Hood Canal Bridge
Ecosystem Impact Assessment Plan

DRAFT – February 29, 2016

Prepared by:

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Cite document as: Hood Canal Bridge Assessment Team. 2016. Hood Canal Bridge Ecosystem Impact Assessment Plan. Long Live the Kings, Seattle, WA.

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Contents

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 more often than considered natural for a fjord ecosystem and ocean acidification threatens commercially important shellfish beds in Hood Canal moreso 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 12 feet (3.7 meters) 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 and higher mortality rates suggest the bridge is impeding migration and increasing predation. Recent research also shows 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 climate change.

In 2015, federal, state, tribal, and nonprofit partners convened to develop the Hood Canal Bridge Ecosystem Impact Assessment Plan (Plan). The Plan is designed to pinpoint how the bridge is negatively affecting ESA-listed juvenile steelhead and salmon survival and the health of the Hood Canal ecosystem, and then guide actions that simultaneously address ecosystem impacts and maintain the bridge.

The Plan will address two primary questions:

I. **How is the bridge acting as a functional barrier to juvenile steelhead and salmon migration and leading to increased mortality?**

We must determine where mortality is greatest along the bridge, who the predators are, and functionally how the bridge leads to increased predation. Causal agents may include the pontoons as a functional 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 in the bridge may change water properties and aggregate plankton, attracting planktivorous salmon and steelhead and increasing their susceptibility to predation.

II. **How does the bridge impact the entire Hood Canal ecosystem?**

Because species throughout Hood Canal respond to changes in water quality, and also 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. We must determine the strength of bridge impact on circulation and water quality, including dissolved oxygen, temperature, acidity, and nutrient dynamics. 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.

A suite of thirteen interconnected assessment components will be implemented. An ensemble of data collection methods including acoustic telemetry, hydroacoustic sampling, net sampling, and visual surveys will be used to characterize the behavior and distribution of steelhead, salmon and forage fish, their predators, and plankton as prey near versus away from the bridge. Direct assessments of interactions between harbor seals and steelhead will also be performed. Current profilers, light sensors and noise measuring accelerometers will characterize the intensity and spatial extent of physical impacts of the bridge. 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 draw span 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 and salmon survival and more broadly characterize the extent to which the bridge may be affecting the health of the Hood Canal ecosystem as a whole.

The results of this assessment will drive an analysis of corrective actions. 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 confirmed, we will work with our partners and others to establish a suite of proposed management actions, and then simulate, field test, and fully implement appropriate management solutions that won't adversely affect the bridge as a transportation corridor.

The assessment will last 3.5 years (2016-2019) and cost $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—leaving a remaining need of $3.2 million. Beyond the $4 million 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.

Overview

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 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, teaming with life including salmon and steelhead that define their home and the purpose of their visit.

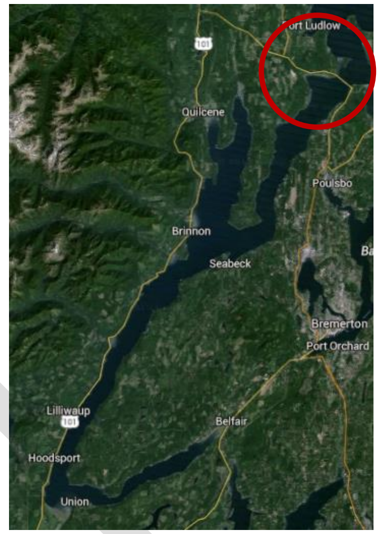


Figure 1. Hood Canal Bridge is located at the north end of Hood Canal near its entrance to Puget Sound (Google Maps).

All salmon originating from Hood Canal rivers must pass under the Hood Canal Bridge as juveniles on their way out to the Strait of Juan de Fuca and the Pacific Ocean (Figure 2). 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 address sources of nutrient inputs 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 on the rise.

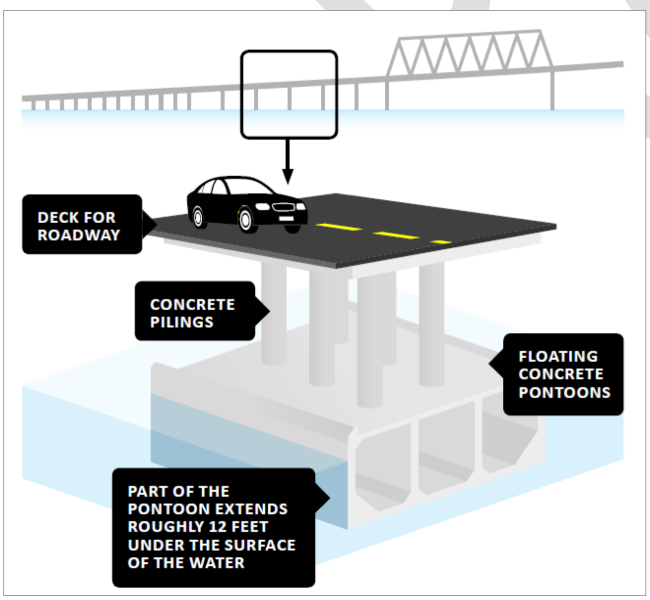


Figure 2. The Hood Canal Bridge floats on pontoons that span much of the width of Hood Canal and extend roughly 12 feet (3.7 m) underwater (image property of Long Live the Kings).

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 3.7 meters underwater (Figure 3). Recent studies indicate the bridge is a barrier to fish passage. Slower migration times and higher mortality rates suggest the bridge is impeding migration and increasing predation (Moore et al. 2013). Recent research also shows that the bridge may disrupt water circulation (Khangaonkar and Wang 2013), increasing residence and flushing times in Hood 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 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. [1]

A collaboration of federal, tribal, state, and nonprofit partners have convened to complete the following Hood Canal Bridge Ecosystem Impact Assessment Plan. This assessment plan will pinpoint how the bridge is negatively affecting Hood Canal water quality and salmonid survival, providing the information needed to execute management actions to address the bridge impacts.

Two overarching questions direct the Assessment Plan:

A. How is the bridge acting as a functional barrier to juvenile steelhead and salmon migration and leading to increased mortality?
B. How does the bridge impact the entire Hood Canal ecosystem?

Thirteen specific assessment components are guided by these questions and described in this report, all working together to provide a comprehensive picture of the impact of the Bridge. A draft suite of potential management actions that will not adversely affect the bridge as a transportation corridor are also outlined in this plan. As specific causal agents of impact are confirmed, we will work with our partners and others to test, refine, and fully implement appropriate management solutions.

[1] 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 4). 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. 2010, 2013). However, the mechanisms by which the bridge affects mortality are poorly understood.

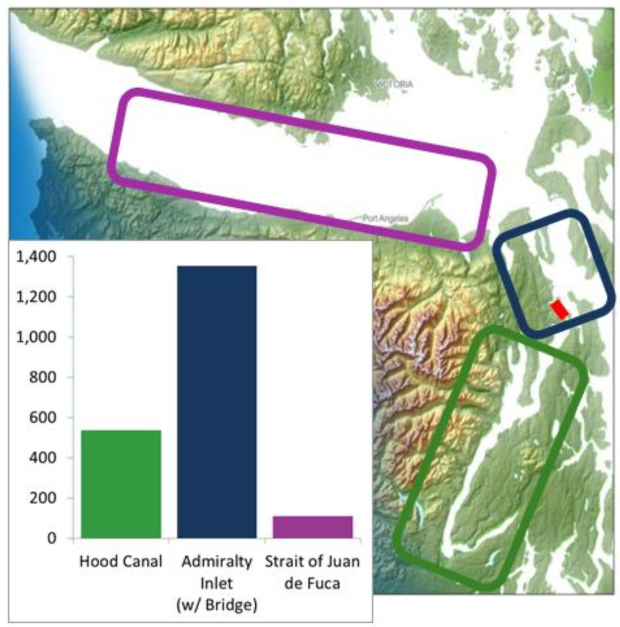


Figure 3. Number of juvenile steelhead that die per kilometer traveled on their migration to the Pacific Ocean: in Hood Canal, Admiralty Inlet (includes mortality at Hood Canal Bridge), and Strait of Juan de Fuca. Further investigation revealed the bridge itself is the primary location of high steelhead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

Determining the exact locations and causes of bridge-related mortality may benefit all Hood Canal salmon species. 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). Furthermore, an exploratory hydroacoustic survey of fish densities around the Hood Canal Bridge, performed by the Port Gamble S'Kallam Tribe during the salmon and steelhead outmigration period, suggests the bridge affects overall fish distribution (Figure 5).

While other salmon of concern may be affected (in particular ESA-listed Chinook), an emphasis on steelhead appears to be the best approach. A body of work has already been established on steelhead impacts at the bridge, providing guidance on next steps. And, specific tools (i.e. acoustic telemetry) that are good at tracking migration behavior and pinpointing sites of instantaneous mortality have been proven viable for use with juvenile steelhead.

Recent acoustic tagging studies performed by NOAA indicate juvenile steelhead migration is significantly slower through the migration segment encompassing the Hood Canal Bridge, and rates of mortality events are much greater in proximity to the bridge relative to other areas of Hood Canal and Puget Sound (Moore et al. 2013). Because juvenile steelhead travel near the water surface during outmigration (Beeman and Maule 2006), the bridge presents a physical obstruction to migration.

Migration delays caused by the bridge are thought to increase the density of smolts near the bridge and facilitate elevated predation rates.

Steelhead and salmon migration and predator behavior may also be affected by changes to water circulation, and 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). Recent work by Khangaonkar and Wang 2013 suggests the Hood Canal Bridge, in the path of the outflow surface layer, affects circulation and estuarine exchange processes. Impacts near the bridge may include 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.

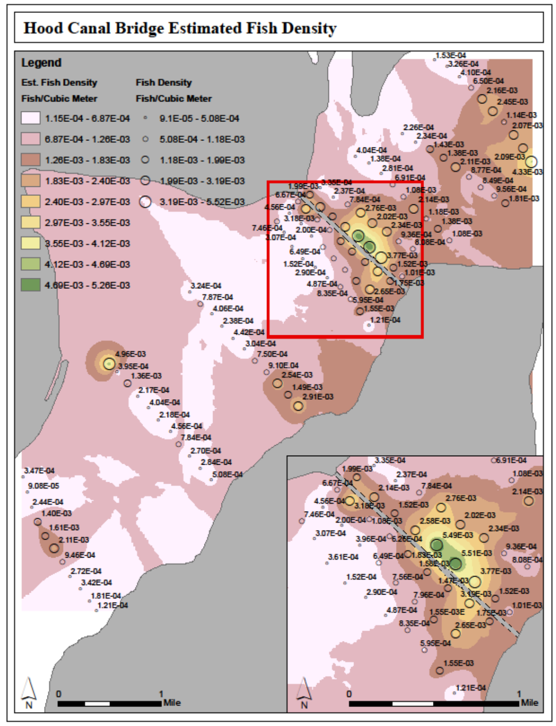


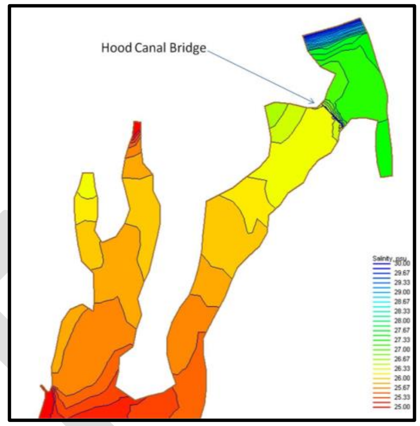
Figure 4. Estimated near-surface fish density within the vicinity of the Hood Canal Bridge (April 2015). Exploratory survey performed by H. Daubenberger, Port Gamble S'Klallam Tribe.

Hood Canal ecosystem effects

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) suggesting the possibility of chronic stress due to anthropogenic alteration of the Hood Canal environment. Construction of the Hood Canal Bridge was completed in 1961.

Furthermore, a recent 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.



Pacific Northwest National Laboratories (PNNL) investigated the possibility that the natural oceanographic structure of fjordal stratification and circulation could be disrupted by hydraulic modifications of the surface brackish layer. The potential for permanent floating structures (such as 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 6).

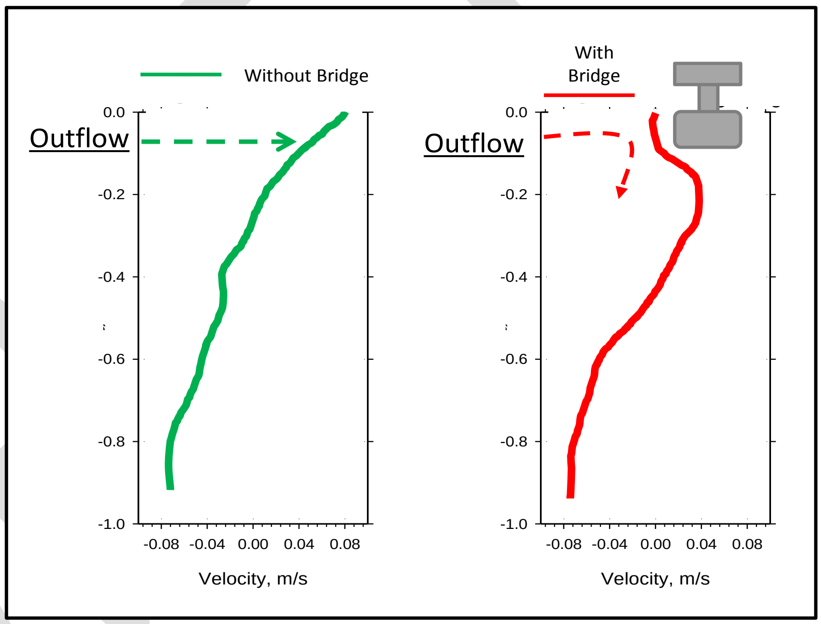


Figure 5. Top figure is modeled illustration of changes in salinity north and south of the Hood Canal Bridge. Bottom figures illustrate modeled impact of the Hood Canal Bridge on water circulation in and out of Hood Canal. (from Khangaonkar 2015, presentation).

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[2]. 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

[2] Site-specific field measurements of eddy viscosity and 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.

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.

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 of the Assessment

The Hood Canal Bridge Impact Assessment will address two primary questions:

I. **How is the bridge acting as a functional barrier to juvenile steelhead and salmon migration and leading to increased mortality?**

   We must determine where mortality is greatest along the bridge, who the predators are, and functionally how the bridge leads to increased predation. Causal agents may include the pontoons as a functional 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 in the bridge may change water properties and aggregate plankton that are prey to salmon and forage fish, increasing susceptibility to predation.

II. **How does the bridge impact the entire Hood Canal ecosystem?**

   Because species throughout Hood Canal respond to changes in water quality, and also 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. We must determine the strength of bridge impact on circulation and water quality, including dissolved oxygen, temperature, acidity, and nutrient dynamics. 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, and killer whales.

A complete list of affiliated sub-questions, the hypotheses being tested, and the evidence needed to support these hypotheses is provided in Appendix B of this report.

Plan Components

A table outlining the components of the assessment is below, followed by a brief description of each activity. Complete descriptions of the components are provided as appendices.

#	Component	BRIDGE IMPACT TO THE ENTIRE HOOD CANAL ECOSYSTEM	BRIDGE AS BARRIER TO JUVENILE STEELHEAD AND SALMON, LEADING TO INCREASED MORTALITY
	Migration behavior, mortality and fish densities around bridge		
1	Track steelhead migration behavior at bridge, and mortality before, at, and after bridge		◆
2	Map fish densities and distribution at vs away from bridge		◆
	Predators, encounters, and impact at vs away from the bridge*		
3	Map predator (marine mammal and bird) densities		◆
4	Assess harbor seal-related steelhead mortality - seal scat/diet analysis		◆
5	Assess harbor seal interactions w/ steelhead and foraging behavior		◆
	Bridge physical influence on surrounding environment**		
6	Measure light and shade impacts to fish and predator behavior		◆
7	Measure noise impacts to fish behavior		◆
8	Collect oceanographic data at bridge (current, salinity, and temperature profiles)	◆	◆
9	Characterize the bridge zone of influence – Hydrodynamic Modeling	◆	◆
10	Characterize fine-scale flow field near bridge pontoons- CFD Modeling	◆	◆
11	Model effect on flushing, biogeochemistry, dissolved oxygen and pH of Hood Canal	◆	
12	Model the subsequent impact to the Hood Canal food web	◆	
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)**		◆

*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.

*In addition to a comprehensive assessment of these mechanistic pathways that may link the Bridge to migrating fish survival, observations of the potential for a structural, artificial reef effect will be performed. Additional details in #14 of the narrative, below.

Migration behavior, mortality and fish densities around bridge

1. Tracking steelhead migration behavior and mortality

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, They also did not 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 consisting of at least 24 Vemco VR2 receivers will allow researchers to triangulate tagged juvenile steelhead positions and map migration paths with a high degree of precision (figure provided as attachment). 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 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.

This component of the assessment provides the core data on fish migration and mortality which the other components will depend upon for inferences regarding the precise mechanisms that lead to mortality at the bridge.

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

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 will be limited to only those fish. Hydroacoustic surveys will be 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. Figure 5 is the result of an exploratory single-day effort by the Port Gamble S'Klallam Tribe to conduct hydroacoustic sampling within the vicinity of the Hood Canal Bridge during the 2015 steelhead outmigration.

Predators, encounters, and impact at vs. away from the bridge

3. Map predator (marine mammal and bird) densities

Simultaneous to the steelhead tracking, predator species (seabird and marine mammal) abundance, locations, distribution, and foraging behavior will be assessed in the vicinity of the bridge. Two 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 may 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).

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

For this assessment component, we will determine whether 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. Recent work involving acoustic transmitters implanted in steelhead smolts combined with seal-mounted acoustic receivers 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. by smolt predators including harbor seals Iremains unknown. To address question of harbor seal predation on salmonid smolts, 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 will 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 (see research component 5, below). 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

5. Assess harbor seal interactions with steelhead and foraging behavior

Migration delays caused by the Hood Canal 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. Thus, predator/prey interactions between the most likely predators (harbor seals/harbor porpoise/cormorants) and steelhead smolts may be influenced by the presence of the Hood Canal Bridge. For harbor seals, one method in quantifying the spatial and temporal overlap withsteelhead smolts involves mounting a GPS tags and acoustic telemetry transcievers instrument pack 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. 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..

Bridge physical influence on surrounding environment

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

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. This activity will measure the magnitude and spatial extent of artificial light and shade impacts near the bridge structure 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 samples will be taken in conjunction with light samples to characterize zooplankton communities 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”). 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.

7. Measure noise impacts to fish behavior

Increased probable 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. 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)? 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? An initial assessment of existing information and some preliminary field data collection will be conducted prior to launching the full-scale study, to confirm whether noise 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 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. Collect oceanographic data at Bridge (current, salinity, and temperature profiles)

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 2-4 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. The data will be used for calibration of the computational fluid dynamics (CFD) model that will be developed with a floating bridge module.

9. Characterize the bridge zone of influence – Hydrodynamic Modeling

One of the primary objectives of this ***Near-field Circulation and Water Quality Modeling*** task is 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 to better represent the effect on continuity and momentum of the flow field. This will be accomplished using the new data collected (component 8) and, if funded simultaneously, the results provided by the CFD model for comparison and calibration during varying seasonal conditions. A quantitative assessment of the effect of Hood Canal Bridge on seasonal near-field circulation and water quality over one a typical year 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). Results from this study will inform fish behavior and juvenile outmigration studies (components 1, 2).

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

A detailed and fine-scale 3-D description of the flow field near the Hood Canal Bridge will be developed using a computational fluid dynamics (CFD) model 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 predator fish species that prey upon salmonids. Unlike the basin-wide setup of the Salish Sea model (component 9) the CFD model will 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. The work will account for differences at low and high tides, and differences between bridge center drawspan states (open versus closed). The results will be used for the calibration of the bridge effects in the larger Salish Sea model. The results will also help fisheries biologists identify potential areas where near-field flow patterns may provide predator fish habitat and other features that may negatively impact juvenile salmon populations.

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

The possibility that the Hood Canal Bridge may have a subtle but persistent and cumulative effect on the residence and flushing of the Hood Canal basin will be examined here. 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 this task, the Salish Sea Model that includes nutrient loads from nearly one hundred point and non-point source loads and oceanic influences will 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) will also be examined. Hood Canal data from Ecology's marine monitoring program and ORCA buoy data will also be processed and utilized. The model will be refined to Skokomish River delta and Lynch Cove intertidal regions to reproduce observed hypoxia. A three-year hydrodynamic simulation including the bridge will be conducted using the refined model grid. This will include biogeochemical processes including sediment diagenesis and calibration to the observed three-year data encompassing hypoxia and fish kill events. Sensitivity tests will be conducted to quantify relative influence of the Hood Canal Bridge and other stressors.

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

The extent to which changes in the circulation of Hood Canal caused by the bridge affect key species in Hood Canal and neighboring basins will be evaluated. The presence of the Hood Canal Bridge may restrict circulation and estuarine exchange processes, resulting in lower DO and exacerbating ocean acidification in southern Hood Canal. 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, will be utilized for this assessment. The Salish Sea Model will 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, will be simulated in each area and depth layer of the model. Specifically, the model will 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 will be conducted. These will include direct effects (e.g., increased predation on juvenile steelhead at the bridge) and indirect effects (e.g., changes in the food web that result from alterations in circulation and water quality). Direct and indirect effects will 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).

Synthesis and other activities

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

The 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 6. Graphical depiction of data layers that will be synthesized.

13a. Geographically weighted regression analyses

The steelhead acoustic tracking data will result in a fine-scale depiction of migration pathways: illustrating which pathways lead to mortality and which 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 250 m increments, covering a two km-wide area parallel to the bridge. Geographically weighted regression techniques will first be used to explore spatial correlations between 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.

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.

13b. Simulate steelhead 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 current description of this component 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) which uses environmental cues, such as oceanographic properties of water, coupled with basic fish behavior rules affecting fish motion. However, due to the uncertainty regarding the pathway of impact, the Assessment Team is delaying a final decision on analysis approach until the initial, phase 1 synthesis work is complete. Regardless, the estimated cost is within reason of the need for this component (see Budget section later in this report).

14. Other assessment activities, "Reef Effect"

In addition to a comprehensive assessment described above, general observations of the potential for a structural, artificial reef effect will be performed. The in-water bridge structure, including the anchor cables and pontoons, aggregate sea life such as anemones, barnacles, mussels, and sponges (Anchor 2008). Of greater potential concern is whether structural voids are changing water properties such that they aggregate euphausiids and other plankton. This could in turn attract planktivorous fish, including juvenile salmon, steelhead, and forage fish. 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 may also be installed underwater at relevant points along the bridge to collect data about the biota adjacent to the bridge. 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. Those regions will then be compared to the fish distribution and densities data obtained from hydroacoustic sampling (described in activity 2) to determine whether there are correlations. 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. This work will be performed by the Port Gamble S'Klallam Tribe.

Potential Outcomes and Steps for Adaptive Management

The results of this assessment will feed into an analysis of potential management actions. The following diagrams outline the causal agents or pathways in which the bridge may be affecting steelhead and salmon survival and the Hood Canal ecosystem as a whole, and describe suites of potential 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 our partners and others to refine these lists of potential management actions, and then simulate, field test, and fully implement appropriate management solutions.

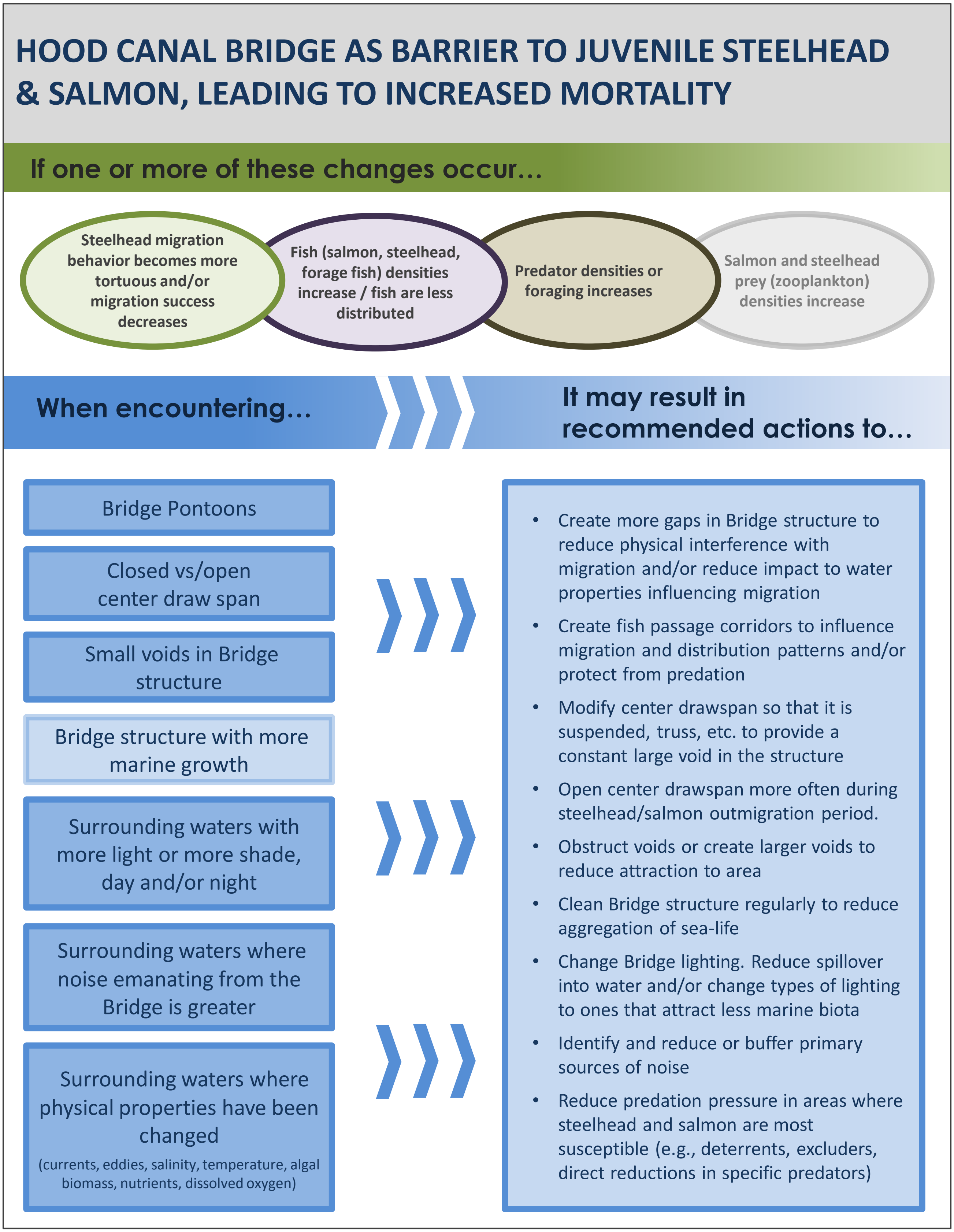


Figure 7. Diagram associating potential findings with potential management actions affiliated with steelhead and salmon survival past the bridge. This is an illustration and not meant to be an exhaustive list. Zooplankton are shaded lightly because analyses of potential variation in prey availability associated with the bridge may or may not occur as part of this assessment.

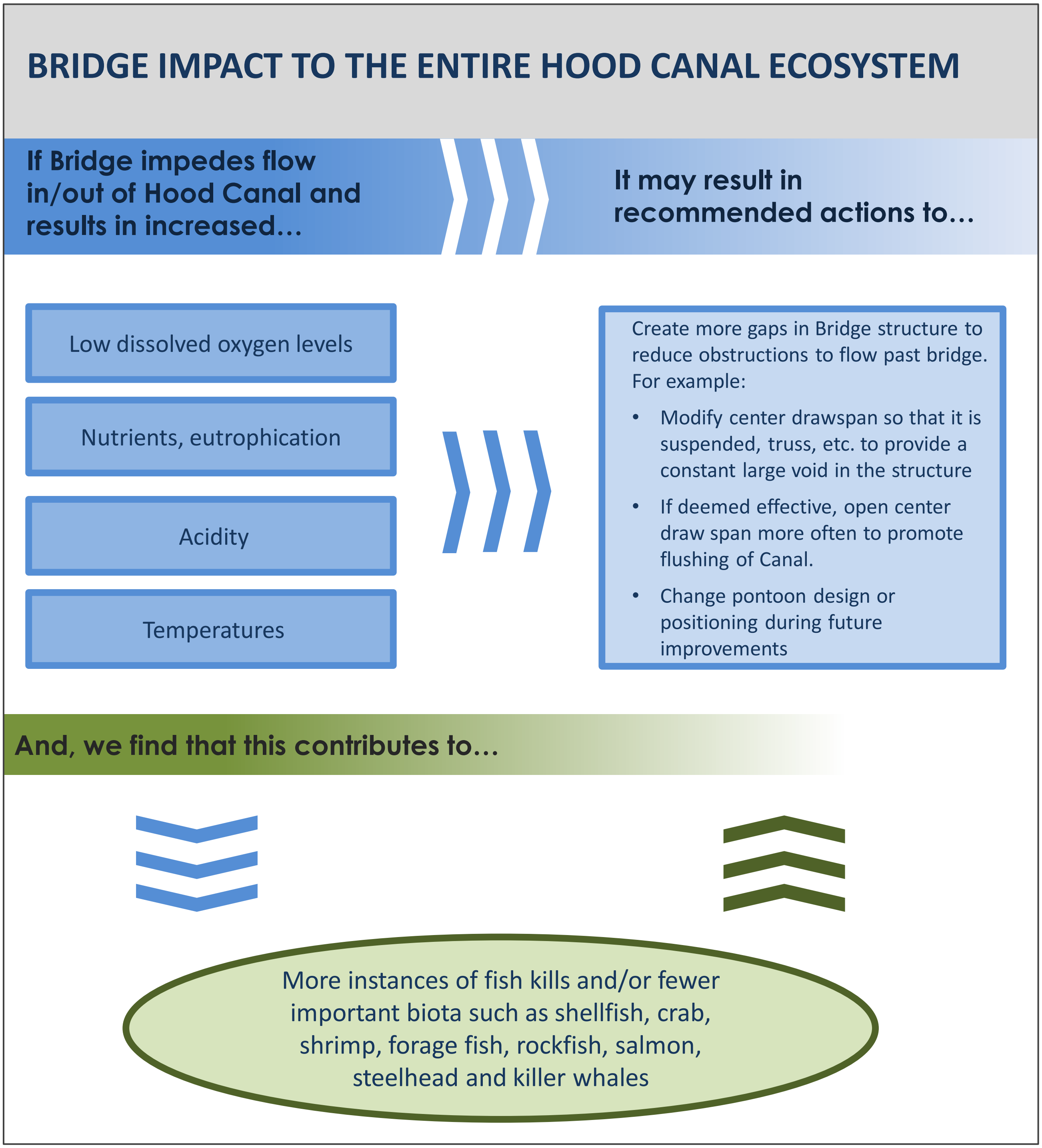
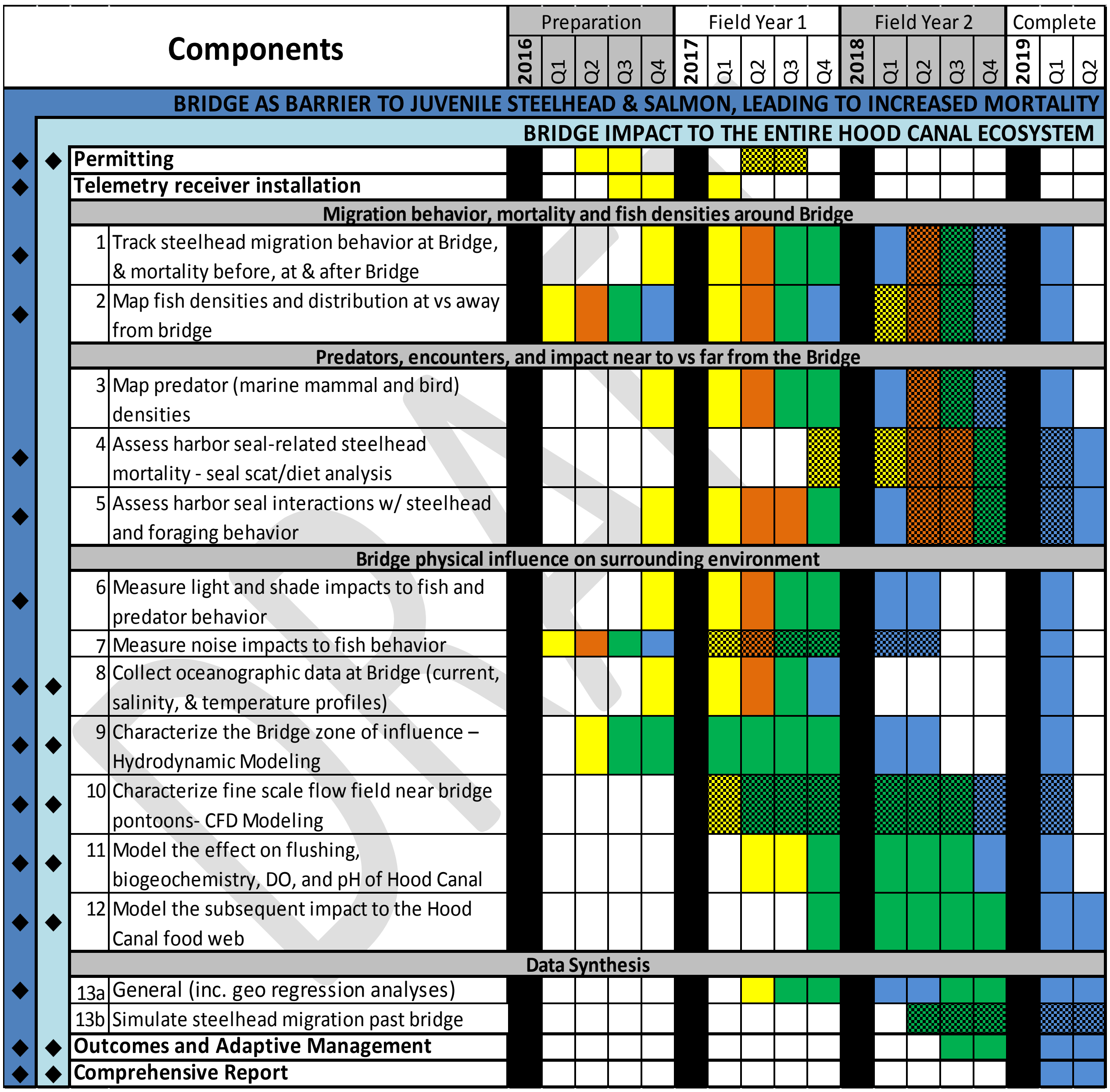


Figure 8. Diagram associating potential findings with potential management actions affiliated with broad-scale impacts to the Hood Canal ecosystem. This is an illustration and not meant to be an exhaustive list.

Work Schedule

The Hood Canal Bridge ecosystem impact assessment will be performed over a 3.5 year period as illustrated in the table, below. All components are staged based upon timing of potential funding availability and how the components inform one another.

Legend Preparation Field Work Analysis Reporting Phase 2 Work



2016 will primarily be a preparation year, with some initial field work to begin mapping fish densities and distribution (2) and potentially to perform a preliminary noise impact analysis (7). Permitting and the installment of the acoustic telemetry lines around the bridge will also begin in 2016. A bulk of the field work will begin in 2017.

Note the checker patterned sections of the timeline. These depict the elements that are considered the second phase of the assessment: work that will ultimately be refined by the results of the initial phase. Regarding the phased elements:

- Phase 2 of Components 1, 2, and 3 (assessing steelhead migration, fish densities, and predator densities) primarily depict the second year of field work. Two years of data collection is critical to ensure environmental variation is accounted for. Phase 2 of component 3 may also include bridge-based predator surveys, whereas phase 1 will likely consist of pilot efforts—including night observation—and planning for phase 2 if formal bridge-based surveys are warranted.
- Phase 1 (2017) of Component 5 (harbor seal-steelhead interactions and foraging) currently involves outfitting four harbor seals near the bridge to enhance coverage of acoustic tagged steelhead, then moving to the full 30 seals in 2018 (phase 2) if the results of phase 1 reinforce the proposed approach.
- Initiating Component 4 (seal impacts via scat/diet) will be reserved until 2018 and is considered a phase 2 element. Its implementation must occur in tandem with phase 2 of component 5.
- For Component 7 (noise impacts), a preliminary analysis is planned to determine whether noise propagating from the bridge is of significant concern. The preliminary analysis may occur in 2016 or 2017, contingent upon approval from WSDOT and US Navy. Phase 2 would then involve a thorough assessment of noise propagation and impact, if warranted. The phases are described on page 50 of this report.
- Component 10 (Computational Fluid Dynamics Modeling) establishes the fine-scale model of the bridge impacts to water properties directly adjacent to the bridge. This work will be informed by Component 9, the broader scale hydrodynamic modeling. Both elements could begin simultaneously; however, they are phased because funding is not yet available to initiate component 10 in 2016.
- Component 13b, a particle tracking model to simulate steelhead movement past the bridge will be reserved until phase 2. The particle tracking model will provide capacity for refining our synthesis analysis, comparing successful and unsuccessful steelhead migration patterns to the impacts of the bridge, and will be the platform for testing/simulating various management actions. The ultimate approach to incorporating data layers in 13b will be informed by the general synthesis work (13a). 13b is also costly and we don't expect funding to be available until later in the assessment process.

Finally, the elements described in Component 14 (page 18) are not depicted on this timeline because the work is being performed when funding allows by the Port Gamble S'Klallam Tribe.

Budget

The following budget describes the costs of the components of this assessment. The costs of phase 1 and 2 are separated and component costs are described by year, consistent with the work schedule described in the previous section.

Bridge Assessment Budget				**Expenses**				
				2016	**2017**	**2018**	**2019**	**Total**
BRIDGE AS BARRIER TO JUVENILE STEELHEAD & SALMON, LEADING TO INCREASED MORTALITY								
	BRIDGE IMPACT TO THE ENTIRE HOOD CANAL ECOSYSTEM							
		Migration behavior, mortality and fish densities around Bridge						
◆		1	Track steelhead migration behavior at Bridge, & mortality before, at & after Bridge	$150,000	$307,527	$165,000	$65,000	**$687,527**
◆		2	Map fish densities and distribution at vs away from bridge	$112,200	$100,000	$100,000		**$312,200**
		Predators, encounters, and impact near to vs far from the Bridge						
◆		3a	Map predator (mammal & bird) densities		$86,524	$86,524		**$173,048**
◆		3b	Aerial surveys to est. harbor seal abundance		$49,216	$49,216		**$98,432**
◆		4	Assess harbor seal-related steelhead mortality - seal scat/diet analysis			$158,141		**$158,141**
◆		5	Assess harbor seal-related steelhead mortality - seal scat/diet analysis		$88,458	$344,760	$60,840	**$494,058**
		Bridge physical influence on surrounding environment						
◆		6	Measure light and shade impacts to fish and predator behavior		$34,670			**$34,670**
◆		7	Measure noise impacts to fish behavior	$50,000	$200,000	$100,000		**$350,000**
◆	◆	8	Collect oceanographic data around bridge (current, salinity, & temperature profiles)		$100,000			**$100,000**
◆	◆	9	Characterize the Bridge zone of influence – Hydrodynamic Modeling	$50,000	$100,000	$100,000		**$250,000**
◆	◆	10	Characterize fine scale flow field near bridge pontoons- CFD Modeling			$150,000		**$150,000**
	◆	11	Model the effect on flushing, biogeochemistry, dissolved oxygen, and pH			$450,000	$100,000	**$550,000**
	◆	12	Model the subsequent impact to the Hood Canal food web			$75,000	$75,000	**$150,000**
		Data Synthesis						
◆		13a	General (inc. geo regression analyses)*		$25,000	$35,000	$15,000	**$75,000**
◆		13b	Simulate steelhead migration past bridge			$75,000	$175,000	**$250,000**
		Project Management						
◆			Coordination, permitting, communications and outreach, outcomes/management actions	$54,575	$56,000	$56,000	$63,000	**$229,575**
		TOTAL		**$416,775**	**$1,147,395**	**$1,944,641**	**$553,840**	**$4,062,651**
		PHASE 1		$416,775	$947,395	$716,000	$253,000	$2,333,170
		PHASE 2		$0	$200,000	$1,228,641	$300,840	$1,729,481

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

** The proposed reef effect assessment (component 14) is currently proposed as being performed in-kind. Data are not currently available regarding the value of this work.

The assessment will last 3.5 years (2016-2019) and cost $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.

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 3.7 meters underwater, and forms a partial 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 mixtools 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 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 is 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 observation and 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 July 2018. 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)

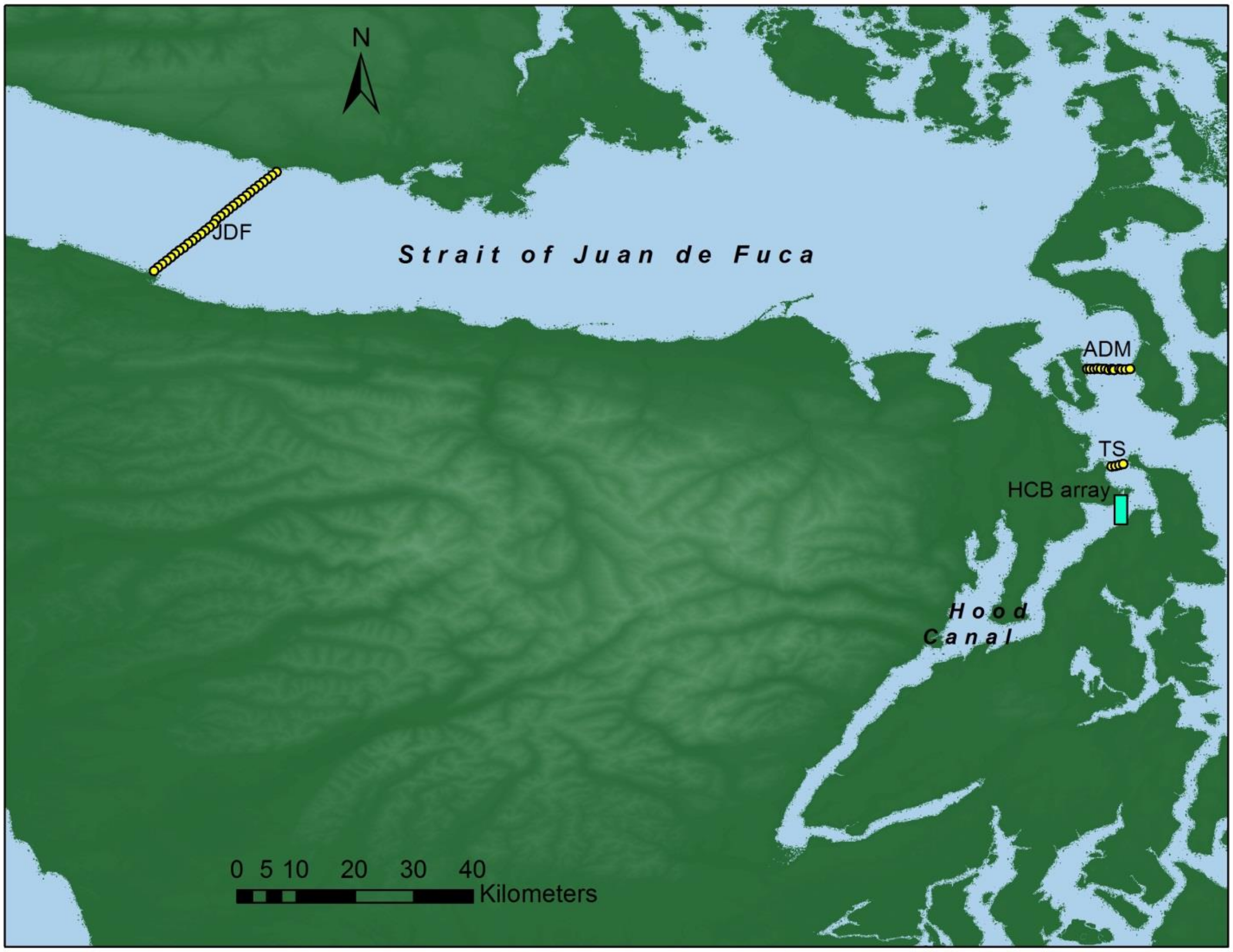


Figure 1. Map of study area showing the proposed telemetry receiver array at the Hood Canal Bridge (HCB), and receiver lines at Twin Spits (TS), Admiralty Inlet (ADM), and the Strait of Juan de Fuca (JDF).

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 be used to understand the relationship between tagged steelhead and all other fish in terms of their size, distribution, and abundance. 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 salmonid 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.

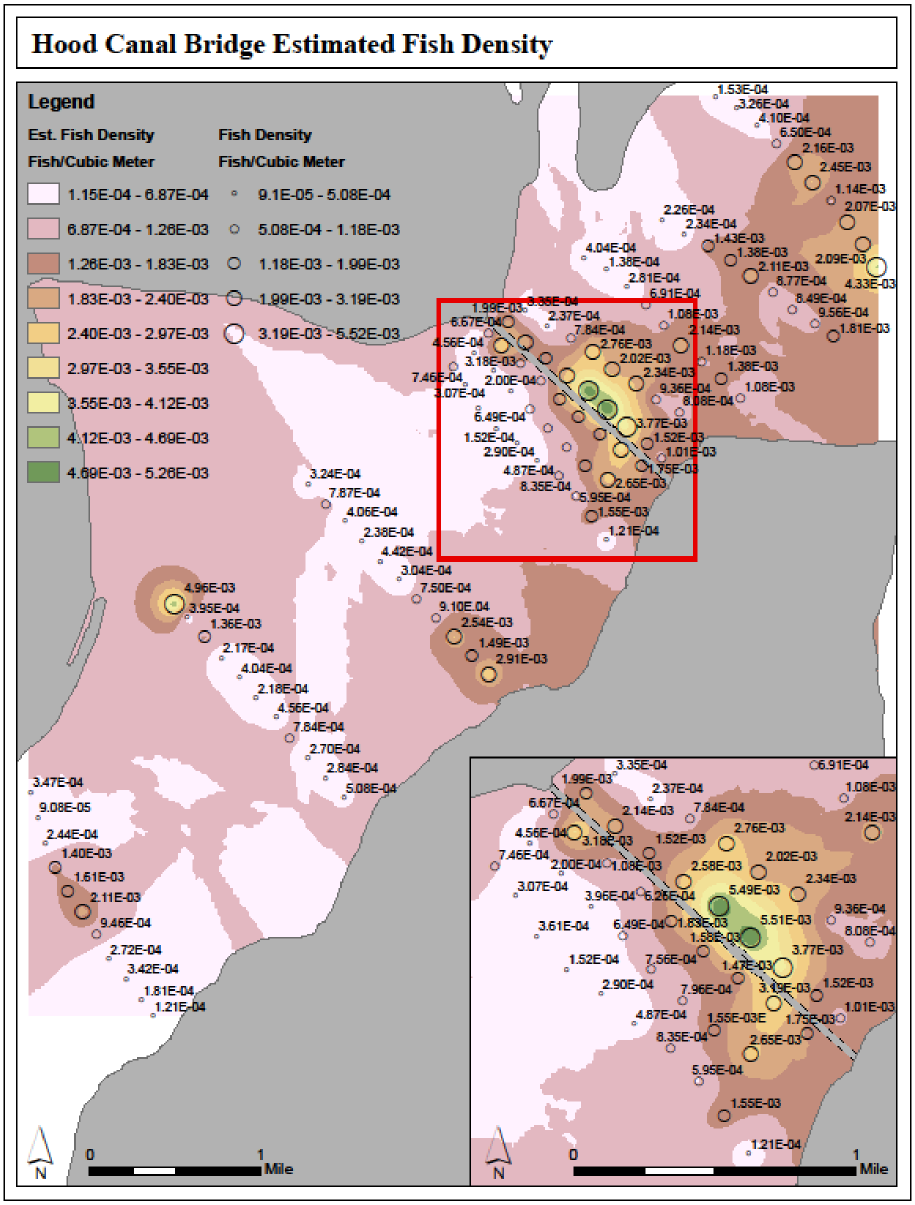


Figure 1 Estimated near-surface fish density within the vicinity of the Hood Canal Bridge.

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.

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 (dependent upon need)

Bridge-focused predator surveys may also be conducted from the bridge or bridge pontoon deck, if access is allowed. For phase 1, bridge-based surveys may be piloted, with formal, more intense surveys occurring in phase 2 if ultimately warranted. 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[3]. 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.

AERIAL SURVEYS FOR HARBOR SEALS

These surveys will complement our boat-based estimates of the number of harbor seals on the water. Following protocols described in Jeffries et al. 2003, WDFW will conduct aerial surveys (two per month between 1 April to 30 June) plus a population assessment survey in October of harbor seal haulout sites in and adjacent to Hood Canal as described in Jeffries et al. 2000 in 2016 and 2017. Surveys will be flown at 600-800 feet (183-244 m) at a speed of 80 kts. Each survey will require a chartered plane (Cessna 206) with one pilot experienced in conducting harbor seal surveys, one primary observer/photographer and one secondary observer/recorder.

After the data are gathered, a technician will count and record the numbers of adult and pup harbor seals present at each site from digital photos, and will enter results into a WDFW database corrected using techniques described in Huber et al. 2001, Jeffries et al. 2003, and London et al. 2012.

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 analyses 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.

[3] 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. 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 hardparts will then be removed from the jar leaving behind the ethanol-preserved scat matrix for genetic analysis (Thomas et al. 2014).

Prey hardparts analysis

To remain consistent with the way previous harbor seal diet work in the region has been conducted using hard prey remains (i.e. hardparts), we will use the "all structures" approach to identify harbor seal prey contained in individual scat samples. Prey hardparts retained in the paint strainers will be cleaned of debris using either a washing machine or nested sieves. All diagnostic prey hardparts 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 hardparts 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).

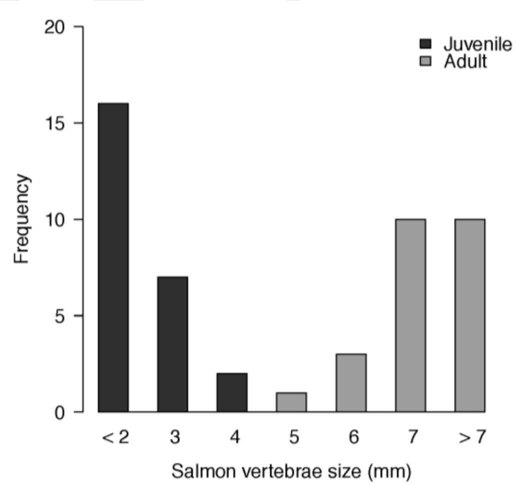


Figure 2. (From Thomas 2015) Frequency of salmon vertebrae between <2 mm and >7 mm, demonstrating the size difference between adult and juvenile salmon bones in seal scats.

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 “5. Assess harbor seal interactions with steelhead, and foraging behavior, via acoustic telemetry” 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. 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 by July 2018. Data will also be presented orally to interested parties and at relevant scientific meetings.

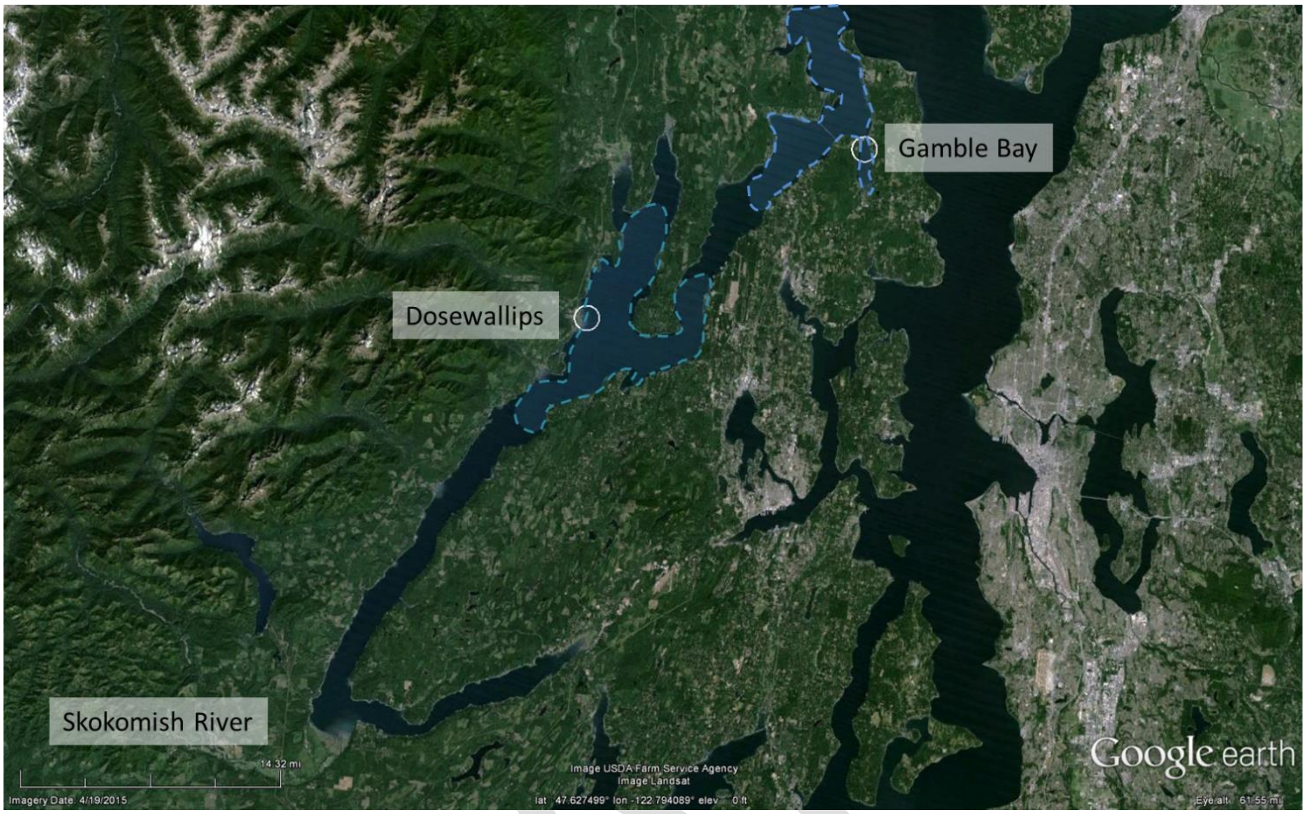


Figure 1. Study area showing 1 km radii surrounding proposed haulout capture areas near (Gamble Bay) and far (Dosewallips) from the Hood Canal Bridge. The blue areas represent the two corresponding hypothetical coverage areas for the two groups of seals (n = 15 per location) to help visualize the areas 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.

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 draw span, may intensify the potential reef effect impact of the voids around, and the opening and closing of, the draw span (reef effect explained on p. 18). 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.

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 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. Correlations 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. 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. 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. These data will be used to characterize zooplankton communities 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, Marty Ingraham, Tarang Khangaonkar, Pacific Northwest National Laboratory. Hans Daubenberger, Port Gamble S'Klallam Tribe.[4]

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 (accompanying passage of a sound) 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 particles) 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.

PHASE 1

For 2016, we propose to deploy measurement system at two to three locations for two weeks to a month. Each measurement system will consist of multiple types of sensors and a data acquisition system. 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)

[4] 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 refining the phase 2 synthesis approach (13b) based upon the findings of 13a.

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 measure 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.

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. 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.
- 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 (study 1), and whether there are any correlations between fish densities (study 2) and predator densities (study 3) and noise.

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

RPS – Evans Hamilton

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. For the bridge-mounted current meter, there exists an access road/platform attached to the floating section of the bridge. 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 draw span 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.

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.

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. 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.

Ancillary Data

A probe will be cast at various times and locations (to be determined) 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 models developed in studies 9 and 10.

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. .

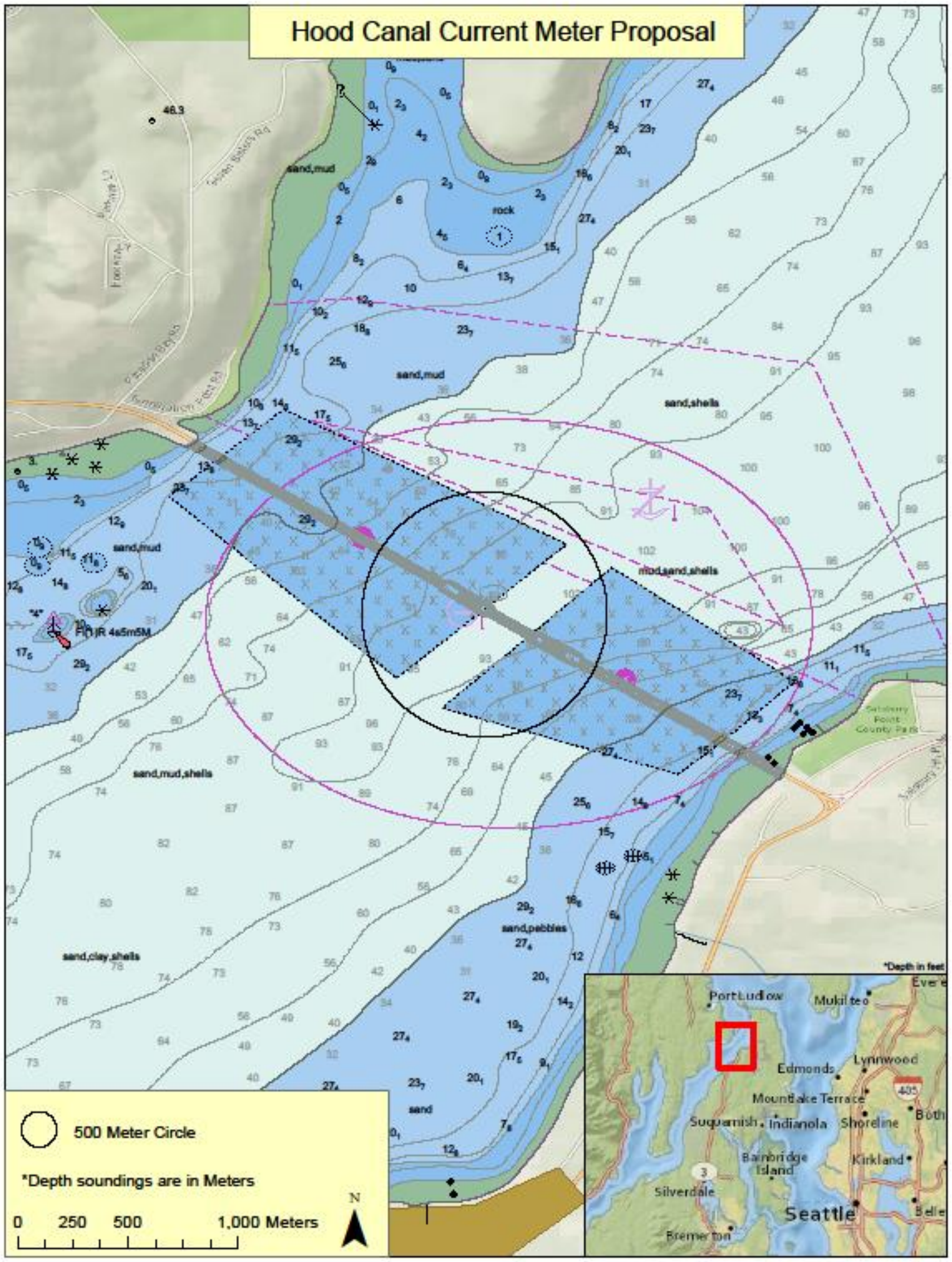


Figure 1. Current meter deployment and detection range. Black circle represents the deployed meter measurement range and purple circle the mobile data collection measurement range

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. A model of Hood Canal basin developed for the U.S. Navy 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. Passive particle tracking will be used to visualize the flow and inform the fish behavior assessment activity.

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

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. 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 by the end of 2018. 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. Review Team - Mindy Roberts , Washington Department of Ecology and Ben Cope, Environmental Protection Agency

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. It is not evident from the data whether anthropogenic influences such as nutrient pollution from wastewater discharge and development have exacerbated natural conditions. Review of available literature and recent research indicates that nutrient and pollutant loads from human contributions alone could not account for the observed low DO events (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 of the Salish Sea including Hood Canal. Hood Canal has historically supported a healthy shellfish industry, which is now beginning to feel the impacts of ocean acidification. Hood Canal waters are especially vulnerable to acidification resulting from a combination of factors, including strong coastal upwelling, nutrient loads, and carbon loads from rivers and runoff. 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, 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[5] data collection and fish 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-

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

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 by July 2019. Data will also be presented orally to interested parties and at relevant scientific meetings.

12. 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 3-D simulator of marine ecosystems. 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). 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. 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;
- Estimates of the relative impacts of different bridge effects on key species—for example, the degree to which fish abundance is affected by direct bridge-related predation impacts vs. bridge-related lethal DO levels vs. bridge-related changes in salinity vs. bridge-related changes in ocean acidification vs. bridge-related changes in food web structure. Key species of concern include but are not limited to ESA-listed salmon and steelhead, rockfish, shrimp, oysters, and killer whales.

- Estimates of impacts of aggregations of jellies adjacent the bridge, potentially affecting prey availability (pers. comm. H. Daubenberger 2015).
- Estimates of how future climate change and human population/urbanization/coastal development effects might interact with bridge effects.

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 by July 2018. 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 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 and to the best extent possible, will represent bridge center drawspan state (open versus closed).

13b. 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
A. How is the bridge acting as a functional barrier to juvenile steelhead and salmon migration and leading to increased mortality?						
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) 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
What influences/predicts fish behavior, distribution, and 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
	Is the bridge causing a structural, artificial reef effect?	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.	14,2		Underwater video observations identify in-water bridge structures with significant sea-life growing on them, and those regions correlate with increased densities of fish captured via hydroacoustic sampling and video	Hans Daubenberger
	Are fish with active acoustic tags more susceptible to predation than those with silent tags?	Fish with delayed and continuously pinging acoustic tags do not have significantly different survival rates.	1		Equivalency test of two proportions (continous and delayed) with a tolerance of 0.10.	Megan Moore
Do influenced fish have greater susceptibility to predation near/at the bridge?	What are the densities and distribution of predators at the bridge versus away from the bridge?	Predators 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
Can outmigration efficiency be improved at the bridge through structural and/or operational modifications?	Can alternatives such as permanent baypass outlets 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
B. How does the bridge impact the entire Hood Canal ecosystem?						
Does the bridge obstruct ebb - flood currents & impact flushing of brackish outflow	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
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
How does the Hood Canal bridge affect key marine species residing in Hood	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

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