Hood Canal Bridge
Ecosystem Impact Assessment Plan: Framework and Phase 1 Details

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Prepared by:

Hood Canal Bridge Assessment Team and contributing experts (see reverse)

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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. 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 is an important regional transportation asset. It carries traffic across the northern outlet of Hood Canal, drastically shortening the trip between the Olympic and Kitsap peninsulas and in turn supporting tourism and other economic activities. As a 1.5-mile long floating bridge, its pontoons span 83% the width of Hood Canal and extend 15 feet underwater. Because of its location, all salmon and steelhead 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. 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. Additionally, recent research modeling the potential impact of the bridge suggests that the bridge may disrupt water circulation. Fjords depend upon strong surface flows to be replenished with healthy, oxygenated water. The bridge could therefore be contributing to low dissolved oxygen levels and fish kills, and exacerbate effects of ocean acidification—more prevalent in Hood Canal than anywhere else in Puget Sound—and increased temperatures resulting from climate change.

In 2015, federal, state, tribal, and nonprofit partners convened to develop the Hood Canal Bridge Ecosystem Impact Assessment Plan. The plan is 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. The effort is structured following an iterative, adaptive management approach. The work will occur in phases, building from what we know toward actions that simultaneously address impacts and maintain the bridge and its transportation benefit.

This document describes the overall plan framework, its adaptive management structure, and the details of the first phase of the assessment. The full assessment will address 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?**

   We must determine where mortality is greatest along the bridge, who the predators are, and how the bridge functionally leads to increased predation. Causal agents may include the pontoons as a barrier, or changes to water circulation and other water properties, that may slow migration, heighten fish densities and thusly increase susceptibility to predation. Light, shade and noise impacts from the bridge may also affect fish and/or predator behavior. Finally, structural voids near the center of the bridge may change water properties and aggregate plankton, attracting planktivorous salmon and steelhead (or their fish prey) and increasing their susceptibility to 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. Through field data collection and refined modeling, we must confirm the strength of the bridge impact on circulation. From there, we will determine whether Hood Canal water quality—including dissolved oxygen, temperature, acidity, and nutrient dynamics—is affected. If significant, this information will then be used to characterize the extent of impact the bridge is having on the Hood Canal ecosystem and isolate functionally how the bridge is driving ecosystem impacts. Species of critical concern, based on their ecological, commercial, and recreational/tourism importance, include shellfish, crab, shrimp, forage fish, rockfish, salmon, steelhead, seals, eagles, and killer whales.

To help frame the trajectory of this effort, an initial list of potential management actions has been developed in the plan based upon the causal agents being assessed. As specific causal agents are isolated, we will work with our partners and others in subsequent phases to establish a suite of proposed management actions, and then simulate, field test, and fully implement appropriate management solutions that will not adversely affect the bridge as a transportation corridor.

For the first phase of the assessment, the Assessment Team will perform these activities:

- **Track steelhead migration and mortality** – Juvenile steelhead will be acoustically tagged and their migration pattern tracked past the bridge to determine where along the bridge mortality is occurring.
- **Map fish densities** – The distribution and densities of all fish in the area, including Chinook, will be assessed near the bridge to determine where along the bridge the densities are greatest.
- **Identify predators and map their densities** – Predators that are known to eat steelhead and salmon will be identified and their distribution and densities mapped along the bridge.
- **Assess light/shade and noise near the bridge** – By monitoring light and noise in certain places near the bridge and comparing the data to steelhead tracking and fish densities, the Assessment Team will identify relationships and determine if further investigation is warranted.
- **Evaluate the impact of pools and eddies caused by voids at the center of the bridge** – Voids where the bridge center drawspan retracts to let ships pass will be compared to the rest of the bridge to determine whether the voids aggregate plankton, attracting planktivorous salmon and steelhead (or their fish prey) and increasing their susceptibility to predation.
- **Collect and model oceanographic data near the bridge** – Devices will be placed before, under, and after the bridge to precisely measure impacts to water circulation. Models will then be used to determine 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.

The bridge will be assessed under different conditions that could affect the extent of bridge impacts: during ebb and flood tides, day versus night, and when the center drawspan of the bridge—used to allow large ships to pass—is open versus closed. Multiple modeling and analysis approaches will then be used to bring these data together and isolate how the bridge is affecting steelhead survival and how the bridge may impact other salmon, and to characterize the extent to which the bridge may be affecting water circulation and water quality.

The first phase of this assessment will last 3 years (2016-2019) and cost $2.4 million (budget on p. 33). Additional components may be added to the assessment as early as 2018, depending upon what we learn from the first year of work. Beyond this budget, over $1.5 million in staff time and equipment has or is being contributed to assessing the impacts of the Hood Canal Bridge. This includes assessment planning, projected in-kind support over the course of the assessment, and the cost of the studies by NOAA and the Pacific Northwest National Laboratory that are the basis for this assessment.

Background

The Hood Canal Bridge is an important regional transportation asset and provides a vital link connecting the Olympic and Kitsap peninsulas with over 16,000 trips per day[1] 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.

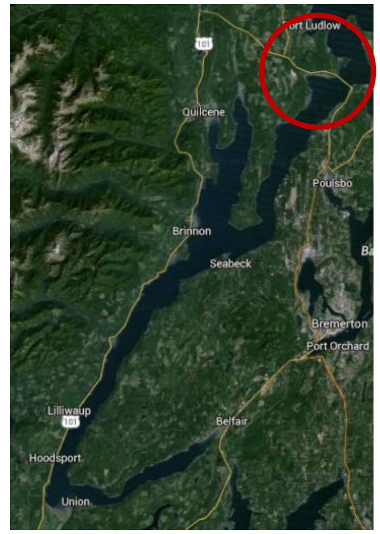


Figure 1. Hood Canal Bridge is located at the north end of Hood Canal near its entrance to Puget Sound (Google Maps).

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 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 efforts to restore and protect these fish and their habitat throughout Hood Canal. Several million more have been spent on research to determine what contributes to low dissolved oxygen events in Hood Canal and to quantify sources of nutrient inputs that may be contributing to these events. Low dissolved oxygen events are responsible for fish kills and other chronic impacts to Hood Canal biota. Finally, impacts of ocean acidification on Hood Canal shellfish beds, vital to the region's economy and culture, are of concern.

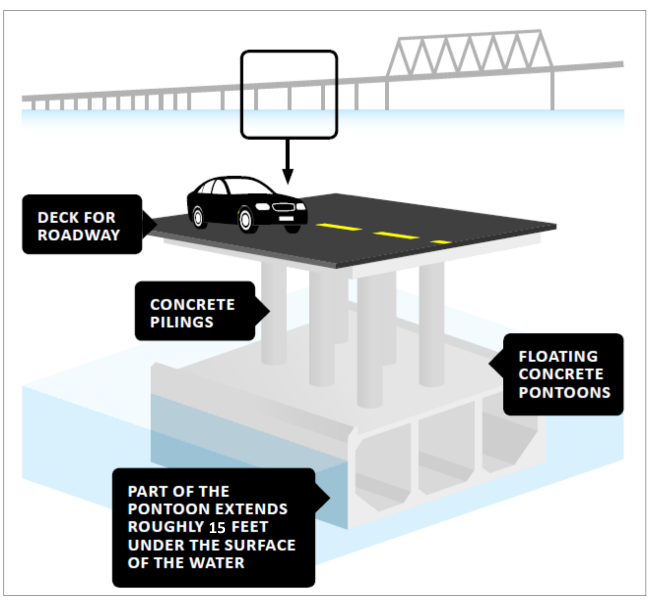


Figure 2. The Hood Canal Bridge floats on pontoons that span much of the width of Hood Canal and extend roughly 15 feet underwater (image property of Long Live the Kings).

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 83% of the width of Hood Canal and extend 15 feet underwater (Figure 2). Recent studies indicate 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 (Moore et al. 2013). Recent research also suggests that the bridge may disrupt water circulation (Khangaonkar and Wang 2013), increasing residence and flushing times in Hood

[1] http://hoodcanalbridge.blogspot.com/2009/04/all-roads-lead-to-mason-county-during.html

Canal. This could lower Hood Canal dissolved oxygen levels and exacerbate the effects of ocean acidification and climate change.

Recently, the Hood Canal Coordinating Council ranked recovery actions for ESA-listed salmon and ranked addressing this dual water quality and migration threat very high; the full value of our millions spent to date will not be realized until this survival bottleneck is addressed.

Addressing bridge effects is also consistent with the Five-Year Strategic Priorities of the Hood Canal Integrated Watershed Plan. For the five-year strategy, one of the five focal areas is salmon and two of the four primary pressures targeted are: a) transportation and service corridors, and b) climate change and ocean acidification. [2]

A collaboration of federal, tribal, state, and nonprofit partners convened beginning in 2015 to complete the following Hood Canal Bridge Ecosystem Impact Assessment Plan. This plan is 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.

[2] http://hccc.wa.gov/Integrated+Watershed+Plan/default.aspx

Evidence and Need

Impacts on outmigrating steelhead (and potentially other salmon and fish)

Puget Sound steelhead populations (including Hood Canal) have declined to less than 10% of historic run sizes over the past three decades and many wild populations now face possible extinction (Federal Registry Notice: 72 FR 26722). Juvenile steelhead mortality in the Puget Sound marine environment is a major cause of the observed population declines, and evidence suggests that the Hood Canal Bridge may significantly contribute to the early marine mortality of steelhead populations native to Hood Canal.

The mortality rate of wild steelhead migrating from Hood Canal natal rivers to the Pacific Ocean is highest between north Hood Canal and Admiralty Inlet, an area that includes the Hood Canal Bridge (Figure 3) (Moore et al. 2010, 2013). Furthermore, recent studies by NOAA indicate the bridge is a barrier to steelhead fish passage: slower migration times and higher mortality rates suggest the bridge is impeding migration and increasing predation (Moore et al. 2013). Specifically:

- Twenty-seven mortality events were detected within the vicinity of the Hood Canal Bridge, while only one mortality was recorded on the other 325 receivers deployed throughout the Hood Canal steelhead migration route.
- Over a five-year period, migrating steelhead smolts were detected at the Hood Canal Bridge array with greater frequency, on more receivers, and for longer durations than smolts migrating past three comparably configured acoustic arrays on their migration route.

However, the mechanisms by which the bridge affects mortality are poorly understood.

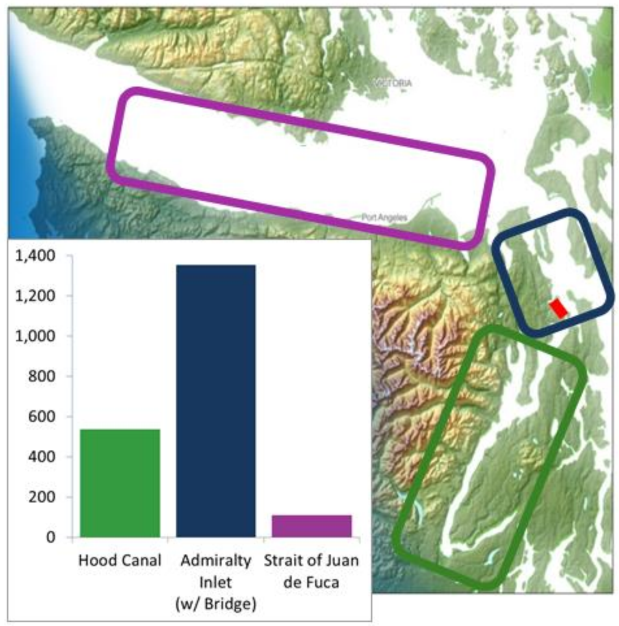


Figure 3. Number of juvenile steelhead that die per kilometer traveled on their migration to the Pacific Ocean: in Hood Canal, Admiralty Inlet (includes mortality at Hood Canal Bridge), and Strait of Juan de Fuca. Further investigation revealed the bridge itself is the primary location of high steelhead mortality (based on Moore et al. 2010 and outmigrant abundance estimates).

The bridge may also adversely affect other fish, including ESA-listed Chinook and summer chum. All juvenile salmon must pass the Hood Canal Bridge while outmigrating, and overwater structures are known to exacerbate predation for many salmon species (Yurk and Trites 2000, Williams et al. 2003, Celedonia et al. 2009, Blair et al. 2010). Data indicate the salmon travel offshore as well as nearshore in Hood Canal, making them potentially susceptible to impacts associated with the bridge pontoons. Juvenile Chinook, coho, chum, and pink salmon occupy and feed in offshore habitats of Hood Canal during their outmigration (Bax et al. 1978, Simenstad and Kinney 1978, Bax and Whitmus 1981, Bax 1983, Bollens et al. 2010. Also see figure 4 for a summary of recent trawl data). Also, acoustically tagged Chinook have been detected by receivers at and immediately east of the center of the Hood Canal Bridge (Chamberlin et al. 2011).

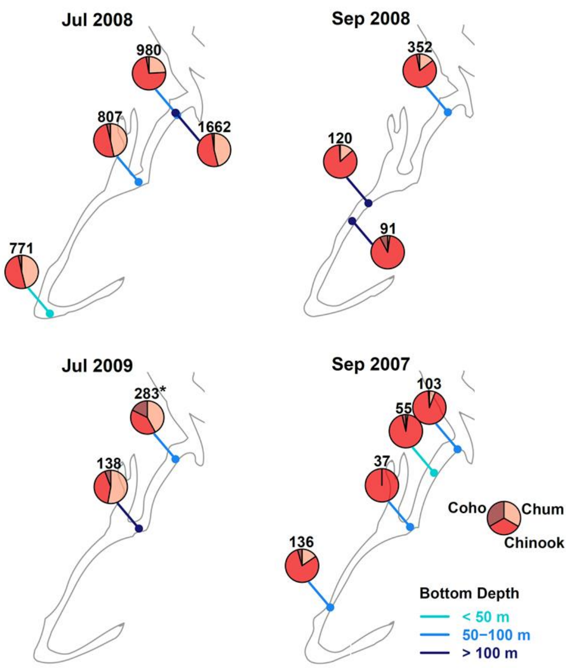


Figure 4. Juvenile salmon catches in the upper 15 m of the water column over a range of bottom depths in Hood Canal in trawl surveys following methods described in Beamish et al. 2000. Dots represent ship location at start of tow; color indicates recorded bottom depth. Pie charts represent proportional catch of juvenile salmon, with total number caught labeled above. All tows were 20 minutes duration except for one 16-minute July 2009 trawl indicated by an asterisk. Figure developed by Iris Kemp, LLTK. Based upon unpublished midwater trawl survey data from July 2008-2009 and September 2007-2008.

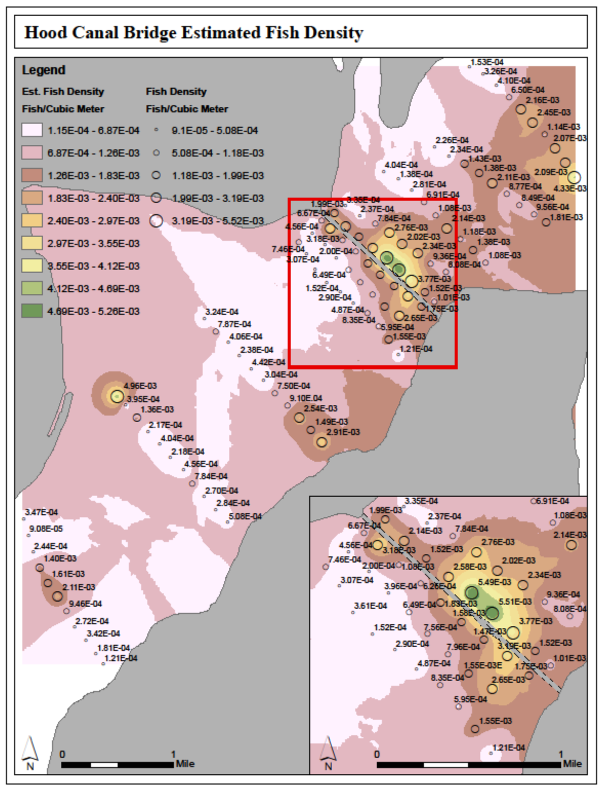


Figure 5. Estimated near-surface fish density within the vicinity of the Hood Canal Bridge (April 2015). Green indicates higher density. Exploratory survey performed by H. Daubenberger, Port Gamble S'Klallam Tribe.

Furthermore, there is direct evidence of an impact of the bridge on fish behavior. An exploratory hydro-acoustic survey of fish densities around the Hood Canal Bridge suggests the bridge affects overall fish distribution, with fish aggregating near the center of the bridge (Figure 5). Although fish species were not distinguished, this survey was performed during the period when juvenile salmon and steelhead are migrating through Hood Canal in the offshore. A closer look at the center of the bridge suggests that specific infrastructure may be playing a role. Water pools in between pontoons where the bridge center drawspan retracts to allow large vessels to pass. Fish, including juvenile chum, have been observed aggregating in these pools presumably to feed on zooplankton

(Figure 6), and seals have also been observed foraging on the fish that are in these pools (pers. comm. Hans Daubenberger, Port Gamble S'Klallam Tribe).

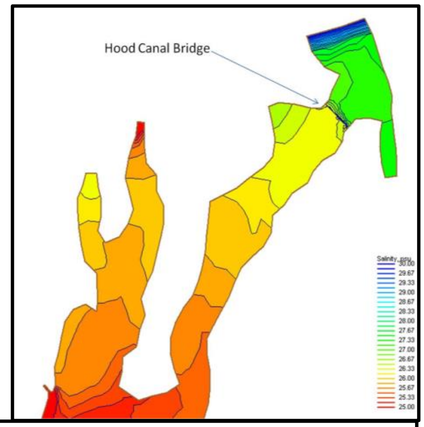
Figure 6. Photograph of biota in the center east pool (inset) of the Hood Canal Bridge on May 12, 2016 by Hans Daubenberger depicts juvenile chum swimming in a cloud of larval crab

Because juvenile steelhead travel near the water surface during outmigration (Beeman and Maule 2006), the bridge pontoons may present a physical obstruction to migration, increasing the density of smolts near the bridge and facilitate elevated predation rates. If not the pontoons themselves, their impact on water properties may have the same affect. The localized impact of the pools between the pontoons is one example. However, localized circulation impacts may extend the entire length of the bridge pontoons (Khangaonkar and Wang 2013). Impacts near the bridge may include the creation of eddies in the bridge pontoon wakes during tidal flows, increased vertical mixing, and altered temperature profiles. The bridge may also cause pooling of brackish outflow water, increased settling of algae and detritus, and re-entrainment in the exchange flow from Admiralty Inlet entering Hood Canal along the bottom. These hydrodynamic effects may influence juvenile steelhead outmigration and increase smolt vulnerability to predation.

Steelhead and salmon migration and predator behavior may also be affected by light and noise/sound levels. Light and noise levels are increased at the bridge relative to surrounding waters. The bridge is lit and well-traveled with approximately 16,000 vehicle trips per day. Increased noise levels may disorient fish, while increased light levels may enable visual predators to target prey more effectively (Popper and Carlson 1998, Myrberg Jr 1990, Yurk and Trites 2000).

Potential impacts on Hood Canal water circulation and water quality

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. It is well known that fjords tend to become anoxic, especially in the presence of a sill. This is the case in parts of Hood Canal, such as Lynch Cove and Dabob Bay, where low dissolved oxygen conditions have been observed since the 1950s (e.g., Barnes and Collias 1958, and Collias et al. 1974) and have been of great interest due to recurring fish kills in the 2000s (e.g., Curl and Paulson 1991; Paulson et al. 2006; Newton et al. 2007).



Unimpeded outflow of brackish water from typical fjords through the shallow surface layers is of utmost importance since it is responsible for setting up stratification, salinity gradients, and resulting exchange flow and flushing of the basin needed for maintenance of water quality. Studies have shown that the structure of currents and stratification in fjord-like basins within Puget Sound may easily be disturbed. Wind-induced coastal currents and upwelling, causing movement of low dissolved oxygen waters to the surface layers, have been associated with some of the past major fish kill events (e.g., Kawase 2007). Despite the episodic nature of recorded major events, evidence indicates that oxygen concentrations in the 1990s and 2000s were consistently lower in the southern reaches of Hood Canal than before the 1960s (e.g., Newton et al. 2007).[3] Construction of the Hood Canal Bridge was completed in 1961.

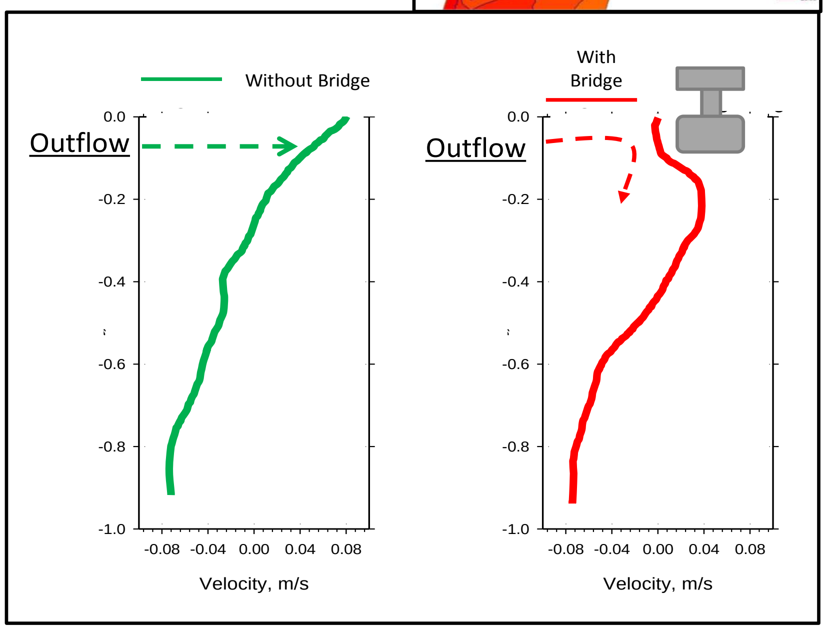


Figure 7. Top figure is modeled illustration of changes in salinity north and south of the Hood Canal Bridge. Bottom figures illustrate modeled impact of the Hood Canal Bridge on water circulation in and out of Hood Canal. (from Khangaonkar 2015, presentation).

Pacific Northwest National Laboratories (PNNL) investigated the possibility that the natural oceanographic structure of fjordal stratification and circulation could be

[3] *A study by PNNL (Brandenberger et al. 2008) on Hood Canal is often quoted to make the point that hypoxia events in Hood Canal may be natural events. This work, based on reconstructions of redox-sensitive metal indicators, suggests hypoxia has occurred in Hood Canal well before human alterations beginning in the 1900s. However, the reconstruction time line does not extend past the approximate year 2000 and is unable to resolve the timing of short-lived hypoxia events that led to fish kills in Hood Canal during the early 21st Century.*

disrupted by hydraulic modifications of the surface brackish layer. The potential for permanent floating structures (in this case the floating Hood Canal Bridge across the width of the Canal) to alter the circulation and flushing characteristics of the system was examined using a three-dimensional finite volume coastal ocean model (Khangaonkar and Wang 2013). The results suggest 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 (Figure 7). 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 point to the possibility that the presence of the floating bridge might have increased the residence times in the basin by 8 to 13 percent. Validation using field observations and three-dimensional numerical models as proposed in this report are needed to assess with higher accuracy whether the numerical model based results are realistic.

While these numbers seem small, such a reduction in the ability for Hood Canal to flush could be a key factor leading to low dissolved oxygen levels, impacting the entire Hood Canal food web. Reduced dissolved oxygen could cause short-term stress to hypoxia-intolerant organisms, forcing mobile species to move out of their preferred distributions and potentially causing mortality events in sessile species. These changes, in turn, could create opportunities for predators, competitors, or prey species that are tolerant of low dissolved oxygen. Longer-term effects may include shifts in community structure and energetic pathways as opportunistic, hypoxia-tolerant species become more dominant.

A recent EPA and WA Department of Ecology review and synthesis of available information on human impacts to dissolved oxygen in Hood Canal identified the Hood Canal Bridge as one of the factors needing examination (Cope and Roberts 2013). The report concluded that the effect of the bridge on circulation as identified in Khangaonkar and Wang (2013) may affect water quality and recommended additional work to quantify the bridge's effect on dissolved oxygen.

The bridge impact on residence time and flushing of the basin may also affect surface temperatures, biogeochemical cycling including nutrient uptake and algae growth, sedimentation, and pH, all of which may create other pathways of impacts to the entire Hood Canal ecosystem.

Species of critical concern based on their ecological, commercial, and recreational/tourism importance include shellfish, crab, shrimp, forage fish, rockfish, salmon, steelhead, and killer whales.

Objectives and Framework

The Hood Canal Bridge Ecosystem Assessment Plan is 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 assessment is structured following an adaptive management approach. Adaptive management is often loosely defined. For the purposes of this assessment plan we will use the term to describe an iterative process where work will occur in phases, building from what we know as described in the "Evidence and Needs" section above. As we create a refined understanding of how the bridge interacts with steelhead, salmon and the greater ecosystem, solutions will be developed, tested and ultimately implemented that simultaneously address impacts and maintain the bridge and its transportation benefit. An Assessment Team will carry out the science and will work with a Management Committee to develop and implement the solutions. External reviewers will engage along the way and the process will include methods to engage and receive feedback from the community: to ensure assessment findings and associated solutions are accepted and fully implemented[4]. This process is consistent with Washington States chosen approach to managing environmental natural resource issues and a similar process is used to manage Lake Washington's Sockeye population (Tetra Tech, 2006.

This document focuses primarily on the first phase of the assessment and describes the framework and structure that will be utilized for the entire assessment. Some suggestions for future phases are included.

Framework

The Hood Canal Bridge Ecosystem Impact Assessment is built around a multi-question framework developing possible adaptive management solutions as we execute:

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?**

   In order to develop specific solutions that address the specific causal linkages between the bridge and steelhead mortality, we must determine where steelhead mortality is greatest along the bridge, who the predators are, and functionally how the bridge leads to increased predation. Furthermore, given the evidence that fish distribution, which likely includes listed Chinook and chum salmon, may be influenced by the bridge (Figure 5, above), we must also determine whether there are relationships between fish distribution, steelhead mortality, and specific aspects of the bridge. Causal agents may include the pontoons as a barrier, or changes to water circulation and other water properties, that may slow migration, heighten fish densities and thusly increase susceptibility to predation. Light, shade and noise impacts from the bridge may also affect fish and/or predator behavior. Finally, structural voids near the center of the bridge may change water properties and aggregate plankton, attracting planktivorous salmon and steelhead (or their fish prey) and increasing their susceptibility to predation.

   Specific sub-questions are as follows:

[4] See the Organizational Structure section for additional details about Team composition and reviewer and interested public inclusion.

A. What are fish migration behavior and fish distribution patterns at versus away from the bridge? For steelhead, what defines a successful migration past the bridge versus one that results in mortality?

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

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

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

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?

F. How do we fix the issue?

In order to differentiate between what is common in the Hood Canal environment and what is unique to the area directly at or around the bridge, this assessment will compare impacts at the bridge versus away from the bridge[5]. Furthermore, Questions A-E will be addressed simultaneously and coordinated in space and time, so that we can isolate causal linkages between the bridge and the mortality of steelhead. These questions will also indicate linkages that may affect mortality between the bridge and altered behavior of salmon and other fish. Work will be sequenced so that phase 1 provides enough data to validate and assess the strength of various causal links between mortality, distribution, predation and the influence of the bridge on the surrounding environment (question E). Subsequent phases may include efforts to establish a refined understanding of the strength of particular impacts, if needed to inform solutions development. That said, we are confident that phase 1 will narrow the field of causal linkages between the bridge and mortality enough that solutions (question F) can begin to be assessed in phase 2.

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. Through field data collection and refined modeling, we must confirm the strength of the bridge impact on circulation. From there, we must determine whether Hood Canal water quality—including dissolved oxygen, temperature, acidity, and nutrient dynamics—is affected. If significant, this information will then be used to characterize the extent of impact the bridge is having on the Hood Canal ecosystem and isolate functionally how the bridge is driving ecosystem impacts. Species of critical concern based on their ecological, commercial, and recreational/tourism importance include shellfish, crab, shrimp, forage fish, rockfish, salmon, steelhead, seals, eagles, and killer whales.

[5] 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.

Specific sub-questions are as follows:

A. Does the bridge obstruct ebb - flood currents & impact flushing of brackish outflow water?

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

C. How does the Hood Canal bridge affect key marine species residing in Hood Canal?

D. If the impact is significant enough to warrant action, how do we fix the issue?

These questions will be addressed in a step-wise process. The results of Khangaonkar and Wang 2013 provide evidence that the bridge does impede the flushing of Hood Canal; however, at the time no field data in the vicinity of the bridge were available to perform this analysis. Therefore, phase 1 will focus on question A., validating and increasing the accuracy of the Khangaonkar and Wang 2013 results, using field data and three-dimensional numerical models. Furthermore, a preliminary assessment of whether the obstruction to flow may translate to impacts to dissolved oxygen, temperature, pH and nutrient dynamics throughout Hood Canal will be performed to coarsely assess question B. This will be accomplished using the Salish Sea Model (Khangaonkar et al 2012) with an updated biogeochemical module capable of simulating sediment diagenesis, hypoxia, pH and alkalinity using the hydrodynamic solution with a refined grid in Hood Canal developed during this study, applied with and without the bridge. The results of this will then be used to determine whether proceeding with an extensive investigation of potential impacts to the Hood Canal ecosystem (questions B and C), along with an investigation of potential solutions (question D) is warranted.

Combining the two primary objectives of determining bridge effects on juvenile steelhead and salmon outmigrants and the entire Hood Canal ecosystem in this assessment is warranted due to the value in integrating assessment activities. Much of the same oceanographic data are required to assess near-bridge oceanographic effects on outmigrating steelhead and salmon as are required to assess the oceanographic effects of the bridge that could lead to Hood Canal-wide changes in physical, chemical and biological properties.

Toward solutions

To help frame the trajectory of this effort, an initial list of potential management actions has been developed in the plan based upon the causal agents being assessed. Figures 8 and 9, below, outline the causal agents or pathways in which the bridge may be affecting steelhead (and potentially other salmon) survival and the Hood Canal ecosystem as a whole, and describes suites of potential near-term management actions that will not adversely affect the bridge as a transportation corridor. These diagrams are intended to be illustrative and are by no means detailed or exhaustive. As specific causal agents are confirmed, we will work with the Assessment Team, Management Committee, and external reviewers to refine these lists of potential management actions, and then simulate, field test, and fully implement appropriate management solutions.

Phase 1 assessment results will clarify and refine the list of potential causal agents. As an outcome of this phase, we will review the results of phase 1 to: a) work with our partners and others to refine the suite of potential management actions, in particular those related to the impact of the bridge on outmigrating steelhead (and potentially Chinook and chum salmon), b) reach agreement on remaining data gaps that must be addressed. Subsequent phases will focus on filling data gaps and simulating, field testing, and fully implementing appropriate management solutions that won’t adversely affect the bridge as a transportation corridor.

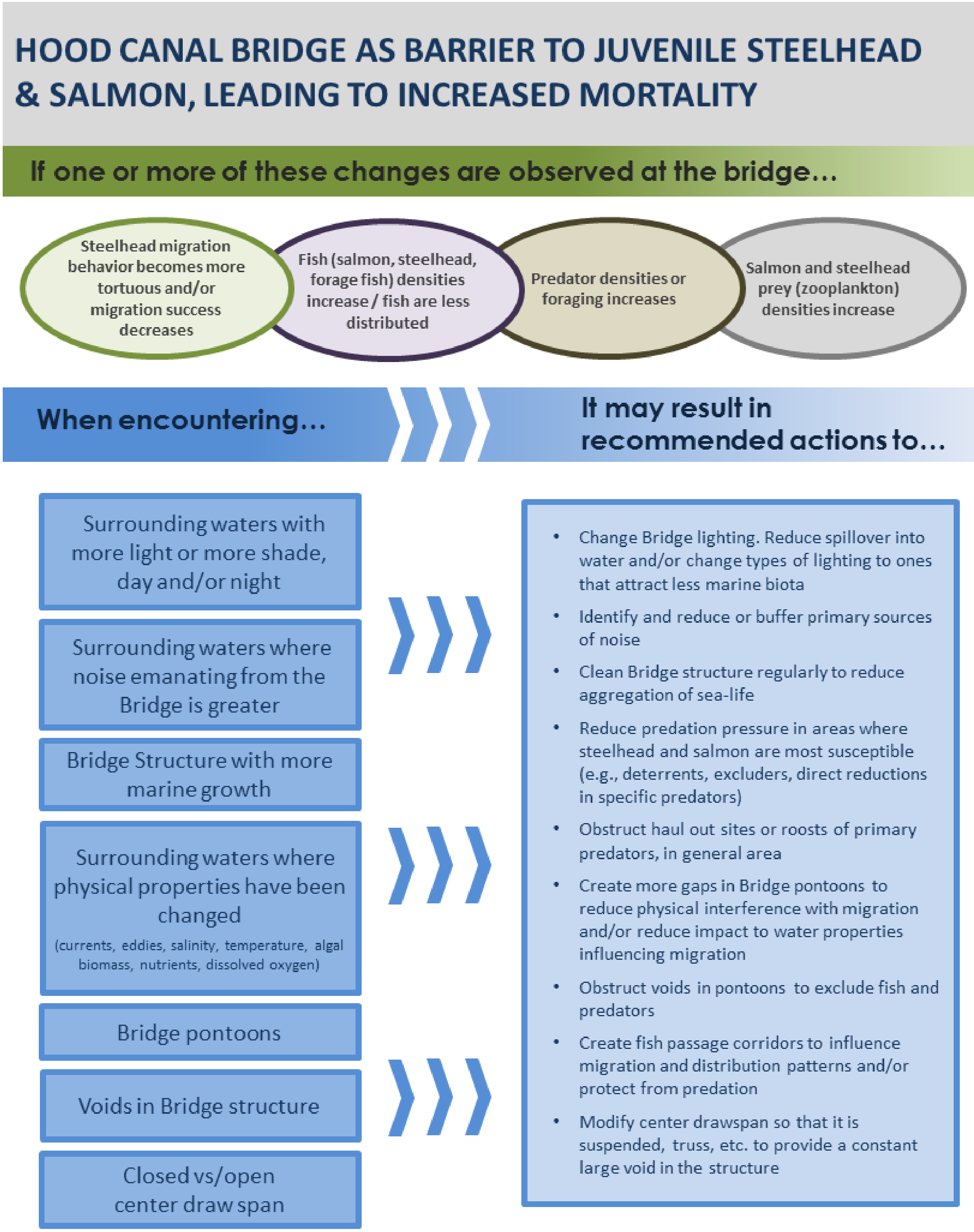


Figure 8. Diagram associating potential findings with potential management actions affiliated with steelhead and salmon survival past the bridge. This is an illustration and not meant to be an exhaustive list.

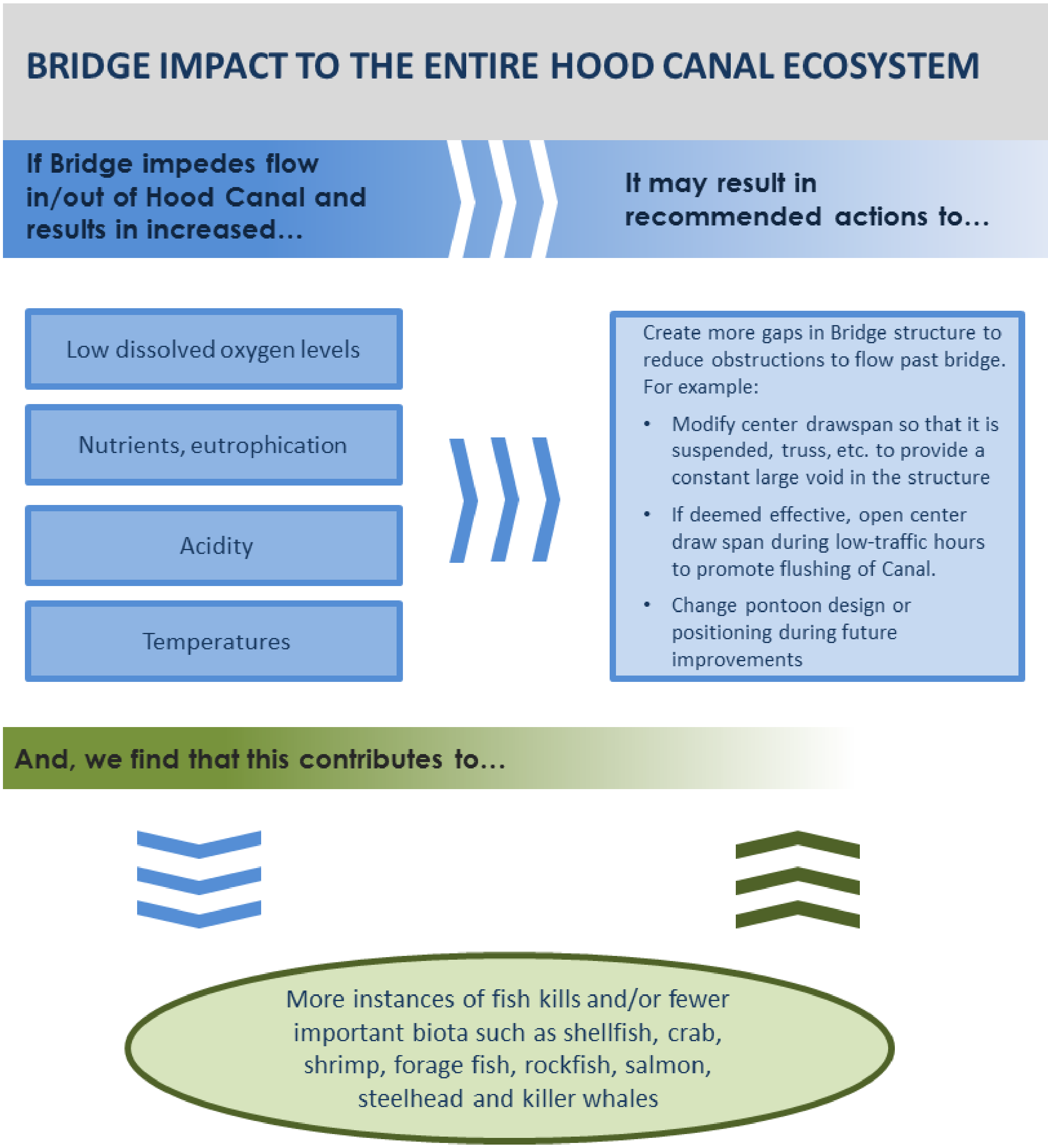


Figure 9. Diagram associating potential findings with potential management actions affiliated with broad-scale impacts to the Hood Canal ecosystem. This is an illustration and not meant to be an exhaustive list.

Assessment Components

The following provides a brief description of the assessment components relative to the questions outlined in the Objectives and Framework section, above. Extended descriptions of assessment components are provided in Appendix A. Details of Individual Components The components, both those that will occur in phase 1 and components for consideration in subsequent phases, are numbered for cross-reference among sections. **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 B: Hood Canal Bridge Impact Assessment Matrix".

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 away[6] from the bridge? For steelhead, what defines a successful migration past the bridge versus one that results in mortality?

The following assessment components provide the core data to articulate steelhead migration and mortality patterns, and fish distribution patterns. These are the primary response variables when assessing spatial-temporal relationships between the bridge, steelhead mortality and the risk of mortality to other salmon (see component 13).

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

Megan Moore and Barry Berejikian, NOAA Northwest Fisheries Science Center

Acoustic tagging and tracking will be used to describe fine-scale migration patterns of steelhead as they encounter the Hood Canal Bridge and to identify migration paths associated with survival and mortality. Previous telemetry projects have indicated that steelhead smolts mortality increases at the Hood Canal Bridge, relative to nearby areas along the migration path. However, those initial efforts lacked the precision needed to isolate mortality along the span of the bridge area; nor did they have the predation, circulation, noise, and light data needed to establish the mechanistic pathways of mortality. For this project, a fine-scale two-dimensional acoustic telemetry array will allow researchers to triangulate tagged juvenile steelhead positions and map migration paths with a high degree of precision. A line of receivers will be deployed on the seafloor on either side of the bridge, spaced about 200 m apart, and will cover the entire channel from the east to the west shore. Stationary transmitters will be deployed in several known locations to calibrate the system. An additional line of acoustic receivers will be deployed near the outlet of Hood Canal at Twin Spits (TS) so that migration paths of smolts which survived

[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.

past the bridge can be compared to migration paths of smolts which were not detected past the bridge and presumed dead. This project will also utilize two existing receiver lines at Admiralty Inlet (ADM) and the Strait of Juan de Fuca (JDF). These high-resolution data will feed a powerful analysis of how migration path characteristics (location, time, depth) at the bridge affect survival odds.

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

Hans Daubenberger, Port Gamble S'Klallam Tribe

Juvenile steelhead are typically larger than other juvenile salmon migrating out of Hood Canal. Their size, large enough to accommodate acoustic tags, and uniquely rapid outmigration behavior, makes them ideal for assessing site-specific mortality using acoustic telemetry. However, juvenile Hood Canal summer chum and Chinook, listed as threatened under the Endangered Species Act, also encounter the bridge as the migrate to the Pacific Ocean. Due to their smaller size at outmigration and highly variable marine life-history patterns (some even stay in Puget Sound and Hood Canal to adulthood), it is difficult to assess these fish using acoustic telemetry. Therefore, we cannot assess individual fish behavior and mortality patterns of juvenile Chinook and chum at the bridge. However, we can assess the distribution of fish, including juvenile Chinook and chum, at the bridge versus away from the bridge, via hydro-acoustic surveys of the upper water column. As such, hydro-acoustic surveys will performed along six parallel transects (within 50 m of bridge, 200m, 500 m, 1000 m, 1500 m, 2000 m, 8,000 m) covering areas to the north and south of the bridge that are equal in distance to the length of the bridge.

Figure 5, in the Evidence and Need section above, is the result of an exploratory single-day effort by the Port Gamble S'Klallam Tribe during the 2015 steelhead outmigration. This exploratory effort clearly depicts how fish distribution data may help isolate relationships between specific aspects of the bridge and fish behavior. Because these data will be collected in a manner spatially and temporally similar in nature to the other data being collected in this assessment, we will be able to assess relationships between the fish distribution data and steelhead migration and mortality patterns, predator distribution, and/or the physical influences of 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 caused by the Hood Canal Bridge are hypothesized to increase the density of steelhead smolts near the bridge, channel migrating smolts through more densely concentrated routes, and facilitate elevated predation rates at these locations. Furthermore, hydro-acoustic data suggest the densities of other fish, including Chinook and chum, may increase near specific locations of the bridge. Thus, predator/prey interactions between the most likely predators (harbor seals/harbor porpoise/cormorants) and salmon and steelhead may be influenced by the presence of the Hood Canal Bridge. The following describes how this will be assessed.

3. Map predator (marine mammal and bird) densities

Scott Pearson and Steve Jeffries, Washington Department of Fish and Wildlife

The primary goal of phase 1 is to assess the predator species (seabird and marine mammal) composition, abundance, locations, distribution, and foraging behavior at, versus away from the bridge. This information will document the specific list of potential steelhead and salmon predators and will provide spatial-temporal distribution data that will confirm whether predator distribution is unique at the bridge. These data will also be used to assess specific relationships between predator distribution, fish distribution, steelhead mortality and the physical influences of the bridge. A better understanding of the specific predators and their behavior is critical to assessing management solutions. For example, if the primary predator is the harbor seal, it might be feasible to exclude them from nearby haulouts or to modify the bridge to make it more difficult for seals to capture steelhead.

Two survey approaches will be implemented. **At-sea surveys** will be performed to identify predators and their locations and quantify abundance in relation to distance from the Hood Canal Bridge - both to the north and to the south. This will allow us to determine if any potential steelhead predator (see Pearson et al. 2015, Table 1) is more abundant closer to than farther from the bridge during the steelhead smolt outmigration window, 1 April – 30 May. If predation is responsible for the apparently high mortality near the bridge, then we might expect the responsible predator(s) to be more abundant near the bridge. Survey methods will follow Raphael et al. (2007). **Bridge-based** predator surveys will also be conducted from the bridge, consisting of continuous counts of predator seabird and marine mammal species in prescribed time intervals interspersed with focal animal observations to assess foraging behavior (Altman 1979). Bridge-based surveys will include added focus on the pools and eddies created by bridge pontoons adjacent the center drawspan (also see assessment component 14).

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

Steven Jeffries, Scott Pearson, Monique Lance, Kenneth Warheit, Washington Department of Fish and Wildlife. Megan Moore and Barry Berejikian, NOAA Northwest Fisheries Science Center. Austen Thomas, Smith-Root

There have been numerous observations of harbor seals utilizing the bridge for foraging. Port Gamble S'Klallam Tribe (PGST) staff have observed seals when working in the area over the past several years. In 2016, PGST staff set up GoPro and BlueView cameras on a portion of the bridge and documented seals foraging. Furthermore, WSDOT staff have indicated seals and their pups utilizing ledges adjacent pools formed in the bridge pontoon structure (pers. comm. Hans Daubenberger, PGST).

However, the presence of harbor seals has not been documented in a quantitative fashion, nor in a manner that can illustrate their abundance and behavior at the bridge is unique. Furthermore, the broad suite of potential predators using the bridge, to weigh relative potential impacts, is not yet characterized. For example, harbor porpoise are commonly spotted in the vicinity of the bridge. Therefore, the broader predator analysis (component 3) is prioritized for phase 1. If harbor seals do in fact rise to the top of the list of likely culprits, additional analysis of harbor seals may be warranted.

The Assessment Team drafted two interconnected assessment components to further assess harbor seal related steelhead (and other salmon) mortality: seal diet analysis and an assessment of seal-steelhead interactions and seal foraging behavior. **For the seal diet analysis (component 4)**, if implemented, the Assessment Team will determine the extent to which the bridge influences harbor seal-related steelhead mortality by comparing the diets of seals that forage at the bridge versus seals that forage away from the bridge in Hood Canal estuaries. It is hypothesized that the Hood Canal Bridge alters the migratory behavior of juvenile steelhead in ways that increase their vulnerability to steelhead predators such as harbor seals. To address question of harbor seal predation on juvenile steelhead and salmon, recent developments in the field of molecular scatology coupled with hard parts identification of adults and juvenile salmon have enabled simultaneous quantification and species identification of salmonids in harbor seal diet samples (i.e. scats). These techniques can be used to determine whether seal predation is one of the sources of increased steelhead mortality at the bridge. GPS packs will be affixed to seals to characterize the foraging areas of the treatment/near-to bridge seals and control/away-from bridge seals, and to confirm the validity of the treatment/control study design. Sites where juvenile steelhead (and Chinook) predation by seals likely occur will be identified by combining foraging areas with diet data for each respective site.

To **analyze seal-steelhead interactions and seal foraging behavior (component 5)** and to quantify the spatial and temporal overlap with steelhead smolts instrument packs will be mounted on the pelage of an individual harbor seals. The mounted instrument packs include GPS and acoustic telemetry transceivers, and are capable of detecting acoustic telemetry transmitters implanted into steelhead smolts (Berejikian et al. 2015), so that interactions between the two species can be quantified and georeferenced. Instrument packs will be mounted on harbor seals captured at haulout areas within foraging distance of the Hood Canal Bridge and on seals captured at haulout areas in Hood Canal at river mouths away from the bridge to provide detailed information on impacts of the Hood Canal Bridge on steelhead migratory behavior and survival.

C. WHAT IS THE INFLUENCE OF THE BRIDGE ON THE SURROUNDING PHYSICAL ENVIRONMENT, AT VS AWAY FROM THE BRIDGE?

As explained in the Evidence and Need section, there are numerous pathways through which the bridge can lead to fish mortality. The Assessment Team concluded that the most likely pathways include the pontoons acting as a barrier--or changes to water circulation and other water properties as a result of the pontoons—slowing migration, heightening fish densities and thusly increasing susceptibility to predation. Light, shade and noise impacts from the bridge may also affect fish and/or predator behavior. The following describes the specific assessment components.

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

Hans Daubenberger, Port Gamble S'Klallam Tribe and Iris Kemp, Long Live the Kings (in coordination for Keister Lab, University of Washington, for zooplankton analysis)

Artificial light and shading impacts may be created by the overwater structure of the bridge and the overhead lights installed on the bridge deck. Studies of overwater structures have documented light and shade impacts on fish behavior (foraging, schooling, migration path) and predator behavior. Lighting may attract zooplankton and alter foraging patterns of fish near the bridge, and may increase predation risk by enabling visual predators to more effectively target prey. Conversely, shaded areas may provide cover for predators and decrease avoidance capability of juvenile steelhead.

For **phase 1** of the assessment, a pilot analysis of light impacts will be performed. The magnitude and spatial extent of artificial light and shade impacts near the bridge structure will be coarsely measured and compared to average light levels in Hood Canal away from the bridge, and assess the potential impacts to local biota. Georeferenced light and turbidity measurements will be taken at the bridge and along transects perpendicular to the bridge during daylight, full moonlight, and low moonlight to characterize light and shade in the immediate vicinity of the bridge and determine how far away from the bridge light/shade impacts decrease to ambient levels.

Zooplankton densities and community composition will be assessed in conjunction with light sampling. These data will be used to characterize zooplankton communities in various levels of light. The results will also provide a general map of zooplankton densities and community composition near and away from the bridge. Finally, a focused assessment of zooplankton will occur at the pools and eddies adjacent the center drawspan given initial observations suggest there are disproportionately high levels of plankton congregating there (see Figure 6. Also see component 14).

Correlations between intensities of light and shade and zooplankton aggregations, steelhead migration behavior, fish presence and densities (salmon, forage fish and their predators), and predator (bird, mammal) presence and densities will be assessed. This work will result in GIS layers describing the magnitude and spatial extent of light and impacts caused by the bridge, and the potential associated effects on biota in the vicinity. A more precise investigation of light impacts may be warranted in future phases, depending upon the results of this analysis.

7. Measure noise impacts to fish behavior

Daniel Deng, Ki Won Jung, Jayson Martinez, Tarang Khangaonkar, Pacific Northwest National Laboratory. Hans Daubenberger, Port Gamble S'Klallam Tribe[7]

Mortalities of steelhead were consistently observed at the Hood Canal Bridge during 2006-2010, with the exception of 2009 (Moore et al 2013). In 2009, the Hood Canal Bridge was closed to vehicle traffic during the steelhead smolt outmigration and no probable mortalities were observed at the bridge. Portions of the bridge were being replaced at this time; therefore, the extent of coverage across Hood Canal by the pontoons was less, reducing the potential for a physical obstruction to steelhead migration. However, this observation raises questions about noise impacts. Specifically, do anthropogenic noises produced by vehicle traffic on the bridge interfere with the normal behavior of outmigrating steelhead smolts, and/or does this provide a masking effect for potential predators resulting in the measured increase of probable mortalities as recorded at the Hood Canal Bridge by Moore et al. (2013)? The objective of this assessment activity is to establish whether there is a relationship between steelhead smolt behavior and the anthropogenic noises (and or affiliated pressures emanated) associated with the Hood Canal Bridge. And, if so, does a change in behavior lead to an increased probability of mortality?

For **phase 1**, a pilot assessment of noise propagation will occur. Sound pressure and particle motion data will be collected and analyzed from 2 field locations during the steelhead outmigration period, prior to launching the full-scale study, to confirm whether noise

[7] The U.S. Navy has also stated interest in participating in this part of the assessment.

propagation should be considered as one of the primary pathways the bridge could be affecting salmon and steelhead migration behavior and survival. If warranted, data collection will be repeated in the next phase and expanded to 6-7 stations within the immediate vicinity of the Hood Canal Bridge during the steelhead smolt outmigration period. The more extensive dataset will then be used to numerically simulate underwater acoustic noise propagation using a finite element method (FEM) model.

8 & 9. Collect data and characterize the bridge zone of influence (impact to flows, salinity, temperature gradients)

While the pontoons themselves may act as a barrier to migration, there's also a chance the relationship between the pontoons and fish behavior is more complex. As stated in the Evidence and Need section, the pontoons may result in oceanographic disturbances, including the creation of eddies in the bridge pontoon wakes during tidal flows, increased vertical mixing, and altered temperature profiles. The bridge may also cause pooling of brackish outflow water, increased settling of algae and detritus, and re-entrainment in the exchange flow from Admiralty Inlet entering Hood Canal along the bottom. These hydrodynamic effects may influence juvenile steelhead outmigration and increase smolt vulnerability to predation.

In phase 1, we will characterize the bridge zone of influence. Components 8 and 9, to be implemented in phase 1, are described in the next section as they inform both the assessment of impacts to fish passing the bridge and the assessment of the ability for Hood Canal to flush.

Depending upon the results of phase one, a more refined understanding of the bridge zone of influence on fish behavior may be warranted. A detailed and fine-scale 3-D description of the flow field near the Hood Canal Bridge can be developed using a **computational fluid dynamics (CFD) model** (component 10 in Appendix A) capable of simulating non-hydrostatic flow fields near rigid structures. Near-field impacts may include development of eddies in the bridge pontoon wakes during ebb and flood flows, increased vertical mixing affecting stratification and salinity gradients, and altered temperature profiles. These fine-scale hydrodynamic effects may also influence the migration of juvenile fish and provide zones that are favorable to fish species that prey upon salmonids. Unlike the basin-wide setup of the Salish Sea model, a CFD model would consist of a smaller domain local to the bridge but at a much higher resolution, sufficient to capture the eddies and characterize the wake zones which outmigrating steelhead smolts may encounter during peak ebb and flood flows. This model could also be used in conjunction with a Eulerian-Lagrangian-Agent method, individual based model (component 13b in Appendix A) to simulate infrastructure changes to the bridge, for solutions testing.

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

14. Comparative assessment of fish, predator, zooplankton densities in pools and eddies vs away from them

Hans Daubenberger, Port Gamble S'Klallam Tribe. Scott Pearson, Washington Department of Fish and Wildlife

Preliminary data suggest pools and eddies near the center of the bridge may have a very unique impact to fish. Water pools in between pontoons where the bridge center drawspan retracts to allow large vessels to pass. Fish, including juvenile chum, have been observed aggregating in these pools presumably to feed on zooplankton (Figure 6), and seals have also been observed foraging on the fish that are in these pools (pers. comm. Hans Daubenberger, Port Gamble S'Klallam Tribe). A preliminary assessment will be performed that compares aggregations of biota in the water passing through structural voids in the bridge (and the surrounding bridge infrastructure) to areas without voids and to the large openings on the east and west sides of the Hood Canal Bridge where water more freely passes. Underwater video observations and plankton tows will be used to characterize sea life including affiliated fish and zooplankton assemblages. DIDSON and/or Blueview acoustic imaging equipment will be installed underwater to collect data about the biota in and around the pools. Turbidity measurements will be taken to account for the effects of turbidity on the results. These observations will be performed at multiple points along the tidal cycle to ensure each area is appropriately characterized. In addition, a surface video observation station will be set up to determine whether seabirds and marine mammals are subsequently attracted to areas with structural voids. Those regions will then be compared to the fish distribution and densities data obtained from hydroacoustic sampling (described in activity 2), predator composition and distribution data from activity 3 and zooplankton data from activity 4 to determine whether what is occurring in the pools is in fact unique. This work will be performed by the Port Gamble S'Klallam Tribe in coordination with WDFW and Long Live the Kings.

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)

Megan Moore, NOAA Northwest Fisheries Science Center

The collection of detailed movement paths of individual steelhead (component 1) and the distribution of salmon and forage fish (component 2) will permit a wide range of analysis approaches that explore the characteristics of steelhead movement paths and mortality, fish distribution, and their sensitivity to the physical impacts of the Bridge.

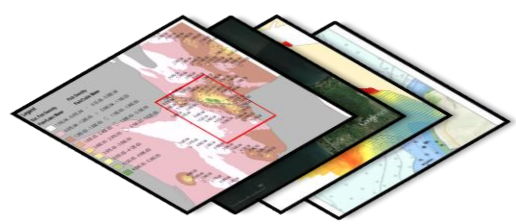


Figure 10. Graphical depiction of data layers that will be synthesized.

In **phase 1**, a **geographically weighted regression analysis (component 13a)** will be performed to explore spatial correlations between steelhead migration and mortality patterns, fish (including salmon and forage fish) distribution, and spatially explicit variables such as predator and zooplankton distribution and the physical impacts of the bridge. This includes the pontoons themselves, and the light/shade, noise, water circulation, and water quality impacts being studied. Comparisons of impacts during day (high levels of light and traffic noise) and night (low levels of light and traffic noise), tidal cycles, and bridge center drawspan state (open versus closed) will be included.

Depending upon the results of phase 1, more detailed analyses may be warranted. For example, comprehensive modeling—such as a Eulerian-Lagrangian-Agent method, individual based model (13b in Appendix A) — can be used to simulate the bridge impacts to steelhead migration and subsequently test various solutions.

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

A. Does the bridge obstruct ebb - flood currents & impact flushing of brackish outflow water?

The results of Khangaonkar and Wang 2013 provide substantial evidence that the bridge does impede the flushing of Hood Canal; however, at the time no field data in the vicinity of the bridge were available to perform this analysis. **Phase 1** will focus on validating and increasing the accuracy of the Khangaonkar and Wang 2013 results. Two activities will be performed to accomplish this:

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

Kevin Redman and Mike Taylor RPS – Evans Hamilton. Tarang Khangoankar, Pacific Northwest National Laboratory

Oceanographic data collection will provide data for calibration of hydrodynamic models and for field confirmation of the hypothesis that the Hood Canal Bridge affects currents and mixing in the region near the bridge. For the purpose of this study, near-field is defined as the region where the influence of the bridge on currents, salinity, and temperature variables is noticeable relative to ambient (far-field) conditions. Prior analysis and fish tracking studies have shown that bridge pontoons block the surface currents in the upper 3.7 m of the water column. This alters the velocity structure near the bridge. The added mixing due to flow under the bridge also alters stratification (salinity and likely temperature profiles) as predicted in the model results by Khangaonkar and Wang (2013). To capture these near-field effects, data will be collected over 4 weeks using bottom- and bridge-mounted ADCP velocity profilers at stations upstream and downstream of the bridge. CTD measurements (salinity and temperature) and boat mounted ADCP transects during peak ebb, flood, high tide and low tide periods are also planned.

9. Characterize the bridge zone of influence – Hydrodynamic Modeling

Tarang Khangaonkar, Taiping Wang, Wen Long, Marshall Richmond, Pacific Northwest National Laboratory

The field data will be used to quantify the bridge's zone of influence. We expect this zone of influence region to be one to two bridge widths (18 to 36 m) normal to the direction of flow for tidal currents but could be much larger - one to two Hood Canal channel widths (2.4 to 4.8 km) - for variables such as temperature and salinity. In this task the intermediate-scale Salish Sea Model (salish-sea.pnnl.gov) developed by PNNL in collaboration with Ecology and EPA will be refined for Hood Canal basin along with incorporation of the Hood Canal Bridge module. The prior approximate representation of the bridge in the model will be improved with the field data collected to better represent the effect on continuity and momentum of the flow field. A quantitative assessment of the effect of Hood Canal Bridge on seasonal near-field circulation and water quality over 2 years will be conducted. The results will help identify a zone of influence on currents and parameters such as salinity, temperature, and algal biomass, and dissolved oxygen around the structure based on change relative to ambient. The work will account for differences at low and high tides, and differences between bridge center drawspan states (open versus closed).

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

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 have not yet been examined.

In order to determine whether an assessment of Hood Canal ecosystem-wide impacts should continue to be pursued, we must develop some relative understanding regarding whether the bridge obstruction to flow translates to impacts to dissolved oxygen, temperature, pH and nutrient dynamics. Therefore, **in phase 1**, a coarse analysis will be accomplished by Tarang Khangaonkar (PNNL) using the Salish Sea Model (Khangaonkar et al 2012). An updated biogeochemical module capable of simulating sediment diagenesis, hypoxia, pH and alkalinity should be available by early 2018. This, paired with a refined grid in Hood Canal developed during this study, will be applied in the Salish Sea Model with and without the bridge. The results of this will then be used to determine whether proceeding with an extensive investigation of potential impacts to the Hood Canal ecosystem (questions B and C), along with an investigation of potential solutions (D) is warranted.

11. [Potential] Model the effect on flushing, biogeochemistry, dissolved oxygen, and pH of Hood Canal

Tarang Khangaonkar, Wen Long, Laura Bianucci , Pacific Northwest National Laboratories

If the phase 1 analysis suggests circulation and water quality throughout Hood Canal are affected, a more refined assessment of those impacts may be warranted. More could be done building upon the Salish Sea Model to address this. The Salish Sea Model, which includes nutrient loads from nearly one hundred point and non-point source loads and oceanic influences, could be used to test sensitivity of the system to increased flushing time due to the Hood Canal Bridge. Effects of the bridge on physical presence and blockage (e.g., pooling of brackish outflow water, increased settling of algae and detritus, and possible re-entrainment in the exchange flow) could be examined. Hood Canal data from Ecology's marine monitoring program and ORCA buoy data can also be processed and utilized. The model would be refined to Skokomish River delta and Lynch Cove intertidal regions to reproduce observed hypoxia. A three-year hydrodynamic simulation including the bridge would be conducted using the refined model grid. This would include biogeochemical processes including sediment diagenesis and calibration to the observed three-year data encompassing hypoxia and fish kill events. Sensitivity tests would be conducted to quantify relative influence of the Hood Canal Bridge and other stressors.

C. How does the Hood Canal Bridge affect key marine species residing in Hood Canal?

12. [Potential] Model the subsequent impact to the Hood Canal food web

Chris Harvey, Isaac Kaplan, and Correigh Greene, NOAA Northwest Fisheries Science Center. Tarang Khangaonkar, Pacific Northwest National Laboratories. Brandon Sackmann, Integral Consulting

If the phase 1 analysis suggests circulation and water quality throughout Hood Canal are affected by the bridge, the value of future actions to address bridge impacts would be greatly informed by an assessment of how key species in Hood Canal and neighboring basins are affected. Species throughout Hood Canal respond to changes in water quality and residence time; because they interact with one another, any effects of the bridge on ecosystem processes or vulnerable species may ripple throughout the food web in unknown ways. The Atlantis modeling software, which is a 3-D simulator of marine ecosystems, is being built for Puget Sound via the Salish Sea Marine Survival Project (www.marinesurvivalproject.com) and could be utilized for this assessment. Hydrodynamic and water quality impacts modeled in previous stages of the assessment would drive the physics and nutrient loading of the Atlantis ecosystem model. The ecology and biomass dynamics of key species groups, ranging from phytoplankton to fishes to marine mammals, would be simulated in each area and depth layer of the model. Specifically, the model would simulate their daily growth, feeding, local movement, migration, reproduction, and survival in response to environmental conditions as driven by the circulation model. A quantitative assessment of food web-scale effects of the Hood Canal Bridge would be conducted. Effects would be evaluated under present conditions (i.e., contemporary climate and human population/urbanization, and underlying circulation models both with and without the bridge) and future conditions (future climate and human population/urbanization projections, and underlying circulation models both with and without the bridge).

Work Schedule

Phase 1 of the assessment began in 2016 and will conclude during the summer of 2019. Below is a table describing the work schedule. The table is organized based upon the plan's question framework. Note: per previous sections, due to the step-wise approach being applied to determining whether there are broad impacts to the entire Hood Canal Ecosystem, only sub-questions II.A. and II.B. will be addressed during phase 1.

I. HOW IS THE BRIDGE ACTING AS BARRIER TO JUVENILE STEELHEAD MIGRATION, LEADING TO INCREASED MORTALITY?					
HOW DOES THE BRIDGE INFLUENCE OTHER FISH, INCLUDING SALMON?					
Assessment Components		2016	2017	2018	2019
A. What are fish migration behavior and fish distribution patterns? For steelhead, what defines a successful migration past the bridge vs one that results in mortality?					
1	Track steelhead migration behavior at Bridge, & mortality before, at & after Bridge				
2	Map fish densities and distribution at vs 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?					
3	Map predator (marine mammal and bird) densities				
C. What is the influence on the surrounding physical environment, near vs away from the bridge?					
6,7	Pilots: Assess light/shade and noise impacts to fish and/or predator behavior. Assess zooplankton composition + response.				
8,9	Collect data and characterize the bridge zone of influence (impact to flows, salinity, temperature gradients)				
D. What are the impacts of pools and eddies created by bridge pontoons adjacent the center drawspan?					
14	Comparative assessment of fish, predator, zooplankton densities in pools and eddies vs away from them				
E. Data Synthesis: 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?					
13a	Geographic regression analyses				

II. IS THE BRIDGE IMPACTING THE ENTIRE HOOD CANAL ECOSYSTEM?					
Assessment Components		2016	2017	2018	2019
A. Does the bridge obstruct ebb - flood currents & impact flushing of brackish outflow water?					
8	Collect oceanographic data at the bridge				
9	Characterize bridge zone of influence – Hydrodynamic Modeling				
B. What is the impact of Hood Canal bridge on basin wide circulation and water quality?					
11	Initial test on effect on Hood Canal water quality				

⇨	Workshops = review results relative to next steps				
⇨	Comprehensive report with recommendations				

Legend	
Implementation period	
Field Activities	
Analysis	

Components 1,2,3,6 and 7 will be implemented for two years of field research (2017-2018) to account for among year variation. The Port Gamble S'Klallam Tribe initiating the hydro-acoustic surveys (component 2) in 2016 because funds were available to do so, adding an additional year of data.

A workshop will be held at the end of 2017, after the first year of comprehensive field research. Early results will be presented and reviewed by the Assessment Team, Management Committee, and invited external reviewers. Workshop participants will at that time determine whether any assessment modifications should be made. Additions or modifications will be considered prior to 2018 in part due to the cost savings afforded by implementing them simultaneously with the fish and predator tracking occurring throughout phase 1. If warranted, additions/modifications for 2018 that may be considered include enhanced light and sound assessments (broader implementation of components 6 and 7), a direct assessment of seal-steelhead interactions (components 4 and 5), and more comprehensive work to characterize the bridge impacts to Hood Canal Circulation and Water Quality (e.g., full implementation of component 11). All additions or modifications would also be contingent upon funds available. No additions or modifications are considered in the phase 1 budget. Substantial modifications would in effect initiate a second phase of work.

A second workshop plus a series of meetings will be held in late 2018/early 2019 to review the results of phase 1 and: a) work with our partners and others to refine the suite of potential management actions, in particular those related to the impact of the bridge on outmigrating steelhead (and potentially Chinook and chum salmon), b) reach agreement on remaining data gaps that must be addressed. Subsequent stages will focus on filling data gaps and simulating, field testing, and fully implementing appropriate management solutions that will not adversely affect the bridge as a transportation corridor. These meetings and workshops will again involve the Assessment Team, Management Committee and external reviewers. We will also engage any additional, relevant management representatives, legislators, or stakeholders at this time.

Deliverables

Phase 1 deliverables include:

1. A 2017 early results and next steps report associated with the workshop held at the end of that year. This report will clearly document the initial findings of the assessment and any changes to the direction or scope of the assessment for 2018.

2. Some results of the assessment will be submitted for publication in peer-reviewed journals. This includes but is not limited to: a publication describing steelhead migration pathways that result in mortality or success at the bridge (component 1), a publication more accurately characterizing the bridge impacts to flow (component 9), and a publication that summarizes the findings of the comprehensive, geographic regression analysis (component 13a) that assesses the various potential causal linkages between the bridge, steelhead mortality and fish distribution.

3. A comprehensive report describing:
    - The methods and outcomes of each assessment component
    - The results of the comprehensive geographic regression analysis and the initial assessment of Hood Canal-wide water quality impacts.
    - A refined suite of potential management actions related to the impact of the bridge on outmigrating steelhead (and potentially Chinook and chum salmon), a determination of whether

any should be tested or simulated in phase 2, and some rough concepts for how these tests should be implemented
- A list of remaining data gaps that must be addressed in phase 2.

The comprehensive report will be distributed for review by the Management Committee and external reviewers, and the Management Committee will approve before it is finalized.

Organizational Structure

The following organizational structure is used for the assessment process.

Assessment Team: The Assessment Team is charged with developing and implementing the Assessment Plan. The Assessment Team consists of scientists who: a) conducted studies of the Hood Canal Bridge on salmon and water circulation that were the basis for this assessment, b) are local experts on Hood Canal biota, and/or c) are experts in the various disciplines required to execute the assessment. Washington Department of Transportation staff also participate to ensure strong collaboration with the entity most affected by this effort and to ensure knowledge about the Bridge structure and function, and history of prior environmental assessment work, is communicated with the Assessment Team. Assessment Team members are listed on the back of this document's cover page and with their respective responsibilities in the "Assessment Components" section, above. The Assessment Team meets regularly (at least 4 times per year) to coordinate on development and implementation of the Assessment Plan. The Assessment Team will report to the Management Committee.

Contributing Experts: Some scientists who are participating are considered contributing experts versus Assessment Team members. These participants have smaller roles and/or are not critical as agency or tribal representatives. These participants do not have decision-making authority.

Management Committee: The Management Committee will provide oversight of the assessment process, maintain coordination with the relevant agencies, and help develop, test and ultimately establish management actions based upon the assessment. While this body will have no authority to mandate certain actions, it does serve as a formal conduit to make recommendations. The Committee may consist of, at a minimum, members from the Hood Canal Coordinating Council, Port Gamble S'Klallam Tribe, Washington Department of Fish and Wildlife, Washington Department of Transportation, Washington Department of Ecology, U.S. Navy, NOAA Fisheries, Jefferson County, Mason County, Kitsap County, Puget Sound Partnership, and other relevant partners as warranted. Cooperation from all these entities is necessary to protect the diversity of regional interests concerning transportation, tourism, tribal rights, fisheries management, and environmental health. The Management Committee will be strongly tied to the Hood Canal Coordinating Council as they are the coordinating body for addressing Hood Canal environmental issues. The Management Committee will meet periodically to review progress, help address interagency and/or financial issues, and make decisions regarding next steps. The Management Committee is under development.

External Reviewers: External reviewers will be retained periodically to review findings and proposed next steps, including a review of the comprehensive report that is the primary phase 1 deliverable. These reviewers will either be experts in relevant fields and/or have specific local knowledge. Funding for external reviewers is included in the project management portion of the budget.

Project Management and Coordination: Long Live the Kings (LLTK) is the project manager, responsible for ensuring the assessment is carried out consistent with this plan. LLTK provides coordination, technical support, funding/contract management, and communications support for the project. In this role and as funding is available, LLTK will:

1. Coordinate and facilitate[8] Assessment Team and Management Committee meetings, the workshops described in the "Work Schedule" section, and other meetings to engage relevant stakeholders;
2. Maintain a project management web site and a public web presence for collaboration and outreach, respectively.
3. Provide technical support: obtain permits, participate as co-investigator on various assessment components, and lead the writing of the comprehensive report described in the "Deliverables" section.
4. Maintain links with other relevant initiatives in the region.
5. Perform communications and outreach, such as through the public web site, presentations at workshops and conferences, strategic use of broadcast and print media, etc.

In addition to these tasks, LLTK helps pursue funding for the assessment as this is not currently a funded mandate.

Decision Making

Decisions will normally be made by consensus. When necessary, the facilitator will clearly explain the proposed decision to the group and check for consensus. If there is any question or doubt about whether consensus has been achieved on an issue, any member of the Assessment Team or Management Committee can request that a motion be made on the subject, according to Robert's Rules of Order, in which case, after discussion, a ¾ majority vote will decide the issue. Decisions about the implementation strategy for the Assessment Plan will also take into account the logical sequence of assessment components, alignment among assessment components, and the amount of funds available for implementation.

[8] As facilitator, LLTK will ensure that a complete and accurate description of the matters discussed, decisions made, and actions recommended are captured during meetings, and is responsible for distributing meeting summaries, decisions, and action items reports and other documents to the Assessment Team and Management Committee. The facilitator also ensures that meeting business is conducted in a timely and efficient manner and that each member has the opportunity to contribute and be heard.

Budget

The following budget describes the cost of phase 1. The costs are broken out by year and component.

Phase 1 Budget				Expenses				
				2016	2017	2018	2019	Total
BRIDGE AS BARRIER TO JUVENILE STEELHEAD (AND POTENTIALLY SALMON), LEADING TO INCREASED MORTALITY								
	BRIDGE POTENTIAL IMPACT TO ENTIRE HOOD CANAL ECOSYSTEM							
◆		1	Track steelhead migration behavior at Bridge, & mortality before, at & after Bridge	$150,000	$260,400	$225,000	$50,000	**$685,400**
◆		2	Map fish densities and distribution at vs away from bridge	$112,200	$100,000	$100,000	$15,000	**$327,200**
◆		3	Map predator (marine mammal & bird) densities at vs away from bridge		$86,600	$86,600	$10,000	**$183,200**
◆		6	Pilot: Assess light/shade impacts to fish and predator behavior. Assess zooplankton comp.		$45,000	$40,000		**$85,000**
◆		7	Pilot: Assess noise impacts to fish behavior		$50,000	$50,000		**$100,000**
◆	◆	8	Collect oceanographic data around bridge		$100,000			**$100,000**
◆	◆	9	Characterize the Bridge zone of influence	$50,000	$100,000	$100,000		**$250,000**
	◆	11	Initial analysis of the effect on flushing, biogeochemistry, dissolved oxygen, and pH			$50,000	$50,000	**$100,000**
		14	Comparative assessment of fish, predator, zooplankton densities in pools and eddies vs away from them		$45,000	$45,000	$10,000	**$100,000**
◆		13	Synthesis: Geographic Regression Analysis		$45,000	$45,000	$15,000	**$105,000**
◆			Project management: Coordination, comprehensive analyses and recommendations reporting, permitting, subcontract mgmt, and communications	$55,000	$135,000	$95,000	$77,500	**$362,500**
			TOTAL	**$367,200**	**$967,000**	**$836,600**	**$227,500**	**$2,398,300**

*Additional costs associated with data synthesis are covered under element 1. NOAA will be performing much of the synthesis analyses.

**Additions/modifications may be made for 2018, depending upon 2017 early findings and funds available. They may include enhanced light and sound assessments (components 6 and 7 = $300k), a direct assessment of harbor seal-steelhead interactions (components 4 and 5 = $600k), and more comprehensive work to characterize the bridge impacts to Hood Canal Circulation and Water Quality (e.g., full implementation of component 11 = add $350k). The cost of other potential components for future phases, discussed in this document, include fine-scale Computational Fluid Dynamics modeling at the bridge (component 10 = $150k), simulating steelhead migration past bridge (13b = $250k), modeling subsequent impacts to Hood Canal food web ($150k).

Phase 1 of the assessment will last approximately 3 years (mid 2016 to early 2019) and cost $2.4 million. To date, $800,000 has been raised for the assessment—$688,000 from the Salmon Recovery Funding Board and $112,000 from the Port Gamble S'Klallam Tribe. The Port Gamble S'Klallam Tribe has also submitted a request for $150,000 via a BIA funding proposal. These funds only partially satisfy needs associated with phase 1 of the assessment plan.

In addition to the funds raised, over $1.5 million in staff time and equipment has or is being contributed to assessing the impacts of the Hood Canal Bridge (not included in the above budget). This includes assessment planning, projected in-kind support over the course of the assessment, and the cost of the studies by Moore et al. (2013) and Khangaonkar and Wang (2013) that are the basis for this assessment.

The adaptive management process, in which this assessment is framed, will also help ensure costs are managed when assessing and addressing bridge impacts. First, an iterative approach to assessing the problem and testing solutions increases the chances that money is directed at the correct actions. Second, creating a decision-making framework has the opportunity to reduce the costs of inaction. Reducing the lag between scientific findings and implementing solutions reduces costs associated with time and any negative impact that may be occurring in the ecosystem. Third, this adaptive management process attempts to avoid the cost of litigation. Historically, fish passage barrier removal and the incidental take of endangered species have often been addressed through litigation. While the costs associated with the 2016 US v. Washington Fish Barrier Removal litigation are not clear, the House Committee on Natural Resources reports that taxpayer dollars paid for over $15 million in attorney fees defending ESA listings in the US between 2009 and 2012 (House Committee on Natural Resources, 2012). Moreover, costs incurred by an adaptive management process are diffused among more than one group, lessening the financial burden for all parties.

Appendix A. Details of Individual Components

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

Megan Moore and Barry Berejikian, NOAA Northwest Fisheries Science Center

Overview

The Hood Canal Bridge (HCB) spans the northern outlet of Hood Canal in Puget Sound, extends 15 feet underwater, and forms a barrier for steelhead migrating from Hood Canal to the Pacific Ocean. Individually coded acoustic telemetry transmitters implanted in juvenile steelhead and strategically placed receivers capable of detecting the transmitters have been used to track steelhead behavior throughout Hood Canal and the greater Puget Sound from 2006-2010 (Moore et al. 2015). The results indicate 27 probable mortality events (where the tag remains stationary, assumed to have fallen to the sea bed) were recorded within proximity of the receivers at the Hood Canal Bridge, whereas, the other 325 receiver deployments in Puget Sound only detected one stationary tag (Moore et al. 2013). Migrating steelhead were also detected more frequently and for significantly longer time periods at the HCB than at three similarly monitored Puget Sound locations (mid-Hood Canal, Admiralty Inlet, and the Strait of Juan de Fuca; Moore et al. 2013). Migration delays caused by the bridge are hypothesized to increase the density of smolts near the bridge, channel migrating smolts through more densely concentrated routes, and facilitate elevated predation rates at these locations.

Objectives

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 planned study would obtain close approximations (5 to 20 m; *cf.* Roy et al. 2014) of the path of each tagged steelhead as they approach and encounter the Hood Canal Bridge to understand which areas, structures, depths, and/or behaviors are associated with migration delay or mortality, and which facilitate passage. High resolution fish positions will allow for a powerful evaluation of how path characteristics (location, time, depth) affect the odds of survival. The study will test the following hypotheses:

H_{01}: Location of migrating steelhead before, during, or after HCB encounter does not affect bridge residence time or odds of survival

H_{02}: Timing of arrival at the HCB does not affect bridge residence time or odds of survival

H_{03}: Depth of migrating steelhead before/during/after HCB encounter does not affect bridge residence time or odds of survival

H_{04}: Behavior of tagged steelhead categorized as survivors does not differ from (pre-mortality) behavior of steelhead categorized as mortalities or behavior of smolts that die at other locations

Study design

STUDY POPULATION

Fish collection and tagging: Wild steelhead smolts will be collected at a WDFW-maintained weir in Big Beef Creek and with a rotary screw trap on the South Fork Skokomish River, the mouths of which are located 26 and 75 kilometers south of the HCB, respectively. Smolts will be held overnight in flow-through circular tanks at the Big Beef Creek research station, or near the collection site on the bank of the Skokomish River. Vemco V8 acoustic transmitters (69 kHz, 7 mm diameter, 20.5 mm length, 2.2 g) will then be surgically implanted in 200 smolts as outlined in Moore et al. (2010). An additional 50 smolts will be implanted with larger V9 depth sensor acoustic transmitters (69 kHz, 9 mm diameter, 21 mm length, 2.9 g) to assess the preferred depth of steelhead smolts at various stages of HCB encounters, and to inform fish position calculations. Smolts will be held overnight and released approximately 24 hours post-surgery into either the Big Beef Creek estuary or at river kilometer 13.5 of the Skokomish River.

DATA COLLECTION

Receiver deployment: An array of at least 24 Vemco VR2 acoustic receivers will be deployed on the seafloor to triangulate 2-dimensional paths of migrating steelhead smolts. A line of receivers will run on either side of the HCB, spaced about 200 meters apart, and will cover the entire channel from the east to the west shore (Figure 2). Stationary transmitters will be deployed in several known locations to calibrate the system. Deployments will be made in March to allow time for testing and fine-scale adjustments. This receiver arrangement will yield high resolution tagged fish positions, which will be grouped to create individual fish paths through the monitored area (approximately 300 meters out from either side of the HCB). After the steelhead migration period, all receivers will be collected via acoustic release and downloaded using Vemco software.

The study will take advantage of two existing receiver lines at Admiralty Inlet (ADM) and the Strait of Juan de Fuca (JDF), further along the Hood Canal steelhead migration path (Figure 1). An additional line of receivers would be deployed near the outlet of Hood Canal at Twin Spits (TS). Detection at TS, ADM or JDF receivers would identify a tagged steelhead as a ‘survivor’, and continuous detection for a long time period on one or more receivers would indicate a ‘mortality’. Migratory paths of survivors will be compared to paths of known mortalities (stationary tags) and presumed mortalities (those not detected at TS, ADM or JDF) to identify migratory pathways resulting in mortality and survival. Predation events on tagged steelhead will be indicated by close examination of abrupt changes in tag trajectories, travel times exceeding the capacity of swimming steelhead, or other significant departures from typical steelhead behavior (Melnychuck et al. 2013, Gibson et al. 2015).

Additional mortalities, as indicated by continuous detection of a transmitter at one location over an extended period (aka “stationary” tags), will be identified using boat-based mobile tracking methods. Stationary tags have been identified in previous Salish Sea salmonid studies using both fixed arrays (Moore et al. 2013) and boat-based mobile tracking methods (Melnychuk et al. 2013), as well as by using data from mobile receivers affixed to harbor seals (Berejikian et al. 2016). The stationary tag is presumed to be located near where it was deposited by a predator, either directly after a predation event or after being passed through the predator’s digestive tract. The main objective of this mobile tracking effort is to determine the locations of any stationary acoustic tags on the seafloor.

Mobile tracking transects will be spaced 200 m north and south of the detection range of the fixed receiver array. The boat mounted hydrophone will be deployed every 400 meters along each transect. Harbor seal haulouts will be monitored using similarly spaced transects.

Transmitter predation bias (aka 'dinner bell' hypothesis)

In experimental enclosures, researchers have found the sound emission of 69 kHz transmitters to be audible to marine mammals (Cunningham et al. 2014), and used by grey seals to learn prey location (Stansbury et al. 2014).). An analysis of the effect of transmitter noise on predation of tagged steelhead smolts was carried out in 2014 in south and central Puget Sound. Similar proportions of smolts with delayed transmitters (2 of 43; 4.6%) and continuous transmitters (2 of 50: 4%) were detected at the JDF line, indicating that no effect of acoustic noise on predation could be detected (Berejikian et al. 2016). To test whether predators at the HCB use acoustic signals from transmitters to locate and capture tagged steelhead smolts, two experimental groups of transmitters will be used in the proposed study. The first group of tags (n=200) will be standard V8 or V9 depth transmitters, continuously pinging every 30-90 s, while the second group (n=50) will be programmed to delay activation for 7 days, which is the minimum travel time from release to the JDF line (obtained from earlier studies of steelhead smolt migration behavior in Hood Canal). The delayed tags will begin transmitting after the 7-day delay, in order to be detected at subsequent receiver lines, where survival will be compared between groups. A greater proportion of delayed transmitters over continuous transmitters detected at the JDF line would suggest that predators are using the acoustic signal to locate and capture smolts. A similar proportion of JDF detections from the delayed and continuous groups would indicate no effect of the acoustic signal on mortality from predation.

Data analysis

Detection data from the 24-receiver array nearest the Hood Canal Bridge will be sent to Vemco data analysts, who will calculate positions of each transmitter detection and return the data for further analysis. Transmitter positions will be displayed using Vemco graphical software to visually assess migration paths. Behavioral analyses will take a two-step approach. First, the mix-tools package in R (Benaglia et al. 2009) or a similar clustering tool will be used to classify the trajectories of individual fish migrants into general categories based on the behavioral and spatial characteristics of each migration path (e.g., turning angles, step length, tortuosity, approach location). Cormack-Jolly-Seber mark-recapture models will then be used to estimate the survival probability associated with each migration category. A multi-model approach will then be used to compare the survival probability of smolts in each migration behavior using Akaike's Information Criteria (AIC; Burnham and Anderson 2010) and estimate survival rates specific to each behavioral type. In the second tier of the behavioral analysis, multinomial regression models will be used to determine the effect of certain factors (e.g., release time, migration depth, time of day) on the probability of adopting the behavioral categories described above. These two analyses combined will estimate the survival probability of specific behavioral types and the factors that affect their manifestation.

Mobile tracking data will be spatially analyzed to determine the extent to which stationary tags occur in association with the Hood Canal Bridge, or with seal haul-outs or roosts of any frequently occurring avian predators (determined via component 3). Density of stationary tags in close proximity to the bridge will be compared with the density of tags located farther away from the bridge along the migration pathway. Determining the locations of stationary transmitters by mobile tracking will increase the power to determine factors affecting migration past the bridge by providing the locations of a greater number of stationary tags (mortalities).

Outcomes

This telemetry study will provide high-resolution migration paths of migrating steelhead smolts so that problem areas and factors affecting migration behavior or vulnerability can be identified. Data from the proposed array will provide specific information about where steelhead smolts are located as they approach the HCB, then how/if that trajectory changes during HCB encounter. We expect to identify associations between localized bridge characteristics, migratory behavior and mortality. The analyses will provide the basis for operational or engineered approaches (lighting, flow diversion) to decrease the HCB impacts. This study has the potential to be integrated with the harbor seal predation component by providing tagged fish that can be detected by seals instrumented with GPS tags and Vemco Mobile Transceivers. Implemented in conjunction with the predator observations (and potentially diet studies), this telemetry work will help identify areas where modified behavior resulting from encounter with the HCB increases susceptibility of steelhead smolts to predation, and will indicate potential for predator deterrent measures to increase survival of migrating steelhead smolts.

Once specific effects of the HCB are demonstrated, further study may be needed to evaluate specific measures that may be proposed to mitigate the problem.

Deliverables

Results of the telemetry study will be summarized and submitted for publication to a peer-reviewed scientific journal by early 2019. Data and analyses will also be used in comprehensive analyses, comparing the results to the output of the other studies listed in this report. Data will also be presented orally to stakeholders and at relevant scientific meetings.

Figures

(see following pages)

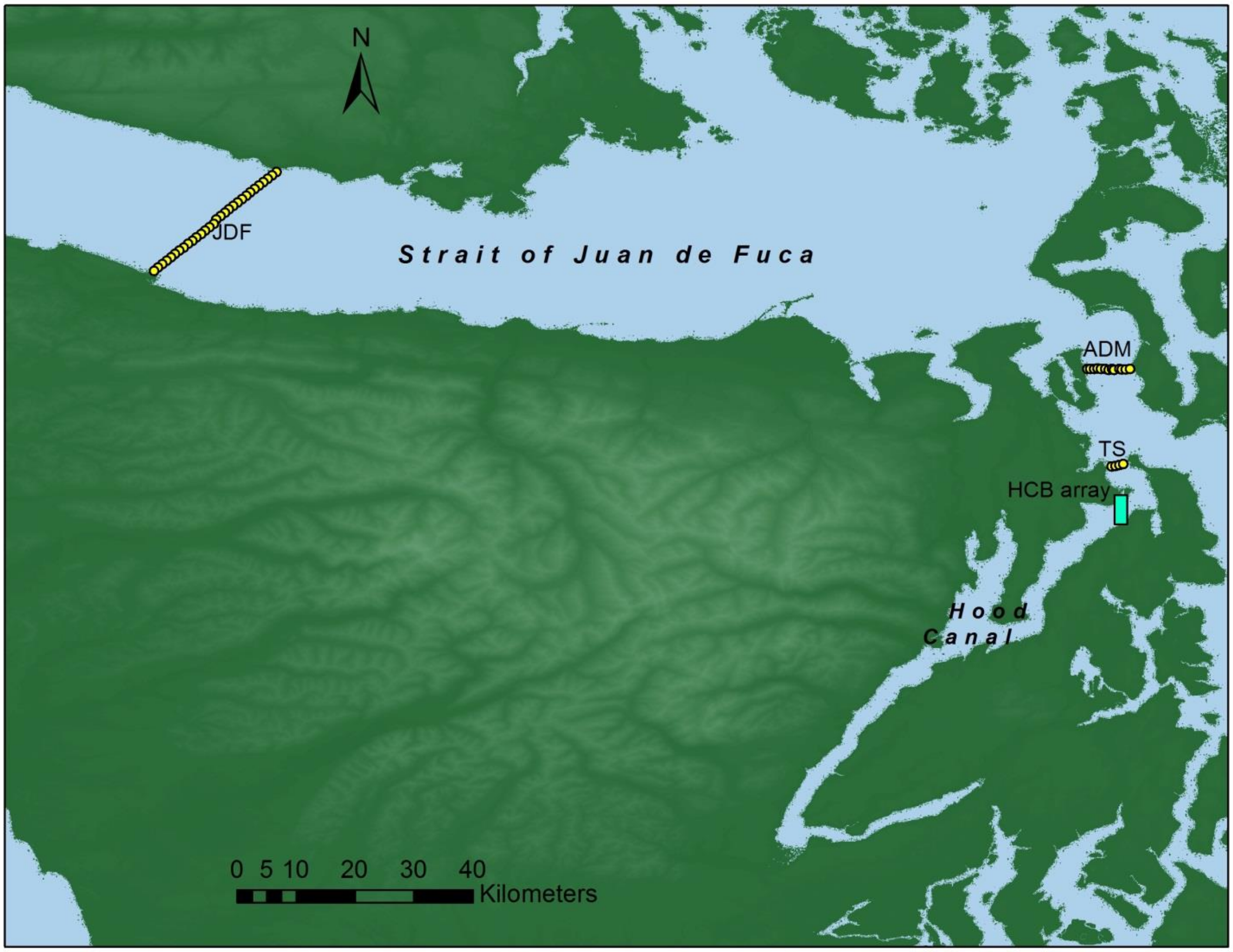


Figure 1. Map of study area showing the proposed telemetry receiver array at the Hood Canal Bridge (HCB), and receiver lines at Twin Spits (TS), Admiralty Inlet (ADM), and the Strait of Juan de Fuca (JDF).

Figure 2. Locations of telemetry receivers deployed to obtain 2-D calculated positions of tagged steelhead smolts continuously throughout their migration past the Hood Canal Bridge. Orange labels reference VR2 receivers planned for seabed deployment, and green labels reference locations of stationary transmitters deployed at known locations to calibrate the receiver system.

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

Hans Daubenberger, Port Gamble S'Klallam Tribe.

Overview

The bridge assessment relies on acoustic tagging and tracking to describe fine-scale migration patterns of tagged steelhead as they encounter the Hood Canal Bridge and identify migration paths associated with survival. Acoustically tagging individual fish provides a great level of detail for those fish which have been tagged; however, data is limited to only those fish. Hydroacoustic surveys will help understand the relationship between tagged steelhead and other biota by allowing comparison of tagged steelhead characteristics and migration paths against the distribution and density of biota in the upper water column. Figure 1.1 is the result of an exploratory single day effort by PGST to conduct hydroacoustic sampling within the vicinity of the Hood Canal Bridge during the 2015 steelhead outmigration.

Objectives

The objective of this activity is to understand the impact the Hood Canal Bridge has on the densities and distribution of salmon, steelhead, and forage fish. This will be achieved by mapping the density and distribution of fish at and progressively away from the bridge.

Study design

This activity will be located in the marine waters surrounding the Hood Canal Bridge. The Hood Canal Bridge is a 2.4 km long floating bridge crossing the northern outlet of Hood Canal. It is supported by wide pontoons that extend 3.7 m (12ft) underwater, forming a fish migration/passage and water circulation barrier in the nearshore and marine environment. Most of the work will occur within a 2 km radius of the Hood Canal Bridge.

The Port Gamble S'Klallam Tribe will utilize the hydroacoustic equipment and sampling techniques that were developed and deployed during the 2011-2014 Hood Canal and Admiralty Inlet Nearshore Assessment Project. The Tribe will use 200 kHz Biosonics DT-X split-beam digital transducers. The transducers will be mounted on a towed body with side-looking and down-looking orientations and will be towed at a speed of ≅ 4 knots (2 m/s). Acoustic data will be georeferenced using an integrated Garmin GPS receiver. A CTD will also be towed at 1 m depth during surveys, and CTD casts will occur on each side of the bridge at the transect nearest the bridge (within 50m of bridge) and the transect farthest from the bridge, at a minimum. Turbidity will also be measured at each CTD cast location. Acoustic surveys will be conducted four times during the months of April and May. During each month three of the four surveys will be conducted during daylight hours, and the additional survey will be conducted at night (optimally during low moonlight and full moon), between dusk and dawn. We will employ a systematic transect design consisting of predetermined, evenly-spaced, parallel transects; figure 2, below depicts the anticipated transect locations for this project. The proposed approach includes six parallel transects (within 50 m of bridge, 200m, 500 m, 1000 m, 1500 m, 2000 m, 8,000 m) that cover areas to the north and south of the bridge that are equal in distance to the length of the bridge. However, the spacing will be finalized during study preparation.

Hydroacoustic sampling will also be used to assess the zooplankton community in proximity to the bridge. Down-looking 70 kHz and 200 kHz Biosonics DT-X split-beam digital transducers will be towed along transects perpendicular to the bridge. At each end of a transect, a near-to/away-from bridge net tow will be conducted. See the description of assessment component 6, below, for additional information about the methods used to assess the zooplankton community.

Hydroacoustic data will be analyzed using Echoview by Myriax which allows for single target fish detection. The acoustic data will be grouped by 100 meter cells (smaller, 100 m cells on first 2 transects), and fish per cubic meter within each cell will be calculated. The GPS data collected will be imported into ArcGIS and/or other spatial analysis packages and a shape file will be created to illustrate fish densities within the vicinity of the Hood Canal Bridge (see figure 1 for an example).

Outcomes

Hydroacoustic data will be used to delineate estimated fish density and distribution within the area surrounding the Hood Canal Bridge (see figure 1, below as an example). Data from hydroacoustic surveys will be integrated with results from the broader Hood Canal Bridge Impacts Assessment.

Deliverables

The final product developed as a result of this undertaking will be a GIS dataset and maps delineating estimated fish distribution and abundance within the vicinity of the Hood Canal Bridge. The GIS dataset will be accompanied by a report detailing the methods used to collect and analyze the acoustic data and interpretations derived from it. These data will be used in the comprehensive analysis, component 13a.

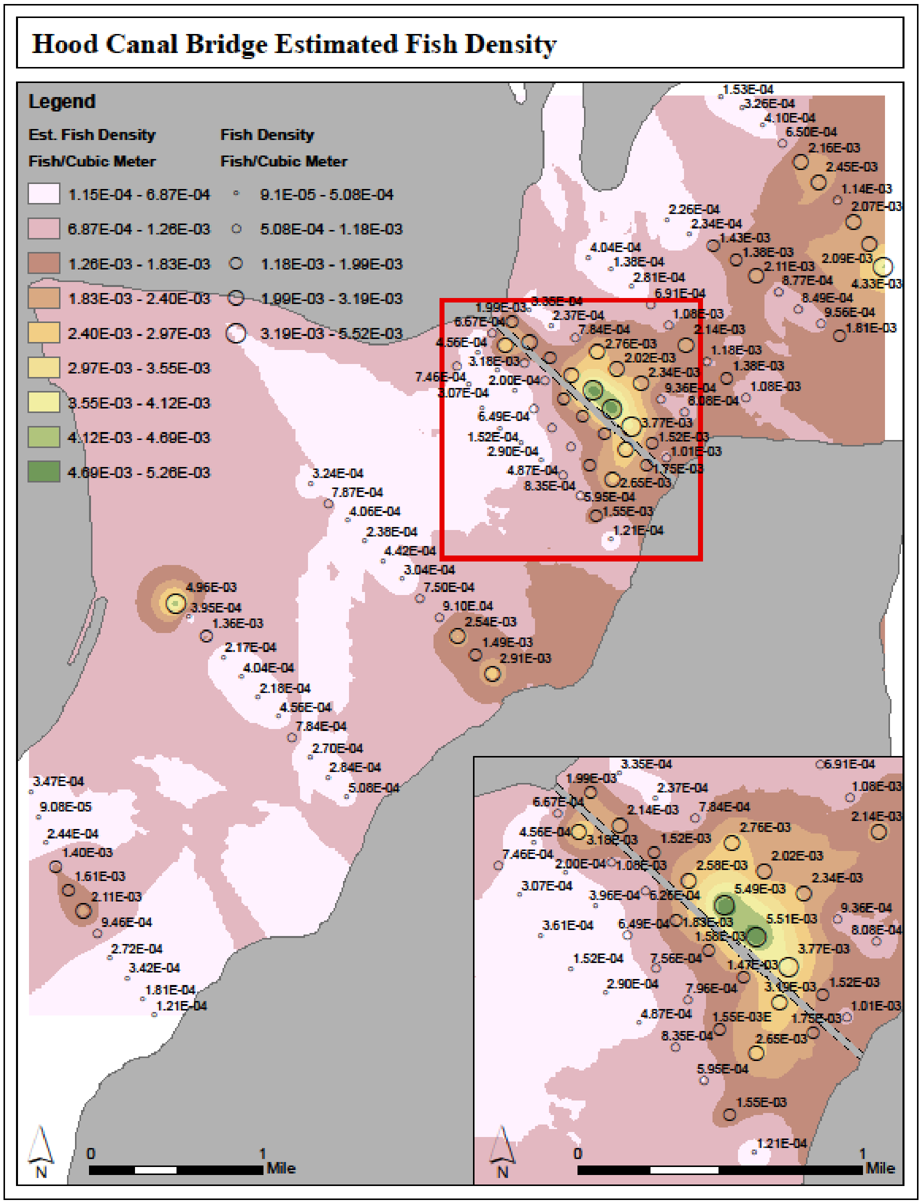


Figure 1 Estimated near-surface fish density within the vicinity of the Hood Canal Bridge.

Imagery ©2015 Google, Map data ©2015 Google 2000 ft

Figure 2 Anticipated hydroacoustic transect locations.

3. Map predator (marine mammal and seabird) densities

Scott Pearson and Steve Jeffries, Washington Department of Fish and Wildlife. Hans Daubenberger, Port Gamble S'Klallam Tribe

Objectives

1. Identify and estimate abundance of potential steelhead (and Chinook salmon) smolt predators at the Hood Canal Bridge during the steelhead smolt outmigration period (1 April – 30 May).
2. Determine if potential avian and mammalian steelhead (and Chinook salmon) smolt predators are more abundant near the Hood Canal Bridge during the steelhead smolt outmigration period (1 April – 30 May).
3. Determine harbor seal abundance based on haulout counts in Hood Canal during the steelhead smolt outmigration window (1 April – 30 May).

Approach

At-sea surveys

WDFW (Steve Jeffries and Scott Pearson Co-PIs) propose to use boat-based line-transect/distance based surveys (Buckland et al. 2001, 2004) to assess the change in predator abundance with distance from the Hood Canal Bridge - both to the north and to the south. This will allow us to determine if any potential smolt predator (see Pearson et al. 2015, Table 1) is more abundant closer to than farther from the bridge during the steelhead smolt outmigration window, 1 April – 30 May. If predation is responsible for the apparently high mortality near the bridge, then we might expect the responsible predator(s) to be more abundant near the bridge. Survey methods will follow Raphael et al. (2007). Weekly surveys will consist of 20 km long transects that zig-zag between the east and west shores of Hood Canal starting at the bridge. They will be conducted from a 7.3 m (24-ft) Almar boat with twin-outboard engines. Survey speed will be 8-12 knots (4-6 m/s), and survey effort will be ended if glare obstructs the view of the observers, or if Beaufort wind scale is 3 or greater for more than 25% of a transect. Beaufort 3 is described as a gentle breeze, 7-10 knot (3.6-5.1 m/s) winds, creating large wavelets, crests beginning to break, and scattered whitecaps.

Transects will initially run from shore to shore and parallel to the bridge. The first transect on either side of the bridge will be 100 m from the bridge edge and then spaced 200 m apart for the first five transects on each side of the bridge. For these transects we will map the location of every predator observed using offsets or hand-held laser range finders integrated with GPS units. This species-specific predator information will then be brought into an Arc GIS environment to develop continuous predator density surfaces for comparison with fish and abiotic information. For the next five transects, we will place them approximately 600 m apart from each other and perpendicular to the shore but no longer parallel to the bridge. Detections from these transects will be used to estimate predator densities (not spatial distribution) and used to determine if species-specific or fish predator densities as a whole are higher near the bridge.

BRIDGE-BASED SURVEYS

Bridge-focused predator surveys will also be conducted from the bridge or bridge pontoon deck. Day-long surveys would be conducted, up to two days a week throughout the steelhead smolt migration window. These surveys will consist of continuous counts in prescribed time intervals interspersed with focal animal observations to assess foraging behavior (Altman 1979). We will again map the location of every predator observed using offsets or hand-held laser range finders integrated with GPS units. This species-specific predator information will then be brought into an Arc GIS environment to develop continuous predator density surfaces for comparison with fish and abiotic information. Extra care will be used to assess the predator composition where voids in the Bridge occur and are being assessed for a reef effect, as described in activity 14 in the body of the report, above. This work will allow us to determine the composition, abundance, and behaviors of potential steelhead and salmon smolt predators (seals, porpoises, seabirds) foraging adjacent to the Hood Canal Bridge and will complement the boat-based abundance surveys. Similar to the boat-based surveys, survey effort will be ended if glare obstructs the view of the observers, or if Beaufort wind scale is 3 or greater for greater than 25% of the day. This work will provide the detailed information needed to assess potential smolt predation at the bridge.

The timing of the both the at-sea and bridge-based surveys will be coordinated with research activities 1 and 2 that detail steelhead outmigration and fish distribution at the Bridge[9]. Bridge-based surveys will also include one or more night surveys (during low moonlight and full moonlight) to capture predator foraging behavior and compare it to the results of study 6, where light and shade impacts are measured.

Deliverables

The data collected will be mapped in ArcGIS and/or other spatial analysis packages. The final product developed as a result of this undertaking will be a GIS dataset for use in comprehensive analysis (13a) in combination with studies 1, 2 and others, and maps delineating estimated marine mammal and bird abundance (identifying potential predators vs. those that would not prey on smolts) within the vicinity of the Hood Canal Bridge. The GIS dataset will be accompanied by a technical report detailing the methods used to collect and analyze the data and interpretations derived from it.

[9] For example, steelhead will reach the Bridge 2 to 3 days after being tagged. Based on this, tagging and surveys will be aligned accordingly.

4. Potential Phase 2: Using harbor seal scat analysis to assess bridge impacts on seal-related juvenile steelhead (and Chinook) mortality

Steven Jeffries, Scott Pearson, Monique Lance, Kenneth Warheit, Washington Department of Fish and Wildlife. Austen Thomas, Smith-Root

Overview

It is hypothesized that the Hood Canal Bridge alters the migratory behavior of juvenile steelhead (and potentially Chinook) in ways that increase their vulnerability to predators such as harbor seals. Recent work involving acoustic transmitters implanted in steelhead smolts combined with seal-mounted acoustic revivers supports the idea that harbor seals are a probable mechanism of juvenile steelhead mortality; however, the degree to which the Hood Canal Bridge influences the probability of predation by harbor seals remains unknown. Direct evidence of juvenile salmon mortality has been observed; however, there has been no association established between this mortality and the presence of the Hood Canal Bridge (Lance and Jeffries 2009). No direct evidence of harbor seal predation on juvenile steelhead currently exists for Hood Canal due to previous methodological limitations, and such evidence is needed to definitively identify harbor seals as the mechanism of mortality resulting in low juvenile steelhead survival. Recent developments in the field of molecular scatology have enabled simultaneous quantification and species identification of salmonids in harbor seal diet samples (scats), thereby providing data useful for direct evidence of mortality due to seal predation.

Objectives

Objective 1 – Determine if the Hood Canal Bridge influences harbor seal-related steelhead (and potentially Chinook) mortality.

To evaluate whether the Hood Canal Bridge influences the ability of seals to consume steelhead, one would need to compare seal consumption of juvenile steelhead in the bridge impacted area under two contrasting scenarios: 1) with the presence of the bridge; 2) without the presence of the bridge. This comparison is clearly not possible. The best alternative to that design is to compare seal-related mortality in two areas that are similar in many ways with the exception of the presence of the bridge (i.e., treatment = bridge-impacted area; control = non-bridge impacted area). Previous studies of harbor seal diets indicate that seal consumption of salmonids is highest in river estuaries and areas where salmonids are concentrated by spatial boundaries (Olesiuk 1993). Salmonid predation tends to be much lower outside of estuaries where fish are dispersed. Thus, if the Hood Canal Bridge does not influence seal-related steelhead and Chinook mortality, we would expect the harbor seal predation rate to be much lower in the bridge-impacted area than in nearby estuaries. However, if the bridge does influence seal-related mortality, we would expect harbor seal consumption of juvenile steelhead and Chinook to be equal to or higher than non-bridge impacted estuary sites in Hood Canal. Using this logic, we arrive at the following null hypothesis:

H_0: Harbor seal predation on juvenile steelhead (and potentially Chinook) is greater in the non-bridge impacted estuaries of Hood Canal than harbor seal predation on juvenile steelhead and Chinook in the bridge-impacted area.

Objective 2 – Provide direct evidence of juvenile steelhead predation by harbor seals in Hood Canal.

As stated previously, currently no direct evidence exists of harbor seal consumption of juvenile steelhead in Hood Canal (Pearson et al. 2015). We will therefore use a recently developed harbor seal diet analysis methodology that combines DNA metabarcoding and prey bone analysis to determine the species and life sage of salmonids consumed by seals (Thomas 2015). Adult steelhead and other salmon species are present in the Hood Canal system during the period of time when juvenile steelhead outmigrate; thus, it is essential that the harbor seal diet estimates we produce differentiate between the different salmonid species and life stages. By applying these newly-developed techniques to harbor seal scat samples collected in the bridge-impacted area and non-bridge impacted areas, we will produce the first such direct evidence of harbor seal predation on juvenile steelhead.

Objective 3 – Determine the foraging areas of harbor seals near the bridge and away from the bridge.

Harbor seals are highly mobile predators, often moving 20-30 km away from their haulout sites on a daily basis to find preferred foraging areas (Peterson et al. 2012). The treatment/control design we propose for assessing the impact of the bridge on seal-related steelhead (and potentially Chinook) mortality relies on the assumption that seals hauling out near the bridge also forage near the bridge, whereas those hauling out far from the bridge do not forage near the bridge. Therefore, in conjunction with the diet comparison between the two contrasting areas, we must also determine the foraging areas of seals that haul out at both sites. The proposed work involving seal-mounted acoustic receivers (see assessment Component 5, following this section) provides an ideal opportunity to determine the foraging areas of seals at both sites using Fastloc GPS transmitters integrated in the “instrument packs”. If a representative sample of the seal subpopulation at each location is tagged with GPS transmitters, we can confidently identify the areas where those subpopulations forage and confirm where juvenile steelhead predation by seals likely occurs (combining foraging areas with diet data for each respective site), and confirm the validity of the treatment/control study design.

Study Design

Scat Sampling

Harbor seal scat will be collected from harbor seal haulout areas that are similar in many ways with the exception of the presence of the bridge (treatment = bridge-impacted area; control = non-bridge impacted area). The primary haulout sites targeted will be those paired with efforts to assess the foraging areas of seals (objective 3, above, and described in “Foraging Areas Assessment” section, below). A suite of secondary locations/haulout sites have also been identified, primarily as backups for achieving adequate sample sizes; however, without concurrent seal foraging data, the utility of the results will be limited.

Site type	**Haulout Locations***	
Treatment/near-to bridge seals	Port Gamble Bay Net Pens	Colvos Rocks, Klas Rocks, and Snake Island, beach near Case Shoal
Control/away-from bridge seals	Dosewallips estuary	Duckabush, Hamma Hamma, and Skokomish estuary

*paired with seal foraging areas assessment

Approximately 70 scats will be collected from each site every ten days to two weeks between mid-March and mid-June, for a total of eight collections, targeting low-tide temporal windows when appreciable numbers of scats can be acquired. Collections may occur for an additional two months, through mid-August, to also capture the extent of the juvenile Chinook outmigrant window (for a total of 12 collections).We will strive to collect 70 harbor seal scat samples from each seal haulout site during each collection trip. This sample size is a rule of thumb determined from a statistical power analysis for seal and sea lion diet studies (Trites and Joy 2005).

At the haulout sites, each individual scat sample will be collected using a disposable wooden tongue depressor and placed in a zip-lock plastic bag lined container with a 126 µm nylon mesh paint strainer (Orr et al. 2003). Samples will be taken to the lab and frozen at -20°C within six hours of collection (King et al. 2008). Later, samples will be thawed and filled with ethanol before being manually homogenized with a disposable depressor inside the paint strainer to separate the scat matrix material from hard prey remains (e.g. bones, cephalopod beaks). The paint strainer containing prey hard parts will then be removed from the jar leaving behind the ethanol-preserved scat matrix for genetic analysis (Thomas et al. 2014).

Prey hard parts analysis

To remain consistent with the way previous harbor seal diet work in the region has been conducted using hard prey remains (i.e. hard parts), we will use the “all structures” approach to identify harbor seal prey contained in individual scat samples. Prey hard parts retained in the paint strainers will be cleaned of debris using either a washing machine or nested sieves. All diagnostic prey hard parts will be identified to the lowest possible taxon using a dissecting microscope and reference fish bones from Washington and British Columbia, in addition to published keys for fish bones and cephalopod beaks. Samples containing prey hard parts identifiable only to the family level (e.g. Clupeidae) and bones identifiable to the species level of the same family (e.g., Pacific herring, *Clupea pallasii*) will both be tallied (Lance et al. 2001).

Salmonid bones recovered from seal scats will be differentiated into either adult or juvenile based on visual inspection by a morphological prey identification expert. A clear size difference exists between juvenile and adult salmon bones which is apparent to taxonomists upon visual inspection (Figure 2).

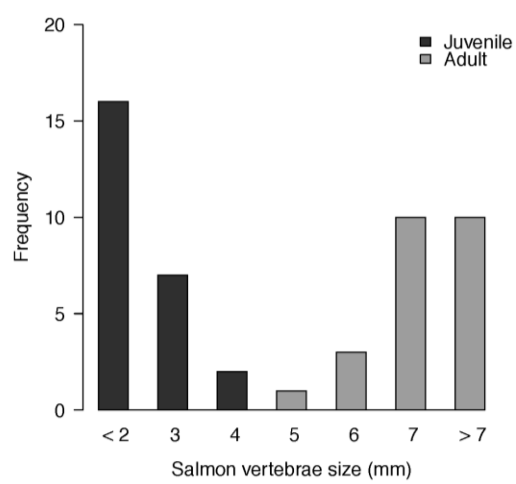


Figure 2. (From Thomas 2015) Frequency of salmon vertebrae between <2 mm and >7 mm, demonstrating the size difference between adult and juvenile salmon bones in seal scats.

DNA metabarcoding diet analysis

The DNA metabarcoding marker we will use to quantify fish proportions is a 16S mDNA fragment (~ 260 bp) previously described in Deagle et al. (2009) for pinniped scat analysis. We will use the combined Chord/Ceph primer sets: Chord_16S_F (GATCGAGAAGACCCTRTGGAGCT), Chord_16S_R (GGATTGCGCTGTTATCCCT), Ceph_16S_F (GACGAGAAGACCCTAWTGAGCT), and Ceph_16S_R (AAATTACGCTGTTATCCCT). This multiplex PCR reaction is designed to amplify both chordate and cephalopod prey species DNA.

To ensure accurate salmon species identification, a secondary metabarcoding marker will be used to quantity the salmon portion of seal diet, because the primary 16S marker is unable to differentiate between coho (*Oncorhynchus kisutch*) and steelhead (*Oncorhynchus mykiss*) DNA sequences. This marker is a COI "minibarcode" specifically for salmonids within the standard COI barcoding region: Sal_COI_F (CTCTATTTAGTATTTGGTGCCTGAG), Sal_COI_R (GAGTCAGAAGCTTATGTTRTTTATTCG). The COI amplicons will be sequenced alongside 16S such that the overall salmonid fraction of the diet will be quantified by 16S, and the salmon species proportions within that fraction will be quantified by COI.

For all DNA sequences successfully assigned to a sample, a BLAST search will be done against a custom 16S or COI reference database. A sequence will be assigned to a species based on the best match in the database (threshold BLASTN e-value < 1e-20 and a minimum identity of 0.9), and the proportions of each species' sequences will be quantified by individual sample after excluding harbor seal sequences or any identified contaminants (Caporaso et al. 2010). Samples will be excluded from subsequent analysis if they contain < 10 identified prey DNA sequences.

Harbor seal population diet percentages will be calculated from the DNA sequence percentages of individual samples in a collection - where seal population diet percentage for a particular prey species represents the average species DNA sequences % calculated from all samples in the collection. The percentage of juvenile steelhead (and Chinook) in harbor seal population diet will be estimated based on the co-occurrence of steelhead (and Chinook) DNA and juvenile salmon bones in seal scat samples (Thomas 2015).

Collaborators at WDFW and NMFS will use the resulting percentage of juvenile steelhead and Chinook in harbor seal diet (combined with seal population size and energy requirements) to estimate the numbers of smolts eaten by seals in each sub-region. Lastly, comparisons will be made between the seal-related steelhead mortality rate (based on scatological analysis) and the survival of steelhead populations in each sub-region studied. Scat-based estimates of steelhead mortality from seals will also be compared to telemetry-based estimates of predation as a means of validation for both methods.

Foraging Areas Assessment

A total of 16 harbor seals will be captured and tagged (under Marine Mammal Protection Act Research Permit 13430) in March 2017 prior to the first smolt tagging. Eight seals will be captured at the treatment/near-to bridge haulout sites and eight will be captured at the control/away-from bridge haulout sites. Instrument packs will be affixed to each seal and will record foraging times, depths and locations. These data will be used to characterize the forage areas of the treatment/near-to bridge seals and control/away-from bridge seals, confirm where juvenile steelhead (and Chinook) predation by seals likely occurs (combining foraging areas with diet data for each respective site), and confirm the validity of the treatment/control study design. See the Study Design section of "**Error! Reference source not ound.**" for a complete description of the instrument packs and deployment and recovery process.

Outcomes and Deliverables

The scat analysis data combined with the foraging areas assessment will help characterize the relative impact of harbor seals on steelhead (and potentially, Chinook) near-to vs far-from the Hood Canal Bridge. The final product will be a detailed technical report that will aid the assessment of potential management actions in response to how the bridge is affecting juvenile steelhead (and potentially, Chinook) survival.

5. Potential Phase 2: Assess harbor seal interactions with steelhead, and foraging behavior, via acoustic telemetry

Barry Berejikian, Megan Moore, NOAA Northwest Fisheries Science Center. Steve Jeffries, Washington Department of Fish and Wildlife. Austen Thomas, Smith-Root

Overview

Migration delays caused by the Hood Canal Bridge are hypothesized to increase the density of smolts near the bridge and facilitate elevated predation rates at these locations. Thus, predator/prey interactions between harbor seals and steelhead smolts may be influenced by the presence of the Hood Canal Bridge. One method proven effective in quantifying the spatial and temporal overlap of harbor seals and steelhead smolts involves mounting GPS tags and acoustic telemetry hydrophones ('instrument packs') on the pelage of an individual harbor seal. The mounted instrument packs are capable of detecting acoustic telemetry transmitters implanted into steelhead smolts (Berejikian et al. 2016), so that interactions between the two species can be quantified and georeferenced. Instrument packs will be mounted on harbor seals inhabiting the area near the Hood Canal and on those inhabiting areas less impacted by the bridge to provide detailed information on impacts of the Hood Canal Bridge on steelhead migratory behavior and survival.

Objectives

The primary objectives are 1) to determine whether the interactions between harbor seals and steelhead in the vicinity of the Hood Canal Bridge differ from interactions in areas less influenced by the bridge, and 2) describe the nature of the interactions under both sets of conditions. Here, an interaction is defined as the co-occurrence of a steelhead smolt acoustic tag and an instrumented harbor seal that detects the tag. Harbor seals outfitted with GPS tags and acoustic telemetry receivers will provide spatial and temporal data on the locations of steelhead tags that will complement data from the fixed array that is part of the steelhead tracking study (Appendix 1). This approach has been effective at identifying the locations of dead (stationary tags) and live (surviving to a later point in the migration) steelhead smolts (Berejikian et al. 2016). In addition to describing the spatial and temporal aspects of the interactions between the two species, we will test the following specific hypotheses:

H_{01}: The proportion of stationary steelhead tags found near harbor seal haulouts near the bridge does not differ from the proportion of stationary tags near haulouts far from the bridge.

H_{02}: The proportion of stationary steelhead tags detected by the harbor seals near the vicinity of the Hood Canal Bridge does not differ from the proportion of stationary tags detected by harbor seals far from the bridge.

H_{03}: Parameters quantifying the spatial and temporal overlap of tagged steelhead and harbor seals are similar near and away from the bridge (e.g., total number of steelhead detected, duration and frequency of detections, spatial and temporal distribution of detections).

Study Design

TAGGING AND STUDY AREA

The steelhead smolts being monitored as part of this study are the same as those in Appendix 1, which describes the tagging locations and methods. A total of 30 harbor seals will be captured and tagged (under Marine Mammal Protection Act Research Permit 13430) in March 2017 prior to the first smolt tagging. Eight seals will be captured at near bridge haulouts and eight will be captured at away from bridge haulout areas in Hood Canal. Each seal will be weighed, measured, and fitted with an instrument pack glued to the pelage with quick-set Epoxy. Each pack will contain 1) a Vemco mobile transceiver (VMT) capable of detecting the V7 transmitters (69 kHz), 2) a satellite-linked time depth recorder (TDR) and Fastloc GPS transmitter (model MK10AF, Wildlife Computers, Redmond, WA, USA, www.wildlifecomputers.com), 3) a VHF transmitter (164-165 MHZ, Advanced Telemetry Systems; www.atstrack.com) used for locating the instrument packs after they are shed by the harbor seals. All three instruments will be consolidated in a single floatation pack, which will be attached to the seal along the dorsal mid-line, on the anterior portion of the back. The GPS receivers will be programmed to transmit ARGOS and GPS data and to store Fastloc GPS locations on the tag every 10 minutes. Time and depth data will be recorded every 10 seconds. Only Fastloc GPS positions that incorporate data from five or more satellites will be used to minimize error (Hazel 2009). The VMTs will be continuously 'listening' for steelhead tags from the time of deployment until recovery. Harbor seals will shed the instrument packs when they molt in late summer after smolts have completed their migration through Hood Canal. As many packs as possible will be located and recovered. In 2014, 11 of 12 packs were recovered from harbor seals instrumented in Puget Sound.

DATA ANALYSES

We will determine the location of detected steelhead tags using the timestamps provided by the GPS units and VMT receivers to 'associate' VMT detections of tagged steelhead with the detecting seal's location. We will merge the Fastloc GPS timestamp data for a particular seal with the VMT timestamp data for steelhead tags detected by the same seal and calculate the minimum time differences (lag) between each VMT detection of a steelhead tag and the detecting seal's GPS location. Stationary tags near the Hood Canal Bridge that are part of the bridge hydrophone array (Appendix 1) will be detected by harbor seal VMTs. The distance between a GPS location of the seal within a specified time interval and the known sentinel tag location will provide an estimate of the error in the actual location of a VMT detection associated with a specific lag (i.e., time between VMT detection and GPS location). We may also interpolate locations when VMT detections occur between two GPS locations as has been done in other studies (e.g., Lidgard et al. 2014) for detections in which the Fastloc GPS location frequency is insufficient. Detected tags will be categorized as stationary (indicating mortality) if they are repeatedly detected in the same location. Tags detected by harbor seals and later detected at stationary arrays will be categorized as 'survivors'. Some tags will be detected by seals and never heard from again, and these will be categorized as having an 'unknown' fate.

We will use G-tests of independence to test the null hypothesis that the proportion of stationary steelhead tags detected near each haulout (within a 1 km radius) is independent of the haulout location (Dosewallips versus Gamble Bay). We will also use G-tests of independence to test the null hypothesis that the proportion of tags detected anywhere outside the haulout areas is independent of colony (Dosewallips versus Gamble Bay). Stationary tags will be enumerated as defined above. To determine the number of tags that were not detected as stationary, the number of smolts released into the

Skokomish River that survive to the vicinity of each of the two seal tagging locations (Dosewallips and Gamble Bay) will be estimated based on instantaneous mortality by distance estimates (number of mortalities/km; Moore et al. in prep). The number of smolts surviving to the Hood Canal Bridge will be estimated based on a mark-recapture analysis (see Appendix 1) and with the large number of fixed receivers the estimate should have very low associated error. The number of smolts surviving to the vicinity of the Dosewallips will be estimated by multiplying the estimated instantaneous mortality rate by the distance from smolt release to the Dosewallips haulout location (the inferred midpoint of the seal foraging areas), and subtracting the calculated mortalities from the number of smolts entering Hood Canal. The same calculation will be applied to infer the number of available smolts in the Hood Canal Bridge vicinity. Data will be scaled to incorporate variation in the duration of instrument pack deployments, the number of packs recovered, and core foraging areas for each colony.

Outcomes

This study combined with the diet analysis (Component 4) and fine-scale migratory behavior data (Component 1) will provide detailed information on the susceptibility of steelhead smolts to predation by harbor seals and how the Hood Canal Bridge influences predation risk. Harbor seals are just one of several potentially important predators on steelhead smolts in Hood Canal. In addition to assessing predation risk by harbor seals, the harbor seal-mounted instruments will provide locations of stationary and migrating steelhead smolts that may indicate other potential predators or locations that impact steelhead survival near and far from the Hood Canal Bridge.

Deliverables

Results of the telemetry study will be summarized and submitted for publication to a peer-reviewed scientific journal. Data will also be presented orally to interested parties and at relevant scientific meetings.

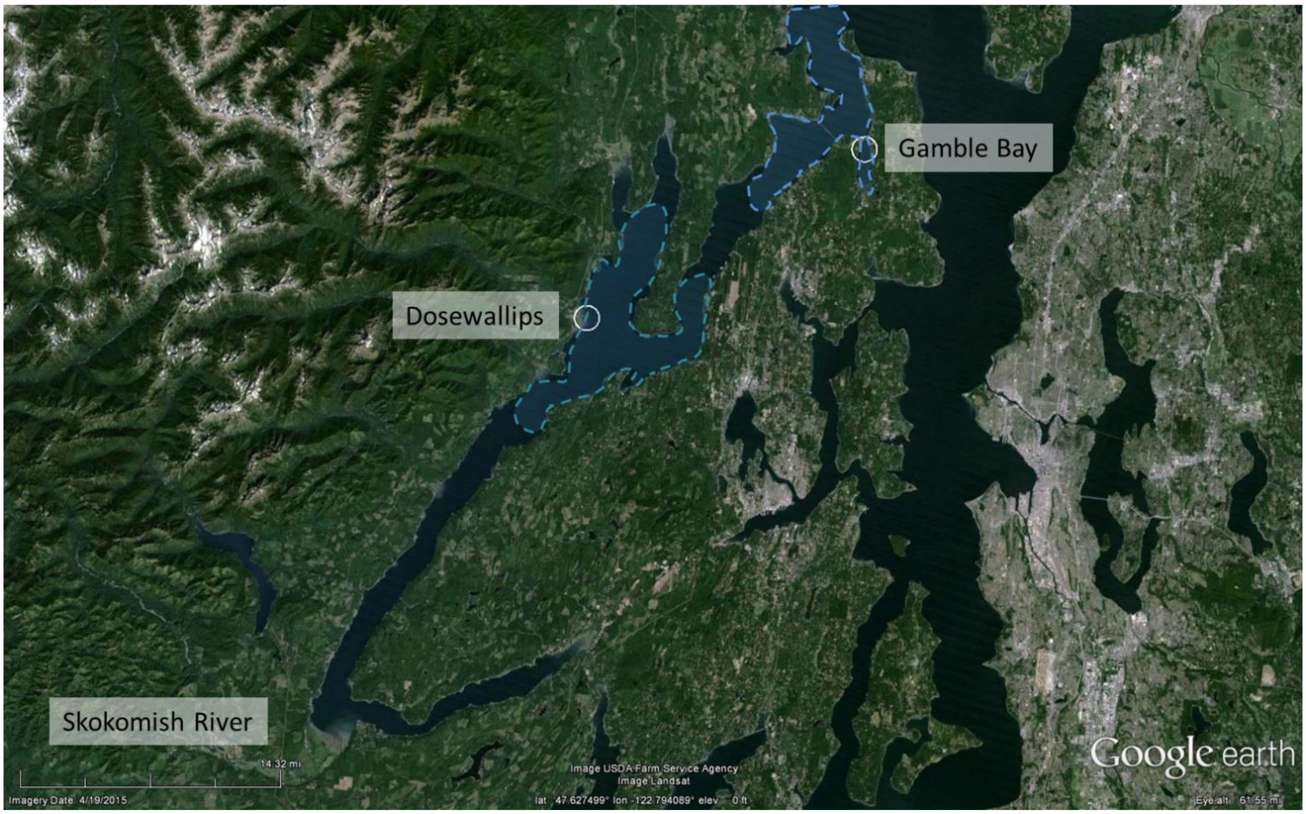


Figure 1. Study area showing 1 km radii surrounding proposed haulout capture areas near (Gamble Bay) and far (Dosewallips) from the Hood Canal Bridge. The blue areas represent the two corresponding hypothetical coverage areas for the two groups of seals (n = 15 per location) to help visualize the areas in which they may detect steelhead tags. Smolts will be collected, tagged, and released into the Skokomish River.

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

Hans Daubenberger, Port Gamble S'Klallam Tribe and Iris Kemp, Long Live the Kings (in coordination for Keister Lab, University of Washington, for zooplankton analysis)

Overview

Overwater structures are known to exacerbate predation for many salmon species (Yurk and Trites 2000, Williams et al. 2003, Celedonia et al. 2009, Blair et al. 2010). Shading caused by overwater structures and artificial light sources installed on such structures can influence fish behavior (foraging, schooling) and spatial distribution, increase predation risk and decrease avoidance capability, and disrupt migration patterns (Nightingale et al. 2006).

Shading caused by the Hood Canal Bridge may provide cover for predators. In the Puntledge River system on Vancouver Island, British Columbia, harbor seals have been observed after dusk utilizing a light-shadow boundary, caused by a bridge and its lighting, to intercept salmon smolts migrating downstream (Trites et al. 1996). In the Hudson River estuary, piscivorous fish may similarly use light-shadow boundaries created by overwater structure (Able et al. 2013). Outmigrating salmon and steelhead may also use the shade to avoid visual predators; however, this behavior may ultimately make them more susceptible to predation (Celedonia et. al. 2009).

Although WSDOT has installed overhead lighting that is intended to focus on the Hood Canal Bridge deck (pers. comm. Carl Ward, WSDOT 2015), spillover into the surrounding waters may be occurring. Artificial light affects salmonid swimming and migration behavior, potentially increasing predation risk (Tabor et al. 1998, Juell and Fosseidengen 2004, Prinslow et al. 1980). The "antipredation window" for juvenile salmonids – where foraging potential is maximized and detection by predators is minimized – may be reduced or eliminated altogether by artificial illumination (Scheuerell and Schindler 2003). Predators attacking from below are better able to distinguish prey silhouettes against a light background (Hobson 1966). In one Hood Canal study, spiny dogfish were attracted to artificial lighting that illuminated prey fishes (Prinslow et al. 1980) Other studies have documented birds and large-bodied (>500mm) piscivorous fish aggregate near artificial lighting and overwater structure, and hypothesized that artificially-lit environments provide increased predation opportunity (Becker et al 2013, Williams et al. 2003). Additionally, lighting closer to the water, around the bridge drawspan, may intensify the potential reef effect impact of the voids around, and the opening and closing of, the drawspan (reef effect explained on p. 24). Lighting may attract zooplankton, which in turn could attract forage fish and outmigrating juvenile salmon (Roger et al. 1979, Keen 2014, Celedonia et al. 2009, Prinslow et al. 1980).

Objectives

The objectives of this study are to assess:

1) The magnitude and spatial extent of potential changes in light caused by both artificial lighting and shading of the bridge structure compared to ambient/mean day and night light levels in Hood Canal away from the Bridge.
2) Correlations between intensities of light and shade and steelhead migration behavior, zooplankton aggregations, fish presence and densities (salmon, forage fish), and predator (bird, mammal, and potentially fish) presence and densities.

Study Design

1. Assess magnitude and spatial extent of potential changes in lighting

The following approach is an adaptation of what Williams et al. 2003 used to assess light impacts at ferry terminals. **This is a pilot study** which includes the minimum sampling necessary to attain a preliminary understanding of whether, where, and when light/shade levels near the bridge differ from levels away from the bridge and whether, where, and when light/shade levels vary along the bridge at given diurnal/nocturnal periods. If results of phase 1 work suggest a biological response that may be influenced by light/shade levels, comprehensive light/shade characterization will be considered for phase 2.

Light measurements will be recorded using LI-COR LI-193SA spherical quantum sensors and an LI-1500 light sensor logger. The sensors measure photosynthetically active radiation, or PAR (µmol m-2s-1), which is the spectrum of light between 400 and 700 nm that supports photosynthetic production and growth. The spherical quantum sensor is waterproof for use in aquatic environments, and collects light from all directions. PAR readings will be established from averages of instantaneous readings over a specific time interval (e.g. 15 seconds). GPS readings are taken simultaneously with all PAR readings using this system.

Light measurements will occur up to three times per year or three times across two years, once during low moonlight, once during a full moon, and once during the day to capture daytime shading. Light measurements will occur from the bridge (foot surveys from pontoons) to characterize light and shade in the immediate vicinity (including under the pontoons), and also along boat-based transects running perpendicular to the bridge. Bridge segments of 100 m will be selected to represent infrastructure and lighting (e.g., east/west spans to land, pontoon section, drawspan). Within each of these segments, boat-based transects be conducted every 20 m on both north and south sides of the bridge. The transects will begin as close to the bridge as possible and then continue away from the bridge until light levels remain constant and representative of natural lighting for that area. The minimum distance traveled away from the bridge will be 100 m.

Continuous light measurements will be recorded above the water's surface. To avoid shadows and interface from vessel lighting, the PAR sensor will be mounted on a shield and pole above the vessel cabin. Above-surface measurements will be averaged over 5 m increments. In-water measurements will occur at 0.1 m, 3.7 m, 5 m, and 10 m water depth at selected points along at least one boat-based transect representing each bridge segment. Voids along the bridge pontoons where water flows more rapidly will be sampled more intensively, in conjunction with work to observe the potential for a reef effect, as described in activity 14 in the body of this report. Finally, one scuba or ROV dive may occur during the day to characterize light levels immediately under the bridge pontoons if these measurements cannot be accomplished from the bridge itself. Turbidity measurements will be taken at all in-water measurement locations to account for impacts on light readings.

Lighting type will also be documented and results compared to the literature as it has been found that different types of light (e.g., mercury vapor, incandescent, quartz iodide) produce different responses in marine biota (Hanlon et al. 1979). Juvenile steelhead, coho, and chinook have been reported to increase night activity in response to mercury vapor lights, and under some conditions are strongly attracted to these lights (Nemeth and Anderson 1992, Puckett and Anderson 1987), possibly because they emit primarily in blue and ultraviolet spectra. Environmental context is critical; fish responses to lighting can vary according to lighting type, light intensity, and ambient light conditions.

2. Correlate with biological data

The results of step 1 will be mapped as a GIS layer and analyzed in ArcGIS and/or other spatial analysis packages with the biological data collected in studies 1, 2, and 3 (see component 13). Potential relationships between intensities of light and shade and steelhead migration behavior, fish presence and densities (salmon, forage fish and their predators), and predator (bird, mammal) presence and densities will be assessed. Studies 1, 2, and 3 will include night assessments where practical (optimally at low moonlight and full moon) and day vs night will be analyzed.

The zooplankton community will be sampled near to and away from the bridge using multi-frequency hydroacoustic sampling and surface net tows to determine whether zooplankton densities and relative species composition differs near to versus away from the bridge, and whether/how zooplankton species/densities vary along the bridge in conjunction with different bridge features. Down-looking 38 kHz and 200 kHz Biosonics DT-X split-beam digital transducers will be towed along transects perpendicular to the bridge. At each end of a transect, a near-to/away-from bridge net tow will be conducted. Due to the physical constraints of zooplankton sampling near the bridge, tows will be conducted during no/low tidal current velocities. Net tows will consist of a 1 m diameter single-ring net with 500 micron mesh towed vertically over the top 10 m of the water column. Nets will be weighted to enable vertical sampling in eddies near the bridge. A depth-profiling sensor will be attached to the net, and non-vertical tows will be discarded from analysis. Plummet net tows will also be considered for sampling eddies, as they are most effective for catching fast-moving zooplankton (e.g., krill) within a small area (Julie Keister, *pers. comm.*). These data will be used to characterize zooplankton species composition near and away from the bridge, and to determine whether zooplankton abundance is disproportionately high in the upper water column near the voids (i.e., a potential “reef effect”). Zooplankton data will also be included in spatial analyses to describe associations of zooplankton abundance and density with light/shade and fish presence and densities. Any visual observations of large surface aggregations of zooplankton encountered during light surveys will be documented.

DIDSON or Blueview acoustic imaging equipment may be used to assess the potential for a reef effect, as described in activity 14 in the body of this report. Areas with the potential for additional night lighting impacts as well as reef effect will be taken into consideration. DIDSON footage has been successfully used to assess light impacts on estuary biota (Becker et al. 2013, Able et al. 2013, Able et al. 2014). Because acoustic imaging does not depend on light (unlike video imaging), the equipment is not likely to disturb or attract biota. Additionally, DIDSON produces images of similar clarity regardless of light level and degree of turbidity in the water column (Able et al. 2014).Turbidity measurements will be taken over the course of the study to verify minimal effects of turbidity on image clarity, and to associate turbidity levels with fish presence and densities.

Outcomes and Deliverables

This work will result in GIS layers describing the magnitude and spatial extent of light impacts. Correlations with biological data will be documented as part of the synthesis analyses that will occur in this assessment and in the final Hood Canal Bridge Assessment technical report.

7. Measure noise impacts to fish behavior

Daniel Deng, Ki Won Jung, Jayson Martinez, Tarang Khangaonkar, Pacific Northwest National Laboratory. Hans Daubenberger, Port Gamble S'Klallam Tribe[10]

Problem Statement

Research recently conducted by NOAA's Manchester Research Laboratory 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 the exception of 2009. In 2009, the Hood Canal Bridge was closed to vehicle traffic during the steelhead smolt outmigration and no probable mortalities were observed at the bridge. This observation raises several questions including; do anthropogenic noises produced by vehicle traffic on the bridge interfere with the normal behavior of outmigrating steelhead smolts, and/or does this provide a masking effect for potential predators resulting in the measured increase of probable mortalities as recorded at the Hood Canal Bridge by Moore et al. (2013)?

Objective

The objective of this assessment activity 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?

Study Design

The behavior of salmon in response to underwater sounds is still largely unknown. Salmon have relatively poor hearing with a sharp cut-off frequency of 380 Hz. Typically, salmon are sensitive to particle motion (bulk motion of water resulting from pressure wave propagation) rather than sound pressure, so it is necessary to measure the particle motion in addition to sound pressure. The particle motion will be measured using accelerometers and sound pressure will be measured by hydrophones.

This study will be performed in two phases. Phase 1 will be 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.

PILOT: PHASE 1

For 2017, we propose to deploy a measurement system at two to three locations for a period of two weeks to a month. Each measurement system will consist of a data acquisition system and multiple

[10] The U.S. Navy has stated interest in participating in this study component as well. Also, Dr. Tim Essington, U. of Washington, also contributed to the development of this section. The initial proposal included Essington performing a correlated random walk model of steelhead migration to test for noise impacts. After further discussion with Dr. Essington, it was concluded that the proposed data synthesis approach described in component 13a will be able to test for noise impacts, in combination with other variables being assessed. Dr. Essington will be consulted when on any refinements to synthesis analyses in phase 2.

types of sensors. To measure the particle motion (via the structural vibration of the bridge) in terms of acceleration in three (x-, y-, and z-) directions, three high-sensitivity (approximately 1000 mV/g) accelerometers will be rigidly mounted in perpendicular directions. The sound propagated into the water will be measured using omnidirectional hydrophones mounted to the bridge underwater. We will also perform measurements from two locations using boats for a few hours (as control testing). We will then use these fixed location measurements to estimate the 2-D sound level contours from the bridge for these few hours. Based on these contours from the control testing, we will then have a simple linear model to predict sound attention from the bridge measurements for the month. This will be a crude model which will not account for environmental variability within the month nor account for water depth. Underwater speakers will be used to transmit known signals to calibrate the attenuation model during the control testing. Power for the devices will come from the bridge deck, provided by WSDOT.

A microphone (optional) will be deployed to measure the sound pressure generated by the traffic through the bridge in air. This optional microphone data will provide information relating traffic noise in air to sound pressure levels underwater. Traffic cameras will also be installed for monitoring traffic through the bridge if WSDOT cannot provide the level of traffic information detail needed from their cameras.

POTENTIAL: PHASE 2

If warranted, data collection will be repeated and expanded to 6-7 stations within the immediate vicinity of the Hood Canal Bridge during the steelhead smolt outmigration period. The more extensive dataset will then be used to numerically simulate underwater acoustic noise propagation using a finite element method (FEM) model which solves the acoustic wave equation. Numerical simulation modeling, such as finite difference method (FDM)-based modeling and FEM-based modeling, has been widely used for estimating how much energy is lost (i.e., transmission loss) with a given sound source in underwater acoustics in the frequency domain (Long et al. 2016, Lin et al. 2012). Our numerical model will provide a map of the transmission losses near the bridge. Using this map and the more extensive dataset, the sound pressure level can be evaluated as a function of position. This model will serve as an advanced tool to understand the behavioral response of migrating fish to acoustic noise mainly created by man-made structures. We propose developing the simulation model of underwater noise propagation through the following steps:

- Develop a 2-D multilayered FEM model that can illustrate the simplified fjord profile section including Hood Canal Bridge in order to first investigate the effect of the presence of the bridge and the complex bathymetry on the transmission loss. The multilayered FEM model will comprise air, the water, and the sediment to understand the sound transmission through different layers and its reflections between layers. In this step, each layer is considered as a homogeneous medium.
- Compare numerically simulated steady-state pressure values with the noise measurements by the hydrophones in both frequency and time domains.
- Incorporate other profiles such as water temperature, salinity, and flow velocity into the 2-D model. The effect of temporal changes in those profiles on the noise propagation will also be studied to estimate the amount of anthropogenic sound near the bridge where steelhead appear to stay for longer periods, which might have resulted in higher mortality.
- Develop a 3-D multilayered FEM model by extending the 2-D model.

Outcomes and Deliverables

We expect to characterize anthropogenic energy (sound and pressure) emanating from the Hood Canal Bridge. Phase 1 will result in a report that describes the detailed measurements and derived metrics of sound pressure and particle motion at two locations over a period of two weeks to a month and will provide preliminary simulation results from the sound attenuation regression analysis. If the results of phase 1 suggest a more detailed representation of noise propagation is needed, then phase 2 will be implemented. If implemented, phase 2 will result in a detailed acoustic field map reflecting variability in parameters (e.g., water temperature, salinity, and flow velocity) and serve as a tool to assess behavioral effects of sound on migrating fish given by Hood Canal Bridge.

For phases 1 and 2, the data will then be used in the synthesis analysis to quantify, within the bounds of available data, the extent to which anthropogenic energy (sound and pressure) affects the normal migration of steelhead smolts moving past the Hood Canal Bridge (component 1), and whether there are any correlations between fish densities (component 2) and predator densities (component 3) and noise.

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

Kevin Redman and Mike Taylor RPS – Evans Hamilton. Tarang Khangoankar, Pacific Northwest National Laboratory

Overview

Oceanographic data collection is planned to provide data for calibration of hydrodynamic models and for field observations of how the Hood Canal Bridge affects currents and mixing in the region near the bridge. Near-field, for the purpose of this scope, is defined as the region where the influence of the bridge on currents, salinity, and temperature variables is noticeable relative to the ambient (far-field). We expect this zone of influence region to be one to two bridge widths (18 to 36 m) normal to the direction of flow for tidal currents but could be much larger, one to two Hood Canal channel widths (2.4 to 4.8 km), for variables such as temperature and salinity. Prior analysis and fish tracking studies have shown that bridge pontoons block the surface currents in the upper 3.7 m of the water column. This alters the velocity structure near the bridge. The added mixing due to flow under the bridge also alters stratification (salinity and temperature profiles) as predicted in the modeling results by Khangaonkar and Wang (2013). Water depth at the bridge is anticipated to be approximately 90-100 m and 87-100 m outside the no-anchor zone (see attached bathymetric chart). Current measurements will be collected over a two-week period at three locations described below. In addition, mobile currents along transects upstream and downstream of the bridge will be measured during peak ebb and flood tides. CTD measurements and water levels will also be collected during the measurement period.

Objectives

The objective of this field study is to generate velocity, temperature, and salinity profile data in the vicinity of Hood Canal Bridge over a two to four-week period. The velocity profile data will be used to evaluate the effect of the presence of the floating bridge on the ebb and flood tidal currents as they traverse the bridge location. This data will be used for calibration of the hydrodynamic models. Salinity and temperature profiles upstream and downstream of the bridge will be used to assess the impact of the bridge on mixing near the surface, salinity, and temperature.

Study design

Current Measurements - Deployed

Current measurements will be taken a) immediately below the floating bridge section, b) 500 m upstream of the bridge, and c) 500 m downstream of the bridge (Figure 1). Currents will be measured using Acoustic Doppler Current Profilers (ADCPs) capable of measuring current velocity profiles and water level. Single-point current meters and CTDs (conductivity, temperature, depth) will also be deployed with each ADCP. For the bridge-mounted current meter, there exists an access road/platform attached to the floating section of the bridge (to be attached to east side of bridge Pontoon K). Attachment of an ADCP to the platform will provide a profile of the water current at and below the bridge and eliminate the need for multiple meters placed at discrete depths (e.g., 2 m, 5 m, 10 m, etc). The two current meters deployed upstream and downstream for the bridge will be mounted within our low relief bottom mount (BM). Placement will take into consideration the ability to collect data that reflects differences in water properties for when the bridge center drawspan is open vs. closed. In addition to the ADCP, the BM also contains a buoy/release system for diverless recovery. The BM has been successfully used in currents of up to 6 knots (3 m/s) and water depths up to 50 m. For deeper locations a short taut-wire mooring can be used. Moorings along the center line of the canal may require a permit to drop anchor. There exists a no-anchor zone of approximately 1000 m around the floating section of the Hood Canal Bridge. This may limit the nearness of the deployment locations for these two current meters. The frequency of these ADCPs will need to be 300 or 600 kHz for full water column current profiles. The equipment will be deployed for one month to collect over a full lunar cycle.

Underwater Current Measurements

Mobile current profiles will be measured along cross-canal transects both upstream and downstream of the bridge during peak ebb and peak flood tides. High-resolution, along-channel transects will also be performed following the water path or streamlines, perpendicular to and landward/seaward of the bridge. These data will help correlate the *in situ* data collected from the BM with what may occur across the canal at different tidal phases. The mobile measurements will be collected over two time periods: approximately two hours centered on the mid-point (peak) of the flood tide and two hours centered on the mid-point (peak) of the ebb tide. The mobile current survey will be conducted during daylight hours over the appropriate flood tide and ebb tide based on the predicted tides during the measurement period. Measurements will run past the peak periods for both tide phases to ensure capture of the maximum tidal currents.

To conduct the mobile current surveys, an ADCP will be mounted on the side of the survey vessel. The ADCP is mounted on a pole with the transducer oriented downward to provide a current profile through the water column from near the water surface to near the bottom along planned transects. If necessary, the pole can be retracted for fast transit between transects.

Additional Data

A probe will be cast at various times and locations (to be determined) in conjunction with the mobile current profiles to collect conductivity, temperature, and depth (CTD) records through the water column. At a minimum CTD casts will be collected near peak ebb, peak flood, and during slack water. A water level station will be installed near the bridge during the current measurement period. The pressure sensor for the station will be surveyed to the nearest benchmark to post-process the data relative to mean lower low water. CTD casts will also be performed during the hydroacoustics surveys performed by Port Gamble S'Klallam Tribe (research component 2, above).

Outcomes

This study will produce an oceanographic dataset characterizing currents and stratification near and under the Hood Canal Bridge. These data will be used to calibrate the oceanographic models developed.

Deliverables

Results of the oceanographic field study will be an Excel database containing processed data complete with associated field notes and datum information. This will include time series of ADCP data from three stations at 1 m bins in the water column, salinity and temperature profiles during peak ebb, flood, high and low tide intervals, and results of the mobile current surveys in graphical and digital formats. .

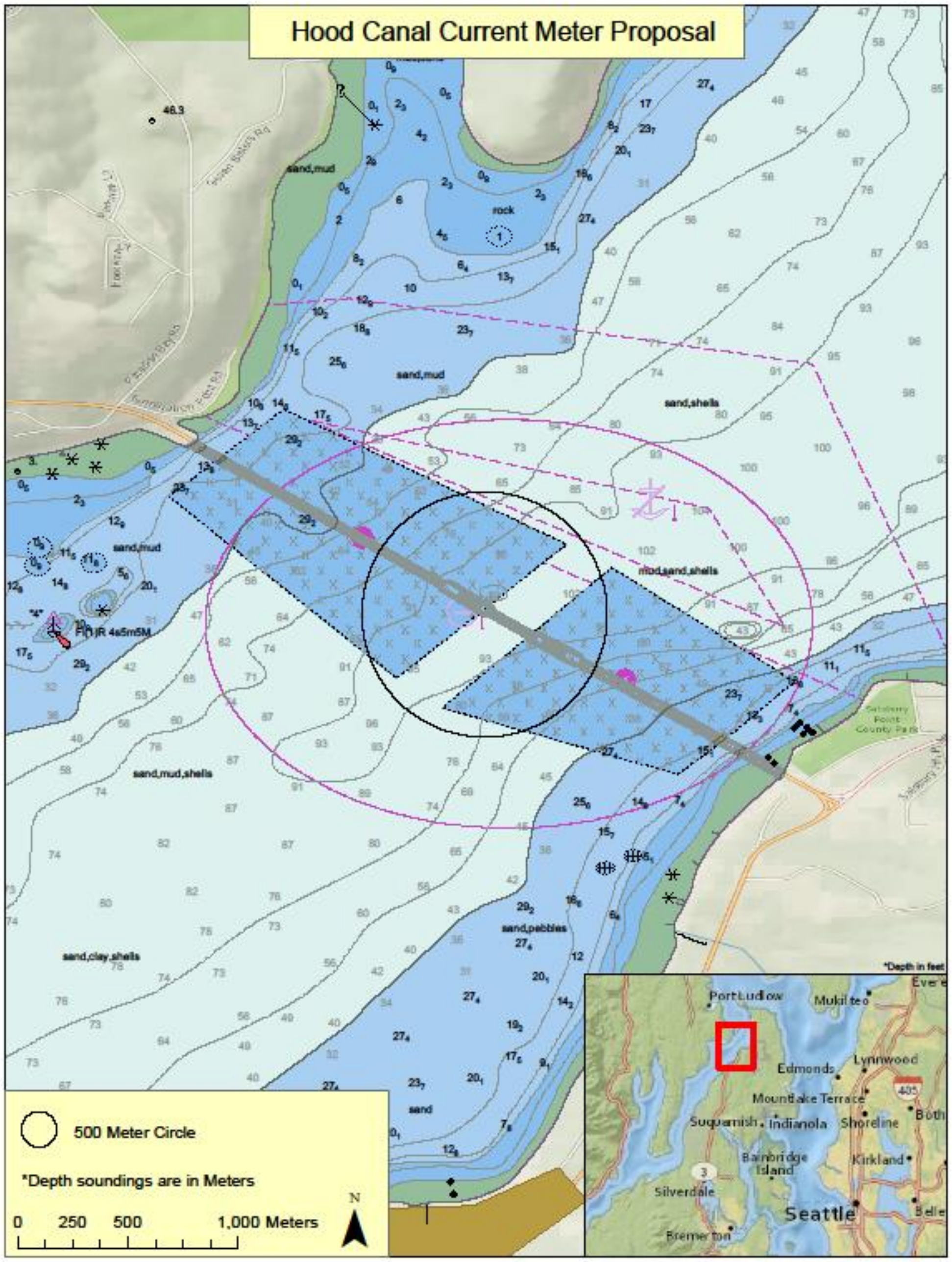


Figure 1. Current meter deployment and detection range. Black circle represents the deployed meter measurement range and purple circle the mobile data collection measurement range

9. Characterize the bridge zone of influence – Hydrodynamic Modeling

Tarang Khangaonkar, Taiping Wang, Wen Long, Marshall Richmond, Pacific Northwest National Laboratory

Overview

PNNL researchers conducted a preliminary analysis of tidal hydrodynamics in Hood Canal and hypothesized that the presence of a floating bridge across the width of Hood Canal and in the path of the brackish outflow layer may be affecting circulation and estuarine exchange processes (Khangaonkar and Wang 2013). Hood Canal exhibits deep narrow estuarine characteristics of classic fjords where outflow of freshwater occurs through a shallow surface layer and the mean circulation and mixing is dominated by the influence of freshwater outflow over that of tidal currents (Skjoldal et al. 1995, Rattray 1967). Studies have shown that the structure of currents and stratification in fjord-like basins within Puget Sound may be easily disturbed (Cannon 1972, Klink et al. 1981, and Lavelle et al. 1991). If the disturbance to the brackish outflow due to the bridge is confirmed, it would likely affect water quality in the near-field region around the bridge. Near-field impacts may include development of eddies during ebb and flood flows, increased vertical mixing affecting stratification and salinity gradients, and altered temperature profiles. Physical presence and blockage due to the structure could result in pooling of brackish outflow water, increased settling of algae and detritus, and possibly re-entrainment in the exchange flow from Admiralty Inlet entering Hood Canal along the bottom.

Objectives

The objective of this effort is to revise the computation of the bridge effect on Hood Canal hydrodynamics and water quality using an updated bridge module based on the combined results of calibration to field monitoring data and, if available, high-resolution computational fluid dynamics (CFD) analysis (a companion PNNL assessment activity). The results will inform fish behavior and juvenile outmigration assessments.

Study design

The prior published effort on Hood Canal Bridge effects included numerous approximations in the analytical as well as numerical methods. In the absence of site-specific data, the analysis relied on fitting the predicted profiles to historical information, and the representation of the bridge in the numerical model was a simplified continuity block only, approximating the effects on pressure and momentum terms. This effort will use the site-specific data from study 8 and will be conducted iteratively with the companion CFD modeling effort, if both are funded simultaneously. The CFD model will provide high-resolution simulation of hydrodynamics near the bridge pontoon structures. Hood Canal oceanographic data collected and analyzed by the U.S. Navy (BAE 2007), who will also be referenced when constructing this model.

The resulting data will be used for bridge module improvements and calibration. The Salish Sea Model developed by PNNL in collaboration with Ecology and EPA (Khangaonkar et al. 2011, Khangaonkar et al. 2013) will be upgraded with improved bridge block computations. The model will be calibrated to near-field data and effects on circulation and water quality recomputed.

Specific tasks will include the following:

1. Review of near-field data (study 8) and, if available, CFD model (study 10) results to assess the importance of non-hydrostatic effects near the bridge structure
2. Upgrade of the bridge block and incorporation into the Hood Canal region of the Puget Sound Georgia Basin (Salish Sea) biogeochemical and water quality model
3. Simulation of effect of the bridge on near-field water quality gradients (salinity, temperature, algal biomass, nutrients, and dissolved oxygen) – Year-long runs (2014/15)
4. Simulation of effect of the bridge when center drawspan is open vs closed, and during ebb and flood tides.
5. Development of information on boundary conditions for CFD modeling analysis

Regarding accounting for wind impacts: the refined Hood Canal grid will be embedded in to PNNL's Salish Sea model, which is forced by wind data from University of Washington's (UW) WRF model over a 12-km grid over the Salish Sea. We will also examine availability of data on a finer (4-km grid) and data available from meteorological monitoring sites near the Hood Canal Bridge, especially during the field data collection period, to ensure wind effects are properly incorporated in the analysis. The model is capable of reproducing wind effects and baroclinic circulation, and it is expected to capture seiche effects that may occur during strong winds.

Outcomes

A quantitative assessment of the effect of Hood Canal Bridge on near-field circulation and water quality analyzed over a typical one-year duration cycle accounting for seasonal variability. The results will help identify and characterize a zone of influence on currents and parameters such as salinity, temperature, and algal biomass, and dissolved oxygen around the structure based on change relative to ambient.

These data will then be used in the synthesis analysis to quantify, within the bounds of available data, the extent to which changes to near-field circulation and water quality affect the normal migration of steelhead smolts moving past the Hood Canal Bridge (study 1), and whether there are correlations among fish densities (study 2), predator densities (study 3), and these water properties.

Deliverables

Results of the modeling study will be summarized and submitted for publication to a peer-reviewed scientific journal by the end of 2018. Data will also be presented orally to interested parties and at relevant scientific meetings.

10. Potential Phase 2: Characterize fine-scale flow field near bridge pontoons- CFD Modeling

Marshall Richmond, Cindy Rakowski, Tarang Khangaonkar, Gary Johnson, Pacific Northwest National Laboratory

Overview

Recent studies by NOAA Fisheries (Moore et al. 2013) have highlighted potential effects of Hood Canal Bridge on migrating juvenile salmonids. Near-field impacts may include development of eddies in the bridge pontoon wakes during ebb and flood flows, increased vertical mixing affecting stratification and salinity gradients, and altered temperature profiles. These fine-scale hydrodynamic effects may also influence the migration of juvenile fish and provide zones that are favorable to predator fish species that prey on salmonids. Through a combination of analytical treatment and preliminary circulation modeling, PNNL researchers have provided a preliminary indication that the floating bridge may disrupt Hood Canal circulation and stratification (Khangaonkar and Wang 2013). That effort relied on assumptions related to eddy viscosity and mixing which are in need of field verification and calibration to detailed flow field data near the pontoon structures. This work will provide the fine-scale velocity field information near the bridge pontoon structures in support of circulation model calibration and interpretation/analysis of fish movement data near the bridge.

Objectives

The objectives of this effort are to develop a high-resolution computational fluid dynamics (CFD) model to assess non-hydrostatic near-field effects of the bridge pontoon structures on Hood Canal hydrodynamics and water density, develop an updated bridge module for use in the large-scale model, and provide hydrodynamics information to fisheries biologists.

Study design

The prior effort on Hood Canal Bridge effects included numerous approximations in the numerical methods and did not attempt to capture fine-scale flow features such as the wakes of the pontoon structures. In this project, we will develop a high-resolution CFD model with spatial resolution near the bridge and pontoon wake zones on the order of 0.5 ft (0.15 m) or less. The CFD model is non-hydrostatic, allowing it to simulate the near-field effects of flow acceleration around the pontoons and the dynamics of their wakes. We will apply a commercial CFD software package (STAR-CCM+) that runs on parallel high-performance computer systems available at PNNL (Rakowski et al 2005). Inflow and outflow boundary conditions to the model will be developed from the large-scale FVCOM model. To reduce the computational effort in this initial phase, the CFD model will not resolve surface waves and will use maximum flood and ebb conditions to simulate the system in a quasi-steady mode. However, the model is capable of simulating those effects and this could be included in a future project phase. Passive particle tracking will be used to visualize the flow and inform the fish behavior assessment activity. Specific tasks will include the following:

- Development of a high-resolution geometry model (CAD) of the in-water bridge structure and bathymetry to create the CFD model computational mesh

- Comparison of CFD simulations to field observations of velocity, temperature, and salinity (collected as part of a companion assessment activity)
- Simulation of the effect of the bridge on near-field flow features for maximum flood and ebb tide scenarios with particle tracking and flow visualizations for use by fisheries biologists
- Development of the bridge block module that can be incorporated into the large-scale FVCOM model of the Hood Canal region of Puget Sound

Outcomes

This activity will produce numerical simulations of Hood Canal Bridge structure effects on near-field hydrodynamic processes. The results will help fisheries biologists assess whether near-field flow patterns affect steelhead migration, or juvenile salmon, forage fish, or predator foraging behavior. These data will also be used in the synthesis analysis to enhance the results of study 9 and better quantify, within the bounds of available data, the extent to which changes to circulation and water quality affect the normal migration of steelhead smolts moving past the Hood Canal Bridge (study 1), and whether there are correlations among fish densities (study 2), predator densities (study 3), and these water properties.

Deliverables

Results of the modeling study will be summarized and submitted for publication to a peer-reviewed scientific journal. Data will also be presented orally to interested parties and at relevant scientific meetings.

11. Model the effect on flushing, biogeochemistry, dissolved oxygen and pH of Hood Canal

Tarang Khangaonkar, Wen Long, Laura Bianucci, Pacific Northwest National Laboratories

[This section describes the comprehensive approach to modeling the effect on flushing, biogeochemistry, dissolved oxygen and pH of Hood Canal. **In phase 1**, a coarse version of this analysis will be accomplished by Tarang Khangaonkar (PNNL) using the Salish Sea Model (Khangaonkar et al 2012). An updated biogeochemical module capable of simulating sediment diagenesis, hypoxia, pH and alkalinity should be available by early 2018. This, paired with a refined grid in Hood Canal developed during this study, will be applied in the Salish Sea Model with and without the bridge.]

Overview

Sustained low dissolved oxygen (DO) levels (hypoxia) and recurring fish kills in Hood Canal have been the subject of many investigations (Barnes and Collias 1958, Collias et al. 1974, Curl and Paulson 1991, Paulson et al. 2006, Newton et al. 2007, Kawase 2007). However, the causes and effects have not yet been fully determined. It is well known that fjords tend to become anoxic naturally and sediment cores from Hood Canal confirm that it has experienced low dissolved oxygen events since pre-European settlement (Brandenberger et al. 2008, 2011). Cope and Roberts (2013) found that local anthropogenic impacts are not likely to cause fish kills in the main arm. However, they could not rule out an impact on oxygen of regulatory significance in Lynch Cove. Review of available literature and recent research indicates that human loadings of nutrients cause a relatively small depletion in dissolved oxygen in the range of 0.03 ppm to 0.3 ppm in lower Hood Canal (Cope and Roberts 2013). Potential impacts from climate change, sea level rise, sediment enrichment, *Hood Canal Bridge*, and Skokomish River diversion have not yet been examined. Similarly, preliminary research conducted by PNNL indicates that the presence of a floating bridge across the width of Hood Canal and in the path of the outflow surface layer may be affecting circulation and estuarine exchange processes resulting in an increase in residence time (Khangaonkar and Wang 2013). The effect on residence time and flushing of the basin could also affect surface temperatures, biogeochemical cycling including nutrient uptake and algae growth, sedimentation, and pH, thereby impacting the ecosystem.

Several monitoring programs indicate declining pH in the coastal marine waters that reach the Salish Sea including Hood Canal. Hood Canal has historically supported a healthy shellfish industry, which is now citing the impacts of ocean acidification. Hood Canal waters are especially vulnerable to acidification resulting from a combination of factors, including strong coastal upwelling and long residence times. There is much concern that the effects of the bridge on flushing and circulation may exacerbate ocean acidification effects.

Objectives

The objective of this effort is to simulate the biogeochemical balance in Hood Canal including nutrient consumption, phytoplankton growth, death, settling, and decay, and occurrences of low DO levels in Lynch Cove. This assessment will include the floating bridge, Lynch Cove, and Skokomish tidal flats and cover a three-year period from 2005 through 2007 encompassing the HCDOP[11] data collection and fish

[11] Hood Canal Dissolved Oxygen Program – University of Washington.

kill years. The relative contributions of the bridge and other stressors to the hypoxia problem in Hood Canal would then be quantified through sensitivity tests.

Study design

We propose using the Salish Sea biogeochemical model developed by PNNL in collaboration with Washington State Department of Ecology and U.S. EPA for this effort (Khangaonkar et al. 2011, Khangaonkar et al. 2012). The model includes nutrient loads from nearly one hundred point and non-point source loads and oceanic influences. Hood Canal is part of the model domain and an effort to incorporate sediment diagenesis processes into the computations is underway. Specifically, the following tasks will be conducted using the available tool:

- Acquisition and processing of monthly monitoring and ORCA buoy data from Hood Canal region
- Refinement of the model grid in Skokomish River delta and Lynch Cove intertidal regions
- A three-year hydrodynamic simulation using the refined model grid including the bridge
- Simulation of biogeochemical processes including sediment diagenesis and calibration to the observed three-year data encompassing hypoxia and fish kill events
- Simulation of carbonate chemistry and pH in Hood Canal
- Sensitivity tests to quantify relative influence of the Hood Canal Bridge and other stressors on pH and DO

Outcomes

A quantitative assessment of the effect of Hood Canal Bridge on system-wide water quality parameters in Hood Canal with a focus on temperature, salinity, nutrients, algae, DO, and pH. The results will help guide water quality management actions and will feed into a companion research effort on ecosystem and food web impacts in Hood Canal.

Deliverables

Results of the modeling study will be summarized and submitted for publication to a peer-reviewed scientific journal. Data will also be presented orally to interested parties and at relevant scientific meetings.

12. Potential Phase 2: Model the subsequent impact to the Hood Canal food web

Chris Harvey, Isaac Kaplan, and Correigh Greene, NOAA Northwest Fisheries Science Center. Tarang Khangaonkar, Pacific Northwest National Laboratories. Brandon Sackmann, Integral Consulting

Overview

Puget Sound faces many stresses, particularly in Hood Canal where threats such as low dissolved oxygen (DO), eutrophication, and ocean acidification are exacerbated by long water residence times and possibly by human activities. New research indicates that the presence of the Hood Canal Bridge may restrict circulation and estuarine exchange processes, resulting in poorer water quality. It may also result in slower migration and reduced survival of juvenile steelhead. Because species throughout Hood Canal respond to changes in water quality, and because they interact with one another, any effects of the bridge on ecosystem processes or vulnerable species may ripple throughout the food web in unknown ways.

Objectives

The objective of this effort is to simulate the extent to which changes in the circulation of Hood Canal, caused by the Hood Canal Bridge, affect key species in Hood Canal and neighboring basins. Not only are there effects that can be attributed directly to the bridge (for example, changes in water quality, lower survival of surface-migrating fish), but there are also indirect effects, such as effects to species that feed on or compete with species that experience one or more of the direct effects. Simulation modeling will help to better anticipate the effects of the bridge throughout the ecosystem.

Study design

We propose using the Atlantis modeling software (Kaplan et al. 2012), which is a spatially and temporally explicit 3-D simulator of marine ecosystems, from the physics through the food web and up to human activities such as fishing, nutrient loading and marine resource management. Species groups, ranging from algae to fish to marine mammals, will be simulated in each area and depth layer of the model; the model simulates their daily growth, feeding, migration, reproduction, and survival in response to environmental conditions. The model can be used to test the effects of different climate, management, and infrastructure drivers on the ecosystem. Drs. Harvey and Kaplan are presently developing a Puget Sound Atlantis model for a different (but related) project.

The physics and nutrient loading of the model will be driven by the Salish Sea biogeochemical model, an extant oceanography model that has been used to simulate the effects of the bridge on circulation in Hood Canal (Khangaonkar and Wang 2013) and which has been used to make climate change predictions through the mid- to late-21st century (Roberts et al. 2013). Dr. Khangaonkar can run the Salish Sea biogeochemical model both with and without the Hood Canal Bridge, in order to estimate the effects of the bridge on circulation and water quality (see Project #11 above). We will use these alternate Salish Sea biogeochemical model projections to drive the Atlantis model; we will examine differences between Atlantis model outputs with the bridge present vs. the bridge absent to determine the bridge's relative influence on the Hood Canal ecosystem. The Atlantis model framework is flexible enough to serially add in different mechanisms to test a variety of hypotheses related to potential bridge effects.

The following tasks will be conducted using the model:

- Comparative estimates of the effects of Hood Canal circulation on food web structure, both with the bridge and without the bridge. We will first create a "baseline" simulation by driving the Atlantis model with Puget Sound circulation derived from a repeating loop of years 2005-2007 in the Salish Sea biogeochemical model (see Project #11 above) in the absence of the bridge. We will then create a "treatment" simulation by driving the Atlantis model with a repeating loop of 2005-2007 circulation that includes the bridge. We will compare "baseline" and "treatment" model outputs for 3-D cells in Hood Canal to determine if there is a conspicuous effect of the bridge on food web structure and abundance of key species of concern (including but not limited to ESA-listed salmon, rockfish, shrimp, Dungeness crabs, and killer whales).
    - The effects of the bridge in this comparison would be physical alone: namely, circulation impacts, effects on movement and distribution of planktonic species, and impediments to migratory species that swim at shallower depths than the bridge draft.
    - Model outputs to be compared will include changes in abundance and distribution of Hood Canal biota, changes in vital rates affected by temperature and salinity, and changes in diets of key consumers in the region of the bridge.
- Estimates of the effects of the Hood Canal bridge on ocean acidification. The Salish Sea biogeochemical model can also simulate the effect of the bridge on pH (see Project #11 above). Using several in-press studies on Atlantis model simulations of direct and indirect pH effects in the California Current food web, we will add pH-mortality relationships for different combinations of calcifying groups embedded in the food web, and run simulations with both the "baseline" and "treatment" models.
- Estimates of the effects of the Hood Canal bridge on DO. The Salish Sea biogeochemical model can also simulate the effect of the bridge on DO (see Project #11 above). Similar to the aforementioned pH comparisons, we will develop DO sensitivity relationships for key fishes and invertebrates, and run simulations with both the "baseline" and "treatment" models.
- Estimates of cumulative bridge effects. Simulate and compare different combinations of stressors (circulation; circulation + pH; circulation + DO; circulation + pH + DO) in the "baseline" and "treatment" models to estimate the relative importance of each, and the extent to which they are exacerbated by the presence of the bridge.
- Estimates of how future climate change and human population/urbanization/coastal development effects might interact with bridge effects, using forward projections of the Salish Sea biogeochemical model.

Outcomes

This study will produce a quantitative assessment of present and future food web-scale effects of the Hood Canal Bridge. The results will help guide fish and shellfish management and conservation efforts. The results will also complement a research effort on the effects of the Hood Canal Bridge on flushing, biogeochemistry, and DO.

Deliverables

Results of the study will be summarized and submitted for publication to a peer-reviewed scientific journal. Data will also be presented orally to interested parties and at relevant scientific meetings.

13. Synthesize patterns of migration behavior, 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)

Megan Moore and Barry Berejikian, NOAA Northwest Fisheries Science Center. Tarang Khangaonkar, Pacific Northwest National Laboratories (most of the Assessment Team will also contribute)

The output of the various assessment components will result in geographically and temporally referenced datasets that will be explored for spatial-temporal correlations that can help explain the pathways by which the bridge affects steelhead migration and survival, and overall salmon and forage fish distribution. Steelhead migration and fish distribution data describe the primary response variables, while predator densities/distribution (component 3) and zooplankton composition (built into components 2 and 6) data describe intermediate variables, and the bridge's physical presence and associated light/shade, noise, circulation, and water quality impacts data (components 6-10) describe explanatory variables. All data will be collected over the peak of the steelhead migration period (May), will represent day and night, tidal cycles, and to the best extent possible, will represent the bridge center drawspan state (open versus closed). The data collected will spatially cover the entire span of the bridge (the width of Hood Canal), with highest resolution data captured adjacent to the bridge to the north and south.

13a. Geographically weighted regression analyses

The steelhead acoustic tracking data will result in a fine-scale depiction of migration pathways, illustrating which lead to mortality and which lead to survival of outmigrating steelhead. Anomalous tag behavior and dropped tags may also provide locations of mortality events. Data generated from hydroacoustic sampling of the habitat surrounding the bridge will provide the distribution of juvenile salmon (and forage fish) at 100 m increments, covering a 2 km-wide area parallel to the bridge. Geographically weighted regression techniques will first be used to explore spatial correlations among steelhead migration and mortality patterns, salmon and forage fish distribution, and spatially explicit variables such as predator and zooplankton distribution and the physical impacts of the bridge. This includes the pontoons themselves, small voids in the pontoon structure, and the light/shade, noise, water circulation and water quality impacts being studied. Included will be comparisons of impacts during day (high levels of light and traffic noise) and night (low levels of light and traffic noise), tidal cycles, and to the best extent possible, will represent bridge center drawspan state (open versus closed). The results of this analysis will be presented in the comprehensive report for the bridge assessment, and summarized for publication in a peer-reviewed journal.

13b. Potential Phase 2: Simulating migration past Hood Canal Bridge

Guided by the findings of 13a, the Bridge Assessment Team will determine what method of modeling is best for simulating the bridge impacts to steelhead migration. This simulation will be used to test various management scenarios (see the next section of this report) and will also provide a null model, where no bridge exists, to further articulate the impact of the bridge. The following description focuses on the hypothesis that the movement and behavior of outmigrating steelhead is affected by the impact of the bridge on water velocity and quality. It recommends the development of a fish migration pathway tracking model based on the Eulerian-Lagrangian-Agent method (individual based model). However, due to the uncertainty regarding the pathway of impact, the Assessment Team is delaying a final decision on analysis approach until the geographically weighted regression analyses are complete.

OVERVIEW

The movement and behavior of outmigrating fish is likely affected by connectivity and ambient environmental parameters, such as water depth, velocity, salinity, and temperature. Depending upon species and size some outmigrating juvenile salmon and steelhead favor brackish water and shallow depths. The presence of the bridge in the outflow upper layer likely affects the velocity and water quality (salinity/temperature) gradients creating a zone of influence which could be detected by the fish. This likely also results in longer migration times and higher density of smolts near the bridge. The probable mortality was notably lower (0%) during extended "open center span" conditions in 2009 during the Hood Canal Bridge East Half replacement project (Moore et al. 2013).

OBJECTIVE

The objective of this effort is to develop a fish migration pathway tracking model based on the Eulerian-Lagrangian-Agent method (individual based model) which uses environmental cues, such as oceanographic properties of water coupled with basic fish behavior rules affecting fish motion. This model will evaluate whether the effect of bridge span opening (approximately six month duration) provided significant improvement in outmigration efficiency. Alternative management actions may then be developed through sensitivity simulations.

STUDY DESIGN

As part of the Bridge Assessment, tracking of high resolution fish movement near the bridge and near-field hydrodynamic and water quality data collection and modeling activities are under consideration. Our approach is to utilize resulting synoptic site-specific data set to set up and calibrate a fish-like particle tracking model (FTM). The model would then be applied for 2009 conditions to assess the effects of bridge span open/closed configurations on juvenile migration. Specifically we anticipate completion of the following tasks:

- Correlate high resolution of fish movement with velocity and water quality, and underwater noise data near the bridge to develop fish behavior characteristics and fish movement rules
- Calibrate FTM using bridge-site specific fish movement rules and behavior guidance
- Simulate hydrodynamics and water quality near the bridge – Year 2009 environmental conditions
- Apply FTM for Year 2009 conditions to assess the effect of open center bridge span condition
- Conduct sensitivity tests for model parameters and alternatives

OUTCOMES

An understanding of how juvenile outmigrants approach the Hood Canal Bridge and navigate under the structure will be developed through the set up and calibration of FTM using near-field fish tracking data. Analysis of Year 2009 conditions, with and without the bridge center span will help quantify the impact of the bridge on outmigrant behavior and passage and migration efficiency.

Appendix B: Hood Canal Bridge Impact Assessment Matrix

Primary Questions	Sub Questions	Hypotheses	Comp #	Synthesis (13a,*b*)	Evidence to accept hypotheses	Lead Investigators
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) 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	*	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 subsequent receiver lines. 3) Approach location is not similar to exit location. 4) Approach trajectory is not similar to encounter trajectory.	Megan Moore
	Is successful steelhead migration past the bridge associated with specific behavioral parameters (tortuosity, residence time, depth of encounter, habitat usage area, range of detections)?	More time spent near to bridge, encounters with bridge pontoons, more tortuous path, etc. increases probability of steelhead mortality.	1	*	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	Megan Moore
	What are the densities and distribution of salmon, steelhead and forage fish at the bridge versus away from the bridge?	Salmon, steelhead and forage fish congregate at higher densities near to the bridge (in bridge Zone of Influence) vs away from the bridge.	2	*	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.	Hans Daubenberger
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 are the densities and distribution of predators at the bridge versus away from the bridge?	Predators X,Y,Z congregate at higher densities near to the bridge vs away from the bridge.	3	*	At-sea transect surveys (visual observations) and bridge-based surveys indicate higher densities of predators at vs away from the bridge.	Scott Pearson
	What is the spatial correlation between key predators and steelhead (and other fish, including Chinook) near to vs away from the bridge?	Habitat usage is more highly correlated adjacent to the bridge compared to farther away.	1,2,3	*	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.	Megan Moore, Scott Pearson
	Are stationary tags more numerous near the bridge than elsewhere?	Stationary tags will be present in higher densities near the bridge than in more distant areas of Hood Canal.	1,*5*		Density of stationary tags is higher within bridge Zone of Influence than outside (spatial statistics)	Megan Moore, Barry Berejikian
	What is the spatial and temporal overlap between harbor seals and steelhead near to vs away from the bridge?	*Parameters quantifying the spatial and temporal overlap of tagged steelhead and harbor seals are different near to vs away from the bridge.*	1,*5*	*	*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)*	*Megan Moore, Steve Jeffries, Barry Berejikian*
	Is predation by harbor seals on juvenile steelhead and Chinook greater near to vs away from the bridge?	*Predation on steelhead and Chinook by harbor seals is greater near the bridge vs in the non-bridge impacted estuaries of Hood Canal.*	*4*		*Scat analysis combined with foraging behavior data suggest predation of steelhead and Chinook is greater near to vs away from bridge*	*Steve Jeffries, Austen Thomas*
		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.	*5*		*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*	*Barry Berejikian*
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)?	Temporal and biological parameters affect probability of steelhead survival.	1	*	Probability of survival is explained by release time, smolt size, or smolt condition in a mixed effects regression model.	Megan Moore
	Is successful steelhead migration past the bridge associated with light level encountered? Are fish densities associated with light levels encountered?	Artificial light over habitat adjacent to the HC bridge and/or shade under the bridge increases susceptibility of predation.	6,1,2	*	Probaility of survival is explained by light level encountered over migration path, tested with geographically weighted regression methods	Hans Daubenberger
	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?	The bridge traffic generates noise and vibrations which propagate through the water column, affecting the out-migrating behavior of the steelhead smolts.	7,1,2	*	Probaility of survival is explained by noise level encountered over migration path, tested with geographically weighted regression methods	Daniel Deng
	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?	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.	8,9,1,2	*	Probability of survival is explained by thermal experience, salinity levels, and/or currents encountered over migration path, tested with geographically weighted regression methods	Evans Hamilton, Tarang Khangaonkar
	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?	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.	*10*,1,2	*	Probability of survival is explained by encounters with wakes and eddies or salinty and temperature gradients at bridge tested with geographically weighted regression methods	Marshall Richmond
	Are fish with active acoustic tags more susceptible to predation than those with silent tags?	Fish with delayed and continuously pinging acoustic tags have significantly different survival rates.	1		Equivalency test of two proportions (continous and delayed) with a tolerance of 0.10.	Megan Moore
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?	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.	14		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.	Hans Daubenberger
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?			13a,*b*	See * in column	Geographically weighted regression analysis illustrates strong relationships between changes in steelhead migration behavior, fish distribution, predator densities and distribution, and the bridge pontoons or specific ways the bridge is influencing the surriounding environment.	Megan Moore, Tarang Khangaonkar
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?*		*13b*	*	*Modeled alternatives reduce changes to migration behavior.*	*Tarang Khangaonkar*

Primary Questions	Sub Questions	Hypotheses	Comp #	Synthesis (13a,*b*)	Evidence to accept hypotheses	Lead Investigators
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 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.	**8,9,*10***		Model simulations with no bridge show significantly different current structure, temperature and salinity profiles, and/or stratification than model simulations with bridge.	Tarang Khangaonkar
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?	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.	**11**		Enhanced Salish Sea biogeochemical model illustrates relative impact of bridge vs other stressors to surface temperatures, biogeochemical cycling, sedimentation, and pH.	Tarang Khangaonkar
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 basins?*	*Impacts of the bridge to circulation and water quality subsequently impact the Hood Canal food web.*	***12***		*An Atlantis, ecosystem simulation model demonstrates impacts to key species, especially those of commercial, recreational and cultural importance.*	*Chris Harvey*
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*					

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

Appendix C: Responses to Reviewer Comments

Washington State Department of Transportation (WSDOT), completed by University of Washington Expert Review Panel

Panel Composition: Parker MacCready, John B. Mickett, Jan Newton, Thomas Quinn, and Charles Simenstad

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The Washington State Department of Transportation asked the panel the following questions [in gray dialog boxes]:

In response to the question, "Is the study plan based on the best available science? Do the conclusions and assumptions, based either on scientific studies specific to the Hood Canal Bridge or otherwise relevant, support this study plan? Are the questions/hypotheses testable given the existing data and proposed to be acquired?" The panel suggested the following:

1. ... However, combining the two major objectives of reviewing bridge effects on juvenile steelhead and bridge effects on the overall ecosystem is not justified given the broad scope. **The panel recommends that the two study elements be organized into separate phases**. The studies validating the potential effects of the Bridge as a barrier, potential mortality factor to juvenile steelhead and salmon, and oceanographic measurements around the bridge (Phase I) should be given higher priority. A following phase could be considered for assessing the potential impact of the Bridge on the structure and function of the entire Hood Canal ecosystem (e.g., hypoxia, acidification) after further evaluation and research planning (Phase II).

   Response: *Combining the two primary objectives of determining bridge effects on juvenile steelhead and salmon outmigrants and the entire Hood Canal ecosystem is valid due to the value in integrating assessment activities. Much of the same oceanographic data are required to assess near-bridge oceanographic effects on outmigrating steelhead and salmon as are required to assess the oceanographic effects of the bridge that could lead to Hood Canal-wide changes in physical, chemical and biological properties. Second, the Team*[12] *considers the data from Moore et al 2013*[13]*, and preliminary data regarding bridge impacts to fish densities (figure 4 in body of plan), sufficient to warrant moving past validating that there is an impact associated with the Bridge to understanding mechanistically how the Bridge impacts steelhead survival—and at a minimum other fish behavior, including salmon—so that solutions can be recommended. Doing so requires simultaneous collection of data on the presumed mortality vector (predation) and potential pathways (pontoons themselves, impacts to physical water properties, noise, light and shade).*

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[12] And others, including the Hood Canal Coordinating Council who considers assessing the Bridge impacts a high priority.

[13] Moore et al 2013 reflects 5 years of field data clearly indicating unique mortality patterns at the bridge versus elsewhere in Puget Sound. Moore, M., Berejikian, B.A., and Tezak, E.P. 2013. A floating bridge disrupts seaward migration and increases mortality of steelhead smolts in Hood Canal, Washington State. PLoS ONE 8(9): e73427. doi: 10.1371/journal.pone.0073427.

That said, the Team has revisited the phasing and has revised the plan based upon the Team's interpretation of all of the Reviewers' comments presented in this Appendix, in aggregate. Funds currently available to initiate the assessment have also influenced the phasing. The revised approach is to present a fully fleshed out phase 1, but retain the descriptions of other components that may be part of phase 2. Phase 2 will be formalized in subsequent years contingent upon the results of phase 1 and via the adaptive management process clarified in the plan. Consistent with reviewer comments, Phase 1 will prioritize a detailed understanding of steelhead mortality at the bridge. To ensure the causal linkages between the Bridge and steelhead mortality can be articulated, the Team will simultaneously assess mortality, the presumed mortality vector (predation) and potential pathways (pontoons themselves, impacts to physical water properties, noise, light and shade). The preliminary data suggesting a bridge impact on fish distribution is also compelling enough to warrant a continued analysis of fish distribution relative to potential impacts, in phase 1. Furthermore, observations of potential impacts of the pools between pontoons adjacent the center drawspawn warrant further investigation in phase 1.

While there has been numerous observations of harbor seals utilizing the bridge for foraging (see response to comment 5, below), it is not yet well documented nor in a quantitative fashion comparing densities and behavior at versus away from the Bridge. Furthermore, the broad suite of potential predators using the Bridge, to weigh relative potential impacts, is not yet characterized. Therefore, the broader predator analysis (component 3) is prioritized, and the Team will delay heightened focus on harbor seals (e.g. diet and comprehensive interaction analysis) until more data are available to confirm/refute its value.

The Team also agrees with reviewers that the initial analysis of noise, light and shade should be performed as proof of concepts. The noise component of the assessment was already developed accordingly, and the light and shade component was only drafted as a proof of concept. The Team has clarified this in the report, but maintains that these proof of concept components must occur in phase 1 based upon the position stated in paragraph 2, above.

Regarding bridge impacts to the entire Hood Canal ecosystem: the Team agrees that we should prioritize improving the accuracy of our understanding of the Bridge impact to flow. However, the Team disagrees that the approach laid out in this plan requires substantive changes (see responses to comments 3, 6, 7). Instead, the Team favors limiting phase 1 to assessing the near-field effects of the bridge on flow along with only a very preliminary assessment of how this may translate to impacts to dissolved oxygen, temperature, pH and nutrient dynamics throughout Hood Canal. This would be accomplished using the Salish Sea Model (Khangaonkar et al 2012) with an updated biogeochemical module capable of simulating sediment diagenesis, hypoxia, pH and alkalinity using the hydrodynamic solution with a refined grid in Hood Canal developed during this study, applied with and without the bridge. The results of this will then be used to determine whether proceeding with an extensive investigation of potential impacts to the Hood Canal ecosystem is warranted.

Please see the revised plan for details.

2. The review panel indicated that first of the two primary questions addressing studying the bridge "as a barrier to juvenile steelhead and salmon migration and leading to increased mortality" (Assessment Plan, p.4) is more tractable than the second study question.

a. The panel noted that the variation in survival of steelhead among years and among populations within different regions of Puget Sound does not strongly support the hypothesis that the Hood Canal populations are experiencing markedly lower survival than other regions (e.g., Goetz et al. 2015; Moore et al. 2015).

b. In order to determine movement patterns and indication of areas causing migration delay, a higher sample size should be utilized.

Response: *In response to part a, The Team does not claim that the early marine survival of Hood Canal steelhead, from river mouth to the Pacific Ocean, is markedly lower than other regions in Puget Sound. Instead, while there was a lack of support for an effect of region on steelhead survival in Moore et al. (2015), there are some finer scale patterns in the survival data that do support a substantial effect of bridge mortality. Specifically:*

- *Survival of steelhead smolts through Hood Canal is higher than survival of South and Central Sound populations over comparable migration distances, yet the survival from the Hood Canal bridge to Admiralty Inlet (25 km) is very low (see Figure 5 in Moore et al. (2015), causing overall survival to be similar to South and Central Puget Sound populations by the time they leave the Puget Sound. Therefore, Hood Canal populations may have the potential to survive at much higher rates than South and Central Puget Sound populations in the absence of mortality caused by the Hood Canal Bridge.*

- *In Moore et al (2013), twenty-seven mortality events were detected within the vicinity of the Hood Canal Bridge, while only one mortality was recorded on the other 325 receivers deployed throughout the Hood Canal steelhead migration route.*

- *In Moore et al (2013), over a five-year period, migrating steelhead smolts were detected at the Hood Canal Bridge array with greater frequency, on more receivers, and for longer durations than smolts migrating past three comparably configured arrays on their migration route.*

In response to part b, based on the 2010 data (see Moore et al. 2013), tagging 200 steelhead, we predict that sample sizes would increase to 29 mortalities and 30 survivors (expanded because of the additional receiver line). An additional 50 steelhead will be tagged to assess depth of migration at the bridge, and they will increase the power of the assessment. These sample sizes will provide sufficient ability to determine differences in migratory pathways exhibited by smolts with different fates (dead at the bridge vs surviving).

3. The second study question addressing **“the bridge impact to the entire Hood Canal ecosystem” (Assessment Plan, p. 4) is more speculative and requires substantially more justification and detail to establish a ‘proof of concept’**. The study by Khangaonkar and Wang (2013) provides some suggestive support for the hypothesis that the bridge may disrupt mean flow and water properties within Hood Canal; however, enhanced field surveys and in---depth modelling is encouraged rather than relying on the minimal field observations described in the plan at this time. Evaluation by modeling and field measurements could be deployed to test critical assumptions and predictions before embarking on a full---fledged research program. For instance, there is some uncertainty with the assumption of utilizing previous literature that studied a bridge with 100% constraint, where the Hood Canal Bridge only blocks 85% of the canal width.

Response: *A floating object that occupies more the 50% of the brackish outflow layer in Hood Canal obstructs the tidal exchange between Hood Canal and Puget Sound. This is inherently obvious to the scientific community familiar with tidal circulation. This was demonstrated clearly using three different methods – (a) Analytical Treatment, (b) Numerical Model of Simplified Channel with Bridge, and (c) Model of Hood Canal with Bridge in the paper by Khangaonkar and Wang (2013). The results in the paper are not speculative suggestions but are quantitative and conclusive. However, there is room to improve the accuracy of the results. The limitation has been that the numerical incorporation of the bridge in the hydrodynamic model has thus far been through an approximate treatment. The treatment erred in the conservative direction: that is the actual effect could be stronger than that reported in the paper. The approach provides a full continuity block but underestimates the effect on momentum terms. The simulation results indicate that the bridge alters velocity and temperature fields close to the bridge and the large-scale ecosystem impacts are inferred from the fact that flushing time or residence times are increased.*

In Phase 1, it is our plan to refine the Hood Canal representation by a 10-fold increase in grid resolution. The Bridge module will include an improved representation of the physical barrier that blocks the velocities and momentum. In Phase 1, our focus will be on the near-field zone of influence. Oceanographic data collection is designed specifically to refine and validate an existing model and associated assumptions (see response to comment 25 for additional details). The model refinement will also allow more accurate representation of the geometric features of the bridge that occupies ≈ 85% of the width. This was considered a more cost effective approach compared to intensive empirical data collection scheme.

The Assessment Team has moved fine-scale oceanographic modeling at the bridge, and full-scale modeling of potential impacts to dissolved oxygen/pH/nutrient dynamics, to phase 2 and have left them in conceptual form. Once phase 1 results are completed, the Team, along with input by external reviewers, can determine whether additional physical data collection is warranted.

In response to the question, “Are there inherent uncertainties that need to be resolved before moving to a mechanistic understanding of an acknowledged impact?” The panel suggested the following:

4. The review panel indicated that there is little data available prior to bridge construction, however there **may be opportunities for partnering with other research studies or utilizing past data** to reduce uncertainty.

Response: *Based on the increasing presence, persistence, and distribution of hypoxia in Hood Canal during the 1990-2000’s compared to 1930-60’s, as well as, successive fish kills during the early 2000’s, Newton et al. (2008) concluded that hypoxia conditions were becoming more severe in Hood Canal. Hood Canal exhibits fjord like characteristics of strong stratification, slow flushing, and restricted mixing which often lead to hypoxic conditions that are common in fjords. However, these conditions may be exacerbated by anthropogenic stressors such as nutrient enrichment and ocean acidification (Feeley et al. 2010). The floating Hood Canal Bridge could also be one such stressor that affects flushing and mixing, based on results presented in Khangaonkar and Wang (2013). A study by PNNL (Brandenberger et al. 2008) on Hood Canal is often quoted to make the point that hypoxia events in Hood Canal may be natural events. This work, based on reconstructions of redox-sensitive metal indicators, suggests hypoxia has occurred in Hood Canal well before human alterations beginning in the 1900s. However, the* *reconstruction time line does not extend past the approximate year 2000 and is unable to resolve the timing of short-lived hypoxia events that led to fish kills in Hood Canal during the early 21st Century. The Hood Canal Bridge was constructed in 1962, and its contribution to the hypoxia events in Hood Canal has not been quantified. A recent EPA/DOE review (Cope and Roberts 2013) concluded that the potential effects of Hood Canal Bridge and Skokomish River Diversion on Hood Canal hypoxia are two man-made changes that have not been characterized based on available literature and need to be addressed.*

In response to the question, "How could the approach, methodology, and analysis of any specific study component be improved to maximize potential interpretations of findings?" The panel suggested the following:

5. The investigators are encouraged to provide better scientific focus for the Assessment Plan. It is advised to **remove broad generalizations that have little scientific basis and detract from the more substantive evidence**.

    a. For example, casting the study as addressing juvenile steelhead and salmon along the length of the bridge when previous studies document juvenile steelhead and several species of salmon migrating only in relatively shallow nearshore (e.g., intertidal) waters.

    b. Another example mentioned previously includes characterizing mortality of juvenile steelhead from Hood Canal as abnormally high when this is not representative of the available data that indicates mortality rates vary extensively by Puget Sound region between season and year of outmigration.

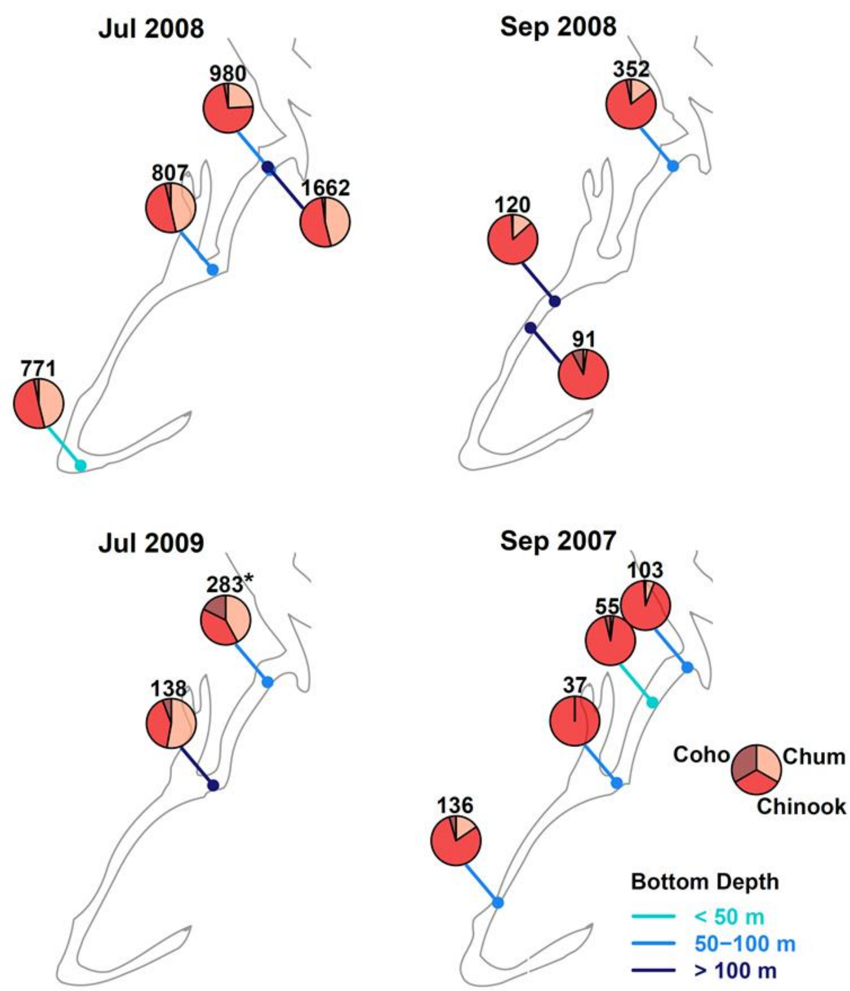
    Response: *The Assessment Team has attempted to clarify what may be considered broad generalizations in the report, and via the detail provided below in reference to the examples provided by the Reviewers.*

    <u>*Regarding example "a"*</u>*: First, steelhead smolts have been shown to distribute fairly evenly during Hood Canal outmigration (Moore et al. 2010), and are thus likely to encounter the bridge pontoons in high proportions. Second, juvenile salmon habitat use "has" been documented extensively in both nearshore and offshore waters throughout Puget Sound, including Hood Canal. In general, chum, pink, and subyearling chinook salmon occupy shallow nearshore habitats upon entering Puget Sound and move further offshore into neritic/epipelagic habitats in Puget Sound as they grow (Fresh et al. 1981, Simenstad et al. 1982, Beamish et al. 1998, Duffy et al. 2005, Duffy et al. 2010). Documented use of Hood Canal offshore habitat by juvenile salmon is summarized as follows:*

    Prior studies report offshore catches of juvenile chum, chinook, coho, and pink salmon, as well as outmigrating juvenile steelhead in Hood Canal (Bax et al. 1978, Bollens et al. 2010). Bax et al. (1978) observed peak nearshore chum CPUE occurred slightly prior to peak offshore chum CPUE, suggesting movement from nearshore to offshore habitats. Juvenile salmon feed extensively on pelagic zooplankton in Hood Canal, particularly crab larvae (Simenstad and Kinney 1978), suggesting offshore habitat utilization. Additional studies document that chum salmon distributed across the entire width of Hood Canal during outmigration (Bax and Whitmus 1981, Bax 1983). Acoustically-tagged chinook were detected by receivers at and immediately east of *the center of the Hood Canal Bridge (Chamberlin et al. 2011), providing direct evidence of salmon outmigration through offshore waters in Hood Canal.*

Additional unpublished trawl data and investigator observations suggest that juvenile salmon occupy epipelagic habitat in areas that are most likely to be affected by potential impacts from the bridge. Juvenile chinook and chum have been caught by midwater trawl in the upper 15 m of the water column over bottom depths ranging from 30-165 m, including tows in proximity to the Hood Canal Bridge (supporting figure 1, below). In addition, anecdotal and photographic observations (supporting figure 2, below) taken from the lower deck of the Hood Canal Bridge document large numbers of juvenile chum in the surface waters at the middle of the bridge.

<u>Regarding example b</u>: See response to comment 2, above.



Supporting Figure 1. Juvenile salmon catches in the upper 15 m of the water column over a range of bottom depths in Hood Canal in July and September midwater trawl surveys, 2007-2009. Dots represent ship location at start of tow; color indicates recorded bottom depth. Pie charts represent proportional catch of juvenile salmon species (coho, chum, chinook). Total number juvenile salmon caught is labeled above each pie. All tows were 20 minutes except for one July 2009 tow indicated by an asterisk: this tow was 16 minutes. Trawl survey methods follow Beamish et al. 2000. Figure developed by Iris Kemp, *LLTK. Based upon unpublished midwater trawl survey data from July 2008-2009 and September 2007-2008.*

Supporting Figure 2. Photograph of biota in the center east pool (inset) of the Hood Canal Bridge on May 12, 2016 by Hans Daubenberger depicts juvenile chum swimming in a cloud of larval crab.

6. Suggested proposal revisions include identifying the interdependence of study components to resolve the concern that linkages between Phase I and Phase II components are not clear or robust. **Key assessment components should be differentiated from components that could begin as pilot projects to develop a proof of concept for further study**. For example, pilot studies of the effects of light and noise on fish could be incorporated in Phase II planning. See the Appendix for further details.

   The panel further indicated that physical measurements should be conducted simultaneously with fish measurements in order to obtain a more mechanistic understanding of fish and potential predator responses to the dynamic environmental conditions around the Bridge. See the Appendix for specific feedback on approach, methodology, and analysis of specific study components.

   Response: *The Review Team has clarified the interdependence of the study components via substantive revisions to the assessment plan. See the response to comment 1, above, and the revisions to the report itself. The Team agrees that physical measurements should be conducted simultaneously with fish measurements. Hence the reason they are phased simultaneously.*

In response to the question, “How could the approach, methodology, and analysis of any specific study component be improved to maximize potential interpretations of findings?” The panel suggested the following:

7. **It is uncertain which of the many different study components will act independently or linearly, and how they should be organized to accommodate these factors**. Although the Assessment Plan includes diagrams that map potential findings with potential management actions for Phases I and II (Figs. 8 and 9, respectively), **there is no indication of interdependent studies and datasets that would need to be linked in time and space**.

   Response: *“Appendix B:* Hood Canal Bridge Impact Assessment Matrix” *clearly indicates the interdependency of the various study components. The body of the report has also been improved to clarify these interdependencies. Furthermore, the phasing has been improved upon based in part upon Reviewer comments.*

8. If results are determined, it is also unclear if WSDOT can respond with feasible adaptive management techniques. As the study plan indicates, Outcomes and Adaptive Management is delegated to Q3 and Q4, after the completion of field work. **The panel questions whether this timeline suggests that adaptive management would take place utilizing modeling simulations and other analytical results**.

   Response: *Along with revisions made to phasing, we have improved the description of process and timeline related to adaptive management. Yes, solutions will be developed and tested based upon analytical results and model simulations.*

9. Secondly, the physical factors affecting the fish (light, noise, flow, waves, etc.) **may not elicit linear responses**, and they may or may not act independently. These sources of uncertainty could potentially affect both steelhead mortality and broader ecosystem responses.

   Response: *The Team will use a multi-model approach, to enable direct comparison of the effects of the measured environmental variables on fish movement parameters. See component 5, and Appendix B for description of how components are inter-related. This approach, along with efforts to collect both impact (flow, noise, light, predators, zooplankton) and response (migration patterns and fish densities) data on similar temporal and spatial scales, will provide the Team with the best shot possible to isolate specific mechanisms for mortality. The Team agrees more than one pathway for mortality may be at play, but certainly not all. Therefore, this approach helps narrow the field and develop solutions to empirically test, to determine whether they elicit a positive response.*

In response to the question, “Is there a critical study component missing? The panel suggested the following:

10. Other than an expansion of the current hypothesis and study design for each component indicated in the Appendix, **the panel did not identify components missing.** The primary concern identified by the panel was **whether such a broad set of study components could provide coherent recommendations for future mitigation of any effects that the Hood Canal Bridge is <u>having on the surrounding ecosystem</u>**.

Response: *See responses to comments 1 and 7-9, above. Furthermore, please note that phase 1 has now been constrained to focus primarily on isolating how the bridge impacts outmigrating steelhead and salmon. Secondarily, phase 1 increase the accuracy of effects to mean flow and provide an initial glimpse of how the bridge may impact the water properties and, thusly, the ecosystem of Hood Canal. If validated, these data will lend to a more refined approach that can provide a clearer tie to specific recommendations for future mitigation.*

The panel also had a three overarching recommendations

11. Improve the study design elements as indicated in the Appendix.

    Responses in the following section.

12. **Implement strategic phasing of components. Strategic phasing of the study components can help cut costs and timing of the project by differentiating between components that are warranted for determining changes in fish behavior and circulation changes** before addressing other components that could be initially deployed as proof of concept studies. This will also enable more accurate cost estimation as they can be scaled up from pilot studies.

    Response: *The plan has been modified. See response to comment 1 and the plan as a whole.*

13. **Introduce a competitive request for proposal and independent review to maximize scientific integrity**.

    Response: *The origin and nature of this assessment plan does not lend to a competitive request for proposals. This is not a situation such as a permitting process, where WSDOT has money and can produce a request for proposals for an environmental assessment. Instead, this is a call to action. Concerned resource managers and scientists who have already begun to investigate the impacts (in particular Khangoankar, Moore, Daubenberger) of the bridge convened to establish a collaborative, multi-disciplinary approach that: a) enables the comprehensive science needed to assess the bridge impacts and b) includes the various parties necessary to bring the outcomes to bear on management. Beyond the Assessment Team, there is currently a small Management Committee that utilizes the Hood Canal Coordinating Council, and the Management Committee will be expanded to ensure all appropriate agencies are engaged throughout the process. Independent review of the results of the work will occur through peer review of publications and Management Committee review of the comprehensive report on phase 1 results. We have also added a placeholder for an external independent review of the comprehensive report, pending funds raised. The process and construct, including collaborator, manager and expert engagement has been clarified in the Plan.*

    Furthermore, the plan itself is the request for funds. Without it, the money could not be raised to complete the work.

The panel's Appendix suggested the following

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

13. This study does not clearly identify the critical mechanism for steelhead mortality. A primary hypothesis could be structured as Do Hood Canal steelhead have anomalously low survival compared to other populations in Puget Sound and the Salish Sea, and if so, is this related to the bridge or not? The Keogh River, B.C. population has been in decline for years (Ward 2000), and there is broad agreement that the Puget Sound populations are experiencing lower survival rates than in past decades. Therefore, low survival is not a recent phenomenon but rather a pattern that has been going on for some time, nor is it confined to Hood Canal. When examining the paper by Moore et al. (2015), the effect of the "region" (Hood Canal vs. northern Puget Sound vs. south---central Puget Sound) was a very minor contributor to the variance in steelhead survival as indicated by telemetry results.

    Response: *Though there was a lack of support for an effect of region on steelhead survival in Moore et al. (2015), there are some finer scale patterns in the survival data that do support a substantial effect of bridge mortality. Specifically, survival of steelhead smolts through Hood Canal is higher than survival of South and Central Sound populations over comparable migration distances, yet the survival from the Hood Canal bridge to Admiralty Inlet (25 km) is very low (see Figure 5 in Moore et al. (2015)), causing overall survival to be similar to South and Central Puget Sound populations by the time they leave the Puget Sound. Therefore, Hood Canal populations may have the potential to survive at much higher rates than South and Central Puget Sound populations in the absence of mortality caused by the Hood Canal Bridge. The fact that Hood Canal populations survive at similar rates over the entire early marine migration does not preclude the possibility that the bridge reduces steelhead survival in Hood Canal. For example, if predation by seals is a primary factor affecting the survival of steelhead smolts in Puget Sound, the Hood Canal Bridge may be increasing Hood Canal population predation levels, while other factors are increasing predation levels for Salish Sea populations migrating through different basins. The Hood Canal Bridge has been identified as a source of mortality that may have the potential for mitigation, which may increase the potential of Hood Canal steelhead to migrate to the Pacific Ocean in higher numbers.*

    To address the point that steelhead survival declines are more recent than the construction of the Hood Canal Bridge, there may be factors that interact with the bridge that have changed over the same time period as steelhead declines. Again, if harbor seal predation is a substantial mortality vector, the increase in Puget Sound seal abundance (Jeffries et al. 2003), and the subsequent increase in interactions at the bridge may be limiting the ability of Hood Canal populations to recover.

14. The paper by Moore et al. (2013) presents some intriguing data. The difference in delay between surviving steelhead smolts and steelhead presumed dead (delay up to 3 months) is remarkable, given the general tendency for steelhead smolts to travel quickly in Puget Sound (e.g., Goetz et al. 2015), and elsewhere (Romer et al. 2013; Chapman et al. 2015). This part of the study merits closer attention, although the net effect on survival may not be clear. While sonic tracking studies are good for describing movement patterns and areas of delay (e.g., Moore et al. 2010. 2012, 2013), a rigorous study of marine survival would require larger sample

sizes to garner confidence. The coded wire tagging projects and PIT tag studies typically have orders of magnitude more fish than were implanted with sonic tags.

Response: *The scale of coded wire and PIT tag studies is very different from the scale of the proposed acoustic telemetry study at the bridge. Coded-wire tag studies cover the life span of the species (2-7 years), while this acoustic tag study will take place over just a few weeks. PIT tag studies on the Columbia measure survival over hundreds of kilometers, while this study focuses survival over a distance of less than 10 kilometers. Furthermore, the rate of recapture of acoustic tags (that is, identified by an acoustic receiver vs actually collected) is much higher than PIT or coded-wire tags, increasing power of smaller sample size. Altogether, the smaller sample sizes applied can be used with reasonable confidence. Furthermore, acoustic telemetry tools in this study have the advantage of measuring both fine scale behavior and survival due to relatively short migration distances over short periods of time. Finally, the feasibility of using PIT or coded-wire tags to assess such mortality is very limited. How would enough wild steelhead be captured to perform such as study? How would enough return adults be sampled? How do you isolate impacts of the Bridge? Lengthy discussion comparing various approaches for assessing early marine mortality of steelhead have occurred via the Salish Sea Marine Survival Project. Documentation is available upon request.*

Concerns about the need to rationalize whether or not early marine mortality in Puget Sound (including at the Hood Canal Bridge) may be significantly affecting overall survival has been addressed via the Salish Sea Marine Survival Project. See "Research Work Plan: Marine Survival of Puget Sound Steelhead" for details.[14]

15. The Assessment Plan should also consider utilizing 2-D acoustic data to enable testing the hypothesis that probability of survival is explained by thermal experience, salinity levels, and/or currents encountered over migration path. This will depend on results from the additional 50 smolts that will be implanted with larger V9 depth sensor acoustic transmitters (69 kHz, 9 mm diameter, 21 mm length, 2.9 g) to assess the preferred depth of steelhead smolts at various stages of bridge encounters, and to inform fish position calculations.

    Response: *We agree. Depth is the most important factor to test initially due to the relevance of migration depth to the success of migration past submerged pontoons, as well as the utility of the data for position calculations. We may be able to pair CTD data with 2D behavioral data to understand thermal or salinity preferences during migration, and possible disruption of those gradients resulting from the HCB, which may affect migration routes.*

16. Further suggestions for study design include an alteration in receivers before and after the bridge. The current study places receivers on either side of the bridge, **but lacks a control section to indicate the natural behavior of the fish** (travel rate, day---night timing, back---tracking, etc.) and survival rate in an unconfined stretch prior to reaching the bridge. An alternative design option would include two lines south of the bridge and one north of it, so that there would be an open water to open water reach, an open water to bridge reach, and a bridge to open water reach. The proposal has a line at Twin Spits that would serve some of this function, but two receiver lines prior to the bridge would be very informative.

[14] http://marinesurvivalproject.com/wp-content/uploads/FINAL-WORK-PLAN-PS-steelhead-marine-survival-31Jan2014.pdf.

Response: *Moore et al. (2013) used a similar approach by comparing behavior at the Hood Canal Bridge to behavior at a Mid-Canal line, the Admiralty inlet line, and the Strait of Juan de Fuca line. Behavioral alteration associated with the bridge has been established. The proposed study focuses on fine-scale behavioral patterns, with a design that uses successful migrants as controls, and compares the attributes of a successful or unhindered path to those of a mortality or delayed migration path past the bridge. In this way, we can better determine the factors associated with delayed or unsuccessful migration.*

The use of depth---sensing transmitters will provide very important information but the only concern would be whether this will necessitate unusually large fish, which might not be fully representative.

Response: *We agree. The fish large enough to accommodate the larger depth tags will be on the larger end of the distribution. However, previous years of telemetry data analysis on these same populations have revealed no effects on behavior or survival related to size. Therefore, we feel comfortable that the larger fish will be a reasonable representation of the whole population, and that this is a necessary assumption to make in order to gain depth information.*

17. In addition, further testing of what is referred to as the “dinner---bell hypothesis” does not seem warranted based on data reported so far (e.g., Berejikian et al. 2016). This does not mean that this hypothesis must be totally dismissed, but inclusion of a test within the context of the bridge does not seem warranted at this time.

    Response: *Since there has only been one Puget Sound study that has accepted the null dinner-bell hypothesis, and because the geography is different (i.e., there was not a barrier that affects migration behavior in play in the previous south/central Puget Sound study) we feel that more study is warranted. In fact, this component is necessary to address any concerns that marine mammals are specifically targeting tagged animals in the specific context of migration past the Hood Canal Bridge.*

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

18. The review panel **suggests the use of net catches to distinguish target calibration with fish sampling**. Steelhead are likely to represent a small fraction of the fish community, so systematic sampling of species composition with nets would be essential to sort out whether the targets are herring, salmon or other species. This is a major task and the net sampling might be complicated by the need for ESA permits for Chinook salmon, summer chum salmon and steelhead. If steelhead migrate close to the surface, this is likely the very region most difficult to sample accurately with hydroacoustic gear. In addition, how will “hydroacoustic surveys used to understand the relationship between tagged steelhead and all other fish in terms of their size, distribution, and abundance, and to characterize the distribution of salmon and forage fish at the bridge versus away from the bridge” (Assessment Plan, p. 13) distinguish among fish targets? Will calibration with net catches be utilized? Target calibration with fish sampling is not indicated in this study design.

    Response: *We acknowledge the limitations of this study design. A surface-oriented, side-looking acoustic approach will allow for enumeration of targets and target density (number of targets in a given area) near the water surface. Side-aspect target strength varies widely based on fish* *orientation, lateral movement, and position within the sonar beam as well as species-specific morphology and behavioral characteristics (Burwen and Fleischman 1998, Boswell and Wilson 2008, Lilja et al. 2004), thus precluding species identification or fish size determination. For these reasons, net catches cannot be used to calibrate the hydroacoustic data in this study.*

We understand that the hydroacoustic data will not represent only salmon species, nor will it provide specific density estimates of ESA-listed chinook and chum salmon or steelhead. However, it will show whether and how the bridge affects distribution of fish in the upper water column. Visual observations (at minimum, presence/absence of taxa near bridge) will be recorded, providing qualitative insight into the fish species using bridge-adjacent habitats.

Hydroacoustic surveys will help understand the relationship between tagged steelhead and other biota by allowing comparison of tagged steelhead characteristics and migration paths against the distribution and density of biota in the upper water column. For example, are migration paths that result in mortality of tagged steelhead associated with high densities of epipelagic biota?

C. Map predator (marine mammal and bird) densities.

19. This study's assumption that ocean---type Chinook, chum and pink salmon are also vulnerable to a bridge effect is **unjustifiably speculative, given their generally shallow, nearshore migration patterns**. However, this could be further studied from the results of the predation analysis.

    Response: *The "assumption" that Chinook, pink and chum salmon may also be vulnerable to a bridge effect is explained in response to comment 5, above.*

    This study should also include mapping of bird and seal densities in order to answer the question. Are the potential predators (other than fishes) concentrated around the bridge, on one side or the other?

    Response: *This is exactly our goal. We will have high resolution information on the location of bird and mammal predators near the bridge. We will use this information to create a density surface by species of potential predators as identified in Pearson et al. 2014 (our steelhead report). These density contour maps will then be correlated with similar contour maps of steelhead travel routes and with contour maps that describe fish densities and distribution around the bridge.*

    As noted above, it is unclear what the conclusions of this portion of the study would imply for adaptive management.

    Response: *The first goal is to identify the potential predators and then consider potential solutions. For example, if the primary predator is the harbor seal, it might be feasible to exclude them from nearby haulouts or to modify the bridge to make it more difficult for seals to capture steelhead.*

D. Assess harbor seal---related steelhead mortality --- seal scat/diet analysis.

20. Although the seal scat/diet analysis offers some conclusive data, it is uncertain exactly what the data will be based on. What proportion of hatchery steelhead w/ CWT or PIT tags, might also appear in scat sampling? Will otoliths be identified and analyzed from seal scat collections? The paper by Berejikian et al. (2016) implies that the seals were not the obvious culprit in the mortality of steelhead. Other papers such as the work by Olesiuk (1993) indicated that salmonids are a very small fraction of the diet of seals, who eat primarily herring and other non--- salmonids. The paper by Yurk and Trites (2000) seems to be an unusual and perhaps a unique situation, where the seals are using the light---dark contrast under a bridge in a river to prey on smolts. If this is the case, then visual observations would immediately identify this factor because seals would be seen at the bridge on regular basis.

    Until the presence of seals around the bridge is clearly documented, and the hypothesis that the bridge indeed affects survival is fully tested and supported, this piece of the study may not be supported at this stage.

    Response: *First, harbor seals have been observed utilizing the bridge for some time. Port Gamble S'Klallam Tribe (PGST) staff have observed seals when working in the area over the past several years. In 2016, PGST staff set up GoPro and BlueView cameras on a portion of the bridge and documented seals foraging. Furthermore, WSDOT staff have indicated seals and their pups utilizing ledges adjacent pools formed in the bridge pontoon structure (pers. comm. Hans Daubenberger, PGST). Furthermore, the Hood Canal Bridge could very well be functioning to give seals a predation advantage by providing artificial light and shade scenarios, similar to the way Yurk and Trites (2000) documented a different bridge functioning to provide seals a predation advantage. This is why investigating light and shade impacts is a necessary first step to include: to determine whether this is a pathway that enables predation.*

    That said, the Team agrees there has yet to be a quantitative assessment of predators (composition, abundance) at the bridge and relative to areas beyond the bridge zone of influence. This is what will occur in phase 1 via assessment component 3. These data will be used to spatially compare the migration routes of steelhead near the bridge in relation to the distribution of its potential predators as identified in Pearson et al. 2015. The Team has decided to move this diet analysis assessment component to phase 2 and keep it in concept form until we learn from component 3.

    Some seals are specialists (Wilson et al. 2014). If you have specialists, even predation by a few individuals can potentially have a large impact. The scat analysis will provide information on percent steelhead in diet (molecular work) and how diet composition varies among individuals. The parallel hard part analysis will allow us to attribute the steelhead portion of seal diet to adult and juvenile fish. This information coupled with recently completed population and haulout surveys will allow us to estimate the potential impact of seals on outmigrating smolts.

    We also know that as prey fields change so do the diets of predators. For example, in years of low pink smolt abundance, rockfish become more vulnerable to seal predation, even though they constitute a small proportion of the total diet (Ward et al. 2014). We also know that predation rates vary spatially. For example, steelhead are a much larger portion of the seal diet in the Comax area but are almost non-existent in other parts of the Salish Sea (Lance et al. 2012).

Finally, the interpretation that the paper by Berejikian et al. (2016) does implies "that the seals were not the obvious culprit in the mortality of steelhead" is incorrect. This was a study to determine whether seals and steelhead were interacting at all in Puget Sound, which it clearly documented.

E. Assess harbor seal interactions w/ steelhead and foraging behavior.

21. There may be some uncertainties associated with this study component. How will GPS tags and acoustic telemetry transceiver instrument packs on the pelage of individual harbor seals detect acoustic transmitters implanted into steelhead smolts? How are data acquired or retrieved from recovered transceivers? Given the results reported by Berejikian et al. (2016) and the comments related to component #4 (seal diet analysis), this portion of the study may not be supported at this stage.

    Response: *Due to the interconnectedness with the diet analysis, the Team has decided to keep this component in phase 2 but leave in concept form until we learn from component 3 in phase 1. The Team is targeting performing a pilot analysis of seal foraging and seal-steelhead interactions in phase 1 if funds allow.*

    Many of the details on how data were generated, acquired, and retrieved are described in Berejikian et al. (2016). Briefly, acoustic receivers capable of decoding transmissions from steelhead transmitters will be fixed to individual seals, such that a record will be generated on the seal receiver when that individual encounters a tagged steelhead within approximately 100 m or less. The duration and location of each encounter can then be ascertained from the frequency of detection and associated timestamp on the receiver coupled with the GPS coordinates calculated by the GPS tag. In the context of this study, location of encounters will be very important in identifying geographic areas or bridge structures where high numbers of seal x steelhead interactions occur. Furthermore, direct predation can be determined if a tagged steelhead is consumed by an outfitted seal, as continuous transmissions of the consumed tag will be recorded by the seal receiver until the tag is expelled from the predator gut. Receiver data and accurate GPS data are retrieved when the outfitted seal molts and the pack falls off, to be located via a VHF radio tag which is also included in the seal pack.

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

22. The measurement of light and shade deserves more detail. What is meant by "magnitude and spatial extent of artificial light and shade impacts near the bridge structure" (Assessment Plan, p. 14)? Will this include impacts to fish, or impacts to environment? Will diurnal light measurements will be acquired throughout the day, with changing solar azimuth? Will the data inform a geospatial shade model that can then provide a time---integrated estimate of shading contrast relative to the Bridge's structure? This component could be tested after conducting visual surveys of predators present at the bridge and documentation of the behavior of the fish to review activity, depth, and duration of time spent at bridge. This portion of the study may not be supported at this stage.

    Response: *We agree with reviewers that the current design for light and shade measurements is limited, and the language in the plan has been adjusted to more clearly articulate this as a pilot study. Per the response to comment 1, above, it's necessary to perform this work in phase 1—*

simultaneously with the assessments of steelhead migration patterns, fish and predator distribution, and plankton composition—in order to spatially and temporarily compare the data and determine whether there are correlations via geographically weighted regression techniques (see component 6).

This project component was designed as an adaptation of light impact assessment at ferry terminals (Williams et al. 2003). The current study design represents the minimum sampling needed to determine whether, where and when light/shade levels in areas near the bridge differ from areas away from the bridge and whether, where and when light/shade levels vary along the bridge at given times of the day and night. If the results suggest there are correlations between light levels and a biological response, then a more in-depth analysis will be considered for phase 2.

23. Presumably, the portion of the study that will "characterize zooplankton communities near and away from the bridge" (Assessment Plan, p.14) will be conducted during no/low tidal current velocity, otherwise it may be unlikely to detect a bridge effect. There may be an opportunity to partner with others research projects regarding zooplankton, such as Julie Kiester (UW, Oceanography).

    ***Response:** The intent of this project component is to determine whether zooplankton densities and relative species composition differs near to versus away from the bridge, and whether/how zooplankton species/densities vary along the bridge in conjunction with different bridge features. Due to the physical constraints of zooplankton sampling near the bridge, tows will be conducted during no/low tidal current velocities. The Team has consulted Dr. Julie Keister during the design of this assessment component, and we will continue to interface with Dr. Keister.*

G. Measure noise impacts to fish behavior.

24. The panel suggests inclusion of more detail and citations to support "numerically simulate underwater acoustic noise propagation using a finite element method (FEM) model" (Assessment Plan, p. 15). This portion of the study may not be supported at this stage.

    ***Response:** The plan has been updated with more detail and references. Furthermore, this assessment is established in two phases, with the first phase being a pilot/proof of concept to determine whether noise impacts should be a concern worthy of further investigation. Starting with a proof of concept is consistent with the recommendations of the WSDOT review panel. However, it's necessary to perform the pilot work in phase 1—simultaneously with the assessments of steelhead migration patterns, fish and predator distribution, and plankton composition—in order to spatially and temporarily compare the data and determine whether there are correlations via geographically weighted regression techniques (see component 13*

H. Collect oceanographic data at bridge (current, salinity, and temperature profiles)

25. Khangaonkar and Wang (2013) provided significant support for the hypothesis that the floating bridge significantly disrupts the mean flow and water properties in Hood Canal. Until there is unequivocal information on the mortality of steelhead caused by bridge effects, such detailed data should be considered a low priority.

However, additional proposal design considerations include additional mooring locations indicated on study plan map. The downward looking ADCP on the bridge will deliver useful data, but the two bottom---mounted upward---looking ADCPs nearby may miss important areas of the water column because the upper 10---20% is contaminated by reflections. Vessel mounted ADCPs will also deliver useful data, but are likely difficult to interpret because of expected strong tidal and spatial variability near the bridge. It may be beneficial to include moored observations (currents and CTD) nearby that focused on the top 30 meters. A key quantity to resolve will be the average thickening of the upper layer landward of the bridge. This may take a longer mooring record than the few weeks proposed because wind events are likely important. More moorings may be required to understand cross---channel structure. The detailed spatial structure, e.g. internal lee waves, would be better resolved with a profiling CTD operated by a moving vessel. This can also be done in combination with the vessel ADCP surveys. It is unclear how the proposed observations will provide the “site-specific field measurements of eddy viscosity” (Hood Canal Bridge Assessment Team, 2016, p.10) that the model requires.

Response: *Although Khangaonkar and Wang (2013) provided sufficient evidence that the bridge significantly disrupts the mean flow and water properties in Hood Canal, the results were based on mathematical modeling only without the benefit of field measurements and validation using observed data. No data has been collected in the near-field (within 2-3 bridge widths) that is available to assess the zone of influence that is predicted by analytical and theoretical models. The proposed data collection is specifically for the purpose of (a) providing a field confirmation of the alteration of velocity, salinity, and temperature profiles under (or close) to the bridge relative to ambient conditions and (b) provide data to help calibrate and improve the representation of the bridge block module within the FVCOM hydrodynamic model of Hood Canal and the Salish Sea.*

The proposed data collection is limited in scope due to budget constraints and is designed to provide coverage over two neap/spring cycles during the migration period. We consider this as a bare minimum needed to allow field confirmation of the effect of the obstruction to tidal ebb and flood currents and the impact on near-field stratification. It is during this time that numerous other biological data collection activities are also planned. Collecting this minimal oceanographic information is essential, not only for model calibration, but also to provide characterization of oceanographic conditions during the field activities that will be in progress in spring of 2017.

The project team is aware that the bottom mounted current meters will miss the upper 10 % of the water column. Model calibration will be conducted using the 90% of water column data and additional data that will be obtained from the surface layer through boat based transects in the long-shore and cross-shore directions. The upper layer currents will be obtained from a suspending a current meter directly below the bridge and boat based transect during ebb and flood. This approach was the only feasible alternative given limited mooring options in the navigation channel and the presence of anchor cables for the bridge pontoons.

We concur with the review comments; however, that items such as (a) resolving thickening of the freshwater layer landward of the bridge, and (b) spatial structure, e.g. internal lee waves are desirable but beyond the scope of this Phase 1 effort. The comment in the assessment plan suggesting direct measurements of site-specific eddy viscosity measurements were in connection with the consideration that eddy viscosity numbers would be altered by the presence of the bridge. This affects the analytical model, which uses fixed eddy viscosity values. However, they *are not a requirement in the large-scale FVCOM model of Salish Sea, where eddy viscosity and momentum diffusion terms are computed through an internal turbulence closure scheme. As part of the model calibration, we will compare the predicted velocity, salinity, and temperature profiles with observed data to ensure internally computed eddy viscosities provide reasonable results. Field measurements of eddy viscosity are also considered out of scope for this Phase 1 work. The plan has been edited accordingly.*

I. Characterize the bridge zone of influence – Hydrodynamic Modeling.

26. The panel expressed concerns about the study relying on modeling constrained by minimal field observations, but should have a significantly enhanced field survey component near the bridge. These observations should address how and to what extent the bridge modifies flow and water properties, and the variability of this influence, if flow/stratification modification significantly influences the flushing of Hood Canal, and whether the bridge has a significant impact on smolt survival. It is also unclear what data will be used to validate the 2014---15 biogeochemical simulations.

    Current planned hydrological sampling could be expanded, so as not to rely on imperfect models to obtain accurate details, such as mixing rates. With the capability to capture data on this scale, including a model may provide the best benefit for this project. With high---resolution along---channel transects following the water path or streamlines, perpendicular to and upstream/downstream of the bridge, this study could be able to identify flow and water mass changes as a consequence of the bridge. As these changes probably depend on flow rate and stratification, this should be done at times to bracket this range of variability as best as possible. In particular, this study component should measure the influence of the bridge during high run---off conditions when the surface layer is very fresh, in addition to during more typical stratification conditions. As it is proposed, cross---channel transects parallel to the bridge may also be useful in identifying variability in this direction such as the flow structure near and around gaps in the pontoons—potentially leading to insight for remediation.

    Response: *We concur with the reviewer's concern that we are relying on minimal oceanographic data collection for this effort. However, we disagree on the suggestion to embark on an extensive data collection program upfront to determine how and to what extent the bridge modifies flow and water properties including flushing, and the variability of this influence. A comprehensive multi-year monitoring program with sufficient spatial coverage and scope would be cost prohibitive. We expect this project to occur in multiple phases. In this Phase 1 effort, constrained by available budget, our approach is to collect sufficient information needed for the establishment/calibration of a 3-D model. The data collected at fixed locations near and under the bridge will be used to demonstrate that the model correctly reproduces the alteration of velocity, temperature and salinity profiles during a month long deployment. Thus, the validated model may then be applied over a year-long period to develop an understanding of the extent to which the bridge modifies flow and water properties, and the variability of this influence. The model can be applied to assess whether flow/stratification modification significantly influences the flushing of Hood Canal. The model results may also be used in subsequent phases to design subsequent and targeted field data collection plans and for evaluating alternatives for mitigation of observed effects.*

In response to review comments, in addition to current, salinity, and temperature profiles at fixed locations under the bridge, and at landward, and seaward stations, our data collection now includes high-resolution along-channel transects following the water path or streamlines, perpendicular to and landward/seaward of the bridge. Also, included are bank-to-bank transects along the bridge.

27. Winds should also be addressed in study design. Neglecting wind forcing could result in overlooking one of the primary ways that the bridge may influence flow and basin residence time. In the main stem of Hood Canal, wind---forced seiche---like motions, have as much kinetic energy as the tides. Near the bridge they are likely weaker than the tides, but still significant. This influence on surface stress in turn influences flow. Within fjords, with very strong shallow stratification, winds can rapidly accelerate and drive strong flows in the near---surface layer. As these shallow flows can easily exceed tidal flows, it is suggested that the study's fieldwork targets periods when winds have a significant influence on the near---surface flow. Additionally, the wind---driven flows are more baroclinic, or depth---dependent, than the tidal flows, which may be relatively uniform over depth except near the bottom. During strong southerly winds, near--- surface, wind---driven outflow could lead to mid---depth or deep inflow and water mass renewal.

    Response: *Although not explicitly described, the model development effort includes tasks such as refinement of the model grid near the Hood Canal Bridge as well as the entire basin. The refined Hood Canal grid will be embedded in to PNNL's Salish Sea model, which is forced by wind data from University of Washington's (UW) WRF model over a 12-km grid over the Salish Sea. We will also examine availability of data on a finer (4-km grid) and data available from meteorological monitoring sites near the Hood Canal Bridge, especially during the field data collection period, to ensure wind effects are properly incorporated in the analysis. The model is capable of reproducing wind effects and baroclinic circulation, and it is expected to capture seiche effects that may occur during strong winds.*

J. Characterize fine---scale flow field near bridge pontoons--- CFD Modeling.

28. The Assessment Plan should address how the proposed STAR---CCM+ model treats stratification and stratified turbulence.

    Response: *STAR-CCM is a computational fluid dynamics code with comprehensive options for the simulation of a multitude of different flow regimes, both steady and unsteady in time, from inviscid or laminar flow, through transitional flows to fully turbulent, and both incompressible and compressible flows. The STAR-CCM model will be applied for a short duration corresponding to peak ebb and peak flood currents conditions. The model domain will extend ≈ 5 km landward and seaward of the bridge and will incorporate bridge pontoon definitions at a detailed resolution. The stratified initial conditions and boundary conditions of the domain will be obtained from a previously computed solution of Hood Canal from the Salish Sea Model of tidal circulation.*

K. Model effect on flushing, biogeochemistry, dissolved oxygen and pH of Hood Canal.

29. Extension to ecosystem effects on Hood Canal hypoxia and ocean acidification is considerably more speculative and requires further justification and perhaps more strategic data collection/analyses than proposed in this study. For example, there is considerable lack of rationale and explanation. Why will the model grid be refined in the Skokomish River Delta and how will this be relevant to the bridge? What data will be used to constrain the calibration of sediment diagenesis? Will ORCA buoy data be utilized answer these questions? This portion of the study may not be supported at this stage.

Response: *There is no speculation in the fact that hypoxic conditions exist in Hood Canal. As described in Feely et al. (2010), strong stratification, slow flushing, and restricted mixing lead to hypoxic conditions (Newton et al., 2002, 2003, 2008). Khangaonkar et. al. (2013) provides quantitative evidence using three separate methods that natural flushing time could be increased by about 10% and is one of the numerous factors known to contribute to hypoxic conditions. One of the objectives of this effort is to quantify the relative contribution of the Hood Canal Bridge to the hypoxia and acidification issue as part of ecosystem impacts. Contribution to hypoxia and acidification may also come from nutrient loads, changes to Skokomish delta due to operation of* Lake *Cushman reservoir and hydroelectric facility resulting in increased sedimentation and sediment diagenesis in the Lynch Cove region. Hence, the need to refine the model in the southern reaches of the domain where hypoxia and acidification problems are most pronounced.*

That said, the Team agrees with previous comments that a better handle on impacts to mean flow is the priority. Therefore, per our response to comment 1, the Team favors limiting phase 1 to assessing the near-field effects of the bridge on flow along with only a very preliminary assessment of how this may translate to impacts to dissolved oxygen, temperature, pH and nutrient dynamics throughout Hood Canal. This would be accomplished using the Salish Sea Model (Khangaonkar et al 2012) with an updated biogeochemical module capable of simulating sediment diagenesis, hypoxia, pH and alkalinity using the hydrodynamic solution with refined grid in Hood Canal developed during this study, applied with and without the bridge. The results of this will then be used to determine whether proceeding with an extensive investigation of potential impacts to the Hood Canal ecosystem is warranted.

L. Model the subsequent impact to the Hood Canal food web.

30. This portion seems out of scope for determining Hood Canal Bridge effects. How will diverse direct and indirect effects, other than the Bridge, be untangled from the Bridge's effects? How will "exacerbated ocean acidification" (Assessment Plan, p.17) be tested? Since the Atlantis model does not simulate geochemical processes driving variability in ocean acidification, does this come from the Salish Sea Model?

Response: *We have added considerable detail to the Atlantis model study plan. The scope of the Puget Sound Atlantis model is certainly larger than Hood Canal; however, the model is in development for a separate but related project, and testing the bridge effect is an ideal ecosystem-scale perturbation experiment to run in Atlantis, given that much of Hood Canal's ecology is influenced by basin-scale circulation patterns and by species that migrate into and out of the system.*

The detail on the simulations has been expanded to specify how we would untangle the bridge effects through side-by-side comparisons of "baseline" (no bridge) and "treatment" (bridge present) simulations. The ocean acidification simulations will be informed by several in-press papers that Kaplan, Harvey and others have authored on the California Current ecosystem; these papers describe the sensitivities of key calcifying groups to pH variability (as a proxy for OA impacts), and apply those sensitivities to Atlantis simulations of direct and indirect food web impacts of OA. We now clearly specify that the pH dynamics will be driven by the Salish Sea model (as will DO dynamics).

Dr. Mindy Roberts, Washington State Department of Ecology

1. Journal articles for documentation will not provide sufficient data for regulatory-based actions. If that's not a potential outcome, then continue. If you do anticipate or want to remain open to regulatory actions, additional detail in the methods and results would be warranted; these are not reported sufficiently in journal articles. While these are important in academic circles, they do not substitute for a final report with stakeholder and peer review by organizations with an interest in the outcome.

   Response*: A comprehensive final report will be completed and will undergo review be relevant management agencies and local and regional governments. The plan has been adjusted accordingly. Please also see the response to comment 13 in the section titled "Washington State Department of Transportation (WSDOT), completed by University of Washington Expert Review Panel", above.*

2. Not clear how Task 10 is related. (Also,) wind waves seem very important. What if not funded?

   Response: *Task 10 was proposed under the assumption that detailed analysis of turbulent flow under the bridge would be needed to resolve the fine-scale turbulent flow structure near the bridge pontoon shells. Anecdotal evidence suggests that during ebb and flood, the pontoon structure and associated fittings lead to fine-scale eddys which trap and affect the movements of marine organisms and could also impact out migrating juveniles. The CFD model would also be used as part of alternative analysis for design changes and to provide detailed information that could be used to parameterize the circulation model representation of the Hood Canal Bridge Block. If not funded, the work would still be done be done with the Salish Sea Model, if necessary in non-hydrostatic mode: an approximate representation of the bridge block relative to the CFD model which can explicitly incorporate flow around solid walls and submerged hull structures.*

   Secondly, the influence of the floating bridge on wind waves is the most visible effect. During windy conditions surface waves on one side of the bridge are blocked leaving calm water on the other side. While this effect may be visually dramatic its influence on large scale circulation is likely small. Model includes wind explicitly and its effect on circulation and currents and mixing is part of the computational framework already.

3. Not clear how data collected in Task 8 will be used since the model is planned to be run for 2006-08. The modeling of the Task 8 conditions don't describe what they plan to use for open boundary or river boundary conditions, so it's hard to see how this will all be tied together. See text for a few suggestions for where to describe these links a bit.

   Response: *For sensitivity assessment, previously calibrated model runs and processed data from Years 2006-2008 are available for use. Field data collection as part of this project is planned for April of Year 2017 and could be also selected as the candidate year based on the project schedule. However our approach is to use the short duration data collection period for fine tuning the bridge module representation in the Salish Sea Model. For year-long application focused on biogeochemistry including DO and pH prior years with monitoring data from Ecology's monthly data collection program would be preferred. This could be one of the years from 2006-2008 o* *r more recent years such as 2013-2014.*

4. The Task 8 data collection seems only to coincide with Quarter 2 – critical times for fish. If you are going to evaluate seasonal conditions here, don't you need seasonal data collected?

   Response: *Oceanographic data will be collected over a short-term period to improve and calibrate the circulation model. Seasonal conditions will be simulated.*

5. Concerning tasks 9-11 (oceanographic modeling of Bridge and Hood Canal). When you model this dataset, what will you use for open boundary conditions and river inputs? Do you need additional data to establish those boundaries during these more intensive studies?
   Even at this high level, the document should address how the model will set the open boundary conditions and what will be used for river inputs. This section and the appendix are high on details on the model itself. I expect the open boundary condition to *strongly* influence conditions within Hood Canal, so mention plans here and detail in appendix. Same for river inputs.

   Response: *Modeling of Hood Canal will not conducted as a standalone basin. Our plan is to conduct this analysis using an embedded high resolution representation of Hood Canal within the Salish Sea Model. The river inputs and boundary conditions for the Salish Sea model will be developed using the same procedures as described in Khangaonkar et al. (2012) and http://salish-sea.pnnl.gov. The open (Pacific Ocean) boundaries will be developed using monitoring data from Department of Fisheries and Oceans, Canada or World Ocean Atlas data set and river flow data will be from a combination of U.S. geological Survey and hydrological analysis.*

6. Concerning the statement "peak ebb and flood tides." Give some thought to when this occurs – neap conditions during low-flow season might be most critical in terms of oxygen, when the longest residence time occurs. However, this might not be when the biota are most sensitive.

   Response: *We will consider this.*

7. Concerning the sentence, "Optional: Collection of a full lunar cycle of current measurements. Equipment leases are on a per month basis. A full measurement period of one month rather than two weeks will cost the same amount." This is a good idea so you can do a full analysis.

   Response: *Collection will occur over an entire lunar cycle. The plan has been modified.*

8. Concerning the statement, "…calibration to field monitoring data and, if available, high-resolution computational fluid dynamics (CFD) analysis (a companion PNNL assessment activity). The results will inform fish behavior and juvenile…"Describe how this relates to Tasks 9, 11, 12

   Response: *In Task 9, the hydrodynamic solution will be generated with the Hood Canal Bridge incorporated in the Salish Sea model. The hydrodynamic solution will be used to conduct biogeochemical simulations in Task 11 to assess the impacts on flushing, biogeochemistry, dissolved oxygen and pH of Hood Canal. The results from Task 11 will feed into Task 12 to assess ecosystem and food web impacts.*

9. Concerning the statement, "…a typical one-year duration cycle accounting for seasonal variability." Our work in progress with PNNL indicates that each model run should repeat a year twice to get the best results, at least for water quality.

   Response: *Although not explicitly stated, 1 one-year duration run always includes a 1-year warm up run. We will be running the model for two years and using only the 2^{nd} year results for our analysis.*

Dr. Roberts also provided several comments regarding specific language in the plan. Edits to the plan were made accordingly.

Ben Cope – Environmental Protection Agency

1. *Mr. Cope identified that project management, communications, process and deliverables all could use some clarification in the revised plan. This has been addressed in revisions to the plan.*

2. *Mr. Cope recommended that the final comprehensive report be peer reviewed by paid external reviewers. See response to comment 13 in the section titled "Washington State Department of Transportation (WSDOT), completed by University of Washington Expert Review Panel", above.*

3. *Mr. Cope also provided several comments regarding specific language in the plan. Edits to the plan were made accordingly.*

References

Able, K.W., Grothues, T.M., and Kemp, I.M. 2013. Fine-scale distribution of pelagic fishes relative to a large urban pier. Marine Ecology Progress Series 476: 185-198. DOI: 10.3354/meps10151.

Able, K.W., Grothues, T.M., Rackovan, J.L., and Buderman, F.E. 2014. Application of mobile dual-frequency identification sonar (DIDSON) to fish in estuarine habitats. Northeastern Naturalist 21 (2): 192-209.

Altman, J. 1979. Observational Study of Behavior: Sampling Methods. Behaviour 49: 227-267.

Anchor Environmental. 2008. Reconnaissance survey of biological community: Hood Canal Bridge pontoons. Prepared for BRIDGECO.

BAE Systems Applied Technologies. 2008. Naval Base Kitsap Bangor Supplemental Current Measurement Survey, August 2007 Field Data Report. BAE Systems Applied Technologies, Inc. 1601, Research Boulevard, Rockville, Maryland 20850-3173.

Barnes, C.A. and Collias, E.E.. 1958. Some considerations of oxygen utilization rates in Puget Sound. Journal of Marine Research, vol. 17, No. 1, pp. 68-80.

Bax, N. J. 1983. The early marine migration of juvenile chum salmon (Oncorhynchus keta) through Hood Canal – its variability and consequences. Ph.D. Dissertation, University of Washington, Seattle, WA.

Bax, N. J. and Whitmus, C. J. 1981. Early marine survival and migratory behavior of juvenile chum salmon released from the Enetai Hatchery, Washington in 1980. Fisheries Research Institute at the University of Washington. FRI-UW-8109.

Bax, N. J., Salo, E. O., Snyder, B. P., Simenstad, C. A., and Kinney, W. J. 1978. Salmonid outmigration studies in Hood Canal. Final Report, Phase III. FRI-UW-7819.

Beamish, R. J., Folkes, M., Sweeting, R., and Mahnken, C. 1998. Intra-annual changes in the abundance of coho, Chinook, and chum salmon in Puget Sound in 1997. *In* Puget Sound Research Proceedings 1998. Puget Sound Water Quality Action Team, Olympia, Wash. pp. 531–541.

Beamish, R. J., McCaughran, D., King, J. R., Sweeting, R. M., and McFarlane, G. A. 2000. Estimating the abundance of juvenile coho salmon in the Strait of Georgia by means of surface trawls. North American Journal of Fisheries Management 20: 369-375.

Becker, A., Whitfield, A.K., Cowley, P.D., Jarnegren, J., and Naesje, T.F. 2013. Potential effects of artificial light associated with anthropogenic infrastructure on the abundance and foraging behaviour of estuary-associated fishes. Journal of Applied Ecology 50, 43-50.

Beeman, J.W. and Maule, A.G. 2006. Migration depths of juvenile Chinook salmon and steelhead relative to total dissolved gas in a Columbia River reservoir. Transactions of the American Fisheries Society 135: 584-594.

Benaglia, Tatiana, Chauveau, Didier, Hunter, David R., and Young, Derek. 2009. mixtools: An R Package for Analyzing Finite Mixture Models. Journal of Statistical Software **32**(6), 1-29. http://www.jstatsoft.org/v32/i06/.

Berejikian, B.A., Moore, M.E., and Jeffries, S.J. 2015. Predator-prey interactions between harbor seals and migrating steelhead smotlts revealed by acoustic telemetry. Marine Ecology Progress Series. DOI: 10.3354/meps 11579.

Blair, G., Watson, B., Britney, E., and Lestelle, L. 2010. Effects analysis of SR-520 bridge design Option A on Lake Washington Chinook salmon. Technical Memorandum prepared for Washington State Department of Transportation. 35 pp.

Bollens, S. M., vanden Hooff, R., Butler, M., Cordell, J. R., and Frost, B. W. 2010. Feeding ecology of juvenile Pacific salmon (Oncorhynchus spp.) in a northeast Pacific fjord: diet, availability of zooplankton, selectivity for prey, and potential competition for prey resources. Fisheries Bulletin 108: 393-407.

Boswell, K. M. and Wilson, C. A. 2008. Side-aspect target-strength measurements of bay anchovy (Anchoa mitchilli) and Gulf menhaden (Brevoortia patronus) derived from ex situ experiments. ICES Journal of Marine Science 65: 1012-1020.

Brandenberger, E. Crecelius, P. Louchouarn, S. Cooper, K.McDougall, E. Leopold, Ph.D., and G. Liu. 2008. Reconstructing Trends in Hypoxia Using Multiple Paleoecological Indicators Recorded in Sediment Cores from Puget Sound, WA. NOAA Coastal Hypoxia Research Grant Number: NA05NOS4781203

Burnham, K.P. and Anderson, D.R. 2010. Model selection and multimodel inference: A practical information-theoretic approach, Second Edition. Springer-Verlag, New York.

Burwen, D. L. and Fleischman, S. J. 1998. Evaluation of side-aspect target strength and pulse width as potential hydroacoustic discriminators of fish species in rivers. Canadian Journal of Fisheries and Aquatic Sciences 55: 2492-2502.

Cannon, G.A. 1972. Wind Effects on Currents Observed in Juan de Fuca Submarine Canyon. Journal of Physical Oceanography, vol 2, pp 281-285.

Caporaso, J.G., Kuczynski, J., Stombaugh, J., et al. 2010. QIIME allows analysis of high-throughput community sequencing data. Nature Methods 7, 335-336.

Celedonia, M.T., Tabor, R.A., Sanders, S., Damm, S., Lantz, D.W., Lee, T.M., Li, Z., Price, B.E., Gale, W., and Ostrand, K. 2009. Movement and habitat use of Chinook salmon smolts, northern pikeminnow, and smallmouth bass near the SR-520 bridge. Report to the Washington State Department of Transportation. 121 pp.

Chamberlin, J. W., Kagley, A. N., Fresh, K. L., and Quinn, T. P. 2011. Movements of yearling chinook salmon during the first summer in marine waters of Hood Canal, Washington. Transactions of the American Fisheries Society 140(2): 429-439.

Collias, E.E., McGary, N., and Barnes, C.A. 1974. Atlas of physical and chemical properties of Puget Sound and approaches. Washington Sea Grant 74-1, Seattle, Washington.

Cope, B. and Roberts, M. March 2013. Review and synthesis of available information to estimate human impacts to dissolved oxygen in Hood Canal. Prepared by Washington State Department of Ecology and U.S. EPA. Ecology Publication No. 13-03-016. EPA Publication No. 910-R-13-002.

Cunningham, K.A., Hayes, S.A., Wargo Rub, M.A., and Reichmuth, C. 2014. Auditory detection of ultrasonic coded transmitters by seals and sea lions. The Journal of the Acoustical Society of America 135: 1978.

Curl Jr., H.C. and Paulson, A.J. 1991. The biochemistry of oxygen and nutrients in Hood Canal. *In*: Puget Sound Research '91 Proceedings, Volume 1, T.W. Ransom (Ed.), Puget Sound Water Quality Authority, Olympia, WA, pp. 109-115.

Deagle, B.E., Kirkwood, R., and Jarman, S.N. 2009. Analysis of Australian fur seal diet by pyrosequencing prey DNA in faeces. Molecular Ecology 18, 2022-2038.

Duffy, E. J., Beauchamp, D. A., and Buckley, R. M. 2005. Early marine life history of juvenile Pacific salmon in two regions of Puget Sound. *Estuarine, Coastal and Shelf Science* **64**(1): 94-107.

Duffy, E. J., Beauchamp, D. A., Sweeting, R. M., Beamish, R. J., and Brennan, J. S. 2010. Ontogenetic diet shifts of juvenile Chinook salmon in nearshore and offshore habitats of Puget Sound. *Transactions of the American Fisheries Society* **139**(3): 803-823.

Feely, R. A., S. Alin , J. Newton , C.L. Sabine , M. Warner, A. Devol , C. Krembs, C. Maloy. The combined effects of ocean acidification, mixing, and respiration on pH and carbonate saturation in an urbanized estuary. Estuarine, Coastal and Shelf Science 88 (2010) 44

Fresh, K. L., Cardwell, R. D., and Koons, R. R. 1981. Food habits of Pacific salmon, baitfish, and their potential competitors and predators in the marine waters of Washington, August 1978 to September 1979. Washington Department of Fisheries Report No. 145. 58 pp.

Garono, R. J., Simenstad, C. A., Robinson, R., and Ripley, H. 2004. Using high spatial resolution hyperspectral imagery to map intertidal habitat structure in Hood Canal, Washington, U.S.A. Canadian Journal of Remote Sensing 30(1): 54-63.

Gibson, A.J.F., Halfyard, E.A., Bradford, R.G., Stokesbury, M.J.W., Redden, A.M. 2015. Effects of predation on telemetry-based survival estimates: insights from a study on endangered Atlantic salmon smolts. Canadian Journal of Fisheries and Aquatic Sciences 72, 728-741.

Haas, M. E., Simenstad, C. A., Cordell, J. R., Beauchamp, D. A., and Miller, B. S. 2002. Effects of large overwater structures on epibenthic juvenile salmon prey assemblages in Puget Sound, Washington. Report prepared for Washington State Transportation Commission. WA-RD 550.1.

Hanlon, R.T., Hixon, R.F., Forsythe, J.W., and Hendrix Jr., J.P. 1979. Cephalopods attracted to experimental night lights during a saturation dive at St. Croix, U.S. Virgin Islands. The Bulletin of the American Malacological Union, Inc. 53-58.

Hobson, E.S. 1966. Visual orientation and feeding in seals and sea lions. Nature 210: 326-327.

Huber, H.R., Jeffries, S.J., Brown, R.F., DeLong, R.L., and VanBlaricom G. 2001. Correcting aerial survey counts of harbor seals (*Phoca vitulina richardsi*) in Washington and Oregon. Marine Mammal Science 17(2): 276–295.

House Committee on Natural Resources. 2012. Millions of Taxpayer Dollars Spent on Endangered Species Act Litigation and Attorney Fees. House Committee on Natural Resources Press Release. Retrieved from http://naturalresources.house.gov/newsroom/documentsingle.aspx?DocumentID=285999

Jeffries, S.J., Gearin, P. J., Huber, H. R., Saul, D. L., and Pruett, D.A. 2000. Atlas of seal and sea lion haulout sites in Washington. Washington Department of Fish and Wildlife, Wildlife Science Division, 600 Capitol Way North, Olympia WA pp. 150.

Jeffries, S.J., Huber, H. , Calambokidis, J., and Laake, J. 2003.Trends and status of harbor seals in Washington state: 1978-1999. Journal of Wildlife Management 67(1): 207-218.

Juell, J. and Fosseidengen, J.E. 2004. Use of artificial light to control swimming depth and fish density of Atlantic salmon (*Salmo salar*) in production cages. Aquaculture 233: 269-282.

Kaplan, I.C., Gray, I.A., and Levin, P.S. 2012. Cumulative impacts of fisheries in the California Current. Fish and Fisheries 14: 515-527.

Kawase, M. 2007. Response of a Hood Canal circulation model to a wind event preceding September 2006 fish kill. *In*: Proceedings of 2007 George Basin Puget Sound Research Conference. Vancouver, British Columbia, March 26-29, 2007.

Keen, O.S., Love, N.G., and Linden, K.G. 2014. Nitrate photochemistry in the context of water reclamation. *In:* Water Reclamation and Sustainability 229-246. doi:10.1016/B978-0-12-411645-0.00010-9.

Keister, J.E. and Winans, A.K. 2015. Salish Sea Marine Survival Project Zooplankton Sampling Protocol. University of Washington, Seattle, WA.

Khangaonkar, T. and Wang, T. 2013. Potential alteration of fjordal circulation due to a large floating structure – numerical investigation with application to Hood Canal basin in Puget Sound. Applied Ocean Research 39: 146-157.

Khangaonkar, T., Sackmann, B., Long, W., Mohamedali, T., and Roberts, M. 2012. Simulation of annual biogeochemical cycles of nutrient balance, phytoplankton bloom(s), and DO in Puget Sound using an unstructured grid model. Ocean Dynamics 62: 1353–1379. doi: 10.1007/s10236-012-0562-4.

Khangaonkar, T., Yang, Z., Kim, T., and Roberts, M. 2011. Tidally averaged circulation in Puget Sound sub-basins: comparison of historical data, analytical model, and numerical model. Journal of Estuarine Coastal and Shelf Science 93(4): 305-319.

King, R.A., Read, D.S., Traugott, M., and Symondson, W.O.C. 2008. INVITED REVIEW: Molecular analysis of predation: a review of best practice for DNA-based approaches. Molecular Ecology 17: 947-963.

Klink, J.M., Obrien, J.J., and Svendsen, H. 1981. A simple model of fjord and coastal circulation interaction. Journal of Physical Oceanography 11(12): 1612-1626.

Lance, M. M., Chang, W. Y., Jeffries, S. J., Pearson, S. F., and Acevedo-Gutiérrez, A. 2012. Harbor seal diet in northern Puget Sound: implications for the recovery of depressed fish stocks. Mar Ecol Prog Ser 464:257-271.

Lance, M.M., and S.J. Jeffries. 2009. Harbor seal diet in Hood Canal, South Puget Sound and the San Juan Island archipelago. Contract Report to Pacific States Marine Fisheries Commission for Job Code

497; NOAA Award No. NA05NMF4391151. Washington Department of Fish and Wildlife, Olympia WA. 30 pp.

Lance, M.M., Orr, A.J., Riemer, S.D., Weise, M.J., and Laake, J.L. 2001. Pinniped food habits and prey identification techniques protocol, Alaska Fisheries Science Center, National Marine Fisheries Service, Seattle, WA p. 41.

Lavelle, J.W., Cokelet, E.D., and Cannon, G.A. 1991. A model study of density intrusions into and circulation within a deep, silled estuary – Puget Sound. Journal of Geophysical Research—Oceans 96(C9): 16779–16800.

Lilja, J., Marjomaki, T. J., Jurvelius, J., Rossi, T., and Heikkola, E. 2011. Simulation and experimental measurement of side-aspect target strength of Atlantic salmon (Salmo salar) at high frequency. Canadian Journal of Fisheries and Aquatic Sciences 61: 2227-2236.

Lin, Ying-Tsong, Jon M. Collis, and Timothy F. Duda. "A three-dimensional parabolic equation model of sound propagation using higher-order operator splitting and Padé approximants." The Journal of the Acoustical Society of America 132.5 (2012): EL364-EL370

London, J.M., Ver Hoef, J.M., Jeffries, S.J., Lance, M.M., and Boveng, P.L. 2012. Haul-out behavior of harbor seals (*Phoca vitulina*) in Hood Canal, Washington. PLoS ONE 7(6): e38180. doi:10.1371/journal.pone.0038180.

Long, Wen, Ki Won Jung, Zhaoqing Yang, Andrea Copping, and Z. Daniel Deng. "Coupled Modeling of Hydrodynamics and Sound in Coastal Ocean for Renewable Ocean Energy Development." Marine Technology Society Journal 50, no. 2 (2016): 27-36.

Melnychuk, M.C., Christensen, V., Walters C.J. 2013. Meso-scale movement and mortality patterns of juvenile coho salmon and steelhead trout migrating through a coastal fjord. Environmental Biology of Fish 96: 235-339.

Moore, M., Berejikian, B.A., and Tezak, E.P. 2010. Early marine survival and behavior of steelhead smolts through Hood Canal and the Strait of Juan de Fuca. Transactions of the American Fisheries Society 139: 49-61.

Moore, M., Berejikian, B.A., and Tezak, E.P. 2013. A floating bridge disrupts seaward migration and increases mortality of steelhead smolts in Hood Canal, Washington State. PLoS ONE 8(9): e73427. doi: 10.1371/journal.pone.0073427.

Moore, Megan E., Berejikian, Barry A., Goetz, Frederick A., Berger, Andrew G., Hodgson, Sayre S., Connor, Edward J., and Quinn, Thomas P. 2015. Multi-population analysis of Puget Sound steelhead survival and migration behavior. Marine Ecology Progress Series 537: 217-232. DOI: 10.3354/meps11460.

Myrberg Jr., A.A. 1990. The effects of man-made noise on the behavior of marine animals. Environment International 16(4-6): 575-586.

Nemeth, R.S. and Anderson, J.J. 1992. Response of juvenile coho and chinook salmon to strobe and mercury vapor lights. North American Journal of Fisheries Management 12(4): 684-692.

Newton, J., Van Voorhis, K., 2002. Seasonal Patterns and Controlling Factors of Primary Production in Puget Sound's Central Basin and Possession Sound. Publication #02-03-059. Washington State Department of Ecology, Environmental Assessment Program, Olympia, Washington.

Newton, J.A., Siegel, E., Albertson, S.L., 2003. Oceanographic changes in Puget Sound and the Strait of Juan de Fuca during the 2000e01 drought. Canadian Water Resources Journal 28, 715-728

Newton, J., Bassin, C.,Devol, A.,Kawase,M.,Ruef,W.,Warner, M.,Hannafious, D.,Rose, R., 2008. Hypoxia in Hood Canal: an overview of status and contributing factors. In: Proceedings of the 2007 Georgia Basin Puget Sound Research ConferenceGeorgia Basin Puget Sound Research Conference, Vancouver, British Columbia.

Nightingale, B., Longcore, T., and Simenstad, C.A. 2006. Artificial night lighting and fishes. In: Rich, C., Longcore, T. (eds): Ecological Consequences of Artificial Night Lighting. Island Press, Washington, DC: 257-276.

Olesiuk, P.F. 1993. Annual prey consumption by harbour seals (*Phoca vitulina*) in the Strait of Georgia, British Columbia. Fishery Bulletin 91: 491-515.

Orr, A.J., Laake, J.L., Dhruw, M.I., et al. 2003. Comparison of processing pinniped scat samples using a washing machine and nested sieves. Wildlife Society Bulletin 31: 253-257.

Paulson, A.J., Konrad, D.P., Frans, L.M., Noble, M., Kendall, C., Joshberger, E.G., Juffman, R.L., and Olsen, T.D. 2006. Freshwater and saline loads of dissolved inorganic nutrients to Hood Canal and Lynch Cove, Western Washington, U.S. Geological Survey Scientific Investigations Report, 2006-5106, 92 p.

Pearson, S.F., Jeffries, S.J., Lance, M.M., and Thomas, A.C. 2015. Identifying potential juvenile steelhead predators in the marine waters of the Salish Sea. Washington Department of Fish and Wildlife, Wildlife Science Division, Olympia.

Peterson, S.H., Lance, M.M., Jeffries, S.J., and Acevedo-Gutiérrez, A. 2012. Long distance movements and disjunct spatial use of harbor seals (*Phoca vitulina*) in the inland waters of the Pacific Northwest. PLoS ONE 7: e39046.

Popper, A.N. and Carlson, T.J. 1998. Application of sound and other stimuli to control fish behavior. Transactions of the American Fisheries Society 127(5).

Prinslow, T.E., Whitmus, C.J., Dawson, J.J., Bax, N.J., Snyder, B.P., and Salo, E.O. 1980. Effects of wharf lighting on outmigrating salmon, 1979. FRI-UW-8007. Fisheries Research Institute, University of Washington, Seattle, WA.

Puckett, K.J. and Anderson, J.J. 1987. Behavioral responses of juvenile salmonids to strobe and mercury lights. University of Washington, Fisheries Research Institute. Technical Report FRI-UW 8717, Seattle, WA.

Puget Sound Partnership. 2009. Puget Sound Action Agenda. www.psp.wa.gov.

Rakowski, C.L., Richmond, M.C., Serkowski, J.A., and Johnson, G.E. 2005. Forebay computational fluid dynamics modeling for the Dalles Dam to support behavior guidance system siting studies.

PNNL-15689, Pacific Northwest National Laboratory, Richland, WA. http://www.pnnl.gov/publications/.

Raphael, M.G., Baldwin, J., Falxa, G.A., Huff, M.H., Lance, M., Miller, S.L., Pearson, S.F., Ralph, C.J., Strong, C., and Thompson, C. 2007. Regional population monitoring of the marbled murrelet: field and analytical methods. Gen. Tech. Rep. PNW-GTR-716. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 70 p.

Rattray Jr., M. 1967. Some aspects of the dynamics of circulation in fjords. *In*: Estuaries, Publication No. 83, America Association for the Advancement of Science, pp. 52-62.

Roberts, M., Mohamedali, T., Sackmann, B., Khangaonkar, T., and Long, W. 2013. Dissolved oxygen assessments for Puget Sound and the Straits: impacts of current and future nitrogen sources and climate change through 2070. Publication No. 13-03-0xx. Washington State Department of Ecology, Olympia, WA.

Roy, R., Beguin, J., Argillier, C., Tissot, L., Smith, F., Smedbol, S., and De-Oliveira, E. 2014. Testing the VEMCO Positioning System: spatial distribution of the probability of location and the positioning error in a reservoir. Animal Biotelemetry 2(1). http://www.animalbiotelemetry.com/content/2/1/1

Scheuerell, M.D. and Schindler, D.E. 2003. Diel vertical migration by juvenile sockeye salmon: empirical evidence for the antipredation window. Ecology 84(7): 1713-1720.

Simenstad, C. A. and Fresh, K. L. 1995. Influence of intertidal aquaculture on benthic communities in Pacific Northwest estuaries: scales of disturbance. Estuaries 18(1A): 43-70.

Simenstad, C. A. and Kinney, W. J. 1978. Trophic relationships of outmigrating chum salmon in Hood Canal, Washington, 1977. Final Report prepared for Washington State Department of Fisheries. FRI-UW-7810.

Simenstad, C. A., Fresh, K. L., and Salo, E. O. 1982. The role of Puget Sound and Washington coastal estuaries in the life history of Pacific salmon: an unappreciated function. Academic Press, Inc. ISBN 0-12-404070-5.

Simenstad, C. A., Garono, R. J., and Robinson, R. 2001. Mapping intertidal eelgrass habitat in the vicinity of the Hood Canal floating bridge, Washington, using high resolution hyperspectral imagery. Appendix A in Mapping of Subtidal and Intertidal Habitat Resources: Hood Canal Floating Bridge, Washington. Report prepared for the University of Washington and the Washington State Department of Transportation. WA-RD No. 523.1.

Skjoldal, H.R., C. Hopkins, K.E. Erikstad, and Leinaas, H.P. 1995. Ecology of Fjords and Coastal Waters. Elsevier Science B.V., Amsterdam, The Netherlands.

Stansbury, A.L., Götz, T., Deecke, V.B., and Janik, V.M. 2015. Grey seals use anthropogenic signals from acoustic tags to locate fish: evidence from a simulated foraging task. Proceedings of the Royal Society B 282: 1798.

Tabor, R.A., Brown, G., and Luiting, V.T. 1998. The effect of light intensity on predation of sockeye salmon fry by prickly sculpin and torrent sculpin. USFWS Report, Seattle, Washington.

Taylor, J.C., and Maxwell, S.L. 2007. Hydroacoustics: lakes and reservoirs. *In*: Salmonid field protocols handbook: techniques for assessing status and trends in salmon and trout populations. American Fisheries Society, Bethesda, Maryland.

Tetra Tech. 2006. Adaptive Management Plan Cedar River Sockeye, Prepared for Seattle Public Utilities. Project #2190030

Thayer, G. W. and Phillips, R. C. 1977. Importance of eelgrass beds in Puget Sound. Marine Fisheries Review 39(11): 18-22.

Thomas, A.C. 2015. Diet analysis of pacific harbour seals (*Phoca vitulina richardsi*) using high-throughput dna sequencing. Doctoral dissertation thesis, University of British Columbia.

Trites, A.W. and Joy, R. 2005. Dietary analysis from fecal samples: how many scats are enough? Journal of Mammalogy 86: 704-712.

Trites, A.W., Beggs, C.W., and Riddell, B. 1996. Status review of the Puntledge River summer chinook. Fisheries Centre, University of British Columbia. S96-16: 34 pp.

Ward, E. J., Levin, P. S., Lance, M. M., Jeffries, S. J. and Acevedo-Gutiérrez, A. 2012. Integrating diet and movement data to identify hot spots of predation risk and areas of conservation concern for endangered species. Conservation Letters, 5: 37–47. doi:10.1111/j.1755-263X.2011.00210.x

Williams, G.D., Thom, R.M., Southard, J.A., O'Rourke, L.K., Seargeant, S.L., Cullinan, V.I., Shreffler, D.K., Moursund, R., and Stamey, M. 2003. Assessing overwater structure-related predation risk on juvenile salmon: field observations and recommended protocols. Report prepared for the Washington State Department of Transportation. Contract DE-AC06-76RLO 1830. 50 pp.

Wilson, K., Lance, M., Jeffries, S., and Acevedo-Gutiérrez, A. 2014. Fine-scale variability in harbor seal foraging behavior. PLoS ONE 9(4): e92838. doi:10.1371/journal.pone.0092838

Yurk, H. and Trites, A.W. 2000. Experimental attempts to reduce predation by harbor seals on out-migrating juvenile salmonids. Transactions of the American Fisheries Society 129: 1360-1366.