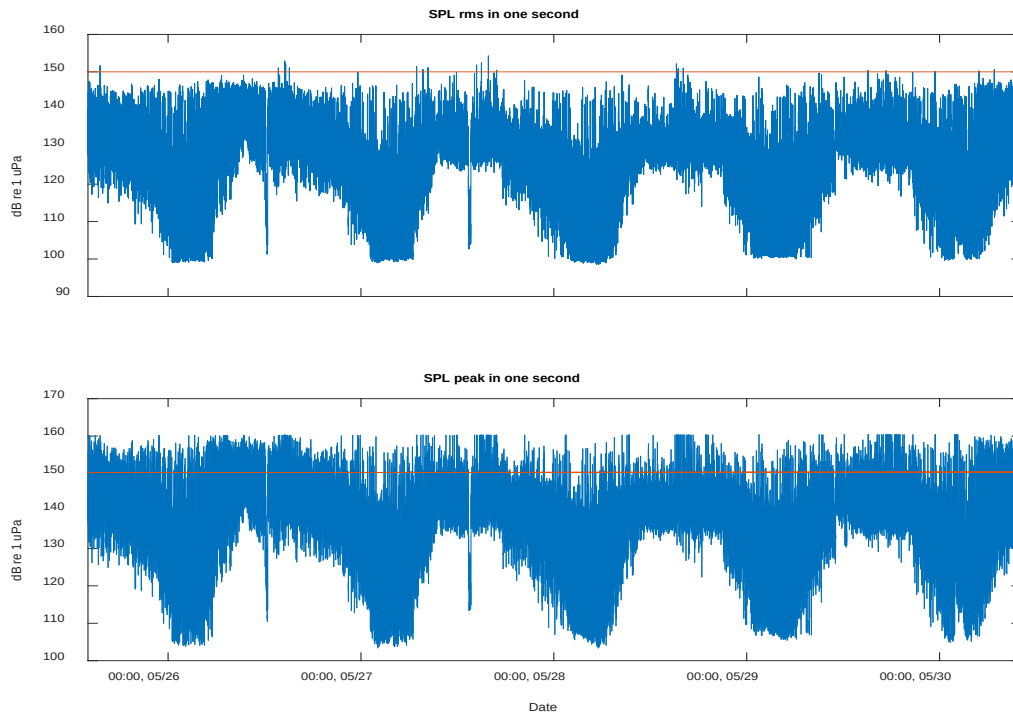


Figure 4.2: RMS and peak sound pressure levels calculated with every one-second data at Site 1.

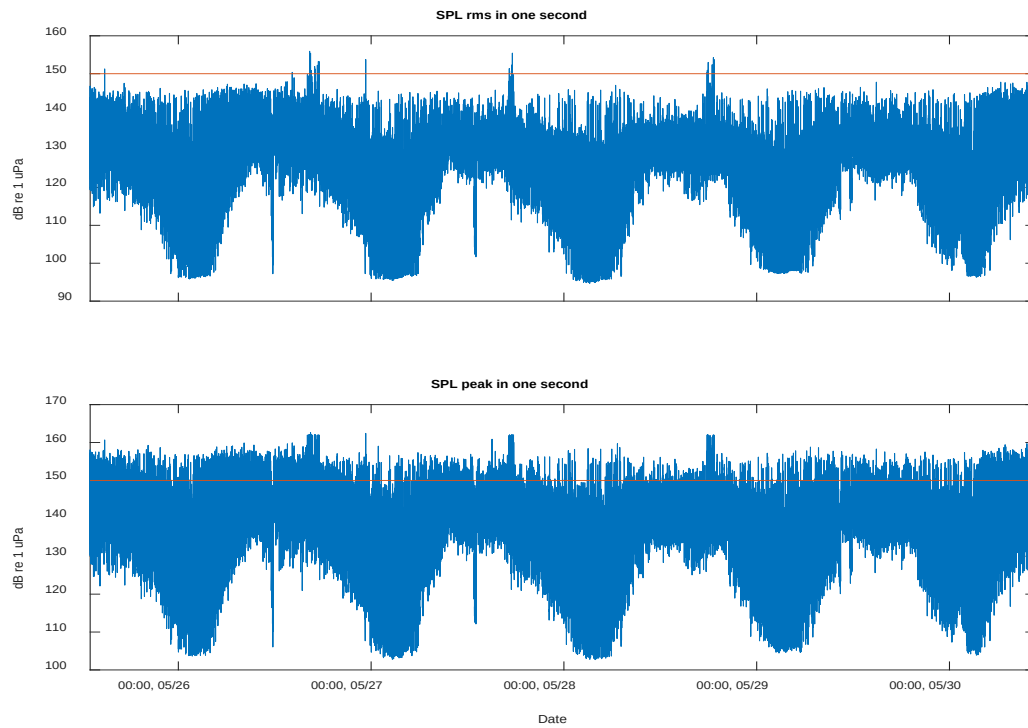


Figure 4.3: RMS and peak sound pressure levels calculated with every one-second data at Site 2.

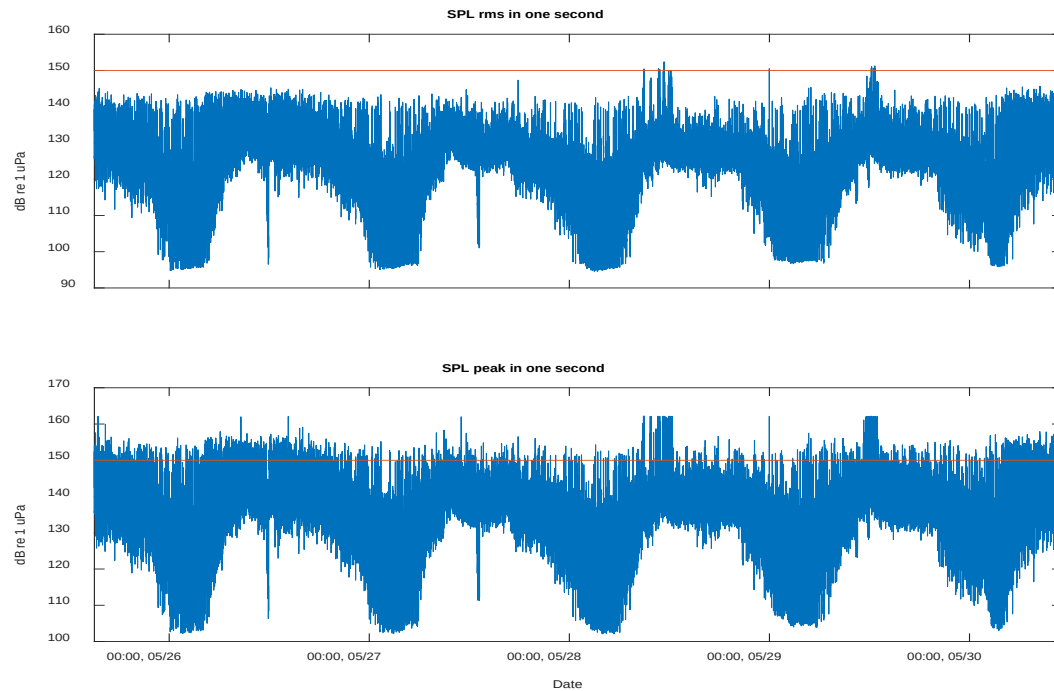


Figure 4.4: RMS and peak sound pressure levels calculated with every one-second data at Site 3.

4.2 Acceleration

Similar to the sound pressure data, two examples of acceleration data files were compared to characterize the vibration in the field experiment. The acceleration waveforms with vehicles crossing the bridge during high traffic hours in the afternoon (Figure 4.5) and with no vehicles on the bridge during late night (Figure 4.6) were compared. Vehicles crossing the bridge were identified by the wave packets in each component of acceleration magnitudes. During the late night when no vehicles were crossing the bridge, the acceleration was much lower than during high traffic hours. A comparison of the above two examples of acceleration magnitudes in 0.5-1000 Hz and 5-10 Hz bands was shown in Figure 4.7. Combined with the sound pressure analysis in section 4.1, the two examples presented validated the experimental method, which was designed to measure the accelerations caused by the vehicles crossing the bridge.

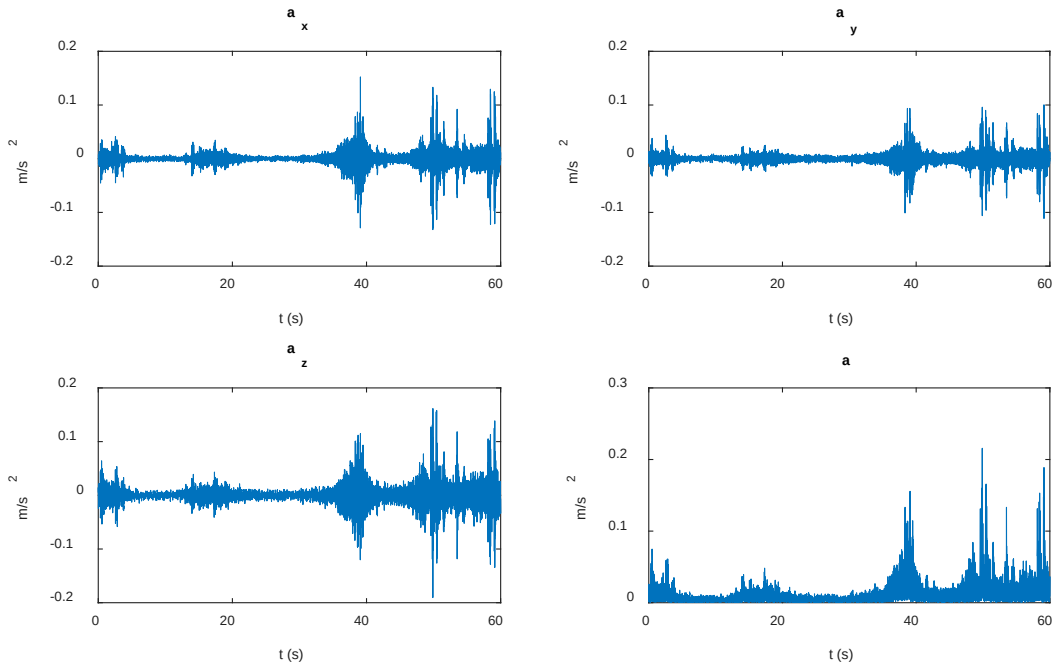


Figure 4.5: An example of acceleration (a_x , a_y , a_z and magnitude) when vehicles were crossing the bridge during high traffic hours in the afternoon.

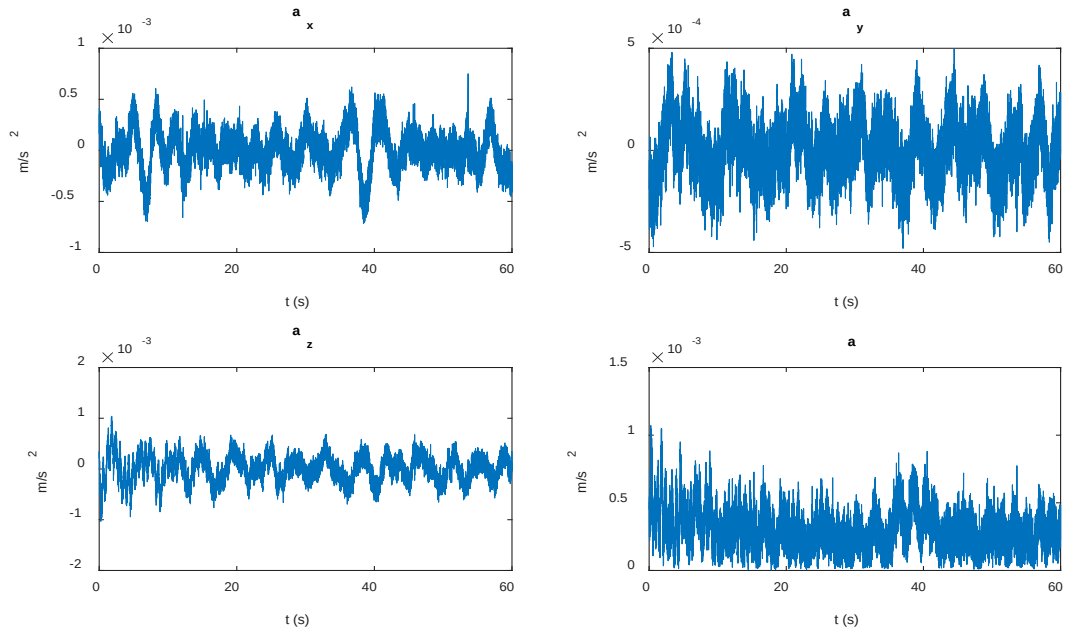


Figure 4.6: An example of acceleration (a_x , a_y , a_z and magnitude) when no vehicles were crossing the bridge during late night.

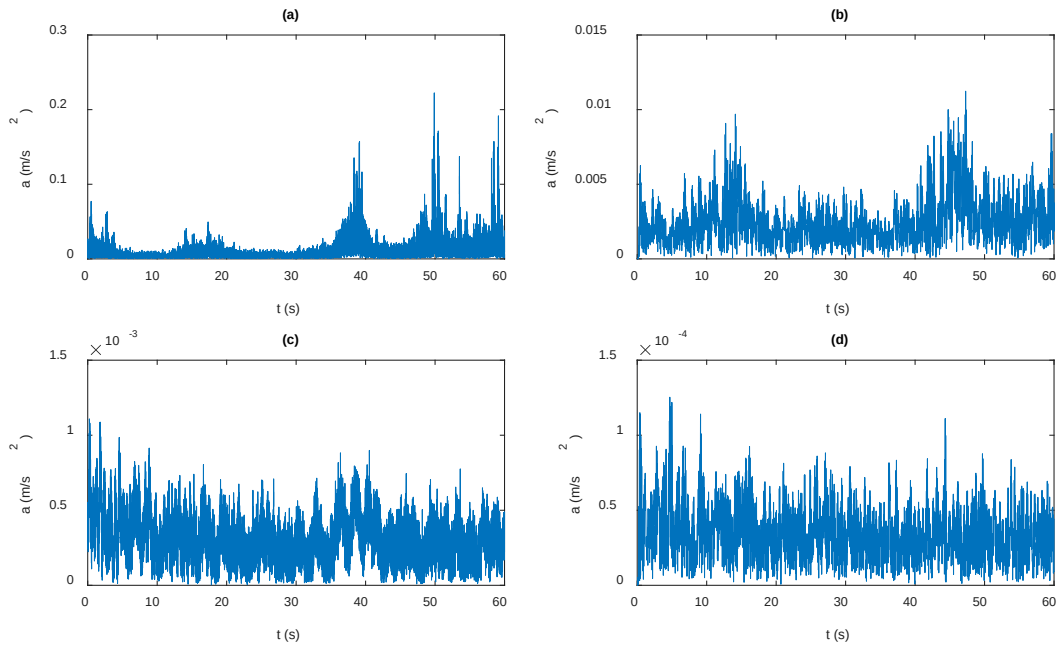


Figure 4.7: (a) Acceleration magnitude in 0.5-1000 Hz band with vehicles crossing the bridge during high traffic hours in the afternoon. (b) Acceleration magnitude in 5-10 Hz band at the same time as (a). (c) Acceleration magnitude in 0.5-1000 Hz band with no vehicles crossing the bridge during late night. (d) Acceleration magnitude in 5-10 Hz band at the same time as (c).

Using data in every second, acceleration RMS and peak values were calculated in two frequency bands: the first band included all frequencies from 0.5 to 1000 Hz, the other covered only the infrasound band from 5 to 10 Hz. Both types of accelerations were plotted with a red threshold line of 0.01 m/s^2 , as shown in Figure 4.8, 4.9 and 4.10. Acceleration RMS values in the 5-10 Hz band exceeded the threshold occasionally at all sites. By comparison, accelerations at Site 2 (the site closest to the metal drawbridge section) were higher than accelerations at Site 1 and 3. The acceleration calculated with every one-minute period of data (Figure 4.11) showed a clearer diurnal variation than the accelerations calculated in every second (Figure 4.9).

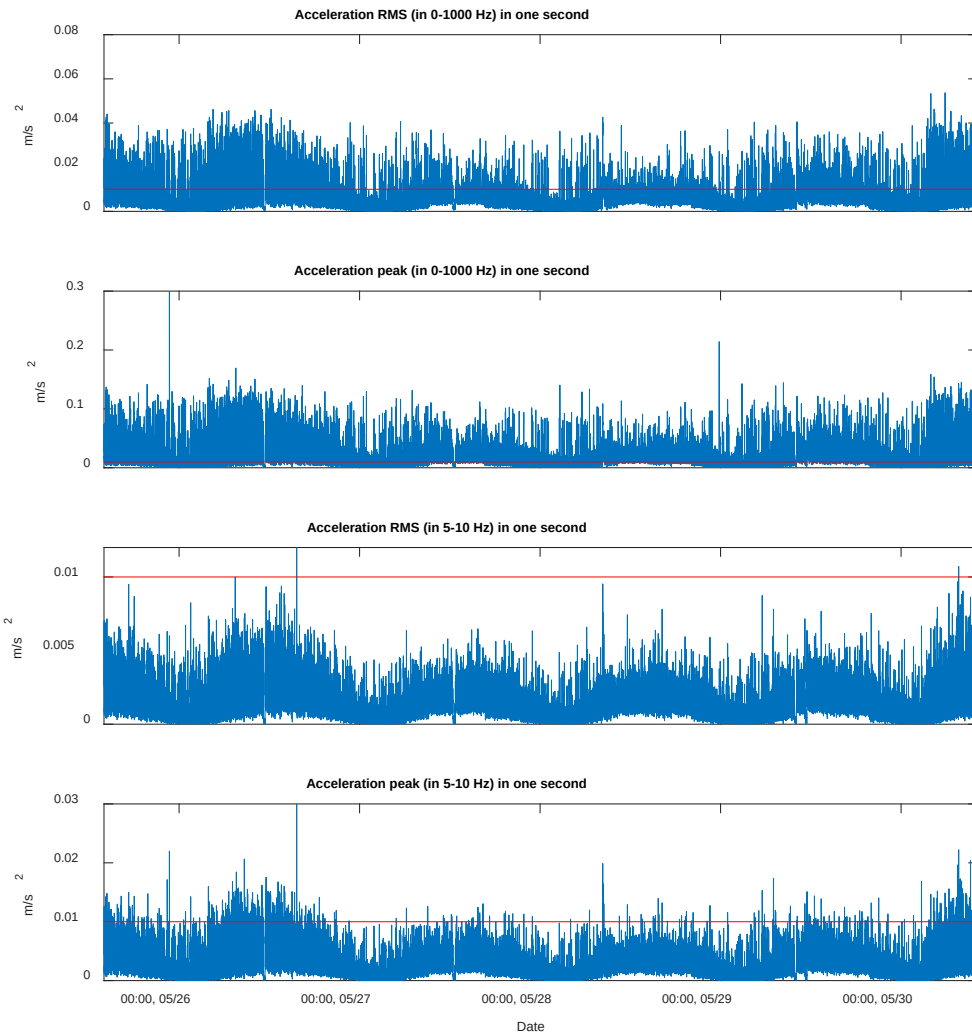


Figure 4.8: RMS and peak accelerations calculated with every one-second-long data at Site 1. Top two panels are accelerations in the 0.5-1000 Hz band. Bottom two panels are accelerations in the 5-10 Hz band.

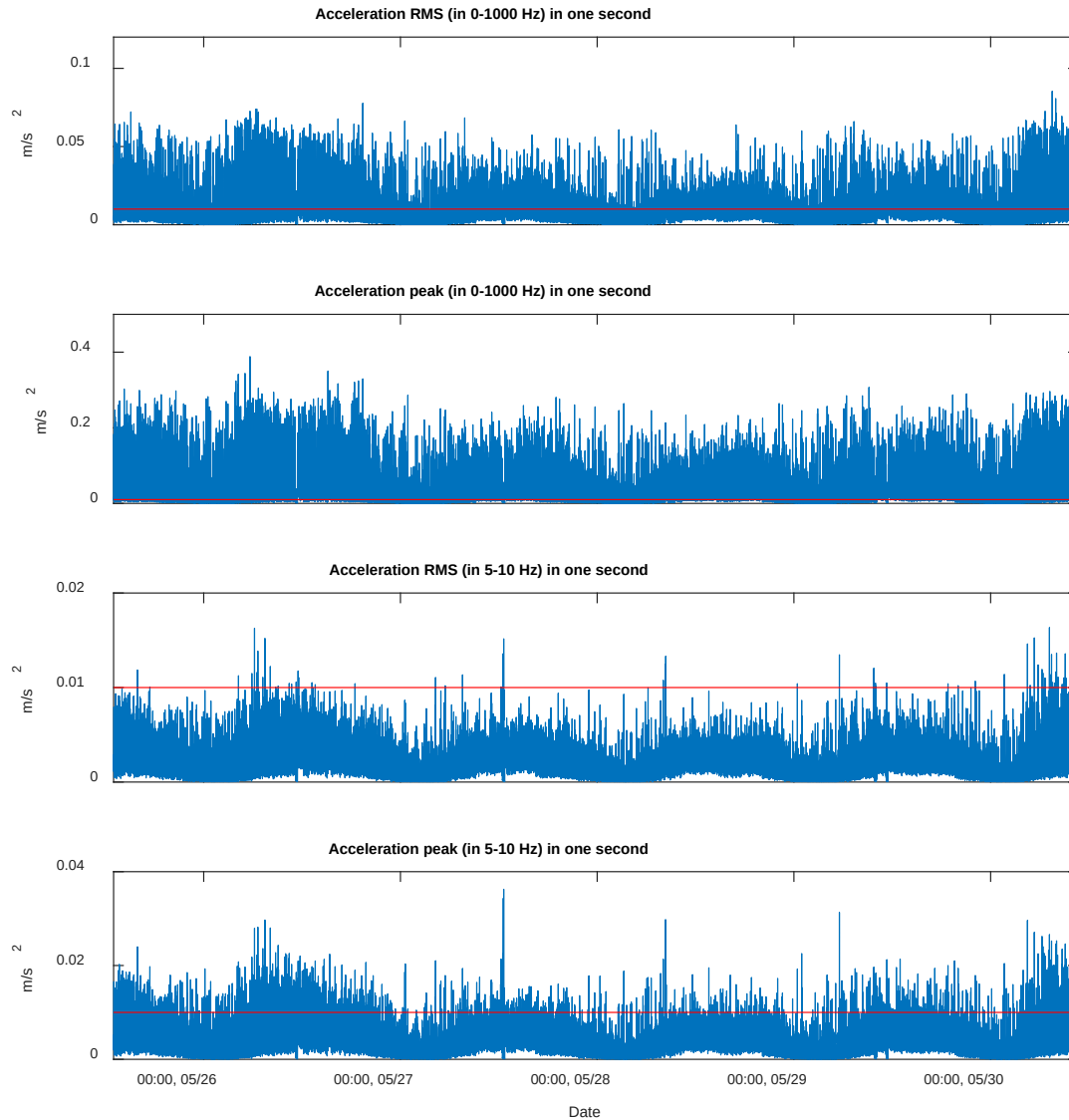


Figure 4.9: RMS and peak accelerations calculated with every one-second-long data at Site 2. Top two panels are accelerations in the 0.5-1000 Hz band. Bottom two panels are accelerations in the 5-10 Hz band.

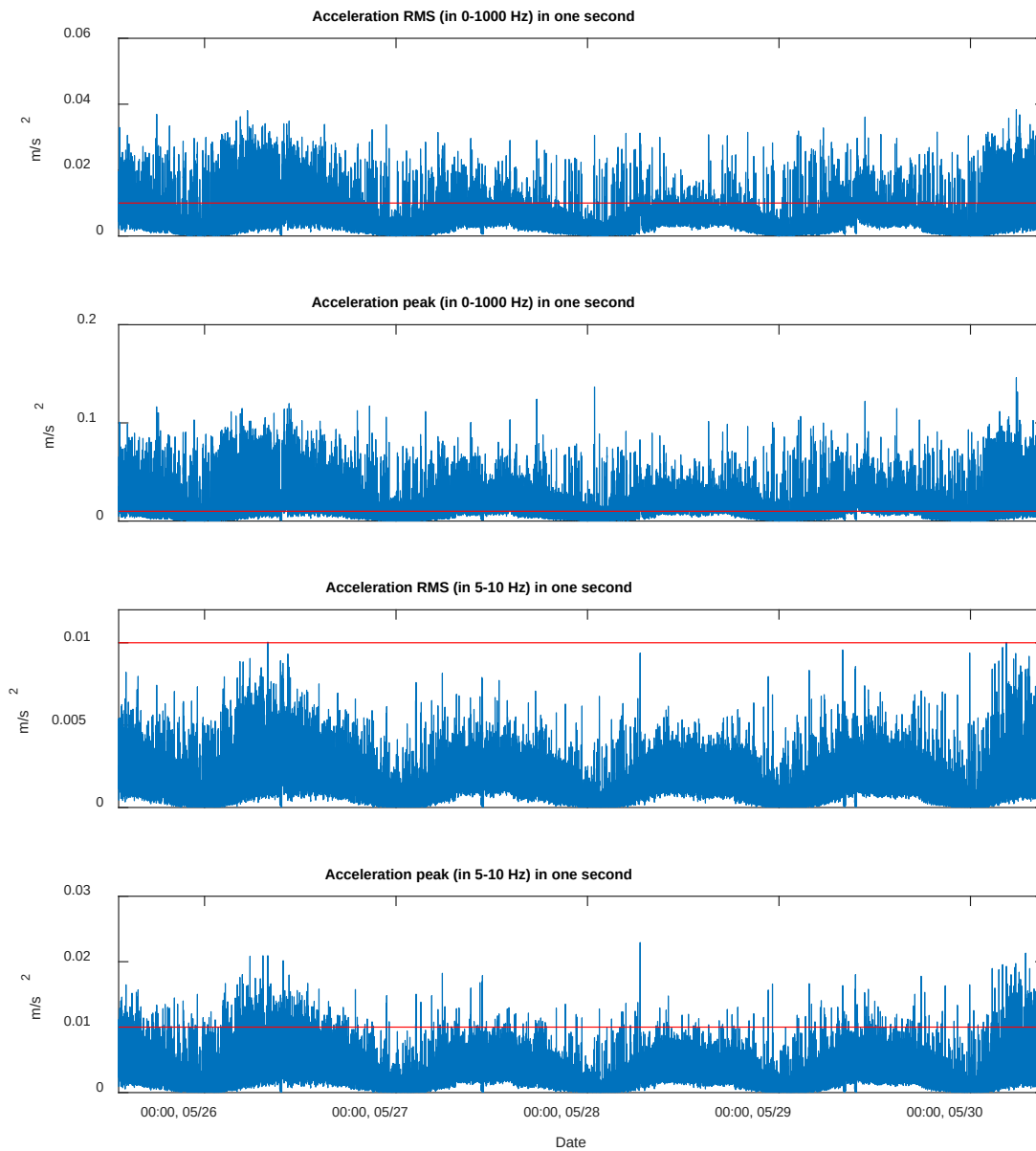


Figure 4.10: RMS and peak accelerations calculated with every one-second-long data at Site 3. Top two panels are accelerations in the 0.5-1000 Hz band. Bottom two panels are accelerations in the 5-10 Hz band.

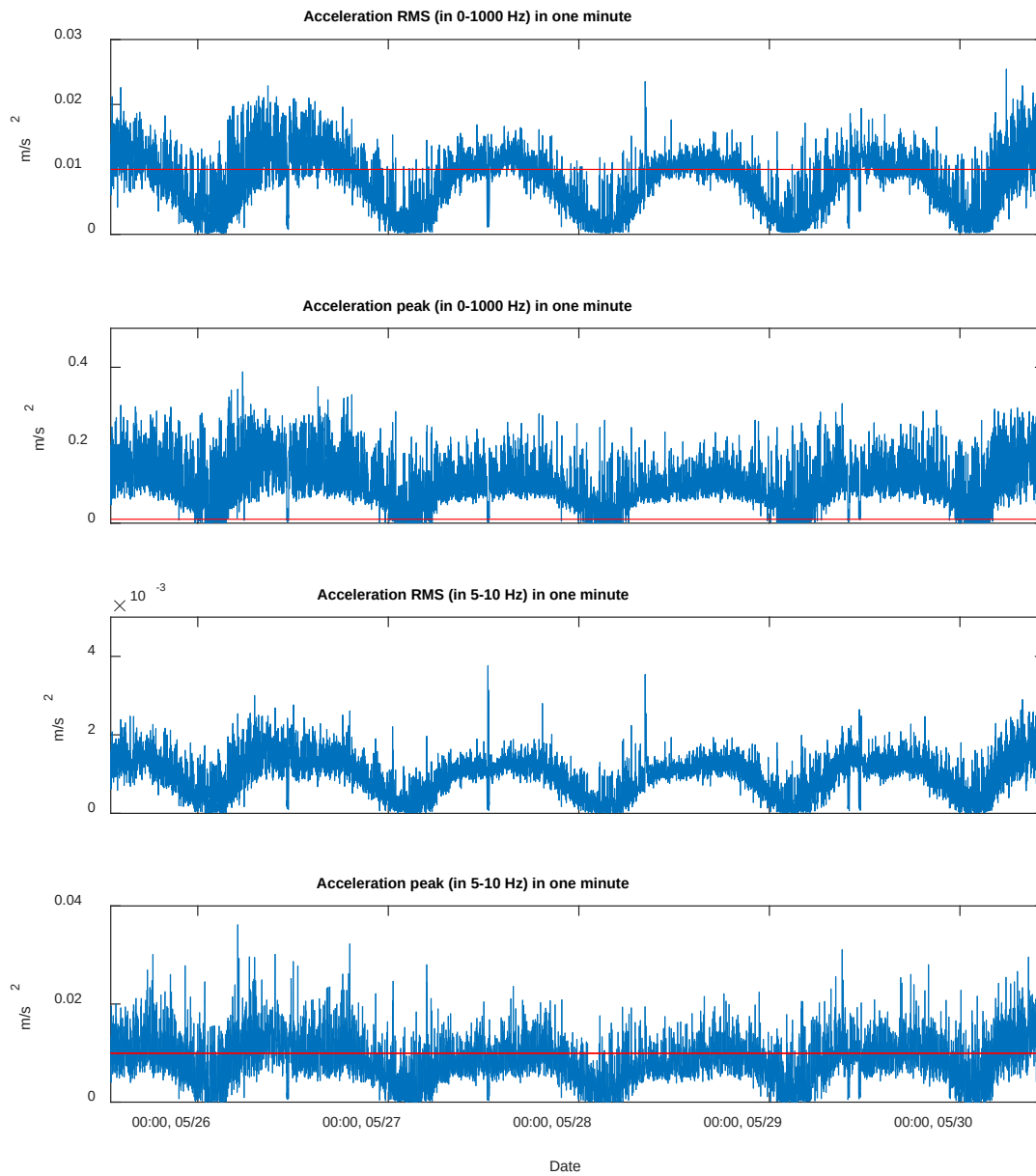


Figure 4.11: RMS and peak accelerations calculated with every one-minute-long data at Site 2. Top two panels are accelerations in the 0.5-1000 Hz band. Bottom two panels are accelerations in the 5-10 Hz band.

4.3 Traffic volume

Traffic volume on May 26th, 2017 was plotted in the next two figures. Figure 4.12 shows the traffic variation with hours in each bound. Figure 4.13 shows the traffic volume of four types of vehicles. The traffic volume data were only available on an hourly basis, thus RMS SPLs and accelerations were calculated in every hour to correlate with the hourly traffic volume. Table 2 shows the correlation coefficients with P values. Among all three sites, Site 2 has the strongest correlation with the traffic volume in both RMS SPLs and accelerations, with up to 90.53% correlation coefficient. Besides, accelerations in 5-10 Hz band have higher correlations with traffic volume than accelerations in 0.5-1000 Hz band. Figure 4.14 helps to visualize the correlation between SPLs/accelerations and traffic volume.

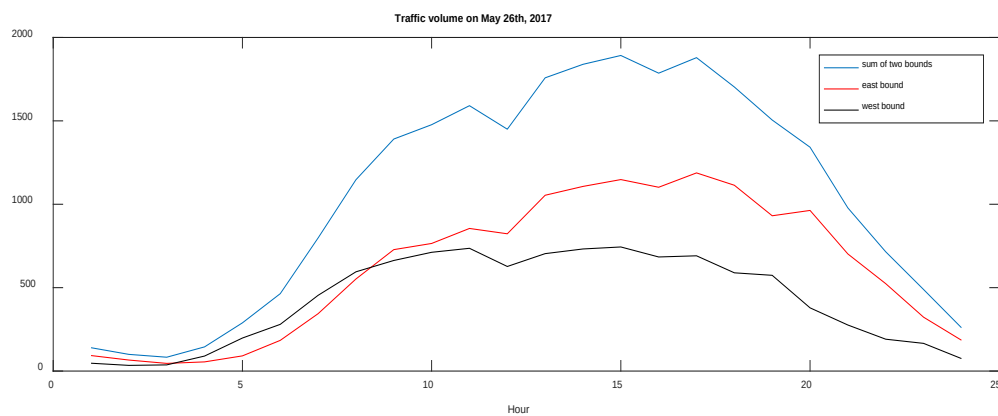


Figure 4.12: Traffic volume on May 26th, 2017.

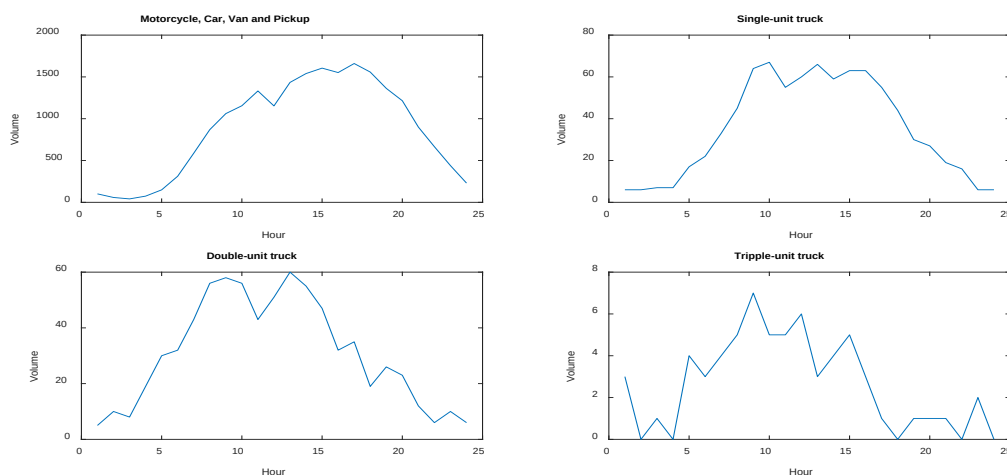


Figure 4.13: Traffic volume of different types of vehicle on May 26th, 2017.

Table 2: Correlation coefficient R (with P-values) between SPL/acceleration and hourly traffic volume

Site	SPL_rms (in 5-800 Hz band)	acc_rms (in 0.5-1000 Hz band)	acc_rms (in 5-10 Hz band)
1	0.7787 (P<0.001)	0.7921 (P<0.001)	0.8856 (P<0.001)
2	0.8589 (P<0.001)	0.8886 (P<0.001)	0.9053 (P<0.001)
3	0.8159 (P<0.001)	0.8052 (P<0.001)	0.8238 (P<0.001)

4.4 Wind speed

In addition to traffic volume on the bridge, wind was another potential factor that could affect sound pressure and acceleration that were measured at the three sites. Wind waves brake when they hit the bridge pontoon, and noise and vibrations were generated accordingly. The hourly mean wind speed was correlated with RMS SPLs and accelerations, respectively. Correlation coefficients with P values are shown in Table 3. The correlation coefficients are not as strong as those obtained with traffic volume. Variation of wind speed with hours in the first week is also shown in Figure 4.14.

Table 3: Correlation coefficient R (with P-value) between SPL/acceleration and hourly mean wind speed

Site	SPL_rms (in 5-800 Hz band)	acc_rms (in 0.5-1000 Hz band)	acc_rms (in 5-10 Hz band)
1	0.2590 (P<0.001)	0.2594 (P<0.001)	0.3135 (P<0.05)
2	0.2771 (P<0.001)	0.3055 (P<0.001)	0.3120 (P<0.001)
3	0.2181 (P<0.05)	0.4552 (P<0.001)	0.4706 (P<0.001)

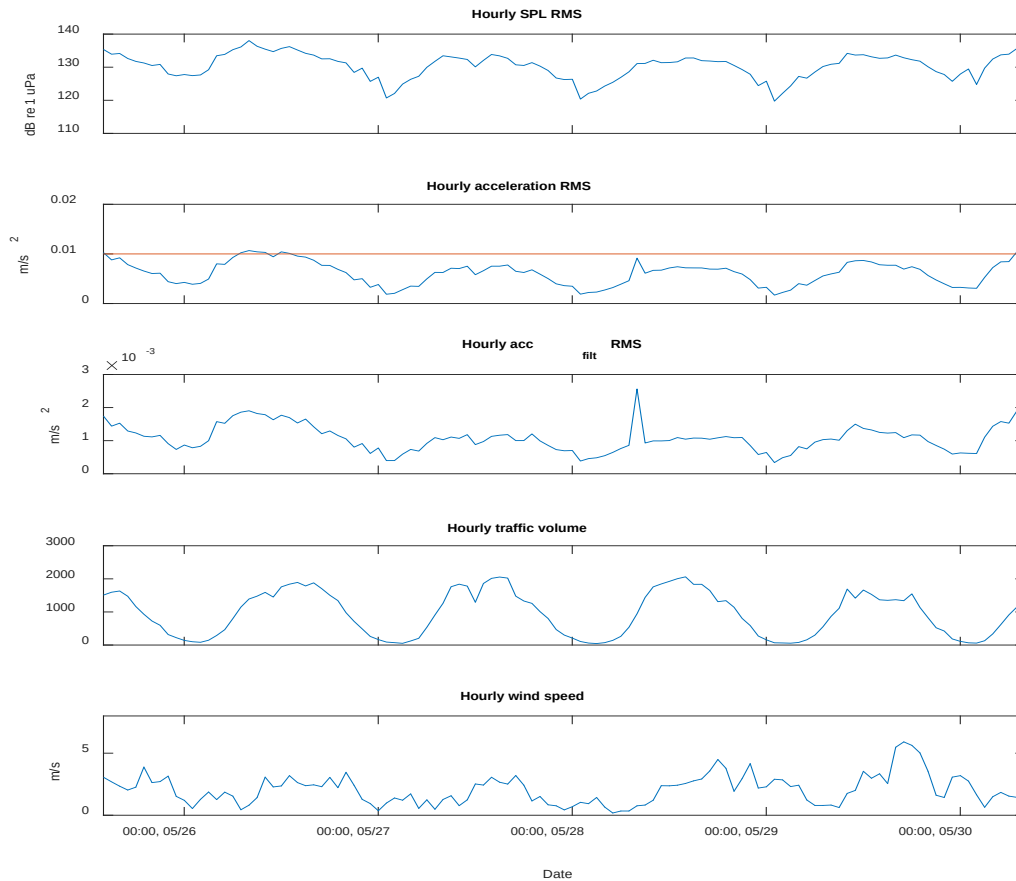


Figure 4.14: Hourly SPLs, accelerations, traffic volume and mean wind speed at Site 1.

5 Sound measurement near the bridge

5.1 Sound attenuation with distance

To evaluate sound attenuation with distance from the bridge, a sound broadcasting test was performed prior to demobilization of the measurement sites. A Clark Synthesis Diluvio (AQ339) underwater speaker that was powered by an InterM A-120 120 W amplifier was deployed from the bridge. The amplifier was connected to a laptop for audio playback. The laptop had a MATLAB script that plays a sequence of sounds listed in Table 4, with a silence of 4 s between sounds. This sequence repeats a total of 5 times. Based on the measurement of the speaker in the acoustic tank of our lab, the source level of the five-second 290 Hz continuous sound was 134.6 dB re 1 μPa at 1 m.

Table 4: Description of sounds broadcast from underwater speakers

Description	Duration (s)	Frequency (Hz)	Quantity
Continuous Tone	5	290	1
Hanning-Weighted Pulse	0.111	290	4

Sounds were broadcast from the bridge and were collected in the boat using a RESON TC4032-1 hydrophone (same model as measurement sites) and a National Instruments USB-6366 data acquisition system. Prior to collecting data with this hydrophone the functionality of the system was verified by using a portable test device (pistonphone) that generates a known signal in the hydrophone.

This testing was conducted at three locations on the south side of the bridge (Figure 5.1; Table 5). At each test point, the boat motor was running and used to stay stationary at the testing site. Each data file was six-minute long. An example of the raw data is plotted in Figure 5.2. In the waveforms, the transmitted signals were masked by ambient noise. In the spectrum, there was a high peak at the broadcast frequency of 290 Hz. A bandpass filter of 288-292 Hz was applied to the six-minute-long data file to obtain the 290 Hz sounds. Then, at each test point, the five-second-long 290 Hz signals were extracted from the bandpass filtered data. The RMS SPLs were calculated using the extracted 290 Hz signals at each test point, as shown in Figure 5.3. At test point 1, 2, and 3, five repetitions of broadcast were identified with 1 minute intervals between two successive broadcasts. The red squares showed the mean of SPLs calculated using the five repetitions, while the error bar corresponded to the standard deviation of five repetitions of the test point. The source level at 1 m was 132.6 dB. From 1 m to 120 m, the SPL decreases linearly with $\log(r)$, which is consistent with the cylindrical spreading loss in the shallow water environment. Thus, the attenuation with distance from the bridge was measured successfully in the field experiment.



Figure 5.1: Test points from boat to receive the sound broadcast on the bridge.

Table 5: GPS locations of test points from boat to receive the sound broadcast on the bridge

Test point	Distance (m)	Latitude	Longitude
1	62	47.860707°	-122.627417°
2	80	47.860554°	-122.627607°
3	120	47.860305°	-122.627923°

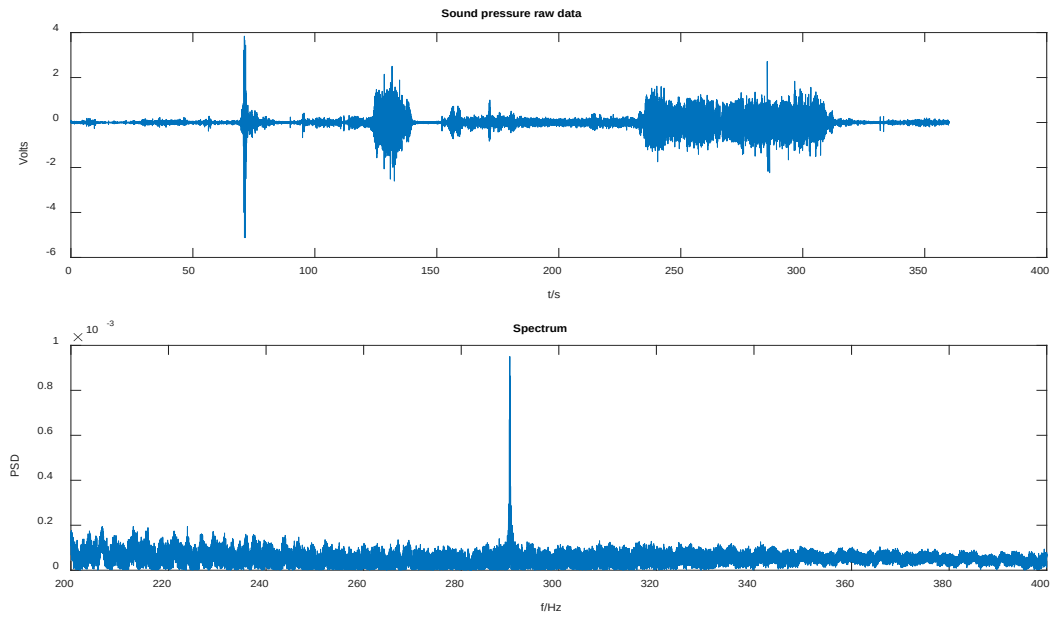


Figure 5.2: Sound pressure and corresponding spectrum at test point 1. A peak appeared at 290 Hz broadcast frequency.

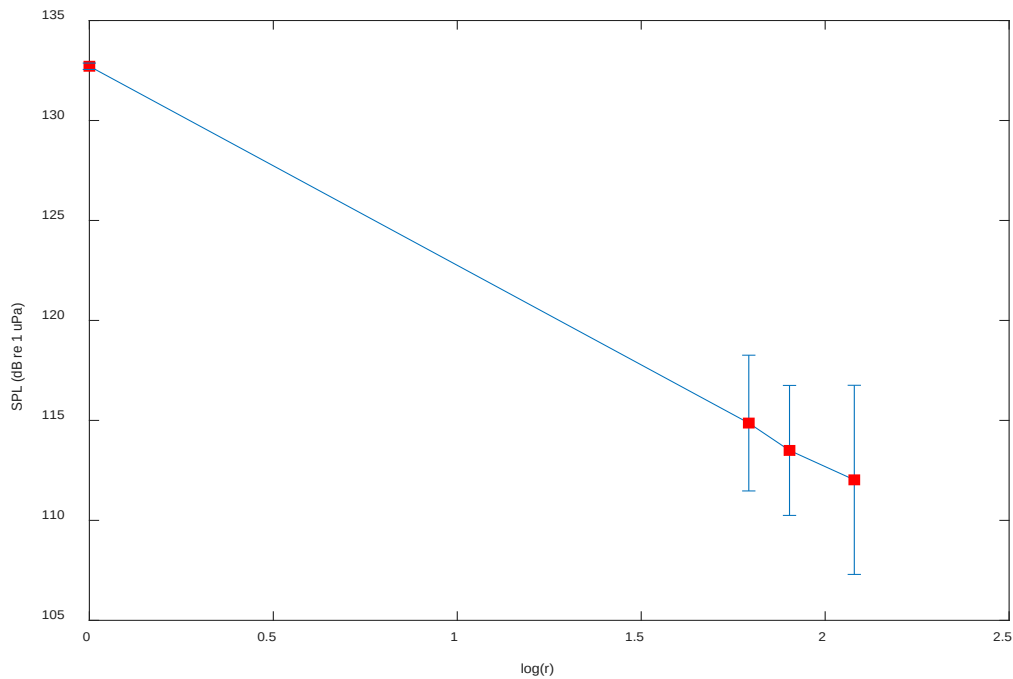


Figure 5.3: Sound pressure attenuation with distance from the bridge in log scale. SPL decreases linearly with $\log(r)$, which is consistent with the cylindrical spreading loss in shallow water.

5.2 Background noise level near the bridge

Sound pressure data were collected while the boat motor was off and the boat was drifting near the bridge with the current. The same hydrophone and data acquisition system used for the sound attenuation experiment were used for this testing. Four drifting tracks were traversed with a six-minute long data file recorded along each track. In this case, the collected sound pressure was a function of location and time. SPL_{rms} and SPL_{peak} were calculated within every second so that the instantaneous variation of background noise level with time and location could be analyzed. The results are shown in Figure 5.4 and 5.5. It appears that the SPL_{rms} varies from 105 dB to 130 dB along drifting tracks. It is about 20 dB less than the SPL_{rms} measured at the sites along the bridge. Considering that the distance of drifting track to the bridge is over 70 m, the corresponding transmission loss is close to 20 dB. Observed SPL_{rms} values are below the threshold of 150 dB re 1 μ Pa RMS suggested by NOAA Fisheries and U.S. Fish and Wildlife Service. The results give us a taste of how loud the traffic noise is at a distance over 70 m from the bridge. Since we didn't have permission to get closer to the bridge, the area within 70 m from the bridge was not evaluated in this test. However, it should be noted that in the area close to the bridge, the sound field is much more complicated than the far field. More attention should be given to the near field (less than 70 m) of the bridge in future work.

One location on track 1 and one location on track 2 were selected from the GPS data. The sound pressure within 10 seconds was assumed to be recorded at these two locations, ignoring the drifting of the boat during the selected time span. Then, using linear regression, the relationship between the SPLs at these two locations and the SPLs at the three sites on the bridge were established. Using the established linear model, the SPLs over the first week at the two locations were obtained, as shown in Figure 5.6 and 5.7. No SPLs over threshold were observed.

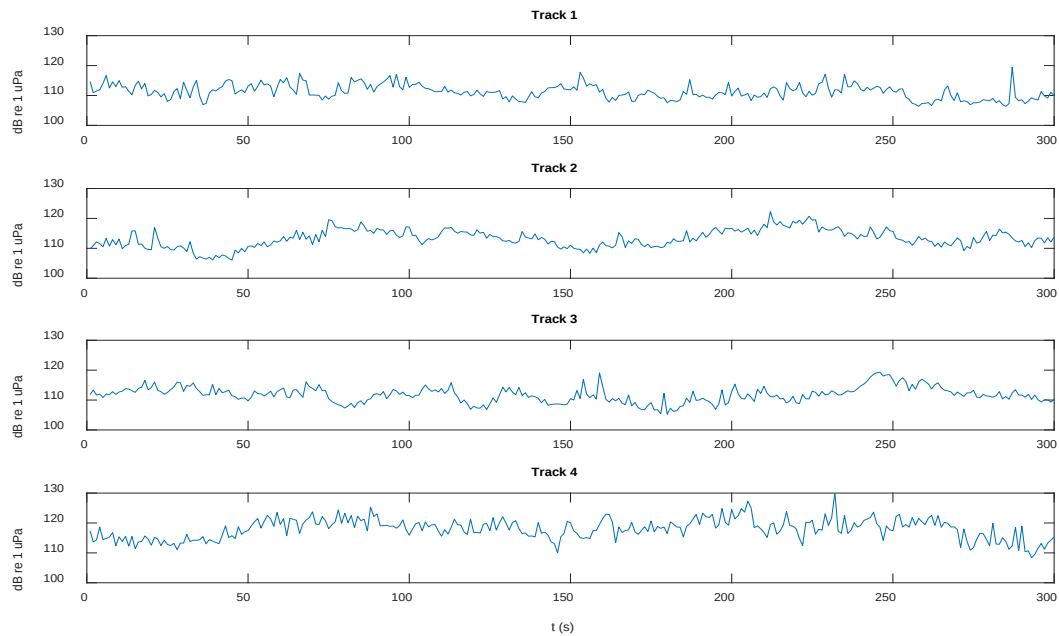


Figure 5.4: SPL_{rms} calculated within every second along four tracks of the drifting boat.

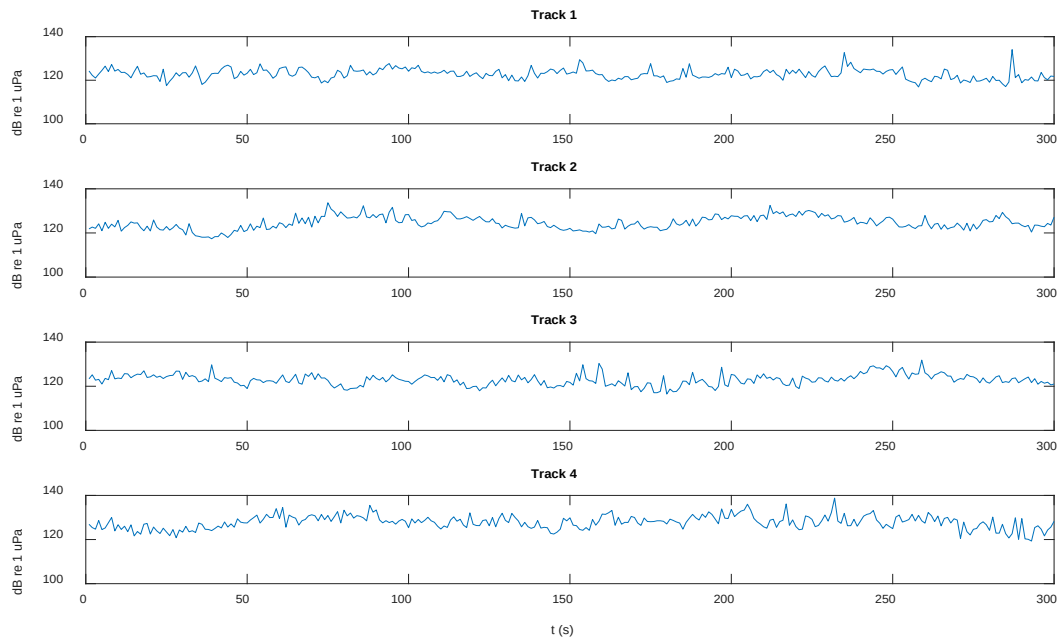


Figure 5.5: SPL_{peak} calculated within every second along four tracks of the drifting boat.

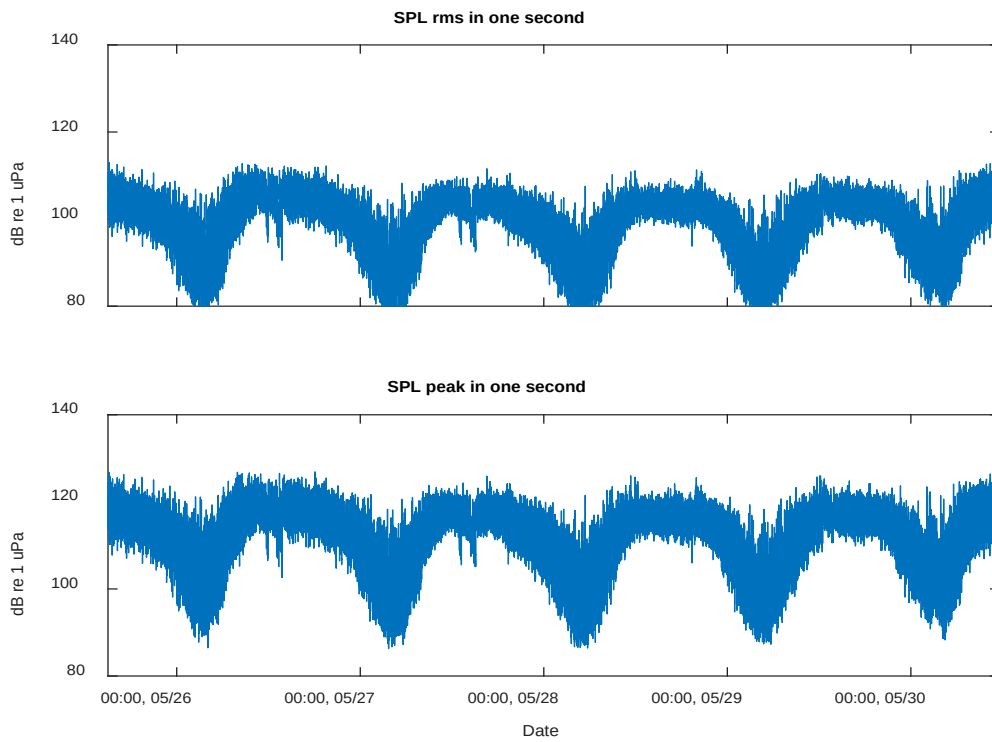


Figure 5.6: Sound pressure levels at location 1 over the first week.

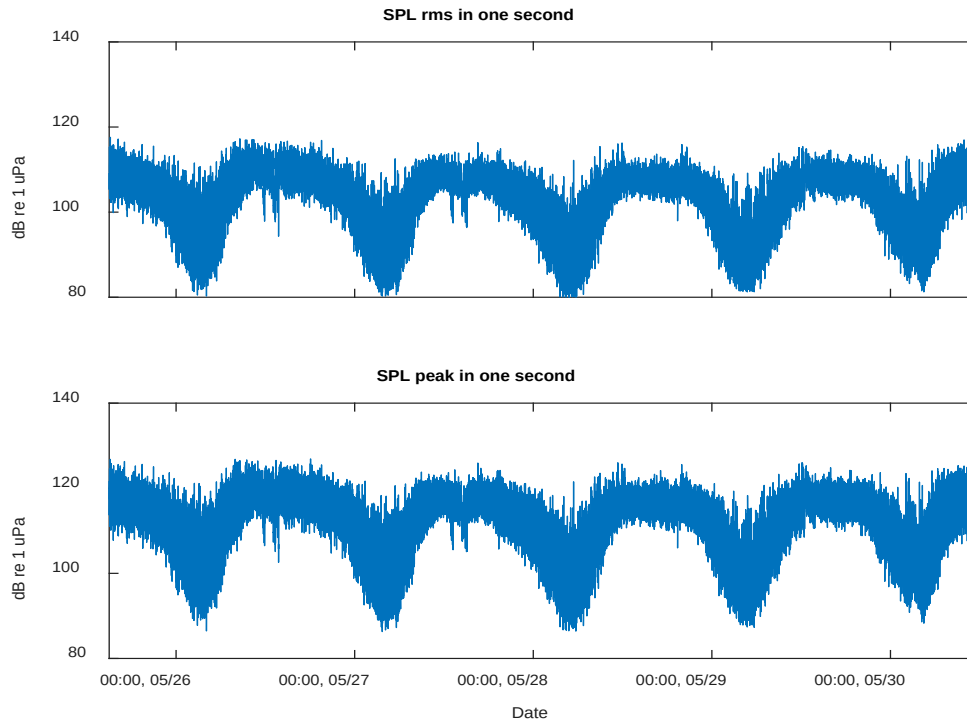


Figure 5.7: Sound pressure levels at location 2 over the first week.

6 Summary

To characterize the anthropogenic energy (sound and vibration) generated from the Hood Canal Bridge, we deployed three measurement systems along the bridge, each of which was composed of a hydrophone, three accelerometers, a data acquisition system and a solar power system. We collected one month of data, and calculated SPLs and particle accelerations within every second, every minute and every hour. Observed SPL_{rms} were mostly below the threshold of 150 dB re 1 μ Pa RMS suggested by NOAA Fisheries and U.S. Fish and Wildlife Service. The particle accelerations were calculated in the 0.5-1000 Hz band and 5-10 Hz band, respectively. From Knudsen et al (1992, 1994, 1997), juvenile Atlantic salmon showed avoidance response to a particle acceleration of 0.01 m/s² at 5-10 Hz band both in laboratory tanks and in a river. Our measurements showed that particle accelerations at all three sites were occasionally over the threshold. The hourly SPLs and particle accelerations were significantly correlated with the traffic volume and the wind speed. Strong correlations (R up to 0.9053) were observed between the RMS particle accelerations in 5-10 Hz band and the traffic volume.

In addition to the measurement on the bridge, we also measured sound pressure near the bridge from a boat. Sound attenuation with distance from the bridge was measured by broadcasting sound from the bridge and recording sounds from the boat. SPLs along four tracks of the drifting boat were also calculated, which yielded four snapshots of the sound pressure field in the area. A simplified linear regression model was developed using SPLs at two locations near the bridge and the three deployment sites on the bridge.

Overall, the measurements from our pilot field trial showed that the triaxial accelerations of bridge pontoons were strongly correlated with the bridge traffic volume and could potentially reach the level for avoidance behavior established for juvenile salmon. However, more detailed measurements over a longer period of time and more sophisticated sound propagation models are required for establishing whether there is a relationship between steelhead smolt behavior and the anthropogenic noises.

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Appendix A: Frequency response of hydrophones and accelerometers

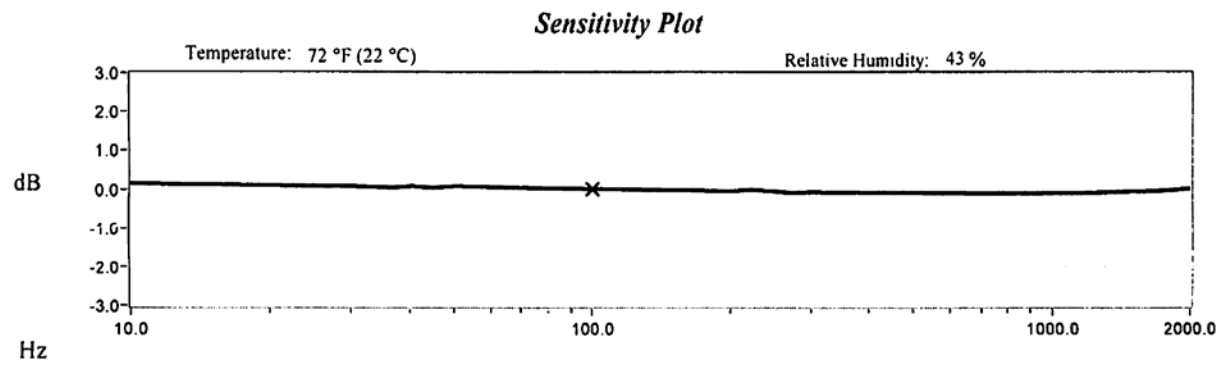


Figure A1: Sensitivity plot of ICP Accelerometer model 393A03, serial number 43375.

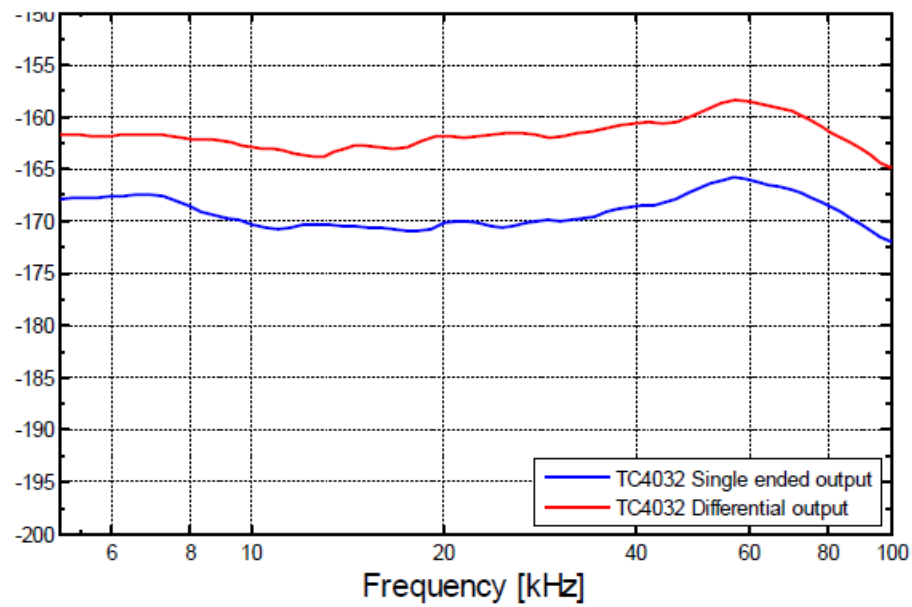


Figure A2: Receiving sensitivity of hydrophone ResonTC4032.

Appendix B: Calibration of hydrophones and accelerometers

	Hydrophone	Hydrophone Power Supply	Hydrophone Cable	Hydrophone Sensitivity (@ 250 Hz, single-ended)	Noise floor (pistonphone off + Hydrophone + OBS)
ND01	Reson TC4032 (S/N: 2411015)	EC6073 (S/N: 0002139)	TL8144 100M-008	-168.1 dB re 1 V/uPa	105.8 dB re 1 uPa
ND02	Reson TC4032 (S/N: 2411067)	EC6073B (S/N: 0003509)	TL8144 100M-013	-170.0 dB re 1 V/uPa	106.9 dB re 1 uPa
ND03	Reson TC4032 (S/N: 2411065)	EC6073B (S/N: 0003504)	TL8144 100.5M-003	-170.1 dB re 1 V/uPa	108.9 dB re 1 uPa
Accelerometer Set 1	ICP Signal Conditioner S/N	Accelerometer S/N	Sensitivity (manufacturer)	Noise floor (OBS + Accelerometer)	Sensitivity (calibrated)
Channel 1	00029449	00043376	1020 mV/g	8.40 mm/s ²	996.1 mV/g
Channel 2	00029444	00043477	998 mV/g	7.35 mm/s ²	968.3 mV/g
Channel 3	00029448	00043378	977 mV/g	9.21 mm/s ²	963.2 mV/g
Accelerometer Set 2	ICP Signal Conditioner S/N	Accelerometer S/N	Sensitivity (manufacturer)	Noise floor (OBS + Accelerometer)	Sensitivity (calibrated)
Channel 1	00029442	00043377	1004 mV/g	7.75 mm/s ²	975.1 mV/g
Channel 2	00029323	00043574	1000 mV/g	8.72 mm/s ²	963.6 mV/g
Channel 3	00029446	00043573	976 mV/g	7.82 mm/s ²	939.9 mV/g
Accelerometer Set 3	ICP Signal Conditioner S/N	Accelerometer S/N	Sensitivity (manufacturer)	Noise floor (OBS + Accelerometer)	Sensitivity (calibrated)
Channel 1	00029443	00043375	1015 mV/g	6.38 mm/s ²	994.1 mV/g
Channel 2	00029450	00043571	1003 mV/g	6.43 mm/s ²	975.6 mV/g
Channel 3	00029445	00043475	1020 mV/g	6.42 mm/s ²	1000 mV/g

[Appendix E. Khangaonkar et al. 2018](#)

Hydrodynamic zone of influence due to a floating structure in a fjordal estuary – Hood Canal Bridge impact assessment

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Article

Hydrodynamic Zone of Influence Due to a Floating Structure in a Fjordal Estuary—Hood Canal Bridge Impact Assessment

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Abstract: Floating structures such as barges and ships affect near-field hydrodynamics and create a zone of influence (ZOI). Extent of the ZOI is of particular interest due to potential obstruction to and impact on out-migrating juvenile fish. Here, we present an assessment of ZOI from Hood Canal (Floating) Bridge, located within the 110-km-long fjord-like Hood Canal sub-basin in the Salish Sea, Washington. A field data collection program allowed near-field validation of a three-dimensional hydrodynamic model of Hood Canal with the floating bridge section embedded. The results confirm that Hood Canal Bridge, with a draft of 4.6 m covering ~85% of the width of Hood Canal, obstructs the brackish outflow surface layer. This induces increased local mixing near the bridge, causes pooling of water (up-current) during ebb and flood, and results in shadow/sheltering of water (down-current). The change in ambient currents, salinity, and temperature is highest at the bridge location and reduces to background levels with distance from the bridge. The ZOI extends ~20 m below the surface and varies from 2–3 km for currents, from 2–4 km for salinity, and from 2–5 km for temperature before the deviations with the bridge drop to <10% relative to simulated background conditions without the bridge present.

Keywords: Hood Canal; floating bridge; Salish Sea; hydrodynamics; Finite-Volume Community Ocean Model (FVCOM); circulation; anthropogenic impact; zone of influence; Salish Sea model

1. Introduction

Hood Canal is a fjordal sub-basin within the Salish Sea region of Pacific Northwest. The Salish Sea is a collective name given to waterbodies that include the Strait of Juan de Fuca, Strait of Georgia, Puget Sound, and all their connecting channels and adjoining waters (see Figure 1). In the spring and summer, many Salish Sea sub-basins regularly experience algae blooms, and some of the sub-basins such as Hood Canal, East Sound, and regions of South Sound show signs of hypoxia [1]. Development of a comprehensive water-quality model of the Salish Sea was initiated in response to the above concerns about management of nutrient pollution and the assimilative capacity of the Salish Sea [2–4]. Of particular interest was the ability to simulate low dissolved oxygen (DO) events in the Salish Sea, including those responsible for fish kills and other chronic impacts in the Hood Canal region. Numerous studies were conducted in the past to determine what contributes to low DO events in Hood Canal, such as natural meteorological and oceanographic conditions, as well as anthropogenic causes, such as excessive nutrient loading [5,6].

The Hood Canal sub-basin includes a unique anthropogenic modification in that it hosts the Hood Canal Bridge (HCB), which is one of 11 floating bridges in use in the world. The geographic location of this 1992-m-long bridge, about 10 km from the mouth of Hood Canal, is indicated in Figure 1.

Hood Canal is a 110-km-long narrow fjord-like sub-basin of Puget Sound with an average width of 2.4 km, a mean depth of 51.1 m, and a maximum depth of ~187 m, and it has a sill approximately 10–20 km from the mouth. The floating section of the bridge occupies ~85% of the width of Hood Canal, with a fixed opening at either end for small vessel traffic. The bridge has a design draft of 4.57 m. As part of the Salish Sea model development process, presence of the floating bridge was considered but not included in the model set-up under the assumption that effects of the bridge were likely a local phenomenon and unlikely to have a significant impact on the larger-scale Salish Sea model performance.

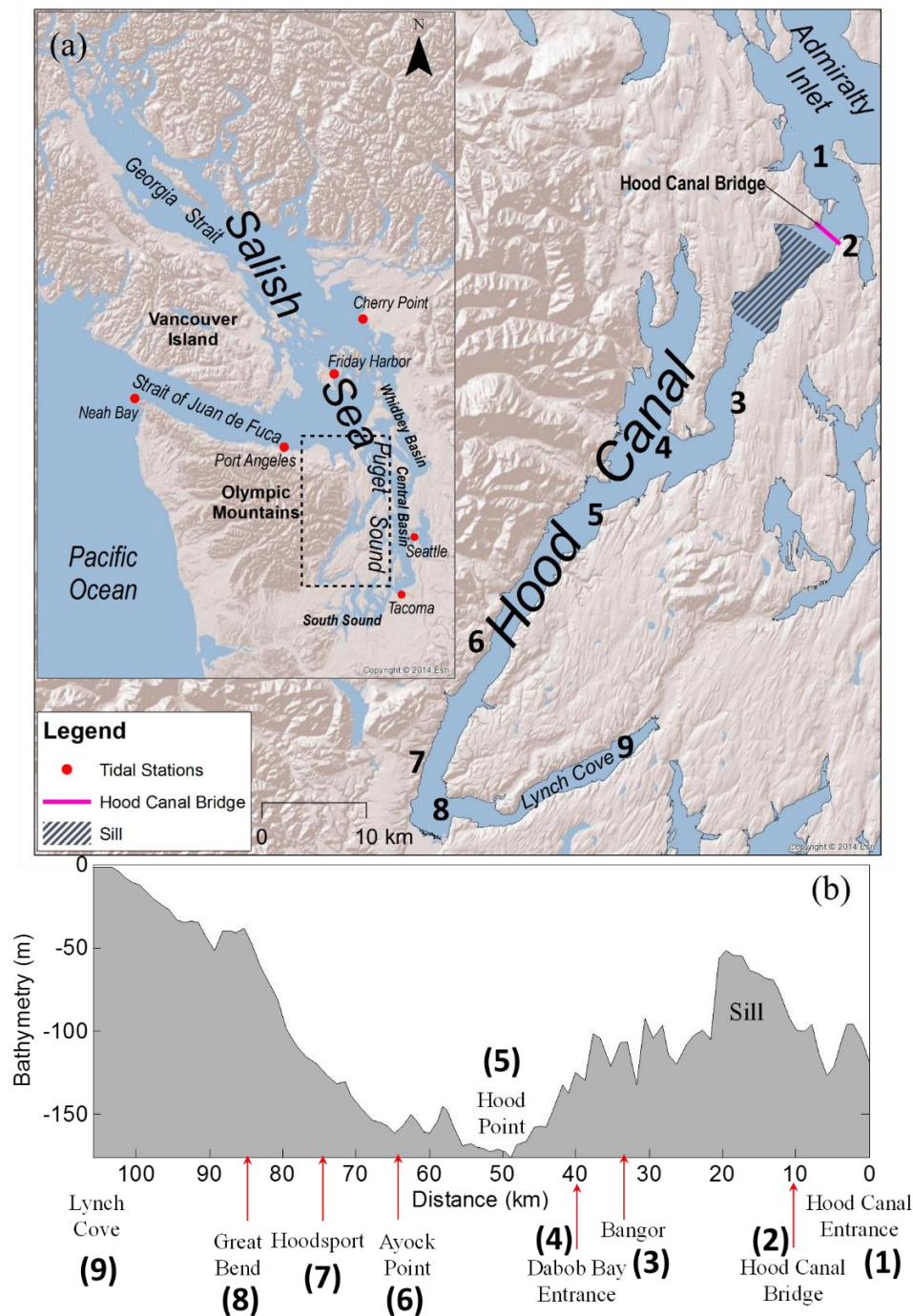


Figure 1. (a) Oceanographic regions of Salish Sea including Northwest Straits, Puget Sound, and the inner sub-basins—Hood Canal, Whidbey Basin, Central Basin, and South Sound; (b) bathymetric profile of Hood Canal study area.

However, recent research suggests that the bridge may, in fact, alter hydrodynamics and has the potential to increase flushing time in Hood Canal. Circulation here exhibits classic fjord characteristics of a shallow brackish layer at the surface over a deep long and narrow saltwater column that is vulnerable to disruptions due to the presence of floating structures, which could constrict the mixing and transport in the upper layers of the water column [7]. Recent studies also indicate that the bridge is a barrier to fish passage. Slower migration times, higher mortality rates in the vicinity of the bridge relative to other areas on their migration route, and unique behavior and mortality patterns at the bridge suggest the bridge is impeding steelhead migration and increasing predation [8].

In this paper, we present an assessment of the near-field impact of the floating bridge on the tidal hydrodynamics in the Hood Canal fjord environment as a component of the Hood Canal Bridge Environmental Impact Assessment study [9]. In particular, we focus on quantifying the spatial extent of the change in hydrodynamic parameters, such as currents, salinity, and temperature, in the vicinity of the bridge relative to ambient conditions. This near-field region of deviation from ambient background is the zone of influence (ZOI), defined arbitrarily as the distance from the bridge where relative difference induced by the structures reduces to <10% of the maximum deviation. This was accomplished through an application of the Salish Sea model [4] with the HCB embedded in high resolution. We present a summary of field data collected at the bridge, set-up and calibration of the Salish Sea model with a floating bridge module, and application of the model to the development of quantitative estimates of ZOI dimensions. These results inform companion studies addressing the impacts on the swimming behavior and observed mortality of out-migrating juvenile steelhead at HCB. Although this study discusses site-specific efforts, the results and the concern about potential ecological impacts are applicable to all floating bridges worldwide.

2. Materials and Methods

2.1. Oceanographic Data Collection

Oceanographic data collection was planned with two objectives: (1) field confirmation of the hypothesis that the HCB obstructs and alters near-field surface currents; (2) provide near-bridge data for the calibration of hydrodynamic models. Near field, for the purpose of this scope, is defined as the region where the influence of the bridge on current, salinity, and temperature variables is noticeable relative to the ambient (far field). Based on a prior modeling effort [7], the ZOI was expected to vary from as small as one to two bridge widths (18–36 m) normal to the direction of flow, to a much larger region covering several Hood Canal channel widths (2.4–7.2 km), for variables such as currents, temperature, and salinity.

In situ current and conductivity, temperature, and depth (hereafter CTD) measurements were collected over a four-week period, from late April to early June 2017, at three locations near HCB [10]. Figure 2 shows the locations of the stations (a) immediately below the floating bridge span, (b) approximately 500 m upstream (south) of the bridge, and (c) approximately 500 m downstream (north) of the bridge. The bridge-mounted current meter (a) was attached to the floating section of the bridge. Attachment of the acoustic Doppler current profiler (ADCP) to this platform provided a profile of the water currents directly below the bridge. In addition to the ADCP, the bridge-mounted system also included a single-point Aquadopp current meter attached approximately 1 m below the hull of the bridge to collect in situ current data as close to the structure as feasible. The upstream and downstream deployment locations were constrained by the fact that they needed to be bottom-mounted (outside of marine traffic in the surface waters) and away from HCB mooring lines. Also, the maximum water depth at the bridge central span was ~101 m and posed a challenge for the upward-looking ADCP instrument's ability to penetrate the surface layers. They were, therefore, deployed at a depth of approximately 50 m and as far from the shoreline as possible. Continuous CTD measurements were obtained from the bridge and bottom-mounted stations along with CTD casts during deployment and recovery.



Figure 2. Hood Canal Bridge (HCB) study area showing the floating bridge and the 2017 oceanographic data collection program station locations relative to the bridge.

2.2. The Salish Sea Model Set-Up

The Salish Sea model is an externally coupled hydrodynamic and biogeochemical model developed by the Pacific Northwest National Laboratory in collaboration with Washington State Department of Ecology to support coastal estuarine research, restoration planning, water-quality management, and climate-change response assessments in the region [2–4]. The model was constructed using the unstructured grid Finite-Volume Community Ocean Model (FVCOM) [11] version 2.7 framework and integrated-compartment model biogeochemical water-quality kinetics [12,13]. To facilitate enhanced exchange with the Pacific Ocean, the Salish Sea model grid was expanded to include coastal waters around Vancouver Island and the continental shelf from Canada’s Queen Charlotte Strait to Oregon’s Waldport, south of Yaquina Bay [14]. The model kinetics were also improved through the addition of sediment diagenesis and carbonate chemistry [15], and it is capable of reproducing the observed biogeochemical conditions of the Salish Sea (salinity (S), temperature (T), dissolved oxygen (DO), nitrate, algal biomass, and pH), including near-bed hypoxia in key locations such as the Lynch Cove region of Hood Canal, Penn Cove, and East Sound [4].

Figure 3a shows the Salish Sea model domain and grid with 16,012 nodes and 25,019 triangular elements. The vertical configuration of the model uses 10 sigma-stretched layers distributed using a power law function with an exponent P-Sigma of 1.5, which provides more layer density near the surface. The model was set up for the year 2017 covering the near-field data collection period of April through June. The model is loaded with daily values of freshwater inflow from a total of 23 major gauged rivers, 46 ungauged streams for which flows were estimated through hydrological analysis, and 100 wastewater flows [16]. The model is forced with wind and heat flux at the water surface. Meteorological inputs were obtained from Weather Forecasting Research Model reanalysis data generated by the University of Washington. Tidal forcing at the open boundary was based on tidal constituents (S2, M2, N2, K2, K1, P1, O1, Q1, M4, and M6) derived from the Eastern North Pacific or ENPAC model [17]. Temperature and salinity profiles at the boundary were extracted from World Ocean Atlas 2013 version 2 [18,19] climatological fields of in situ temperature and salinity at a 1° grid

interpolated to the model boundary nodes. Spin up for the hydrodynamic model was conducted through a one-year run initiated from stationary conditions (zero initial velocity and water surface elevation) with uniform T (7°C) and S (32 practical salinity units (PSU)). The simulation was then repeated using year-end results as the restart initial condition.

As a preliminary step, Salish Sea model validation over the entire domain was first conducted to ensure that modification of the model grid and layering scheme (described in the following section) did not alter the overall model performance. This was done using year-long monitoring data available from a prior year (2014). The error statistics of water-surface elevation, S, and T were computed at nine tide stations and 24 water-quality stations maintained by Washington State Department of Ecology and shown in Figure 3b. Overall calibration results for T and S at all stations were found to be reasonable. Relative water-surface elevation errors were less than 10% at all stations within Puget Sound in United States (US) waters. Domain-wide T root-mean-square error (RMSE) was 0.94°C with a bias of -0.03°C . The domain-wide S error was 0.96 PSU with a bias of -0.24 PSU. Model skill scores were also high for T and S with Willmott skill score (WSS) [20] values of 0.96 and 0.80, respectively (see Table 1).

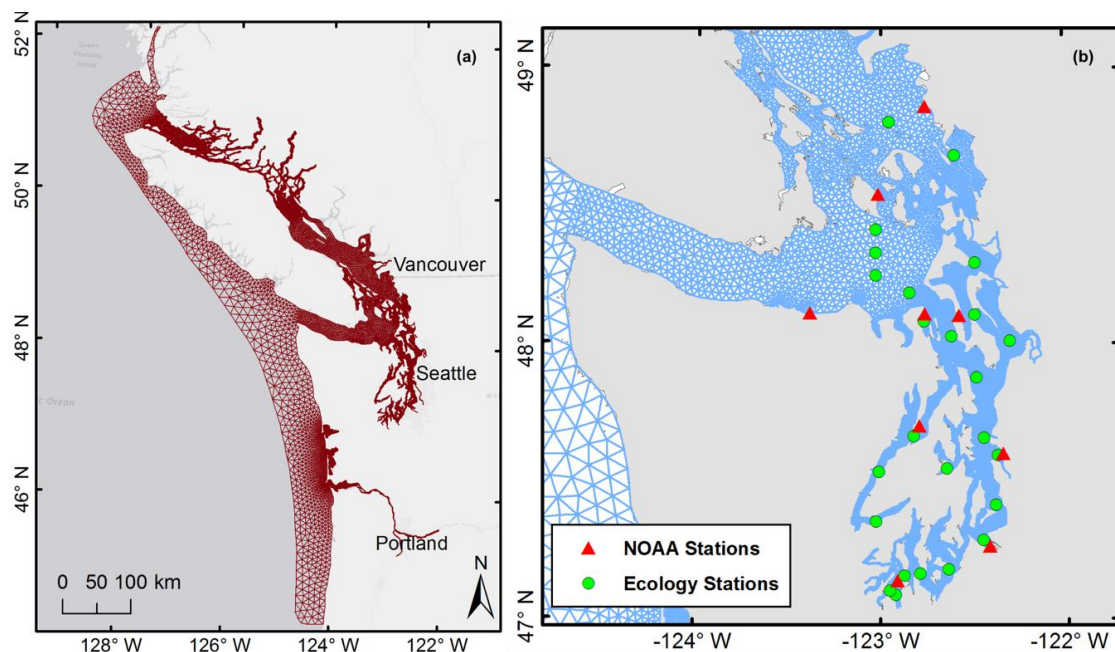


Figure 3. (a) Salish Sea model domain and finite-volume grid; (b) monthly water-quality monitoring stations from Washington State Department of Ecology.

Table 1. Salish Sea model overall error statistics and skill score for temperature and salinity calibration data for the year 2014 from monthly monitoring profiles.

	Mean Error (Bias)			RMSE			WSS		
	Max	Min	Ave	Max	Min	Ave	Max	Min	Ave
T ($^{\circ}\text{C}$)	0.97	−1.77	−0.03	2.29	0.40	0.94	0.99	0.78	0.94
S (PSU)	0.09	−0.93	−0.24	2.27	0.39	0.96	0.90	0.60	0.80

RMSE = root-mean-square error; WSS = Willmott skill score; T = temperature; S = salinity; PSU = practical salinity unit; Max = maximum value of site-specific error statistic among 21 Puget Sound stations; Min = minimum value of site-specific error statistic among 21 Puget Sound stations; Ave = global error statistic considering data and model results from all stations.

2.3. Hood Canal Bridge Module Implementation

The FVCOM framework used in the Salish Sea model is a three-dimensional, free-surface, terrain-following solver for the primitive form of Navier–Stokes equations. The model uses

an unstructured grid in the horizontal dimension and sigma-stretched coordinate system in the vertical dimension. The floating bridge in this framework may be best approximated by a rectangular barge-like pontoon (see Figure 4 for HCB profile and cross-section details). However, representation of the rectilinear shape of the pontoons in this discretized framework requires special attention. While the width and the horizontal dimensions may be represented in a straightforward manner by suitable refinement and arrangement of the triangular elements, representing the uniform draft in a terrain-following sigma coordinate system poses a particular challenge. The dimensions of the bridge were specified as 1992 m long and 18.3 m wide, with a draft of 4.57 m. Figure 5 shows a close-up of the model grid refinement for the HCB region of the domain. The following three techniques were explored:

- (a) *Implementation of a velocity block*: This approach is identical to that described by Khangaonkar and Wang (2013) [7] where the impermeable surface block was incorporated into FVCOM with modification of both external and internal modes of the solver. For the baroclinic internal mode, the horizontal velocities at the selected cells and surface layers were always specified as zero such that no horizontal flow was allowed to pass through. During the barotropic external mode calculations, the cross-sectional water column depth at selected cells occupied by the block was adjusted to a new reduced value by subtracting the blocked layer thickness from the total water depth. This modification accommodates the presence of the rigid structure but is an approximation, as non-hydrostatic components of the pressure term, which are likely to be strong in the near field, are neglected. Effects of the bridge on momentum terms are addressed, but are done so as an indirect effect of setting the surface boundary to zero velocity without affecting the pressure term.
- (b) *Implementation of momentum sink at the bridge using form drag*: In this approach, the cells occupying the bridge are populated with hypothetical cylinders similar to a densely packed kelp farm. The drag from the cylinders set to sufficiently high value results in blockage of nearly ~95% of surface currents. Although this represents a leaking bridge, the implementation allows effects on continuity, as well as momentum, terms of the governing equations. The implementation of form drag from suspended cylinders in the water column was described by Wang et al. (2013) [21]. This method also requires local modification of the bathymetry to a representative average depth under the bridge for representation of the rectangular shape of the bridge pontoons.
- (c) *Free surface pressure modification with a bottom drag*: This method relies on modification of the free surface pressure boundary condition; an increase in pressure equivalent of 4.57 m of head results in a model response of 4.57 m depression of the free surface. This method is an improvement over (a) and (b) in that bathymetry is unaltered. In addition to modifying the free surface, the method also employs drag formulation for the layer immediately under the bridge. This results in flow passing the bridge under modified pressure with suitable reduction in velocity induced by the form drag.

The efficacy of each method was tested by examination of predicted velocity, temperature, and salinity profiles relative to the data collected. Results showed that all methods provided similar performance in terms of near-field impacts to the flow field. For simplicity, the continuity/velocity block method (a) was retained for the remainder of the analysis.

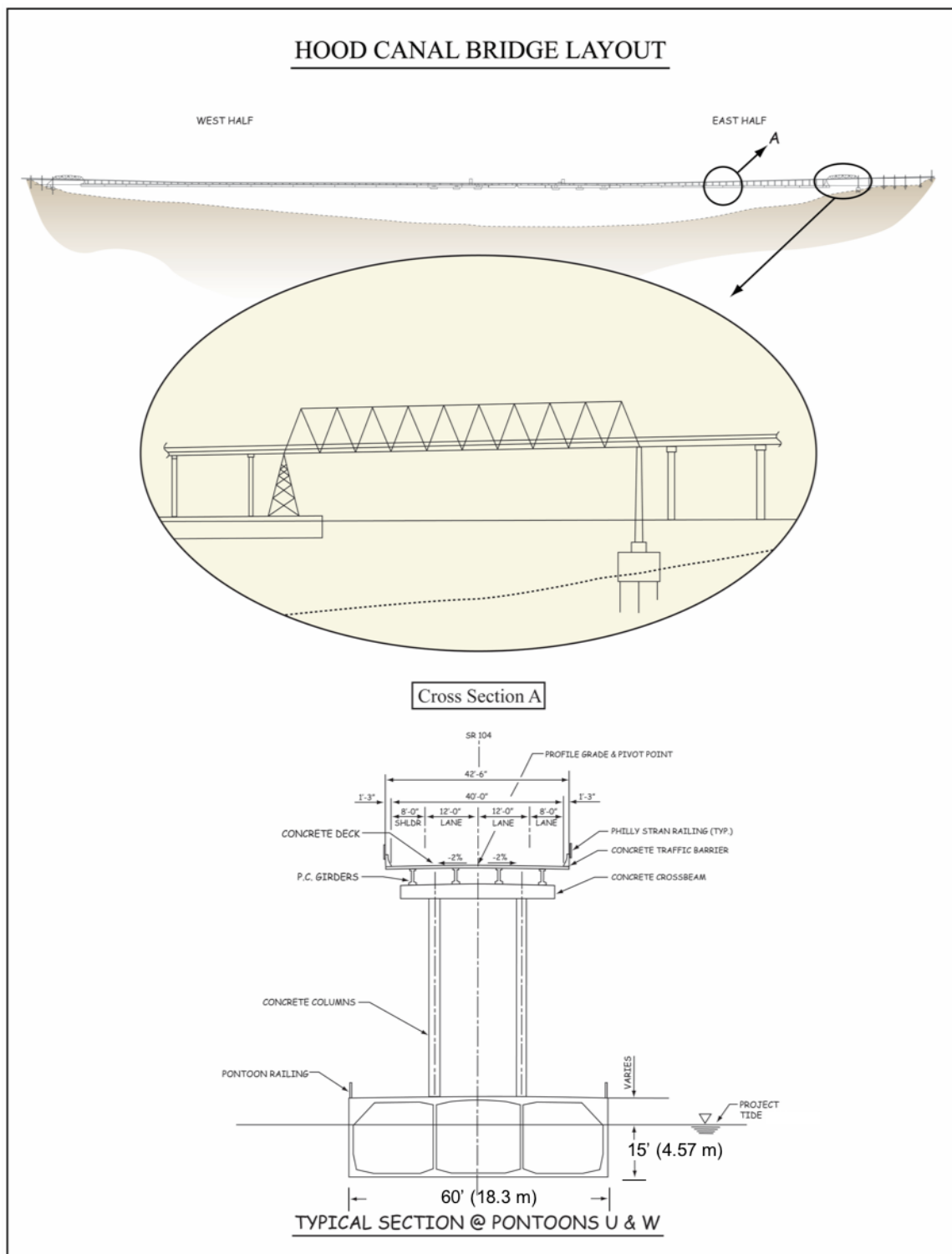


Figure 4. HCB layout with pontoon cross-section and east span details. Detail A is a sectional view across the width of the bridge.



Figure 5. Salish Sea model grid with refinement in the region to facilitate incorporation of the bridge block elements. The grid size is refined such that cell centers are separated by the bridge width distance of 18.3 m. The bridge draft is represented by two layers whose combined thickness is equal to 4.57 m.

2.4. Near-Field Model Validation

The near-field model validation consisted of comparison of predicted water surface elevations, currents, salinity, and temperature results with data measurements during the 2017 field program.

Water surface elevations: Water surface elevation measurements were collected at a station located on the east bank of Hood Canal. Figure 6 shows a comparison of measured data and water surface level simulated by the model. Absolute mean error (AME) or bias at this station was 0.013 m, and RMSE was 0.42 m, which is an error of 8% relative to the tidal range of 5.34 m (Table 2).

Salinity and temperature: In addition to velocity profiles, North ADCP, Bridge ADCP, and South ADCP stations also provided salinity and temperature data. Temperature and salinity data were measured at a depth of 1 m below the bridge hull (5.57 m depth) at the Bridge ADCP station, while at the North ADCP and South ADCP stations, these data were collected at a depth of ~50 m near the seabed. Figure 7 shows the time-series comparison of observed data and simulated salinity and temperature at the three ADCP locations. The salinity variation at the three ADCP stations was successfully reproduced in the model simulations. Predicted temperature variations were also in good agreement with observed data.

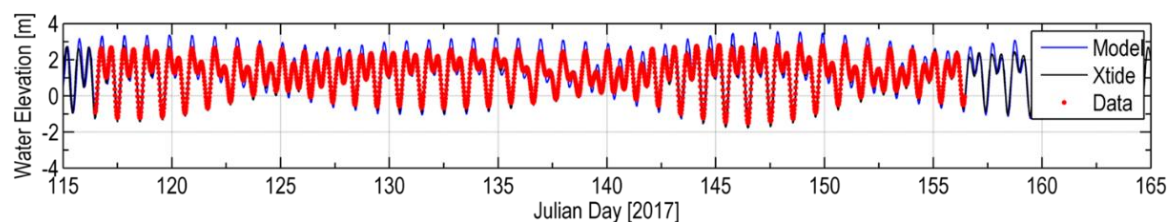


Figure 6. Time series of model result, NOAA harmonic (Xtide) prediction, and observed data for sea-water elevation. Time is shown as Julian days in 2017.

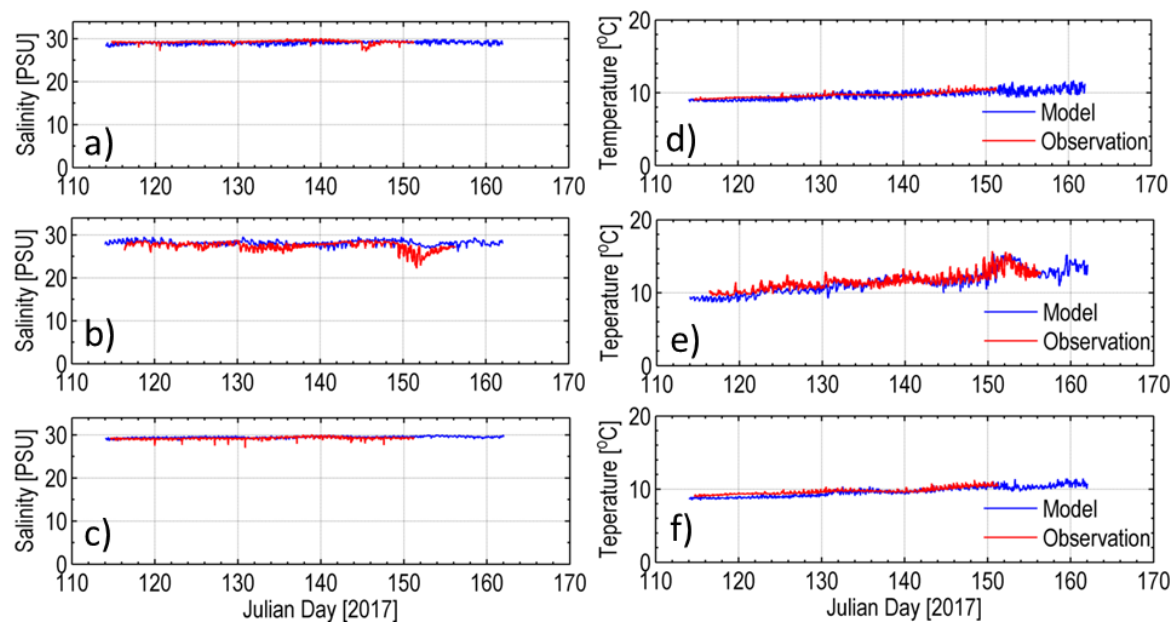


Figure 7. Time series of model results and observed data for salinity (left panel) and temperature (right panel) from 31 May and 1 June 2017. Plots (a,d) are a comparison for the North acoustic Doppler current profiler (ADCP) station; plots (b,e) are for the Bridge ADCP station; and plots (c,f) are for the South ADCP station.

Table 2. Salish Sea model calibration error statistics and skill score for water elevation. AME = absolute mean error.

	AME	RMSE	WSS
Elevation (m)	0.013	0.420	0.960

The error statistics (AME and RMSE) between model predictions and field observations are listed in Table 3. The AME and RMSE for salinity for most stations were less than 1 PSU except for the Bridge ADCP station. The model predicted higher salinity compared to observed data at Julian day 151 when the salinity dropped to 22 PSU. The temperature AME and RMSE were <1 °C for all stations, demonstrating a good match of model predictions with temperature data near the bridge.

Table 3. Salish Sea model validation error statistics and skill score for temperature and salinity at different locations near Hood Canal Bridge (HCB). ADCP = acoustic Doppler current profiler; CTD = conductivity, temperature, and depth.

Station	Temperature			Salinity		
	AME	RMSE	WSS	AME	RMSE	WSS
North ADCP	0.22	0.56	0.74	0.21	0.57	0.30
South ADCP	0.08	0.40	0.85	0.12	0.36	0.41
Bridge ADCP	0.41	0.79	0.90	0.82	1.29	0.47
North CTD	0.47	0.91	0.80	0.33	0.86	0.68
South CTD	0.50	0.80	0.90	0.65	1.03	0.72

A series of CTD casts were also conducted north and south of the bridge. These CTD casts were collected at peak ebb and peak flood, as well as during slack water conditions. The observed salinity and temperature profiles were then compared with simulated temperature and salinity at the same location and time. Figures 8 and 9 show examples of comparisons between observed and simulated salinity and temperature profiles at the north and south CTD cast locations, respectively.

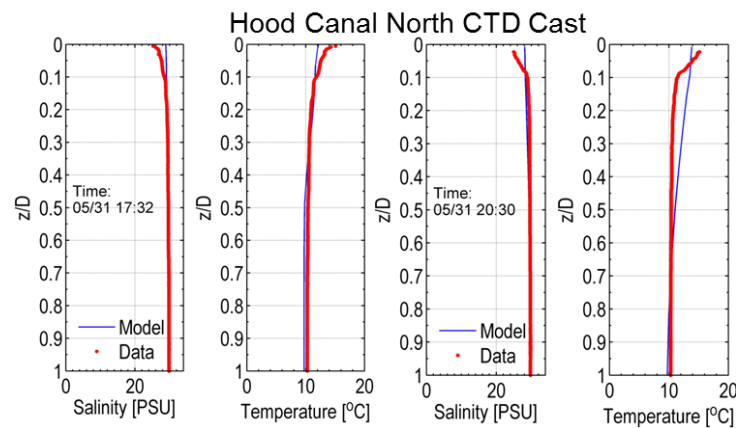


Figure 8. Comparisons of predicted and observed salinities at peak ebb and peak flood north of HCB on 31 May 2017.

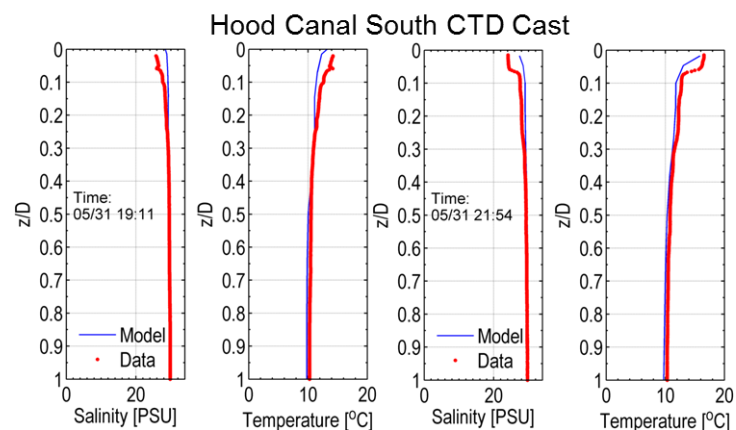


Figure 9. Comparisons of predicted and observed salinities at peak ebb and peak flood south of HCB on 31 May 2017.

The error statistics of temperature and salinity at the north and south CTD locations are also listed in Table 3. For temperature, both locations had AME ~ 0.5 °C with RMSE < 0.8 °C. For salinity, AME and RMSE were 0.65 and 1.03 PSU, respectively. Although overall error statistics for the profiles were acceptable, examination of the results, especially for salinity, shows that the stratification in the upper 10% of the water column in the model is not as strong as in the data. This could be due to the limitation of the model confined to 10 sigma-layers. It could also be associated with near-field mixing induced by the bridge module as incorporated using the cell velocity block option. The results were similar for the three methods used for approximating the bridge block.

Currents: Current predictions at the North ADCP station, the South ADCP station, and the Bridge ADCP station were compared against field observations. The comparisons were selected at depths of 4 m, 9 m, 24 m, 39 m, 54 m, and 69 m. To better illustrate the comparison, velocities were decomposed into longitudinal and transversal components and are provided in Figure 10. The predicted phase of the velocity and the velocity magnitude associated with flooding and ebbing are in good agreement with the field observations. Figure 10 shows a comparison of predicted and observed velocities for different depths at the Bridge ADCP Station. At a depth of 9 m, the ADCP data bin nearest to the surface, the effect of HCB is reflected in both predicted and observed velocities.

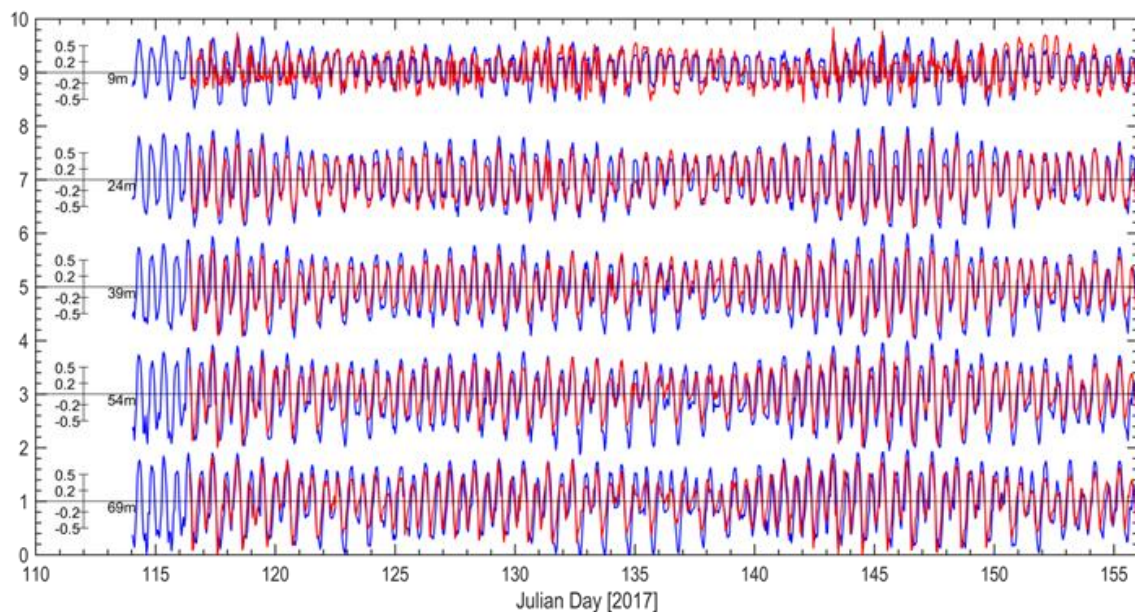


Figure 10. Comparisons of predicted (blue) and observed (red) velocities for different depths at the Bridge ADCP station (example).

In addition to ADCP measurements, in an attempt to get as close to the bridge, pontoon, and hull as possible, a single-point measurement was conducted using an Aquadopp instrument, located 1 m below HCB. Figure 11 shows a comparison between predicted currents and observed data. The model appears to be overestimating the velocity during peak ebb. This region immediately below the bridge is known to generate eddies and shed vortices as the ebbing water is forced under the bridge. The model is unable to resolve these fine-scale eddies, which is one explanation for the error. Due to the fact that the model currently does not include skin friction at the bridge, the slip velocity in the model immediately below the bridge is, therefore, higher than the data.

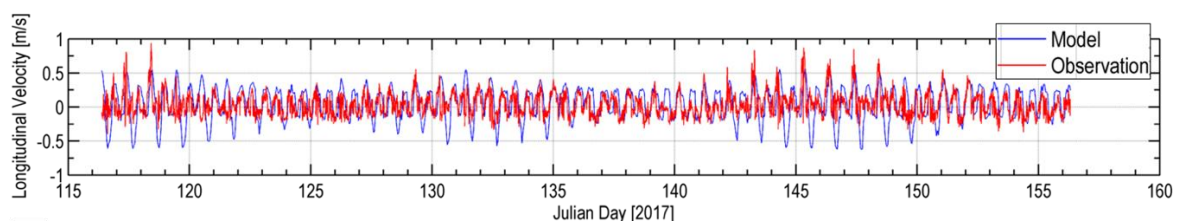


Figure 11. Comparisons of predicted and observed velocities just below HCB.

The corresponding error statistics for current comparisons are summarized in Table 4. All stations had AME < 0.03 m/s. The RMSE for all stations was < 0.21 m/s, except for the Aquadopp single-point measurement, where a higher RMSE of 0.33 m/s was noted. It is noted that these errors are of magnitude comparable to the sustained swimming velocity of a 120-mm Juvenile Coho Salmon (~ 0.64 m/s) and the maximum swimming velocity for a 60–63-mm Juvenile Chum Salmon (~ 0.14 m/s) [22,23]. The WSS for the Aquadopp station was low (0.36) compared to other stations due to the complexity of the measurement. However, the WSS for the North ADCP, the South ADCP, and the Bridge ADCP was > 0.89 , suggesting that the model calibration results were of sufficient quality for use in ZOI calculations.

Table 4. Salish Sea model calibration error statistics and skill score for velocities.

Station	AME	RMSE	WSS
North ADCP	0.00	0.14	0.94
South ADCP	0.02	0.21	0.89
Bridge ADCP	0.03	0.21	0.92
Aquadopp	0.02	0.33	0.36

To assess the effect of HCB on near-field currents, we examined the data during peak ebb and flood periods for every tidal cycle at the North, South, and Bridge ADCP stations. The expectation was that the effect of the bridge on currents would be at a maximum during peak currents. Figure 12a shows the time series of depth-averaged longitudinal velocity at the bridge. Red triangles and yellow triangles indicate selected peak ebb and flood times, respectively, at which velocity information was extracted in each tidal cycle. The averages of predicted peak velocity profiles during flood and ebb are shown in Figure 12b–g along with measured data.

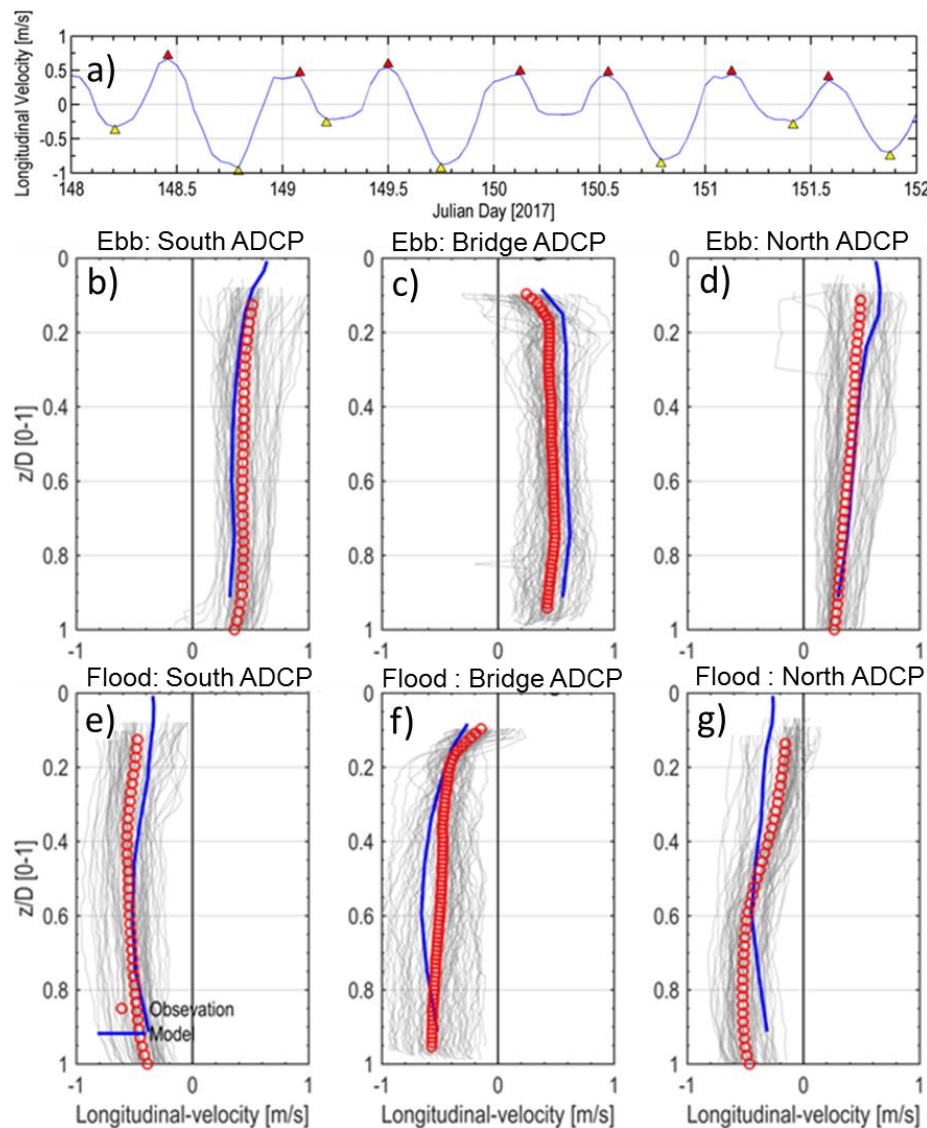


Figure 12. (a) Time series of depth-averaged velocity at bridge; (b–g) comparisons of predicted and observed average velocity profiles at the South, Bridge, and North ADCP stations during maximum flood and ebb tide periods. Gray thin lines represent daily velocity profiles during peak ebb and flood periods.

Positive velocity represents ebb or outflowing current direction due north toward the mouth of Hood Canal. Negative velocity indicates flood tidal currents due south in the opposite direction. Figure 12b–g show that the model is able to match the peak observed average velocity well at all stations during ebb and flood. The velocity reduction due to HCB is reproduced well by the model, as shown in Figure 12c,f. This confirms that the implementation of the bridge module in the Salish Sea model is successful in reproducing the reduction in velocity near the bridge. Small discrepancies were found at all stations that were attributed to approximations associated with smoothing of bathymetry and grid resolution. Similarly, representation of HCB in a sigma-coordinate framework required flattening of the depths immediately below the bridge, resulting in slightly higher velocities in the water column.

3. Results

3.1. Zone of Impact—Surface Layer

To characterize the bridge influence on the near-field environment, two sensitivity test scenario runs were performed. In test 1, the bridge block (1992 m long, 18.3 m wide, and 4.57 m deep) was completely removed, representing the conditions without the bridge. In test 2, the central (movable) span of the bridge with a length of 182 m was left in the open position with the bridge pontoons present in place. The central span is typically opened to allow ship and boat traffic to pass providing a third opening for tidal transport, with the two permanent openings present at the east and west ends of the bridge. To characterize the ZOI, baseline conditions from the summer of 2017 with the bridge in place were compared with the simulated results from the sensitivity tests (1) without the bridge and (2) with the central span open. Comparisons were conducted for predicted currents, salinity, and temperature, and ZOI estimates were obtained through quantifying the difference relative to existing or baseline conditions.

Figure 13 shows contour and velocity vector plots of existing conditions with HCB during ebb and flood. Peak ebb and flood times were selected during a typical spring tide on 27 April 2017, at 10:00 a.m. and 6:00 p.m., respectively, for this examination based on the expectation that maximum impact of the bridge block, reducing the currents to zero, would be strongest during the spring tides and during ebb and flood times. Figure 13a,b are currents with HCB present during the ebb and flood, respectively, for the surface layer. The surface layer occupies the upper 3% of the water column. The ebb currents in the surface layers are stronger than those during the flood. The effect of the HCB structure on currents is noticeable at the bridge where velocity was set to 0 m/s and a shadow of reduced currents exists immediately behind during both ebb and flood.

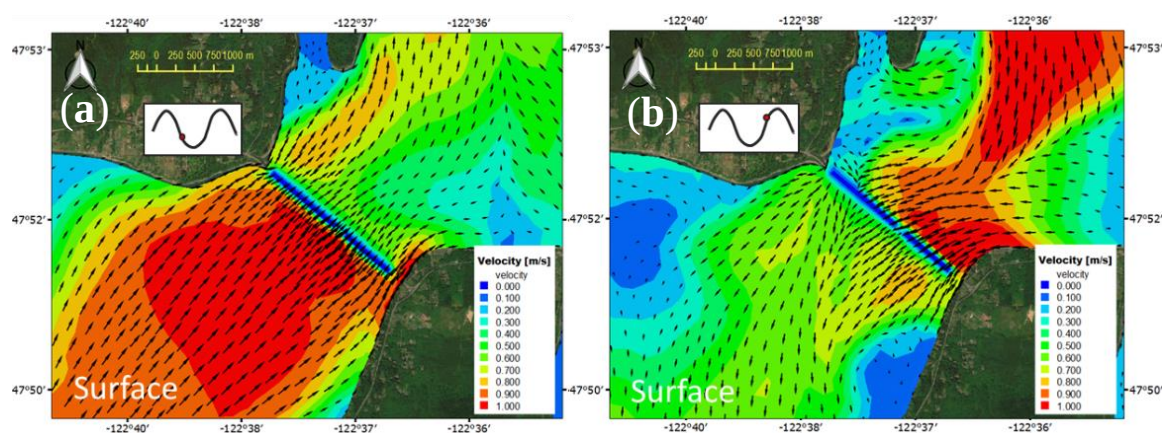


Figure 13. Predicted horizontal velocity contour and vector plots for the baseline scenario with HCB present for (a) ebb and (b) flood currents in the surface layer. (Typical spring tide on 27 April 2017).

Figure 14 shows the same simulation but without the bridge with a much larger region occupied by currents in the >1 m/s bands.

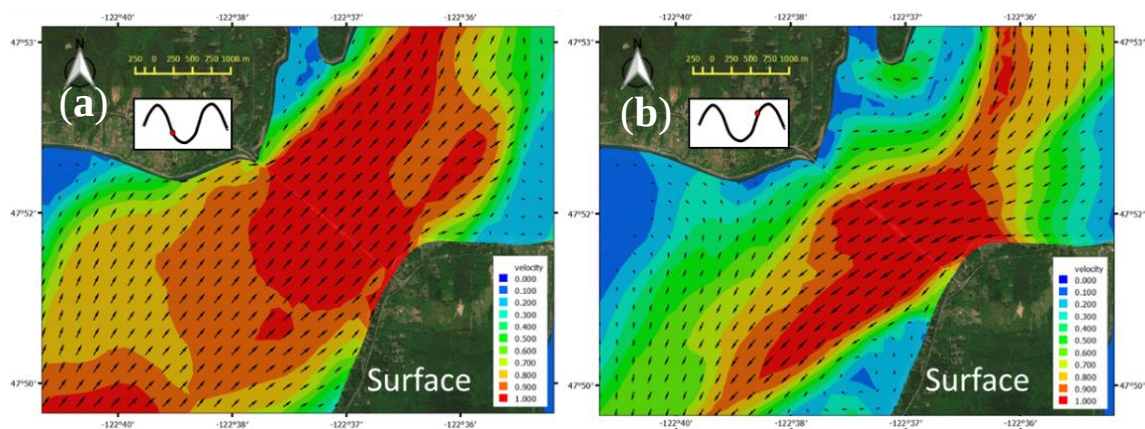


Figure 14. Predicted horizontal velocity contour and vector plots for test 1 scenario without HCB present for (a) ebb and (b) flood currents in the surface layer. (Typical spring tide on 27 April 2017).

Figure 15 shows surface layer currents with the central span open. The current patterns are similar to those at baseline conditions shown in Figure 13. Relative to the size (length) of the bridge blocking the surface layer, the central span represents an opening of $\sim 9\%$. The effect of the opening on the currents is most visible in the form of the jet behind the bridge during both ebb and flood.

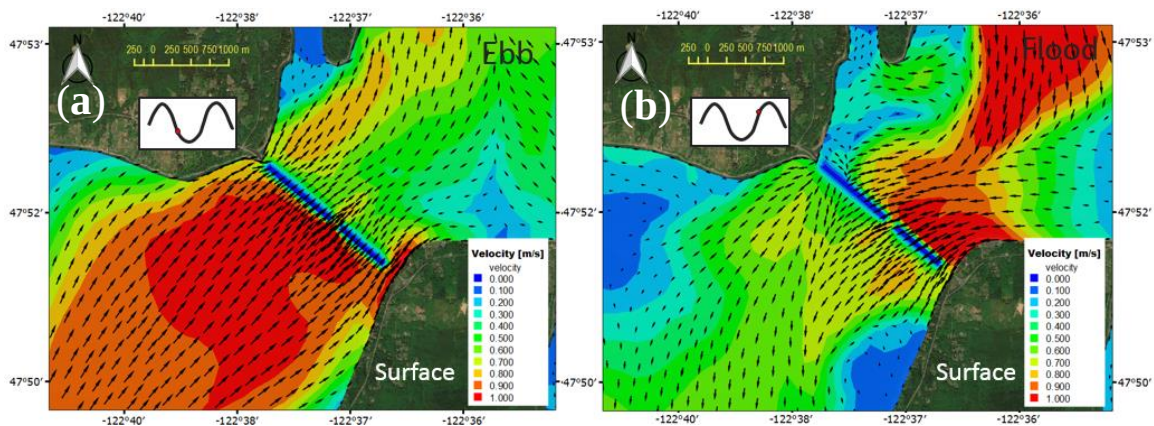


Figure 15. Predicted horizontal velocity contour and vector plots for test 2 scenario with HCB present and middle span open for (a) ebb and (b) flood currents in the surface layer. (Typical spring tide on 27 April 2017).

The ZOI is best characterized using plots of difference between simulated results from the baseline condition (with the bridge) relative to tests 1 and 2 to provide a direct assessment of the bridge impact. Figure 16a,b show a difference (reduction) in currents during peak ebb and flood with the bridge relative to test 1 without the bridge. Figure 16c,d show a reduction in currents during peak ebb and flood relative to the condition with the bridge draw span open. The effect of the bridge on surface currents is noticeable over a distance of ~ 1 – 2 Hood Canal widths in either direction (~ 2 – 5 km). Effect of the bridge span opening on currents is limited (~ 0.25 Hood Canal width, < 600 m), but prominent during the ebb tide with stronger surface currents.

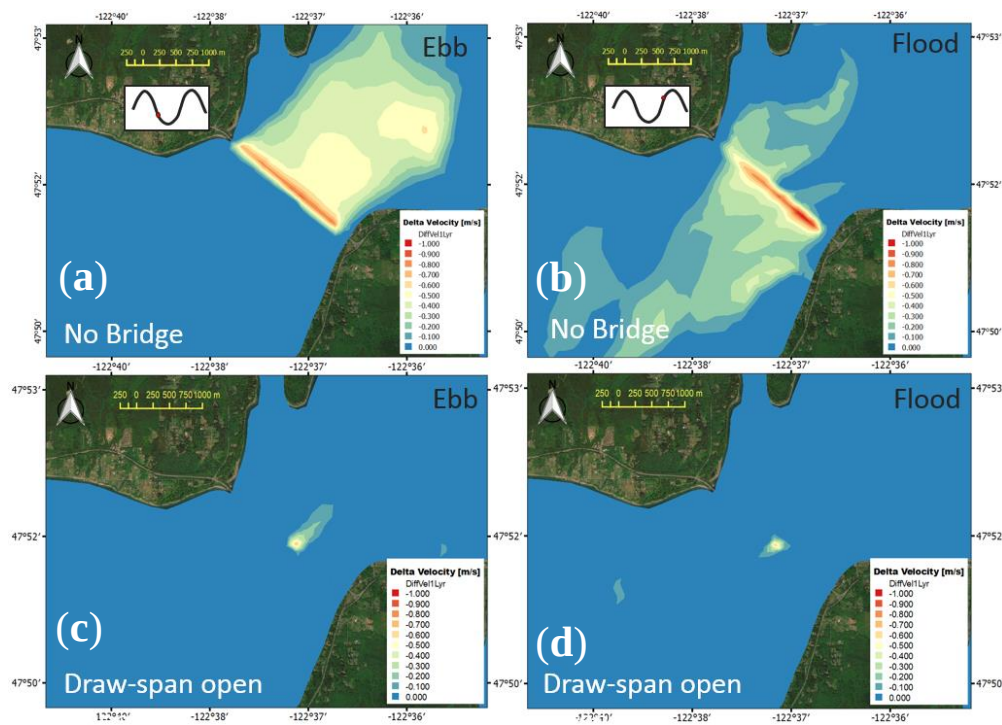


Figure 16. (a,b) Velocity difference of baseline scenario with HCB relative to test 1 without HCB during peak ebb and flood; (c,d) velocity difference of baseline scenario with HCB relative to test 2 with draw span open during ebb and flood. (Typical spring tide on 27 April 2017).

These difference plots in the plan view provide a qualitative estimate of the size of the ZOI for currents in the surface layer. The spatial pattern and extents were similar in nature with the influence of HCB most prominently seen behind the bridge during peak ebb and flood conditions. In all cases, the maximum difference of the baseline condition relative to the scenarios was at the bridge itself. In the surface layer, the maximum current difference was -0.88 m/s, the maximum salinity difference was $+0.23$ PSU, and the maximum temperature difference was -0.49 °C for the selected spring tide on 27 April 2017. The effect of the bridge dissipates with distance from the structure. Unlike velocity, where the effect is directly the result of blocked currents, the influence on salinity and temperature is more complex due to the presence of strong stratification and the increased mixing of surface layers at the bridge. Vertical transects analyzed in the next section provide a better understanding of the influence of the bridge on salinity and temperature.

3.2. Zone of Impact—Vertical Transect

To further quantify the spatial extent of ZOI on current, salinity, and temperature variables in this environment with strong vertical stratification, simulation results were examined along a mid-channel transect across HCB. The assessment was done using two transects: (a) Transect-a, approximately 2.5 km long (length scale of Hood Canal width) across the bridge to provide a detailed characterization of near-field effects; and (b) Transect-b approximately 20 km long (distance from the bridge to the mouth of Hood Canal) to allow examination over larger distances over full tidal excursion (see Figure 17). The results were analyzed as difference plots similar to the plan view maps in the previous section, during the selected typical spring tide of 27 April 2017, at peak ebb (147.42 Julian days (JD), 27 May 2017 10:00 a.m.) and peak flood times (147.75 JD, 27 May 2017 6:00 p.m.).

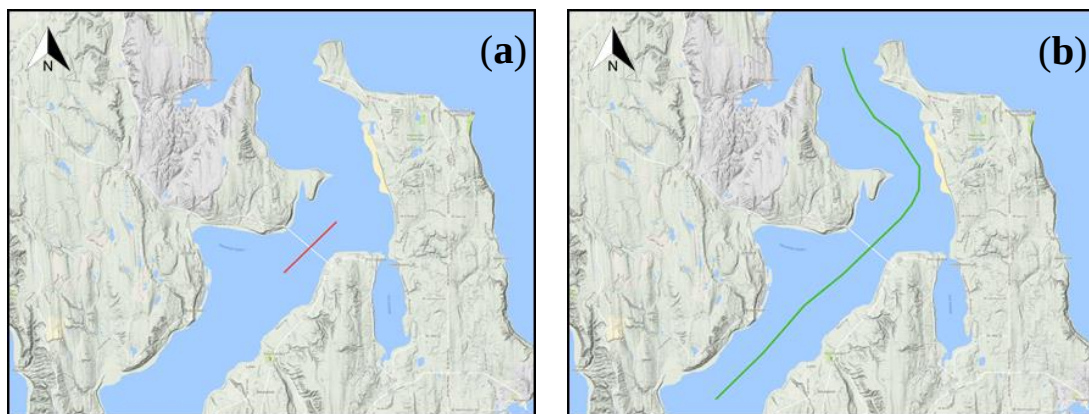


Figure 17. Transects for assessment of zone of influence (ZOI) in a vertical plane: (a) short transect for near-field effects; (b) longer transect to examine the effects over full tidal excursion.

The near-field effects of HCB on the current, salinity, and temperature in a vertical two-dimensional plane near the ZOI for the example spring tide period are shown in Figures 18–20, respectively, using the shorter Transect-a. The distance between -1.25 km and 0 km represents the section south of the bridge, while that between 0 km and 1.25 km represents the downstream section north of the bridge. As in the surface plan view maps, a reduction in current magnitudes behind the bridge is seen during the flood and ebb. Figure 18a,b show that the currents are reduced behind the bridge relative to the scenario without the bridge. The vertical transect shows that the effect extends beyond the 1.25 -km transect length on either side of the bridge and the effect is noticeable mostly in the upper ~ 10 – 15 m of the water column. Figure 18c,d show a similar relative difference in currents relative to the scenario with bridge draw span open. The effect is minor with a change of up to 0.3 m/s seen at the draw span opening, extending <500 m from the bridge.

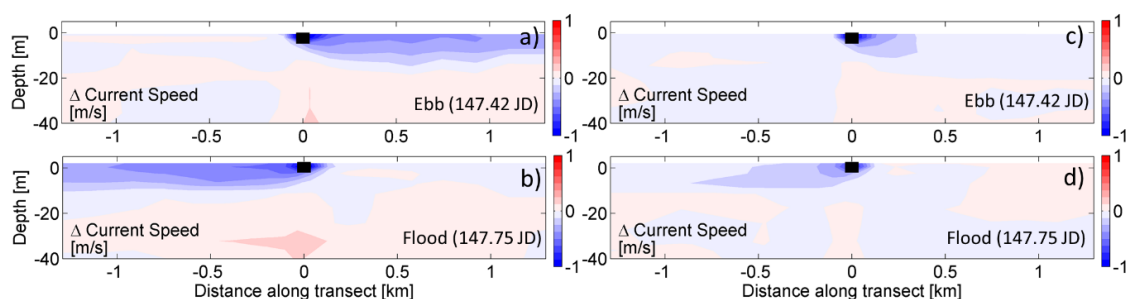


Figure 18. (a,b) Velocity difference of baseline scenario with HCB relative to test 1 without HCB during peak ebb and flood; (c,d) velocity difference of baseline scenario with HCB relative to test 2 with draw span open during ebb and flood. (Typical spring tide on 27 April 2017).

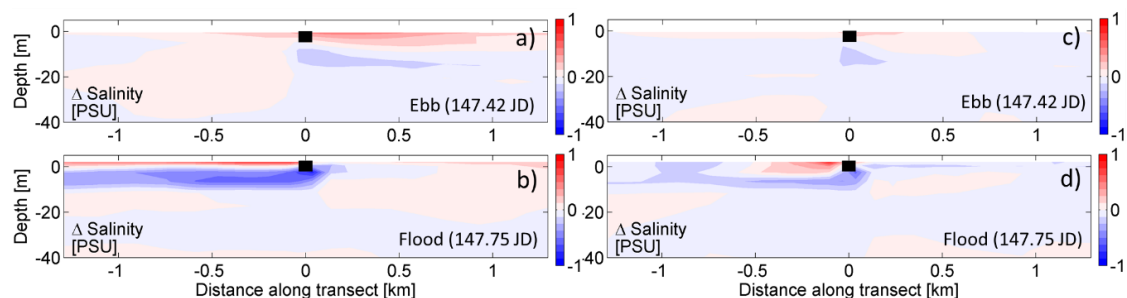


Figure 19. (a,b) Salinity difference of baseline scenario with HCB relative to test 1 without HCB during peak ebb and flood; (c,d) velocity difference of baseline scenario with HCB relative to test 2 with draw span open during ebb and flood. (Typical spring tide on 27 April 2017).

Figure 19a,b show the effects of HCB on salinity through difference plots relative to test 1 without the bridge, during ebb and flood, respectively. The surface layer salinity immediately behind the bridge was higher. This was due to the blocking effect of the bridge holding the fresher (lower salinity) water back during flood and ebb. The traversing surface layer was forced to flow under the bridge, resulting in reduced salinity in the deeper layers below the bridge. A similar effect is seen relative to test 2 with the draw span open. Figure 19c,d show a small increase in surface salinity behind the bridge relative to the scenario with the draw span open. Plan view plots are consistent with velocity difference plots in that the effect of test 2 was restricted to a small region near the span opening. Salinity was lower in the layers immediately below the bridge due to fresher water being forced to lower layers by the presence of the bridge relative to the condition with draw span open.

The effect of HCB on temperature is similar to that predicted on salinity. Thermal stratification surface heat flux results in water temperatures in the surface layers being warmer than lower layers. The presence of the bridge holds the surface layers back, resulting in cooler waters immediately behind it relative to test 1 without the bridge during ebb and flood, as shown in Figure 20a,b. The warmer water was forced to traverse underneath the bridge, resulting in warmer waters in the deeper layers behind the bridge. Figure 20c,d show a similar effect but on a smaller scale with a small increase in surface temperature behind the bridge relative to the scenario with the draw span open. Temperatures were higher in the layers immediately below the bridge due to warmer water being forced to lower layers by the presence of the bridge relative to the condition with draw span open.

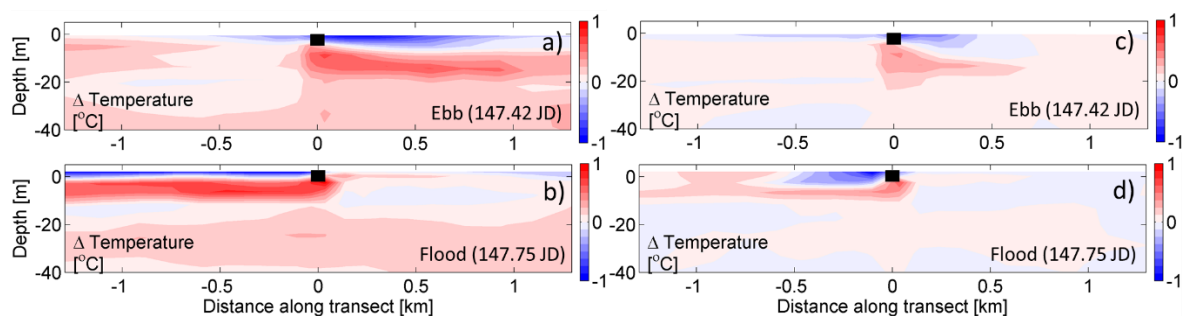


Figure 20. (a,b) Temperature difference of baseline scenario with HCB relative to test 1 without HCB during peak ebb and flood; (c,d) velocity difference of baseline scenario with HCB relative to test 2 with draw span open during ebb and flood. (Typical spring tide on 27 April 2017).

4. Discussion

Zone of Influence—Quantitative Assessment

The ZOI extends beyond the Hood Canal width scale of 2.4 km based on the results presented in Section 3. However, to quantify spatial extent, environmentally significant influence must first be defined. Maximum difference induced by HCB relative to test 1 on currents without the bridge occurred at the bridge itself and decayed or dissipated with distance from the bridge. For the purpose of this assessment, we defined ZOI as the distance at which the maximum difference (Δ) dropped to 10% of its value for current and salinity parameters (e.g., if maximum $\Delta = 1$ m/s, then ZOI is where $\Delta = 0.1$ m/s).

We first assessed the horizontal extent of ZOI by examining the changes in surface currents induced by the bridge relative to test 1. With a focus on impacts during peak tidal currents, we averaged multiple (71) peak ebb and peak flood instances over the calibration simulation period (25 April–11 June 2017). We then examined the vertical longitudinal extent of the ZOI by examining the relative difference of the variables for all depth layers along Transect-b over a distance of 20 km. Figure 21 shows the average difference in peak currents due to the presence of HCB relative to test 1 for the 10 model layers. The distance between -10 km and 0 km represents the region south of the bridge, while that between 0 km and 10 km represents the region north of the bridge. Model layers were distributed

using a power law with an exponent of 1.5 such that layers had a higher concentration near the surface. Surface layer 1 occupied 3% of the water column and the bottom layer 10 occupied 15% of the water column. For currents, based on averaging multiple peak ebb and peak flood instances, maximum difference (-0.70 m/s) occurred during the ebb and in the surface layer, extending ~ 2.02 km north before dropping to -0.07 m/s (10% of the maximum difference). The maximum difference during the flood (-0.57 m/s) also occurred in the surface layer and the influence extended up to 3.43 km. It is interesting to note that, while there was a reduction in surface currents, the model generated a compensating increase in bottom-layer currents during flood, as well as ebb. The zone of influence, therefore, extends over the entire water column. It is important to note that this ZOI for currents is based on average impacts during peak currents. The ZOI spatial extent is smaller at all other times with smaller-magnitude currents.

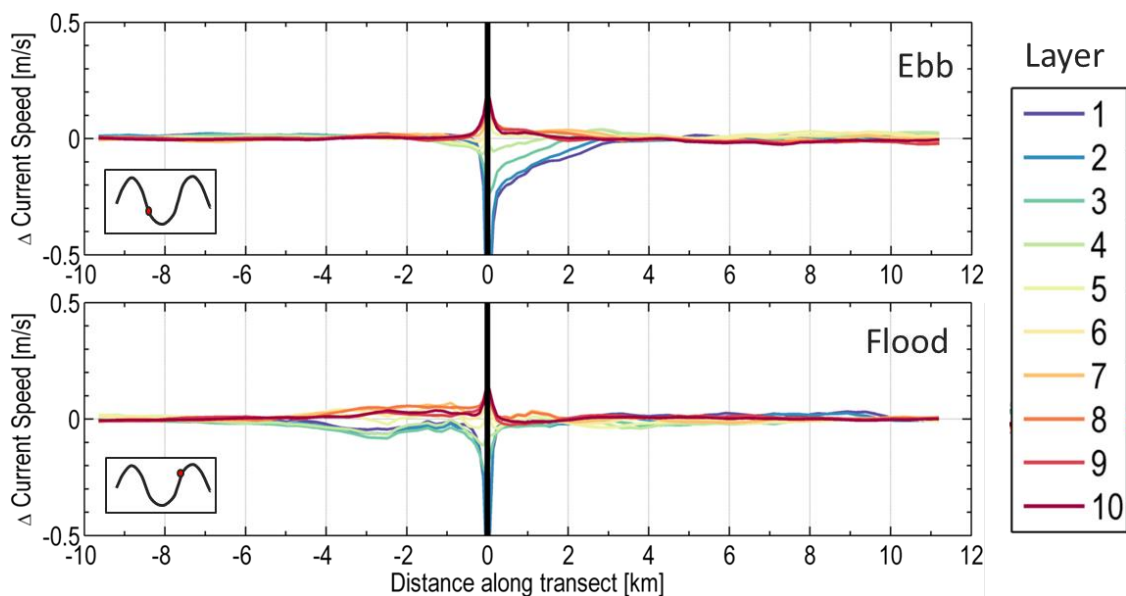


Figure 21. Difference in current magnitudes due to HCB relative to test 1, plotted along Transect-b for all model layers. The (top) panel presents peak ebb and the (bottom) panel presents peak flood results averaged over the calibration period of 25 April–11 June 2017. (The distance between -10 km and 0 km represents the region south of the bridge, while that between 0 km and 10 km represents the region north of the bridge).

Further examination of the results showed that, unlike velocity, peak instantaneous difference between baseline with bridge and test 1 without the bridge for temperature and salinity did not always occur at the bridge and occurred at various times in the tidal cycle. Peak instantaneous differences that vary in space and time make it difficult to define the ZOI. The approach for temperature and salinity was, therefore, to develop an average ZOI, taking into consideration all time steps.

Figure 22 shows the difference in salinity due to the presence of HCB relative to test 1 computed by averaging the differences over all hourly time steps for each layer. The average salinity difference results show a consistent pattern north and south of the bridge. The peak influence in average salinity occurred at the bridge, and, as described in Section 3, it was controlled by the mixing induced by the structure during ebb and flood. This resulted in an increase in salinity in the upper layers above the bridge draft depth (0 – 4.57 m) and a corresponding reduction in salinity in the lower layers below the draft from 4.57 m to ~ 20 m. The near-bed layers were unaffected. Also noticeable is the extent of the effect north of the bridge in the surface where the surface layers show elevated salinity levels $\sim +0.1$ PSU that extend all the way to the mouth of Hood Canal. The effects of bridge-induced mixing resulted in higher salinity concentrations in the surface layers that were transported north in the surface outflow direction. This resulted in persistent and elevated levels of background salinity difference north of the

bridge of 0.06 PSU over 4–10 km. The maximum difference (Δ) in salinity at the bridge was +0.42 PSU that extended 1.96 km to the south before dropping to 10% (0.04 PSU). ZOI determination to the north was complex as background salinity increased past the salinity 10% Δ level. The ZOI to the north was, therefore, provided as a range from 3.80 km where salinity Δ dropped to 10% above the background level of 0.1 PSU to Hood Canal mouth at ~10 km.

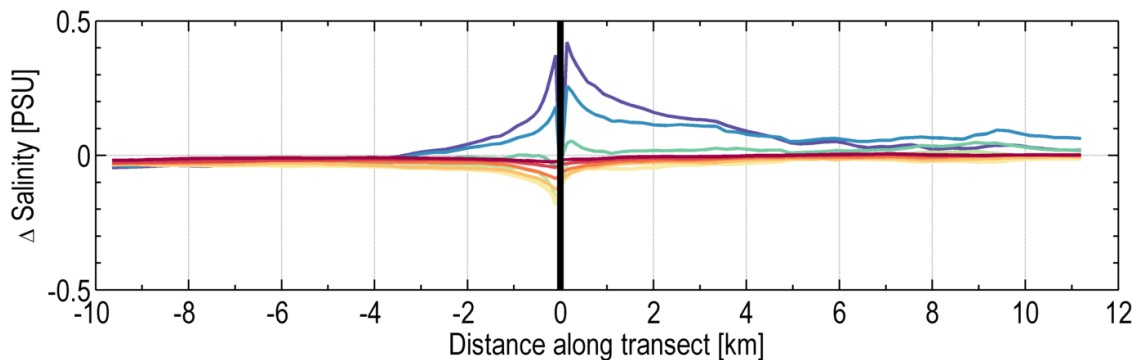


Figure 22. Difference in salinity due to HCB relative to test 1, plotted along Transect-b for all model layers. The plot shows average salinity difference for all hourly time steps over the calibration period of 25 April–11 June 2017. (The distance between −10 km and 0 km represents the region south of the bridge, while that between 0 km and 10 km represents the region north of the bridge).

Figure 23 shows the difference in temperature due to the presence of the bridge relative to test 1 for the 10 model layers. The effect of HCB on temperature, based on averaging the difference for all hourly time steps over the period of 25 April–11 June 2017, was similar to that for salinity. The influence of the bridge on near-field temperature, due to the mixing induced by the bridge, resulted in a decrease in upper layer temperatures and an increase in temperature in lower layers below the draft from 4.57 m to ~20 m. The near-bed layers were unaffected. The effect of the bridge on temperature is noticeable in the downstream region north of the bridge where the surface layers showed a reduction in temperature levels that extended all the way to the mouth of Hood Canal. The maximum average difference ($-0.49\text{ }^{\circ}\text{C}$) in the surface layers, a reduction in surface temperatures, dissipated to 10% ΔT ($0.05\text{ }^{\circ}\text{C}$) ~2.23 km to the south. However, as in the case of salinity, temperature ZOI determination to the north was complex as there was a decrease in background temperature difference of $0.11\text{ }^{\circ}\text{C}$, over 4–10 km, that exceeded the temperature 10% ΔT level. The ZOI to the north was, therefore, provided as a range from 4.51 km where temperature ΔT dropped to $0.16\text{ }^{\circ}\text{C}$, 10% Δ above the background level, to Hood Canal mouth at ~10 km. It is noted, however, that the bridge caused an increase in temperatures in the lower layers of up to $0.20\text{ }^{\circ}\text{C}$.

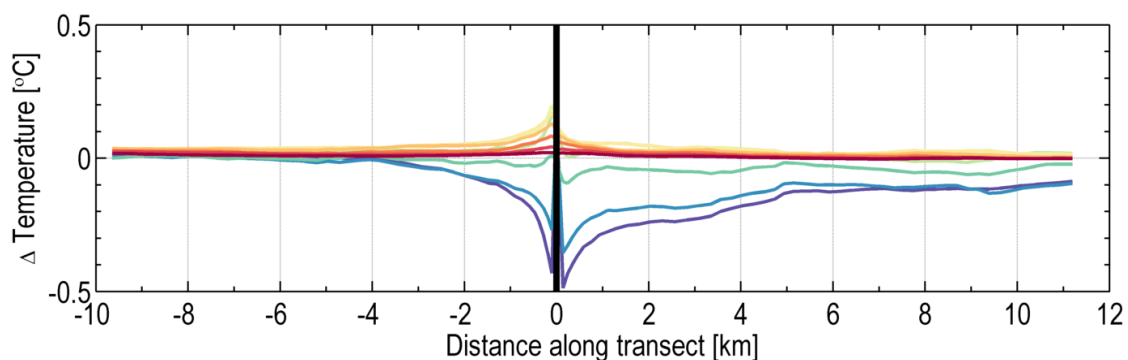


Figure 23. Difference in temperature due to HCB relative to test 1, plotted along Transect-b for all model layers. The plot shows average temperature difference for all hourly time steps over the calibration period of 25 April–11 June 2017. (The distance between −10 km and 0 km represents the region south of the bridge, while that between 0 km and 10 km represents the region north of the bridge).

Table 5 summarizes the ZOI dimensions for the parameters of interest examined using the criterion of a reduction in maximum difference Δ to 10% of its value.

Table 5. Summary of zone of influence (ZOI) characterizing distances over which the difference in predicted maximum difference Δ due to the presence of the bridge relative to the test 1 scenario without the bridge was reduced to 10% of its value. Results in this table are based on an average of all peak ebb and flood instances over the period of 25 April–11 June 2017 for velocity, and an average of all time steps for salinity and temperature.

Variable	Max. (Δ)	South HCB	North HCB
		ZOI (km)	ZOI (km)
Velocity (m/s)	−0.70	2.02	3.43
Salinity (PSU)	0.42	1.96	3.80–10
Temperature (°C)	−0.49	2.23	4.51–10

Although the ZOI calculations and the values presented in Table 5 above used average values of maximum differences, it is noted that instantaneous differences could be as high as 1.22 m/s, 1.66 PSU, and 2.16 °C for velocity, salinity, and temperature, respectively.

5. Conclusions

A combination of oceanographic field data measurements and modeling-based assessment were used to ascertain whether the presence of HCB impacts near-field oceanographic parameters. While some effect was expected simply due to the existence of a large floating object in the path of the tidally influenced fjord-like waterbody of Hood Canal, the extent of influence was not quantified in the past. The results were conclusive in that both field data and model results showed that HCB blocks the movement of surface layer currents over ~85% of the width of Hood Canal. The openings at each end of the bridge (15% of the Hood Canal width) do carry a portion of the tidal flow; however, these openings are in shallow depths and do not fully compensate for the surface layer blockage. As a result, the current profile structure in the water column is altered. The reduction in surface layer currents and tidal flow is compensated by a corresponding increase in bottom-layer currents and flow. The impact is also felt in salinity and temperature magnitudes, particularly in the upper 20 m of the water column.

The ZOI was defined as the distances over which the difference in predicted maximum difference due to the presence of the bridge relative to the conditions without the bridge was reduced to 10% of its value. Based on the simulation conducted using 2017 spring conditions, the ZOI for current extends 3.43 km to the north and 2.02 km to the south of HCB. Maximum current difference based on the average of peak currents was −0.70 m/s at the surface layer. Similarly, the ZOI for salinity extends 3.80 km to the north and 1.96 km to the south, over which salinity deviated from the condition without the bridge. Maximum salinity difference was an increase of 0.42 PSU in the surface layers and an increase of 0.26 PSU in layers immediately below the bridge, based on a temporal average over the duration of the simulation. The ZOI for temperature extends 2.23 km to the south of HCB, over which temperature deviated from the condition without the bridge. Maximum temperature difference at the bridge was a decrease 0.49 °C in the surface layers and a decrease in temperature of 0.36 °C in layers immediately below the bridge, based on a temporal average over the duration of the simulation.

The near-field influence of the bridge on physical parameters of currents, salinity, and temperature as quantified by ZOI extends over 1.96 km to 5.15 km, which is roughly one to two Hood Canal width scales. Our study concludes that the influence on temperature and salinity is restricted to the upper 20 m, but extends through the water depth for current. The influence on temperature and salinity persists beyond the ZOI all the way to the mouth of Hood Canal at the confluence with Admiralty Inlet. The downstream effect is associated with fjord-like estuarine circulation. The brackish outflow in Hood Canal is restricted to surface layers. The presence of the bridge affects this net outflow through

blockage and added turbulence and mixing. The persistent impact is seen in salinity and temperature downstream of the bridge, even after tides are averaged out.

Author Contributions: T.K. led the investigation and was responsible for conceptualization, methodology, and model development and application. T.W. developed the bridge module software. A.N. was responsible for processing and analysis of model results and field data. T.K. and A.N. analyzed the simulation results and developed the methodology for quantifying and summarizing the results.

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[Appendix F. Khangaonkar & Nugraha 2019](#)

Hood Canal Bridge impact on basin-wide water quality – initial analysis

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Hood Canal Bridge Impact on Basin-Wide Water Quality – Initial Analysis

**Hood Canal Bridge Ecosystem Impact Assessment
Study – Component 11**

June 2019

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DRAFT

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1.0 Introduction

The *Hood Canal Bridge Ecosystem Impact Assessment*, led by Long Live the Kings (LLTK) in partnership with the Hood Canal Coordinating Council, tribes, and state and federal agencies, was initiated in 2016. The primary focus of the study is identifying the cause of high steelhead mortality at the Hood Canal Bridge (HCB) and assessing the bridge's effects on water quality. The study plan (HCB Assessment Team 2016) included numerous components and the schedule was divided into two phases. Phase 1 focused on the near-bridge or near-field impacts on juvenile steelhead migration caused by the floating barrier of the bridge, and an initial assessment of the basin-wide impact of the HCB on the Hood Canal ecosystem. As part of the HCB Impact Assessment project team, Pacific Northwest National Laboratory (PNNL) has led the study components related to modeling the HCB effects on currents, characterization of the near-field zone of influence, acoustic noise impacts, large-scale impacts on circulation, and water quality.

PNNL led component 11 of the study plan, which addresses the question “What is the impact of Hood Canal Bridge on basin-wide circulation and water quality?” The Component 11 objective was to conduct an initial analysis of the effects of HCB on flushing, biogeochemistry, dissolved oxygen (DO), and pH. As planned, this initial modeling-based analysis would be conducted using already available data for model validation and using model developments completed previously (Components 8 and 9 of the study plan). The effort would provide a first indication of whether HCB has a large-scale impact on Hood Canal. If so, a more detailed investigation would be undertaken during the next phase of the study.

The analysis was conducted using the Salish Sea Model (SSM) (Khangaonkar et al. 2019, 2018). The results, contrary to expectations, showed that the HCB impacts on large-scale circulation were negligible, the flushing time was not affected, and as a result, water-quality response examined at selected monitoring stations far away from the HCB showed practically no change. To ensure best use of available resources, the investigation was terminated with this finding because it was clear that the large-scale circulation and water-quality response provided by the SSM was not sensitive to the presence of the HCB. This white paper style document provides a summary of the findings derived from this effort.

1.1 Background

The natural ecosystem in Hood Canal is controlled by tidal hydrodynamics in a long deep basin that has classic fjord-like features. Mean circulation and mixing here are dominated by the influence of freshwater runoff, presence of a large sill near the mouth, and strong tidal action. The estuarine circulation in Hood Canal consists of a balance between the shallow surface layer outflow of buoyant freshwater and a corresponding inward-bound saltwater compensation current immediately below the surface layer that is essential to sustaining the water quality and overall health of the canal. The net transport and exchange in the deepest layers is muted and it is for this reason that fjords tend to become anoxic, especially in the presence of a sill. Parts of Hood Canal, such as Lynch Cove and Dabob Bay, are known for their low DO conditions that have been observed since the 1950s (e.g., Barnes and Collias 1958; Collias et al. 1974) and have been of great interest because of recurring fish kills in the 2000s (e.g., Curl and Paulson 1991; Paulson et al. 2006; Newton et al. 2007).

The possibility that these naturally occurring hypoxic conditions could be exacerbated by anthropogenic influences was of interest. PNNL had conducted a preliminary investigation of the

hypothesis that the natural oceanographic structure of fjordal stratification and circulation could be disrupted by hydraulic modifications of the surface brackish layer. The influence of a permanent floating structure (in this case the floating HCB across the width of the canal) on the circulation and flushing characteristics of the system was examined under simplifying assumptions (Khangaonkar and Wang 2013). The results suggested that the bridge produces a local, zero-velocity, surface boundary condition that dampens current magnitudes, especially in the upper water column, and slows down the fjordal water flushing/renewal process. Although the overall cross-sectional area occupied by the floating bridge is small, it is a large fraction of the outflow layer. The preliminary results pointed to the possibility that the presence of the floating bridge might have the potential to increase the residence or flushing times in the basin by 8 to 13 percent.

These results were notably based on conceptual, analytical, and sub-basin-scale numerical models, and without any site-specific field validation. Yet, while these numbers seemed speculative and small, if true, such a reduction in the ability for Hood Canal to flush naturally was regarded as a potential factor that could lead to the worsening of hypoxic conditions, thereby affecting the entire Hood Canal food web. A recent U.S. Environmental Protection Agency (EPA) and Washington State Department of Ecology (Ecology) review and synthesis of available information about human impacts on DO in Hood Canal identified the HCB as one of the factors needing further examination (Cope et al. 2013). The report concluded that the effect of the bridge on circulation as identified by Khangaonkar and Wang (2013) might have the potential to affect water quality, and it recommended additional work to quantify the bridge's effect on DO.

Subsequently, as part of Phase 1 of the HCB Impact Assessment Study, the following two modeling efforts were proposed:

- Hydrodynamic Modeling to Characterize – Hood Canal Bridge Zone of Influence
- Hood Canal Bridge Impact on Basin-Wide Circulation and Water Quality – Initial Analysis.

The hydrodynamic investigation of the HCB Zone of Influence (ZOI) (near-field region of deviation from ambient background) confirmed that HCB, with a draft of 4.6 m covering ~85% of the width of Hood Canal, obstructs the brackish outflow surface layer (Khangaonkar et al. 2019). That effort included validation of the bridge effect using site-specific current profile data collected near the bridge. The results showed that the bridge induces increased local mixing near the bridge, causes pooling of water (up-current) during ebb and flood, and results in shadow/sheltering of water (down-current). The change in ambient currents, salinity (S), and temperature (T) is highest at the bridge location and reduces to background levels with distance from the bridge. The ZOI extends ~20 m below the surface and varies from 2–3 km for currents, 2–4 km for S, and 2–5 km for T before the deviations with the bridge drop to <10% relative to simulated background conditions without the bridge present.

1.2 Objectives: Determine the Impact of HCB on Basin-Wide Water Quality

The overall objective of this study component was to evaluate the bridge's effect on circulation in the basin, which may in turn affect surface T, S, and biogeochemical cycling, including nutrient uptake and algae growth, sedimentation, and pH. Specific objectives broken into sub-tasks were as follows.

- Bridge module development for the biogeochemical model – Incorporation of the HCB in the SSM required development and testing of a Bridge module within the SSM. As part of hydrodynamic modeling to characterize ZOI, a bridge module was developed and validated against the physical oceanographic data (currents, T, and S) collected in June 2017. The objective of this sub-task was to continue that effort and ensure the bridge module performance and functionality in the SSM biogeochemical component as well.
- Initial calibration of the SSM with the embedded HCB module – The objective of this sub-task was to demonstrate validation of the biogeochemical component of the SSM with standard water-quality parameters such as nutrients, algal biomass, DO, and pH with the refined model domain and bridge module activated. The validation would be conducted using data collected by Ecology at 23 stations within Puget Sound, including 3 stations in Hood Canal. The baseline condition with the bridge could then be compared with the scenarios without the bridge or with the bridge span open.
- Initial assessment of the impact of HCB on water quality – Assessment of the HCB impact on water quality would be conducted through scenario (sensitivity) testing. Three scenarios would be compared following 1-year simulation of the entire Salish Sea domain: (1) baseline condition with HCB present, (2) Scenario 1 – HCB removed, and (3) Scenario 3 – HCB present with central span open.
- Circulation and flushing analysis – Circulation and flushing analysis would be conducted to quantify the effect of the bridge on large-scale hydrodynamic parameters such as flushing/residence times and exchange flows, and correlate them with predicted impacts on water-quality parameters such as T, S, DO, and pH.

2.0 Salish Sea Model with HCB Refinement – Setup and Validation

2.1 Approach

The HCB module within the SSM is represented by a structural block on the free surface. This was previously developed through numerous tests using simple channel geometries, and subsequent full-scale tests with HCB embedded within the SSM grid and calibrated using near-field oceanographic data (Khangaonkar and Nugraha 2019). The approach selected was to use this calibrated SSM with the HCB to conduct water-quality simulations. This requires year-long model simulation using conditions from a selected prior year for which water-quality monitoring data were available. Wastewater and river loading information and monthly water-quality monitoring data for the Salish Sea are collected processed by Ecology. Year 2014 (Y2014) was selected for this effort based on the most recent complete data set and SSM water-quality parameter set available to the project team at the time of conducting this study.

2.2 SSM Hydrodynamic Component with the HCB Refinement – Y2014

The SSM is an externally coupled hydrodynamic and biogeochemical model developed by the PNNL in collaboration with Ecology to support coastal estuarine research, restoration planning, water-quality management, and climate-change response assessments in the region (Khangaonkar et al. 2017, 2018). The model was constructed using the unstructured grid Finite-Volume Community Ocean Model (FVCOM) (Chen et al. 2003) version 2.7 framework and integrated-compartment model biogeochemical water-quality kinetics (Cerco and cole 1994, 1995). To facilitate enhanced exchange with the Pacific Ocean, the SSM grid includes coastal waters around Vancouver Island and the continental shelf from Canada's Queen Charlotte Strait to Oregon's Waldport, south of Yaquina Bay.

2.2.1 SSM – Hydrodynamic Component Setup

Figure 1(a) shows the SSM domain and grid with 16,012 nodes and 25,019 triangular elements. The vertical configuration of the model uses 10 sigma-stretched layers distributed using a power law function with an exponent P-Sigma of 1.5, which provides more layer density near the surface. The model was set up for the year 2014. Figure 1(b) shows station locations where Ecology collects monthly water-quality profile data. The model is loaded with daily values of freshwater inflow from a total of 23 major gauged rivers, 46 ungauged streams for which flows were estimated through hydrological analysis, and 100 wastewater flows (Mohamedali et al. 2011). The model is forced with wind and heat flux at the water surface. Meteorological inputs were obtained from Weather Forecasting Research Model reanalysis data generated by the University of Washington. Tidal forcing at the open boundary was based on tidal constituents (S2, M2, N2, K2, K1, P1, O1, Q1, M4, and M6) derived from the Eastern North Pacific or ENPAC model (Spargo et al. 2003). T and S profiles at the boundary were extracted from quarterly monitoring data collected by the Department of Fisheries and Ocean Canada. Spin up for the hydrodynamic model was conducted through a one-year run initiated from stationary conditions (zero initial velocity and water-surface elevation) with uniform T (7°C) and S (32 practical salinity units [psu]). The simulation was then repeated using year-end results as the restart initial condition.

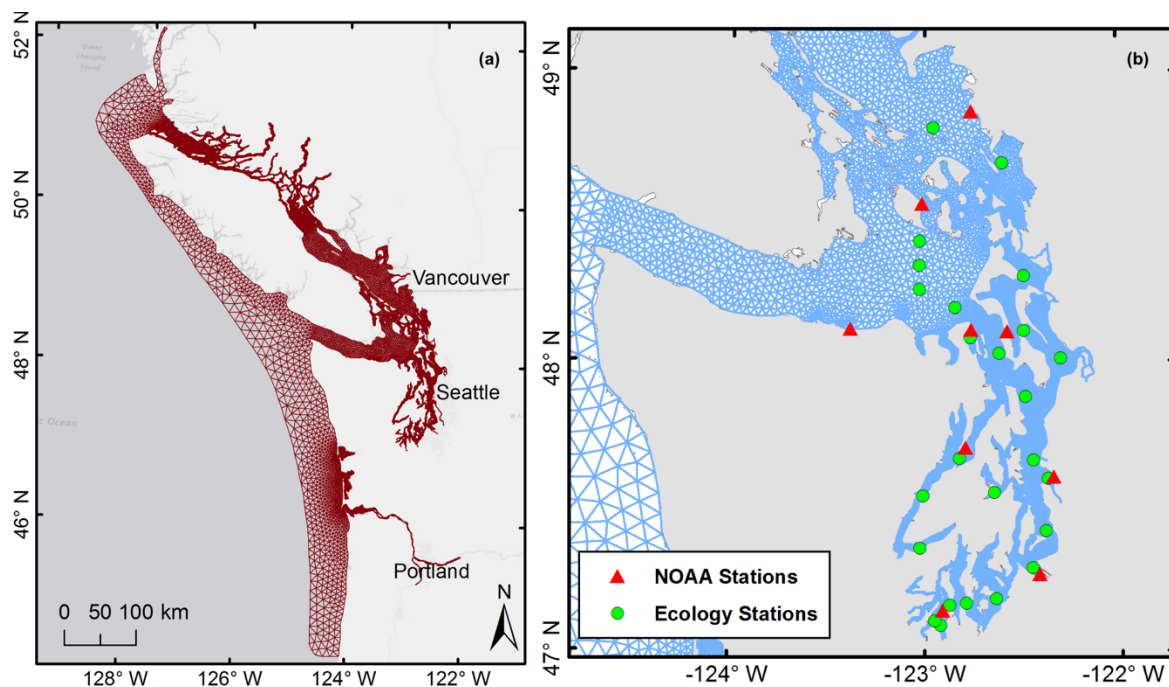


Figure 1. (a) Salish Sea Model domain and finite-volume grid, and (b) monthly water-quality monitoring stations from the Washington State Department of Ecology.

HCB was first implemented in the SSM through a combination grid refinement and code modification.

2.2.2 HCB Module Implementation Summary

The FVCOM framework used in the SSM is a three-dimensional, free-surface, terrain-following solver for the primitive form of Navier–Stokes equations. The model uses an unstructured grid in the horizontal dimension and a sigma-stretched coordinate system in the vertical dimension. The floating bridge in this framework may be best approximated by a rectangular barge-like pontoon. See Figure 2 for HCB profile and cross-section details.

However, representation of the rectilinear shape of the pontoons in this discretized framework requires special attention. While the width and the horizontal dimensions may be represented in a straightforward manner by suitable refinement and arrangement of the triangular elements, representing the uniform draft in a terrain-following sigma coordinate system poses a particular challenge. The bridge was specified as being 1992 m long and 18.3 m wide, and having a draft of 4.57 m. Figure 3 shows a close-up of the model grid refinement for the HCB region of the domain.

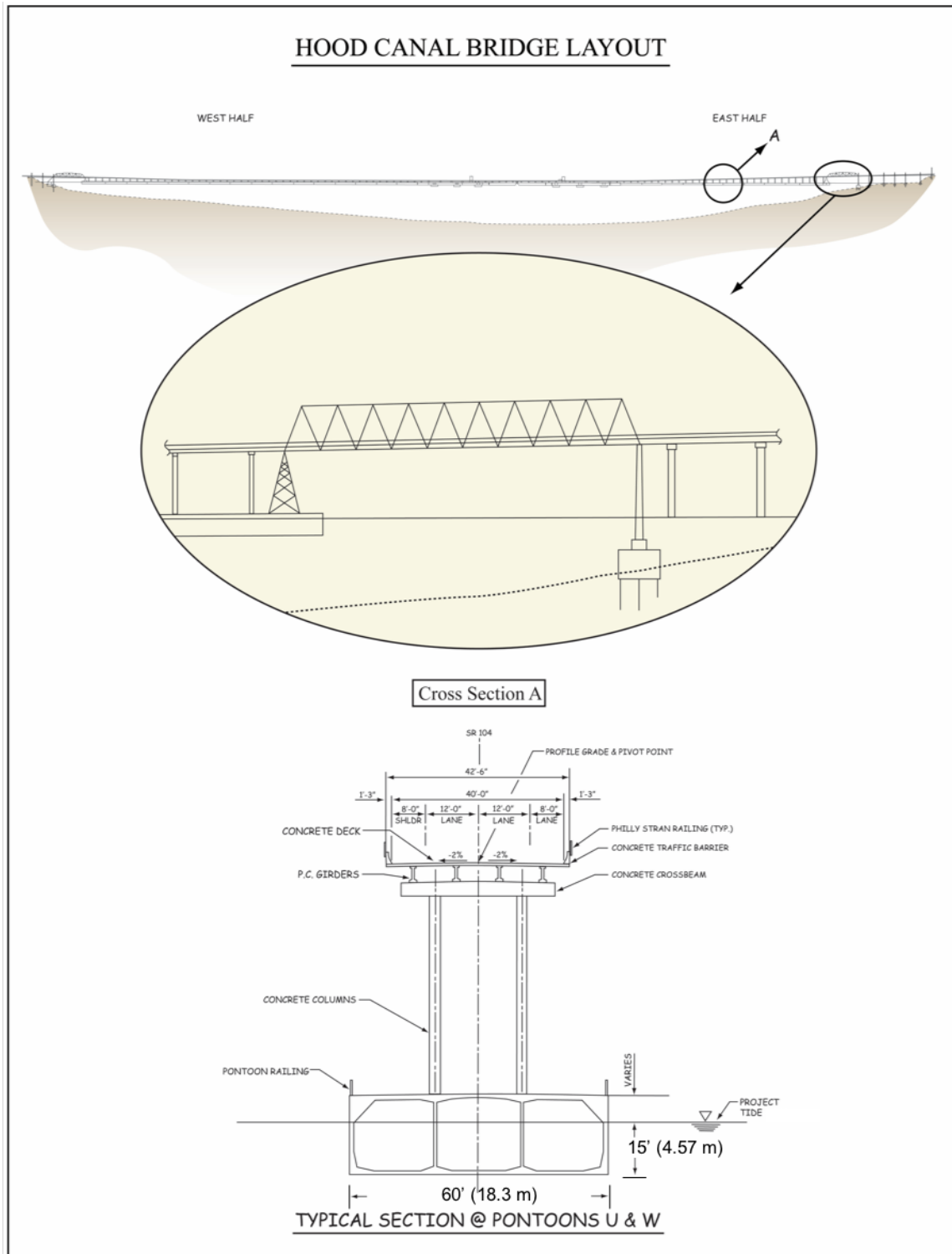


Figure 2. HCB layout with pontoon cross section and east span details. Detail A is a sectional view across the width of the bridge.

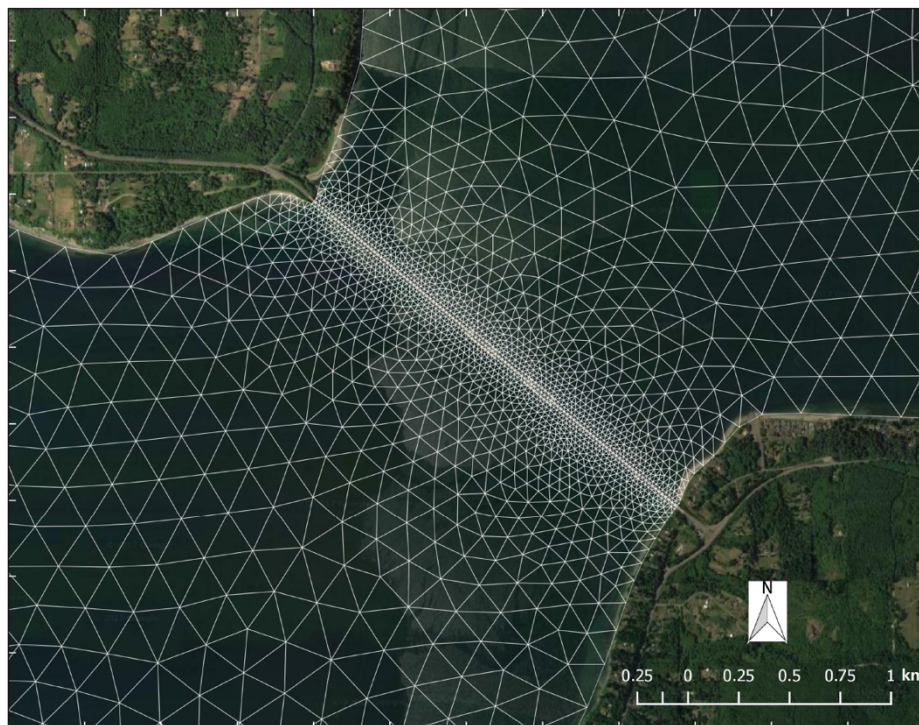


Figure 3. Salish Sea Model grid with refinement in the region to facilitate incorporation of the bridge block elements. The grid size is refined such that cell centers are separated by the bridge width distance of 18.3 m. The bridge draft is represented by two layers whose combined thickness is equal to 4.57 m.

The following three techniques were explored for representing and simulating the free-surface disturbance and blockage of currents by the HCB (Khangaonkar and Nugraha 2019):

1. *Implementation of a velocity block.* This approach is identical to that described by Khangaonkar and Wang (2013) where the impermeable surface block was incorporated into FVCOM with modification of both external and internal modes of the solver. For the baroclinic internal mode, the horizontal velocities at the selected cells and surface layers were always specified as zero, so that no horizontal flow was allowed to pass through. During the barotropic external mode calculations, the cross-sectional water column depth at selected cells occupied by the block was adjusted to a new reduced value by subtracting the blocked layer thickness from the total water depth. This modification accommodates the presence of the rigid structure but is an approximation, because the non-hydrostatic components of the pressure term, which are likely to be strong in the near field, are neglected. The effects of the bridge on momentum terms are addressed but are done so as an indirect effect of setting the surface boundary to zero velocity without affecting the pressure term. This method requires local modification of the bathymetry to a representative average depth under the bridge for representation of the rectangular shape of the bridge pontoons.
2. *Implementation of momentum sink at the bridge using form drag.* In this approach, the cells occupying the bridge are populated with hypothetical cylinders similar to a densely packed kelp farm. The drag from the cylinders set to a sufficiently high value results in blockage of nearly ~95% of surface currents. Although this represents a leaking bridge, the implementation allows for effects on the continuity, as well as momentum, terms of the governing equations. The implementation of form drag from suspended cylinders in the

water column is described by Wang et al. (2014). This method also requires local modification of the bathymetry to a representative average depth under the bridge for representation of the rectangular shape of the bridge pontoons.

3. *Free-surface pressure modification with a bottom drag.* This method relies on modification of the free-surface pressure boundary condition; an increase in pressure equivalent of 4.57 m of head results in a model response of a 4.57 m depression of the free-surface. This method is an improvement over techniques 1 and 2 in that the bathymetry is unaltered. In addition to modifying the free surface, the method also employs drag formulation for the layer immediately under the bridge. This results in flow passing the bridge under modified pressure with suitable reduction in velocity induced by the form drag.

The efficacy of each method was tested by examination of predicted velocity, T, and S profiles relative to the data collected. Results showed that all methods provided similar performance in terms of near-field impacts on the flow field. For simplicity, the continuity/velocity block method (1) was retained for the remainder of the analysis.

2.2.3 SSM – Hydrodynamic Component Validation with HCB Refinement

The SSM hydrodynamic validation over the entire domain was conducted first to ensure that modification of the model grid and layering scheme (described in the following section) did not alter the overall model performance. For consistency with the baseline SSM calibration and model performance assessment, the bridge module was turned off. The validation was done using year-long monitoring data available from 2014. The error statistics of water-surface elevation, S, and T were computed at nine National Oceanic and Atmospheric Administration X-tide stations and 24 water-quality stations maintained by Ecology and shown in Figure 1b. Overall calibration results for T and S at all stations were found to be reasonable.

Relative water-surface elevation errors were less than 10% at all stations within Puget Sound in United States waters. The domain-wide T root-mean-square error (RMSE) was 0.94°C with a bias of -0.03°C. The domain-wide S error was 0.96 psu with a bias of -0.24 psu. Model skill scores were also high for T and S; they had Willmott skill score (WSS) [20] values of 0.96 and 0.80, respectively (see Table 1).

Table 1. Salish Sea Model overall error statistics and skill score for T and S calibration data for the Y2014 from monthly monitoring profiles.

	Mean Error (Bias)			RMSE			WSS		
	Max	Min	Ave	Max	Min	Ave	Max	Min	Ave
T (°C)	0.97	-1.77	-0.03	2.29	0.40	0.94	0.99	0.78	0.94
S (psu)	0.09	-0.93	-0.24	2.27	0.39	0.96	0.90	0.60	0.80

RMSE = root-mean-square error; WSS = Willmott skill score; T = temperature; S = salinity; psu = practical salinity unit; Max = maximum value of site-specific error statistic among 21 Puget Sound stations; Min = minimum value of site-specific error statistic among 21 Puget Sound stations; Ave = global error statistic considering data and model results from all stations.

2.3 SSM Biogeochemical Component with HCB Refinement – Y2014

The biogeochemical component of the SSM is based on CE-QUAL-ICM—a three-dimensional, time variable, integrated-compartment model (Cерco and Cole 1994, 1995). For application to the Salish Sea, an “offline” approach of coupling FVCOM to CE-QUAL-ICM was used; the approach was developed by Kim and Khangaonkar (2012) in collaboration with the University of Massachusetts, Dartmouth, resulting in the FVCOM-ICM code. In this approach, hydrodynamic solution files, created previously (with HCB), are read by the biogeochemical model to conduct computations over the same model framework.

For this effort, we included 19 state variables: two species of phytoplankton (diatoms P1 and dinoflagellates P2), labile and refractory dissolved organic carbon and particulate organic carbon, NH_4 , nitrate ($\text{NO}_2 + \text{NO}_3$), labile and refractory dissolved organic nitrogen and particulate organic nitrogen, PO_4 , DO, dissolved organic carbon (DIC), and total alkalinity. The biogeochemical model includes new upgrades, a sediment diagenesis module that allows directly coupled interaction between the water column and sediments through the processes of organic sediment settling and burial and remineralization and carbonate chemistry with DIC, total alkalinity, pCO_2 , and pH (Bianucci et al. 2018; Pelletier et al. 2017). Figure 4 provides a schematic representation of the biogeochemical processes currently implemented in the SSM through FVCOM-ICM code.

With the aid of the improvements described above, observed biogeochemical cycles (i.e., S, T, DO, nitrate, algal biomass, and pH) in the Salish Sea, including near-bed hypoxia in locations such as the Lynch Cove region of Hood Canal, have been reproduced. The biogeochemical component of the SSM has been described in detail previously (Khangaonkar et al. 2012, 2018). The model has been tested over multiple years and subjected to sensitivity level testing with variation in forcing/loading either due to anthropogenic causes or due to stressors associated with climate-change projections.

To ensure that the SSM biogeochemical module continued to perform with the HCB present without errors, the model was tested with the bridge module implemented. While the hydrodynamic model provides a physical block of advective fluxes, diffusive flux leakage across the bridge could still occur in the biogeochemical component. Tests were conducted with and without diffusion fluxes across the bridge to examine the relative effect on water-quality parameters. The results showed that advective fluxes dominate and diffusive fluxes were negligible. The HCB module from the hydrodynamic model functioned well for water-quality parameters as well.

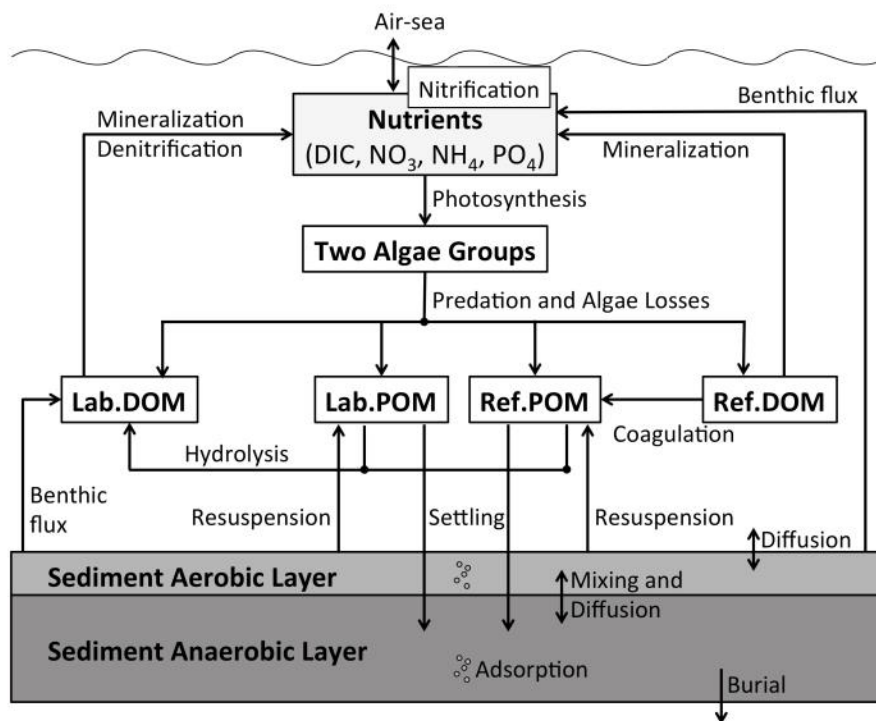


Figure 4. FVCOM-ICM biogeochemical process configuration.

2.3.1 SSM – Biogeochemical Component Setup

The setup of the biogeochemical component of the SSM, including river loads and ocean boundary conditions, was developed using most recent available data from Y2014. These include daily concentrations of nutrient and water-quality constituent loads from a total of 19 major gauged rivers, 46 ungauged streams, and 100 wastewater flows estimated using a combination of hydrological and multiple regression analyses (Mohamedali et al. 2011). Ocean boundary values for nutrients, DO, and algal biomass were also derived from quarterly monitoring data collected from various locations over the continental shelf by the Department of Fisheries and Oceans, Canada, and interpolated to the model ocean boundary in time and space.

2.3.2 SSM – Biogeochemical Component Validation with HCB Refinement

The validation effort involved running the SSM biogeochemical component (or simply the SSM water-quality model) with the grid refinement modifications at the HCB location using all model parameters and inputs consistent with the baseline calibration effort presented by Khangaonkar et al. (2018). The validation effort focused on comparing model predictions with observed nutrients, phytoplankton, and DO monitoring data. The objective was to ensure that modification of the SSM grid and the resulting alteration of the model time step to 8 s instead of the original time step of 40 s did not adversely affect SSM performance. A smaller time step was required with a finer grid to ensure model stability. Results were examined to ensure that the SSM with the bridge refinements continued to function satisfactorily when reproducing the salient water-quality features of the Salish Sea. These features include spring bloom of diatoms followed by late summer bloom of dinoflagellates resulting in strong nutrient consumption from the photic

zone. Of particular importance to Hood Canal is the formation of a hypoxic zone near the Lynch Cove region during late fall months of October and November.

Because the original SSM did not include a bridge block, the baseline simulation was conducted with the bridge block turned off. Figure 5 shows time-series plots at the Hamma station in Hood Canal (HCB003, located the mouth of the Hamma river in the central region of Hood Canal). This serves as a representative Hood Canal station with which to compare simulated surface and bottom layer concentrations of chlorophyll *a*, DO, nitrate, and pH with monthly monitoring data. The upper layer in the SSM occupies 3% of the water column and is representative of the outflow plume of brackish water. The bottom layer, which occupies the lower 15% of the water column in the SSM, is representative of incoming nutrients and DO. The chlorophyll *a* time series shows the combined effect of a spring bloom of diatoms followed by a die-off/predation-induced reduction, and then a late summer bloom attributed to dinoflagellate growth. There is very little algal activity in the winter months of December, January, and February because of low temperatures and the limited availability of light. The surface layer nitrate concentrations show decline and recovery corresponding to algal growth and die-off; concentrations are depleted to near-zero levels at the surface during most of the spring-summer period. This is also true of many other stations in Puget Sound where bottom layer concentrations are also indirectly affected by surface biological activity. This result in Hood Canal and similar results at other stations confirmed that the SSM with the HCB provides performance similar to the original SSM and consistent with observed biogeochemical behavior in Puget Sound.

Of particular interest is the DO response in the Lynch Cove region of Hood Canal for baseline conditions without HCB. Figure 6 shows DO time-series plots and monthly profiles from Lynch Cove Station HCB004. The data and results show that during the winter months, water column DO levels including surface and bottom layers are ≈ 5 -12 mg/L. After the spring bloom, however, the water column DO levels below the photic zone ($\approx$ upper 30 m) begin to drop and continue the decline to hypoxic levels until the culmination of biological activity in late fall. This forms the baseline condition for examination of the impact with the HCB in place.

Error statistics for water-quality parameters were computed at the 24 water-quality stations maintained by Ecology (see Figure 1(b) for station locations). Model performance was evaluated using error statistics such as absolute mean error (AME) or mean error (ME) to assess bias and RMSE. The AME and RMSE of time series with *N* elements are defined as follows:

$$AME = \frac{1}{N} \sum |X_{mdl} - X_{obs}| \quad (1)$$

$$RMSE = \sqrt{\frac{\sum (X_{mdl} - X_{obs})^2}{N}} \quad (2)$$

where X_{mdl} and X_{obs} are the values from the model and observations, respectively. To assess model skill, we computed the WSS (Willmott 1982), which is defined as,

$$WSS = 1 - \frac{\sum (X_{mdl} - X_{obs})^2}{\sum (|X_{mdl} - \bar{X}_{obs}| + |X_{obs} - \bar{X}_{obs}|)^2} \quad (3)$$

where an overbar represents a time average. The WSS is a measure of the level of agreement between the observed and modeled values; a value of 1 indicates perfect agreement and a value of 0 indicates no agreement.

Error statistics presented in Table 2 are consistent with and comparable to those presented by Khangaonkar et al. (2018) as part of the SSM calibration and serve as the quantitative validation demonstration for the modified version of the SSM with HCB-related refinements. Model skill is the highest for T, S, nitrate, and DO. Detailed calibration/validation to ammonia values was not attempted because the concentrations were typically very low relative to dominant nitrate concentrations. Similarly, because the model currently does not include inorganic suspended solids, partitioning of phosphate between the dissolved and particulate phase was not feasible, and therefore calibration/validation to phosphorous data was not attempted. Note that the T and S skill as reported through the biogeochemical model is lower than that obtained directly from the hydrodynamic model. This discrepancy is due to the use of a longer 6 hr sampling interval used in the biogeochemical model as opposed to the hourly interval in the hydrodynamic model.

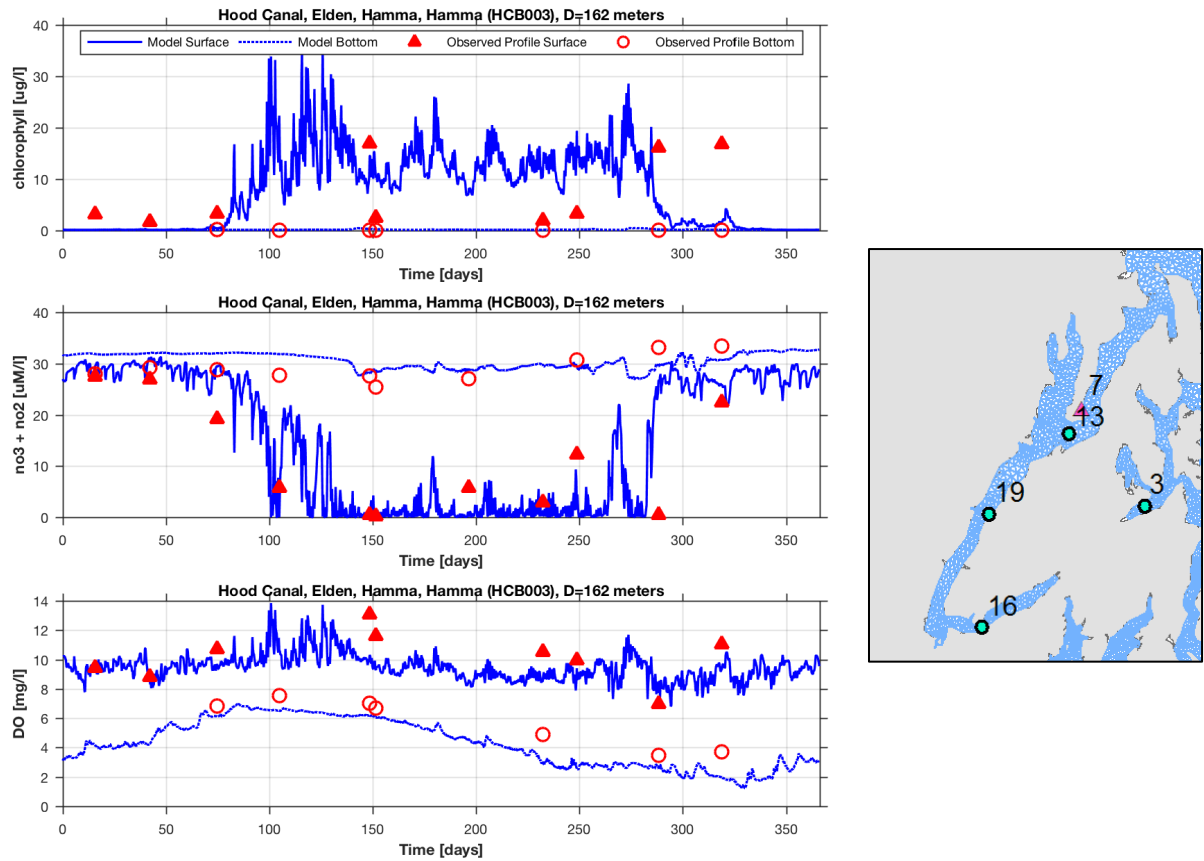


Figure 5. Time series of model results and observed data for chlorophyll *a*, nitrate ($\text{NO}_3 + \text{NO}_2$), and DO from the surface (outflow) and bottom (inflow) layers from a representative location (Hamma Hamma) in the Hood Canal region of the Salish Sea. Time is shown as Julian day in 2014. The Hamma station is indicated by the green dot 19 in the Hood Canal region of the SSM in the inset above.

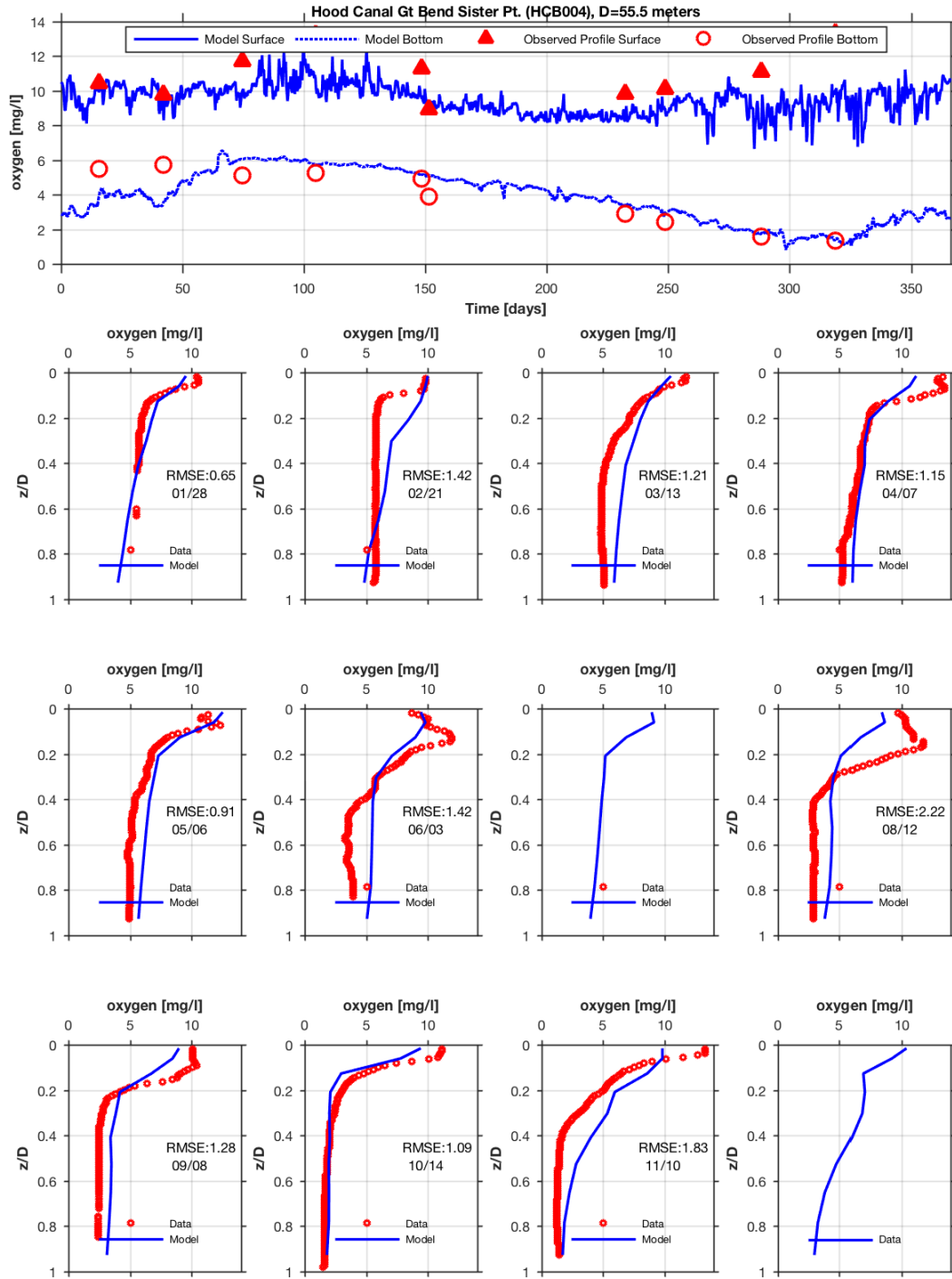


Figure 6. DO time-series plots and monthly profiles from the Lynch Cove. Simulation results from the SSM 2014 run extracted from the Lynch Cove Station HCB004. Station location is indicated by the green dot 19 in the Hood Canal region of the SSM in Figure 5.

Table 2. Salish Sea Model with modified grid. Validation error statistics and skill score for major constituents with calibration data for the Y2014 simulation.

	ME	RMSE	WSS
T (°C)	-0.23	0.88	0.91
S (ppt)	0.10	1.03	0.80
DO (mg/L)	-0.27	1.02	0.89
Nitrate NO ₃ +NO ₂ (μ mol/L)	0.77	6.54	0.90
Chlorophyll a (μg /L)	0.88	4.40	0.69
Ammonium NH ₄ (μ mol/L)	0.27	1.15	0.68
Phosphate PO ₄ (μ mol/L)	0.54	0.89	0.58
pH	0.14	0.22	0.
ME = mean error (bias); AME = absolute mean error; RMSE = root-mean-square error; WSS = Willmott (1982) Skill Score.			

3.0 Assessment of HCB Impact on Water Quality

After validating the hydrodynamic and biogeochemical components of the modified version of the SSM with HCB-related refinements, the model was applied to evaluate the change in simulated water quality of Hood Canal due to the HCB. Based on near-field hydrodynamic results and confirmation of the alteration of near-field currents and S and T, the circulation, and therefore water-quality parameters, were expected to be affected as well. Simulated water-quality variables include a suite of 19 parameters. We adopted an approach by which the effects of the HCB would be first examined for the primary water-quality indicator parameter of interest—DO. The results of this examination would dictate the next steps, such as examining the effects and response of the other water-quality parameters, correlating the impacts on bridge-induced modifications of circulation and transport, and alteration of flushing times. If necessary, additional model simulations and sensitivity tests would be initiated to help understand and interpret simulated water-quality response.

3.1 Examination of the HCB Impact on Hood Canal DO

The baseline biogeochemical simulation for Y2014 (presented in Section 2.3 with the HCB module turned off) was repeated, except this time, the simulation was conducted with the HCB module turned on. First the hydrodynamic solution with the HCB block turned on was prepared. The resulting hydrodynamic solution was used to drive the biogeochemical module with 19 water-quality parameters. All other model inputs remained unchanged.

Predicted results for DO were examined. The results were different from what we had anticipated. The simulated DO time series and profiles at all Hood Canal stations appeared to be unaffected by the presence of the bridge. Examination of all other parameters, including T and S, at the monthly monitoring stations HCB003, HCB004, and HCB010 also provided the same outcome. Water-quality parameters at stations far away from the bridge were not affected significantly. If the bridge had caused a large-scale impact on circulation, the region of Hood Canal with longest flushing times (Lynch Cove) would have shown the strongest response in the bottom layers.

Figure 7 below shows a comparison of predicted DO at the Lynch Cove station HCB004 with and without the HCB block along with monthly monitoring data. The results appear to be nearly identical. A closer inspection showed that the differences were too small to be of practical significance. It is important to note that T and S, which were part of the ZOI examination, showed a clear impact in the surface layers that extended upstream up to a distance of 2–2.2 km before T and S dropped back to ambient levels. The downstream impacts extended all the way to the mouth of Hood Canal. However, in both upstream and downstream directions, the effects were restricted to surface layers and were relatively small in magnitude; maximum near-field changes in T of -0.49°C and in S of 0.42 psu were recorded at the bridge (Khangaonkar and Nugraha 2019). While these near-field impacts on T and would likely be detected by out-migrating fish, it was not immediately evident whether the impact on circulation and flushing would be significant.

The results presented here indicate that the presence of the bridge likely does not cause a large-scale impact on circulation and flushing. Numerous additional sensitivity tests (double precision, variations in HCB block formulation layering schemes, etc.) were conducted to ensure that the results were not a simulation error.

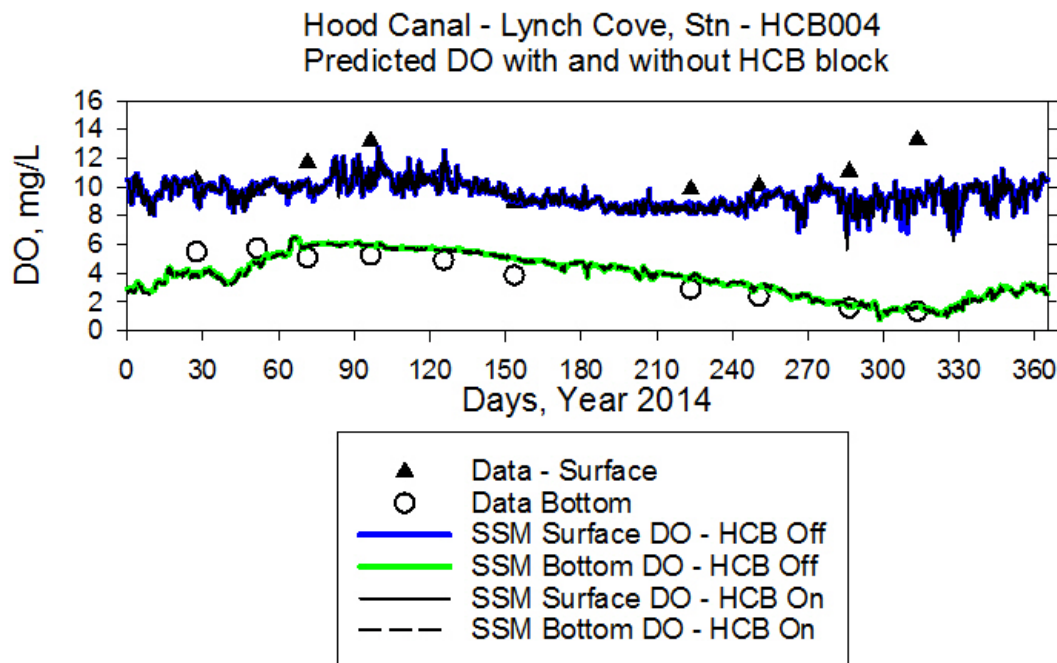


Figure 7. Comparison of predicted DO with and without the presence of the HCB block at the Lynch Cove (HCB004) station in Hood Canal.

3.2 Examination of the HCB Impact on Hood Canal Flushing Time

In consultation with LLTK, the project team decided to conduct one final set of tests to confirm that the lack of sensitivity or the response of water-quality/biogeochemical model to the HCB was consistent with the hydrodynamic model response. Water-quality model results showed that the HCB did cause a significant change in the large-scale biogeochemical behavior of Hood Canal. This would only be possible if the HCB also did not affect the large-scale circulation and flushing behavior of Hood Canal. We adopted the approach of computing and comparing flushing times to examine the gross effects of HCB presence on large-scale hydrodynamic behavior of Hood Canal. Significant modifications to circulation, estuarine exchange, and residence times in Hood Canal would be reflected in the magnitude of change in flushing time.

Flushing time tests were done using a numerical dye tracer using a conservative neutrally buoyant substance. The entire Hood Canal was filled with a uniform tracer concentration of 1 unit. The concentrations of the constituent at the river inflows and open ocean boundary were set to 0 units. The model run was initiated on January 1, 2014, and the dye was allowed to flush out. The hydrodynamic model runs were conducted with and without the bridge. The resulting concentrations were tracked at 10 locations distributed from the mouth of Hood Canal (outermost region of Hood Canal) to the Lynch Cove region (the innermost region of the basin). The open boundary condition for the dye variable was treated with the radiation boundary condition based on the same upwind advection scheme that was used in FVCOM for T and S. The exchange flow to Hood Canal enters the study area from its confluence with Admiralty Inlet at zero dye concentration at depth, and surface outflow ensures that concentration fields inside the model interior escape without being trapped.

Figure 8 below shows time histories of predicted dye concentrations at the 10 stations distributed in Hood Canal. Initial concentrations at all stations were at 1 unit at the beginning of

the simulation on 1/1/2014. The dye is flushed away through dilution and mixing with the new (dye-free) water that enters Hood Canal from the mouth through tidal ebb and flood action and resulting exchange with Admiralty Inlet. The stations nearest to the mouth of Hood Canal (entrance, bridge, and sill) are flushed out first and efficiently as shown in Figure 8. The flushing rate reduces asymptotically as the concentrations drop. As a practical quantitative measure, the end point for completion of flushing is often set arbitrarily at the “e-folding” concentration level when the concentrations drop to $1/e$ or 37% of the initial concentration. The dotted line in Figure 8 indicates “e-folding” flushing concentration of $1/e$ units. The innermost stations at Lilliwaup, Skokomish River, and Lynch Cove take the longest time (>180 days) to flush out to e-folding levels.

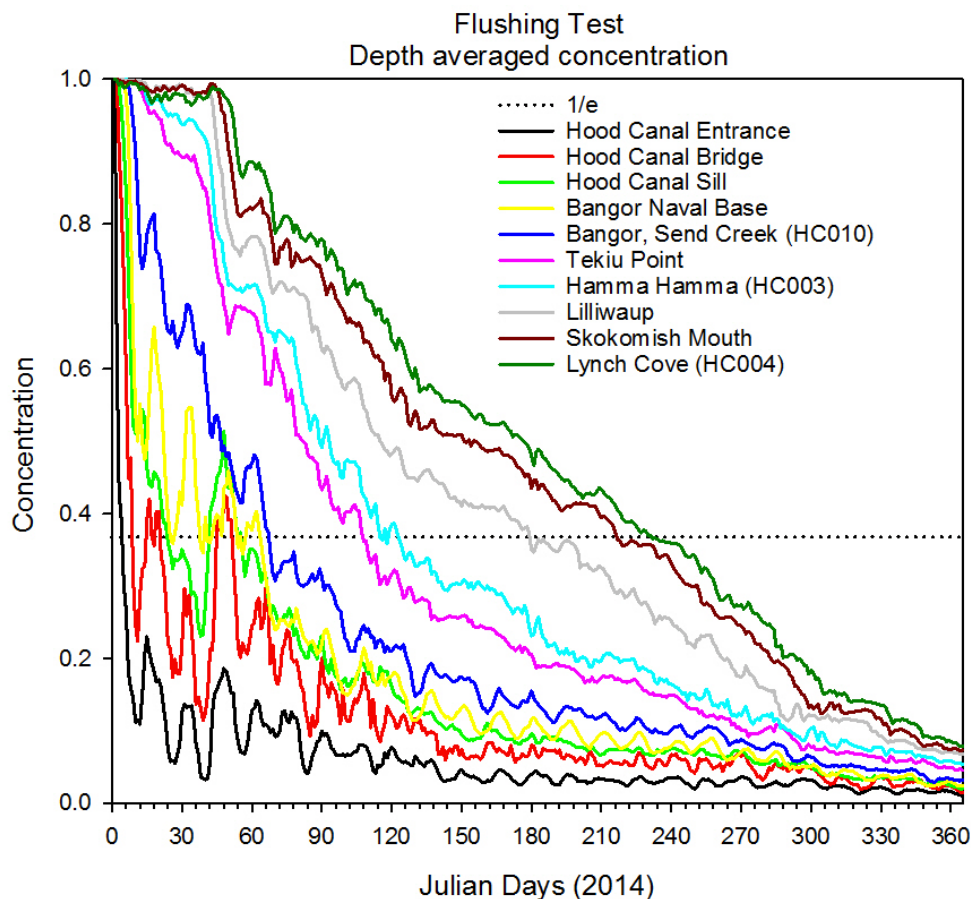


Figure 8. Time histories showing concentrations of conservative dye reduced from the initial condition of 1 unit to the end point concentration following 1 year of simulation. E-folding flushing time is defined as the time taken for the concentration levels to drop to $1/e$ units as indicated by the dotted line.

To evaluate the relative change in flushing times due to HCB, we decided to focus on the inner most Hood Canal location of interest—Lynch Cove. This is the region with most pronounced hypoxia and as shown in Figure 8, a region with a flushing time that exceeds 200 days. If the HCB were to impact flushing times, it would be most evident at locations such as Lynch Cove. We examined dye concentration time histories with and without the HCB at all stations, but only the Lynch Cove station results are presented below for clarity. Figure 9 shows results from three tests; one without the HCB (HCB off) and two tests with the HCB present using two different

approaches for representing the blockage. As shown in Figure 9, the three tests produce nearly identical results. The presence of the bridge simulated in two different ways shows some differences, but they are relatively negligible. All three tests result in e-folding flushing time of ≈ 229 days.

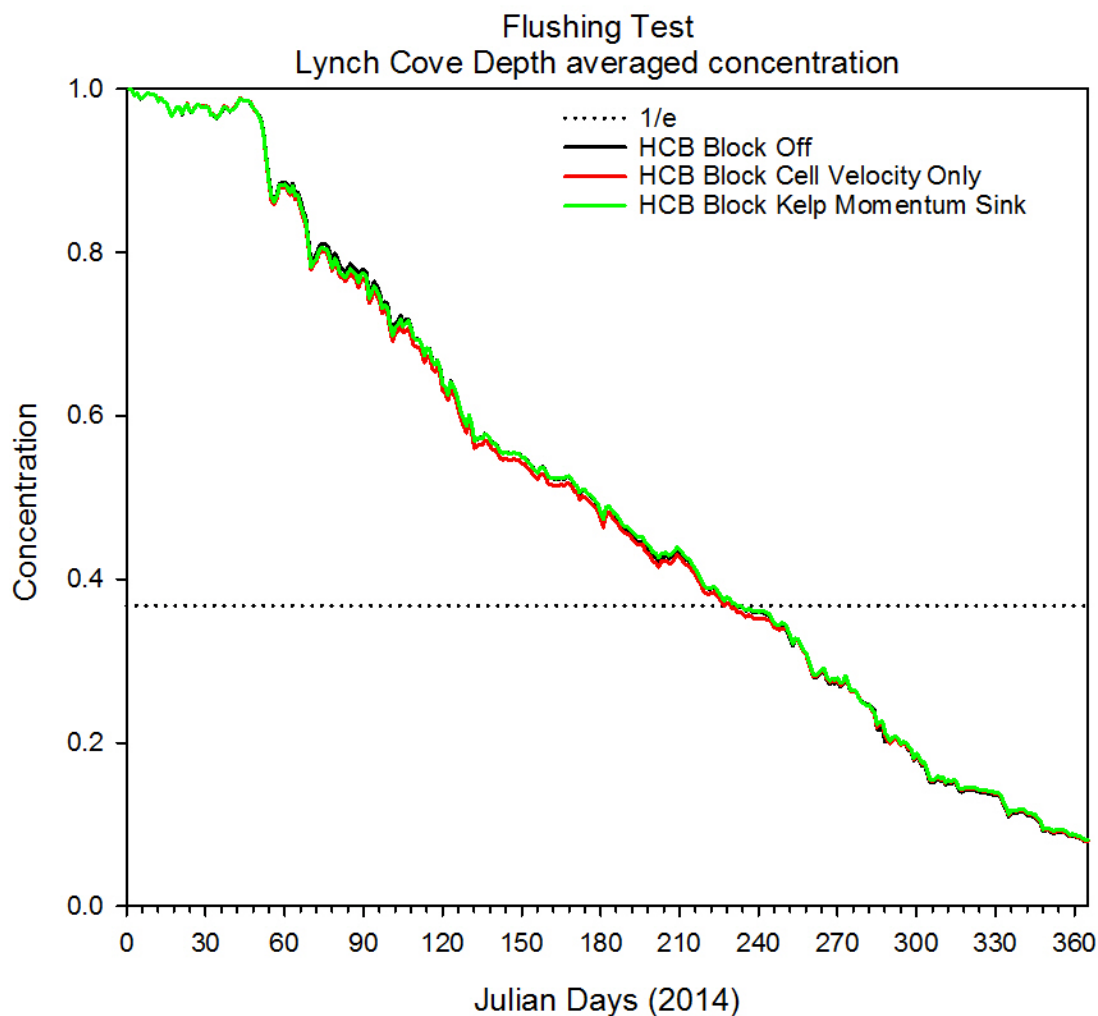


Figure 9. Time histories showing depth-averaged dye concentrations at the Lynch Cove stations (a) Hood Canal without HCB (black line) (b) Hood Canal with HCB represented with a velocity block, and (c) Hood Canal with HCB represented with a momentum sink.

4.0 Summary and Conclusion

4.1.1 Summary

The impact of the HCB on Hood Canal hydrodynamics and water quality was investigated using the SSM. The study team had previously confirmed that HCB or any large floating structure with a draft that penetrates the surface layers of a stratified waterbody creates a ZOI where ambient properties are altered from their natural state (Khangaonkar and Nugraha 2019). Similarly, a prior exploratory investigation by Khangaonkar and Wang (2013) had indicated the possibility that a floating structure like HCB had the potential to increase the flushing time in a fjord-like estuary such as the Hood Canal. These prior findings led to the initiation of this assessment to analyze the possibility that HCB may have an impact on the large-scale circulation and water quality of Hood Canal. In particular, the objective was to evaluate whether the hydrodynamics and flushing processes were affected at levels significant enough to affect biogeochemical processes. Adverse effects of interest were the potential increase in biogeochemical activity due to increased residence and flushing times resulting in increased levels of hypoxia.

The results presented in this evaluation, however, were conclusive in establishing that the effects of the HCB were small and likely restricted to the near-field ZOI. Within the ZOI, the impacts on ambient currents, S, and T are highest at the bridge location and reduce to background levels with distance from the bridge. The ZOI extends ~20 m below the surface and varies from 2–3 km for currents, from 2–4 km for S, and from 2–5 km for T in the upstream direction before the deviations with the bridge drop to <10% relative to simulated background conditions without the bridge present. In effect, the ambient water quality beyond the ZOI rebounds to natural conditions away from the bridge-induced disturbance.

The SSM was used to conduct a quantitative assessment of the HCB-induced impact on large-scale circulation and water quality. To accomplish this, the SSM grid was refined at the HCB location and the effect of the HCB was incorporated such that the velocity and transport through the cells occupied by the bridge were set to zero. The SSM with the HCB refinement was then re-validated against T and S and water-quality data from 26 stations with monthly profiles from the year 2014. The model was then applied to simulate the scenarios with and without the HCB present. The results were as follows.

- An examination of simulated biogeochemical parameters such as T, S, DO, nitrate, and algal biomass at stations within Hood Canal and other Salish Sea locations showed that predicted magnitudes of the variables with the HCB present were relatively unchanged from the conditions without the HCB.
- Examination of hydrodynamic response through computation of flushing time using numerical dye tests showed that the predicted flushing times with HCB present were practically unchanged from the simulation without HCB.

With these findings, the effort was terminated. Additional scenarios (Scenario 3 – HCB present with central span open) were not pursued.

4.1.2 Discussion and Conclusion

We recognize and acknowledge that these results are in direct contradiction to the proposed hypothesis that the HCB has a potential to cause large-scale impacts on circulation and water quality in Hood Canal. The original hypothesis was driven primarily by the early results from the

Khangaonkar and Wang (2013) study. We conducted numerous sensitivity tests to ensure that the new results presented here were reproduced consistently and were not an artifact of model instability or application error. A review of the model application approach and results from the prior assessment and comparison to the new findings from Khangaonkar and Nugraha (2019) provides some insight. We believe that the prior preliminary effort where Hood Canal was simulated in isolation from the rest of Salish Sea, provided a false positive based on inadequately specified ocean boundary conditions. The processes that affect estuarine exchange and circulation in the prior effort were likely affected by placement of the ocean boundary at the Hood Canal mouth. This boundary is relatively a short distance (≈ 10 km) away from the bridge. The S and T gradients affected by HCB were shown to cross the boundary of the prior model domain in subsequent studies. Depth-averaged S gradients directly affect the strength of exchange flow. However, in the prior examination, the ocean boundary at the Hood Canal mouth was fixed and therefore could not accurately sense or react to the HCB-induced changes. The dye dilution and flushing results would also be similarly affected. Without further investigation, we believe that use of a fixed ocean boundary at the mouth of Hood Canal and simulation of Hood Canal in isolation are the most likely reasons for prior false positive results. It appears that the use of the SSM with the embedded HCB and with the ocean boundary sufficiently away from the study area has rectified the error and generated these new conclusions.

These new results indicate that although HCB affects the near-field conditions and creates a ZOI, the change is most significant only at the bridge itself. The deviations or disturbances from the natural ambient conditions are relatively small and they dissipate rapidly with distance from the bridge. These results imply that the HCB impact on the large-scale circulation and water quality of Hood Canal is not significant or that the SSM with the HCB as incorporated in this study is not sensitive enough to detect the impact of the HCB.

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[Appendix G. Hood Canal Bridge Impact Assessment Matrix](#)

The Assessment Team's September 2019 revisit and update to the Assessment Matrix included in the Hood Canal Bridge Ecosystem Impact Assessment Plan: Framework and Phase 1 Details (2016) Appendix B. The 2019 update does not reflect further analysis and synthesis completed in 2020.

Hood Canal Bridge Impact Assessment Matrix+A1:H19

Primary Questions	Sub Questions	Initial Answers to Sub-Questions, based on Phase 1 evidence	Hypotheses	Evidence that would support hypothesis	Evidence collected through Phase 1 research
I. How is the bridge acting as a functional barrier to juvenile steelhead migration and leading to increased mortality? How does the bridge influence other fish, including salmon?					
A. What are fish migration behavior and fish distribution patterns at vs away from the bridge? For steelhead, what defines a successful migration past the bridge vs one that results in mortality?	(1) Are there specific locations where migrating steelhead congregate? (2) Do fish attempting to pass the bridge at certain locations have more success than those passing at other locations? (3) How does approach location differ from exit location? (4) Does approach trajectory differ from encounter trajectory?	(1) Yes. Aggregation of tagged steelhead in corner areas of bridge (the places where cross-pontoons jut out into water). (2) Yes. Fish that approach near open sides pass faster than other locations and are less likely to die/become stationary. (3 & 4) Do we have data to differentiate fish trajectories from predator trajectories? Were successful trajectories constant with same approach & exit locations? Was there an element of chance (i.e., the fish happened to approach/encounter an open span)?	(1) Migration path and other behaviors are altered by encounter with the Hood Canal bridge. (2) Survival past the bridge is dependent on encounter history (where and how) near to the bridge. (3) Detection location of approach location differs from exit location. (4) Detection pattern is altered when tagged fish encounters bridge Zone of Influence.	(1) Telemetry tag detections at HCB are different than at other locations; detections are not uniformly distributed across bridge span. (2) Tags with different histories are not detected with equal frequency at subsequent receiver lines. (3) Approach location is not similar to exit location. (4) Approach trajectory is not similar to encounter trajectory.	Strong evidence for 1 & 2. Tracking and stationary tag data show more stationary tags at bridge vs. away from bridge. Tags that show dive behavior or temperature differences never detected at later receiver lines. Travel rate past bridge is much slower than rate before and after encounter. Some evidence for 3 & 4. Approach location and trajectory not similar for some tagged fish - but similar for others (e.g., those that approach at side openings). Didn't have detection ability far enough ahead of bridge to determine behavioral change, though behavior at the bridge is different than behavior at other monitored locations (i.e., TS, ADM, JDF).
	Is successful steelhead migration past the bridge associated with specific behavioral parameters (tortuosity, residence time, depth of encounter, habitat usage area, range of detections)?	Yes. The quicker a tagged fish can get past the bridge, the higher likelihood of detection at subsequent receiver lines (survival). Depth of first encounter at bridge for all live fish was surface - some fish dove under bridge and were successful, but all tags that had deep repetitive dives were predated upon.	More time spent near to bridge, encounters with bridge pontoons, more tortuous path, etc. increases probability of steelhead mortality.	Probability of survival differs by trajectory type. Trajectory types defined through analysis of behavioral parameters (turning angle, step length, tortuosity, bridge, residence time, etc.) fit using mixed models	Some evidence. Tags that spent longer times at bridge were more likely to become stationary. We can't discern between behavior of steelhead and behavior of predator for tags without depth transmitters, so it's hard to say whether longer time spent at bridge equals higher chance of predation. We do have evidence from depth transmitters that predation occurs rapidly after arrival, which suggests that time at the bridge - beyond the overall delay caused by the bridge - may not decrease odds of survival. It is likely that the delay in migration makes all fish vulnerable, but there may still be some benefit of moving past rapidly. Also evidence from density data that fish get stuck in corners, predation location evidence shows several incidences of predation near corners.
	What are the densities and distribution of salmon, steelhead and forage fish at the bridge versus away from the bridge?	Evidence for higher densities of fish biomass at vs. away from bridge. No strong consistent patterns of fish biomass at the bridge (e.g., no consistent density "hotspots" along bridge infrastructure) - density patterns highly variable along-bridge. Visual observations suggest high densities of chinook, chum, forage fish within bridge pools and in corner areas of bridge. However, hydroacoustic surveys not able to detect this pattern due to study/equipment limitations.	Salmon, steelhead and forage fish congregate at higher densities near to the bridge (in bridge Zone of Influence) vs away from the bridge.	Hydroacoustic transect sampling indicate higher densities of salmon, steelhead and forage fish at the bridge (in bridge Zone of Influence) vs away from the bridge.	Some evidence of higher densities of fish biomass near vs. away from bridge based on center transect sampling when data are combined over SH outmigration period.
	What are the densities and distribution of predators at the bridge versus away from the bridge?	Some/mixed evidence for higher densities of certain predators at the bridge - including harbor seals, which are currently most likely candidate predator based on depth + temperature tag patterns combined with predator behavior literature review. Foraging behaviors and how they affect predator observations collected via boat-based surveys are a big question mark - we don't have appropriate data to develop a correction factor for foraging behavior. Blueview & GoPro data document seal and bird foraging behaviors in bridge pools and seal foraging alongside bridge, using bridge infrastructure (corners) to capture fish. Strong evidence that pigeon guillemots use bridge as artificial shoreline and forage at bridge; however, little evidence that they specifically/exclusively target steelhead (which are at the top of the available prey size range for this species). However, they may impact other, smaller chinook & chum salmon - quantitative data on the degree of impact to these species is outside of the scope of this Assessment.	Predators X,Y,Z congregate at higher densities near to the bridge vs away from the bridge.	At-sea transect surveys (visual observations) and bridge-based surveys indicate higher densities of predators at vs away from the bridge.	Pigeon guillemots: strong evidence for higher densities at vs. away from bridge. Rhinoceros auklets, horned grebes, marbled murrelets, harbor porpoises: no evidence of density diffs at vs. away from bridge. Predators with mixed/some evidence: - Harbor seals in higher density at vs. away from bridge in 2017 only but no difference in 2018. - Cormorants in higher density at vs. away from bridge in 2017 only but not observed at bridge in 2018. - Mergansers in higher density at vs. away from bridge in 2017 only (not enough observations in 2018 to compare). Bridge-based survey data suggest seal and bird foraging at bridge and in bridge pools consistent over 2017-2018. Bridge-based stationary grid observations suggested more seal activity at bridge than away from bridge.

B. Are steelhead and other fish at the bridge more susceptible to predation (vs away from the bridge)? If so, who are the primary culprits?	What is the spatial correlation between key predators and steelhead (and other fish, including Chinook) near to vs away from the bridge?	Predators and fish biomass show a few potential hotspots of overlapping higher densities, but overall no strong spatial correlation. Not included in initial predictions - predator observations at/on the bridge sub-deck suggest seal foraging behaviors that opportunistically use bridge infrastructure (herding fish into corners).	Habitat usage is more highly correlated adjacent to the bridge compared to farther away.	More overlap of minimum convex polygons in bridge Zone of Influence than in areas outside of the Zone of Influence. Comparison of both successful vs unsuccessful migration pathways and stationary tags (mortalities) using geographically weighted regression methods.	The only predator species that was observed in high enough abundances/densities to break down week-by-week (to match steelhead weekly survival estimates) was pigeon guillemots. Comparisons of 2017 fish biomass data to predator survey data suggested a few spots of overlap in higher densities (fish/predator "hotspots"); there did not appear to be high overall correlation.
	Are stationary tags more numerous near the bridge than elsewhere?	Yes, they are.	Stationary tags will be present in higher densities near the bridge than in more distant areas of Hood Canal.	Density of stationary tags is higher within bridge Zone of Influence than outside (spatial statistics)	Strong evidence that most stationary tags were detected very close to the bridge, and predominantly on the south side of the bridge.
	<i>What is the spatial and temporal overlap between harbor seals and steelhead near to vs away from the bridge?</i>		<i>Parameters quantifying the spatial and temporal overlap of tagged steelhead and harbor seals are different near to vs away from the bridge.</i>	<i>Patterns describing spatial and temporal overlap are seen in data (e.g., total number of steelhead detected, duration and frequency of detections, spatial and temporal distribution of detections)</i>	(not addressed - no tagged seal data)
	<i>Is predation by harbor seals on juvenile steelhead and Chinook greater near to vs away from the bridge?</i>		<i>Predation on steelhead and Chinook by harbor seals is greater near the bridge vs in the non-bridge impacted estuaries of Hood Canal.</i>	<i>Scat analysis combined with foraging behavior data suggest predation of steelhead and Chinook is greater near to vs away from bridge</i>	(not addressed - no tagged seal data, scat data)
			<i>The proportion of stationary steelhead tags found near seal haulouts near bridge is greater than the proportion of stationary tags near haulouts far from the bridge.</i>	<i>More stationary tags detected within 1 km of haulouts near the bridge and that have seals that forage more often at bridge vs. those haulouts away from bridge</i>	(not addressed - did not focus on sampling haulouts away from bridge)
C. What is the influence of the bridge on the surrounding physical environment, at vs away from the bridge? Does this effect fish behavior, distribution, or mortality patterns?	Is successful steelhead migration past the bridge associated with temporal or biological parameters (release time, smolt size/condition)?	Release timing of steelhead was related to survival. Not an initial prediction, but it is possible that the mechanism here is related to chinook/coho/other hatchery salmon release times via a buffering effect on predation. Steelhead smolt size & condition is not related to survival probability.	Temporal and biological parameters affect probability of steelhead survival.	Probability of survival is explained by release time, smolt size, or smolt condition in a mixed effects regression model.	Strong evidence of steelhead release time/bridge encounter date ~ survival relationship. No evidence of smolt size or condition effects.
	Is successful steelhead migration past the bridge associated with light level encountered? Are fish densities associated with light levels encountered?	Not enough light data at vs. away from bridge to correlate with tagged steelhead and hydroacoustic data (data confounded by date/time/location along bridge infrastructure).	Artificial light over habitat adjacent to the HC bridge and/or shade under the bridge increases susceptibility of predation.	Probability of survival is explained by light level encountered over migration path, tested with geographically weighted regression methods	Not enough light data at vs. away from bridge to correlate with weekly steelhead survival estimates.
	What is the intensity of traffic-induced noise level as a function of distance from the bridge? Is successful migration past the bridge associated with noise level encountered?	See Deng et al. report for quantified noise levels. No evidence for noise impacting tagged steelhead migration pathways or success.	The bridge traffic generates noise and vibrations which propagate through the water column, affecting the out-migrating behavior of the steelhead smolts.	Probability of survival is explained by noise level encountered over migration path, tested with geographically weighted regression methods	No evidence that traffic noise rises to a level that is impactful to steelhead. No evidence but it is possible that noise may facilitate predation (masking predator noise) - we did not have tagged seal data to assess this possibility.
	What is the physical extent of the bridge Zone of Influence? Is successful migration past the bridge associated with physical forcings of the Zone of Influence? Is this also tidal dependent and/or affiliated with the bridge opening/closing?	ZOI extent is captured in water quality questions below. No evidence of bridge opening/closing effect on tagged steelhead migration paths or success.	The bridge obstructs tidal currents, blocks outflow and piles up brackish water at the surface, increases mixing, and alters natural distribution of currents, salinity, and temperature fields in the ambient waters, resulting in a physical Zone of Influence that could affect outmigrating salmon and steelhead.	Probability of survival is explained by thermal experience, salinity levels, and/or currents encountered over migration path, tested with geographically weighted regression methods	Currents definitely play a part in HCB crossing ability. Evidence shows that the positive (upward) values of the vertical current component prohibit fish from going under - fish only cross under on strong ebb currents.

	What are non-hydrostatic and fine-scale near-field effects of the bridge pontoon structures? Does the bridge induce eddies, and strong currents, salinity, and temperature gradients near the bridge pontoons that affect successful salmon and steelhead migration and/or migration behavior?	We did not create a CFD model that could model fine-scale flow, eddies, etc. In the absence of quantitative model simulations, we relied on visual observations of water flow around bridge infrastructure (corners, pools) to assess potential effects. Visual & video observations suggest that the bridge infrastructure does affect water flow and may create eddies which could potentially impact salmon and steelhead behavior. There is significant near-field effects of bridge on currents, temperature, and salinity within the Zone of Influence as described below.	The bridge pontoons could induce wakes and eddies as the tidal currents are forced to traverse under the bridge. Depending on the strength of the resulting wakes and eddies, the gradients could affect and disorient outmigrating salmon and steelhead.	Probability of survival is explained by encounters with wakes and eddies or salinity and temperature gradients at bridge tested with geographically weighted regression methods	We did not complete a CFD model at bridge as part of phase 1. Opportunistic visual observations from on-bridge surveys suggest that cross-pontoons/corners of bridge infrastructure impact currents, may create eddies, and may redirect fish that encounter them back towards the direction they came (i.e., if a fish starts in middle of channel, it would be redirected back towards middle instead of finding open shoreline area). Visual observations and go-pro video also suggest currents/flow influenced by bridge infrastructure may aggregate zooplankton and small fish into bridge pools.
	Are fish with active acoustic tags more susceptible to predation than those with silent tags?	No. We found no evidence that continuously-pinging tags were more susceptible to predation than silent tags.	Fish with delayed and continuously pinging acoustic tags have significantly different survival rates.	Equivalency test of two proportions (continous and delayed) with a tolerance of 0.10.	There was no evidence of the "dinner bell" effect on tagged steelhead - no significant difference between continous and delayed tag survival.
D. What are the impacts of pools and eddies created by bridge pontoons adjacent the center drawspan?	Is the bridge causing a structural, artificial reef effect? Do ESA listed Chinook or chum salmon, or steelhead, aggregate in the pools and eddies created by the center drawspawn? If so, is it associated with prey densities or does it act as a refuge? Are predators aggregating and foraging there as well?	Evidence collected from on-bridge surveys does suggest that there are high abundances of zooplankton and small fishes (chinook, chum, forage fish) in the pools. However, whether these abundances are significantly higher than in other, non-bridge areas of Hood Canal was not determined through this work. We saw no evidence suggesting that pools/reef effect impacts tagged steelhead behavior or survival. It may affect other salmon like chinook or chum, but quantitative investigation of this impact is beyond the current assessment scope. Evidence does suggest that predators (especially seals and certain bird species) forage within the bridge pools. However, we do not know whether this level of predator activity is significantly higher than predator activity along other non-pool portions of the bridge.	Structural voids change water properties such that they aggregate euphausiids and other plankton. These aggregations attract planktivorous fish, including juvenile salmon, steelhead, and forage fish.	Pool activity data will be compared to data collected in transect and oceanographic surveys (components 2,3,8,9) near and away from bridge to determine whether the pool activity is unique and could be leading to mortality.	No evidence of tagged steelhead occupying/using bridge pool areas. Higher densities of tagged steelhead observed in bridge corner areas & mortality locations observed in bridge corner areas. Visual observations from on-bridge surveys suggest high zooplankton and small fish (chinook, chum, forage fish) activity/abundance within pools. We were not able to collect quantitative data on zooplankton abundances in-pool vs. away from bridge due to issues with flow in pools.
E. Data will be merged to answer: What influences steelhead migration/mortality and fish distribution patterns near the bridge? What are the spatial-temporal relationships between steelhead migration and mortality patterns, fish distribution, predator distribution and how the bridge is impacting the surrounding physical environment?				Synthesis analysis illustrates strong relationships between changes in steelhead migration behavior, fish distribution,	
F. How do we fix the issue?	(THIS IS ONLY ONE EXAMPLE. SIMULATION AND TESTING OPTIONS WILL BE REVIEWED AND CHOSEN BASED UPON THE RESULTS OF PHASE 1) Can alternatives such as permanent bypass passages or planned bridge-span openings in selected sections help eliminate the barrier to juvenile out-migrants and influence their behavior?			Modeled alternatives reduce changes to migration behavior.	(not addressed in Phase 1)
II. Is the bridge impacting the entire Hood Canal ecosystem?					
A. Does the bridge obstruct ebb - flood currents & impact flushing of brackish outflow water?	What is the physical extent of the bridge Zone of Influence (ZOI)?	The bridge obstructs the brackish outflow surface layer, which induces increased local mixing, causes pooling of water (up-current) during ebb and flood, and results in shadow/sheltering of water (down-current). The ZOI for currents, salinity, and temperature extends ~20m below the surface and ranges from 2-5km away from the bridge before deviations in these parameters drop to <10% simulated no-bridge conditions. Citation: Khangaonkar et al. 2018 https://www.mdpi.com/2077-1312/6/4/119	The bridge obstructs tidal currents, blocks outflow and piles up brackish water at the surface, increases mixing, and alters natural distribution of currents, salinity, and temperature fields in the ambient waters.	Model simulations with no bridge show significantly different current structure, temperature and salinity profiles, and/or stratification than model simulations with bridge.	The bridge obstructs the brackish outflow surface layer, which induces increased local mixing, causes pooling of water (up-current) during ebb and flood, and results in shadow/sheltering of water (down-current). The ZOI for currents, salinity, and temperature extends ~20m below the surface and ranges from 2-5km away from the bridge before deviations in these parameters drop to <10% simulated no-bridge conditions. Citation: Khangaonkar et al. 2018 https://www.mdpi.com/2077-1312/6/4/119
B. What is the impact of Hood Canal bridge on basin wide circulation and water quality?	What is the relative contribution of the bridge induced effect on the impairment of water quality (hypoxia and acidification) in Hood Canal?	Model results showed HCB impacts on large-scale circulation were negligible, Hood Canal flushing time was not affected, and water quality parameters at selected monitoring stations far away from the HCB showed practically no change with vs. without the HCB. Citation: Khangaonkar & Nugraha 2019 white paper	The bridge induces an increase in residence time and reduced flushing of the basin impacting surface temperatures, biogeochemical cycling including nutrient uptake and algae growth, sedimentation, and pH, thereby impacting the ecosystem.	Enhanced Salish Sea biogeochemical model illustrates relative impact of bridge vs other stressors to surface temperatures, biogeochemical cycling, sedimentation, and pH.	Model results showed HCB impacts on large-scale circulation were negligible, Hood Canal flushing time was not affected, and water quality parameters at selected monitoring stations far away from the HCB showed practically no change with vs. without the HCB. Citation: Khangaonkar & Nugraha 2019 white paper
C. How does the Hood Canal bridge affect key marine species residing in Hood Canal?	IF THE BRIDGE IS IMPACTING CIRCULATION AND WATER QUALITY FOR THE ENTIRE CANAL, to what extent do changes in the circulation and water quality of Hood Canal, caused by the Hood Canal bridge, affect key species in Hood Canal and neighboring		Impacts of the bridge to circulation and water quality subsequently impact the Hood Canal food web.	An Atlantis, ecosystem simulation model demonstrates impacts to key species, especially those of commercial, recreational and cultural importance.	(not addressed in Phase 1; no evidence justifying further effort)
D. If the impact is significant enough to warrant action, how do we fix the issue?	IF THE BRIDGE IS IMPACTING THE ENTIRE ECOSYSTEM, SIMULATION AND TESTING OPTIONS WILL BE REVIEWED AND CHOSEN BASED UPON THE RESULTS OF PHASE 1				(not addressed in Phase 1; no evidence justifying further effort)

**Components in red italics may be implemented in phase 2, depending upon the results of phase 1. See body of report for details.*

Appendix H. Assessment Team and Management Committee Ranking Exercise: Phase 2 Solutions

This represents the Assessment Team's September 2019 initial brainstorming and discussion regarding options for Phase 2 actions. It does not reflect further analysis or synthesis completed in 2020, nor does it reflect the later engineering consultations, initial solutions development, or prioritization described in Appendix I.

Potential Solutions to Address Steelhead Mortality at the Hood Canal Bridge

Options to decrease potential Chinook smolt, chum smolt, or adult salmonid mortality will be considered separately

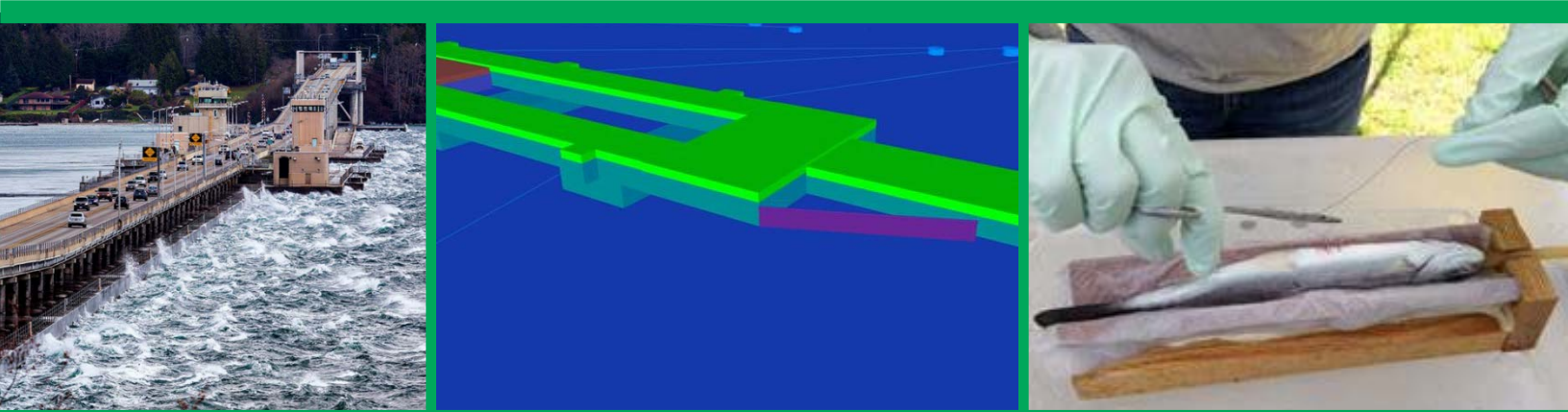
	1 = no; 2 = low potential; 3 = medium potential; 4 = high potential							
	Will it expedite steelhead passage?	Will it reduce efficacy of harbor seals foraging near the bridge?	Feasibility - Is it likely to be implemented in the next 3 years?	Is likely to avoid unintended negative consequences?	Aggregate score	Does the Assessment Team Believe this solution is worth further investigation	Additional questions	Additional Comments
Potential Solution to Test								
Restricting access to cross-pontoon corners	3	3	4	4	14	yes		The Assessment Team generally regarded this potential solution to be the highest priority to test in the short-term.
Replace the bridge with a more "fish Friendly" design	4	4	1	2	11	yes	Significant bridge design and engineering work.	This solution was ranked the highest to address the fundamental problem, but it is a long term solution. The team believes that a design process to consider bridge alternatives would be fruitful because the bridge may experience significant maintenance costs that would make the expense of replacing the bridge more palatable. A cost/benefit analysis, including the costs of addressing ESA obligation in the long term, may be fruitful.
Acoustic Startle Device (Genuswave)	1	3	4	2	10	yes	Ideally, additional testing results related the use of the device.	This technology has limited testing and it is therefore difficult to evaluate. The device is currently planned to be tested in a different location in the Spring of 2020
Reducing light	2	2	3	3	10	yes	A better understand of mortality impacts related to chum and chinook, and more information on the relationship between light, the presence of salmon prey as an attractant for salmon.	The team concluded that this option should remain because of it's feasibility and it's potential impact could make some improvements, but believes it to be a lower priority because telemetry data suggests that steelhead mortality was not occurring at night and the periods darkness are relatively short during the spring steelhead outmigration. This solution may also be more applicable for chum and chinook if further analysis supports that conclusion.
Structure to reduce/disrupt surface water velocity around the ends of the bridge.	3	2	2	3	10	yes	The team needs outside expertise from engineers and fish passage experts more experienced using these tools.	The capabilities of this technology are not well known and this solution would need to be better defined to evaluate it's potential impact.
Restricting access to seal haul-outs near the bridge	1	3	3	2	9	yes	This solution would need to be coupled with a more fine-scale assessment of seal behavior near the bridge and additional predator observations, potentially including seal tagging, predator surveys, and scat sampling	The feasibility of restricting haul outs is uncertain. There is also limited literature supporting the hypothesis that restricting haulouts in an area would reduce predation in that same area.
Pumping water to signal passage	2	1	2	4	9	yes	The team needs outside expertise from engineers and fish passage experts more experienced using these tools.	The capabilities of this technology are not well known and their potential impact in such a large enviroment is questionable.
Guide steelhead to safe passage (bubble curtains or other strat.)	3	1	2	3	9	N/A	The Assessment Team needs additional information regarding potential mechanisms to accomplish this.	The feasibility of this solution is questionable considering the scale and dynamic nature of the water body.
Open/Close the bridge for longer periods during low traffic hours	2	1	3	2	8	no		Telemetry data did not support the hypothesis that bridge openings would expedite steelhead passage. The bridge opening is a relatively small increase in the total open space along the bridge. The bridge openings are not expected to provide a substantial increase in open area of fish to find passage. The potential solution would also negatively impact traffic flow. Therefore, the costs are like to outweigh the benefits.
Acoustic Harassment device (Traditional - loud noise)	1	2	4	1	8	no		Potential unintended consequences to non-targeted marine mammals and the limited efficacy of these devices led the team to conclude that this would not be a potential solution
Reducing noise	1	2	1	4	8	no		Research on noise at the bridge concluded that noise does not reach thresholds that are likley to adversely affect salmon health. This feasibility of this solution is also highly questionable.
Remove marine growth from the bridge	1	1	2	4	8	no		While marine life may be contributing to the reef-effect at the bridge there is little evidence to suggest that this would impact mortality.
Predator exclusion netting	1	3	2	1	7	no		Netting is expected to be quickly fouled and expensive to maintain.
Lethal removal of nuisance predators	1	2	2	2	7	no		Hood Canal is an open environment and seals are ubiquitous around Puget Sound. There is no evidence suggesting individual nuisance animals exist. Substantial legal barriers to this solution exist
Increase turbidity	1	3	2	1	7	N/A		Turbidity may decrease predator's ability to forage at the bridge. The Assessment Team is unaware of any mechanisms to accomplish this.
Remove marine growth and apply Anti-fouling coating	1	1	1	2	5	no		While marine life may be contributing to the reef-effect at the bridge, there is little evidence to suggest that this would impact mortality. Anti fouling coatings can be harmful to the environment. Applying antifouling coating to the bridge is unlikely to be feasible.

Appendix I. R2 Resource Consultants: Phase 2 Scoping and Recommendations

Hood Canal Bridge

Fish Passage Assessment

Phase 1 Study – Final



Prepared for:

Long Live The Kings
Hood Canal Bridge Assessment Team

Prepared by:



15250 NE 95th Street
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August 2020

Hood Canal Bridge Fish Passage Assessment Phase 1 Study – Final

Prepared for:

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Hood Canal Bridge Assessment Team**

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August 2020

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ACRONYMS AND ABBREVIATIONS

Assessment Team	Hood Canal Bridge Ecosystem Impact Assessment Team
BGS	Behavioral Guidance System
ESA	Endangered Species Act
HCB	Hood Canal Bridge
HCB Assessment Plan	Hood Canal Bridge Ecosystem Impact Assessment Plan
HDPE	High Density Polyethylene
LLTK	Long Live The Kings
NMFS	National Marine Fisheries Service
NOAA	National Oceanic Atmospheric Administration
O&M	Operations and Maintenance
OPCC	Opinion of Probable Construction Costs
R2	R2 Resource Consultants, Inc.
USFWS	United States Fish and Wildlife Service
WDFW	Washington Department of Fish and Wildlife
WSDOT	Washington Department of Transportation

1 INTRODUCTION

1.1 Background

The Hood Canal Bridge (HCB) is an important regional transportation avenue and provides a link between the Olympic and Kitsap peninsulas with over 16,000 trips per day by local, regional, and commercial vehicles. During the tourist season, the HCB helps drive the economy by bringing visitors to the Olympic Peninsula to recreate on land and water. Puget Sound residents expect Hood Canal to be a healthy and vibrant ecosystem (HCBAT 2016).

Salmon and steelhead originating from Hood Canal drainages must pass the HCB as juveniles on their way out to the Strait of Juan de Fuca and the Pacific Ocean. They must pass through the bridge again as adults on their return trip to spawn in their natal streams. Three populations of Hood Canal salmon are listed as threatened under the Endangered Species Act (ESA); Puget Sound Chinook, Hood Canal summer Chum, and Puget Sound steelhead. Millions of dollars have been spent on restoration efforts to revitalize and protect these fish and their habitat throughout Hood Canal.

Recent studies indicate the bridge is a migration barrier to fish passage with reduced migration and higher mortality rates in the vicinity of HCB relative to other areas within their migration route. Studies also indicate unique behavior and mortality patterns at the bridge, which suggest the bridge is negatively affecting steelhead migration and increasing predation (Moore et al. 2013; HCBAT 2016). Previous research suggested that the bridge may be affecting water quality throughout Hood Canal by limiting the exchange of water critical to the fjord's health. Phase 1 of the assessment collected water quality data near the bridge to refine existing models in order quantify the bridge's impact to temperature, salinity, dissolved oxygen, nitrate, and algal biomass. Modeling efforts indicate water quality impacts near the bridge, but the assessment did not show significant canal-wide impacts. Additional research is needed to fully understand impacts to marine life near the bridge and understand bridge effects under changing climate scenarios.

Recently, the Hood Canal Coordinating Council determined that the dual concerns regarding water quality and migration effects of the HCB posed a major threat to recovery actions for ESA-listed salmon in Hood Canal. These effects could reduce the value of other regional restoration efforts. Addressing bridge effects is also consistent with the Five-Year Strategic Priorities of the Hood Canal Integrated Watershed Plan (HCBAT 2016). As a response, a collaboration of federal, tribal, state, and nonprofit partners convened beginning in 2015 to produce the Hood Canal Bridge Ecosystem Impact Assessment Plan. The plan was designed to

identify primary sources of mortality to ESA-listed juvenile steelhead, determine whether species are affected, and finally determine to what extent the bridge is impacting the overall health of the Hood Canal ecosystem.

1.2 Purpose: Hood Canal Bridge Ecosystem Impact Assessment Plan Expertise

A collaboration of federal, tribal, state, and nonprofit partners convened beginning in 2015 to produce the Hood Canal Bridge Ecosystem Impact Assessment Plan (HCB Assessment Plan). The plan was designed to identify how the bridge is impacting ESA-listed juvenile steelhead mortality, determine whether other species are affected, and finally determine to what extent the bridge is impacting the overall health of the Hood Canal ecosystem.

The HCB Assessment Plan is an adaptive management approach whereby work progressed in phases and hypotheses were refined as an understanding of how the bridge interacts with steelhead, salmon and the greater ecosystem was developed. The HCB Ecosystem Impact Assessment Team (Assessment Team) conducted the research and initially conceptualized solutions that allowed them to inform the Management Committee, who guided the direction of the overall assessment and provided a link to relevant organizations and communities. The HCB Assessment Plan was consistent with the Washington State chosen approach to managing natural resource issues and a similar process is used to manage other regional salmon restoration programs.

The objective of Phase 1 of the HCB Assessment Plan was to identify the pathways in which the bridge may be affecting steelhead (and potentially other salmon) survival and the Hood Canal ecosystem, and describe potential management actions that will not adversely affect HCB primary function of a regional transportation corridor (HCBAT 2016). As an outcome of Phase 1, the Assessment Team will work with regional partners to refine the suite of potential management actions based on phase 1 findings, in particular those related to the impact of the bridge on outmigrating steelhead, and mutually agree on the highest priority management actions before moving to Phase 2 of the HCB Assessment Plan.

1.3 Scope and Report Overview

R2 Resource Consultants, Inc. (R2) contracted with Long Live The Kings (LLTK), who are coordinators for the Assessment Team, to critique and comment on initial recommendations from the group, develop any potential other recommendations, help the group understand and prioritize potential actions, and recommend actions that could be implemented near-term to mitigate juvenile steelhead mortality at the HCB. R2 was also tasked to summarize an approach to implement the recommended actions, including a schedule and cost estimate. R2 primarily

utilized the preliminary results of field studies conducted under Phase 1 of the HCB Assessment Plan, available literature pertaining to the project components, and their expertise in fish passage in the region to advance and add to the identified management actions or concepts.

R2 met with LLTK and project partners (Assessment Team) in order to review applicable research to develop an understanding of the work done to date and the state of the science sufficient to address the underlying issues and then proceeded to complete the following four tasks:

1. Advance the list of identified solutions prepared by the Assessment Team to date, and develop a comprehensive list of available solutions to meet the project objectives. Identify information gaps that may limit the effectiveness of the feasibility assessment or implementation of a solution, and means to fill the gaps to help prioritize management actions.
2. Perform an initial assessment to prioritize alternatives and select high priority solutions to move forward with a full feasibility assessment and functional design process.
3. Report on the findings, allowing time to incorporate feedback from LLTK and project partners; and
4. Create a scope of work, including both an optimistic and a more realistic schedule for the next phase of the project, which would implement selected near-term actions.

This final report summarizes R2's work efforts during Phase 1 of the HCB Assessment Plan, focusing on the development of management action concepts to move forward during Phase 2 of the plan. The Phase 1 report follows chronologically from the inception of R2 involvement at a kickoff meeting on 30 January 2020 through the most recent iteration of the recommended management action alternatives that were presented during an online Assessment Team meeting on 1 May 2020, issuance of a review draft report dated June 2020, and incorporation of review comments received (Appendix G). The rationale of decision making processes are provided for context; and the report then focuses on the recommended management actions (hereafter referred to as Category 1 actions) that may be designed, constructed, and tested under Phase 2 of the HCB Assessment Plan. A description of each alternative including a sketch, construction cost estimate, and considerations for evaluations are provided. A workplan to implement and evaluate the Category 1 actions is then provided, including a comprehensive schedule, construction cost summary, design and oversight cost summary, and total program (design and construction only) cost summary. This work plan is prepared to a level of detail that would be suitable to use as a framework for the Phase 2 HCB Assessment Project, including the full design, contractor procurement, and construction phases.

2 INITIAL REVIEW OF ASSESSMENT TEAM ALTERNATIVES

2.1 Process Narrative

This section provides a narrative summary of the study process leading to this Phase 1 and the Phase 2 implementation recommendations. LLTK provided meeting notes and correspondence throughout the process that are documented outside this report on the Assessment Team's HCB Impact Assessment "Base Camp" shared project site.

2.1.1 Assessment Team Meeting No. 1 – Kickoff

This kickoff meeting included a smaller group from the Assessment Team as well as fisheries and engineering staff members from R2 on 30 January 2020 at Port Orchard, Washington. During the presentation, the Assessment Team members reviewed the Phase 1 research results and the entire group discussed possible solutions. The objective of the meeting was to fully brief R2 on completed work and current ideas so that they could assist in the development of recommendations and action plans to implement near-term management actions to mitigate juvenile steelhead mortality at the Hood Canal Bridge. A matrix prepared by the Assessment Team that outlined the management actions was distributed to R2 to provide their expert opinions regarding fish passage management actions (Appendix A). Data presentations included high-level overview of the following topics:

1. Juvenile steelhead acoustic telemetry in Hood Canal, 2017-2018 (M. Moore; NMFS);
2. Split-beam hydroacoustic survey of HCB, 2018 (H. Daubenberger; Port Gamble S'Klallam Tribe);
3. Water quality surveys of HCB, 2018 (H. Daubenberger; Port Gamble S'Klallam Tribe);
4. Predator survey of HCB, 2018 (H. Daubenberger; Port Gamble S'Klallam Tribe);
5. Boat-based predator survey of Hood Canal (I. Kemp; LLTK);
6. Hydrodynamic zone of influence, HCB impact assessment (I. Kemp; LLTK);
7. HCB impact on basin-wide water quality (I. Kemp; LLTK);
8. Evaluating the potential influence of the HCB on the density of juvenile steelhead predators (S. Pearson; WDFW); and
9. Salish Sea model, 2018 (I. Kemp; LLTK).

Following the Phase 1 data presentations, the group discussed the HCB management action matrix and the iterative development process beginning with formulation, revision, and

preparation of the final version including final Assessment Team rankings to address salmon mortality at HCB.

2.1.2 Matrix Update

R2 fisheries and engineering personnel reviewed the initial matrix and provided individual comments for each management action. R2 conducted two internal meetings discussing the Assessment Team management actions and cooperatively developed a matrix update that included a broad-based overview of the original 12 solutions and re-organized them according to type of measure, level (guidance, deterrence, and pinniped deterrence), and the potential to test the management action (Appendix B). Each management action also included R2 comments regarding the feasibility of the action and potential data gaps that were identified during their review. R2 participated on an online meeting with members of LLTK on 17 March 2020 to discuss the preliminary HCB matrix update and plan an agenda for a second Assessment Team meeting that will present the R2 Matrix Update.

2.1.3 Assessment Team Meeting No. 2 – Matrix Update

An online Assessment Team meeting was conducted on 6 April 2020. The primary objective of the meeting was to review an updated matrix which was presented by R2 and provided the basis to select near-term solutions to advance to Phase 2. The presentation included an overview of the updated matrix, identified data gaps, and preliminary cost estimates developed by R2 (Appendix C). Upon completion of the presentation, the group reviewed the matrix and mutually agreed to provide comments on the updated matrix in preparation for the final Assessment Team meeting to selection the management actions that will be moved forward to Phase 2.

2.1.4 Assessment Team Meeting No. 3 – Final Management Action Decision

The Assessment Team Meeting No. 3 held on 1 May, 2020 began with N. Rodda (WSDOT) presented an overview of the current bridge design, coast guard permit requirements, potential seal haul out locations on the bridge, and considerations necessary for selections of Phase 2 management actions (Appendix D). Additional steelhead smolt behavioral analyses pertaining to bridge openings was presented by M. Moore (NMFS) while E. Bishop (Westward Ecology) presented results from bridge lighting studies conducted during 2019. Following these presentations, the Assessment Team discussed Phase 2 study designs to test solution effectiveness and additional sampling needed to fill knowledge gaps. Assessment Team leads for Phase 2 studies committed to developing full study designs for Phase 2 steelhead telemetry and corner observations, initial feasibility and cost estimates for studies to fill knowledge gaps

on seal density and behavior at the bridge, bridge impacts to juvenile Chinook and Chum, and bridge impacts to returning adult Chum. The Phase 2 work plans were presented at the next Assessment Team meeting held on 1 July 2020. After the presentations were discussed, the group reviewed the final management action matrix denoting the actions that are suggested to move to Phase 2 of the HCB Assessment (Category I).

2.2 Final Matrix and Decisions

The categories below define how the Assessment Team ranked potential solutions or management actions (Appendix E). Individual management action rankings were based off results the Assessment Team's iterative phased approach depicted in the previous section of this document.

2.2.1 Recommended Concepts for Phase 2

The Assessment Team feels that these management actions are feasible and will effectively reduce juvenile steelhead mortality at the HCB. Potential solutions are unlikely to completely resolve high juvenile steelhead mortality and migration delay at the bridge, and some solutions may also positively impact Chinook and Chum smolts at the bridge. The Assessment Team selected the following solutions because they are feasible in the short-term, unlikely to have unintended negative consequences, and available data and experience supports a reasonable likelihood that these actions would show measurable results to expedite steelhead passage at the HCB.

2.2.1.1 Category 1 Management Actions, Recommended for Early Implementation

Category 1 management actions are solutions that were vetted through the selection process of Phase 1 of the HCB Assessment Plan and are deemed worthy to proceed to Phase 2 of the project. The Assessment Team recommends that these solutions undergo a more substantial feasibility and design process before they are installed and assessed during Phase 2 studies. The alternative numbering scheme used in the evolving versions of the action's matrix is carried forward throughout this section for consistency.

Alternative 1 – Bridge Corner Fillet Structures

The bridge fillet structure will reduce or restrict fish access to the existing pontoon corners. The bridge pontoon corners are hypothesized to slow steelhead migration by creating back-eddies or water velocity anomalies where steelhead are observed on a consistent basis. The corner could also provide mammalian predators a consistent food source resulting from steelhead

circling the corners in a velocity spire. Mammalian predators may also use the structure during foraging which corrals the fish in bridge corners.

To help address this situation, flexible bridge corner “fillets” will be placed at inside corners of east and west abutments, with the hypotheses that they will help to guide fish around the corners. Bridge fillets were originally proposed to be constructed of small-mesh net or flexible plastic material, and would be either 15 ft deep (full bridge depth) or 8 ft deep (half bridge depth) (Figure 2-1). Comments received on the draft report indicated interest in exploring more solid structures in addition to the prototype net or flexible impervious materials.

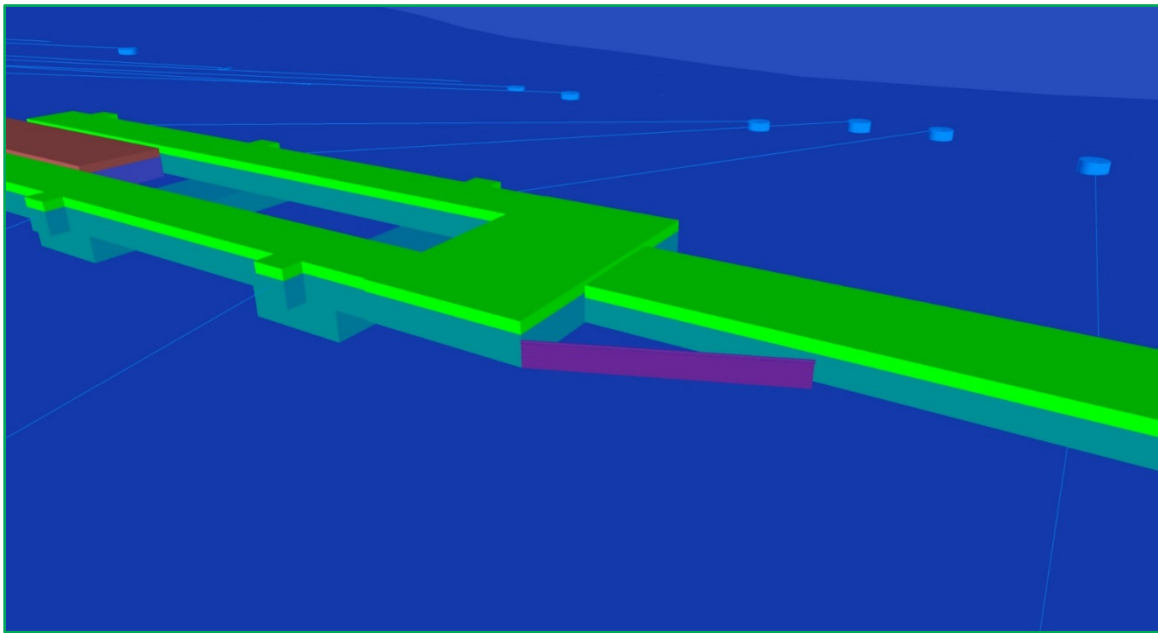


Figure 2-1. Conceptual full depth (15 ft) bridge corner fillet structure developed for installation on Hood Canal Bridge, Washington.

Alternative 5 – Eddy Reduction Structures at Corners

The eddy reduction structure at pontoon corners will eliminate or reduce the size of the eddy that is formed as water passes the existing, 90-degree pontoon corners. The bridge pontoon corners are hypothesized to slow steelhead migration by creating back-eddies or water velocity anomalies where steelhead are visually observed on a consistent basis. The bridge corner may also provide mammalian predators an enhanced location to feed on steelhead circling the corners in a velocity spire. A half-round or bull-nose eddy reduction structure will be constructed out of a flexible plastic or other appropriate material that is 15 ft deep (full bridge

depth) and attached to the corner of the bridge pontoon (Figure 2-2), and will be hydraulically designed for maximum benefit at peak flood and ebb tides.

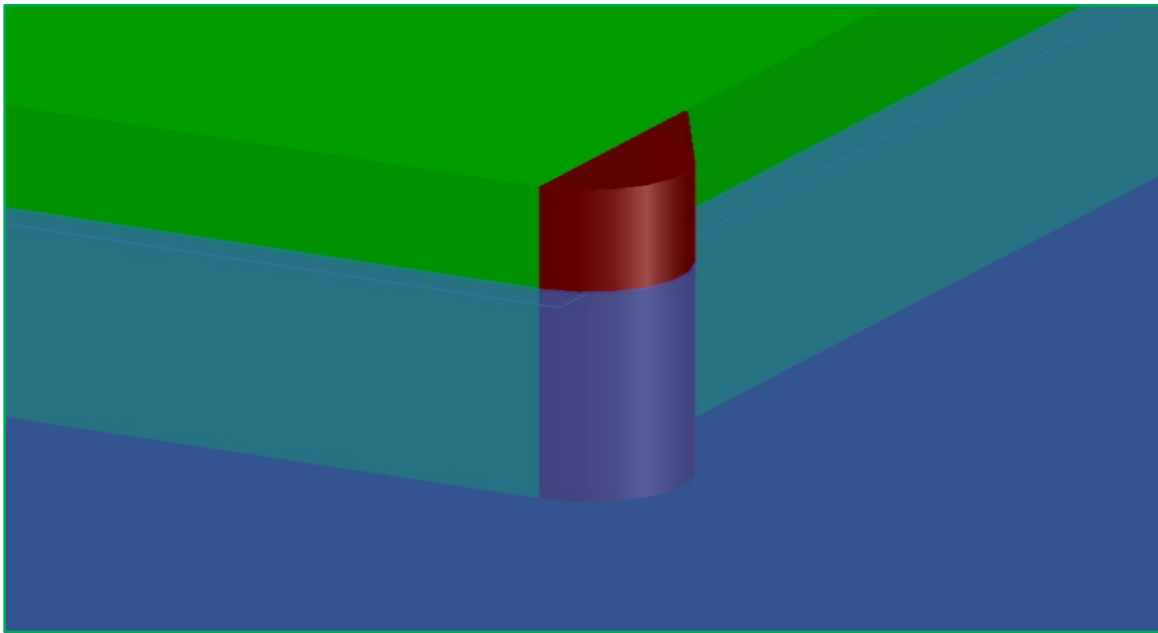


Figure 2-2. Conceptual schematic view of full depth (15 ft) eddy reduction structure developed for installation on Hood Canal Bridge, Washington. Actual size will be determined with hydraulic analysis.

Alternative 9 – Open Bridge Span More for Fish Passage

During the 2017-2018 study period, 30% of steelhead smolt survivors were detected within 330 ft of the center span at some point during their outmigration. Salmon passage also coincided with peak ebb tide cycles whereby many salmon were located on the southern edge of the HCB. The average time spent near the center span was approximately half an hour. Planned bridge openings for fish passage is a relatively low-risk alternative to help expedite passing outmigrating steelhead smolts and is simple way to test the hypothesis that additional fixed openings along the bridge would increase passage. Fish passage bridge openings (Figure 2-3) will be planned during peak migration periods and scheduled to minimize resulting traffic delays when feasible. A public outreach will be important to minimizing impacts to travelers and communicating the purpose of the openings.



Figure 2-3. Scheduled fish passage bridge opening on Hood Canal Bridge, Washington (adapted from Rodda 2020).

Alternative 4 – Lighting at Bridge

Hood Canal Bridge surveys indicated that elevated ambient light conditions approach or exceed levels that affect salmon migration on the south side and in the outboard sections of the two pool areas (Daubenberger and Bishop. 2020). The range of values were consistent over both new moon and full moon survey periods. Based on a literature review, the light levels are within the range that can affect salmon behavior and migration rates (Port Gamble S’Klallam Tribe 2020). Currently, luminaries are placed at 120 ft intervals along the lift deck and double luminaries light the pontoon and work decks of the HCB (Figure 2-4). Lights are high pressure 150-watt sodium bulbs that exude 13,000-16,000 lumens. The HCB has more lighting than other floating bridges because there is not a separated bike path. When bike and car traffic is interspersed, more lighting is required for vehicle and cyclist safety (Rodda 2020). The luminaries could be modified to provide more bridge deck lighting and reduce the amount of light that is radiated into the water or adapted to minimize blue-rich lighting and use “warm” color temperature or filtered light sources but yet retain the safety standards required of mixed-vehicle bridge decks.



Figure 2-4. Light luminaries on the east half of the Hood Canal Bridge, Washington (adapted from Rodda 2020).

2.2.1.2 Category 2 Management Actions, High Ranking but Need Research

Category 2 management actions are solutions that the Assessment Team ranks highly during their iterative vetting procedure but determined they required additional research before they could be tested under Phase 2 of the HCB Assessment Plan. However, Phase 2 may provide an opportunity to conduct the research necessary to implement the solutions during a later phase. The majority of the Category 2 management actions had a high degree of uncertainty regarding either their efficacy to improve passage without creating a major disruption in traffic or level of acceptance from the public.

Alternative 3 – Bridge Re-Design and Replacement/Modifications

Specific portions of the HCB (i.e., corner pontoons and draw span pool) have been identified as creating migration delays and/or mortality of steelhead migrating from Hood Canal. The HCB is 6,420 ft long and contains 36 concrete pontoons that are connected by post-tensioning tendons across pontoon-to-pontoon joints. Replacing the bridge with a more fish friendly design (one that does not block the upper water column along its entire length) was one of the Assessment

Team’s highest ranking alternatives for addressing the juvenile salmonid delay. Additionally, replacing a section of the existing bridge, or even individual spans ranked high. However, given the HCB’s post-tensioned pontoon attachment design makes the removal of individual sections of the bridge difficult and costly. Total replacement of the bridge with a more fish-friendly version (Figure 2-5) is also a very expensive solution that would impact the traffic corridor during construction. If this alternative is advanced in the future, studies of how adult salmon interact with the structure would also be beneficial.

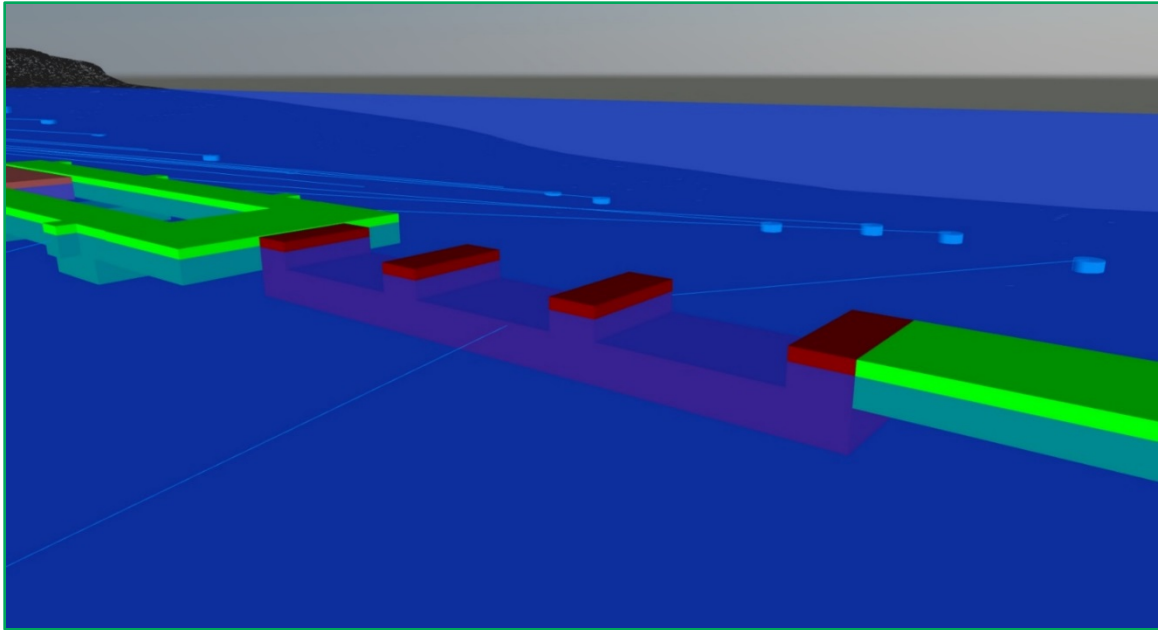


Figure 2-5. Conceptual design of fish friendly draw span on Hood Canal Bridge, Washington.

Alternative 6 – Pinniped Deterrence (excluding lethal removal)

Recent studies indicate that pinnipeds kill more Chinook Salmon in Puget Sound compared to previous levels; they estimated that pinniped consumption estimates increased from 68 to 625 million tons of Chinook Salmon during the period between 1970 and 2015 (Chasco et al. 2017). Harbor seals and harbor porpoises had generally low densities throughout the HCB study area; boat-based surveys may not have fully captured the area directly alongside the bridge due to restrictions on vessel distance from the bridge infrastructure (Figure 2-6). Both species were observed at higher densities near the bridge than away from the bridge in 2017; that pattern was not apparent in 2018, when densities were similar across the entire survey region (Figure 2-6). To date, there has not been an extensive study on behavior of individual pinnipeds at HCB and their predation rate of salmon has not been quantified at HCB.

Pinniped deterrence such as haul out restriction or preventing access to the pontoons was a highly ranked management action, but the Assessment Team determined that more information is required, and the undetermined effect of the action renders it a Category 2 solution. With additional data describing how pinnipeds interact with the bridge and the fish nearby, solutions may be deployed effectively. There is also ongoing work in Puget Sound to test new strategies to reduce pinniped predation on salmon which may inform solutions.

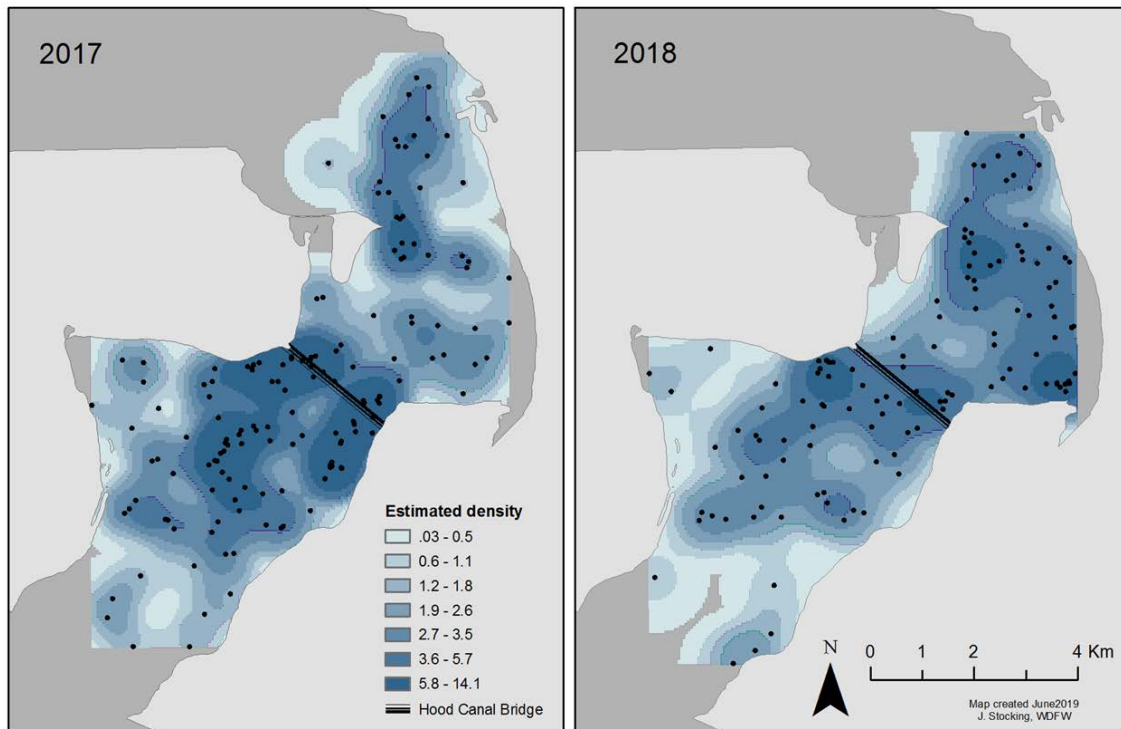


Figure 2-6. Estimated densities (excluding haul out locations) of harbor seals observed within 4 km of Hood Canal Bridge, Washington (adapted from HCBAT 2016).

2.2.1.3 Category 3 Management Actions, Ranked Lower

Category 3 management actions are solutions that were ranked lower than the other actions by the Assessment Team and were not selected to be tested under Phase 2 of the HCB Assessment Plan. The majority of the Category 3 management actions had a high degree of uncertainty regarding either their ability to significantly improve salmon passage/survival at the HCB or their constructability within the short timeline goals of the Assessment Plan.

Alternative 2 – Behavioral Guidance System (BGS)

Behavioral guidance systems are a popular mechanism in the Pacific Northwest, especially at hydroelectric projects, to manipulate salmon behavior in order to move fish to a certain

location. For example, guide nets are commonly used to focus fish migration into the entrance structure on a floating surface collector (Kock et al. 2019). A conceptual level behavioral guidance layout was developed for the HCB (Figure 2-7) but questions regarding marine traffic, anchoring, sustainability, combined with overwhelming capital and operations/maintenance costs associated with the system were reasons to defer this solution from Phase 2 management actions.

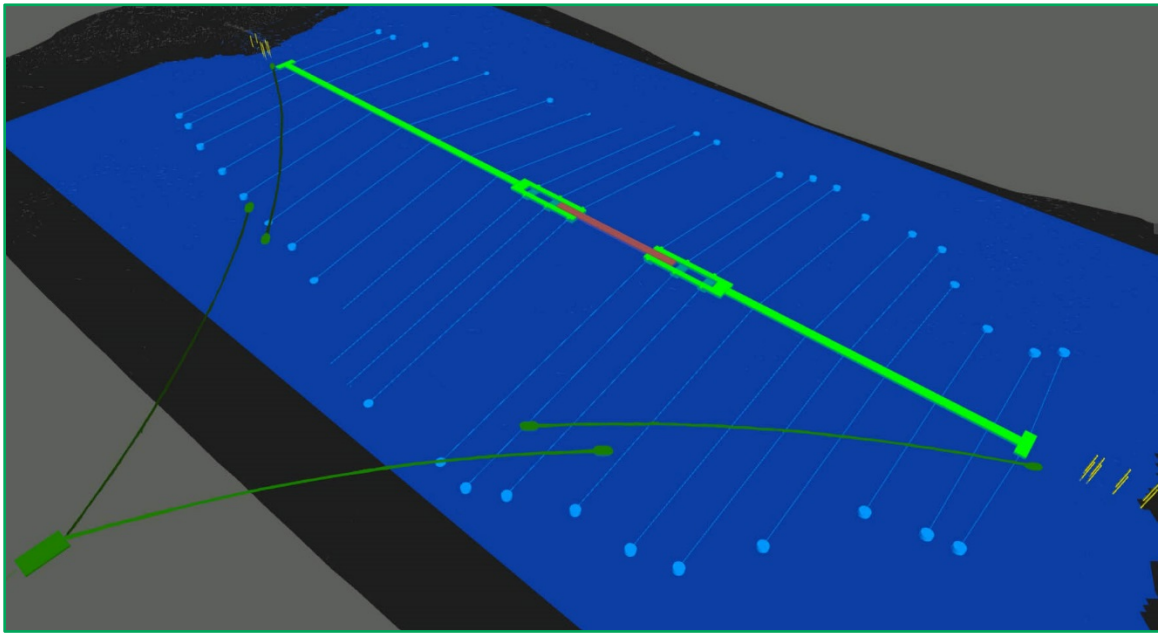


Figure 2-7. Conceptual design of behavioral guidance system for Hood Canal Bridge, Washington.

Alternative 7 – Pumping Water to Signal Fish Passage

The hypothesis of pumping water through portion(s) of the HCB that would induce water currents to signal passage and guide fish around structures that may be restricting passage or delaying migration was conceptually designed for portions of the HCB (Figure 2-8). The Assessment Team determined that the magnitude of pumping needed to overcome the volume of water moving past HCB during ebb tide (i.e., discharge past bridge ~40,000 cfs) was an insurmountable obstacle and did not appear to result in consistent benefits to salmon survival. In addition, the relatively high initial construction and annual maintenance costs were the rationale for deferring pumping water as a management action by the Assessment Team.

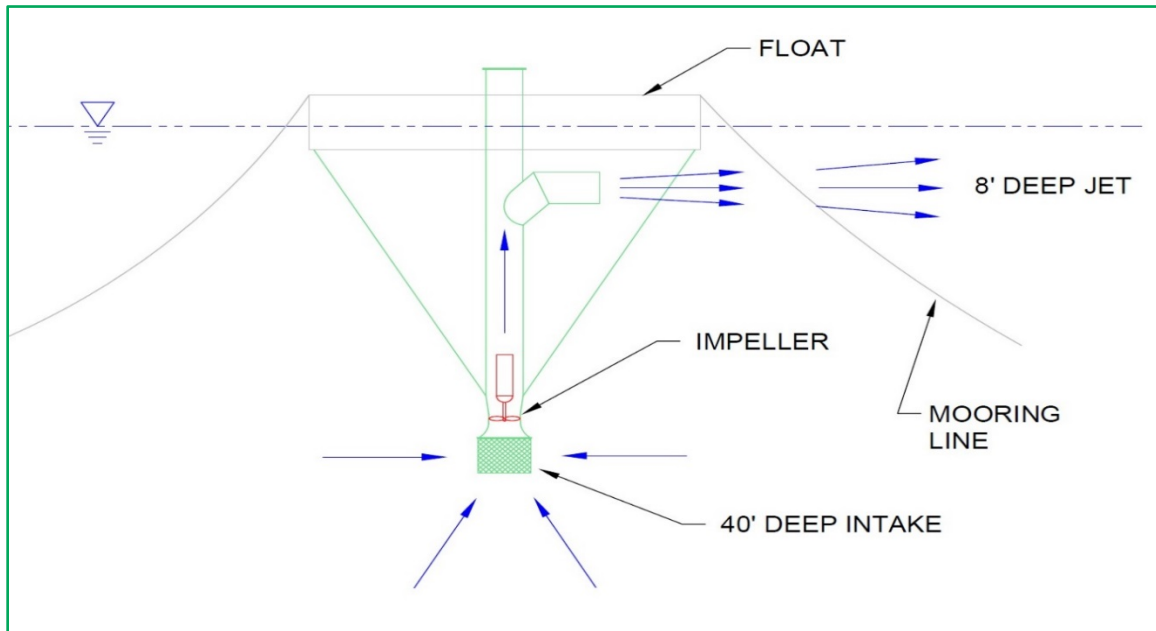


Figure 2-8. Water pumping conceptual design to signal fish passage at Hood Canal Bridge, Washington.

Alternative 8 – Guide Fish with Bubble Curtains

The concept of guiding fish using entrained air or creating a bubble curtain or air bubble barriers to prevent fish from passing is a new and rising technology in the field of fish passage. Applications involving salmon have not been consistently successful; however, a conceptual design was developed for the HCB (Figure 2-9). The lack of consistent positive results from salmon applications throughout the Pacific Northwest and the overwhelming amount of water passing through HCB during ebb tide period were the primary determinants for deferment of the bubble curtain solution. At this location, this concept is considered infeasible.

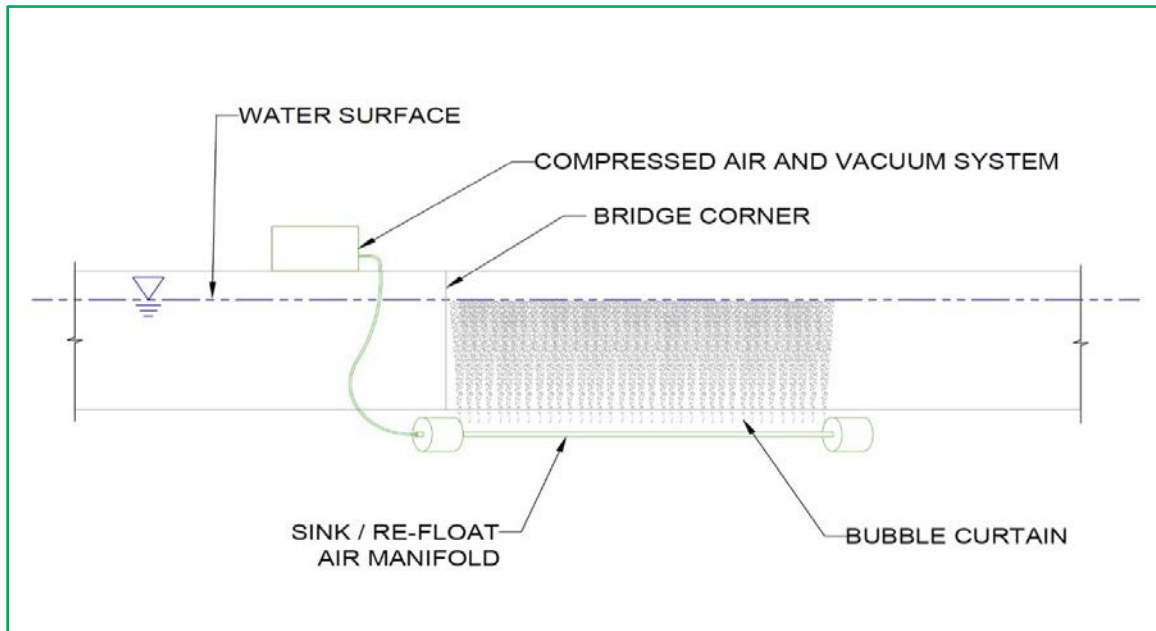


Figure 2-9. Bubble curtain conceptual design to guide fish passage at Hood Canal Bridge, Washington.

Alternative 10 – Noise Reduction

The HCB provides a vital transportation corridor between the Olympic and Kitsap peninsulas, with as many as 15,000 cars passing on weekdays and 19,000 on weekends. Noise such as traffic passing over the HCB is postulated as deterrent to salmon passage thus negatively affecting steelhead survival (Figure 2-10). Acoustic monitoring indicates that noise levels approach and possibly exceed levels that may inhibit steelhead passage at HCB; however, juvenile salmon telemetry studies did not indicate a migration preference during low traffic periods and visual observations on the bridge deck did not detect a behavioral change in response to traffic noise (Deng et al. 2017; Daubenberger and Bishop 2020; Moore 2020). The uncertainty of the effectiveness of noise reduction at HCB and the disruption to the traffic corridor resulted in deferring noise reduction from the Phase 2 management actions.



Figure 2-10. The number of cars passing Hood Canal Bridge, Washington approaches 15,000 on weekdays and 19,000 on weekends.

Alternative 11 – Marine Growth Removal/Control

This concept was originally identified in the brainstorm session of the Assessment Team as documented in Appendix A. During this study, the Assessment Team members agreed that any benefits of removing marine growth (Figure 2-11) on the bridge would be uncertain, and the cost and logistics associated with removal and control type paints were not desirable. This alternative was unanimously agreed to be deferred from additional Phase 2 implementation.



Figure 2-11. Marine growth near pontoon joint on Hood Canal Bridge, Washington (adapted from Anchor 2008).

Alternative 12 – Induced Turbidity

Inducing a turbidity plume or current by means of artificial dye was investigated as a source to reduce predation rates of juvenile salmonids at sections the HCB (Figure 2-12). The assessment of increased turbidity is often linked to salmon outmigration and within certain concentrations is generally accepted as a benefit to outmigrating salmon in the Pacific Northwest (Gregory and Levings 1997). Elevated sediment levels have also been observed to limit visual ability of juvenile salmon (Quinn 2018). The Assessment Team determined that turbidity could potentially cause a disruption of salmon migration and deter passage by fish, and that the quantity of dye needed to be released would be challenging and expensive given the magnitude of flow that occurs at the HCB and deferred this solution from Phase 2 management actions.



Figure 2-12. Conceptualized induced turbidity plume to reduce salmon predation rates at west end of Hood Canal Bridge, Washington.

3 DEVELOPMENT OF CATEGORY 1 ACTIONS/ALTERNATIVES

3.1 Summary of Selected Category 1 Alternatives

As described in Section 2.2.1.1, the Assessment Team agreed that four management actions should be carried forward as Category 1 alternatives, and that R2 should further define the alternatives and implementation plans. To avoid confusion, we maintained each original alternative name to match the numbering convention used in the matrices.

This section provides a more detailed description for each alternative, a discussion of engineering design and feasibility, and initial thoughts on the assessments. The Assessment Team will be leading the development and implementation of biological performance assessments of each action, so this report focuses primarily on the physical design and installation or operation of the measures.

3.2 Alternative 1 – Bridge Corner Fillet Structures

3.2.1 Description

The fillet structure was originally anticipated to be fabricated from high density polyethylene (HDPE) pipe, synthetic netting or fabric that is weighted with a continuous steel chain at the bottom. Figure 3-1 depicts a conceptual elevation and section view of the fillet concept. An HDPE plate is welded to the top of the pipe to deter seals from using the pipe as a haul out location. To our knowledge this technology has not been tested to restrict pinniped access; however, HDPE plates have been effectively installed to keep large wood and trees from entering forebays and could easily be adapted to the fillet structure to test for seal deterrence capabilities at the HCB corner locations. Depending on the height and shape of the plate, stability could also be increased by using a double pipe section. A second plate welded to the bottom of the pipe is for attaching the barrier net or fabric. The fillet has a barrier that extends to a depth of 8 (Alternative 1a) to 15 feet (Alternative 1b), which is intended to be approximately half or full depth of the existing bridge pontoon. A final depth will be decided by the Assessment Team early in the implementation phase based on additional discussion and preliminary cost estimates. The assembly is anticipated to be similar to the fish guidance systems and debris booms that have been fabricated by Pacific Netting Products of Poulsbo Washington, that have been shown to be effective in fish guidance at several hydroelectric projects in the region.

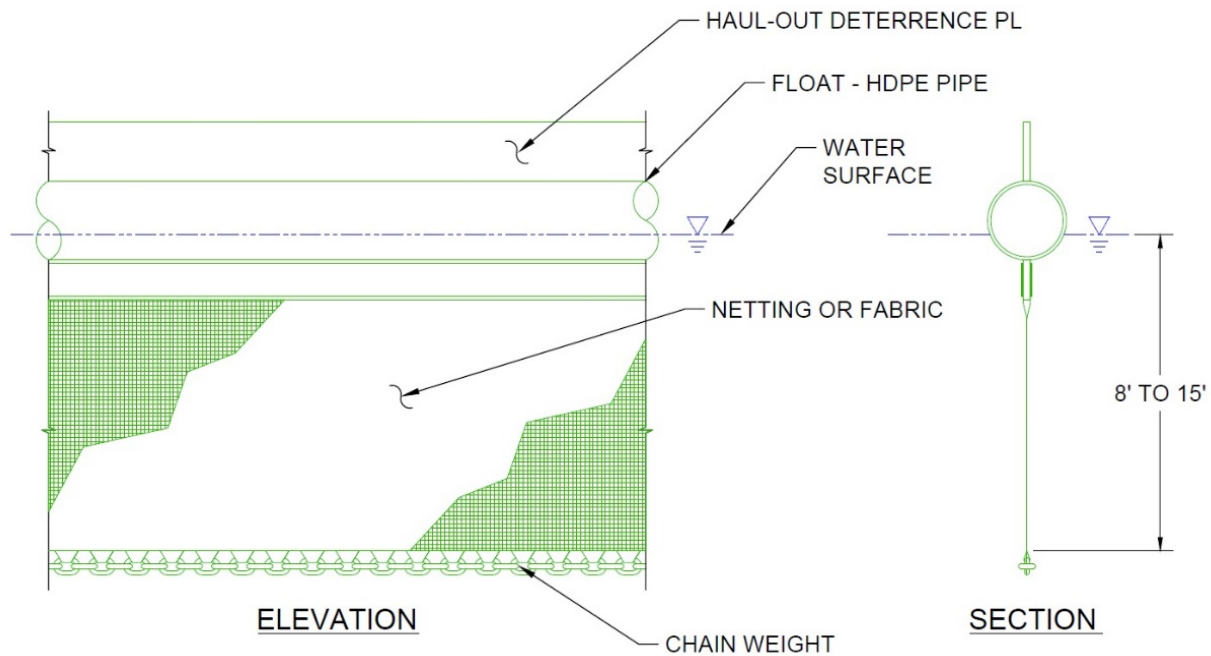


Figure 3-1. Typical fillet detail.

The attachment to the bridge structure will include an elastic type connection to safely absorb energy and limit the forces on both the fillet structure and the bridge during storms events when the fillet structure is subject to very turbulent water conditions (waves and wind). The connections to the bridge will need to be made in a manner that will not unduly load or harm the bridge structure. These connections may include synthetic straps wrapping around the pontoons and fastener plates adhered to the bridge pontoon.

A summary of the opinion of probable construction costs (OPCC) in 2020 US Dollars (USD) is presented in Table 3-1 for both the fillet with 8-feet of depth, and with 15-feet of depth. These costs are for one assembly of each alternative. If fillet structures are deployed at all 4 fixed corners along the bridge the cost would likely quadruple, however some unit cost saving may be realized by fabricating and installing more than one fillet structure.

Table 3-1. Opinion of Probable Cost summaries for Alternative 1*

Alternative Name	Base Estimate OPCC	Low Range OPCC	High Range OPCC
Alt 1a – Bridge Corner Fillet Structure with 8' Depth	\$184,000	\$120,000	\$304,000
Alt 1b – Bridge Corner Fillet Structure with 15' Depth	\$207,000	\$135,000	\$342,000

* Costs are presented in 2020 USD Currency.

These values are considered American Association of Cost Engineers (AACE) International Class 5 cost estimates, which are generally used for concept screening when the engineering design is 0-percent to 2-percent complete and typically has an accuracy of minus 50-percent to plus 100-percent. Each cost estimate value includes a range defined by three capital costs including the base estimated cost, plus a low and high range cost. For our initial planning, the low range is assumed to be minus 35-percent of the subtotal cost while the high is plus 65-percent. The estimates includes a contingency assumed to be 30%. Operations and maintenance (O&M) costs are not included. Additional detail for these estimated costs are provided in Appendix F.

Based on comments received by the Assessment Team on the draft report, examination of a more solid structure with a closed bottom is also desired. This approach can be explored early in the Phase 2 implementation design, and associated cost estimates can be revised based on findings and recommendations.

3.2.1 Engineering Design / Feasibility Work Needed

The design of the fillet structures will require close coordination with WSDOT throughout the design process. The loading conditions will need to be determined prior to final structural design and detailing of the structures, and will involve identifying a design hydraulic condition adjacent to the bridge. The design loading is anticipated to be a complex wave condition that may have been modeled during the original bridge design or subsequent analyses. The first step in coordination is to determine what is available from WSDOT. If suitable design load criteria is not available, then the design team will need to develop and document design loading conditions and verify that the conditions are acceptable with the WSDOT.

After the loading criteria is developed, the fillet structure will be modeled by subjecting it to the criteria and determining the loads on the fillet structure, bridge structure, and connections. Part of the analysis will be interposing energy absorbing elements between the fillet and the bridge to help mitigate the intensity of the loading. The system for fastening the fillet structure to the bridge will need to be developed then reviewed by the WSDOT to make sure it is acceptable for attachment to the bridge. This may require fused type elements that will breakaway to limit the loading to an acceptable maximum.

Overall review meetings will be held with WSDOT throughout the design process to keep them fully informed of the process and recommended design details. Coordination will continue with WSDOT after design and include procurement, construction, and commissioning of the fillet structure. Additional detail and associated timelines is provided in Section 4.

3.2.2 Assessment

The fillet structure will be deployed during the fish passage season then removed and stored in a safe harbor during the off-season. After the fillet structure has been deployed an assessment will be performed to determine its effectiveness. The fillet structure is anticipated to be assessed via telemetry study and visual observations (Blueview and GoPro deployments, on-bridge observer surveys) of non-steelhead fish behavior and pinniped behavior. More detail on the assessment program will be provided in a separate document/process by the Assessment Team.

3.3 Alternative 2 – Eddy Reduction Structure at Corner

3.3.1 Description

The bullnose structure for eddy reduction is anticipated to be fabricated out of HDPE pipe and plates. Figure 3-2 depicts a conceptual layout for the assembly in plan view, mounted to the Southwest corner of the bridge. The bullnose would be approximately 15-feet tall to match the dimension of the submerged portion of the bridge pontoon and include a 2-foot radius and adjacent fillet plate for an overall length of 12-feet. The actual size of the structure may vary after field conditions are considered by observing turbulence during a high ebb tide flow and performing a hydraulic analysis to determine the most efficient shape.

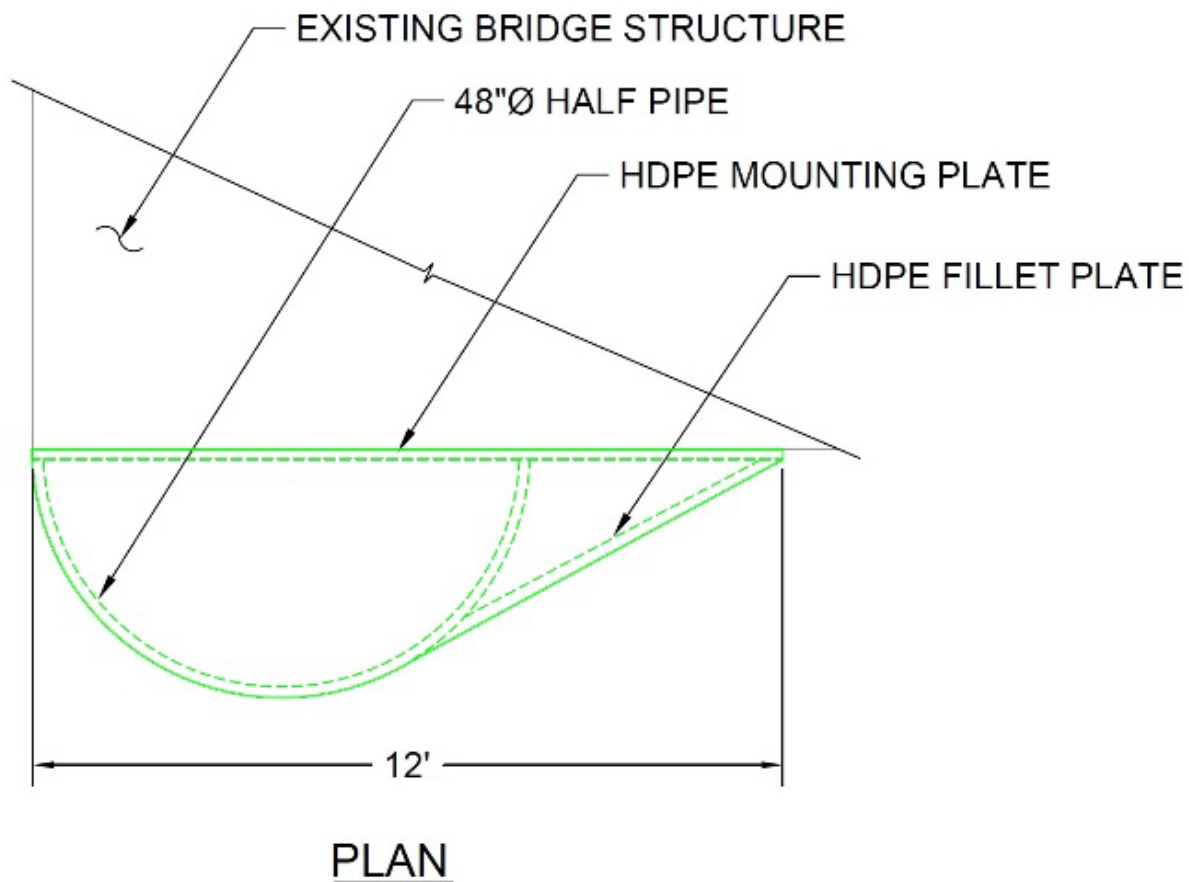


Figure 3-2. Corner bullnose detail, plan view.

The bullnose includes a mounting plate that will fit flush to the bridge structure, a half pipe section extending off the corner of the pontoon, a fillet plate located on the downstream side during ebb tide, and top and bottom plates. The assembly will either need to be designed with drain and vent holes or sealed up and include weights to make it neutrally buoyant when properly deployed.

The opinion of probable construction cost is presented in Table 3-2. This cost is for one assembly. If bullnose structures are deployed on both ends of the bridge the cost would likely double, however some unit cost saving may be realized by fabricating and installing more than one bullnose structure. The assumptions and conditions for this estimate are the same as those described in Section 3.2.1, and additional detail is provided in Appendix F.

Table 3-2. Opinion of Probable Cost summaries for Alternative 2*.

Alternative Name	Base Estimate OPCC	Low Range OPCC	High Range OPCC
Alt 2 – Eddy Reduction Structure at Corner (15' Depth)	\$96,000	\$62,000	\$158,000

* Costs are presented in 2020 USD Currency.

3.3.2 Engineering Design / Feasibility Work Needed

Similar to the fillet structures, the design of the eddy reduction structure will require close coordination with WSDOT throughout the design process. A similar coordination process with WSDOT to the one described in section 3.2.2 is anticipated. Overall review meetings will be held with WSDOT throughout the design process to keep them fully informed of the process. Coordination will continue with WSDOT after design and include procurement, construction, and commissioning of the fillet structure.

3.3.3 Assessment

Similar to the fillet, the bullnose eddy reduction structure will be deployed during the fish passage season then either removed and stored in a safe harbor during the off-season or depending on its design and durability, it may be feasible to leave it in place. After the corner eddy reduction structure has been deployed an assessment will be performed. The bullnose structure is anticipated to be assessed via telemetry study and visual observations (Blueview and GoPro deployments, on-bridge observer surveys) of non-steelhead fish behavior and pinniped behavior. This evaluation will be designed and implemented by members of the Assessment Team with a separate process.

3.4 Alternative 9 – Open Bridge Span More for Fish Passage

3.4.1 Description

This alternative provides opening the center span of the bridge more frequently and possibly for longer durations than is customary for boat passage. The Assessment Teams hypothesized that opening both sides of the bridge draw span for at least an hour during ebbing tides would be most likely to impact fish passage. Figure 2-3 depicts the open span for boat traffic. This alternative requires an operational assessment to determine the potential benefit to fish passage weighed against the inconvenience of the motorized public who use the bridge. Public notification and education will also likely be needed. The timing of the openings will likely

coincide with the peak of ebb tides during the peak fish outmigration periods. This process will be developed further by the Assessment Team.

3.4.2 Engineering Design / Feasibility Work Needed

The current center span bridge opening system can be readily operated, and no design work is needed. Cost estimates are also not desired, as operational costs for bridge operation are currently funded by WSDOT, who will determine the costs and feasibility of bridge openings.

3.4.3 Assessment

The effectiveness of carefully timed bridge opening will likely be assessed via telemetry studies. This Assessment Team will develop further details on an assessment plan and will lead the evaluation.

3.5 Alternative 4 – Lighting at Bridge

This alternative has more uncertainties than the other three Category 1 alternatives; however, the Assessment Team felt it was important to carry forward for ongoing definition and study. There is a growing body of literature regarding the impacts of artificial lighting on salmon passage and predation. Specifically, there is precedent from other bridge construction in Puget Sound that have recently been designed to mitigate these impacts. The Assessment Team will lead further development and definition of considered lighting modifications outside of this report.

4 PHASE 2 WORKPLAN – CATEGORY 1 IMPLEMENTATION

4.1 Introduction

This section provides an overview on a process and budget to implement the current Category 1 alternatives through the design, review, and fabrication/installation phases. Section 4.2 provides an overall implementation schedule. Section 4.3 provides a discussion and construction cost estimates for the range of implementation alternatives, and Section 4.4 provides a cost estimate for the design phase with a roll-up total cost summary. The Assessment Team and Management Committee will be responsible for defining assessment plans and definitions of success for the recommended Category 1 measures.

4.2 Implementation Schedule

As a starting point for discussion, we have assumed a conventional design-bid-build approach, which will provide a conservative schedule to allow for funding procurement, low-bid public works type contracting, and engineering construction oversight. This process would include the following key steps or tasks:

- Procure a design team. This provides the Assessment team time to finalize decisions on what to implement (for example, one fillet and one bull nose, or up to four fillets and two bull noses), define the desired scope, and enter a contract with a design team.
- Task 1 – Design and Consultation. This step will allow for a conventional design process, with good stakeholder/agency communication and will result in a final set of plans and technical specifications that can be used to procure a general contractor for the fabrication/installation of the desired measures.
- Task 2 – Contractor Procurement. This step allows the Assessment Team or other assigned entity (such as LLTK or WSDOT), time to solicit bids, evaluate the bids, and select a general contractor for construction.
- Task 3 – Construction. This phase would be the actual fabrication, installation, and construction of the desired measures. Engineering services from the design team would help to assure the alternatives are fabricated and installed correctly. Design services would include construction oversight, assistance with submittal reviews, addressing questions, and critical construction oversight/inspection/acceptance.

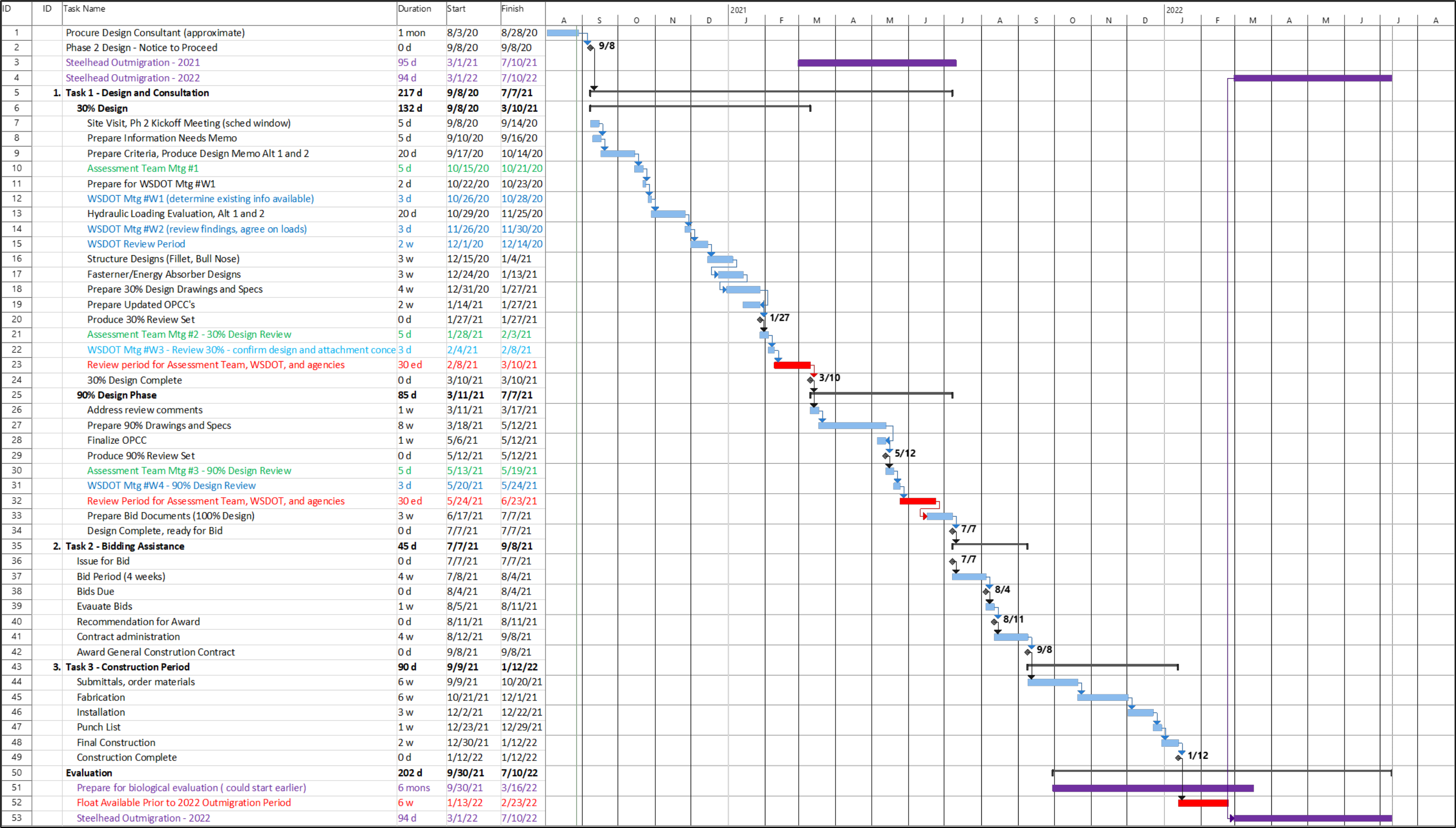
Once the construction is completed, the evaluation phase would proceed. Note that we have not shown the process to prepare evaluation plans and prepare/implement the plans as the Assessment Team will be leading those actions directly.

Figure 4-1 provides a Gantt Chart project schedule that summarizes key steps and timelines to advance the current concepts through construction. This schedule was developed to be conservative with respect to time, and proceeds in a linear fashion allowing for design, coordination meetings, and review periods for the Assessment Team, WSDOT, and natural resource agencies (NOAA Fisheries, WDFW, USFWS, etc.). The schedule targets completion in advance of the steelhead outmigration season starting in early March 2022.

Given the simplicity of these initial structures, we propose conducting formal review meetings at only the 30% and 90% phases of design and have allowed a 30-day review period for comments. With more complex fish facilities, the agencies (WDFW, NMFS) typically desire 30%, 60%, and 90% reviews, so eliminating the 60% review step should be vetted prior to settling on this approach, unless issues arise at the early meeting with loading or with more complex, solid structures (vs. nets) for this initial installation.

The schedule reflects a notice to proceed date of September 8, 2020, and shows the design and selection of a contractor could easily be completed in time for the 2022 outmigration season. If installation of some options is desired in 2021, there is a possibility that the project could be fast-tracked with a Design-Build type contract. This often can save time, but rarely results in any cost savings and is often contingent on funding source restrictions.

Figure 4-1. Gantt Chart project implementation schedule for design-bid-build contracting method.



4.2.1 Task 1 Design Highlights

Key steps of the design process will be to agree on design criteria, especially with WSDOT for attachment to the HCB, and then work through the design drawings and technical specifications with an organized set of review meetings. The ultimate product from the design will be final designs suitable for bid to a general contractor for fabrication and installation of the fillets and bull nose. The steps shown in Figure 4-1 are considered relatively complete with reasonable durations and critical path for this type and scale of project. As noted above, there may be some opportunity to expedite this design if funding allows.

4.2.2 Task 2 Contractor Procurement Highlights

This step is laid out with a conventional approach to retaining a general contractor. The Assessment Team or other entity (such as WSDOT or LLTK) would lead this effort, and the Design Team could provide assistance with orienting potential contractors on project needs, answering contractor questions during bidding, and helping to evaluate bids from qualified contractors.

4.2.3 Task 3 Construction Highlights

The steps shown under Task 3 provide realistic estimates of the duration for key steps of the construction phase. Initial material procurement, fabrication, and installation are the key steps by the contractor. The Design Team can provide associated submittal reviews, assistance with questions, conduct key inspections and recommendations final acceptance.

4.3 Estimated Construction Cost Budget Considerations

Cost estimates for the individual Category 1 alternatives were summarized in Section 3 based on the original net-based fillet structures. Depending on the available budget and desired evaluations there are a suite of options for constructing these early implementation measures that the Assessment Team can consider – based both on goals and on potential funding constraints. For example, the lowest cost option would be to fabricate and install one fillet, and one bull nose. A full program would be to install four fillets, and two bull noses. Costs for the bridge opening and lighting modifications will be addressed separately by the Assessment Team, and Table 4-1 provides a summary of the implementation options for the Category 1 alternatives. If the initial evaluation in the Phase 2 implementation changes the concept from nets to a more solid structure, the cost estimates should be updated.

Table 4-1. Opinion of Probable Construction Cost Summaries for implementation options*

	Base OPPC Estimate		Low Range		High Range
Option 1 - Lowest Cost					
One Alt 1a - 8' Depth Fillet	\$	184,000	\$	120,000	\$ 304,000
One Alt 2 - Bullnose	\$	96,000	\$	62,000	\$ 158,000
Total	\$	280,000	\$	182,000	\$ 462,000
Option 2 Mid Level Cost					
Two Alt 1b - 15' Depth Fillet	\$	414,000	\$	270,000	\$ 684,000
Two Alt 2 - Bullnose	\$	192,000	\$	124,000	\$ 316,000
Total	\$	606,000	\$	394,000	\$ 1,000,000
Option 3 - Full Program					
Four Alt 1b - 15' Depth Fillet	\$	828,000	\$	540,000	\$ 1,368,000
Two Alt 2 - Bullnose	\$	192,000	\$	124,000	\$ 316,000
Total	\$	1,020,000	\$	664,000	\$ 1,684,000

* Costs are presented in 2020 USD Currency.

We suggest the Assessment Team factor these cost summaries into their discussion on the evaluation plans and provide guidance on the desired actions to be implemented.

4.4 Design and Construction Professional Services Work Plan and Estimate

Regardless of the number of fillets or bull nose attachments desired, the work plan and scope for professional engineering services necessary to prepare the final designs and assist with the bidding and construction phases would be about the same. A work plan and planning level engineering design consultation budget was developed that corresponds with the implementation schedule shown in Figure 4-1 is summarized in Table 4-2. This estimate can be updated early in the Phase 2 implementation after the number of measures and final configuration are defined further.

Table 4-2. Professional engineering services fee estimate for design through construction.

Phase	Estimated Cost
Task 1 – Design	\$121,000
Task 2 – Bidding Assistance	\$8,000
Task 3 – Construction Oversight	\$23,000
Total	\$152,000

4.5 Total Implementation Cost Summary

Based on the estimates above, an estimate of the total program cost using the Option 2 Base OPCC Estimate is summarized in Table 4-3. Note that these costs are for design and construction only and do not include costs for the biological assessments. Other combinations of constructed elements can be summarized to prepare a final cost summary of the desired program, along with cost ranges; however, this provides a consolidated summary of likely program implementation costs.

Table 4-3. Total program cost summary to implement Option 2 (using the Base OPCC Estimate from Table 4-1).

Description	Professional Services Cost	OPCC	Total implementation Cost
Option 1 – Lowest Cost (One Alt 1a 8' fillet, One Alt 2 bullnose)	\$152,000	\$280,000	\$432,000
Option 2 – Mid Cost (Two Alt 1b 15' fillets, Two Alt 2 bullnose)	\$152,000	\$606,000	\$758,000
Option 3 – High Cost (Four Alt 1b 15' fillets, Two Alt 2 bullnose)	\$152,000	\$1,020,000	\$1,172,000

4.6 Goals / Evaluation (by others)

The development and implementation of the biological evaluation plans should be developed with close coordination with the Design Team, so all parties understand the objectives, and details/limitations of the alternatives as the design evolves. As noted above, efforts for the evaluation plans will be addressed outside of this report.

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APPENDIX A

HCB Initial Solutions Matrix

Potential Solutions to Address Steelhead Mortality at the Hood Canal Bridge

Options to decrease potential Chinook smolt, chum smolt, or adult salmonid mortality will be considered separately

1 = no; 2 = low potential; 3 = medium potential; 4 = high potential									
Potential Solution to Test	Will it expedite steelhead passage?	Will it reduce efficacy of harbor seals foraging near the bridge?	Feasibility - Is it likely to be implemented in the next 3 years?	Is likely to avoidd unintended negative consequences?	Estimated Cost 4 = <\$10k 3 = \$11k - \$100k 2 = \$101K - \$999K 1 = \$1m+	Aggregate score	In your opinion, regardless of aggregate score, identify the three potential solutions you would try first.	Is there further research that would be NECESSARY perform before piloting the potential solution? If yes, briefly describe the research below.	Additional Comments
Restricting access to cross-pontoon corners	3	3	4	4	2	16	1		
Acoustic Startle Device (Genuswave)	1	3	4	2	3	13	3		
Open/Close the bridge for longer periods during low traffic hours	2	1	3	3	3	12	3		
Acoustic Harassment device (Traditional - loud noise)	1	3	4	1	3	12			
Reducing light	2	2	3	3	2	12			
Replace the bridge with a more "fish Friendly" design	4	4	1	2	1	12			May be realistic to consider as a long term strategy.
Restricting access to seal haul-outs near the bridge	1	3	3	2	2	11			
Structure to reduce/disrupt surface water velocity around the ends of the bridge.	3	2	2	3	1	11			
Pumping water to signal passage	2	1	2	4	1	10			
Reducing noise	2	2	1	4	1	10			
Remove marine growth from the bridge	1	1	2	4	1	9			May be more effective for Chinook/Chum.
Predator exclusion netting	1	3	2	1	2	9			
Lethal removal of nuisance predators	1	2	2	2	1	8			
Remove marine growth and apply Anti-fouling coating	1	1	1	2	1	6			May be more effective for Chinook/Chum.
Optional: Include additional potential solutions below and perform the same exercise									
						0			
						0			

APPENDIX B

HCB Solutions Matrix – R2 Comments

Number	Subset	Type	Level	Potential Solution to Test
1		Guidance	Primary	Restricting juvenile salmonids access to cross-pontoon corners
	1A	Guidance	Primary	15-Foot (full bridge depth) bridge corner fillets
	1B	Guidance	Primary	8-Foot (half bridge depth) bridge corner fillets
	1C	Guidance	Primary	15-Foot (full bridge depth) bridge intermediate fillets
	1D	Guidance	Primary	8-Foot (half bridge depth) bridge intermediate fillets
2		Guidance	Primary	Full guidance net on south side of HCB
	2A	Guidance	Primary	15' Deep 1.9 mile "V" Behavioral Guidance System (BGS)
	2B	Guidance	Primary	8' Deep 1.9 mile "V" BGS
3		Guidance & Deterrence	Primary	Bridge Re-design and replacement/modification
	3A	Guidance & Deterrence	Primary	Replace the entire bridge with a more "fish friendly" design
	3B	Guidance & Deterrence	Primary	Replace middle segment of bridge with more "fish friendly" design
	3C	Guidance & Deterrence	Primary	Replace pontoons of bridge with more "fish friendly" design
4		Deterrence	Secondary	Lighting at bridge
5		Guidance	Secondary	Eddy structure at corners to reduce/disrupt surface water velocity around the ends of the bridge
6		Pinniped Deterrence	Secondary	Deter pinniped activity near the bridge
	6A	Pinniped Deterrence	Secondary	Perform pinniped behavioral study at HCB to better inform decisions
	6B	Pinniped Deterrence	Secondary	Restricting access to seal haul-outs using handrail or netting
	6C	Pinniped Deterrence	Secondary	Restricting access to seal haul-outs using electric mats
	6D	Pinniped Deterrence	Secondary	Acoustic harassment/deterrent device (traditional - loud noise)
	6E	Pinniped Deterrence	Secondary	Lethal removal of nuisance predators
	6F	Pinniped Deterrence	Secondary	Predator exclusion netting
	6G	Pinniped Deterrence	Secondary	Targeted Acoustic Startle Device (Genuswave)
7		Guidance	Secondary	Pumping water to signal passage
8		Guidance	Secondary	Guide fish to safe passage (bubble curtains or other strat.)
9		Guidance	Secondary	Open bridge span more for fish passage
10		Guidance	Secondary	Noise reduction
11		Deterrence	Secondary	Marine growth removal/control
	11A	Deterrence	Secondary	Remove marine growth from the bridge
	11B	Deterrence	Secondary	Remove marine growth and apply Anti-fouling coating
12		Deterrence	Secondary	Induced turbidity

APPENDIX C

HCB R2 Alternatives Development Presentation

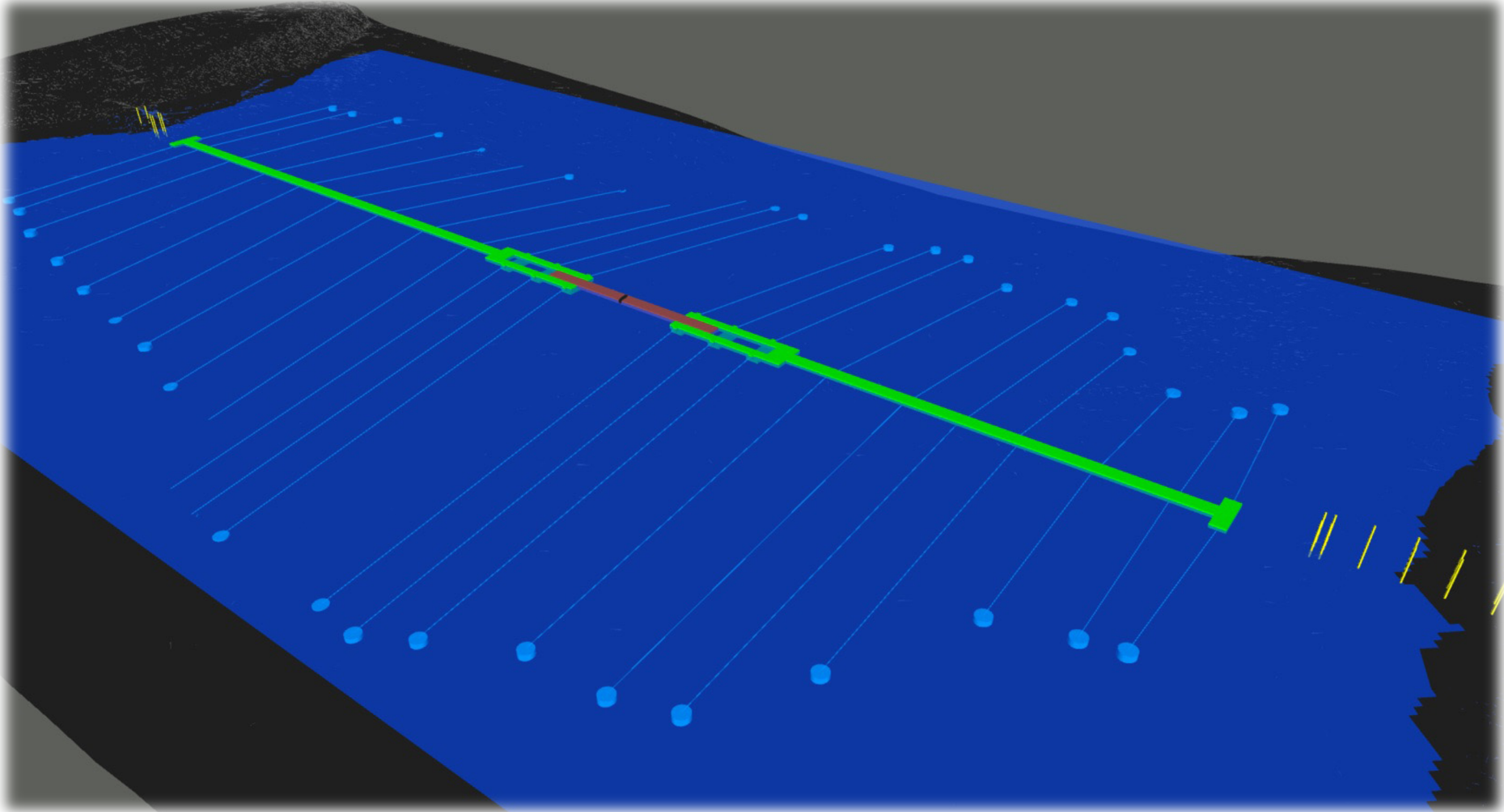


Hood Canal Bridge Fish Passage Alternatives Meeting



April 6 , 2020

Presentation Overview



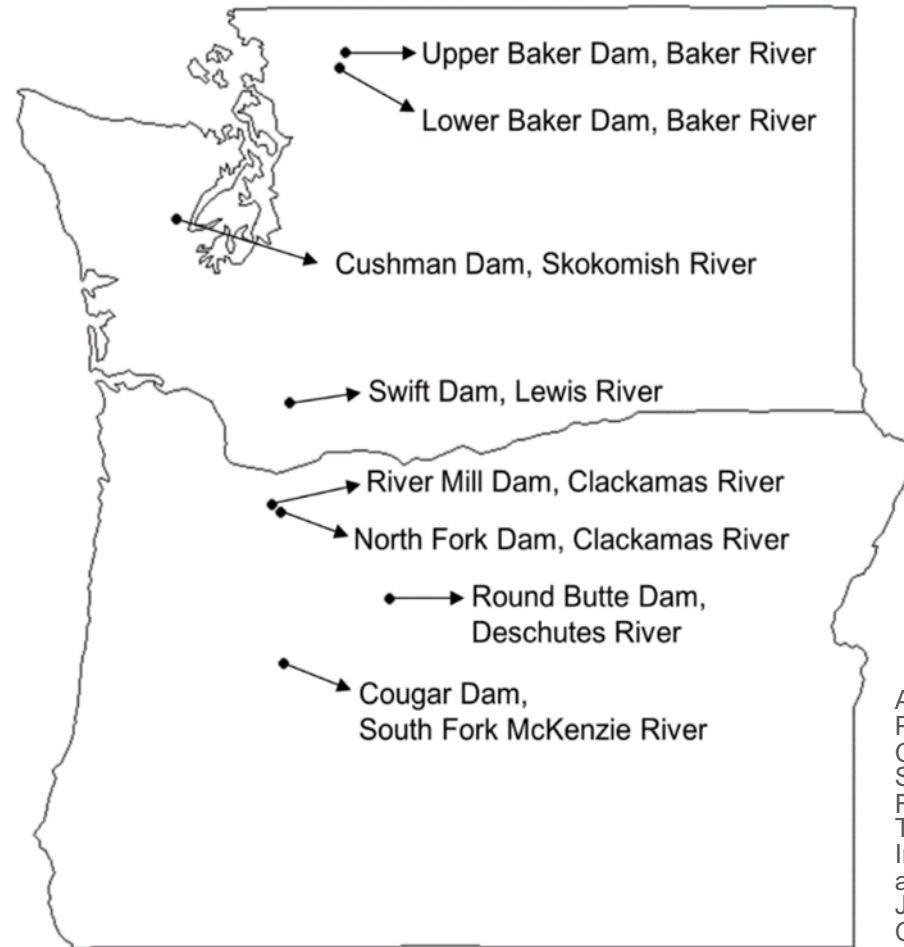
Re-Structured Alternatives Matrix

- 1 – Bridge Corner Fillet Structures
- 2 – Behavioral Guidance System (BGS)
- 3 – Bridge Re-Design & Replacement / Modifications
- 4 – Lighting at Bridge
- 5 – Eddy Reduction Structures at Corners
- 6 – Pinniped Deterrence
- 7 – Pumping Water to Signal Passage
- 8 – Guide Fish with Bubble Curtains
- 9* – Open Bridge Span More for Fish Passage
- 10* – Noise Reduction
- 11* – Marine Growth Removal/Control
- 12* – Induced Turbidity

*Alternatives recommended for deferral

Fish Passage Overview

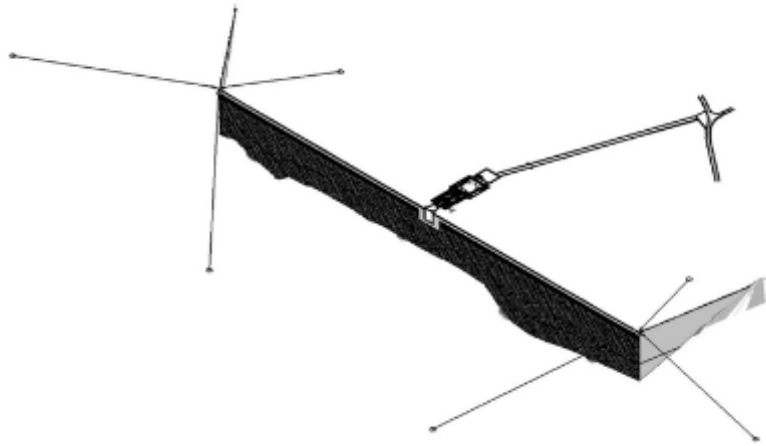
- Second Generation Forebay Collectors



Adapted from: Surface Collectors In The Pacific Northwest: Operating Characteristics And Collection Success. Short Course – Downstream Passage of Fish at High Head Dams. Tobias J. Kock, U.S. Geological Survey. International Conference on Engineering and Ecohydrology for Fish Passage. June 19-21, Oregon State University, Corvallis, OR.

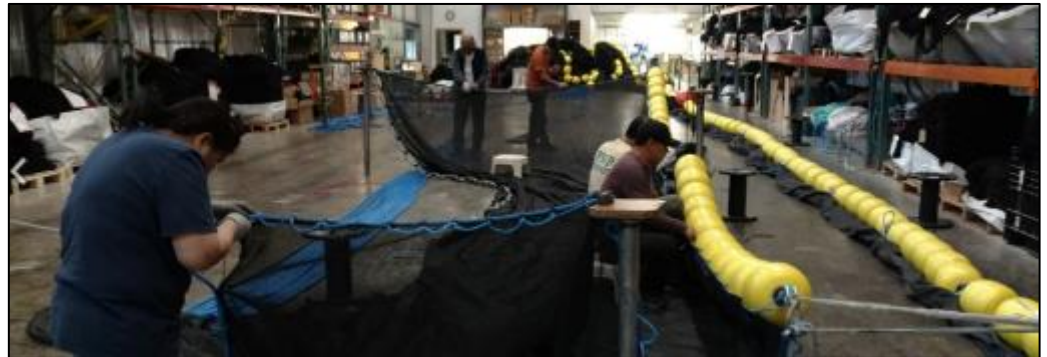
Fish Passage Overview

- Partial vs. Full Depth Net Experience
 - Upper Baker was the first, research from Gulper to FSC over 30 years
 - Full exclusion netting made the difference
 - Swift FSC net system shown



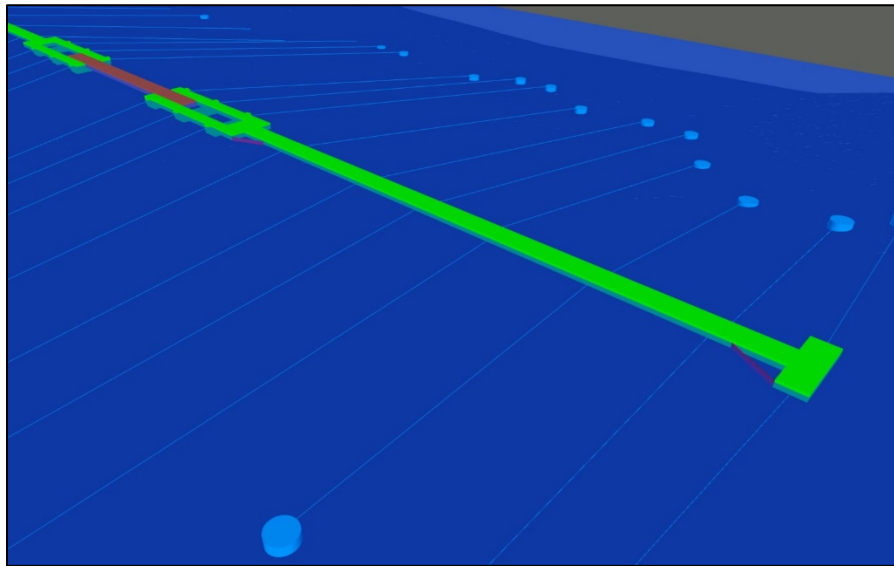
1 – Bridge Corner Fillet Structures

- Examples of Fish Exclusion Systems
 - Baker River Floating Surface Collector (FSC) Exclusion Netting
 - Clackamas River FSC Exclusion Netting
 - Swift FSC Exclusion Netting
 - 8 Surface Collector Systems in Region last 10 years



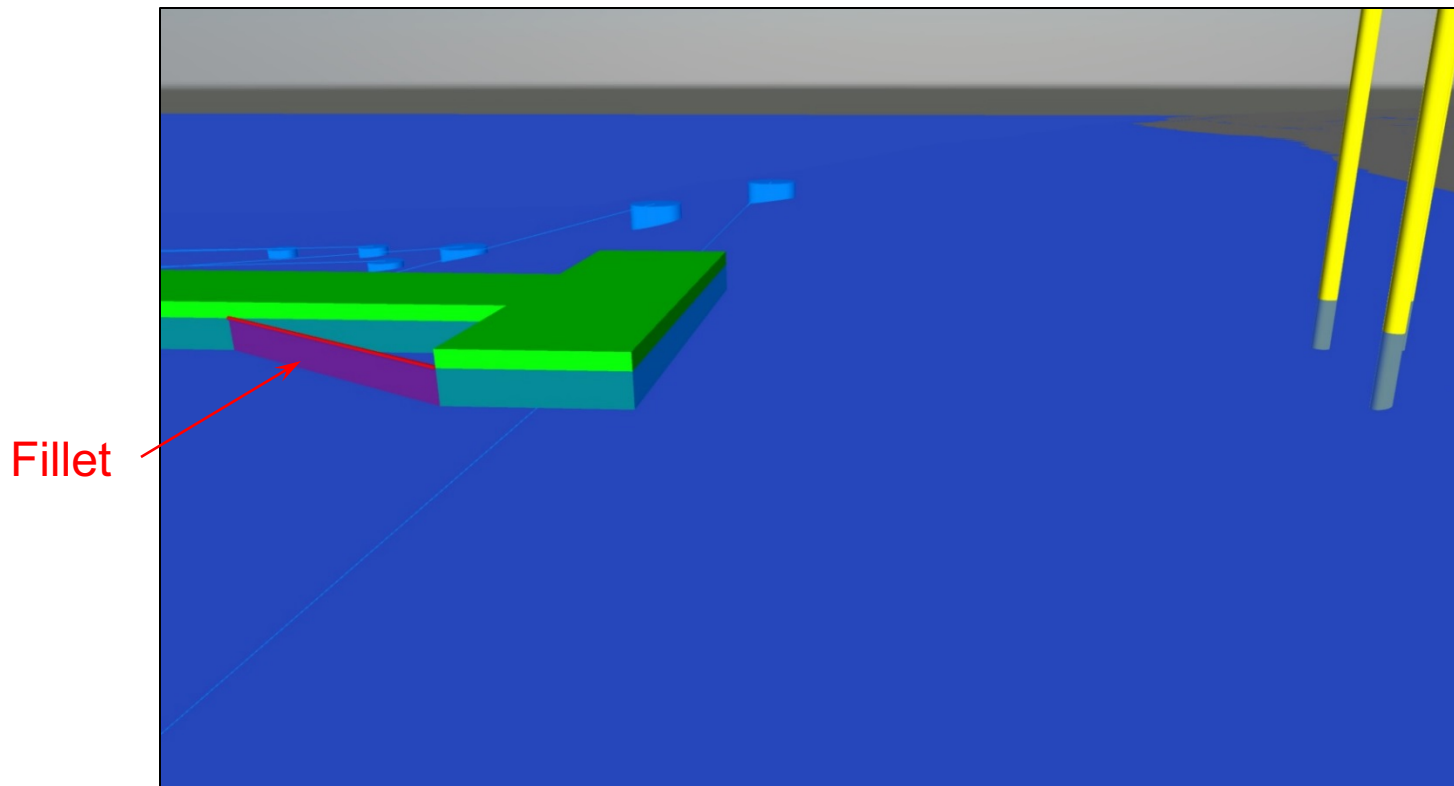
1 – Bridge Corner Fillet Structures

- Fish delay at bridge by reversing direction when corners are encountered resulting in a back and forth path along the south face of the bridge
- Place bridge corner fillets at inside corners of east and west abutments to guide fish around the corners
- 1A – 15' deep x 110' long bridge corner fillets (full bridge depth)
- 1B – 8' deep x 110' long bridge corner fillets (half bridge depth)



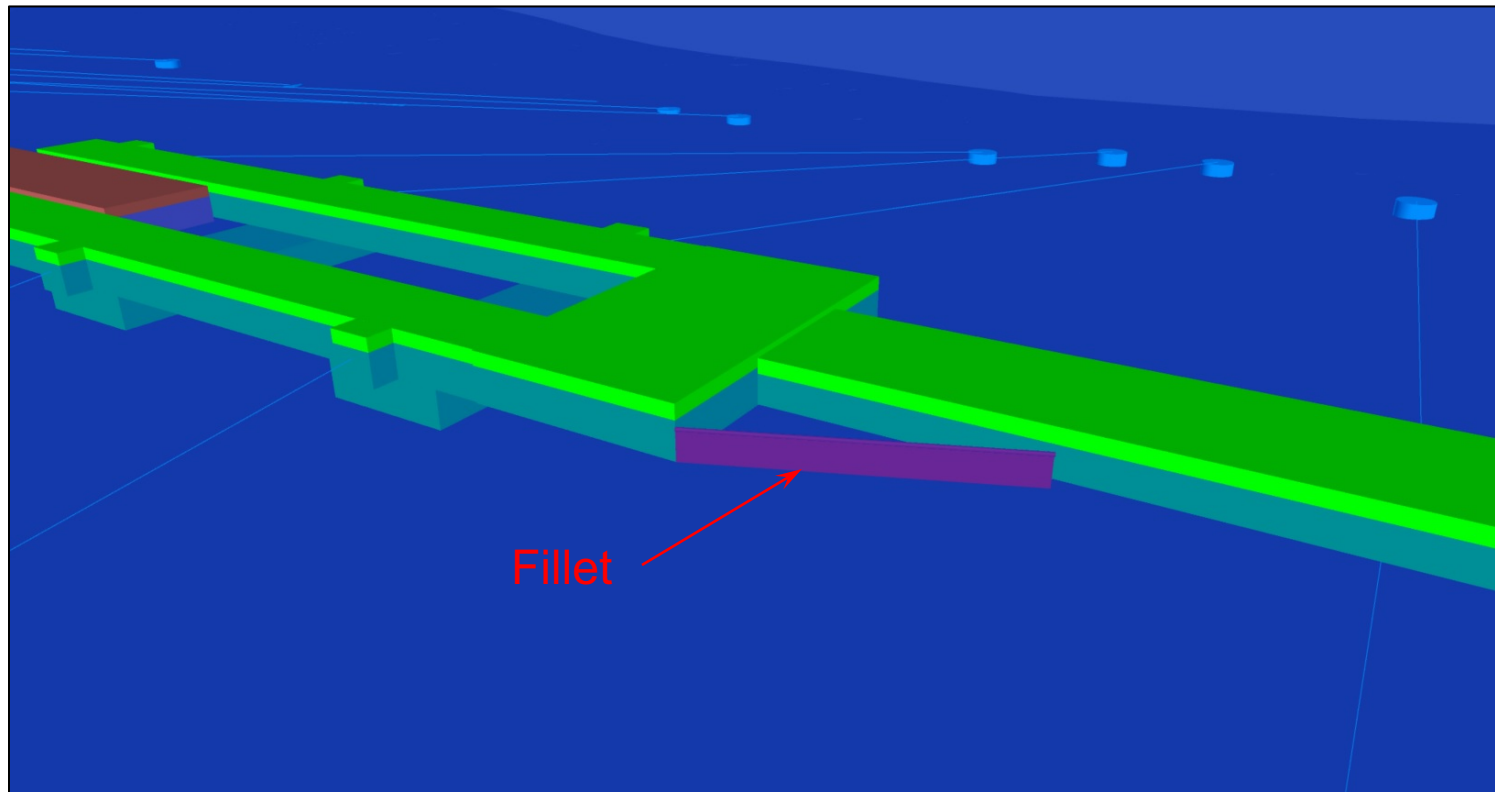
1 – Bridge Corner Fillet Structures

- Details shown of east end (1A -15' full bridge depth shown)
- West end mirror image



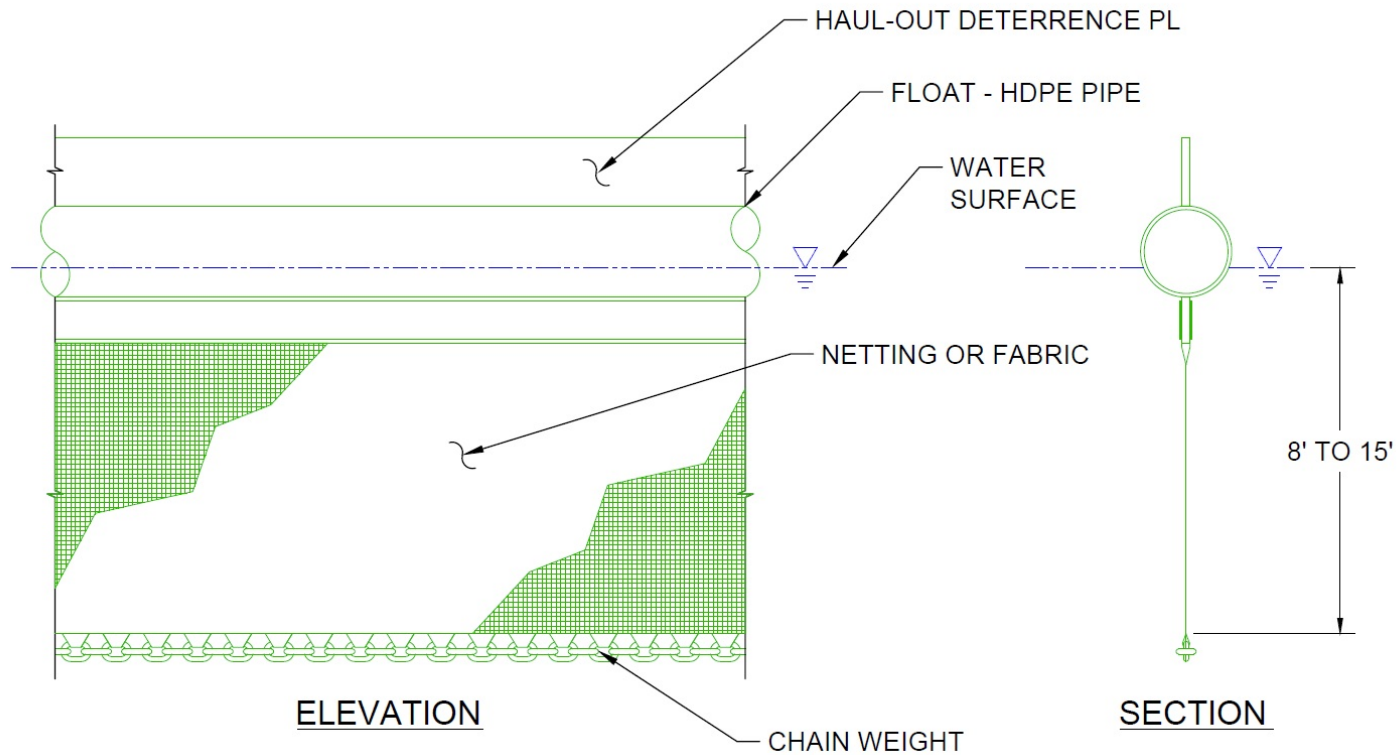
1 – Bridge Corner Fillet Structures

- 1C – Full bridge depth, 15' deep corner fillets at intermediate corners (shown)
- 1D – Half bridge depth, 8' deep corner fillets at intermediate corners



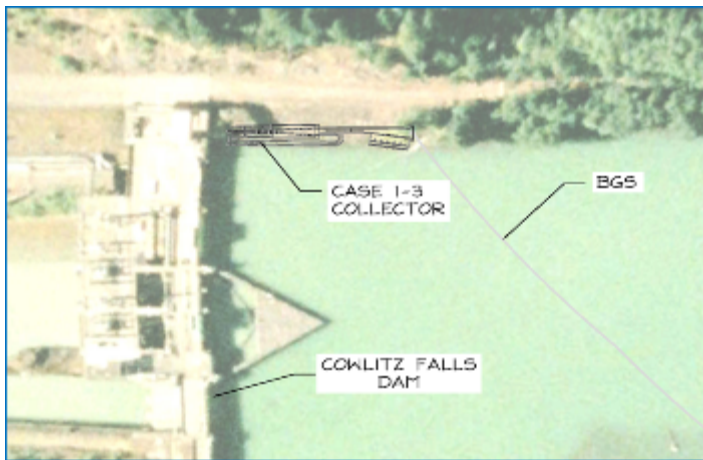
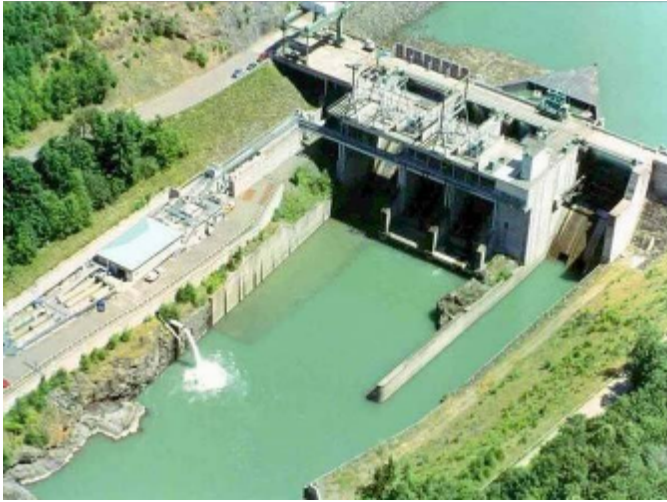
1 – Bridge Corner Fillet Structures

- Barrier structures (typical)
- Flexible energy absorbing bridge connections



1 – Bridge Corner Fillet Structures

- Cowlitz Falls Partial Depth BGS Research



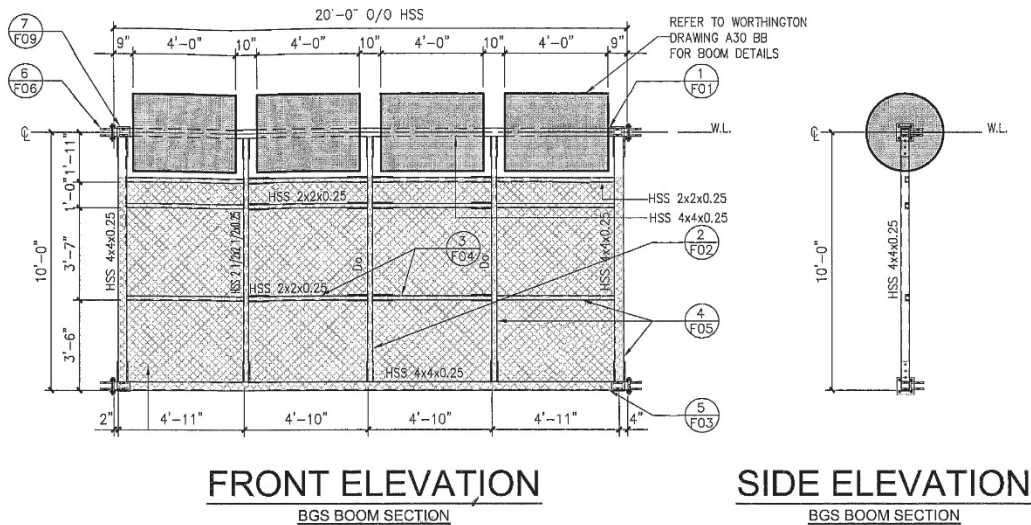
2 – Behavioral Guidance System (BGS)

- Examples
 - HDPE plastic pipe booms (Debris)
 - Supports netting, solid fabric, or panels
 - Boat gates included for access



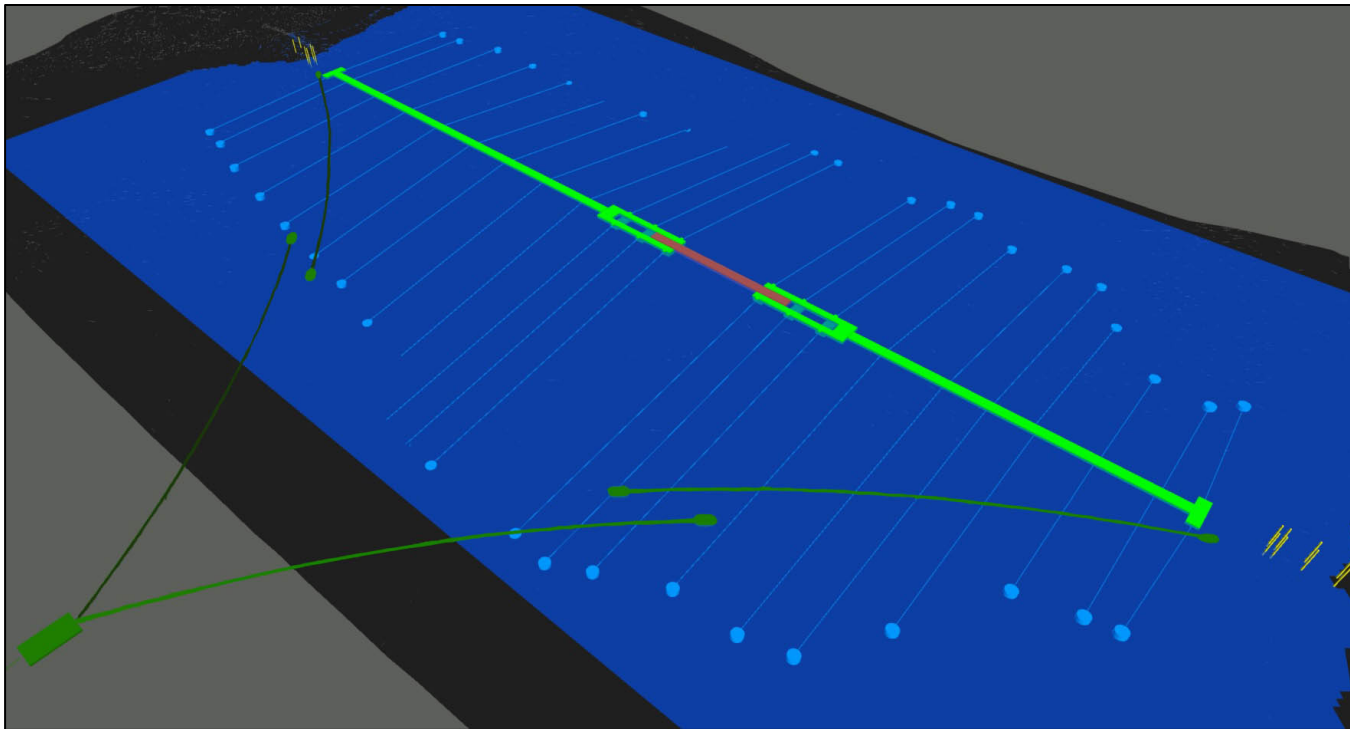
2 – Behavioral Guidance System (BGS)

- Examples
 - Originally used on the Columbia River
 - Currently located at the Cowlitz Falls Dam
 - “Tuff Boom” floats
 - Steel panels chained together



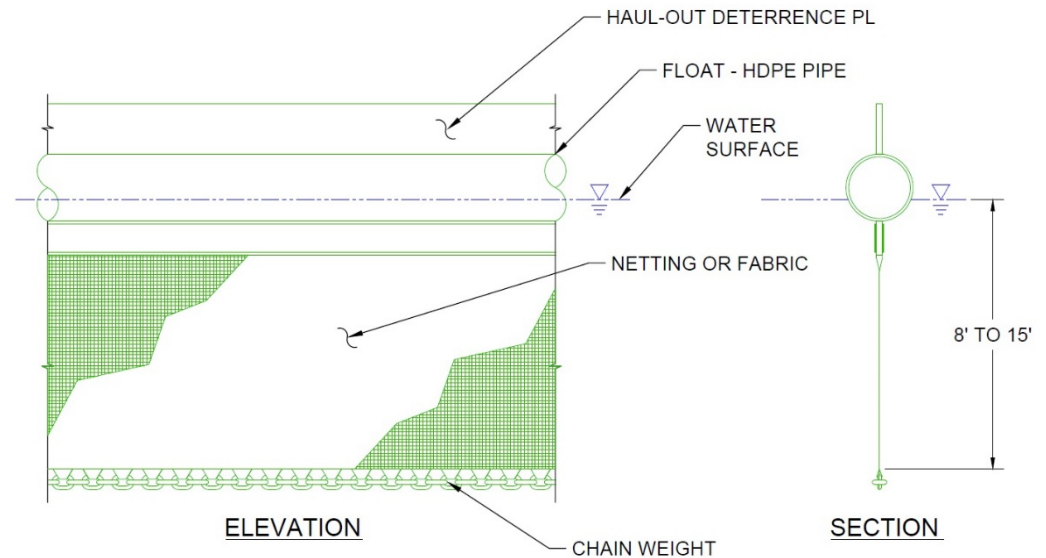
2 – Behavioral Guidance System (BGS)

- Intent to guide fish to the east and west shore openings
- 2A – 15' deep BGS across south side of bridge
- 2B – 8' deep BGS across south side of bridge



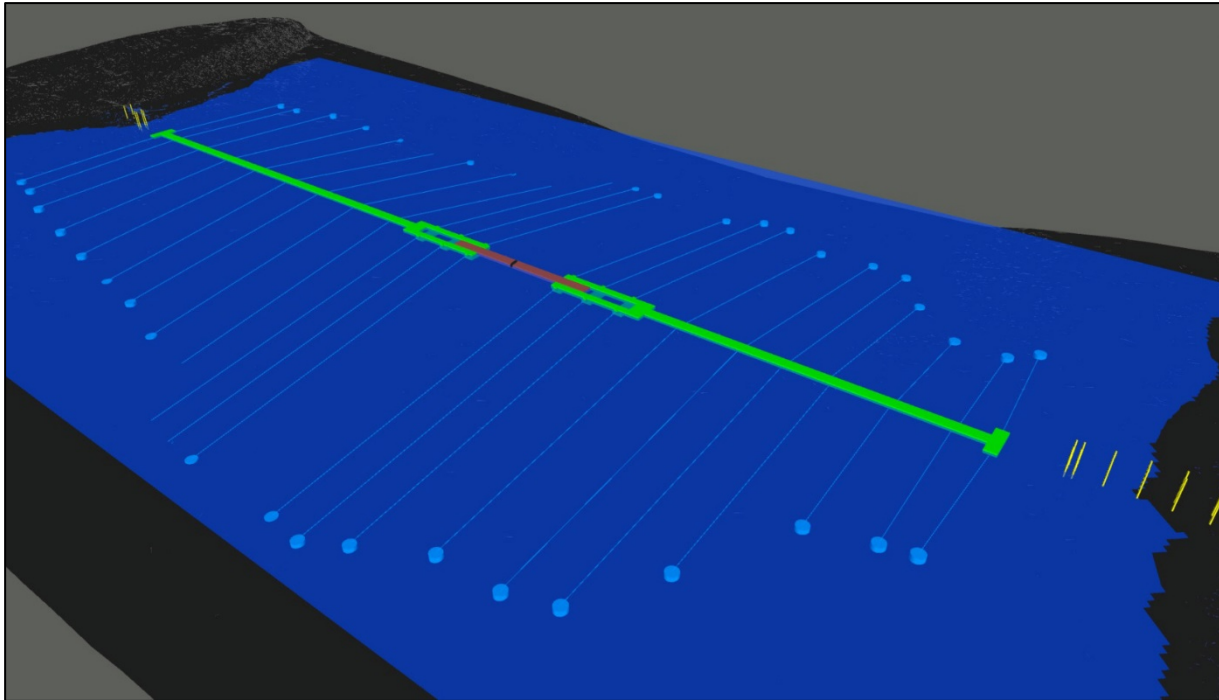
2 – Behavioral Guidance System (BGS)

- Similar barrier to bridge corner fillets
- Anchorage challenges
- Boater access: “shingled” gap, gates, submersible, other
- Maintenance and seasonal removal/storage
- US Navy and other stakeholder concerns



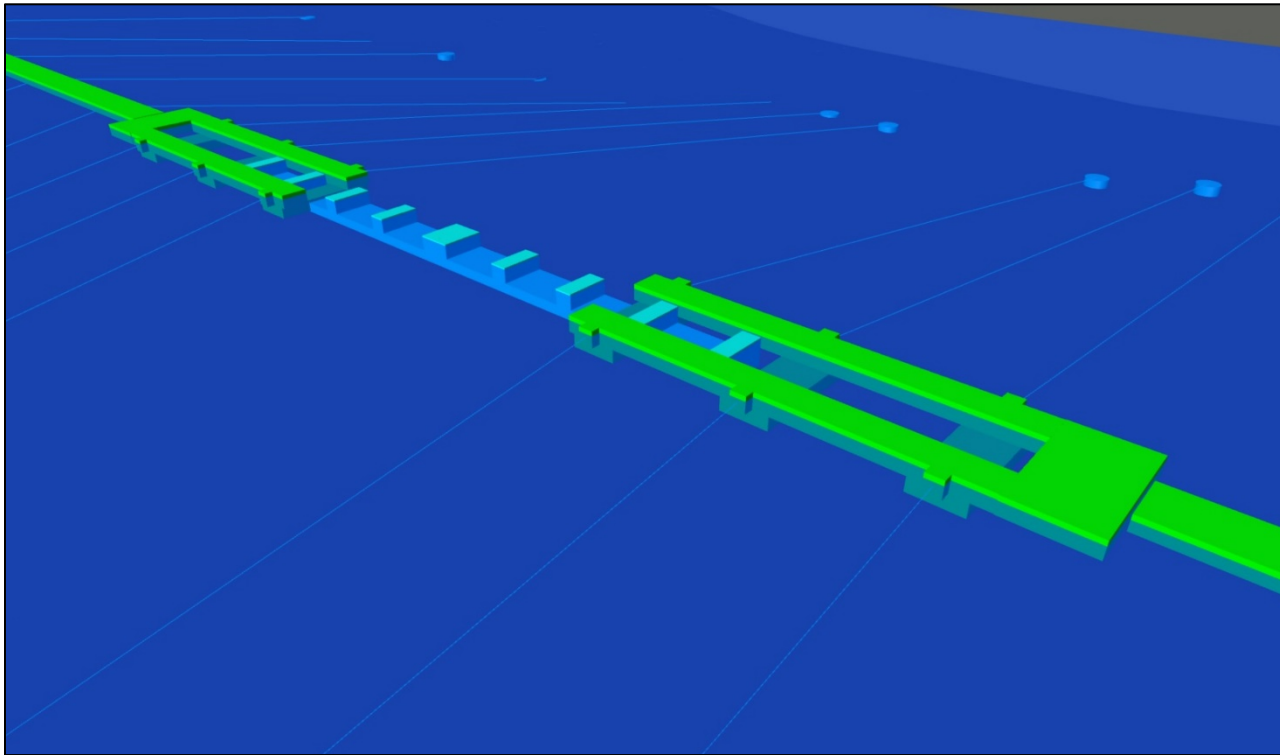
3 – Bridge Re-Design & Replacement / Modifications

- 3A – Complete Bridge Replacement
 - Long term solution with opening and rounded corners
 - High cost (SR 520 = \$4.65 billion in 2017), similar length – huge cost
 - Existing bridge shown without car deck for clarity



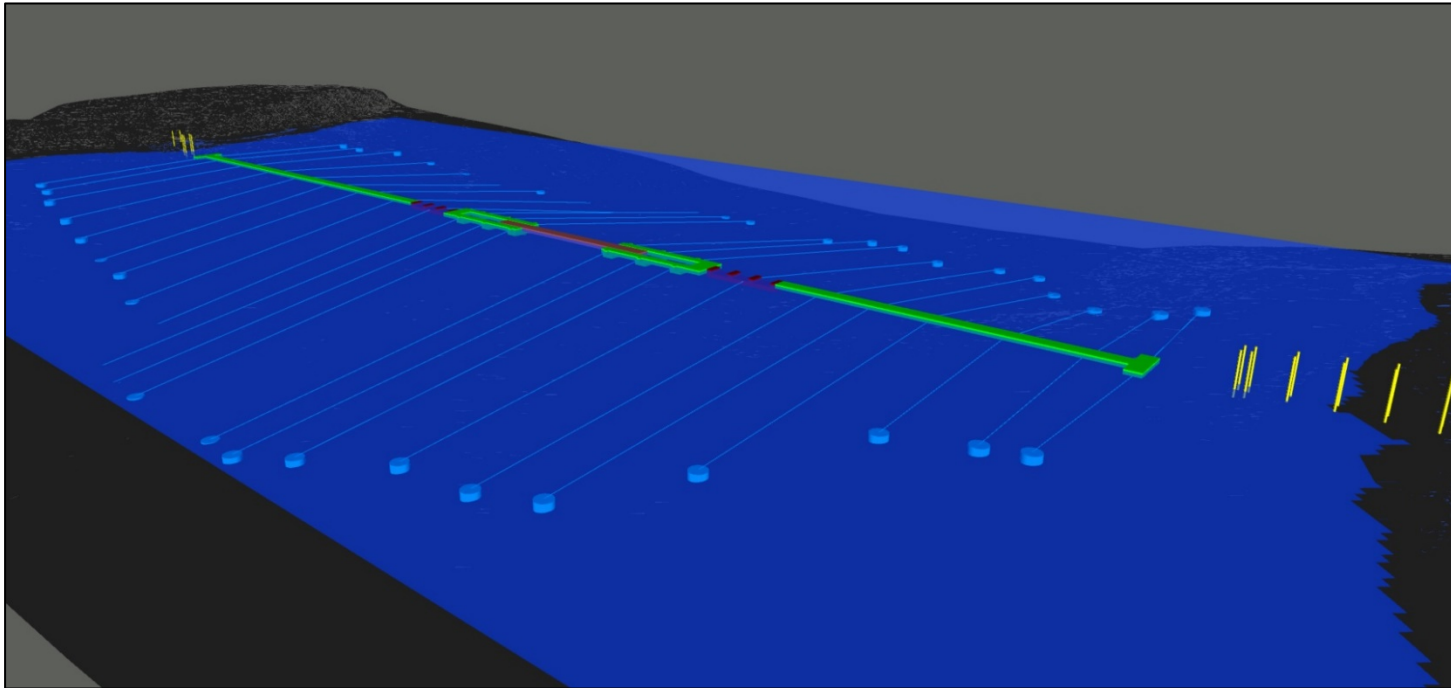
3 – Bridge Re-Design & Replacement / Modifications

- 3B – Replace bridge opening segments with “fish friendly” design
- Replacement pontoons shown: 92’ wide x 15’ water depth x 60’ across
- Significant WSDOT coordination needed
- Rounded submerged corners



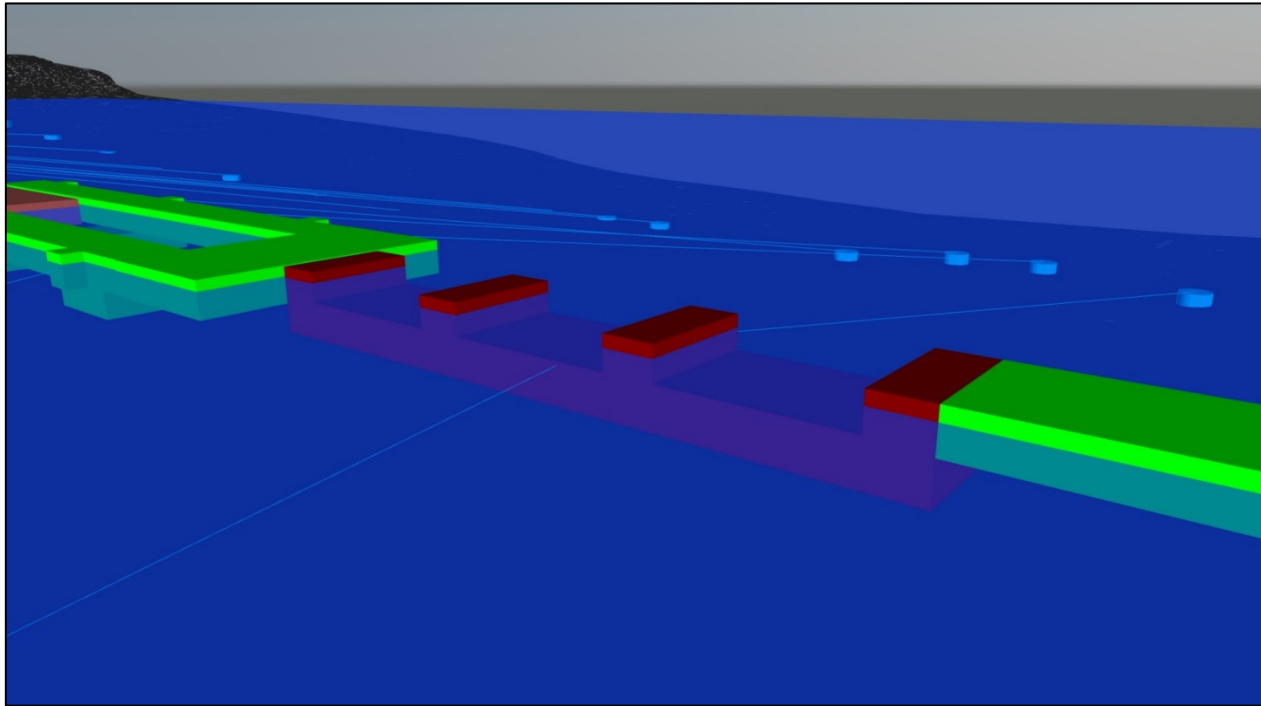
3 – Bridge Re-Design & Replacement / Modifications

- 3C – Replace fixed bridge segments with “fish friendly” design
- Length and location would need to be developed (third points shown)
- Significant WSDOT coordination needed



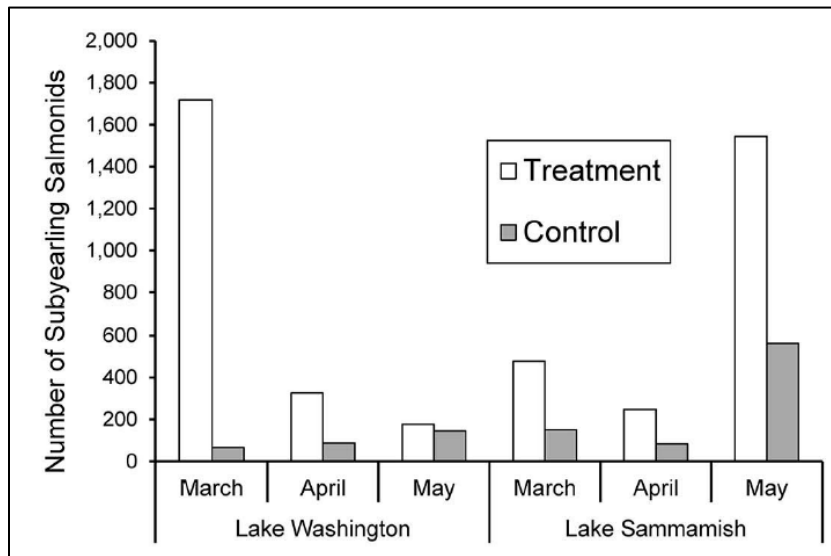
3 – Bridge Re-Design & Replacement / Modifications

- 3C – Replace fixed bridge segments with “fish friendly” design
- Replacement pontoons shown: 87’ wide x 10’ water depth x 60’ across
- Overall dimensions: 360’ long, 40’ deep, and 60’ wide
- Rounded submerged corners



4 – Lighting at Bridge

- Concern that lighting for vehicles attract juvenile salmon and increase predation at night
- Determine number of lights
- Replace lights or add barriers to reduce light in the water
- Consider adding lighting during the day to potentially promote passage under the bridge

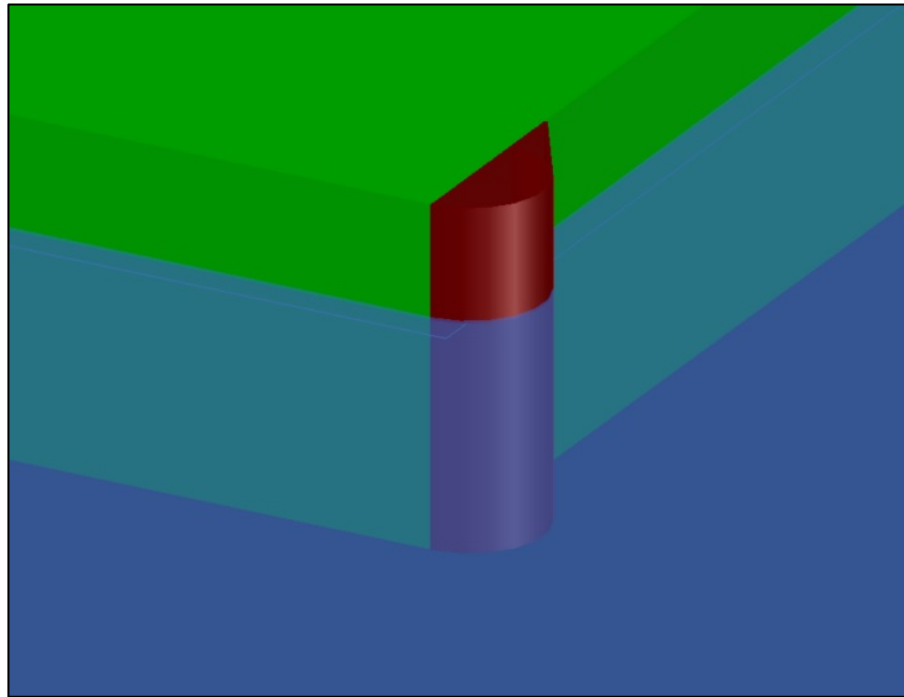


adapted from Tabor et al. (2017)



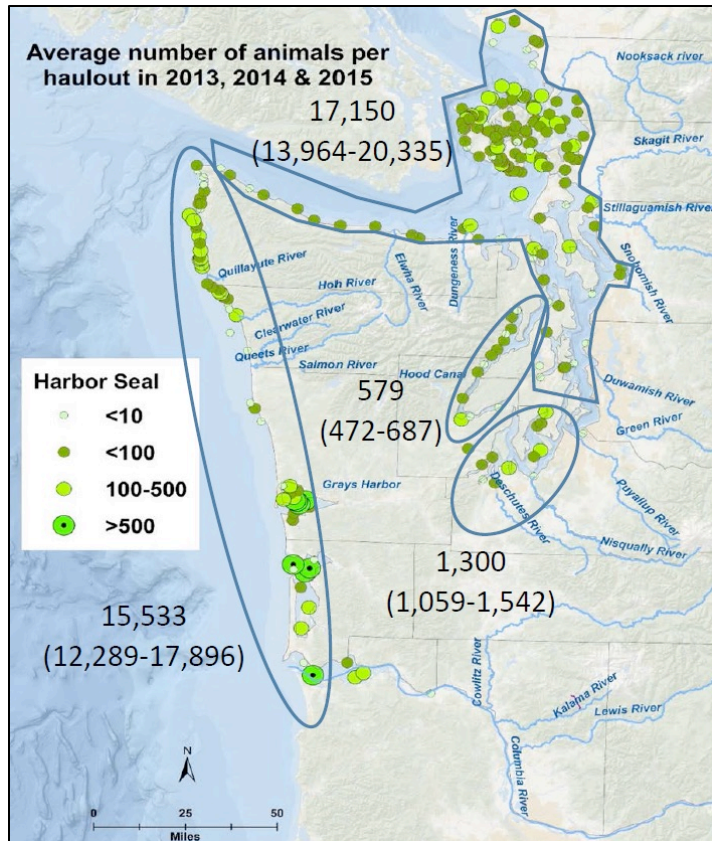
5 – Eddy Reduction Structures at Corners

- Add a half round at the outside corners to eliminate or reduce eddies
- Eddies likely inhibit fish passage and provide predation opportunity
- Design and construction would be straight forward



6 – Pinniped Deterrence

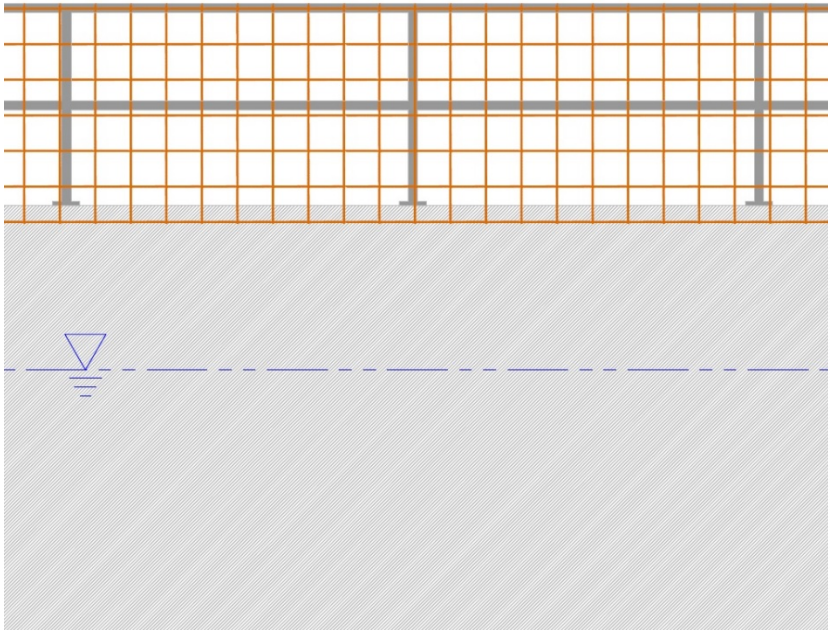
- 6A – Perform a pinniped study to identify specific behavior near the HCB that may prove deleterious to juvenile salmon and steelhead and better inform decisions



adapted from Pamplin et al. (2018)

6 – Pinniped Deterrence

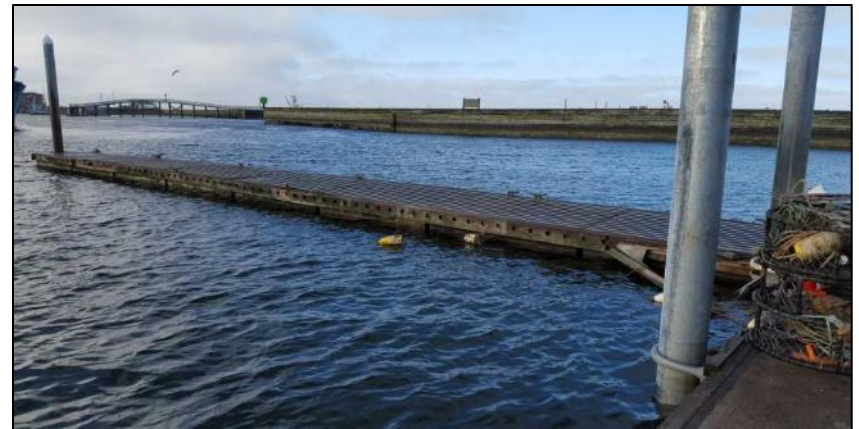
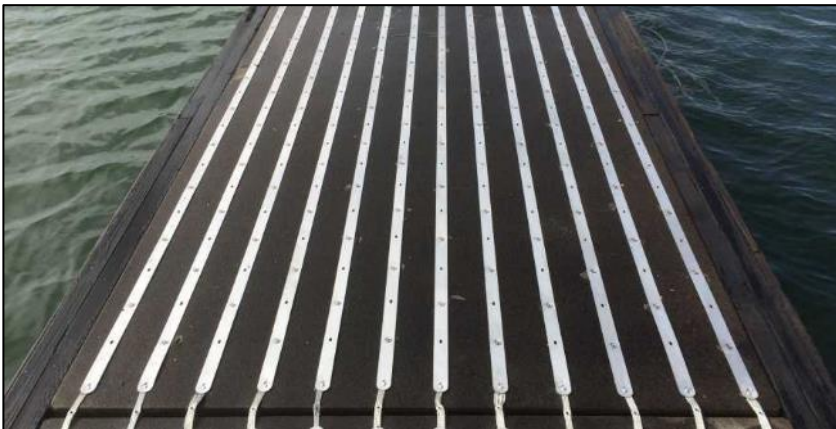
- 6B – Restricting access to haul-outs with handrail or netting
 - Use of handrail, fencing, and netting
 - Need to determine “freeboard” criteria for effective restriction
 - Identify areas that are currently being used (behavior study)
 - MMPA requirements may be cumbersome and long duration, but worth investigation



adapted from LLTK 2020

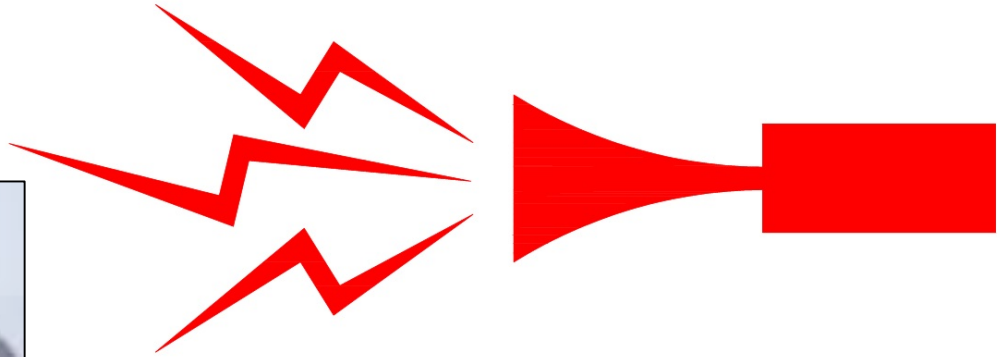
6 – Pinniped Deterrence

- 6C – Restrict use of haul-outs with electric mats
 - Smith Root pinniped dock deterrence
 - Smith Root 12VDC system with photovoltaic power
 - Approved MMPA deterrent mechanism (*pers. comm*; Smith Root; 2020)
 - Integrated system that showed promise on pilot projects
 - Control system operates four mats, \$6,500 per system (320 ft²)



6 – Pinniped Deterrence

- 6D – Acoustic Harassment/Deterrent Device (traditional loud noise)
 - Poor or in some cases uncertain performance
 - Pinniped behavioral adaptation
 - Approved MMPA deterrence mechanism



6 – Pinniped Deterrence

- 6E – Lethal Removal of Nuisance Predators
 - Undesirable option
 - Difficult (long-term) to permit
 - Uncertainty over population levels
 - CR identified individuals after years of behavioral observations

Most recent inland water seal population estimate = 19,000	Reduction in total juvenile Chinook consumption by seals		
	10%	25%	50%
Target seal abundance	17,130	14,300	9,500
Initial removal	1,870	4,700	9,500
Annual removals	255	530	710



adapted from Pamplin et al. (2018)

6 – Pinniped Deterrence

- 6F – Predator Exclusion Netting
 - Difficult to select a mesh size that would not harm certain animals
 - Subject to fouling with marine growth
 - Unintended mortality of other species?



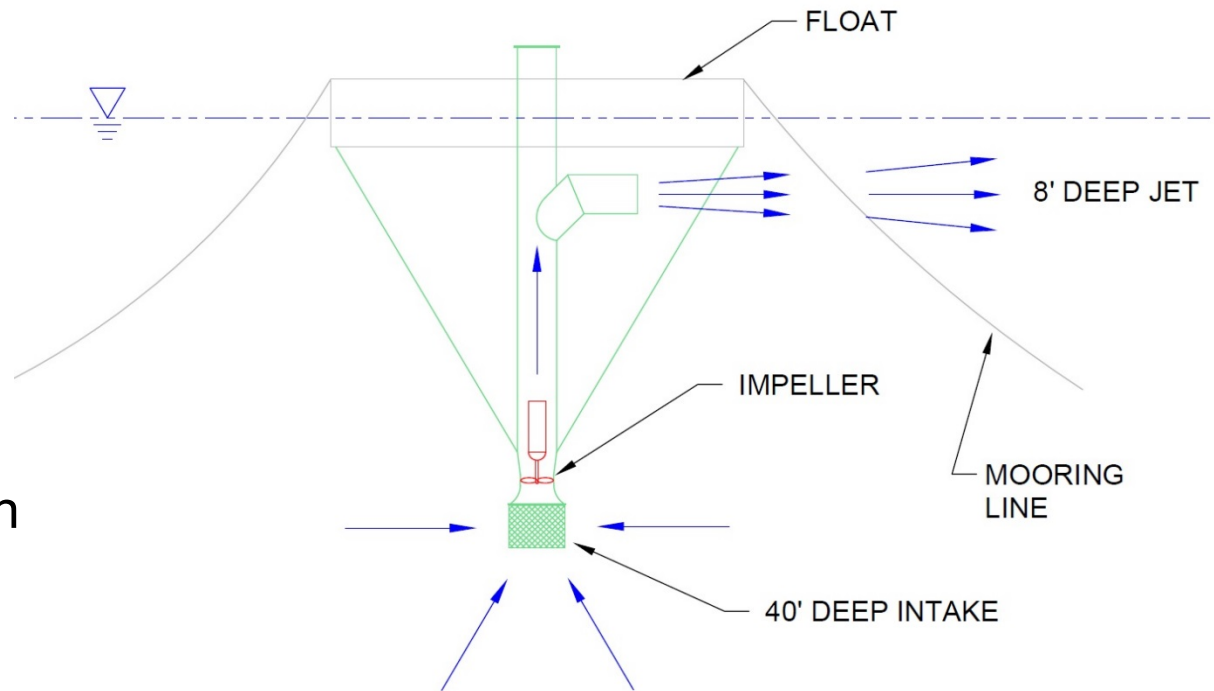
6 – Pinniped Deterrence

- 6G – Acoustic Startle Device
 - Genuswave: Targeted Acoustic Startle Device (ASD)
 - Uncertain effectiveness
 - Frequency may harm sensitive Hood Canal Herring populations
 - MMPA compliant



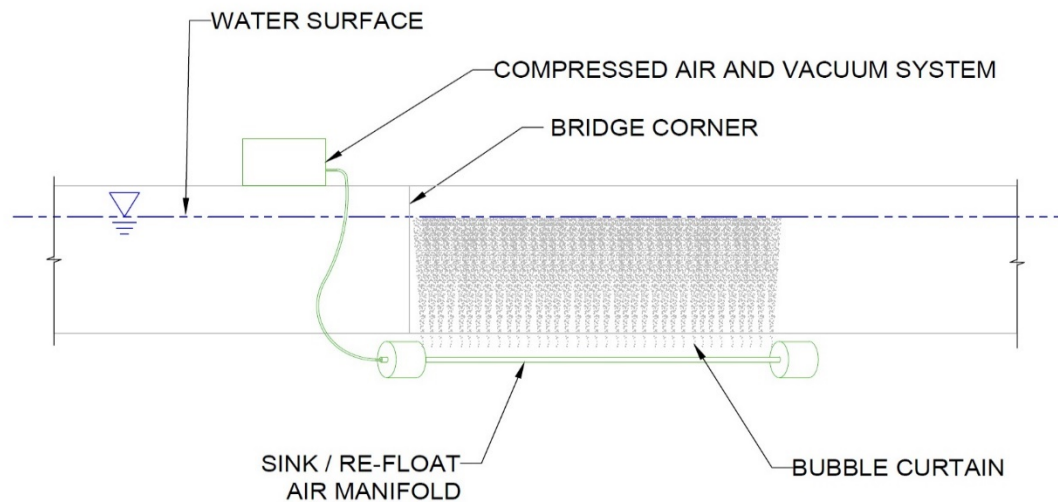
7 – Pumping Water to Signal Passage

- Idea is to induce water currents to signal passage and guide fish around structure
- Difficult to modify the magnitude of flow during ebb tide (flow past bridge end: ~40,000 cfs)
- Axial Flow Pump shown: 75 hp with 100 cfs flow jet
- Costs: \$500,000 capital cost and \$26,000 per season for power (very approximate)



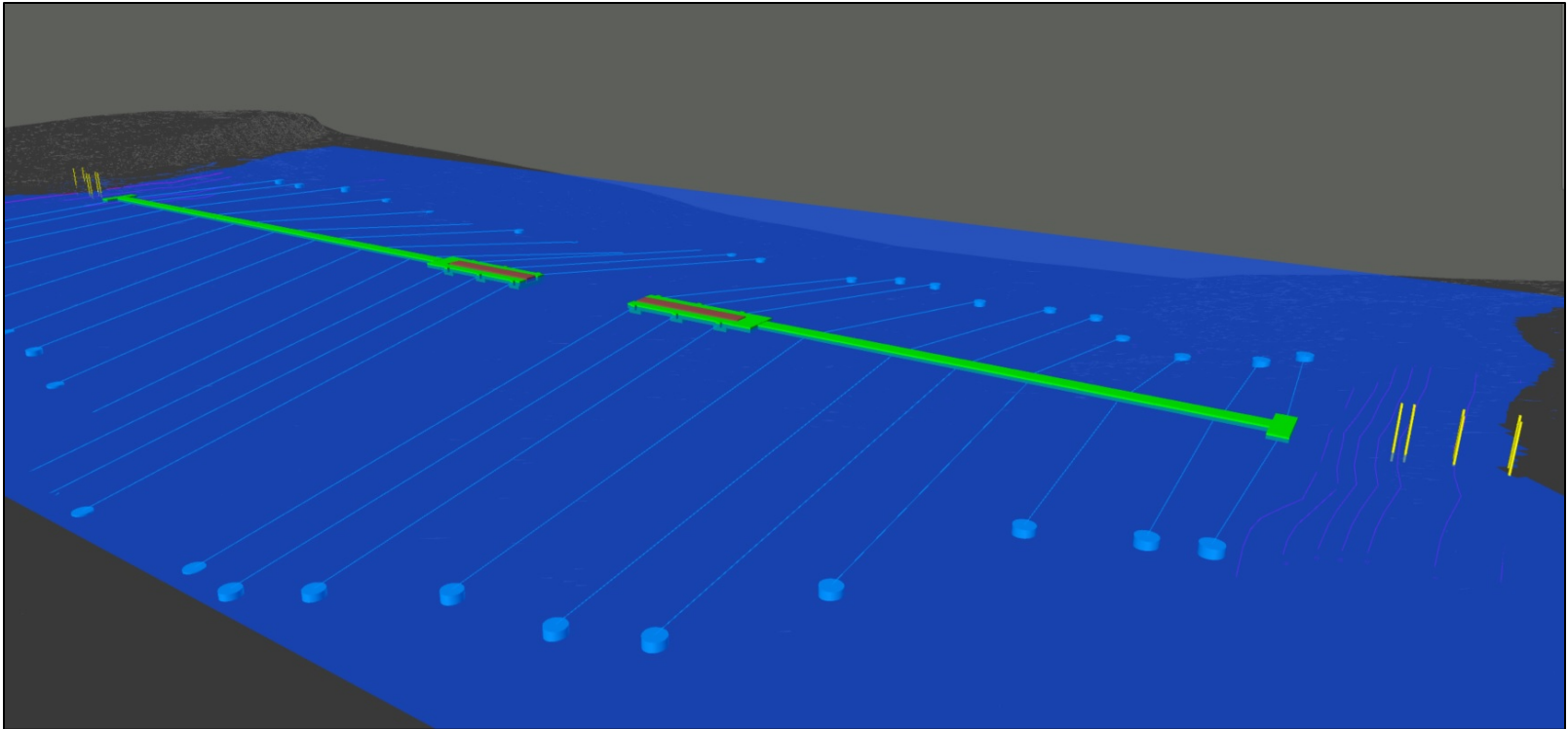
8 – Guide Fish Using Bubble Curtains

- Guide steelhead to promote passage
- Might be an option at the corners formed by the retractable pontoons
 - A 100' long barrier requires about 130 scfm of air flow at a 15' depth
 - 25 hp compressor operating continuously over a 4-month period
 - Costs: \$400,000 capital cost and \$10,000 per season for power (initial estimate)



9 – Open Bridge Span for Fish Passage

- Idea is to open the middle 600 feet of the 6,500 feet long bridge
- Considered infeasible as a result of the inconvenience to motorists



10 – Noise Reduction

- Traffic noise may inhibit fish passage at the bridge
- Hydrophone monitoring indicates that noise levels approach and possibly exceed levels that may inhibit steelhead
- The uncertainty of the effectiveness of noise reduction and the feasibility solutions result in dropping this alternative from further consideration



11 – Marine Growth Control

- Marine growth on the bridge structure may attract chinook and chum to an area of high predation
- The reef-like environment may be beneficial to juvenile salmonids
- Control measures such as mechanical removal (11A) require seasonal duration and anti-fouling coatings (11B) are likely harmful to the environment
- Alternative has been dropped from further consideration



12 – Induced Turbidity

- Inducing turbidity in the water adjacent to the bridge may help hide fish from predators
- Conditions may also deter passage by fish
- Impacting conditions with material such as dye (Rhodamine B) are challenging given the magnitude of flow that occurs
- Cost: \$80,000 / day at 5,000 cfs
- Flow past bridge end: ~40,000 cfs





GROUP DISCUSSION



April 6 , 2020

APPENDIX D

HCB WSDOT Information Presentation

Hood Canal Assessment Team

Current Bridge Design

Nicholas T. Rodda, PE, SE

Floating Bridge & Special Structures Design Manager

May 1, 2020

Overview

- Bridge Design
- Coast Guard Requirements
- Bridge Lighting
- Pontoon Connections
- Knuckle Joints
- Guide Roller Boxes
- Haul Out Locations

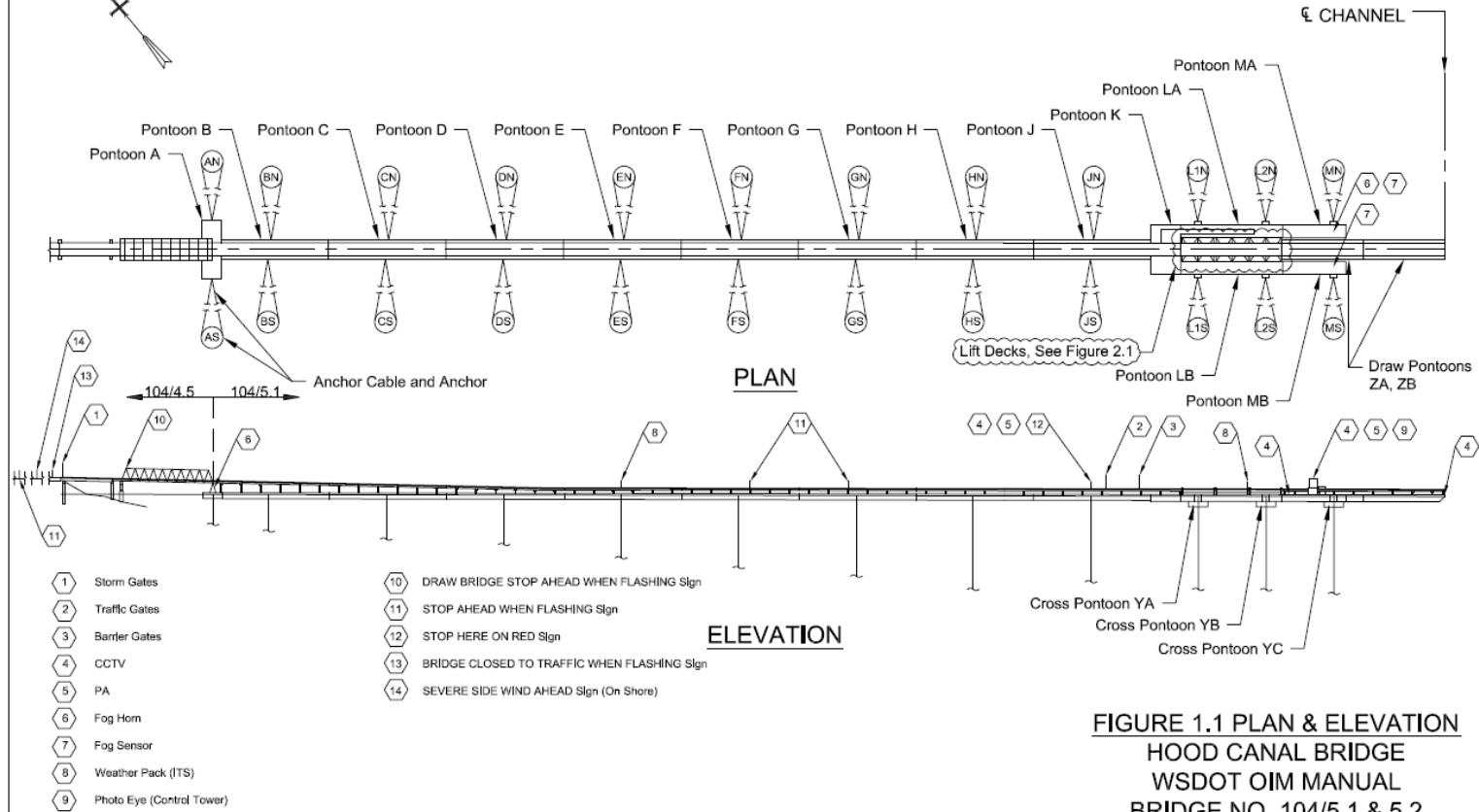


Bridge Design

- Floating Length = 6,420 feet
- Number of Pontoons = 36
- Draw Opening = 600 feet
- Navigation Channel Width = 230 feet
- Average Freeboard = 5 feet
- Average Draft = 13 feet
- Standard Pontoon
 - Length = 360 feet
 - Width = 60 feet
 - Depth = 18 feet
- Draw Pontoons
 - Depth = 21 feet
 - Freeboard = 6 feet
 - Draft = 15 feet



WEST HALF OF HOOD CANAL BRIDGE (104/5.1)



WEST HALF OF HOOD CANAL BRIDGE (104/5.1)

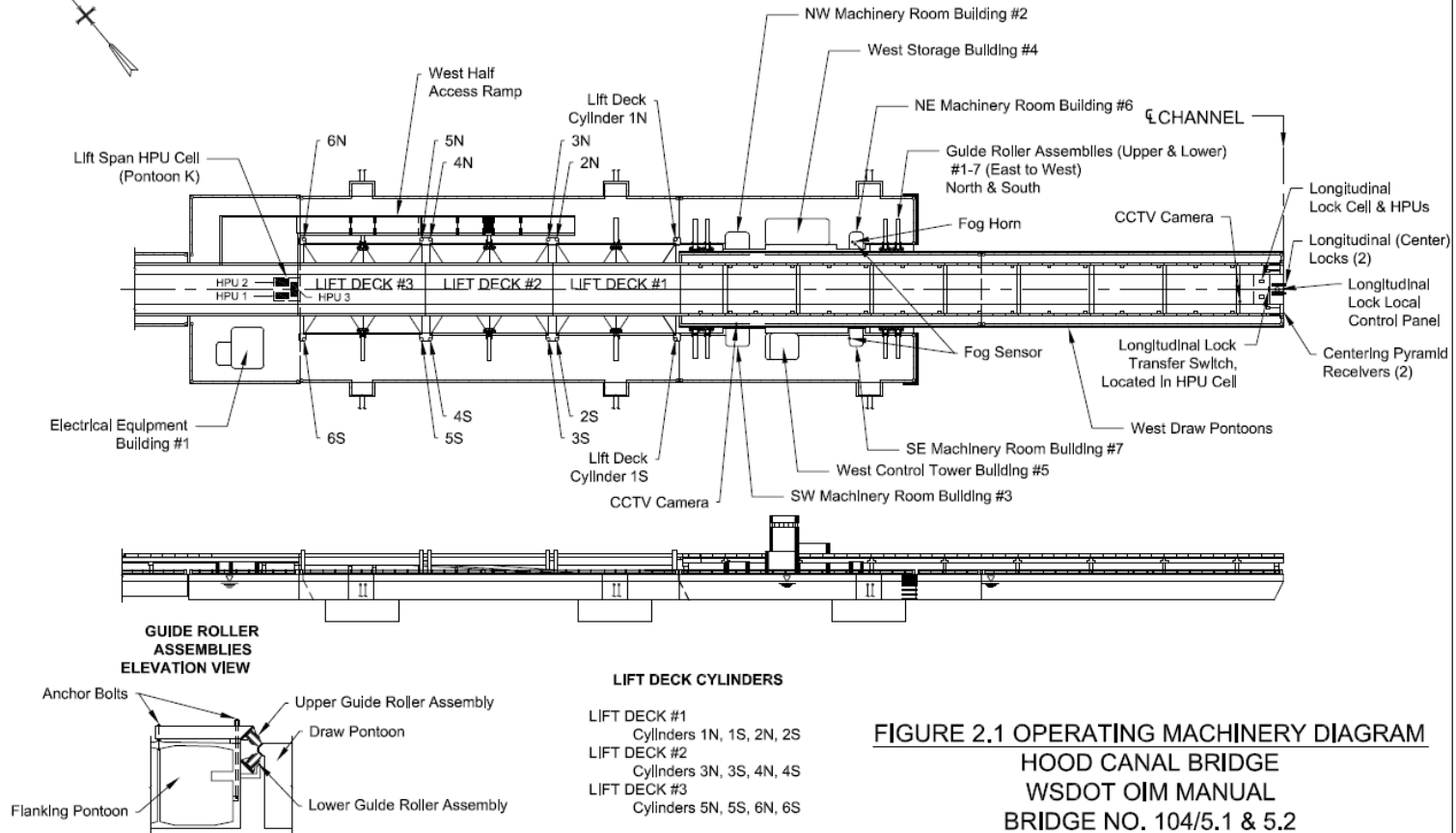
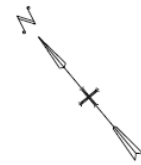


FIGURE 2.1 OPERATING MACHINERY DIAGRAM
HOOD CANAL BRIDGE
WSDOT OIM MANUAL
BRIDGE NO. 104/5.1 & 5.2

EAST HALF OF HOOD CANAL BRIDGE (104/5.2)

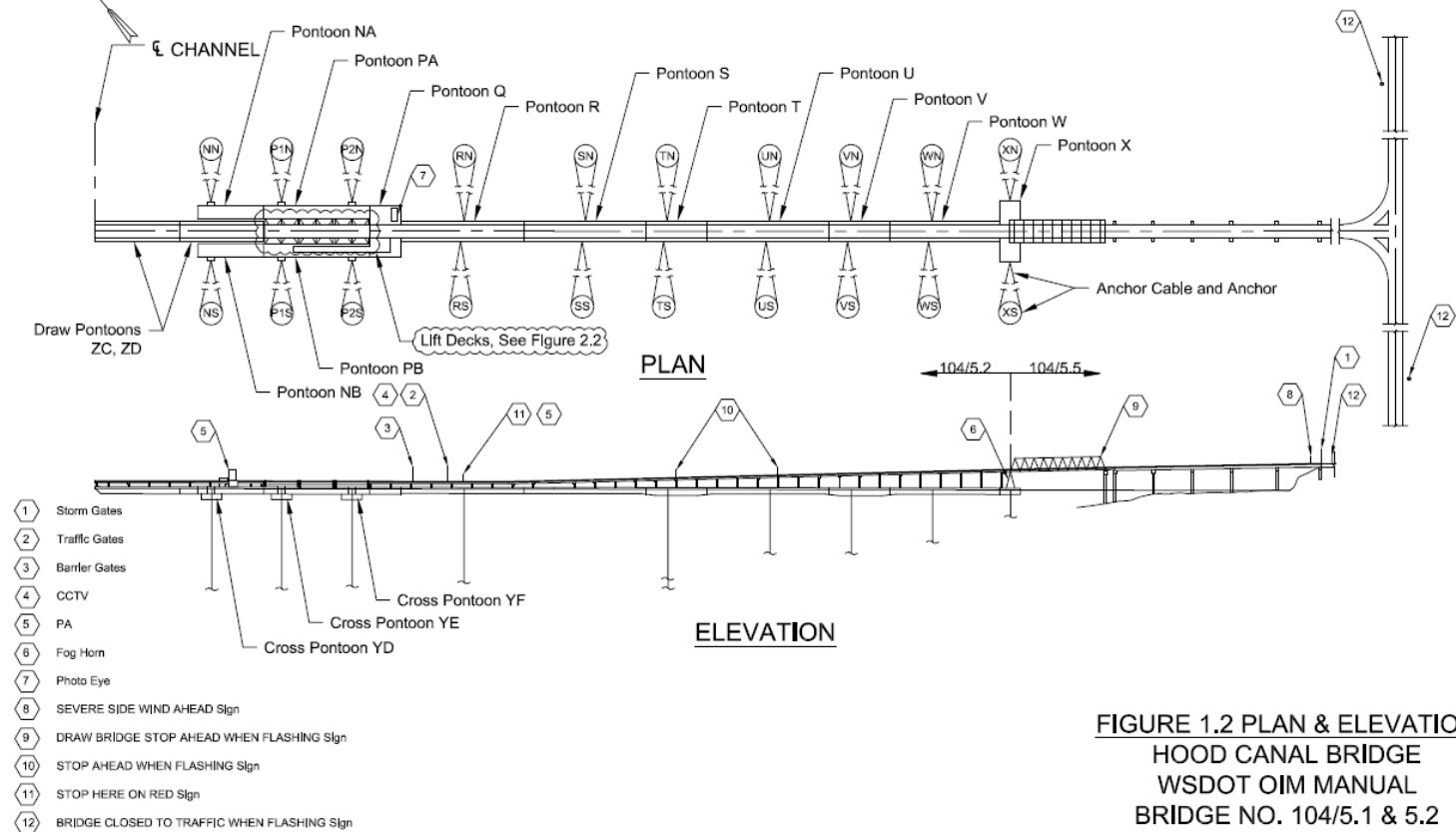


FIGURE 1.2 PLAN & ELEVATION
HOOD CANAL BRIDGE
WSDOT OIM MANUAL
BRIDGE NO. 104/5.1 & 5.2

EAST HALF OF HOOD CANAL BRIDGE (104/5.2)

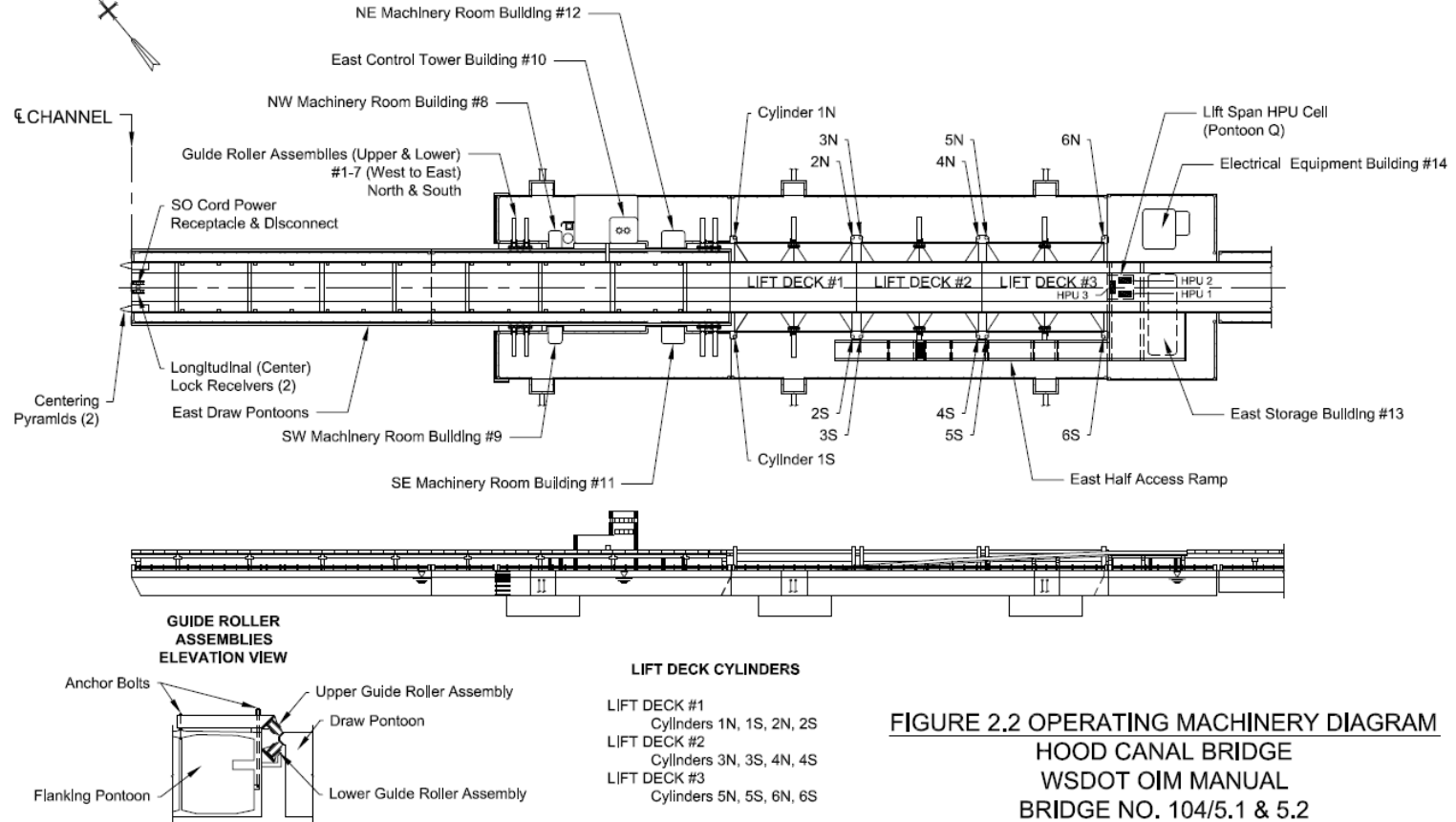


FIGURE 2.2 OPERATING MACHINERY DIAGRAM
HOOD CANAL BRIDGE
WSDOT OIM MANUAL
BRIDGE NO. 104/5.1 & 5.2



Coast Guard Requirements

- Permit for bridge subject to conditions set out by the U.S. Coast Guard
- U.S. Navy is a customer of the bridge – not the permitting body
- Draw span must open for all marine vessels with one hour's notice
 - May 22 to September 30 – private pleasure craft prohibited between 3 and 6:15pm
 - 600 feet full opening; 300 feet openings used for private pleasure craft
- Any modifications to the bridge must be reviewed by the U.S. Coast Guard
- Any modifications to navigable waters is U.S. Coast Guard jurisdiction



East Half

Bridge Lighting

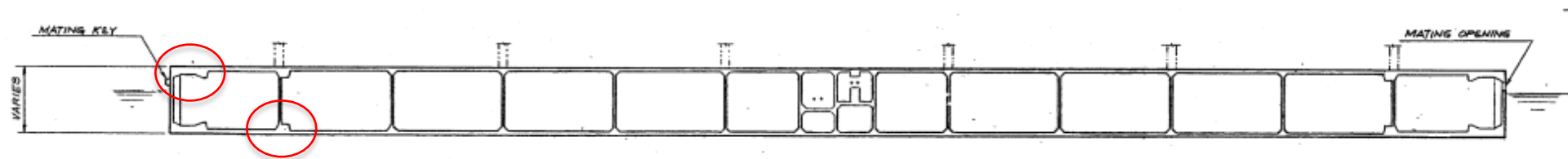
- Luminaires spaced at 120 feet; 100 feet on the lift decks
- Not provided on approach spans, transition spans or the draw span itself
- Double mast arm luminaires provided at lift spans – these light the pontoon deck and roadway
- Some luminaires not installed – designated for future installation
- High Pressure Sodium Bulbs – 150 Watts (13,000 to 16,000 lumens)

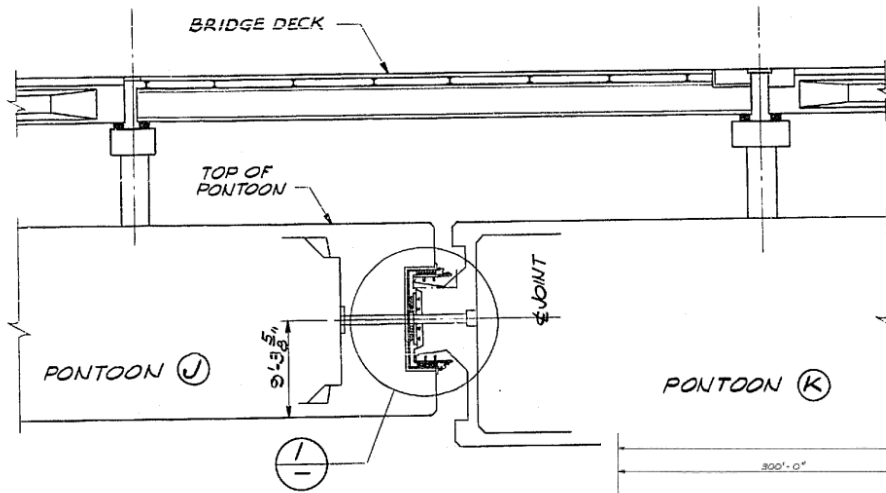
West Half



Pontoon Connections

- Nearly all pontoon connections are made by post-tensioning tendons across pontoon-to-pontoon joints
- Tendons are anchored to “blisters” located at the exterior and first interior bulkheads at each end in a staggered pattern
- Once installed, the tendons are grouted for corrosion protection
 - Pros: Forms a very rugged, strong connection between pontoons – well suited to the Canal
 - Cons: Difficult to separate pontoons if one were to be damaged by a collision
- Only other bridge to use this type of connection is Homer M. Hadley Phase II pontoons

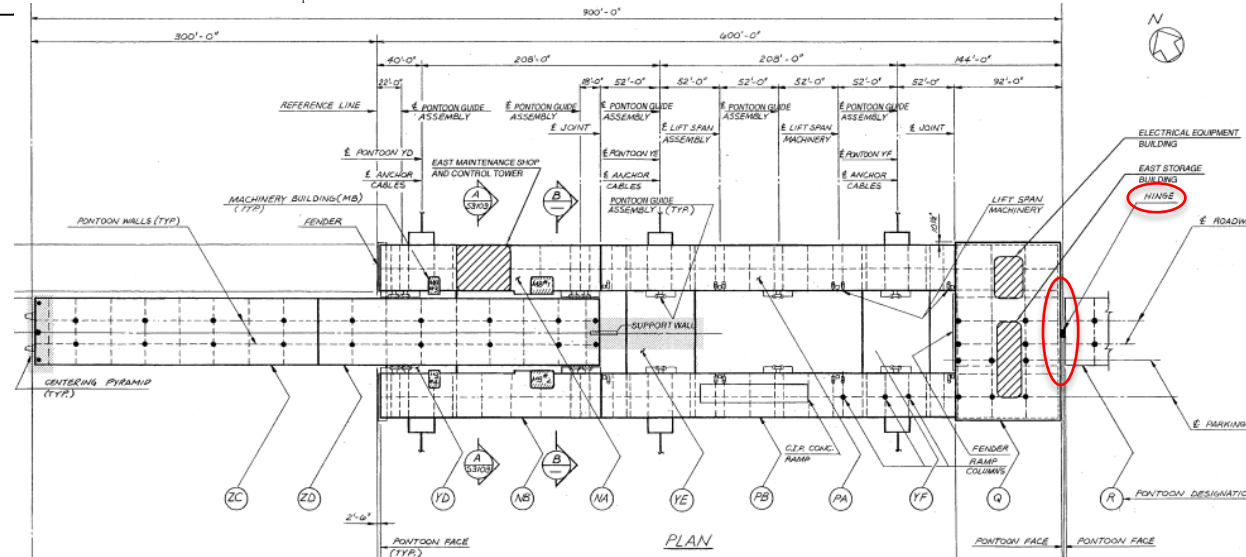




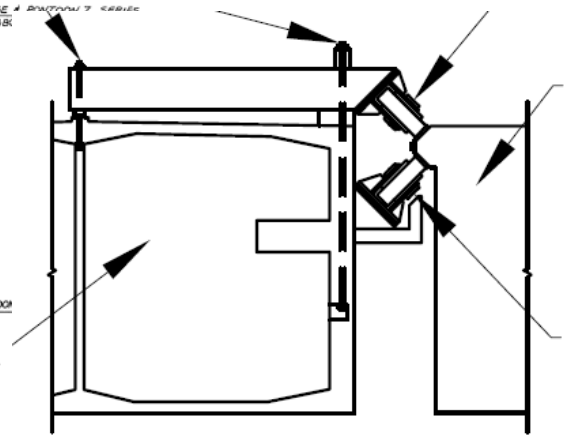
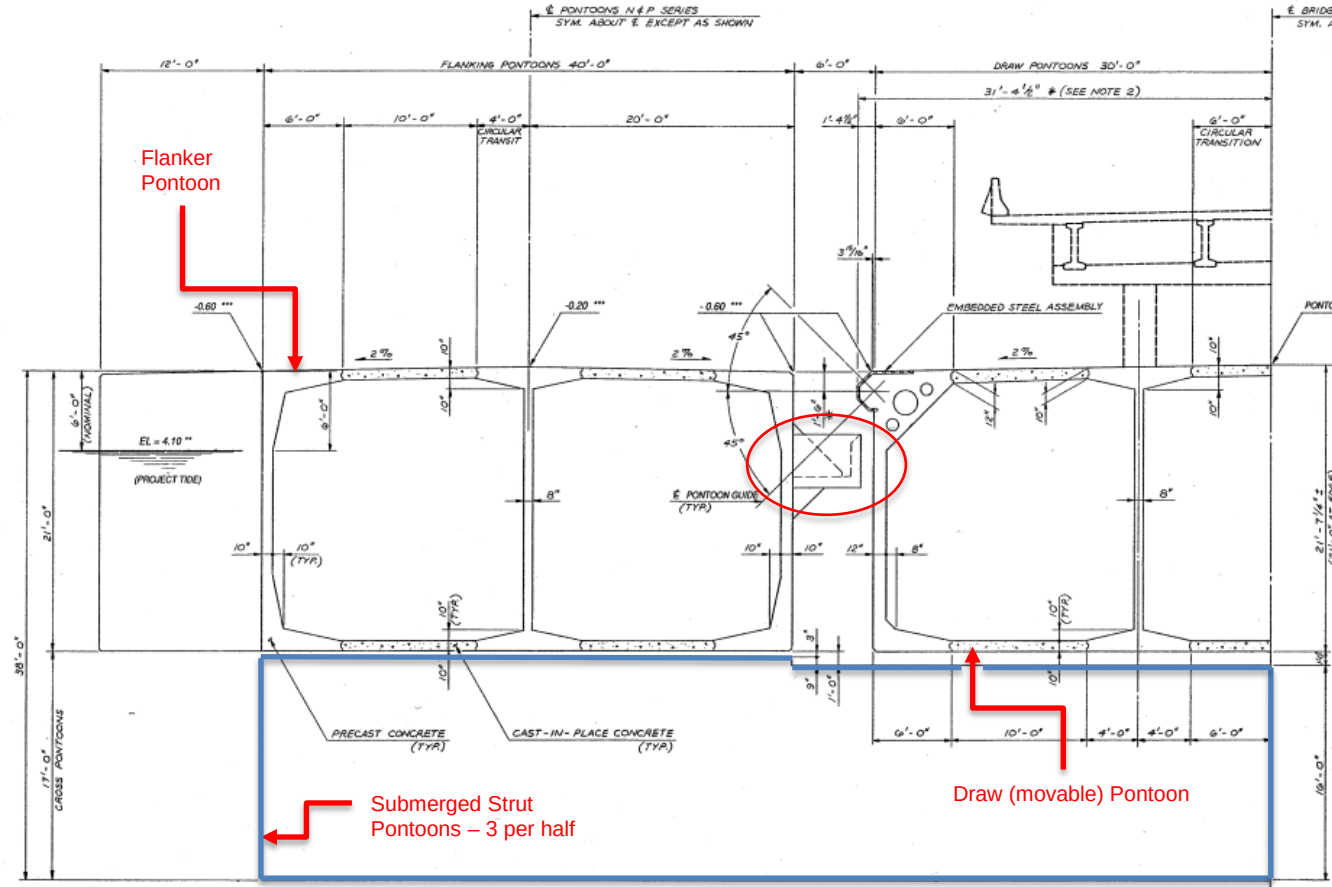
Knuckle Joints

- Pontoons J and R connect to the draw assembly by a “hinge” or “knuckle”
- “Ball-and-Socket” allows 360 degrees of articulation

- Trash gates provided to keep flotsam out of the gap
- Post-tensioning tendons hold pontoons together and prevent translation while bearings allow for rotation



Guide Roller Boxes

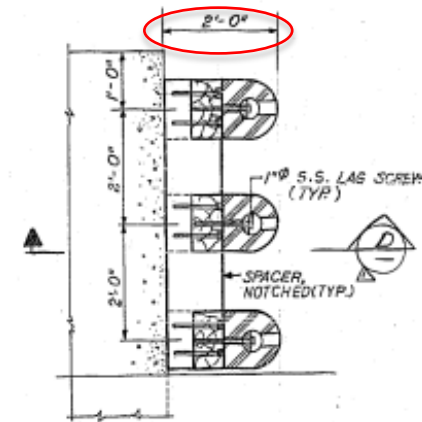
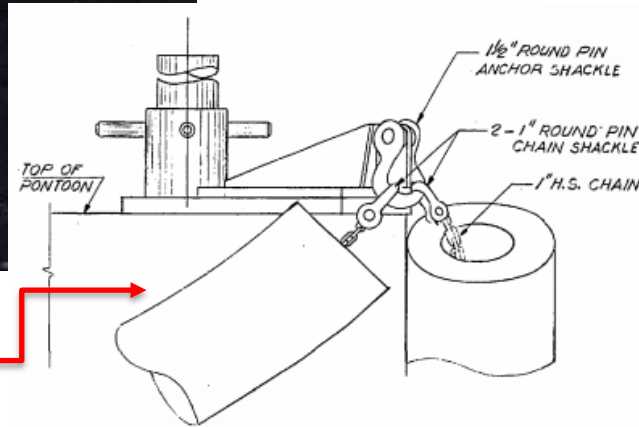




Haul Out Locations

- Seals like to sit on the fenders
 - Pontoons A and X at Nav Channels
 - Flankers near draw span
- Seals like the guide roller boxes – have been observed giving birth there
- Otters are a nuisance – they come up on the pontoons
- Birds like to nest on the superstructure crossbeams

15" diameter



Questions?

- Future or Upcoming Work
 - **Centerlock Upgrades 2021**
 - West Half Hatch Replacement 2021
 - West Half Superstructure Replacement
 - **Lift Deck Repairs**
 - Paint the West Half
 - J-K Tendon Replacement
 - Pontoon Deck Overlay
 - Flanker Fender Repairs



APPENDIX E

HCB Final Solutions Matrix

Potential Solutions to Address Steelhead Mortality at the Hood Canal

Options to decrease potential Chinook smolt, chum smolt, or adult salmonid mortality will be considered separately

R2 Team Update 3/31/2020

This version maintains the Assessment Team's original ideas, and expands on the commentary, and suggested alternatives to carry forward with the R2 Team's input. Recommended concepts are further expanded and clarified with light green shading.

				1 = no; 2 = low potential; 3 = medium potential; 4 = high potential							Assessment Team Comments		R2 Team Comments				
Number	Type	Level	Potential Solution to Test	Field observations at high ebb tide condition possibly with dye	Will it reduce efficacy of harbor seals foraging near the bridge?	Feasibility - Is it likely to be implemented in the next 3 years?	Is likely to avoid unintended negative consequences?	Aggregate score	Does the Assessment Team Believe this solution is worth further investigation	Additional questions	Additional Comments	R2 Comments	R2 Noted Data Needs or Approach	Megan Comments (NMFS)	Emily & Hans Comments (if any comments are unclear, please feel free to contact us directly) (Port Gamble S'Klallum Tribe)	Nick Rodda Comments (WSDOT)	
1	Guidance	Primary	Restricting juvenile salmonids access to cross-pontoon corners	3	3	4	4	14	yes		The assessment team generally regarded this potential solution to be the highest priority to test in the short-term.	Agree with highest priority. This category was expanded into several variations and further developed. See options 1A - 1D below.			This solution has a high potential for success, when implemented in tandem with solution #5. Restricting access to the cross-pontoon corners will likely decrease the time it takes for surface-oriented juvenile salmon to find their way to either of the two open ends of the structure. Once there, additional structure modification to decrease surface water acceleration around the pontoons may mitigate potential avoidance behavior typically associated with changes in velocity.	This may be workable from a structural standpoint. At Pontoons A/B and W/X (adjacent to the navigation channels at the west and east ends of the bridge, respectively) a rigid structure would be fine. At J/K and Q/R at the draw span, there is an articulating knuckle joint which must be free to move.	
1A	Guidance	Primary	15-Foot Depth (Bridge depth) Barrier at inside Corner of East and West Abutments							Would fish be able to get behind this curtain?		110' long 15' deep net barrier with HDPE boom at the top to fillet the corners at the end of the bridge. Design condition will need to address complex wave action at the bridge. DOT may have modeling for this wave action. R2 Team has some ideas about rubber/synthetic energy absorbing connectors. Will consult with AJD Engineering for Phase 2. For barrier material, fine mesh net is one idea. It would likely occlude with marine growth. Could also consider impermeable material (fabric or solid). Material selection will be addressed further in Phase 2. Hydro plant fish passage have demonstrated success with BGS systems, so we are optimistic about these alternatives.	All number 1 series options require design criteria with regard to the loading cases for the barrier. Conditions close to the bridge will result in a very hydro-dynamic condition (rather than just calculating open water conditions with wind speed, fetch, etc.). i.e., waves, reflective waves, bridge reactions, etc. These design conditions were likely modeled and on record with WSDOT, and WSDOT may be able to assist with the loading cases and evaluation.	I would think it would need to be solid so as not to trap anything behind it, and it would need to also be made of solid material (not net) so that it would also help guide the flow.	We agree with Megan's comment. During the outmigration period, there are a significant number of larval fish that may be affected by even a very fine mesh net. Consider a solid polyurethane float.	Pontoons A/B and W/X	
1B	Guidance	Primary	8-Foot Depth (Half Bridge Depth) Barrier at inside Corner of East and West Abutments									Same as 1A but 8' deep. Goal is a reduced depth barrier to help reduce loading and cost.	Actual reduced depth of guidance barrier is uncertain. There is data on BGS systems ranging from 4' to >15' on hydro projects. Could do an evaluation or base on logistics. See above for additional comments.	This would probably work for most salmon	This depth or shallower should be sufficient, based on the tag data. Any fillet used should avoid hard angles, including on the bottom where it meets the pontoon.	Pontoons A/B and W/X	
1C	Guidance	Primary	15-Foot Depth (Bridge Depth) Barrier at Intermediate Corners									110' long 15' deep net barrier with HDPE boom at the top to fillet the corners at the end of the bridge.	The section of the bridge that opens results in corners that are not as readily "filleted" than the fixed sections described in alternatives 1A - 1B. Look into how this works for boat traffic and if guidance features (such as a bubble curtain could be deployed as a secondary barrier and what the constraints are at this location). We do have concerns for bubble curtain effectiveness at ebb and flood tides due to the 2 to 3 fps velocity due to tidal flow and wind.	Yes, these would be worthwhile for all corners	Fillets would be useful at all corners. If it is not possible to add them in the inner center section, then we may consider not adding them to the outside ends of the center section unless in combination with regularly scheduled openings.	At Pontoon J/K and Q/R.	
1D	Guidance	Primary	8-Foot Depth (Half Bridge Depth) Barrier at									Same as 1C but 8' deep.	See above			At Pontoon J/K and Q/R.	
2	Guidance	Primary	Full guidance net on south side of HCB.									New alternative not in original matrix.			We do not recommend this option	This would need to be reviewed, approved and permitted by the US Coast Guard, which has jurisdiction over navigible waterways. No impacts to the bridge.	
2A	Guidance	Primary	15' Deep 1.9 mile "V" Behavioral Guidance System (BGS)									This would be a major facility with significant anchorage issues, impacts on navigation, and concern for durability given velocities, however, there are many systems like this now in existence at hydro plants that are effective for surface oriented out-migrating fish. While this would be major structure with impacts, it would be much less costly than a bridge re-design.	Need to determine open water loading conditions, the need for boat access (such as boat gates, boat access areas, potential to sink/float for passage of large vessels, etc.). Navy and Coast guard would need initial consultation to help define potential feasibility and layout. PNP will be a good vendor resource to help with cost estimating if desired to carry forward for Phase 2. Feasibility is major question, keep in list of options for now to document idea.	Does not seems feasible given constraints of Navy and potential to harm other species			

2B	Guidance	Primary	8' Deep 1.9 mile "V" BGS									Shallower depth may not guide Chinook as effectively as steelhead, but then the bridge may not pose as much of a barrier to deeper oriented migrants.	See above	Does not seems feasible given constraints of Navy and potential to harm other species		
3	Guidance & Deterrence	Primary	Bridge Re-design and replacement / modification.	4	4	1	2	11	yes	Significant bridge design and engineering work.	This solution was ranked the highest to address the fundamental problem, but it is a long term solution. The team believes that a design process to consider bridge alternatives would be fruitful because the bridge may experience significant maintenance costs that would make the expense of replacing the bridge more palatable. A cost/benefit analysis, including the costs of addressing ESA obligation in the long term, may be fruitful.	R2 team agrees with concept. We have broken down the general idea into 3 options that may be feasible in varying timelines (i.e., associated with potential maintenance or safety upgrades if any are planned), and to document specific ideas to communicate for future consideration.	Total bridge replacement timeline likely will not match immediacy of the ESA fish issues.		While construction to replace the bridge is not possible within the scope of Phase 2, conceptual design work can be completed. A fish-friendly bridge would be useful to have on-hand to inform near- or long-term bridge modifications and replacements. Modifications should be explored for feasibility. A fish-friendly replacement design should be available in the event that the current structure reaches the end of its lifespan prematurely due to unforeseen circumstances.	Norway currently has 2 floating bridges which are "discrete" pontoon types, i.e. they are not continuous. This type of bridge uses floating piers to support the superstructure. Norway specifically uses this type of floating bridge for fish passage reasons. Please see Nordhordland Bridge and Bergsoysund Bridge, information is available on Wikipedia.
3A	Guidance & Deterrence	Primary	Replace the entire bridge with a more "fish friendly" design									Primary goal would be to create gaps throughout the entire length of the bridge with streamlined flow passing the structural components and pontoons to allow near continuous surface oriented fish passage.	Consider option to use deeper pontoons with gap between top of pontoon and bottom of bridge deck. Deck could be supported on columns creating surface passage. Must address stability, maintenance, etc. Need to discuss major concepts with WSDOT floating bridge engineers to assess potential feasibly. Outside immediate timeline of this project, just documenting issues.	Yes of course this is the preferred option but VERY unrealistic that it will be an option in phase II.	Norway is currently planning the worlds longest floating bridge at 4 km. This will be a discrete pontoon style bridge. Boat passage is provided by high level navigation channels at one or both ends. Google Bjornafjorden bridge crossing for more information.	
3B	Guidance & Deterrence	Primary	Replace middle segment of bridge with more "fish friendly" design									Consider submerged pontoon concept noted above to create 15' deep open gap in bridge deck with rounded corners to facilitate fish passage even when bridge is closed (open for traffic) so fish can always pass. Goal would be to maximize width of open gaps to extent feasible with structural requirements. Concept developed for discussion replaces the existing retractable pontoons (60' wide x 495' long) with deeper pontoons that allow 4 slots that pass water at a depth of 15' and 92' width across the 60' of pontoon.	Would also eliminate the holding area for pinnipeds, and eliminate the need for supplemental concepts.		The draw pontoon (ZA, ZB, ZC and ZD) draft is limited by the under water struts between the flanking pontoons. This option does not appear feasible without major modifications or replacement of the entire draw assembly.	
3C	Guidance & Deterrence	Primary	Replace pontoons of bridge with more "fish friendly" design								This appears to have the most support of WSDOT - Nick Rodda comments indicated that this option sounds structurally feasible. Goal would be to use pontoons with surface gaps, and span the bridge deck between them. Fish passage portals sized for fish passage (~10' wide by 15' deep ideal) could be evaluated for feasibility with floating bridge structural needs. Could also consider replacement of existing pontoons with submerged type pontoon as noted in 3A. Consider use of 2 to 4 pontoons across entire length of bridge if deemed feasible. Concept developed replaces a 360' long x 60' wide section of fixed pontoon (60' wide x 495' long) with a deeper pontoon that allow 3 slots that pass water at a depth of 10' and 87' width across the 60' of pontoon.	Does WSDOT plan maintenance on existing pontoons that could be tied into a feasibility analysis of this item? Fish passage features at hydro facilities have proven this concept to be effective to enhance migration survival.	This solution appears to have the most WSDOT support (of the bridge redesign options) - Nick Rodda comments during meeting indicated that this option sounds structurally feasible, and I think it would really make a difference for steelhead especially.	As presented, this would be replacing Pontoons J and R at either end of the draw assemblies and replacing them with a modified design to allow more fish passage. This seems feasible from a conceptual standpoint. Wholesale use along the length of the bridge would be less feasible because of how the pontoons are joined together.		
4	Deterrence	Secondary	Reducing light at bridge.	2	2	3	3	10	yes	A better understand of mortality impacts related to chum and chinook, and more information on the relationship between light, the presence of salmon prey as an attractant for salmon.	The team concluded that this option should remain because of it's feasibility and it's potential impact could make some improvements, but believes it to be a lower priority because telemetry data suggests that steelhead mortality was not occurring at night and the periods darkness are relatively short during the spring steelhead outmigration. This solution may also be more applicable for chum and chinook if further analysis supports that conclusion.	Lighting concepts have been tried at hydro projects with varying success. Sometimes lights attract, and sometimes they repel fish passage. NMFS fish passage design protocols require ambient light, or simulation of ambient when ambient is not possible (i.e., in submerged fish passage entrances, Merwin Dam Trap example). Consider lighting plan to help simulate natural light without bridge (i.e., uniform lighting, illuminate passage routes if provided in the day).	Expand concept to both eliminate "distracting" light (moving vehicle lights), and potential add lights to enhance passage (light fish passage portals through bridge" . Determine the number of lights deployed and a typical light detail. This concept has potential, suggest further discussions for secondary use with any planned concepts for early implementation.	This solution is not compelling to me, given the reasons stated in the "Additional Comments" box. I think it would be worth testing for effects on harbor seal behavior or small salmon behavior though, in a year we aren't testing higher priority solutions. Would be helpful to see if harbor seals forage at all at night if lights are off.	We observed a more distinct temporal pattern of seal activity in an unlit section of the bridge than in the east pool area, which is illuminated at night. We therefore think seals may be taking advantage of artificial lighting in the pool areas to hunt more during nighttime hours. In addition to predation activity, available literature indicates that light levels in the pool areas of the bridge exceed the threshold to affect salmon behavior at this life stage. Lights may be drawing salmon to stay and feed in illuminated areas, despite the increased risk of predation, which may be a contributing factor to the observed delay in migration. This impact should be mitigated, based on the literature and our observatons, which we would be happy to expand upon at a future meeting.	Bridge lighting modifications would need to be reviewed by WSDOT Olympic Region as there are safety impacts. Neither of the floating bridges at SR 520 or I-90 on Lake Washington have roadway lighting. There is pedestrian path lighting, but this is done such that light does not shine on the water. I would question if lighting is even necessary? West Half lighting is most likely original to 1982.

5	Guidance	Secondary	Structure to reduce/disrupt surface water velocity around the ends of the bridge.	3	2	2	3	10	yes	The team needs outside expertise from engineers and fish passage experts more experienced using these tools.	The capabilities of this technology are not well known and this solution would need to be better defined to evaluate it's potential impact.	Goal is to utilize a half-round style bullnose panel to eliminate or reduce eddies and provide better flow conditions for expediting fish swimming past this area as shown on Alt 5 figure.	R2 hydraulic engineers note we can use quick paper study, and then help design with field observations at high ebb tide condition with neutrally buoyant drogues (i.e. oranges) or with dye studies. Definitely feasible to design. Could model but field studies likely more efficient.	Engineers supported this idea and indicated high potential effectiveness. If flow can be directed around corners better, and can be installed in conjunction with the fillet solution, I think it's worthwhile to test	See comments on #1	This option is structurally feasible.
6	Pinniped Deterrence	Secondary	Deter pinniped activity near the bridge.	1	3	3	2	9	yes	Further delineated with 8A-8G below. Does the assessment team have enough pinniped behavioral data to recommend a solution. This solution would need to be coupled with a more fine-scale assessment of seal behavior near the bridge and additional predator observations, potentially including seal tagging, predator surveys, and scat sampling	The feasibility of restricting haul outs is uncertain. There is also limited literature supporting the hypothesis that restricting haul outs in an area would reduce predation in that same area.					
6A	Pinniped Deterrence	Secondary	Collect pinniped behavioral data at HCB to further the understanding of various pinniped deterrent actions. For example, identify if animals using bridge are actively foraging on juvenile salmonids and to what degree their predation occurs.						yes	Do the seals that use the pontoons as haul-outs active consume juvenile salmonids at the HCB and to what degree.	Using Columbia River as test case, individuals pinnipeds were documented and marked for removal/relocation.	R2 agrees with need for more data collection. This study would be for individual animals	Assessment team will lead further efforts. R2 can contribute in a review role if desired. Columbia River experience can help guide this process, there is a lot of data available.	I think we need a targeted, well-designed observational study of seals at the HCB, to understand their foraging behavior, abundance, and fine-scale location in relation to known mortality spots (i.e., corners). This data will help us not only provide evidence of impact on salmonids, but also identify predator-related solutions.	Methods intended to deter foraging pinnipeds (selective removal, acoustic devices, netting) are likely not feasible, and we are not confident that measures to limit haul-out sites would measurably enhance fish survival. Our observations indicate that haul-out areas on the bridge are primarily used for pupping, and are not a significant factor in overall foraging behavior at the bridge. Reducing seal presence in the vicinity of the bridge may be futile for such a ubiquitous species, therefore we think Phase 2 efforts should focus on methods which encourage fish passage. Deterrence at haul out locations may be considered if preliminary Phase 2 results indicate this would be an appropriate next step.	
6B	Pinniped Deterrence	Secondary	Restricting access to seal haul-outs near the bridge using handrail or netting device.							Further delineated with 8A-8B. Does the assessment team have enough pinniped behavior data to recommend a solution. This solution would need to be coupled with a more fine-scale assessment of seal behavior near the bridge and additional predator observations, potentially including seal tagging, predator surveys, and scat sampling	The feasibility of restricting haul outs is uncertain. There is also limited literature supporting the hypothesis that restricting haul outs in an area would reduce predation in that same area.	Concept is sound, and could be accomplished with a handrail/netting option, chain link fence, similar barrier ideas that would still provide necessary bridge maintenance access, ability to clean, etc.	To implement, could first develop more information on pinniped barrier criteria (i.e., how much freeboard, how high, what mesh size, what strength is necessary, etc.). Could first identify problem areas and try prototype tests. Be sure to address any potential "take" concerns for MMPA. Initial research by LLTK notes the MMPA may allow testing of these concepts, need to confirm once more details are developed on potential actions.	Not sure how much hauling out can be done on the bridge, or if this is a matter of one or two individuals at a time. I would guess that this wouldn't make a huge impact on predation.	See comments on 6A	
6C	Pinniped Deterrence	Secondary	Restricting access to seal haul-outs near the bridge using electric seal haul-out mats.								The feasibility of restricting haul outs is uncertain. There is also limited literature supporting the hypothesis that restricting haul outs in an area would reduce predation in that same area.	Smith Root is one vendor with a possible product. See next column. Recommend more research and consultation with Smith Root and possibly other vendors for case studies, drill down more into the details, costs, success, failures, and their concerns. Goal is to go into these type concepts with all potential issues identified, sometimes vendors can oversell their products. This comment is not intended as a criticism or concern for any particular vendor, development of new technology is necessary and exciting. It is only intended to make the Assessment Team aware of this issue.	Smith Root electrical seal deterrent mats are constructed as a system that either be linked together or as stand-alone modules. Each mat is 20 ft long X 4 ft wide and utilizes a control system (\$6,500). Each control system can operate four (4) mats and can cover an area of 320 sq. ft. The system also utilizes a solar panel and runs on 12 volt marine battery. Accepted by NOAA as an acceptable measure of deterrence so permit is not needed. Appeared to work in several boat harbors and marinas on west coast and oil drilling platform (Astoria and Westport) to deter CSL from using floats.	see comment above	See comments on 6A	A number of animals have been observed over the years - mainly seals and otters. Some are a nuisance and can cause issues with maintenance of the bridge. Seals regularly use the work platform boxes beneath the guide rollers. These boxes help stagnate the water and prevent marine growth from accumulating on the guide rollers which would be a maintenance issue. Otherwise they could be removed without detriment to the bridge. Other means for discouraging animals from hauling out would in general be welcomed by the maintenance crew.
6D	Pinniped Deterrence	Secondary	Acoustic Harassment device (Traditional - loud noise)	1	2	4	1	8	no		Potential unintended consequences to non-targeted marine mammals and the limited efficacy of these devices led the team to conclude that this would not be a potential solution	R2 agrees with Assessment Team's comments. USACE has had some success at the Ballard Locks, but learned behavior of pinniped appears to render this action useless in the long term. Public appears to support lethal removal to certain extent.	Likely will not be carried forward to Phase 2 at this time. Document for potential future consideration and completeness.	Agree with Assessment team and R2 comments on this one	We do not recommend this option	

6E	Pinniped Deterrence	Secondary	Lethal removal of nuisance predators	1	2	2	2	7	no		Hood Canal is an open environment and seals are ubiquitous around Puget Sound. There is no evidence suggesting individual nuisance animals exist. Substantial legal barriers to this solution exist	R2 agrees with Assessment Team comments. This action will have big concerns for MMPA Take issues, rigorous public process and years to receive permit. >1,000 seals in Puget Sound would need to remove significant number annually to reflect a noticeable change in potential biological removal. Population must be able to reach or maintain optimum sustainable population.	Likely not feasible, maintain for the record.	Not an option for phase II	We do not recommend this option	
6F	Pinniped Deterrence	Secondary	Predator exclusion netting	1	3	2	1	7	no		Netting is expected to be quickly fouled and expensive to maintain.	Netting could be feasible, would require maintenance, good design and installation to facilitate maintenance. Would also require consultation to properly determine a mesh size to deter pinnipeds and not harm/injure other animals (fish, birds, etc.).	MMPA Take concern would require consultation. Could delay potential start date for several years based on Columbia River pinniped timeline. Agree to not move this forward at this time.	Not an option for phase II	We do not recommend this option	
6G	Pinniped Deterrence	Secondary	Acoustic Startle Device (Genuswave)	1	3	4	2	10	yes	Ideally, additional testing results related the use of the device.	This technology has limited testing and it is therefore difficult to evaluate. The device is currently planned to be tested in a different location in the Spring of 2020	Concept has potential, but concerns are also noted for potential negative impact on Herring. Care would have to be taken to assure no negative impacts on herring populations in Puget Sound.	Recommend monitoring testing of this technology elsewhere prior to further advancement of concept for HCB. However, input to other studies to consider testing on Herring would be positive outcome of initial phase. We note that acoustic deterrence devices (ADD's) are highly used and show wide variety of success in aquaculture. Observed learned behavior with pinnipeds in Columbia River system, along with potential for unintended impacts on marine life are noted concerns. Learned behavior limit this option to a short-term (stop-gap) solution.	I agree that waiting to determine efficacy at the Locks is appropriate.	Before considering this option, there needs to be a study on the device's impact to herring. The patent for Genuswave's device indicates that it may effect Clupeids, but notes "fish with specialized hearing... do not usually occur around fish farm locations and so this is not anticipated to be a problem when the invention is used in a fish farm environment." The Hood Canal Bridge is not in a fish farm environment, in fact since 2016, Hood Canal stocks have contributed over half of all herring spawn in Puget Sound.	
7	Guidance	Secondary	Pumping water to signal passage	2	1	2	4	9	yes	The team needs outside expertise from engineers and fish passage experts more experienced using these tools.	The capabilities of this technology are not well known and their potential impact in such a large environment is questionable.	Recommend dropping this concept due to feasibility and metrics of comparison to successful systems in the hydro industry. For example, based on experience with 500 and 1,000 cfs based juvenile bypass systems in forebays, very high flows would be necessary at high costs, and with very little likely return on the investment. See next column for perspective. Bottom line: Any measures that might be implemented would pale in comparisons to the rate of flow during ebb and flood conditions, would be extremely costly, require high energy cost and maintenance in marine environment, and have questionable benefits.	Quick back of the napkin calculations indicate that the estimated flow past bridge at a high ebb condition (3 fps) ≈3.9 million cfs. The flow past the west end of the bridge at 3 fps = 46,000 cfs and 41,000 cfs past east end. These are 40 times order of magnitude of current fish passage technology systems that would accomplish the stated goals of this alternative. It would be difficult to induce flow in a safe manner since reasonable pumping efficiency require relatively high impeller speeds that require screens to protect fish. Using the fish friendly turbine concept as a pump could be considered. A pumping system that would yield 100 cfs would cost on the order of \$500k and require about 60kw to operate (4 month x 30.4 day/month x 24 h/d x \$0.15/kwh = \$26,300 / season). This system would need 400 times that amount for each end of the bridge. We could consider an inverted "L" pipe assembly that uses a submersible axial flow pump that is relatively deep and the top of the piping assembly would discharge near the surface to induce a beneficial flow pattern.	Frank's calculations prove this to be totally ineffective given the conditions at the bridge.	Agree with comments from R2 and Megan	Power needs would need to be reviewed to determine the impact to the State. These could be mounted to the bridge in such a way as to be structurally feasible. No holes would be permitted to be drilled in the pontoons for installation of pumping devices. Also, maintenance would be an issue - the State would not take responsibility for maintenance of such a system.
8	Guidance	Secondary	Guide steelhead to safe passage (bubble curtains or other strategy)	3	1	2	3	9	N/A	The Assessment Team needs additional information regarding potential mechanisms to accomplish this.	The feasibility of this solution is questionable considering the scale and dynamic nature of the water body.	The corners at the bridge opening would likely be difficult to place net fillets in because the pontoon moves. A bubble curtain might work here. And bubble curtains could be substituted at the locations 1A - 1D. However, we believe a bubble curtain in this tidal environment with relatively high (2 to 3 fps ebb and flood flow velocities) would not be very effective. Bubble curtains have shown limited success on steelhead in the hydro industry. However, they have had notable effects on carp and other species. See next column to document metrics on this concept, not likely feasible with meaningful effects.	Need to identify potential areas to implement. Possibly in lieu of net type barriers or to serve as a deterrent to harbor seal within the retractable pontoon pools. Therefore save this concept as consideration for a secondary action. For perspective, implementing a single 100 lf barrier would require about 130 scfm of air flow and would be on the order of \$400k and require about 23 kw to operate (4 month x 30.4 day/month x 24 h/d x \$0.15/kwh = \$10,200 / season).	Agree with R2 assessment that bubble curtain would be ineffective in the face of strong tidal currents. Low potential effectiveness and high cost.	We do not recommend this option	

9	Guidance	Secondary	Open/Close the bridge for longer periods during low traffic hours	2	1	3	2	8	no		Telemetry data did not support the hypothesis that bridge openings would expedite steelhead passage. The bridge opening is a relatively small increase in the total open space along the bridge. The bridge openings are not expected to provide a substantial increase in open area of fish to find passage. The potential solution would also negatively impact traffic flow. Therefore, the costs are like to outweigh the benefits.	R2 agrees with dropping this concept due to little data to prove any meaningful benefit, and it is very incompatible with the bridge purpose. Modifications to pontoons or the opening section noted above would be more feasible.		If WSDOT is amenable to testing this option I think we should. The design of the bridge includes the ability to open!! It seems to me we have to test this before any money can be spent on redesign. Especially in 2018, a large number of tagged steelhead were located between the two pontoons flanking the middle section. If we could open the bridge at night for a significant period of time during the ebb tide I think this option has the potential to make a noticeable difference. If it does not, we have a stronger argument for redesign.	Opening the bridge span may be extremely effective to expedite passing individual fish which encounter the center of the bridge during open periods. While this may be a low overall percentage of outmigrating fish, it would be worth knowing if this mitigation technique caused a measureable difference for a relatively low cost. Information gathered during the testing of this technique may also inform potential bridge modifications. Testing of this technique should consider the same velocity challenges as described in #5.	This is a low or no cost option to the State, if it is deemed to be effective. It should at least be tried for a period of time. Public outreach and coordination with WSDOT Olympic Region would be needed, but I think you could get there. Disruption to the traveling public would be minimized by leaving the draw open for some period in the middle of the night.
10	Guidance	Secondary	Reducing noise	1	2	1	4	8	no		Research on noise at the bridge concluded that noise does not reach thresholds that are likely to adversely affect salmon health. This feasibility of this solution is also highly questionable.	The hydrophone study implied that the noise levels could reach and slightly exceed the thresholds that cause fish avoidance in studies. Use of noise in hydro industry fish passage projects has been largely unsuccessful. We typically reserve this option as a secondary or potential enhancement option for very site specific needs, and more research would be needed. The limited studies on salmonids indicate there is also a learned behavior and fish became acclimated to the noise and started ignoring it.	Little benefit compared to other options, and much more research needed. No proven success in the hydro industry.	Agree with AT and R2 conclusions	We have not observed any effect of noise at the bridge on surrounding fish behavior or abundance.	There is little that could be done from a structural standpoint to mitigate noise.
11	Deterrence	Secondary	Remove marine growth.	1	1	2	4	8	no	Further delineated in 14A-14B below.	Further delineated to 14A-14B. While marine life may be contributing to the reef-effect at the bridge, there is little evidence			We do not recommend this option		
11A	Deterrence	Secondary	Remove marine growth from the bridge	1	1	2	4	8	no		While marine life may be contributing to the reef-effect at the bridge there is little evidence to suggest that this would impact mortality.	R2 agrees with assessment team that this would be a high cost, high maintenance alternative to keep the marine growth clean, with little certainty of passage benefits. The marine growth could be a habitat benefit for juvenile salmonids, and more data would be needed.	Drop due to long-term maintenance needs. Could also affect water quality in short term with routine cleanings.	drop	We do not recommend this option	This would be an awesome thing to have from a preservation standpoint, although I'm not sure how you would accomplish this. I'm also not sure how you could apply an anti-fouling coating in-situ.
11B	Deterrence	Secondary	Remove marine growth and apply Anti-fouling coating	1	1	1	2	5	no		While marine life may be contributing to the reef-effect at the bridge, there is little evidence to suggest that this would impact mortality. Anti fouling coatings can be harmful to the environment. Applying antifouling coating to the bridge is unlikely to be feasible.	See above. Current anti-fouling coatings that meet environmental requirements are costly and not as effective as the prior generation (and more toxic) coatings.	More costly than cleaning with limited benefits and same concerns.	drop	We do not recommend this option	
12	Deterrence	Secondary	Increase turbidity	1	3	2	1	7	N/A		Turbidity may decrease predator's ability to forage at the bridge. The Assessment Team is unaware of any mechanisms to accomplish this.	Interesting concept, one means to implement this idea would be with inert mineral dyes. Rhodamine B (red) and Fluorescein (green) are allowed for river testing, and are commonly used in hydraulic model studies. However, the scale of the flow as noted above is unmanageably large, so this would not likely be feasible due to the large quantities of dye that would be necessary in flowing water. See next column for quick metrics. Drop concept due to permitting, cost, and general feasibility concerns.	NPDES permitting would place this option years down the road, and given quantities of dye needed may never be permittable. From a cost perspective alone, brief research indicates that Rhodamine B dye in bulk costs about \$0.3/lb. and assuming a 10 ppm concentration and a flow of 5,000 cfs (about 10% of flow around one end of the bridge) the resulting feed rate is 270,000 lb./day or \$80,000 /day. We would need 20-times that amount, so consider infeasible.	drop	We do not recommend this option	

APPENDIX F

HCB Opinion of Probable Construction Costs

ITEM	DESCRIPTION	QUANTITY	UNIT	UNIT PRICE	DESCRIPTION TOTAL	ITEM TOTAL
A. General						\$ 29,100
1	Mobilization and Demobilization	1	LS	\$ 14,100	\$ 14,100	
2	Work Barge and Tenders	3	WK	\$ 5,000	\$ 15,000	
B. Floating Boom						\$ 48,000
3	Continuous HDPE Boom	120	LF	\$ 350	\$ 42,000	
4	Anti Seal Haul out HDPE plate	120	LF	\$ 50	\$ 6,000	
C. Netting and Bottom Weight						\$ 16,536
5	Netting or Synthetic Panel (120' x 8')	960	SF	\$ 9	\$ 8,640	
6	Chain Weight at bottom of Net (1" at 15.2 lbs/ft)	120	LF	\$ 66	\$ 7,896	
D. Bridge Fastener						\$ 47,600
7	Energy Absorber Transitions	4	EA	\$ 4,200	\$ 16,800	
8	2 wraps of 6" synthetic strap, fasteners, diver install	2	EA	\$ 15,400	\$ 30,800	
CONSTRUCTION COST						\$ 141,236
Contingency						\$ 42,371
COST - 2020 (rounded to nearest \$1000)						\$ 184,000
Low Range (minus 35% rounded to nearest \$1000)						\$ 120,000
High Range (plus 65% rounded to nearest \$1000)						\$ 304,000
AACE International CLASS 5 Cost Estimate - Class 5 estimates are generally prepared for concept screening. Typically, engineering is 0% to 2% complete. Accuracy -50% to +100% R2 OPCC Disclaimer - The client acknowledges that R2 has no control over costs of labor, materials, competitive bidding environments and procedures, unidentified field conditions, financial and/or market conditions, or any other factors likely to affect the OPCC of this project, all of which are and will unavoidably remain in a state of change, especially in light of the high volatility if the market attributable to Acts of God and other market event beyond the control of the parties. Client further acknowledges that this OPCC is a "snapshot in time" and that the reliability of this OPCC will degrade over time. Client agrees that R2 cannot and does not make any warranty, promise, guarantee or representation, either express or implied. that proposals, bids, project construction costs, or cost of O&M functions will not vary significantly from R2 good faith Class 1 OPCC.						

ITEM	DESCRIPTION	QUANTITY	UNIT	UNIT PRICE	DESCRIPTION TOTAL	ITEM TOTAL
A. General						\$ 36,000
1	Mobilization and Demobilization	1	LS	\$ 16,000	\$ 16,000	
2	Work Barge and Tenders	4	WK	\$ 5,000	\$ 20,000	
B. Floating Boom						\$ 48,000
3	Continuous HDPE Boom	120	LF	\$ 350	\$ 42,000	
4	Anti Seal Haul out HDPE plate	120	LF	\$ 50	\$ 6,000	
C. Netting and Bottom Weight						\$ 27,960
5	Netting or Synthetic Panel (120' x 15')	1,800	SF	\$ 9	\$ 16,200	
6	Chain Weight at bottom of Net (1.25" at 15.2 lbs/ft)	120	LF	\$ 98	\$ 11,760	
D. Bridge Fastener						\$ 47,600
7	Energy Absorber Transitions	4	EA	\$ 4,200	\$ 16,800	
8	2 wraps of 6" synthetic strap, fasteners, diver install	2	EA	\$ 15,400	\$ 30,800	
Total (One Fillet Structure)						\$ 159,560
Contingency						30% \$ 47,868
COST - 2020 (rounded to nearest \$1000)						\$ 207,000
Low Range (minus 35% rounded to nearest \$1000)						\$ 135,000
High Range (plus 65% rounded to nearest \$1000)						\$ 342,000
AACE International CLASS 5 Cost Estimate - Class 5 estimates are generally prepared for concept screening. Typically, engineering is 0% to 2% complete. Accuracy -50% to +100% R2 OPCC Disclaimer - The client acknowledges that R2 has no control over costs of labor, materials, competitive bidding environments and procedures, unidentified field conditions, financial and/or market conditions, or any other factors likely to affect the OPCC of this project, all of which are and will unavoidably remain in a state of change, especially in light of the high volatility if the market attributable to Acts of God and other market event beyond the control of the parties. Client further acknowledges that this OPCC is a "snapshot in time" and that the reliability of this OPCC will degrade over time. Client agrees that R2 cannot and does not make any warranty, promise, guarantee or representation, either express or implied. that proposals, bids, project construction costs, or cost of O&M functions will not vary significantly from R2 good faith Class 1 OPCC.						

ITEM	DESCRIPTION	QUANTITY	UNIT	UNIT PRICE	DESCRIPTION TOTAL	ITEM TOTAL
A. General						\$ 17,400
1	Mobilization and Demobilization	1	LS	\$ 7,400	\$ 7,400	
2	Work Barge and Tenders	2	WK	\$ 5,000	\$ 10,000	
B. Bull Nose Half Round						\$ 27,852
3	Fabrication	1	EA	\$ 15,000	\$ 15,000	
4	Installation	1	LS	\$ 12,852	\$ 12,852	
C. Bridge Fastener						\$ 28,840
5	Energy Absorber Transitions	4	EA	\$ 3,360	\$ 13,440	
6	2 wraps of 6" synthetic strap, fasteners, diver install	1	EA	\$ 15,400	\$ 15,400	
Total						\$ 74,092
Contingency					30%	\$ 22,228
COST - 2020 (rounded to nearest \$1000)						\$ 96,000
Low Range (minus 35% rounded to nearest \$1000)						\$ 62,000
High Range (plus 65% rounded to nearest \$1000)						\$ 158,000
AACE International CLASS 5 Cost Estimate - Class 5 estimates are generally prepared for concept screening. Typically, engineering is 0% to 2% complete. Accuracy -50% to +100% R2 OPCC Disclaimer - The client acknowledges that R2 has no control over costs of labor, materials, competitive bidding environments and procedures, unidentified field conditions, financial and/or market conditions, or any other factors likely to affect the OPCC of this project, all of which are and will unavoidably remain in a state of change, especially in light of the high volatility if the market attributable to Acts of God and other market event beyond the control of the parties. Client further acknowledges that this OPCC is a "snapshot in time" and that the reliability of this OPCC will degrade over time. Client agrees that R2 cannot and does not make any warranty, promise, guarantee or representation, either express or implied. that proposals, bids, project construction costs, or cost of O&M functions will not vary significantly from R2 good faith Class 1 OPCC.						

APPENDIX G

Response to Review Draft Report Comments

1 INTRODUCTION AND CONTENTS

This appendix provides a copy of written review comments provided by the Hood Canal Bridge Assessment Team, along with responses from R2 below each comment. Where appropriate, the final report has also been edited as noted to reflect these comments. R2 thanks the reviewers from the Assessment Team and LLTK for their review and thoughtful comments.

2 COMMENTS FROM NOAA FISHERIES WITH R2 RESPONSES

Review of R2 Report on HCB solutions - Megan Moore, NOAA Fisheries dated 8/6/2020.
Megan's comments are listed as written, and R2's response is listed below in *italic font*.

This document provides a thorough and detailed compilation of the process so far, and clear plans on chosen modifications. My one major concern is that these initial designs have not been vetted by WSDOT yet (document states that they will be involved in the ongoing process but there was no indication that WSDOT has approved these plans yet). I have a few additional comments/questions below:

Regarding the vetting by WSDOT, Megan is correct that WSDOT representatives participated in review meetings, and R2 agrees that the initial stages of the design for the recommended items will need WSDOT engineering and possibly other discipline review. The Phase 2 scope of work will have essential meetings with WSDOT expedited early in the process to confirm WSDOT is amenable to the design concepts proposed, including comments within this appendix, and can identify any concerns to be addressed with the design phase.

Page 6 – Alternative 1 Bridge Fillet Structures – potential materials stated as small mesh net or flexible plastic. A solid material would help deflect water from corners and might reduce tendency to eddy and create more laminar flow.

We understand this comment and recommend exploring solid panel options during the initial Phase 2 scope of work for the design phase in consultation with all parties. A solid structure will impart greater loads on the bridge than a flexible structure, and connection details may be more difficult to design that absorb that energy. A solid structure would also be more costly. Based on the initial concepts and WSDOT comments and concerns, the information developed early in Phase 2 can be reviewed with the Assessment Team and decisions made on how robust/durable this prototype fillets should be given any known budget and schedule constraints. The final report text was edited to note further investigation of materials.

Figure 2-1 – would the fillet structure enclose a triangle of water? I envisioned the structure being solid so that nothing would get trapped behind the structure

A complete enclosed configuration would be more costly and difficult to secure. Leaving the bottom open would provide egress for fish, but we understand the concern for fish that might

enter this space. The Phase 2 scope of work will address this issue and discuss options with HCB Assessment Team members early in the process as noted above.

Page 11 – Alternative 6 seems like a feasible and inexpensive solution to try (though not sure how it fits into the control/treatment framework)

Alternative 6 is the suite of pinniped deterrence measures. We understand that other members of the Assessment Team had some concerns about pinniped deterrence, but this comment is good to record for future implementation consideration. Part of the Phase 2 final design will be balancing how many alternatives to implement and the ability to develop meaningful effectiveness evaluations for each.

Page 11 – the statement about the HC seal population is not accurate or correctly cited, as the data in figure 2-6 is predator density at the HCB only and has not been extrapolated to produce population estimates.

Thank you for pointing this out. Final report was edited as follows.

ORIGINAL TEXT

“Several field studies indicate that pinniped predation on steelhead smolts occurs frequently at the HCB. The most-recent population survey indicates the hood canal harbor seals population is approximately 600 seals per haul out location (Figure 2-6). To date, there has not been an extensive study on behavior of individual pinnipeds at HCB and their predation rate of salmon has not been quantified.”

NEW TEXT

Harbor seals and harbor porpoises had generally low densities throughout the HCB study area; boat-based surveys may not have fully captured the area directly alongside the bridge due to restrictions on vessel distance from the bridge infrastructure (Figure 2-6). Both species were observed at higher densities near the bridge than away from the bridge in 2017; that pattern was not apparent in 2018, when densities were similar across the entire survey region (Figure 2-6). To date, there has not been an extensive study on behavior of individual pinnipeds at HCB and their predation rate of salmon has not been quantified at HCB.

Page 21 (section 3.2.1) Coordination with WSDOT is anticipated, but it isn't clear how much communication has already occurred (i.e., have these preliminary modification designs been discussed and initially or informally approved by WSDOT yet?).

To date the only meetings with WSDOT participation are the Assessment Team meetings associated with the production of the draft report. The Phase 2 scope of work for design will include formal consultation with WSDOT engineering and associated representatives to identify concerns and confirm acceptance of these ideas early in the process as noted above.

Figure 4-1 – We better get going! Kick-off meeting scheduled for next week.

The schedule has been adjusted to reflect the current schedule following the review comments.

Page 30 (4.5) Is it possible to provide an estimate for deployment/installation costs?

The deployment/installation costs will be a function of how many structures are desired for the initial installation. The Phase 2 scope of work will require these estimates to be provided early in the design process.

3 COMMENTS FROM THE PORT GAMBLE S'KLALLAM TRIBE, WESTWARD ECOLOGY AND LLTK WITH R2 RESPONSES

The Port Gamble S'Klallam Tribe, Westward Ecology, and LLTK provided comments on 8/11/2020 via comment bubbles to the PDF copy of the report. The following comments have been compiled from PDF comments, and R2's responses are listed below in *italic font*. Note the page numbers refer to the PDF page in the electronic file. Emily is Emily Bishop, Westward Ecology. EB/HD designates Emily Bishop and Hans Daubenberger (Port Gamble S'Klallam Tribe).

Page: 12, Author: Emily, Sticky Note under 2.1.4 (published page 5).

Thank you, we corrected Emily's company affiliation in the final report.

Page: 14, Author: Emily, Sticky Note

We should aim for a design that eliminates water pooling behind the fillet (a structure with a bottom). The data show that fish transit under the bridge during strong ebb tides. If a void is left between the pontoons and the fillet, fish could become entrapped in that space.

We recommend a solid structure, and advise against any netting. Netting can be damaged by woody debris during storms, and is dangerous for organisms small enough to be caught in the mesh.

Thank you, we understand your concern and NOAA Fisheries had a similar comment above in Section 2. We noted this issue in the final report and will recommend researching options for solid structures in the early stages of the Phase 2 Design. Also, please see response to Page 6 comment above.

Page: 14, Author: LLTK-EB/HD, Sticky Note under Alternative 5 – Eddy Reduction Structures at Corners

EB/HD: Is this true of Megan's data?

Final report was edited as follows.

ORIGINAL TEXT

The eddy reduction structure at pontoon corners will eliminate or reduce the size of the eddy that is formed as water passes the existing, 90-degree pontoon corners. The bridge pontoon corners are hypothesized to slow steelhead migration by creating back-eddies or water velocity anomalies where steelhead are observed to delay on a consistent basis. The bridge corner may also provide mammalian predators an enhanced location to feed on steelhead circling the corners in a velocity spire. A half-round or bull-nose eddy reduction structure will be constructed out of a flexible plastic material that is 15 ft deep (full bridge depth) and attached to the corner of the bridge pontoon (Figure 2-2), and will be hydraulically designed for maximum benefit at peak flood and ebb tides.

NEW TEXT

The eddy reduction structure at pontoon corners will eliminate or reduce the size of the eddy that is formed as water passes the existing, 90-degree pontoon corners. The bridge pontoon corners are hypothesized to slow steelhead migration by creating back-eddies or water velocity anomalies where steelhead are visually observed on a consistent basis. The bridge corner may also provide mammalian predators an enhanced location to feed on steelhead circling the corners in a velocity spire. A half-round or bull-nose eddy reduction structure will be constructed out of a flexible plastic or other appropriate material that is 15 ft deep (full bridge depth) and attached to the corner of the bridge pontoon (Figure 2-2), and will be hydraulically designed for maximum benefit at peak flood and ebb tides.

Page: 15, Author: LLTK-EB/HD, Sticky Note on Figure 2-2.

EB/HD: A structure of this size will not address the eddy created by the corner

Figure 2-2 is intended to be a schematic representation of the idea. The actual size and configuration of the “eddy reduction structure” will be developed further in the Phase 2 design using proper hydraulic design methods of the actual bridge observed during peak flood and ebb tides. Use of photography and drones (such as oranges) will help to define the extents of the structure needed to affectively reduce or eliminate the eddy. The caption for Figure 2-2 was also edited to note this point.

Page: 17, Author: Emily, Sticky Note under Alternative 3 – Bridge Re-Design and Replacement/Modifications

Note that we need to study how adults interact with the structure in order to create a fish friendly design. The migration depth of adult fish may be different from that of juveniles which would influence the depth of pontoons rendered in the conceptual design.

Comment noted and documented for further consideration, Phase 1 only addresses impacts to juvenile steelhead. Text edited in final report to incorporate this comment.

Page: 19, Author: Emily, Sticky Note regarding Figure 2-6 title.

Note in the caption that this figure excludes seals observed on haul-outs during surveys.

Final report was edited as follows:

ORIGINAL TEXT

Figure 2-6. Estimated densities of harbor seals observed within 4 km of Hood Canal Bridge, Washington (adapted from HCBAT 2016).

NEW TEXT

Figure 2-6. Estimated densities (excluding haul out locations) of harbor seals observed within 4 km of Hood Canal Bridge, Washington (adapted from HCBAT 2016).

Page: 22, Author: LLTK-EB/HD, Sticky Note under Alternative 10 – Noise Reduction

EB/HD: Highlighted Sentence and provided comments as follows:

Acoustic monitoring indicates that noise levels approach and possibly exceed levels that may inhibit steelhead passage at HCB;

Confirm this is true? May be worth noting that we did not notice a behavioral change in response to traffic noise. We were on the lower deck during periods when traffic was stopped and fish did not behave any differently.

Final report was edited as follows:

ORIGINAL TEXT

The HCB provides a vital transportation corridor between the Olympic and Kitsap peninsulas, with as many as 15,000 cars passing on weekdays and 19,000 on weekends. Noise such as traffic passing over the HCB is postulated as deterrent to salmon passage thus negatively

affecting steelhead survival (Figure 2-10). Acoustic monitoring indicates that noise levels approach and possibly exceed levels that may inhibit steelhead passage at HCB; however, juvenile salmon telemetry studies did not indicate a migration preference during low traffic periods, nor were they above the threshold known impact other species of juvenile salmon (Deng et al. 2017; Daubenberger and Bishop. 2020; Moore 2020). The uncertainty of the effectiveness of noise reduction at HCB and the disruption to the traffic corridor resulted in deferring noise reduction from the Phase 2 management actions.

NEW TEXT

The HCB provides a vital transportation corridor between the Olympic and Kitsap peninsulas, with as many as 15,000 cars passing on weekdays and 19,000 on weekends. Noise such as traffic passing over the HCB is postulated as a deterrent to salmon passage thus negatively affecting steelhead survival (Figure 2-10). Acoustic monitoring indicates that noise levels approach and possibly exceed levels that may inhibit steelhead passage at HCB; however, juvenile salmon telemetry studies did not indicate a migration preference during low traffic periods and visual observations on the bridge deck did not detect a behavioral change in response to traffic noise (Deng et al. 2017; Daubenberger and Bishop 2020; Moore 2020). The uncertainty of the effectiveness of noise reduction at HCB and the disruption to the traffic corridor resulted in deferring noise reduction from the Phase 2 management actions.

Page 23, Author: Emily, Subject: Sticky Note and highlighted portion below under Alternative 12 – Marine Growth Removal/Control:

Highlighted portion reading:

Concentrations of marine growth on the bridge structure may artificially attract juvenile salmon and steelhead to an area of increased predation risk (Figure 2-11). Portions of the bridge (e.g., east pool at the draw span) contain large marine growth or reef-like structures that appear to attract juvenile salmon during their outmigration where harbor seals have been documented feeding on large schools of juvenile salmon...

We recommend removing this section entirely. In particular, the highlighted portion is inaccurate and misleading. See the comment below for an explanation.

The Hood Canal Bridge adds physical structure to the Hood Canal, which, in turn, attracts fish and their predators. However, the in- water portion of the bridge contains less complexity than a natural shoreline, resulting in a lack of refuge for migrating fish. There are three options to

address this issue. The first option is to reduce the footprint of the structure (i.e. redesign the Hood Canal Bridge to reduce the in-water area). The second strategy is to try and pass fish as quickly as possible through the area, which is what we are aiming to accomplish with periodic openings and with the fillet and bullnose structures. The third strategy would be to encourage physical complexity (i.e. encourage marine growth or add structural changes to mimic the complexity of natural shorelines) at the bridge to increase refugia for juvenile fish while they transit the area.

Page: 23, Author: LLTK EB/HD, Sticky Note related to the above text:

EB/HD: Literatures supports that structure attracts juvenile fish. Nothing in the literature supports that marine growth has the same effect.

This idea was proposed by a guest at an Assessment Team meeting who misunderstood the concept of “artificial reef effect” to mean marine growth.

Portions of the bridge (e.g., east pool at the draw span) contain large marine growth or reef-like structures that appear to attract juvenile salmon during their outmigration where harbor seals have been documented feeding on large schools of juvenile salmon

None of our findings support this statement.

Concentrations of marine growth on the bridge structure may artificially attract juvenile salmon and steelhead to an area of increased predation risk (Figure 2-11).

Response to above comments:

Because the idea of removing or controlling marine growth on the bridge was included in the original Assessment Team matrix (provide in Appendix A), and discussed throughout this study, we feel the overall alternative should be retained in the final report. Text under this section has been revised to read as follows:

Alternative 11 – Marine Growth Removal/Control

This concept was originally identified in the brainstorm session of the Assessment Team as documented in Appendix A. During this study, the Assessment Team members agreed that any benefits of removing marine growth on the bridge would be uncertain, and the cost and logistics associated with removal and control type paints were not desirable. This alternative was unanimously agreed to be deferred from additional Phase 2 implementation.

Page: 26, Author: Emily, Sticky Note under 3.2.1

See previous comment about the fillet structures.

See response above, and final report has been edited to note preference to explore solid structures.

Page: 31, Author: Emily, Sticky Note under 3.5

Category 5 should read Category 1

Agreed, typo fixed in final report.

Page: 32, Author: Emily, Sticky Note under 4.1 introduction

Prior to implementing Category 1 alternatives, a definition of success for each of the proposed mitigation actions should be determined.

R2 agrees with this comment, and we understand the measures of success will be developed by the Assessment Team and Management Committee during Phase 2 planning. Final report text has been edited to note this item in the 4.1 introduction.

Page: 36, Author: Emily, Sticky Note

These cost estimates may be low for a fillet structure that eliminates pooling between the fillet and the bridge.

R2 agrees, this concern has been noted in the final report in the introduction to Table 4-1, and the report notes cost estimates should be updated early in the Phase 2 process when final concepts have been developed further.