Assessing and Mitigating Dock Shading Impacts on the Behavior of Juvenile Pacific Salmon (Oncorhynchus spp.): Can Artificial Light Mitigate the Effects?

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by

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16. Abstract

The shadows from large over-water structures built on nearshore habitats in the Puget Sound can reduce prey abundance and disrupt juvenile Pacific salmon (*Oncorhynchus* spp.) migratory behavior with potential consequences on survival rates. As part of an ongoing project to reduce the effects of ferry terminals on juvenile salmon, this study looked at the effectiveness of a fiber optic lighting system at mitigating dock shading impacts on juvenile salmon behavior. We conducted intensive visual observations, snorkel surveys, and video filming surveys at the Port Townsend Ferry Terminal (dock) from March through August 2008 and 2009 to test whether migrating salmon reacted to changes in light beneath the terminal and whether evident reactions by the salmon were moderated by the fiber optic lighting system.

We found that during high tides shoals of juvenile salmon (primarily pink salmon *O. gorbuscha*) were reluctant to swim under the dock and also under the shaded areas. Overall, less than 15 percent of juvenile salmon shoals penetrated under the terminal, and they typically remained within a few meters from the dock. No salmon swam completely under the dock during our observations in the study period. As a consequence of this dock avoidance behavior, ferry terminals likely delay migration for some juvenile salmon (pink salmon) by several hours per dock encounter, during high tide periods, daylight hours and on sunny days.

Our results also indicated that light transmitted or installed under some old and new terminals could mitigate dock shading impacts on juvenile salmon. However, our experience testing both fiber optic-transmitted natural and *in situ* artificial (halogen) light suggests that such light mitigation systems will need to (1) be more powerful, (2) be regulated to light only shaded areas, (3) operate on a natural light spectrum, and (4) distribute light over a wide area.

The impacts of large over-water structures on juvenile salmon behavior likely alter juvenile salmon migration behavior in shallow nearshore waters, but with an unknown impact to growth and survival. The use of artificial light is a promising mitigation method because fish appeared to respond at a low light level. However, our results were not sufficient to determine whether artificial light could completely mitigate the effects of the dock and eliminate juvenile salmon avoidance behaviors.

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EXECUTIVE SUMMARY

This research was supported by the Washington State Department of Transportation (WSDOT), which is interested in assessing and mitigating the possible impacts of ferry terminals on the marine resources of Puget Sound. Since 1999, WSDOT has been conducting studies to determine the impacts of ferry terminals on both aquatic plant and fish assemblages, with a particular interest in juvenile Pacific salmon (*Oncorhynchus* spp.). Salmon are a very important commercial, recreational, and cultural species in the Pacific Northwest, including many populations that are now listed as threatened or endangered under the Endangered Species Act (ESA).

Following the results from previous studies, WSDOT determined that shading beneath ferry terminals (docks) could potentially have an impact on juvenile salmon behavior and survival by disrupting their vision or migratory path, or by decreasing prey and habitat availability (Nightingale and Simenstad 2001). As a result, WSDOT initiated several projects to investigate techniques to mitigate dock shading effects on migrating juvenile salmon. An early study compared different artificial lighting systems to increase the light level underneath docks, including the Sun Tunnel™, deck prisms, metal halide light, glass blocks, and metal grating (Blanton and Washington 2002). However, none of these lighting or light transmission techniques was particularly successful at significantly increasing the under-dock light level. Moreover, most of the artificial lighting systems required a lot of maintenance, needed a substantial energy supply, and/or had significant, undesirable impacts on the structural integrity of the over-water structure. In 2007, WSDOT, with the assistance of Battelle Marine Sciences Laboratory (BMSL), found a promising new lighting system, the Sunlight Direct fiber optic lighting system. This system could transmit natural light beneath the terminal and supposedly needed less maintenance and less energy, and also induced minimal impact on the structural integrity of the terminal.

Subsequently, we conducted a test study of the ability of this fiber optic lighting system to mitigate dock impacts on juvenile salmon during the out-migration period in 2008 and 2009 at the WSDOT Port Townsend Ferry Terminal (dock). However, because of malfunctions and the destruction of much of the fiber optic lighting system under the dock, the system became inoperable after a year. To continue the experiments with under-dock lighting, we replaced the fiber optic system with a halogen lighting system for the remainder of the study period. This report details the integrated results of these two tests on artificial light to mitigate under-dock shading.

This report begins with a brief review of the previous findings about the effects of over-water structures on juvenile salmon shoaling behavior. These are followed with a description of an intensive field survey conducted at the Port Townsend Ferry Terminal during 2008 and 2009 to provide quantitative data on fish behavior at a ferry terminal. Next, the report presents the study methodology and findings about the efficiency of the fiber optic lighting system in reducing shading impacts on juvenile salmon behavior.

Over-water structures impose three direct or indirect impacts on juvenile salmon: (1) a behavioral barrier to the juvenile salmon outmigration, (2) reduction in salmon prey, and (3) potential migration delay. Large over-water structures create a behavioral barrier for some juvenile salmon because of the extensive shadow they produce below. The acute light contrast with the ambient environment deters juvenile salmon from swimming underneath the dock because a fish’s eye cannot adapt quickly enough to the sudden change in light level. We observed that some small juvenile chum and pink were reluctant to swim under the dock throughout the day and stayed in the shallow, nearshore area where the fish first encountered the dock. This also suggests that shading from large over-water structures may cause a delay in migration for some small juvenile chum and pink salmon. In addition to the dock shading impacts, we also found that the terminal itself appeared to repel some juvenile salmon, as some would not swim underneath the dock even without a distinct shadow.

The Sunlight Direct fiber optic lighting system had a small but significant effect in mitigating dock shading impacts on juvenile salmon behavior. However, the effect of light was not singularly positive. When the lighting system reduced the contrast with the ambient environment, juvenile salmon demonstrated more swimming directionality and swam closer to the dock edge. However, if the system increased the light contrast (i.e., produced a spotlight effect in a non-shaded area), the fish became more disturbed, demonstrating less swimming directionality and increasing their distance from the dock edge.

Although the fiber optic transmission lighting system was somewhat effective in mitigating dock shading impacts, the system was not very robust and became unrepairable after a year of use. Therefore, we would not necessarily recommend the use of a fiber optic lighting system for dock shading mitigation without testing and verifying that the system was more dependable. Such a light transmission system would need to have at least the following characteristics: (1) resistance to marine environment corrosion and other degradation, (2) more efficient light transmission, and (3) better dependability. Other lighting systems might offer more effective light transmission; however, the light quality (electromagnetic color spectrum) would have to be comparable to natural sunlight because otherwise it would likely induce adverse responses in juvenile salmon behavior. Therefore, based on our experience, our general recommendation for future dock shading mitigation is to locate a lighting system that can withstand the marine environment, that follows the shaded area beneath the dock with the time of the day, and that will propagate preferably more than 10,000 lux of white (natural) light at a distance of 2 m from the light source over a wide area (wide enough to cover the shade cast by the over-water structure on the shallow nearshore area).

Given the above constraints on lighting systems, redesign or retrofit of these structures should also be considered as an alternative to a lighting system to minimize shading impacts on small juvenile salmon. Such alternatives might include changing dock height, altering orientation, or using more transparent dock materials.

INTRODUCTION

As a result of rapid demographic expansion in the last decades, the shorelines of Puget Sound, Washington, have seen many changes. Harbors have been constructed in response to regional economic expansion, docks and marinas have been built to enable human transportation and recreational pleasure, and other types of revetments (bulkheads, seawalls) have covered much of the natural shoreline throughout Puget Sound (Williams and Thom 2001). Of the almost 4,000 km of Puget Sound, Washington, shoreline, 27 percent is now armored by vertical bulkheads, rip-rap boulders, and revetments, and almost 40 km^2 are covered by fill, 3 km^2 by breakwaters and jetties, 6.3 km^2 by marinas, and 6.5 km^2 by over-water structures (Simenstad et al. In press). Thus, both the structure and function of various pristine nearshore ecosystems of Puget Sound have been altered (Simenstad et al. 1999). Very notably, the nearshore zone constitutes an important migratory corridor and rearing habitat for many organisms (bird and fish) that rely on these areas to feed, reproduce, hide from predators, or physiologically adapt during the transition to ocean conditions (Simenstad et al. 1999, Nightingale and Simenstad 2001). This is the case for several species and life history stages of Pacific salmon (*Oncorhynchus* spp.), which are an important commercial and cultural species in the northwestern United States and Alaska. Although the individual effects of shoreline modifications and over-water structures (OWS) might not be significant, their cumulative effects have likely contributed to the decline of Puget Sound salmon species (Good et al. 2005) and many other local resident, transient, or migratory fish. Some big over-water structures, such as ferry docks, may disturb the nearby aquatic community composition (vegetation and benthic organisms) by decreasing light availability and are also believed to affect the migratory behavior of juvenile salmonid, which in turn may influence outmigration timing and survival (Nightingale and Simenstad 2001). Therefore, knowledge about the impacts of over-water structures on the fish community can help minimize those impacts in the future. Moreover, several Puget Sound salmon are now listed as threatened under the Endangered Species Act (ESA). This status has magnified the concerns of different agencies such as the Washington State Department of Transportation (WSDOT), Washington Department of Fish and Wildlife (WDFW), US Fish and Wildlife Service (USFWS), National Oceanographic and Atmospheric Administration (NOAA), and Native American tribes about juvenile salmon interaction with ferry terminals.

Relatively few studies in the scientific literature have looked at the effects of ferry terminals on juvenile salmon. Ferry terminals are one of the biggest cases of OWS because of their prominent size and elevation over the water, the effect of which is extensive shading. Since the last century, more than twenty ferry terminals have been built in Puget Sound region, and the system transports over 60,000 passengers on a daily average (*http://www.wsdot.wa.gov/ferries/traffic_stats/annualpdf/2009.pdf*).

Similarly to most fish, juvenile salmon rely heavily on light perception to orient themselves in space, capture prey, school, avoid predators, and migrate along the shoreline to the ocean (Valdimarsson et al. 1997, Nightingale and Simenstad 2001, Valdimarsson and Metcalfe 2001, Mazur and Beauchamp 2003). But large over-water structures such as ferry terminals create a sharp light/dark contrast that disturbs the visual sensitivity of these organisms and that is believed to affect their subsequent behavior (Simenstad et al. 1999, Nightingale and Simenstad 2001).

In this work, we first summarized findings in the literature and report our observations about the impacts of over-water structures on juvenile salmon. We then examined whether a lighting system that reduced the light contrast under a terminal would mitigate the effects of over-water structure shading on juvenile salmon migration behavior. The lighting system (Sunlight Direct) tested in this study concentrated ambient sunlight and transmitted it to areas underneath the dock by using fiber optic cables. We assessed the system's efficacy by combining visual observation surveys, snorkel surveys, and videography of juvenile salmon movement around the dock to analyze changes in their behavior due to the presence of shadow and the use of light, as well as some other demographic and environmental covariates.

REVIEW OF THE RELEVANT LITERATURE

IMPORTANCE OF NEARSHORE ECOSYSTEMS FOR JUVENILE SALMON

The nearshore ecosystems of Puget Sound are complex environments characterized by a multitude of landscape features: bluffs, beaches, mudflats, kelp, eelgrass beds, salt marshes, gravel spits, and estuaries (Williams and Thom 2001). Because of that diversity, these habitats provide a great number of ecological and physical functions: they not only constitute a physical "buffer" from wave action and current energy but also ensure primary production and support a complex food web structure (Simenstad et al. 1979, Simenstad et al. 1982). For example, detritus from nearshore macrophyte production may contribute to zooplankton production (e.g., copepods) in the neretic zone, which are an important food base for juvenile pink (*O. gorbuscha*), Chinook (*O. tshawytscha*) or Pacific herring (*Clupea harenus pallasi*), which are themselves prey items for rockfish (*Sebastes* spp.) and lingcod (*Ophiodon elongatus*) (Simenstad et al. 1999, Williams et al. 2003)

Among the different nearshore habitat types, estuaries play four major roles for juvenile salmonids (Simenstad et al. 1982, Groot and Margolis 1991, Quinn 2005):

(1) Estuaries provide an environment where juvenile salmon can physiologically acclimate to salt water because the mixing of marine and fresh water along the estuarine gradient allows juvenile salmon to volitionally adapt to a high level of salinity.

(2) Estuaries provide productive foraging habitats that are rich in small invertebrates such as harpacticoid copepods, gammarid amphipods, and insects that are important prey resources for juvenile salmon (Miller and Gardner 1977, Bax et al. 1978,

Bax 1982, Duffy-Anderson and Able 2001) and allow high growth rates. The estuary is therefore a critical stage that influences the subsequent survival of juvenile salmon in offshore marine environments. In general, the larger the fish, the higher the chance to survive, although other factors, such as the timing of ocean entry, can also affect survival (Healey 1982a, Cooney and Willette 1996, Quinn 2005).

(3) Estuarine environments also provide refuge areas to protect juvenile salmon from potential predators such as larger juvenile salmonids, sculpin (family Cottidae), cod (*Gadus* spp.), and hake (*Merluccius* spp.) (Williams et al. 2003). Among the many nearshore estuarine habitats of juvenile salmon, eelgrass likely constitutes an important refuge habitat for many demersal fish and juvenile salmonids (Simenstad et al. 1979, Semmens 2008).

(4) Finally, estuaries serve as migratory corridors for juvenile salmon (Simenstad et al. 1999, Nightingale and Simenstad 2001).

Despite these benefits, not all juvenile salmon are equally dependent on nearshore estuaries. Juvenile chum (*O. keta*) and Chinook salmon are believed to be the most estuarine dependent species (Levy and Northcote 1982, Simenstad et al. 1982, Healey 1982a, Bottom et al. 2005) as opposed to coho (*O. kisutch*), sockeye (*O. nerka*), and pink juveniles, which are less estuarine dependent and migrate through the estuary in a few days. Importantly, two of the most estuarine/nearshore dependent species in Puget Sound, the fall Puget Sound Chinook and Hood Canal summer chum, are now listed as threatened under the Engangered Species Act (ESA).

Although there are differences in estuarine use, all juvenile salmon move along nearshore areas early during their seaward outmigration, and depending on the species, life history stage, and the environment, they may stay more or less in these areas (Dames & Moore, Inc and Biosonics 1994, Weitkamp 2001, Williams and Thom 2001). For example, smaller fish generally stay in shallower nearshore habitats, whereas larger fish are distributed farther from shore in deeper waters (Kaczynsk et al. 1973, Healey 1982a)

EFFECTS OF OVER-WATER STRUCTURES ON JUVENILE SALMON

Numerous types of over-water structures now cover much of nearshore Puget Sound (Williams and Thom 2001, City of Bainbridge Island and Battelle Marine Science Laboratory 2003). Among others, floating docks, fixed piers, marinas, and mooring buoys are the most common structures in the region (City of Bainbridge Island and Battelle Marine Science Laboratory 2003) and provide access to water resources for many commercial, recreational, and private activities. Ferry terminals are special cases of fixed piers, with their prominent dimensions (over tens of meters wide and typically a hundred meters long). Because these structures are built on nearshore habitats which can be important for migrating juvenile salmon, OWS inevitably impose potentially significant effects on the ecology of these fish. The first OWS effect on juvenile salmon was documented in 1970, when Heiser and Finn (1970) found that juvenile pink and chum were generally reluctant to penetrate under large piers and that they either stayed close to shore (for smaller fish) or moved offshore (larger fish) by following the dock edges. Since that time, other studies appearing in the literature have cited more diverse and complex findings (Table 1). Generally, these findings can be grouped into three categories: (1) migratory behavior change, (2) increased predation risk, and (3) reduced carrying capacity.

Over-water structures can cause a migratory behavior change when juvenile salmon become confused upon encountering the shadow beneath the dock (Heiser and Finn 1970, Ratté et al. 1985, Taylor and Willey 1997, Shreffler and Moursund 1999). Some of them deviate from their migratory path to deeper waters in order to detour around the dock (Heiser and Finn 1970, Salo et al. 1980). Reflecting on these observations, several authors speculated that the OWS potentially contributed to delays in the migration timing of juvenile salmon. However, most studies were not able to prove this speculation (Prinslow et al. 1979, Prinslow et al. 1980, Shreffler and Moursund 1999, Simenstad et al. 1999, Southard et al. 2006), and only a few were able to show a potential delaying effect (Salo et al. 1980) but without any definitive findings. Conversely, environmental conditions also control the migratory behavior of juvenile salmon (Salo et al. 1980), which could explain the observed differences in juvenile salmon abundance around the naval facility at Hood Canal, Washington, between two consecutive years (Salo et al. 1980).

Over-water structures are also believed to increase the predation risk of juvenile salmon. Although this assertion remains speculative, several authors have hypothesized that the deviation of juvenile salmon migratory course to a deeper area makes them more susceptible to predation (Heiser and Finn 1970, Salo et al. 1980, Williams et al. 2003). Some others have also speculated that nighttime dock lighting can attract juvenile salmon predators and hence increase the predation risk of juvenile salmon (Prinslow et al. 1979, Salo et al. 1980), but they have not successfully demonstrated this assertion.

In addition to the above direct effects discussed above, large OWS such as ferry terminals can also indirectly affect the fitness of juvenile salmonids by decreasing an area's carrying capacity through reduced foraging capacity and decreased refuge from predation beneath the OWS. OWS reduces light availability under the dock, which can limit the growth and reproduction of aquatic plants such as eelgrass, *Zostera marina* (Shafer 1999, Smith and Mezid 1999). Shafer (1999) found that at light levels under 14 percent of surface irradiance[1], eelgrass did not grow under docks. This aquatic vegetation is also important habitat for small invertebrates such as harpacticoid copepods and gammarid amphipods (Nakamura and Sano 2005) that are valuable prey items for juvenile salmon (Haas et al. 2002). However, as demonstrated in the literature summarized in Table 1, observations can be quite different depending on the type of structure involved in the study, time of the study, and location.

Aside from these potentially negative effects of OWS on juvenile salmon, other studies in estuaries have suggested that over-water/shoreline structures can also affect the growth of other juvenile fish. For example, studies conducted in the Hudson River estuary, New Jersey, by Duffy-Anderson and Able (1999, 2001) showed that the feeding and growth rates of winter flounder (*Pseudopleuronectes americanus*) were significantly lower at the edge and under a pier in comparison to those in open waters. The same author obtained a similar result for tautog (*Tautoga onitis*) at the same study site.

To summarize, large over-water structures may impose some potentially adverse effects on juvenile salmon migrating in shallow waters along the Puget Sound shoreline, but the research team found no studies that have proved any beneficial effects of OWS on salmonids.

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[1] A measure of light power incident on a surface ($W.m^{-2}$)

Table 1: Summary of findings and/or speculations concerning the effects of over-water and shoreline structures on juvenile salmon behavior. For any observation, "Y" means suggested affirmation of the effect and "N" means suggested negation/opposition of the effect on juvenile salmon.

Findings		Type of structure	Location	Authors
Observations	**Y/N**			
Juvenile salmon (JS) penetrate under structure	**Y**	Pier Ferry terminal Pier	Commencement Bay, WA Edmonds, WA Seattle, WA	Ratte and Salo 1996 Southard et al. 2006 Taylor and Willey 1997
	N	Bulkhead, breakwater Pier Dock	Puget Sound, WA Seattle, WA Everett, WA	Heiser and Finn 1970 Pentec 1997 Weitkamp 1982
JS stay/move at the shadow edge	**Y**	Dock Pier Ferry terminal	Laboratory Commencement Bay, WA Port Townsend, WA	Gregory and Northcote 1993 Ratte and Salo 1985 Shreffler and Moursund 1999
	N			
JS contoured the structure	**Y**	Naval facility	Hood Canal, WA	Salo et al. 1980
	N			
Presence of ship influenced JS behavior	**Y**			
	N	Pier	Commencement Bay, WA	Ratte and Salo 1985
The structure increases predation risk for JS	**Y**	Bulkhead, breakwater Naval facility	Puget Sound, WA Hood Canal, WA	Heiser and Finn 1970 Salo et al. 1980
	N	Naval fuel pier Pier Pier Docks and bulkhead	Manchester, WA Seattle, WA Seattle, WA Hood Canal, WA	Dames and Moore 1994 Pentec 1997 Taylor and Willey 1997 Bax et al. 1979
The structure increases prey availability for JS	**Y**	Pier	New Jersey, NJ	Duffy-Anderson et al. 2001
	N	Ferry terminals	Puget Sound, WA	Haas et al. 2002
Size structured JS distribution along structure/depth	**Y**	Bulkhead, breakwater Pier Naval fuel pier Warf Ferry terminal Dock	Puget Sound, WA Seattle, WA Manchester, WA Hood Canal Port Townsend, WA Everett, WA	Heiser and Finn 1970 Pentec 1997 Prislow et al 1979 Roni and Weitkamp 1996 Shreffler and Moursund 1999 Weitkamp et al. 1991
	N			
Decrease JS abundance	**Y**	Terminal	Seattle, WA	Miller 1980
	N	Naval submarine base	Hood Canal, WA	Bax 1980

Table 1 continued

Delay of JS migration timing	**Y**	Pier Naval facility Naval facility Terminal Terminal Terminal Over-water structures	Everett, WA Hood Canal, WA Hood Canal, WA Port Townsend Puget Sound, WA Puget Sound, WA Puget Sound, WA	Pentec 1997 Prinslow et al. 1980 Salo et al. 1980 Shreffler and Morsund 1999 Simenstad et al. 1999 Southward et al. 2006 Williams et al 2003
	N			

FISH VISION AND THE IMPORTANCE OF LIGHT

As implied by previous studies, although not definitively proved, one of the primary effects imposed by OWS that alters juvenile salmon behavior is shading of ambient light. Light is an important element that controls fish vision. Most species, including juvenile salmon, rely heavily on light availability to orient themselves in space, capture prey, school, avoid predators, and migrate along the shoreline to the ocean (Nightingale and Simenstad 2001). Three key parameters affect fish response to light: (1) fish species, (2) development stage of the fish, and (3) level of light to which fish are adapted (Feist and Anderson 1991, Boeuf and Le Bail 1999).

Generally, most fish have a minimum light threshold level beneath which feeding success and growth are limited (Brett and Ali 1958, Ali and Hoar 1959, Boeuf and Le Bail 1999, Ryer and Olla 1999). They need some minimum amount of light (contrast) to be able to visually separate an object (prey or predator) from its background and take corresponding measures (attack, hide, flee). Below this threshold, fish feeding may be less successful, and growth may be limited. Above this threshold, fish can adapt their vision to see both in dark and bright areas. However, this threshold value is different among species and ontogenetic stages (Ali and Hoar 1959, Blaxter 1968b, 1968a, Burke et al. 1995, Carvalho et al. 2004). For example, juvenile salmon generally stop feeding at 0.1 lux (equivalent to about 0.001 $W.m^{-2}$) (Ali and Hoar 1959), as opposed to 100 lux (1 $W.m^{-2}$) for juvenile turbot (*Scophthalmus maximus*) (Champalbert and Le Direach-Boursier 1998) and 1 lux (about 0.01 W. $m^{-}2$) for plaice (*Pleuronectes platessa*) (Blaxter 1968a). Additionally, young herring larvae (*Clupea harengus)* have a feeding light threshold of about 0.1 lux and this light level decreases with age to 0.01 lux (Blaxter 1966).

The mechanism underlying fish vision in dark or lighted areas is mainly controlled by the movement of two types of eye cells: rods and cones. Cone cells are mainly responsible for vision in a bright environment (photopic vision) and rods in the dark (scotopic vision) (Hecht 1937). For instance, when light intensity is above the cone thresholds, eyes assume the light-adapted state, cone cells move to the surface of retina, near the source of light, and rod cells elongate away from the retina surface. The opposite mechanism happens for a dark-adapted state (Ali and Hoar 1959). However, when exposed to a sudden light level change, fish eye cells cannot adjust quickly enough, and fish experience momentary "blindness." Juvenile salmon generally need more than 30 minutes to completely recover from such light changes (Ali and Hoar 1959). This recovery period is usually longer when the organism suddenly encounters distinct darkness. The same phenomenon also happens with human eyes (Hecht et al. 1937), and this recovery time increases with age (Ali and Hoar 1959).

Juvenile salmon vision is not only limited by light intensity but also by its quality (light of different spectra). Fish cannot see every color, and their color sensitivity changes with ontogeny to adapt to new environments and new life history stages and ecologies.

For example, salmon fry are more sensitive to lower spectrum light (such as ultra-violet (UV) and green) (Browman and Hawryshyn 1994, Flamarique and Hawryshyn 1996), but as they grow and smoltify, they become more sensitive to blue light and lose their UV vision (Cheng and Flamarique 2004, Cheng et al. 2006). The UV sensitivity of salmon fry is often associated with their freshwater ecology, because green color is prevalent, and with their planktivorous life history stages, during which they feed in surface waters with more abundant UV rays (Cheng and Flamarique 2004); on the other hand, blue color is characteristic of deeper marine waters and is thus associated more with the piscivorous life history stages of larger juvenile salmon (Cheng and Flamarique 2004).

Light is hence an important component of fish vision, but it is also a limited element under water. There is an important reduction of light intensity and loss of color with increasing water depth. The underwater light intensity at different depths follows the Beer-Lambert Law: $I = I_0 * e^{-K_d * z}$, where I_0 is the light intensity at the surface, K_d is the attenuation coefficient (m^{-1}) that varies with wavelength λ, and z is the water depth. This formula indicates that light intensity decreases exponentially with water depth. Furthermore, red is the first color to disappear in water, followed by orange, then yellow. Blue is the only color left in deeper water. The relative decrease of light intensity and loss of color is also influenced by the water composition—turbidity, presence of phytoplankton, and suspended matter—which is taken into account by the attenuation coefficient.

To increase the underwater light level, several authors have tested some artificial lighting systems and studied their impacts on juvenile salmon behavior. Chinook, coho, Atlantic salmon (*Salmo salar*) and steelhead (*O. mykiss*) were observed to usually avoid strobe lights during daytime and nighttime, and fish attraction to light only occurred when light intensity resembled that to which fish were previously adapted (Anderson et al. 1988). Mercury light has been found to cause inconsistent behavior in juvenile salmon, as Chinook and coho first avoided the light but then swam toward it (Anderson et al. 1988). Salo et al. (1977, 1980), Prinslow et al. (1979), and Schreiner (1977) showed that juvenile salmon were generally attracted to OWS' security lighting but that the level of attraction also depended on the light intensity and quality. They also indicated that yellow and white were generally the most attractive color whereas red was the least attractive. However, this result was not specific to juvenile salmon. Fish response to lights also varies among species or stock studied and water velocity (Feist and Anderson 1991).

Therefore, the sections following address the need for more definitive and quantitative tests of the biotic and abiotic conditions that affect juvenile salmon movement behavior around large OWS such as ferry terminals.

RESEARCH OBJECTIVES

The study's research objective was to resolve some of the contradictory information about OWS effects on juvenile salmon behavior by using observation data and results from field surveys at the Port Townsend Ferry Terminal. In addition, the study sought to evaluate the effectiveness of the Sunlight Direct fiber optic lighting system in mitigating dock shading impacts on juvenile salmon behavior.

These major objectives were divided into more specific questions:

1. How do juvenile salmon distribute along large over-water structures? Is there any pattern to their response to the OWS and light shading?
2. How do they behave when encountering the OWS?

   The second question was specifically addressed in a hierarchical structure:

   a. Do juvenile salmon swim along the perimeter of the dock, from shallow to deep water?

      → If YES, does it happen all day long? Or is it time- or tide- (environment) specific?

      → If NOT, do they circumvent the dock, or do they stay around the dock?

      → If they contour the OWS, when does it occur?

      → If they stay in the vicinity, what kind of movement do they follow?

   b. Does OWS cause any potential migration delay risk to juvenile salmon?

The question about increased predation risk that has been argued by several authors was not addressed in this study because the sampling method was not adequate to test this hypothesis.

3. How does juvenile salmon behavior change as a result of the presence of shadow, the use of light, and some other demographic and environmental covariates? This question was addressed by using a specific statistical test and analyzing changes in three fish behavior indicators: (a) juvenile salmon swimming directionality, which assumed that the more disrupted the fish (whether from shadow or light), the more variable its swimming orientation, hence a higher fish angular variance; (b) fish path shape, which assumed that the more disrupted the fish, the more complex its movement around the dock, and (c) the fishes' closest distance from the dock edge, which assumed that the more disrupted the fish, the farther it would stay from the source of disturbance (shadow or light).

RESEARCH APPROACH/PROCEDURES

STUDY SITE

With the cooperation and support of the Washington Department of Transportation, we conducted this study at Port Townsend Ferry Terminal (48°6'40.34"N latitude, 122°45'34.06"W longitude) which is located at the northern part of Jefferson County, Washington, where Puget Sound narrows before opening into the Strait of Juan de Fuca (Figure 1). It is a convergence place for many juvenile salmon species and populations that originate from Puget Sound and Hood Canal. Among the species and populations present are the ESA-listed summer chum that come from Hood Canal and fall Chinook from different areas of Puget Sound (Bax 1982, Good et al. 2005). Therefore, the Port Townsend nearshore area constitutes an important migratory convergence zone for juvenile salmon that move along the shoreline heading to the Pacific Ocean. Furthermore, the terminal is a 36-m wide, 105-m long over-water structure that is oriented north/south (Figure 2).

The bottom substrate at the site consists mainly of fine to coarse sand with some gravel and an eelgrass bed spanning from -1.5 m MLLW (Mean Lower Low Water) down to about -5 m MLLW on both sides of the terminal (west and east) (Thom et al. 2002) (Figure 3). The bottom slope on the west side is quite gentle, from 0 MLLW to -1 m MLLW and from -3 m MLLW to -4 m MLLW, as opposed to the area in between where the slope is about 10 percent. Moreover, a riprap zone extends with a steep slope from 0 MLLW (Figure 3).

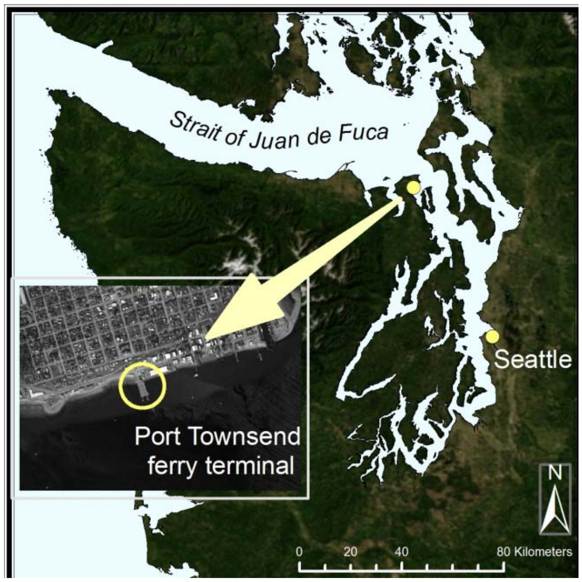


Figure 1: Port Townsend Ferry Terminal location in Puget Sound

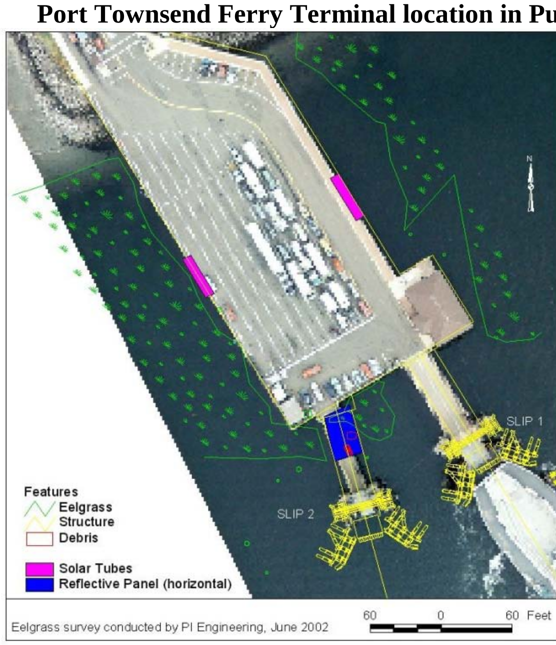
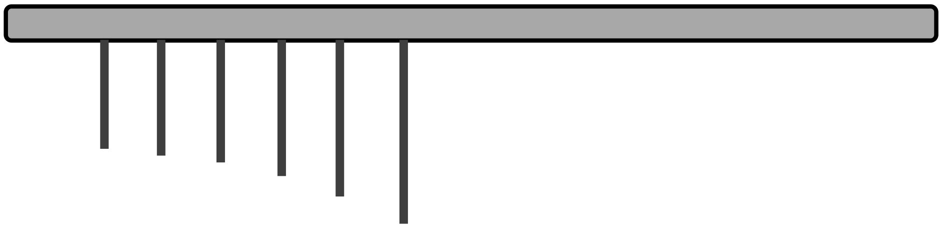


Figure 2: Port Townsend Ferry Terminal habitat map (taken from Thom et al. 2002)



MATERIAL AND METHODS

<u>Visual and Snorkel Surveys Data Collection</u>

We used visual and snorkel surveys to distinguish juvenile salmon, classify their relative abundance, and quantify their shoal behaviors and distributions. These methods have the advantage of being affordable, quick, and easy to apply, and they can be used more extensively than other conventional methods such as video cameras. The only inconvenience is that data could typically not be acquired on days with wind, rain, turbulence, and turbid water (Schreiner 1977, Toft et al. 2007). Another advantage of this methodology is that it relies on human vision, which is one of the most capable visual systems, enabling both far and close field vision, in three dimensions, and with high image quality. Another common technique is the use of computer vision (which will be described later); although computerized systems do not possess all of the above qualities, they have the advantage of enabling video recording and precise behavior measurement.

We conducted surveys between March and mid-August 2008 and 2009, during major juvenile salmon outmigration timing (Schreiner 1977, Simenstad et al. 1982, Groot and Margolis 1991, Quinn 2005, Fresh 2006), at the west side of the terminal (Figure 5). Local environmental conditions highly influenced sampling efficiency, but overall we were able to sample during five days every two weeks during neap tide periods. We found neap tide to be preferable to spring tide because it was generally higher and more stable during the sampling time. The tidal level of interest ranged from 0.5 to 2.0 m MLLW.

Because shading impact is stronger when the sun is brighter and the tide higher, the sampling time was constrained to 0900 to 1800 PDT. Throughout the day, the shadow moved from west to east, and at noon it was located almost directly underneath the terminal (Figure 6).

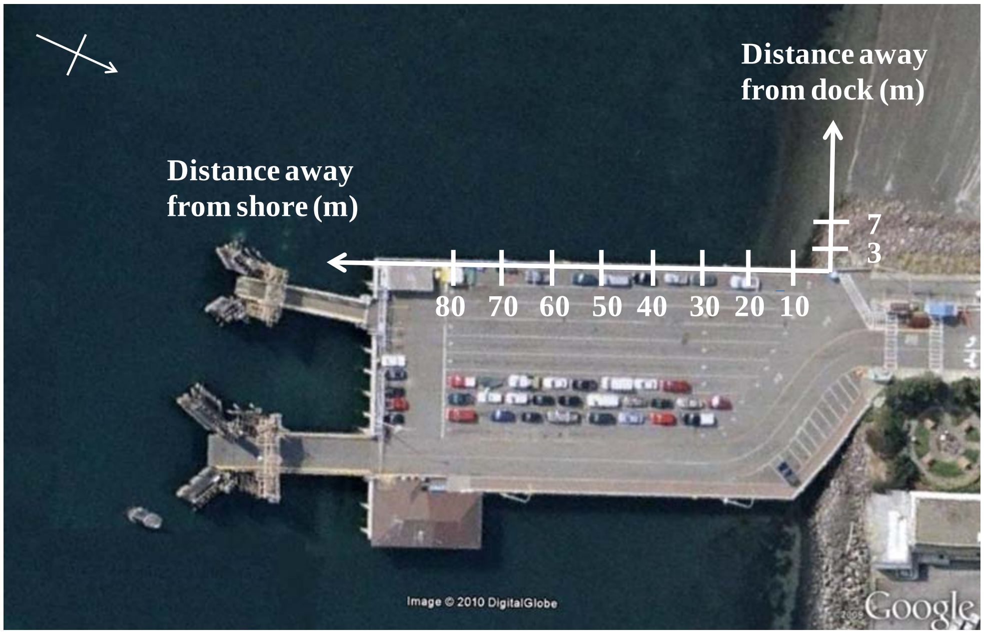


Figure 5: **Explanation of the terminology used in the text. "Distance away from the dock" represents the physical distance from the edge of the dock to the observed object; "Distance away from the shore" represents the physical distance between the observed object and the first terrestrial piling of the terminal.**

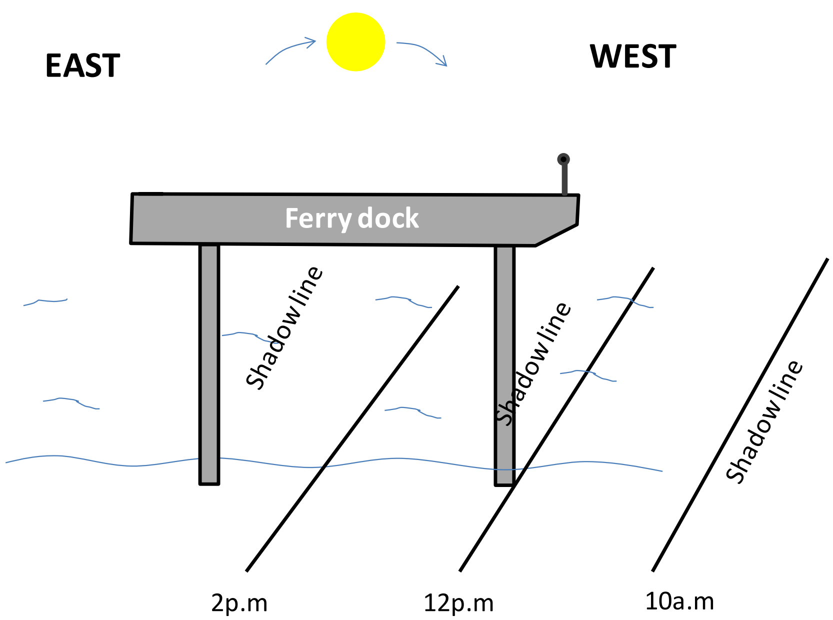


Figure 6: **Shadow line locations relative to the west side of the Port Townsend Ferry Terminal, at different times of the day**

Visual Survey: a Far Field Method

The visual survey was a simple method for studying fish abundance, distribution, and movement along the ferry terminal. It captured the broad view of fish shoal movement around the dock. For this study, we specifically combined two different measurement methods: (1) a visual count survey to evaluate the distribution of fish abundance along the dock, and (2) a fish shoal following survey to determine movement patterns of a fish shoal when close to the dock (Figure 5). However, this over-water method cannot ensure an exact identification of fish species (especially when they are swimming deeper in the water column) or capture precise fish movement and the fish distribution beneath the dock.

Counting

We conducted the visual count survey from above the dock between shore to 90 m away from shore (Figure 5), at 5-m distance increments, every 30 minutes; in 2008, surveys only extended 45 m away from the shore. The survey line is herein called a "transect." At each position on the transect, the observer counted the number of fish (categorical variable: 0-10, 11-20, 21-30, 31-40, 41-50, 51-100, 100-500, >500 fish), identified them (if possible), determined their size (in increments of 2.5 cm), their distance from the dock (-1 to 7 m) (Figure 5), and the time of observation. The observer stayed no longer than 5 seconds at each location to minimize fish movement between areas and to get a "snapshot" of the fish distribution at a specific time (to ensure observation independence). Recording was missing when the observer was doing snorkel surveys. Although each transect observation might not be independent from each other (if fish stay around the dock between two transects), the averaged transect abundances throughout the day could be considered to be independent between days.

Fish Following

We conducted the fish-following survey for 2 minutes from a position above the dock to summarize juvenile salmon behavior around the ferry terminal at different distances from shore (Figure 5). The observer followed a fish shoal; identified its species, number, and size (in 2.5-cm increments); and recorded changes in its swimming behavior. This mainly consisted of drawing the movement path of the fish and taking notes on its major turns, where distances from shore (between 0 to 90 m) and from the dock (-1 to 7 m) were written. Each observation was separated by at least 5 minutes and was chosen randomly but opportunistically (fish needed to be close enough to the dock to be seen) from 0900 to 1800 PDT. Fish counting and fish following were done alternatively from 0900 to 1800PDT. With such an observation method, there was always a risk of recording the same fish shoal twice or more without knowledge. However, shoals are not cohesive, and quite often they would have different companions after a while. Here we supposed that 5 minutes were enough for fish shoals to form a new group and hence show "new" behavior. We also assumed that any of the juvenile salmon shoal behavior interaction with the dock would not induce any learning process such as "local enhancement," "social facilitation," "guided learning," "observational conditioning," or "imitation" (Brown and Laland 2003, Laland et al. 2003). In other words, we assumed that each fish would act independently of its previous behavior.

Snorkel Survey: Close Field Method

As opposed to the general visual surveys, snorkel surveys do not provide a big picture of fish distribution but more detailed information on species, size, and vertical distribution of fish in the water column. Thus, snorkel surveys complement visual surveys. Snorkel surveys are effective whenever the visibility is above 2.5 m (Toft et al. 2007), which we routinely measured with a Secchi disk. The survey was done only in the afternoons in 2008 but was expanded to the mornings in 2009. The starting point of the snorkel survey transect path depended on the water current orientation (Figure 7). Juvenile salmon generally prefer swimming against the current, and their behavior is less affected when the fish are approached from behind (personal experience). We recorded the observation time, species, size (in 2.5-cm increments), number, depth (approximate depth in the water column), and position from shore (first to twelfth dock piling) of the aquatic animal encountered at each transect (from the second piling under the dock to 7 m away) (Figure 7). We kept a minimum distance of 1.5 m from the fish to preserve their natural behavior (Dionne and Dodson 2002). Juvenile salmon species identification was divided into four categories: (1) chum, (2) pink, (3) Chinook/coho, and (4) others. Chinook and coho are difficult to distinguish under snorkeling conditions; hence they were grouped together. The “others” category comprised all salmonids and trouts and was mainly used when identification was not successful.

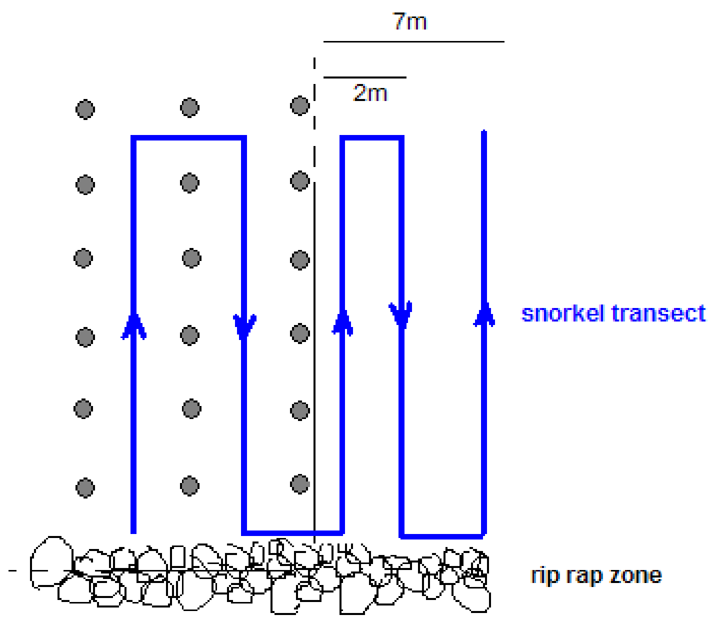


Figure 7: **Scheme of snorkel surveys at the Port Townsend Ferry Terminal. There were five transects parallel to the dock. From left to right: between the second and third under-dock pilings, between the first and second, then at the dock edge, at 2 m away from dock edge, and at 7 m away from the dock.**

Videography Data Collection

As described earlier, videography has the advantage of measuring precise behavior and thus allows more specific tests. An over-water video camera was installed at the edge of the dock, pointing downward perpendicular to the water surface to collect videos of juvenile salmon movement around the dock. The camera was set up at an average distance of 3 m from the water surface, covering an approximate field of view of 175 cm x 260 cm. The motion capture system was composed of a Sony TRV 33 camera (35-mm lens, FL=37mm, x1 magnification), a video acquisition tool (the surveillance software package PY software – Active Webcam), and a FireWire cable (IEEE1394) to transmit video to the computer. The video acquisition system was set up to record six frames per second in RGB color, with an image quality of 720*480 pixels. This setting enabled easy detection of any organisms measuring more than 5 cm. The camera was also equipped with polarized lenses to minimize light refraction from the water surface.

Video surveys were conducted between March and mid-August 2008, and we sampled from 0900 to 1800 PDT during neap tide, on sunny days, when the shadow was strongest; higher tide and brighter sun produced more marked light transition. We found neap tide to be preferable to spring tide because it was generally higher and more stable during the sampling time. The tide varied among the sampled days from 0.5 to 2.0 m MLLW (Mean Lower Low Water).

On each sampling day, conditions permitting, we took a minimum of four video samples of 30 minutes each to determine the combined effects of the presence of shadow at the edge of the dock (video from mid-day *vs* afternoon) and the effects of the artificial lighting system (ON *vs.* OFF).

Environmental Data Collection

In addition to the video data, we also collected some environmental data: current velocity, ambient illuminance, and underwater illuminance. Both underwater and over-water light levels were recorded with a lux meter (Hobo sensor, ONSET Computer Corporation). The underwater illuminance was measured with a buoy attached to the northwestern piling of the terminal (Figure 8), near the video filming location. In this study we considered only the light level at 10 cm under the water surface, which we supposed was a proxy for the light perceived by juvenile salmon swimming around the terminal. Snorkel surveys conducted around the study area also verified that juvenile salmon were generally swimming close to the water surface. Current velocity and direction were interpolated by using videos of floating objects. In this way we did not physically disturb any juvenile salmon behavior, and we determined a close approximation of the currents experienced by the juvenile salmon observed within the video frame. The measurement was conducted by following an object within the video clip and by dividing the linear distance between its entrance in the video frame until its exit with the corresponding travel time.

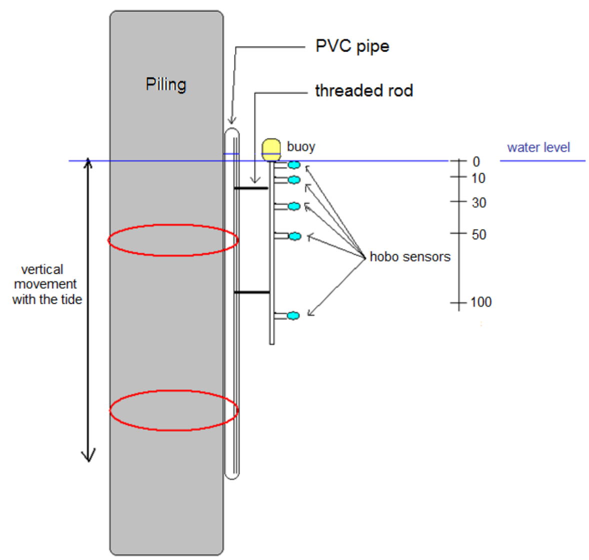


Figure 8: **Scheme of the underwater light measurement. Hobo sensors were attached to a PVC pipe at fixed distances from the water surface (cm) to measure light intensity at corresponding depths. Instruments were set up on the northwestern piling of the Port Townsend Ferry Terminal.**

Visual and Snorkel Surveys Data Analysis

For the visual counting survey, we first converted the count categories into numeric values corresponding to the median of each bin i.e., 5, 15, 25, 35, 45, 75, 200, and 500, respectively. By doing so, we were able to calculate the daily averaged juvenile salmon number, which we used as a surrogate for an index of juvenile salmon daily abundance. We then used these estimates to examine the distribution of juvenile salmon through time and space (at different distances away from shore) along the Port Townsend Ferry Terminal.

For the over-water fish following survey, we summarized shoal movement in terms of its (1) maximum displacement along the terminal's depth gradient, i.e., the closest and farthest distance from shore, (2) closest distance from the dock, and, (3) movement pattern divided into four categories: vertical, horizontal, U-turn, and complex movement. Vertical movement was usually associated with fish swimming against/with the current actively and passively, in an alternate manner. The horizontal movement usually described salmon shoals that followed the dock edge or the shadow line and moved back and forth from the shallow water to the deeper area. U-turn described fish that interacted back and forth with the dock. Finally, complex movement indicated a circuitous fish movement path. The analysis of the above movement characteristics thus provided indication about (1) juvenile salmon shoal movement range along the depth gradient, (2) its location relative to the dock edge, and, (3) its major movement pattern.

Finally, the snorkel transect was primarily designed to provide information about the under-dock fish distribution, abundance, species, and size information. We tested whether there was a significant size difference between the observed juvenile salmon in shallow water versus deeper water, for each year, by using Welch's t-tests (alpha level=0.05). We separated these two-year classes because the species compositions were quite different: 2008 was a juvenile pink year and 2009 was not. Moreover, we organized the observation into a contingency table (time of the day x location relative to the dock edge) to test the significance of difference in number of juvenile salmon outside the dock and under the dock, at different times of the day. We again performed the Welch's t-tests, and we applied a Bonferroni correction (alpha level = 0.05).

Videography Data Analysis

We used PY software (*www.pysoft.com*) to capture the video images of juvenile salmon interacting with the dock and saved them into the Windows Audio Video interleaved format (AVI) for later analysis with the NIH ImageJ image analysis software (*rsbweb.nih.gov/ij*). In this study, we used the plug-in Point Picker to manually track the movements of individual fish and extract two-dimensional coordinates along their path. Automatic tracking cannot work with noisy data such as those taken in natural environments (Myrick 2009), and for this reason, we tracked the fish manually. Fish position was determined every third of a second to avoid over- and under-sampling (Parrish and Edelstein-Keshet 1999, Lemasson et al. 2008). The movement data were then calibrated in real scale (cm per pixel) using data from a day of video calibration: a cubic cage of known dimension was put on water on a calm sunny day and videotaped from different distances above the water. The width of the cube was then measured in pixels (for each distance away from water) and compared to the real value to obtain the pixel per cm ratio. We assumed that this calibration measure was transposable to other days unless there were extreme differences in weather conditions. Finally, coordinates of fish movement path were exported into a tab-delimited text file to further process with the programming language R (*www.r-project.org*).

Extraction of Movement Patterns

Using the data derived from the videography of juvenile salmon movement described above, we adopted three different and relatively independent behavioral metrics of fish spatial use to measure the influence of shading and light treatment on juvenile salmon behavior around the edge of the terminal: a) juvenile salmon swimming directionality, which assumes that the more disrupted the fish (from the shadow or light) the more variable is its swimming orientation, hence a higher fish angular variance; (b) fish path shape, which assumes that the more disrupted the fish, the more complex movement it has around the dock; and, (c) fish closest distance from the dock edge, which assumes that the more disrupted the fish, the further it stays from the source of disturbance (shadow or light).

Path Shape: Perimeter / Area

This ratio is a pure spatial metric that measures the shape of the fish movement path. This metric answers the question, “How much area does the animal use and how does it move through that area?” The higher the perimeter-area ratio, the more movements it makes to cover the area, and the movement is more complex. This ratio is often used in landscape ecology (Riitters et al. 1995) to describe the complexity of a landscape feature.

$$\text{path shape}_i \quad \frac{\text{perimeter of the } i^{th} \text{ path}}{\text{convex hull area of the } i^{th} \text{ path}} \tag{1}$$

The convex hull algorithm (Bradford Barber et al. 1996) was used to calculate the area covered by the fish movement.

Swimming Angular Variation

The Swimming Angular Variation metric is calculated as the circular variance (Batschelet 1981, Fisher 1993) of the fish’s swimming orientation along their path, which we assumed to be a measure of the directionality of fish movement. Equation 2 describes the circular variance of the fish “i” movement path.

$$\text{circular variance}_i = 1 - \frac{1}{n\left(\sum_{j=1}^{n}(\cos\theta_{ij})^2 + \sum_{j=1}^{n}(\sin\theta_{ij})^2\right)} \qquad (2)$$

where n corresponds to the number of times the fish swimming orientation (θ_{ij}) is recorded along their path, and n varies from fish to fish. The calculation of variance is sensitive to the sample size n (Batschelet 1981, Wiens et al. 1997); hence, we kept only observations with minimal sample sizes of 10. The reference for the orientation (θ_{ij}) calculation was the ferry terminal edge line. This dispersion metric varies between [0;1], and the lower the value, the more directional is the fish swimming behavior..

Fish Distance from the Terminal Edge

This was a simple measure of the closest distance from the ferry terminal edge at which an individual fish was observed. This spatial metric gave an indication of how much the fish were avoiding the terminal, such that the greater the distance, the more disrupted the fish.

Analytical Methods

The final data extracted with the above method included 391 individual fish movement observations distributed among 141 shoals and 7 days (between June 12, 2008, and July 12, 2008). Ten factors were measured, and they were divided into experimental, environmental, and demographic categories (Table 2). Because we hypothesized that fish behavior around the terminal would be randomly variable within the grouping factors “date” and “shoal,” we decided to use a linear mixed effect model (Aitkin et al. 1986, Pinheiro and Bates 2000, Lai and Helser 2004, Bolker et al. 2009) as opposed to the multiple regression (MANOVA) or analysis of covariance (ANCOVA) to analyze the effects of these ten factors on juvenile salmon behavior. Several authors have pointed out the importance of simultaneously estimating within- and between-group errors when a grouped data design is considered. When the group effect is ignored, results can be erroneous (Aitkin et al. 1986, Lai and Helser 2004). We implemented the model using the package nlme in R (Pinheiro et al. 2009).

Table 2: Summary table of the variables used in this study. For variables of encoding factor (categorical), the number of categories has been indicated and for numeric factors, the mean and standard deviation have been given.

Variable	Description	Type	Encoding	Summary
Light_fac	Use of light (NO/YES)	Experimental (fixed effect)	Factor	Groups=2
Light_num	Light intensity at 5cm under water surface (lux)	Experimental (fixed effect)	Numeric	Mean=2.6e04; Sd=3.8e04
Shadow	Presence of shadow at the dock edge (NO/YES)	Experimental (fixed effect)	Factor	Groups=2
Date	Day when the observation was made	Environmental (random effect)	Factor	Groups=7
Current	Mean current velocity measured during the time of observation ($cm.s^{-1}$)	Environmental (fixed effect)	Numeric	Mean=5.5; Sd=4.6
Sunlight	Mean sunlight intensity (lux) during the time of observation	Environmental (fixed effect)	Numeric	Mean=1.8e05; Sd =3.5e04
Temperature	Mean water temperature during the time of observation (°C) at 5cm below the surface	Environmental (fixed effect)	Numeric	Mean=13.2; Sd=1.5
Shoal	The fish group to which the observation belongs	Demographic (random effect)	Factor	Groups=141
Shoal size	Number of fish within the observed shoal	Demographic (fixed effect)	Numeric	Mean=13; Sd=1.1
Fish size	Size of the observed fish (cm)	Demographic (fixed effect)	Numeric	Mean=6.2; Sd=0.9

Mixed-Effect Model

Two levels of random effects were inherent in the study design: (1) the shoal effect nested within (2) the date effect. We assumed that the shoal behavior differed among dates because some environmental factors, other than the ones measured in this study, could influence shoal behavior variability. In addition to the random effects, we also included the simplest form of correlation structure, a uniform correlation, between individuals within a shoal. Fish in a shoal are more cohesive and tend to show a higher degree of synchronisation than randomly placed fish (Shaw 1978, Partridge 1981, Couzin et al. 2002, Krause and Ruxton 2002).

The mixed effect model is written as follows:

$$y_{ijk} = \mu + \beta X + Date_i + Shoal_{ij} + \varepsilon_{ijk} \qquad (3)$$

with $Date_i \sim N(0, \sigma^2_{Date} I)$ $\quad Shoal_{ij} \sim N(0, \sigma_i^2 I)$ $\quad$ and $\quad \varepsilon_{ijk} \sim N(0, \sigma^2)$

where μ is the grand mean of juvenile salmon behavior, and β is the vector of coefficients to estimate associated with the vector of variables X (Eq.3) (i.e., light, shadow, temperature, current, sunlight, shoal size and fish size). σ^2_{Date} is a scalar matrix, σ^2_i is a diagonal matrix, and σ^2 is a variance-covariance matrix. i varies from [1:7] (there were seven days total), and $j \in [1{:}141]$ (total of 141 shoals). The within group individual number, k, varied from shoal to shoal.

Model Building, Selection and Assumption Check

The linear mixed effect model described above relied on the hypothesis that data are normally distributed. To ensure this condition, path shape was log transformed, and fish angular variance was square-root transformed. Data on fish closest distance were already approximately normally distributed. We used a backward model selection method in which we started with the most complex model that included all fixed and random effects and meaningful interaction terms. Then we eliminated the least significant fixed effect, one by one, by using marginal F-tests based on the Wald test (Pinheiro and Bates 2000). This procedure reduced the number of models to compare; some authors have criticized the mechanistic comparison of models exploring all parameter combinations

(Anderson and Burnham 2002). We finally selected the best model by using the marginal AIC model selection criteria (mAIC). We needed to be cautious about the routine use of AIC for model comparison. Several authors mentioned that depending on the objective of the study, different types of information criteria should be used for model selection: conditional AIC (cAIC) or marginal AIC (Vaida and Blanchard 2005, Liang et al. 2008, Greven and Kneib 2009). If the focus is on inferring a population parameter, as it was in our study case, then the authors acknowledged the use of mAIC; however, if the focus is on the group structure, then they recommended the use of cAIC (Vaida and Blanchard 2005, Liang et al. 2008, Greven and Kneib 2009). Models with the lowest mAIC values are considered the most parsimonious for representing the data. We concluded that a model was significantly better than another one only if there was a ΔmAIC of 5 or more. If several models performed equally well (ΔmAIC<5), we chose the model that included the explanatory variables “Light” and “Shadow” because the main purpose of this study was to test the effects of “Light” and “Shadow” on juvenile salmon behavior around the terminal. We used the restricted maximum likelihood (REML) method to estimate all model parameters. For model comparison between mixed effect models and non-random effect models (such as MANOVA) with the same fixed effect structures, we used the mAIC criteria, but we fitted the non-random effect model by using the “gls” function in R and compared it to the mixed effect model output by using the function “lme” in R (Zuur et al. 2009).

RESULTS

JUVENILE SALMON ABUNDANCE AT THE PORT TOWNSEND FERRY TERMINAL

All Salmon Species Combined Abundance Changes over Time

Using the general over-water counting survey data, we documented that juvenile salmon were mainly migrating around Port Townsend Ferry Terminal between mid-May to the end of July (Figure 9) during both 2008 and 2009, with a peak migration at the end of June in 2008 and two peaks in 2009 (mid-May and mid-June).

Species Abundance Changes with Time

The results of the snorkel surveys, which differentiated juvenile salmon species (Figure 10), indicated that 2008 observations were mostly dominated by juvenile pink salmon, and they outnumbered (over thousands sometimes) other juvenile salmon until mid-July. Juvenile chum abundance peaked at the end of May, whereas Chinook and coho showed up at the end of June and at the end of July.

In 2009 (a year juvenile pink were not abundant because adults almost exclusively return during odd years), chum salmon were the dominant salmonid observed between the end of May to mid-July. Chinook and coho were the most abundant species in mid-May and in mid-July.

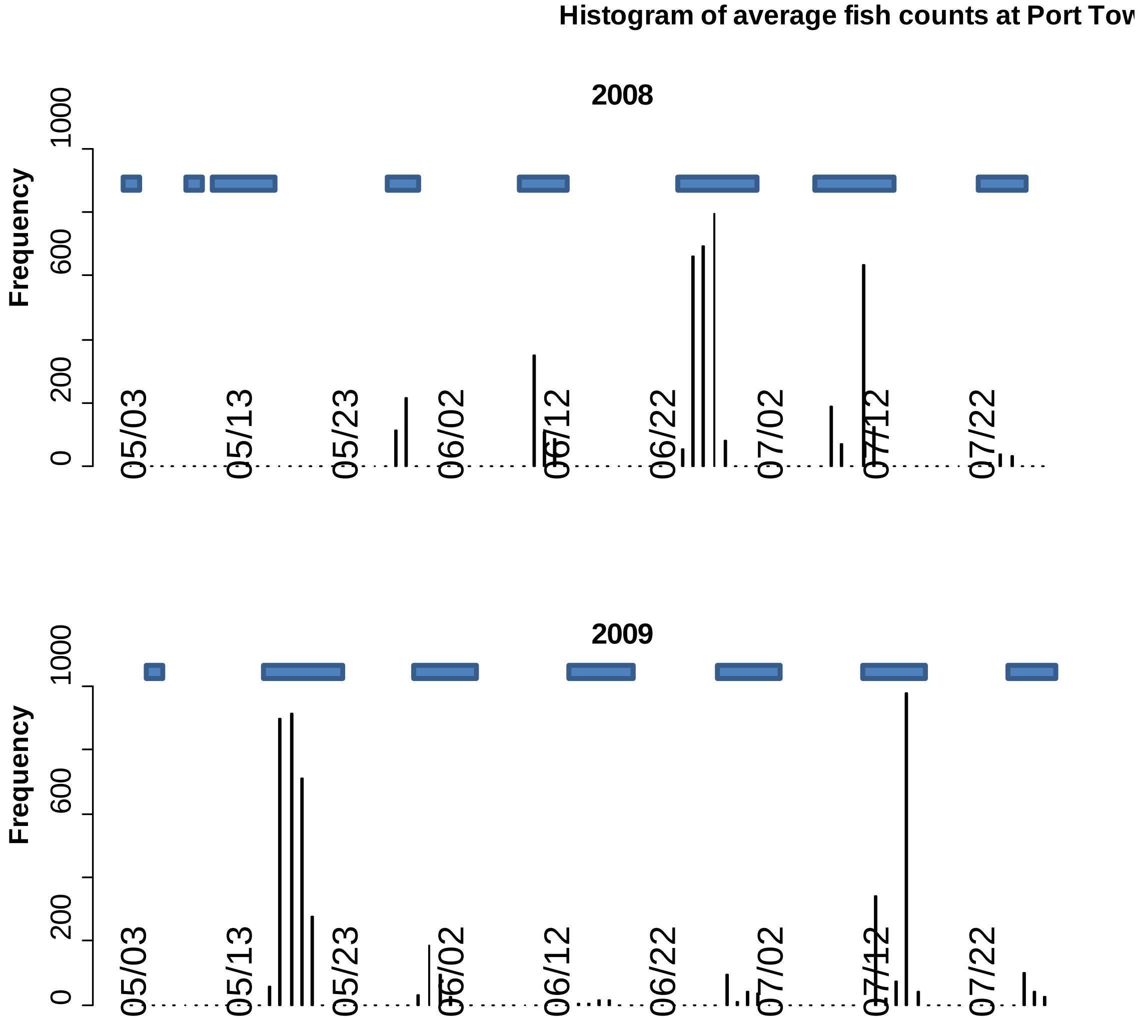


Figure 9: **Temporal variation in juvenile salmon abundance around the Port Townsend Ferry Terminal. Data were taken from the over-water counting survey at the west side of the dock. Each bar represents the average number of juvenile salmon observed among all transects within a day. The horizontal bar on top of the graph represents the sampling events. There were 25 days of surveying each year.**

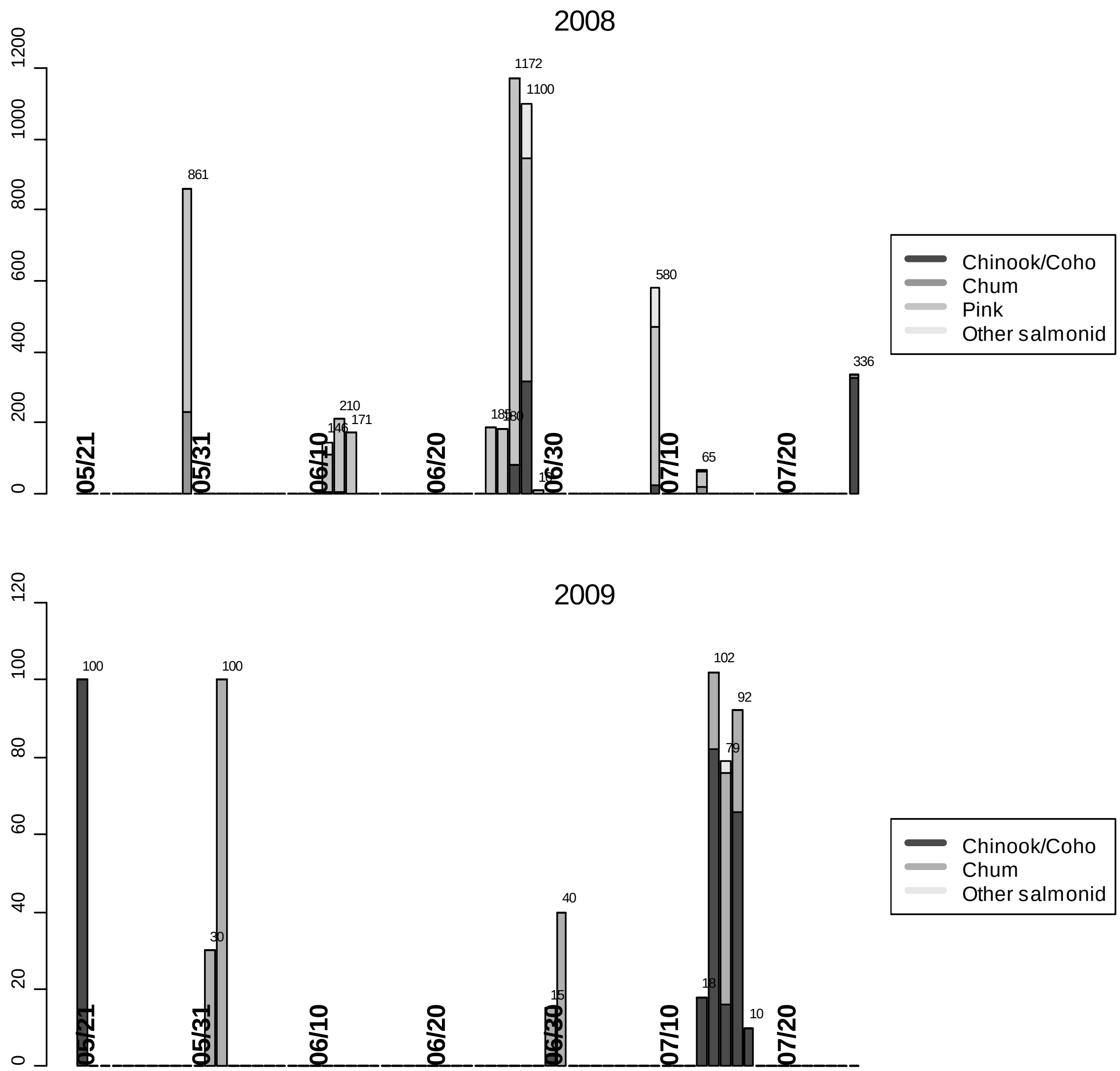
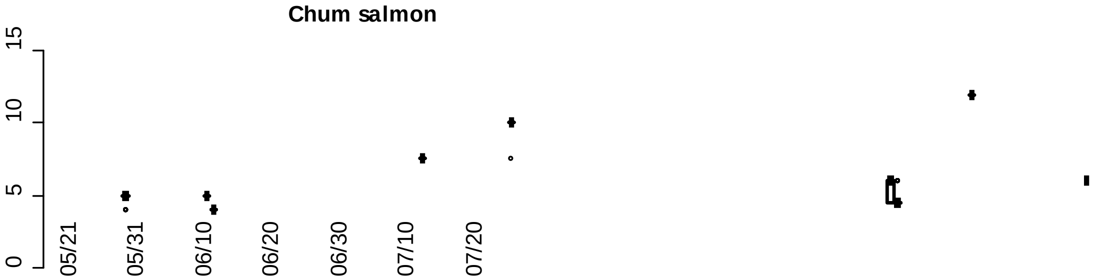


Figure 10: **Temporal variation of juvenile salmon abundance, by species, around the Port Townsend Ferry Terminal, in 2008 and in 2009. Each bar represents the averaged juvenile salmon counts observed during the snorkel surveys. The number above each bar represents the number of samples used to calculate this average.**

<u>Juvenile Salmon Size Changes by Species</u>

There was a clear increase in estimated juvenile salmon length throughout the migration (Figure 11) in both years, except for Chinook and coho. In 2008, the average chum salmon length was 5 cm at the end of May through June and increased to 7.5 cm in July before reaching 10 cm at the end of the month. The same pattern was observed for juvenile pink, which grew from 5 cm at the end of May through June to 7.5 cm at the end of June through July. Chinook and coho were generally bigger than chum and pink, since their first appearance around the terminal at the end of June (10 cm), but they did not show a clear trend in size: they generally measured 10 to 12.5 cm except 25 adult Chinook observed on July 9, 2008. In 2009, juvenile chum salmon measured about 5 cm at the end of May through June, increased up to 7.5 cm at the end of June, and averaged 10 cm at the end of July. Similar to 2008, Chinook and coho were generally bigger. At their first observation in mid-May they measured 15 cm, and they generally kept this size until the end of the observation period (Figure 11).

2008



12). Furthermore, the bimodal fish distribution detected from the over-water counting survey in 2008 (Figure 12) suggested that there might be two or more categories of juvenile salmon: (1) one that stayed in the shallower nearshore area and (2) another that stayed in deeper water (30-40 m). In 2009, the distribution of juvenile salmon was also multimodal, but the whole distribution was shifted to the deeper area. The shallower group of fish was mostly concentrated ~20 m from shore, whereas the deeper group was around 50 m to 70 m from shore. Only a few juvenile salmon were observed in shallow water (<10 m from shore) in 2009.

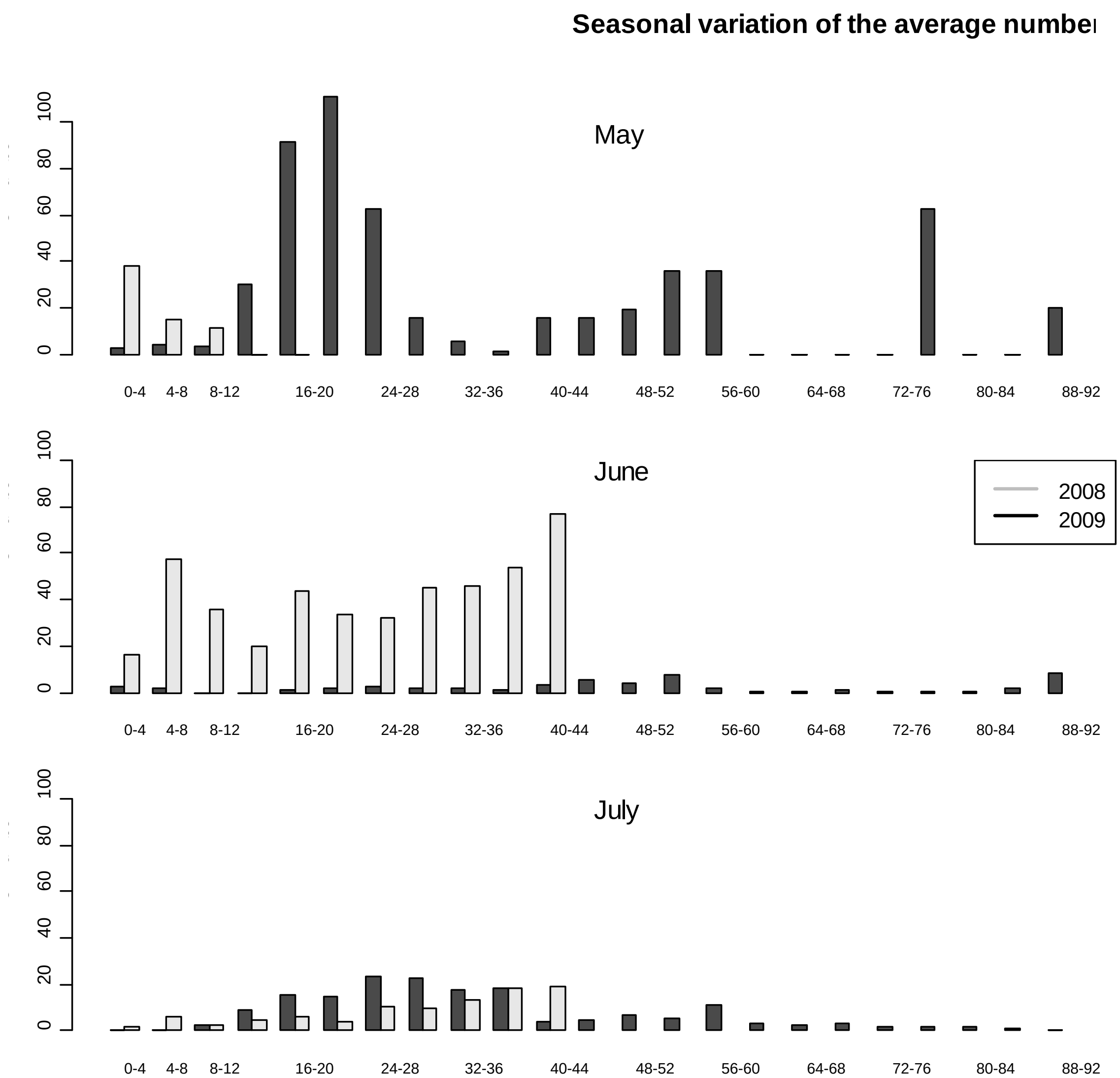
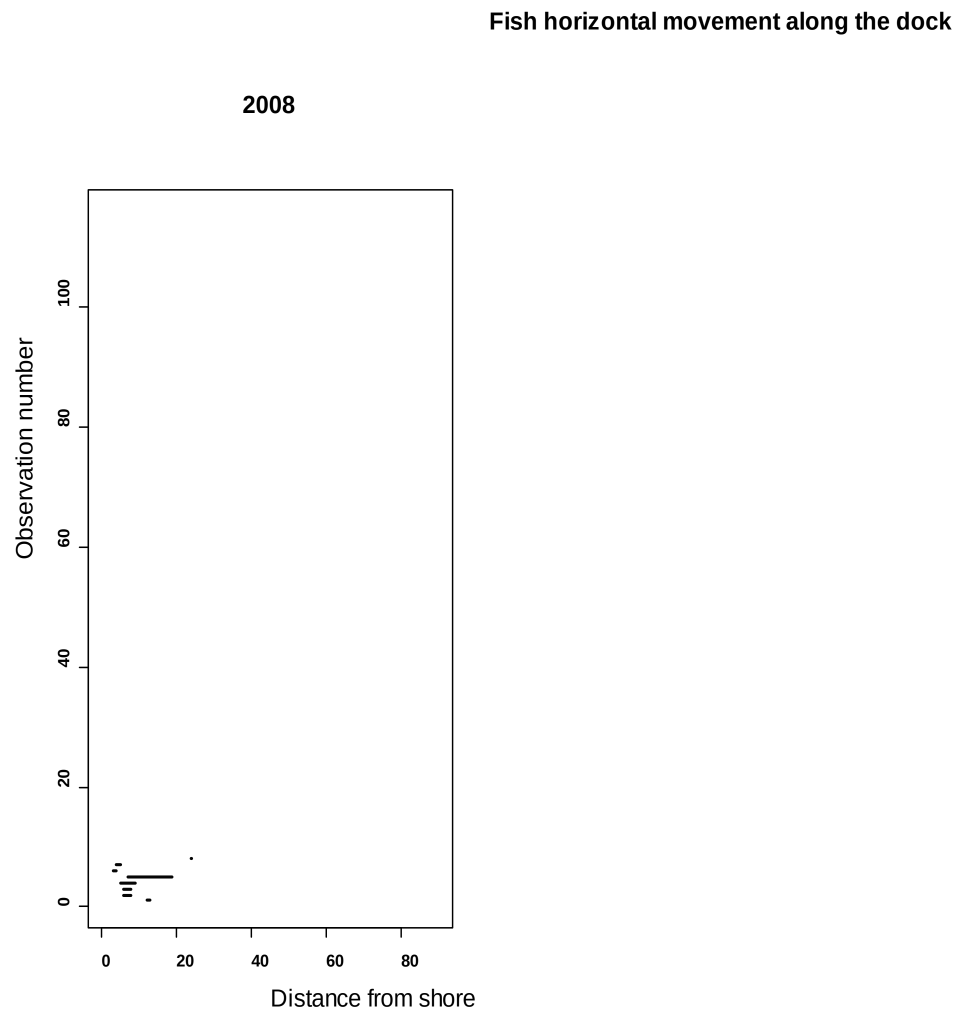


Figure 12: **Seasonal variation in the average number of juvenile salmon observed around the west side of the Port Townsend Ferry Terminal in 2008 and in 2009 as observed with the over-water method. The light grey color corresponds to the juvenile salmon distribution in 2008 (the observation stopped at 45 m from shore), and the dark grey color represents the salmon distribution in 2009.**

The over-water fish-following data also suggested that there were two categories of salmon distributions in both 2008 and 2009: shallower swimmers and deeper swimmers, with the group "boundary" at 17 m from shore. The term "boundary" is used here because almost no fish moved between the shallow and deep water areas delimited by this distance: in 2008, only eight juvenile salmon shoals among 113 crossed this boundary and only two among 58 crossed it in 2009 (Figure 13).



from shore, which was suggested by the fish-following survey. This size differentiation between the shallow and deeper water was mainly a result of the presence of pink and Chinook/coho salmon (see Figure 7 and Figure 14). In 2008, the proportion of pink salmon swimming in shallower water was greater than that in the deeper water, and conversely, the proportion of Chinook/coho was smaller than that in deeper water (Figure 14). Yet Chinook/coho were generally bigger than pink salmon throughout the season (Figure 7). In comparison, Chinook/coho salmon were more abundant in deeper water in 2009 (Figure 14), increasing the average juvenile salmon size as a consequence (Table 4).

Table 3: T-test results for the juvenile salmon size of the two swimming categories: deep water fish *vs* shallow water fish. Results were from the 2008 and 2009 snorkel surveys; *** p-value<0.001; ** p-value<0.01; * p-value<0.05; + p-value<0.1

Year	Groups	Difference	Std error	t value	p-value
2008	Deep-Shallow	1.02	0.062	16.48	2e-16***
2009	Deep-Shallow	2.12	0.416	5.09	5e-07***

Table 4: Juvenile salmon average size (cm) at different periods of the year and for the two swimming categories. Results were from the 2008 and 2009 snorkel surveys. NA indicates that no fish was observed.

2008	**May**	**June**	**July**
Shallow	NA	6.11	7.42
Deep	NA	7.18	8.18
2009	**May**	**June**	**July**
Shallow	NA	NA	10.21
Deep	7.74	6.02	12.33

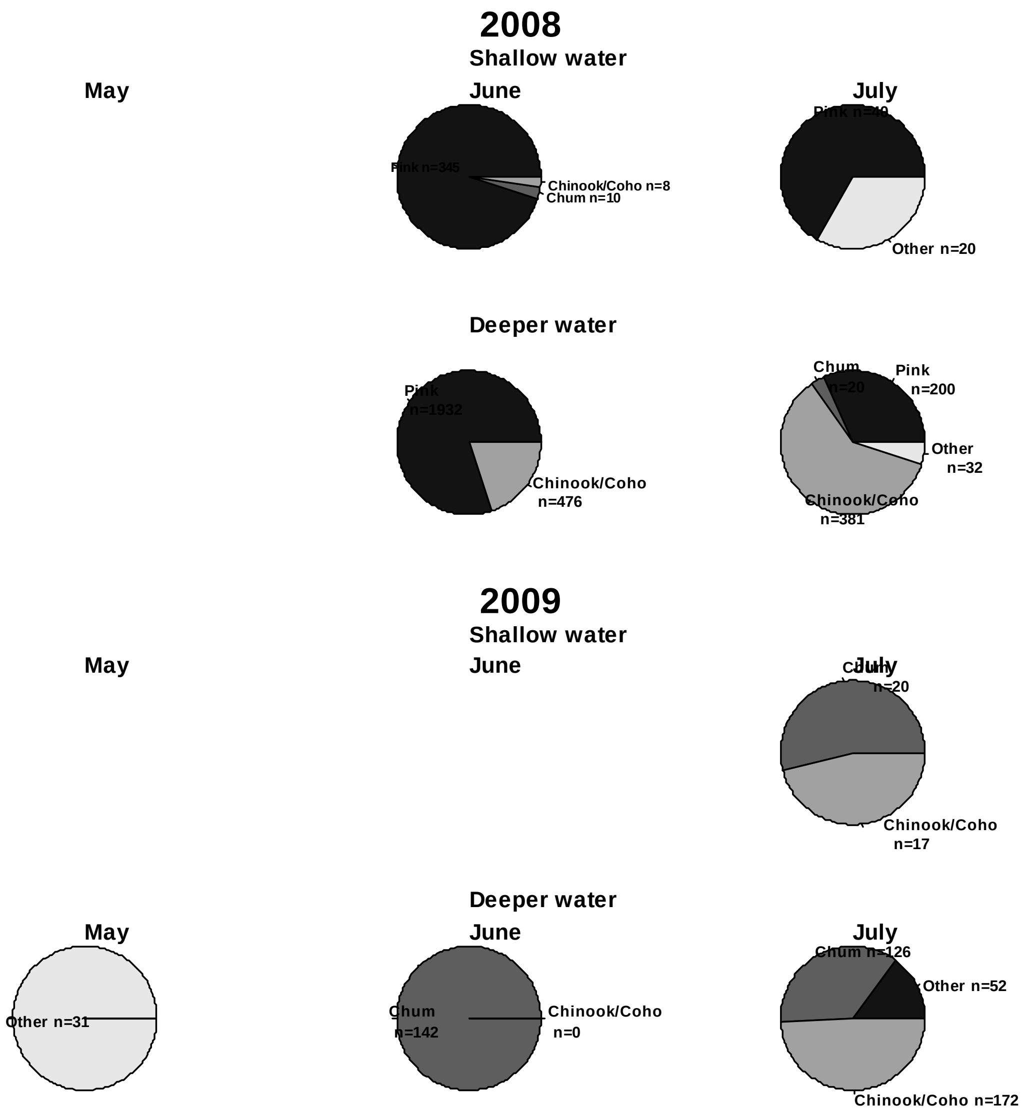


Figure 14: **Proportion of juvenile salmon species by depth category (shallow/deep) and time (May/June/July in 2008 and 2009) observed during the snorkel surveys. The numbers under the legend correspond to the sample size.**

JUVENILE SALMON PENETRATION UNDER THE DOCK

Relatively few juvenile salmon shoals were observed to swim directly under the Port Townsend Ferry Terminal. Of the 151 shoals observed in 2008, only 20 (13 percent) juvenile salmon shoals swam underneath the dock (Figure 15). This proportion stayed almost the same in 2009, when of 71 shoals, only eight (11 percent) were observed underneath the dock. This result was confirmed by the snorkel surveys conducted in 2009, when there were significantly fewer juvenile salmon under the dock, both during the morning (p-value=0.01) and in the afternoon (p-value=0.005) (Figure 16). Because of the few morning snorkel surveys conducted in 2008, this year was excluded from the analysis. Moreover, the snorkel survey indicated that all of the juvenile salmon shoals penetrating under the dock (in 2009) stayed at the first few meters from the dock edge, and none of them crossed the dock during the study time.

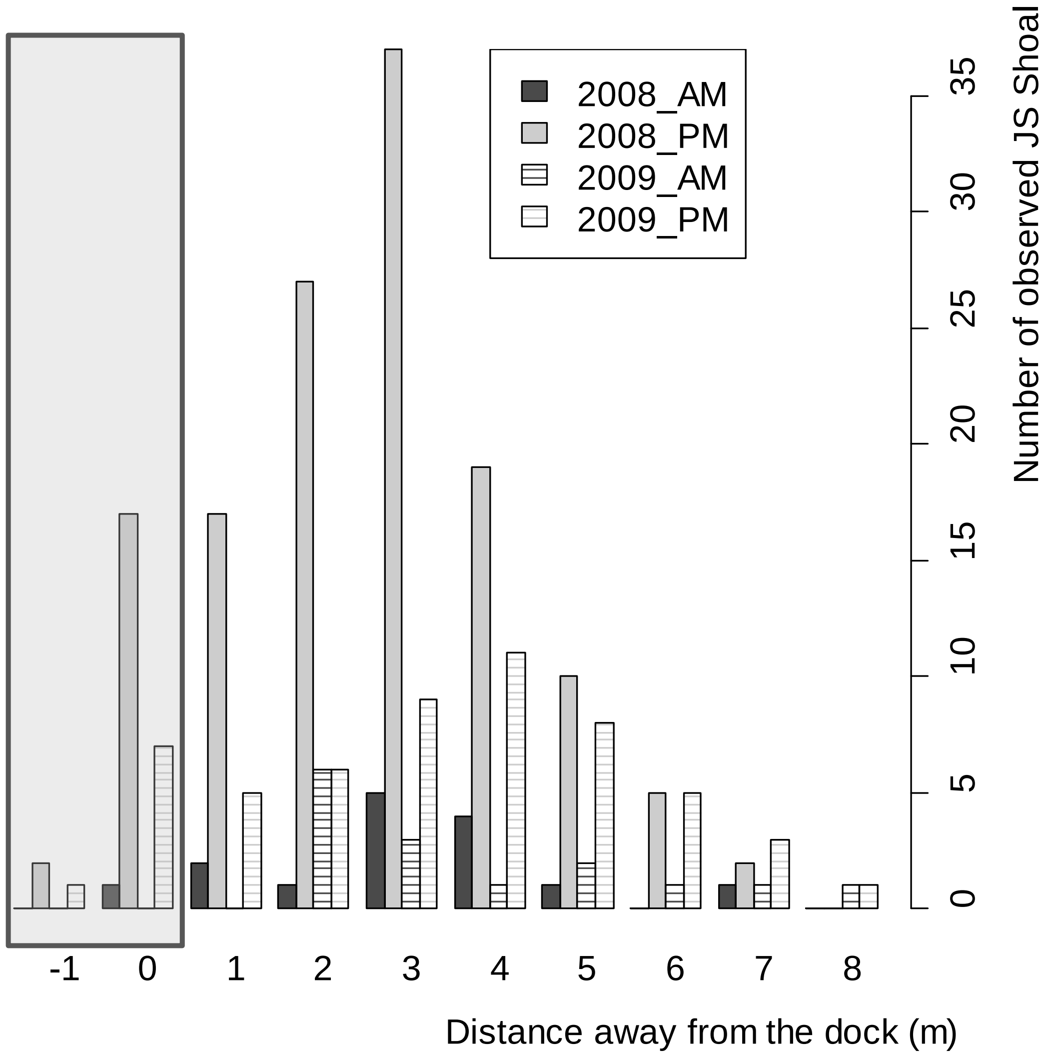
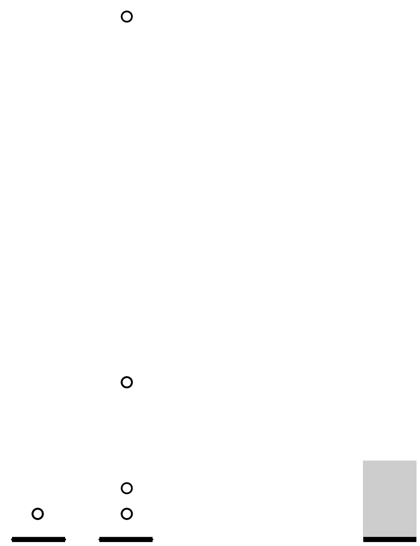


Figure 15: Frequency distribution of the number of juvenile salmon shoals observed at different locations and times of day relative to the edge of the Port Townsend Ferry Terminal. The grey box on the graph indicates the area under the dock. Data were taken from the over-water fish-following survey at the west side of the dock.



the first 20 m from shore (80 percent); on the other hand, juvenile salmon in 2009 were located under the dock at more diverse distances from shore (Figure 17).

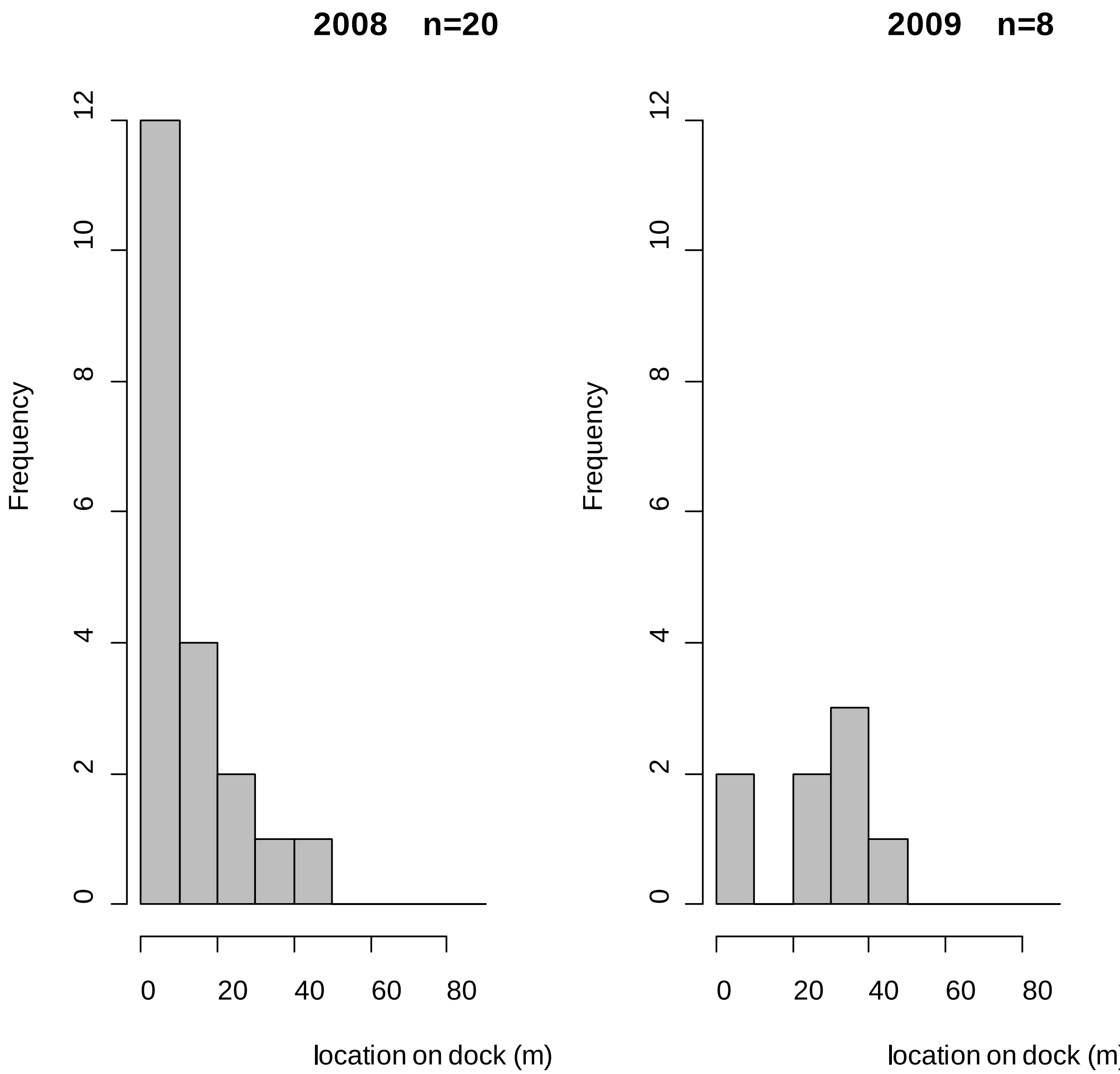


Figure 17: Distribution of juvenile salmon locations under the Port Townsend Ferry Terminal in 2008 and in 2009. Distances were calculated from shore. All but one juvenile salmon under-dock penetration occurred during the afternoon. Data were taken from the over-water fish-following survey.

JUVENILE SALMON MOVEMENT AROUND THE TERMINAL

Juvenile salmon movement around the dock was different between 2008 and 2009. Juvenile salmon did more U-turns than the other types of movement in 2008; this accounted for 51 percent of the total movement types (Figure 18). However, in 2009, juvenile salmon movement was more diffuse: each movement type represented about 20 to 30 percent of the total (Figure 18).

Juvenile salmon also differed depending on the group they belonged to (shallower swimming *vs* deeper swimming). Shallow swimming fish in 2008 mostly did U-turns (62 percent) as opposed to deeper swimming fish, which mostly demonstrated horizontal movement along the dock and did U-turns. In 2009, horizontal and complex movements were the most common patterns for salmon swimming in shallow areas as opposed to vertical and complex movement for deeper water fish.

Fish movement around the dock

in Figure 19). However, no definitive conclusion should be drawn from these simple graphic observations, and rigorous statistical tests are necessary.

Path Shape

None of the eight fixed effects measured in the study (see Table 2) significantly explained the variation of juvenile salmon path shape. The best model was therefore the mixed effect model, which included only the intercept (=grand mean) (M1).

$$\log(\text{path\_shape})_{ijk} = \mu + \text{Date}_i + \text{Shoal}_{ij} + \varepsilon_{ijk} \quad \text{(M1)}$$

This model (M1) improved the fit to the data in comparison to the basic null model (model M1_1 in Table 5) and effectively reduced the amount of residual variability by attributing some of it to the date and shoal random effects (the value of $\sigma_{Residual}$ is lower for M1 than M1_1 in Table 5).

Table 5: Model comparison results for fish path shape (NA means that there is no estimation of the parameter)

Model #	Model description	Df	σ_{Date}	σ_{Shoal}	$\sigma_{Residual}$	AIC
M1	μ+ Date$_i$+Shoal$_{ij}$+ε_{ijk}	11	0.14	c(0.29, 0.83, 0.45, 0.55, 1.8e-08, 0.17, 0.37)	0.47	663
M1_1	μ+ ε_{ijk}	2	NA	NA	0.63	754

Moreover, the within-group correlation was low (rho=0.03). A high correlation value would indicate similarity of movement (in terms of the behavior metric of interest) between individuals within a group, and low correlation would indicate almost independent, non-similar movement.

To summarize, individual variation of path shape was not significantly explained by any experimental (light and shadow), environmental, or demographic factors measured in this study.

Swimming Angular Variance

The presence of shadow and the use of light were the only factors that significantly influenced the variation of Swimming Angular Variance. All other covariates (environmental and demographic factors) did not significantly influence the directionality (Swimming Angular Variance) of juvenile salmon movement. The final model (M2) was described as follows:

$$\sqrt{\text{angular variance}_{ijk}} \qquad a_0 \ \text{Light\_fac} \quad a_1 \ \text{Shadow} \quad a_2 \ \text{Light\_fac Shadow} \quad \text{Date}_i \quad \text{Shoal}_{ij} \quad {}_{ijk} \qquad \text{(M2)}$$

where "Light_fac" and "Shadow" are binary variables that take a value of 1 when the light is ON and the shadow is present at the dock edge, respectively; otherwise, they take a value of 0.

We also tested the model with light as a continuous variable (M2_2; "Light_num" in Table 6), but the model fit to the data was worse than with M2 (higher AIC value) (Table 6).

Table 6: Model comparison results for swimming angular variance (NA means that there is no estimation of the parameter)

Model #	**Model description**	**Df**	σ_{Date}	σ_{Shoal}	$\sigma_{Residual}$	**AIC**
M2	$\mu+a_0*\text{Light\_fac}+a_1*\text{Shadow}+a_2*\text{Light\_fac}*\text{Shadow}+\text{Date}_i+\text{Shoal}_{ij}+\varepsilon_{ijk}$	8	0.08	c(0.12, 0.05, 0.16, 0.08, 0.21, 0.11, 0.08, 0.17)	0.18	-143
M2_1	$\mu+a_0*\text{Light\_fac}+a_1*\text{Shadow}+a_2*\text{Light\_fac}*\text{Shadow}+\varepsilon_k$	5	NA	NA	0.21	-94
M2_2	$\mu+a_0*\text{Light\_num}_k+a_1*\text{Shadow}+a_2*\text{Light\_fac}*\text{Shadow}+\text{Date}_i+\text{Shoal}_{ij}+\varepsilon_{ijk}$	8	0.11	c(0.08, 0.05, 0.13, 0.08, 0.23, 0.13, 0.09, 0.17)	0.19	-101

As with the Path Shape metric, the random effects of dates and shoals significantly improved the fit of the model to the data in comparison to the basic MANOVA (M2_1) (Table 6), and the within-group correlation level was low (rho=0.15).

Juvenile salmon generally had an angular variance of 0.27 (μ^2, Table 7) (not very directional movement) around the dock under control conditions: when the shadow was not present and when the light was OFF. The positive coefficient associated with the light effect (a_0) means that the use of light increased the Swimming Angular Variance in comparison to the control conditions: fish were more disturbed. However, when a shaded edge of the dock was artificially illuminated (i.e., shadow contrast was attenuated), the angular variance decreased (a_2): less disturbed. Furthermore, Swimming Angular Variance was not generally influenced by the presence of shadow at the dock edge (a_1 was not significantly different from 0).

Table 7: **Estimates of the fixed-effects parameters obtained by fitting the model M2 to the swimming angular variance data. The Bonferroni correction was applied to test the significance of each coefficient; *** p-value<0.0003; ** p-value<0.003; * p-value<0.017; + p-value<0.03**

Parameters	Value	Stdev	DF	t-value	P-value
Grand mean, μ	0.52	0.04	267	13.03	0.0000***
Light, a_0	0.13	0.04	114	3.29	0.0012**
Shadow, a_1	-0.03	0.05	114	-0.02	0.5116
Light*Shadow, a_2	-0.15	0.06	114	-2.54	0.0154*
σ^2_{date}	0.08				
σ^2_{shoal}	c(0.12, 0.05, 0.16, 0.08, 0.21, 0.11, 0.08, 0.17)				
σ^2	0.18				
Rho	0.15				

To summarize, the "use of light" and "the presence of shadow at the dock edge" were the only factors that significantly influenced the directionality of juvenile salmon movement around the terminal.

Fish Closest Distance from the Dock Edge

As found with the earlier metrics, Light and Shadow were the only variables that explained with significance the variability in closest distance of observed juvenile salmon to the dock edge.

$$\text{Closest\_point}_{ijk} \quad a_0 \ \text{Light\_fac} \quad a_1 \ \text{Shadow} \quad a_2 \ \text{Light\_fac Shadow} \quad \text{Date}_i \quad \text{School}_{ij} \quad _{ijk} \qquad \text{(M3)}$$

where "Light_fac" and "Shadow" are binary variables (see results from Fish Angular Variance).

As with the other response variables, the fit of the mixed effect model was better than that of the regular MANOVA model (M3_1) and the model with the variable light, as the continuous variable (M3_2) was significantly worse than the model M3 (Table 8).

Table 8: Model comparison results for fish closest distance to the dock edge (NA means that there is no estimation of the parameter)

Model #	Model description	Df	σ_{Date}	σ_{Shoal}	$\sigma_{Residual}$	AIC
M3	$\mu+a_0$*Light_fac+a_1*Shadow+a_2*Light_fac*Shadow+ $Date_i$+ $Shoal_{ij}+\varepsilon_{ijk}$	14	9.97	c(10.85, 31.88, 28.31, 8.86, 6.67, 29.43, 18.30)	22.95	3680
M3_1	$\mu+a_0$*Light_fac+a_1*Shadow+a_2*Light_fac*Shadow+ ε_k	5	NA	NA	30.51	3789
M3_2	$\mu+a_0$*$Light\_num_k$+a_1*Shadow+a_2*Light_fac*Shadow+$Date_i$+ $Shoal_{ij}+\varepsilon_{ijk}$	14	12.0	c(11.8, 35.4, 29.7, 16.1, 2.91e-05, 31.4, 19.7)	21.7	3724

The final model, M3, indicated that the mean distance of a juvenile salmon from the dock edge was 68 cm (μ), and this distance increased by 39 cm when shadow was present at the dock edge (a1) (Table 9): juvenile salmon were more disturbed. However, when light was applied as a treatment in the presence of a distinct shadow, fish were actually closer to the dock edge (a2) (less disturbed), and the average distance from the dock was 85.3 cm ($\mu+a_1+a_2$) (see Table 9). Note that this last distance was still higher than the average juvenile salmon closest distance under the control condition. The within-group correlation level was also low (rho=0.08).

Table 9: The estimates of the fixed-effects parameters obtained by fitting the model M3 to the fish closest distance data. The Bonferroni correction was applied to test the significance of each coefficient; *** p-value<0.0003; ** p-value<0.003; * p-value<0.017; + p-value<0.03

Parameters	**Value**	**Stdev**	**DF**	**t-value**	**P-value**
Grand mean, μ	67.91	5.53	267	13.03	0.0000***
Light, a_0	2.28	5.71	114	3.29	0.6902
Shadow, a_1	38.74	6.21	114	-0.02	0.0000***
Light*Shadow, a_2	-21.34	8.87	114	-2.54	0.0177+
σ^2_{date}	9.97				
σ^2_{shoal}	c(10.85, 31.88, 28.31, 8.86, 6.67, 29.43, 18.30)				
σ^2	22.95				
rho	0.06				

To summarize, the “use of light” and “the presence of shadow at the dock edge” were again the only factors that significantly influenced the distance of juvenile salmon to the terminal edge.

DISCUSSION

There are numerous speculations about and contradictory findings regarding juvenile salmon interaction with large over-water structures. The results of this study at the Port Townsend Ferry Terminal can update and clarify these.

HOW DO JUVENILE SALMON DISTRIBUTE ALONG LARGE OVER-WATER STRUCTURES? IS THERE ANY PATTERN TO THEIR RESPONSE TO THE OWS AND LIGHT SHADING?

We found a bi-modal distribution of juvenile salmon along the Port Townsend Ferry Terminal: juvenile salmon that stayed in the shallow water and those that stayed in deeper water. Most of the time, these two migrating groups swam independently of each other without any exchange. Only rarely did shoals swim back and forth between these two groups. Two explanations might account for these findings.

The first possibility is a size-dependent swimming organization: smaller juveniles occupy the shallow water and bigger ones swim in deeper water. In 2008, smaller juvenile pink made up most of the shallow water group and larger juveniles (Chinook/coho, chum) the deeper group. This finding is also supported by observations made by Heiser and Finn (1970), who found that smaller juvenile pink and chum were reluctant to leave the shoreline areas (thus staying in shallower water) as opposed to larger ones that ventured offshore into deeper water. Simenstad et al. (1982) and Toft et al. (2009) also mentioned that small juvenile pink and chum chose to swim in a shallow, nearshore habitat. Additionally, at the Port Townsend Ferry Terminal, the two groups (shallow *vs.* deep) were delimited by an approximate “boundary line” at 17 m from shore, where depth increased suddenly.

A second explanation is that a critical resource, such as prey or refuge, may cause separation of fish into two groups. In fact, the boundary line at 17 m from shore is also the transition zone from eelgrass to the sandy bottom. Although we do not have any data to support this idea, it is possible that the eelgrass-sand habitat boundary represents two different sources of prey for juvenile salmon. This resource and habitat partitioning happens quite often in stream and estuarine ecologies, where different fish species selectively separate among habitat or prey resources (Ross 1986). Of these two explanations, the second one remains more uncertain.

DO JUVENILE SALMON AVOID SHADING BENEATH OWS?

As described in the literature, we also documented that juvenile salmon avoided and moved a distance away from the shading, staying on the bright side of the shadow edge, during early morning periods. Morning hours were the only time that we were able to evaluate the effects of dock shading because the effects of dock structure and shadow were confounded the remainder of the day. Although we did observe a few juvenile salmon swimming back and forth across the shadow line, we did not observe any factors that could explain this difference in behavior.

DO JUVENILE SALMON PENETRATE UNDER OWS?

In this study, juvenile salmon seldom swam underneath the Port Townsend Ferry Terminal but stayed around 2 to 5 m away from the dock, even in the afternoon when the shadow line moved underneath the dock. This strong behavioral response suggests that the terminal structure itself, in addition to the shadow, prompts avoidance behavior by migrating juvenile salmon. This result is new, as the structural effects of OWS have been often neglected, or at least confounded, in past observations. The few occasions when juvenile salmon did swim under the dock in either 2008 or 2009 were in the afternoon (all but one), and they penetrated only a few meters inside the dock edge. In 2008, most of the fish swam underneath the dock from the shallower area (<17 m), whereas in 2009 they penetrated from more diverse locations along the face of the dock. However, there are limitations to this interpretation because we surveyed only during high tides, and at only one OWS, a ferry terminal; the effects of dock structure on juvenile salmon behavior at low tides, and at different OWS, could be totally different. Southard et al. (2006) observed that some juvenile salmon swam under the Edmonds Ferry Terminal during low tides. This difference could be the result of the cumulative effects of tide level, diminished or no shadow effect, and dock height and size (the Edmonds terminal [24 m] is slightly narrower than Port Townsend Ferry Terminal [36 m]).

To conclude, juvenile salmon did not swim under the Port Townsend Ferry Terminal during high tides, but results should not be generalized to low tides and to other OWS without further investigation.

HOW DO JUVENILE SALMON BEHAVE WHEN ENCOUNTERING THE DOCK? DO THEY MOVE AROUND THE DOCK PERIMETER OR DO THEY STAY AROUND IT?

Juvenile salmon stayed away from the ferry terminal structure and shading. Rather than swimming under the dock, juvenile salmon shoals made four major types of movements along the dock: (1) U-turn, (2) horizontal movement, (3) vertical movement, and (4) complex circuitous movement. In 2008, U-turns were the most common behavior in shallower water and horizontal movement was most prevalent in deeper water. In 2009 however, juvenile salmon shoals demonstrated more diverse swimming patterns. U-turns usually indicated that juvenile salmon were likely staying close, interacting back and forth with the ferry terminal. Horizontal movement, on the other hand, indicated that juvenile salmon swam along the perimeter of the dock (toward shallow water or offshore). As a reminder, pink salmon was prevalent in 2008, therefore this U-turns can potentially be a characteristic of juvenile pink salmon behavioral interaction with the ferry terminal.

Juvenile salmon were on occasion found swimming in a mixed shoal with other species of fish, such as Pacific herring. In late May to early June 2009, mixed shoals of juvenile salmon and herring were observed to originate from the open water and interact with the dock. However, we did not have enough data to make conclusions about the significance of that behavior.

To summarize, juvenile salmon were generally found milling around the dock, and only a few swam offshore along the perimeter of the dock. However, their behavior was potentially different when they formed a mixed shoal with other fish species.

DO OWS CAUSE DELAY IN JUVENILE SALMON MIGRATION?

Our findings suggest that some juvenile salmon species, such as juvenile pink salmon, experienced several hours of migration delay under certain environmental conditions. In 2008, small pink salmon (5 to 7.5cm) were the main species swimming in the shallower water and probably accounted for most of the observed U-turn movements; this might also explain why we did not see as many U-turns in 2009. If these juvenile pink salmon had stayed throughout the observation period in shallow water (Heerhartz, personal communication), we would have observed the same shoals interacting back and forth during the whole diurnal study period (0900-1800PDT) without passing the dock. Although not mentioned in this report, two schools of pink salmon (10-20 individuals) were followed for respectively 45min and 1hour with a snorkel survey and they indeed interacted back and forth with the dock, in the shallow nearshore water. These conditions would produce a potential migration delay for small juvenile pink salmon of more than nine hours a day, per ferry dock encounter, during high tide period, on a sunny day. However, we did not analyze fish movement after 1800PDT, and as mentioned by some authors, juvenile salmon would be likely to swim underneath the OWS as the light-dark transition attenuated (Southard et al. 2006). However, caution should be taken because results may not be applicable to all OWS because they are not built in the same configuration, nor may they be applicable to all days during the migration season or to species other than juvenile pink salmon.

To summarize, there is a high probability that small juvenile pink salmon experienced more than nine hours of migration delay per dock encounter, during high tides, on a sunny day. Unfortunately, there are no data to allow generalization of this finding to other OWS and other salmon species.

OTHER INTERPRETATIONS OF JUVENILE SALMON INTERACTION WITH OVER-WATER STRUCTURES

Ratté et al. (1985) pointed out that juvenile salmon appear to prefer swimming near OWS for cover, but we found no empirical basis for that interpretation in this study. Perhaps if the OWS is small enough to allow light to penetrate under it, hence limiting shading effects and the confusion of juvenile salmon, juvenile salmon may swim around OWS; however, if the structure is as large as a ferry terminal, juvenile salmon will probably avoid it .

Some authors have also found a higher abundance of juvenile salmon near some OWS than farther away from them and have hypothesized that they were probably attracted to the OWS (Bax et al. 1979, Bax et al. 1980). However, our findings suggest that this phenomenon is more likely an artifact of fish aggregation around the edge of the OWS as a result of their cumulative interaction with the dock.

EFFECTS OF LIGHT AND SHADOW ON JUVENILE SALMON INTERACTION WITH FERRY DOCKS

Overall, taking all variables into account, this study showed that the presence of shadow generally caused juvenile salmon to avoid getting close to the Port Townsend Ferry Terminal. This result was confirmed by snorkel and visual observation surveys that were conducted at the same locations throughout the study period (Chap. 1). Only a few salmon shoals swam under the dock, but most of them stayed at a distance of 2 to 5 m from the dock. They generally stayed away from the over-water structures by making U-turns or moving non-directionally. Heiser and Finn (1970) and Weitkamp (1982) also observed that most juvenile salmon did not penetrate under docks. This result conforms to what we know about juvenile salmon vision, that their eyes cannot adjust quickly to sudden extreme light level changes, and they usually need more than 30 minutes to adapt their vision from light to dark (Brett and Ali 1958, Ali and Hoar 1959). This temporary "blindness" could make them more susceptible to predators and physical factors (such as drift by the current), which may explain why they stay in the acclimated light environment and not venture into a dark environment (Anderson et al. 1988). This acclimation period is not specific to fish, as humans also need some time to acclimatize to sudden light changes (Hecht et al. 1937).

In addition to avoiding the dock's shading, juvenile salmon also appeared to avoid the over-water structure itself. Shoals of juvenile salmon observed in this study did not swim under the dock during daylight hours even when the shadow line moved some distance beneath the terminal. The average fish distance from the dock edge during the study period (midday and afternoon) was 68 cm, and additional snorkel surveys around the terminal confirmed that significantly fewer fish were under the dock than outside the dock throughout the day.

Importantly, the application of light did not have just one effect on juvenile salmon behavior. Illumination from fiber optic lights under the dock mitigated the dock shading effects on juvenile salmon only when it reduced the light contrast underneath the over-water structure; then the fish swam closer to the dock in a more directional swimming pattern. However, when fiber optic-transmitted light illuminated a non-shaded area, the migratory behavior of juvenile salmon was more disrupted, their movement became less directional, and they stayed farther away from the dock. This result agreed with observations made by Southard et al. (2006) that juvenile salmon swam under the dock during low tide when the contrast between under-dock light and the ambient environment was lower.

There are some factors to bear in mind when considering the inferences from this study. The first factor is the size of the over-water structure involved in conducting these observations and experiments. When juvenile salmon encounter smaller over-water structures, they may be able to perceive light through the shaded area. In that case, they may be less disturbed by the shadow and may actually migrate under the dock and shade. In freshwater ecosystems, these shade seeking behaviors are usually associated with UV avoidance (Kelly and Bothwell 2002, Holtby and Bothwell 2008), predator avoidance, or prey searching (Quinn 2005). However, no studies have determined the size threshold of marine over-water structures at which changes in juvenile salmon behavior may occur.

The second factor involves the light intensity produced by the fiber optic lighting system. Light intensity decreased rapidly with distance from the source (the lens at the end of the fiber optic cable). For example, by the time light reached the water surface 1.0 m away, it was only about 1/200 of its original intensity. As a result, on a sunny day of 200,000 lux, only about 1,000 lux reached the water surface at 1.0 m. The juvenile salmon behavioral response that we observed might have been stronger or more significant if a more powerful lighting system had been available.

Finally, the light quality (light spectrum) may also have influenced the juvenile salmon responses to the artificial light. Juvenile salmon vision is not only limited by light intensity but also by its quality (radiance profile). Fish cannot see every color in the full spectrum, and their color sensitivity changes with growth and adaptation to new environments. For example, salmon fry are more sensitive to lower bands in the light spectrum (such as UV and green) (Browman and Hawryshyn 1994, Flamarique and Hawryshyn 1996), but as they grow and smoltify, they become more sensitive to blue light and lose their UV vision (Cheng and Flamarique 2004, Cheng et al. 2006). The UV sensitivity of salmon fry is often associated with their freshwater life history, where green color is prevalent, and to their planktivorous lifestyle, as they forage around the water surface with more abundant UV rays (Cheng and Flamarique 2004). On the other hand, blue color is characteristic of deeper marine water and is also associated with the piscivorous life history and ecology of larger salmon juveniles. Unfortunately, we were unable to test the effects of different light quality because of limited resources and the fish observations available to us in this study.

RECOMMENDATIONS

SHOULD THE FIBER OPTIC LIGHTING SYSTEM BE USED?

The Sunlight Direct fiber optic lighting system we tested was a new, promising technology for transmitting natural light underneath the ferry terminal. Its solar tracking system was supposed to maximize light collection and transmit natural light underneath the dock. However, this study demonstrated that, as designed and installed, its use in a natural environment is problematic and therefore not recommended. Wind, rain, and dust quickly disturbed the tracking mechanism, and the system malfunctioned several times during the study period and completely stopped functioning after a year. Moreover, the fiber optic cables were too fragile to be used in a natural environment, where they suffered severe cracks that decreased the efficiency of light transmission. Although this type of lighting system could be effective indoors (for office lighting, museum exposition lighting), we would not recommend the existing design for use in a natural environment (and for a juvenile salmon light mitigation plan). In addition, the system did not produce a lot of light even on a very sunny day (see Appendix A). Better sunlight collection and more robust fiber optic systems designed specifically for shock-proof and all-weather installation would, however, be potentially feasible and desirable for transmitting light underneath large OWS if the light intensity could be increased and the system designed for better reliability.

USEFULNESS OF LIGHT FOR MITIGATING OWS SHADING

One result of our fish path analysis demonstrated that when the shadow edge was partially attenuated by artificial lighting, fish were less disturbed (fish swimming angular variance decreased and fish get closer to the dock edge compared to the control case when shadow was present). However, to be effective, artificial light should illuminate only shaded areas. Therefore, to mitigate dock shading impacts on juvenile salmon behavior, we suggest the following:

We suggest searching for a potential lighting system that can withstand a salt water environment, that illuminates only the shaded area under the OWS, and that will propagate preferably more than 10,000 lux of white (natural) light at a distance of 2 m from the light source over a wide area (wide enough to cover the width of the OWS).

Finally, redesign or retrofitting of large OWS should be employed where possible to minimize extensive shading, perhaps by altering dock height, changing orientation, or using more transparent materials, should be considered as alternatives to extensive light mitigation.

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APPENDIX A.
LIGHT UNDER THE PORT TOWNSEND FERRY TERMINAL: COMPARISON BETWEEN FIBER OPTIC LIGHTING SYSTEM AND HALOGEN LIGHTING SYSTEM

In 2008, a University of Washington student and the Battelle Marine Sciences Laboratory cooperated to conduct a light survey under the Port Townsend Ferry Terminal. The objective of this study was to evaluate the quality and quantity of light produced by the fiber optic lighting system (Figure A-1). Detailed results were presented in Southard et al. (2009), but the main conclusions from this report were as follows:

The ambient light level decreased markedly under the dock (Figure A-2).

The fiber optic lighting system did not provide a significant increase in light level (in either air or in water) in comparison to the natural condition (Figure A-3). In addition, there was a sharp decrease in light level with increasing distance from the light source.

The light quality was very similar to the sunlight.

In addition, the lighting system ceased to function at the end of 2008, and a new lighting system replaced the old one. The “new” system was composed of three sets of 1500-W halogen lights.

In comparing both systems, we observed that the halogen lighting system was more efficient at increasing the general light level (Figure A-4) than the fiber optic lighting system. The fiber optic system produced more light within the first 10 to 12 cm from the source, but the halogen lighting system was more efficient than the fiber optic system at distances greater than that. However, the biggest difference between the two systems consisted in the quality of light: the fiber optic lighting system transmitted white light whereas the halogen transmitted a more yellow wavelength (Figure A-4).

Figure A-1: Image of the fiber optic lighting system. The two dishes above the dock optimize light reception by tracking the sun position, and the cables transmit light underneath the dock.

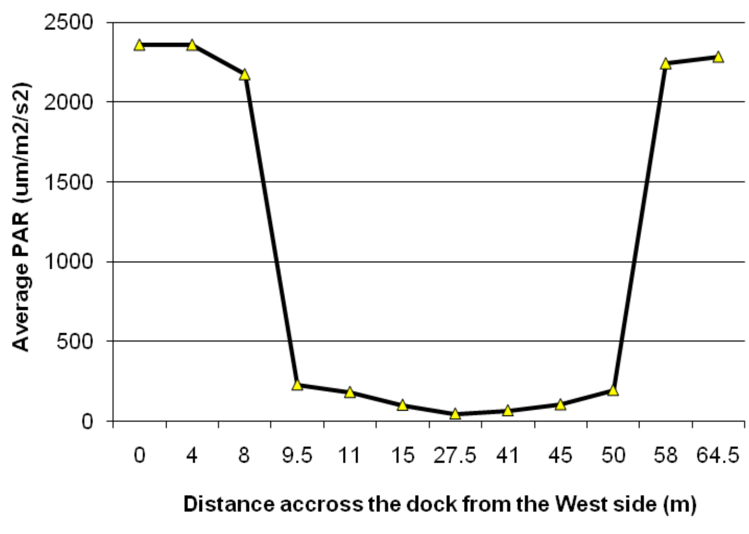

Figure A-2: Light intensity variation across the dock measured on a sunny day from the west side of the dock. Dock edges are located at 6 m and 55 m from the west side. Light levels were measured at 1416 PDT, hence the shadow line had moved farther inside the dock on the west side and was located at about 9 m.

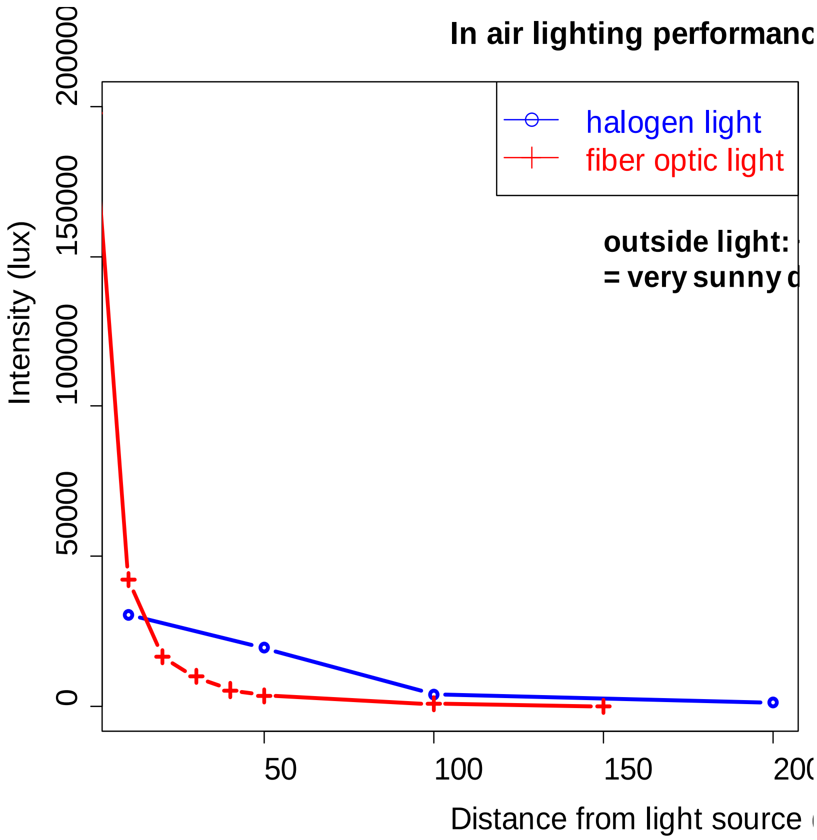

Figure A-3: In-air light diffusion comparison between the fiber optic lighting system (red) and halogen lighting system (blue). The fiber optic lighting system performance depended on the light level at the source (light collected at the dish)

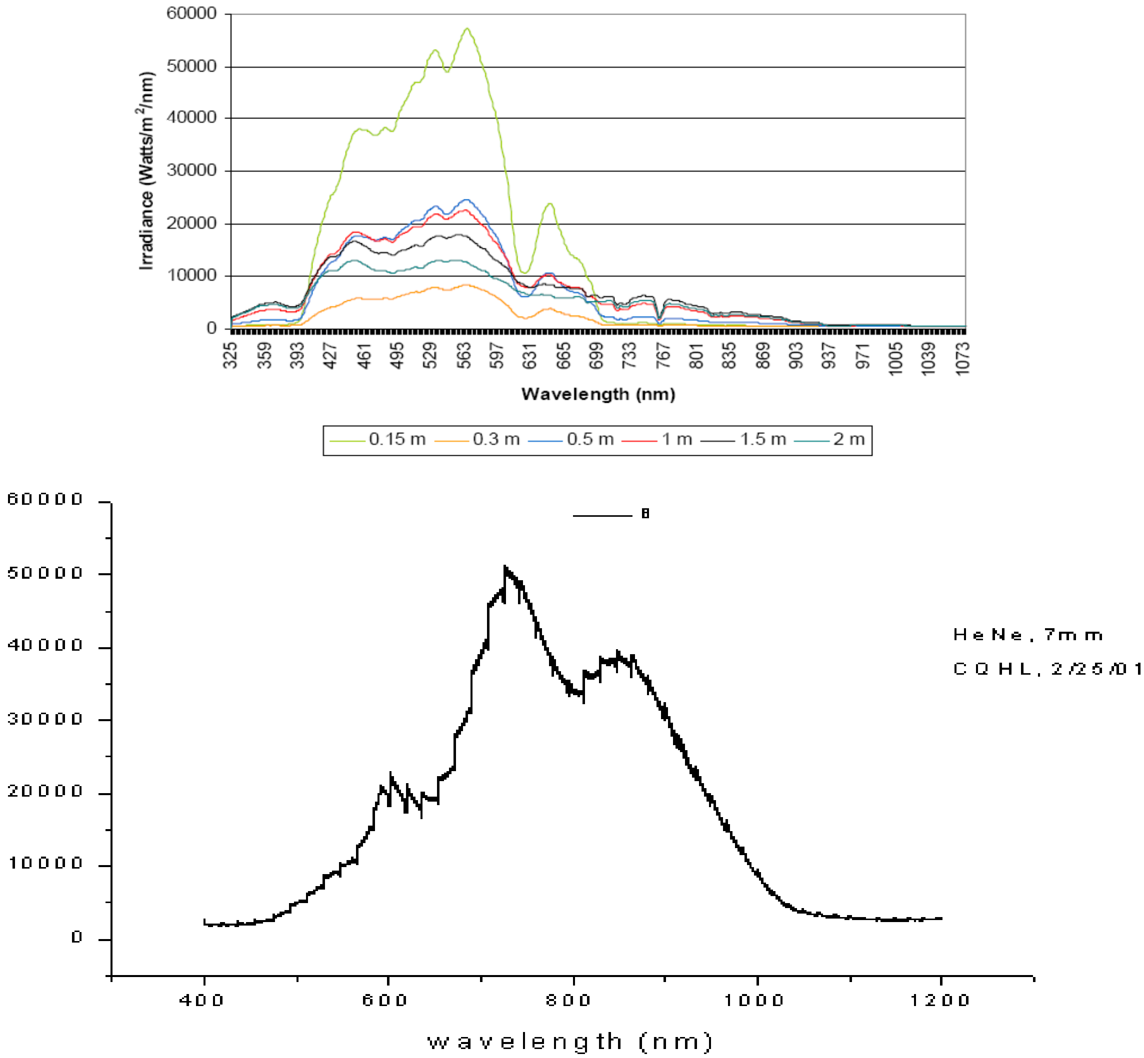

Figure A-4: Spectral radiometer measurements below a) a fiber optic lighting system (adapted from Southard et al. 2009) at different distances from the light source, and b) a halogen lighting system spectral curve.

APPENDIX B. SAND LANCE AND PERCH BEHAVIORAL RESPONSES TO OWS

Although we observed in this study that juvenile salmon avoided the ferry dock structure and shading during daytime, this was probably not the case for all other fish species. At the Port Townsend Ferry Terminal, perch and sand lance were the two other most abundant species (Ono, personal communication; Southard et al. 2006). Perch did not have any problem swimming under the dock (Figure B-1). Among the perch, Shiner perch (*Cymatogaster aggregata*) and pile perch (*Rhacochilus vacca*) were the most common. Pile perch were often swimming around ferry dock pilings; on the other hand, shiner perch were not reluctant to penetrate under the dock but usually did not cross the shadow edge. Sand lances (*Ammodytes hexapterus*) were more abundant under the dock in the morning than outside of the dock (Figure B-1), demonstrating behavior that was basically the opposite of that of juvenile salmon.

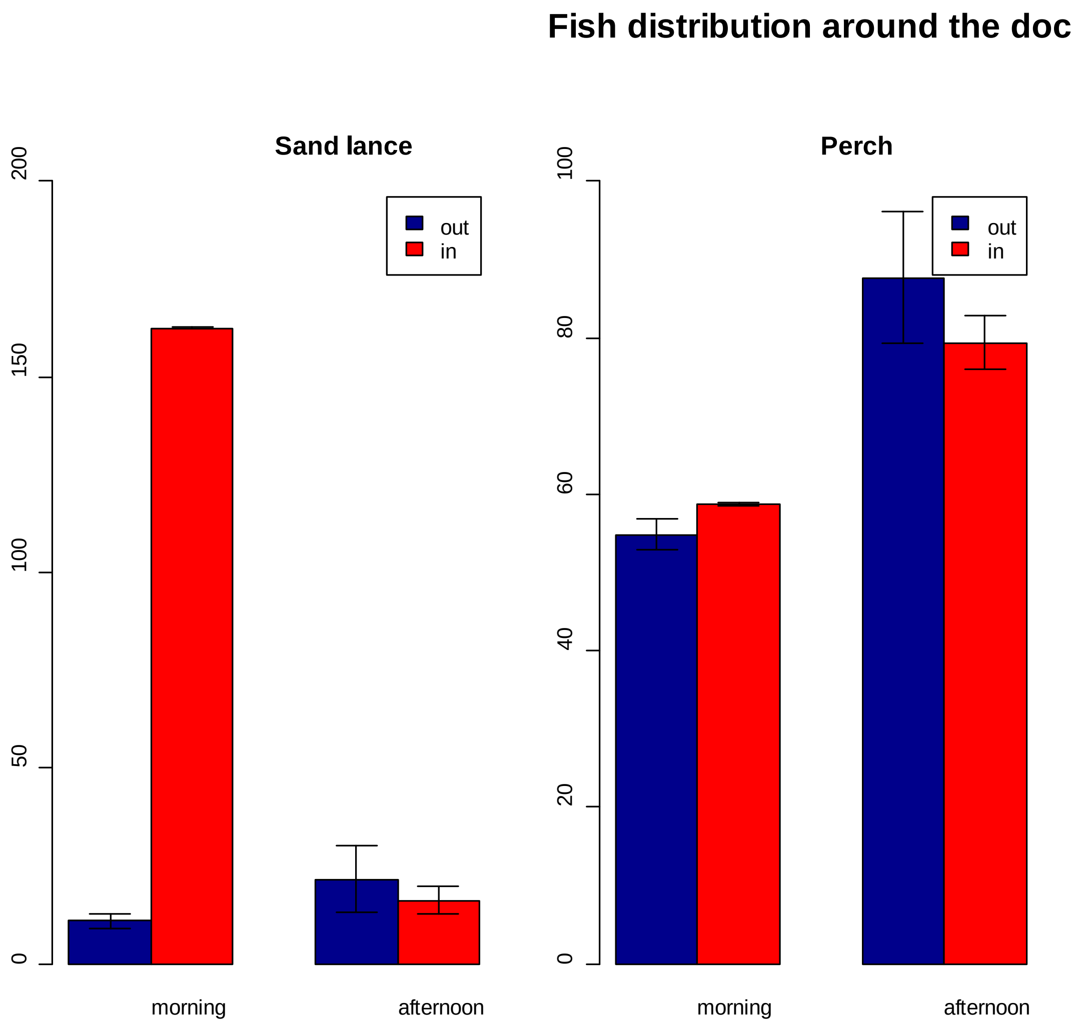

Figure B-1: Sand lance and perch average observation at the west side of the Port Townsend Ferry Terminal, by time of the day (morning *vs* afternoon) and by location (in v*s* out). Data were taken from the snorkel surveys in 2009 (not enough snorkel surveys were done in the mornings in 2008).