Wake Stranding in the Lower Columbia River

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1. INTRODUCTION

1.1 BACKGROUND AND PURPOSE

Wakes produced by deep-draft vessels are known to strand juvenile salmon in portions of the lower Columbia River[1]. Multiple studies have documented and examined the circumstances under which wake stranding occurs, but the magnitude of the impact remains unclear. Of the 25 different factors identified by the National Marine Fisheries Service (NMFS) as limiting the recovery of salmon populations in the Columbia River estuary, wake stranding is considered a primary contributor to a low-priority factor (NMFS 2011).

This document provides a review of wake stranding as the mechanism which could cause mortality for juvenile salmonids and eulachon as a result of wakes caused by deep-drafts. The focus of this review is the lower 104 miles of the Columbia River, between the Pacific Ocean and Vancouver, Washington.

Figure 1. Study Area

[1] General convention is that the lower Columbia River refers to that portion of the Columbia River downstream from the Bonneville Dam (river mile [RM] 146). Stranding has been documented in several locations below River Mile (RM) 104.

1.2 Hydrodynamics of Large Vessels

Waves produced by a vessel in motion are broadly categorized as either long- or short-period (BAW 2005). Short-period waves are produced at the bow and stern as the hull exerts pressure on its surroundings, while long-period waves result from the displacement of water from around the ship (BAW 2005). Short-period waves are generally small in comparison to long-period waves and rarely cause disturbance to the shoreline (Maynord 2004). In contrast, long-period waves can represent large fluctuations in water-level (especially within confined channels), can propagate over long distances, and cause significant disturbance to the shoreline (Maynord 2004, Wolter et al. 2004).

A deep-draft displacement hull making headway in a confined channel causes a rise in water level ahead of the bow and a resulting drop in water level along the flanks (BAW 2005). This level differential is translated along the length of the hull to the stern, where a transversal stern wave forms as water rushes to fill the "hole" in the channel where the ship had been (Maynord 2004, BAW 2005). At the shoreline, these effects are expressed as a subtle rise in water level off the bow, an exaggerated drop in water level along the length of the hull (referred to as "drawdown"), and a rapid uprush/surge from the transversal wave off the stern (referred to as "run-up") (Maynord 2004, BAW 2005) (Figures 2 and 3).

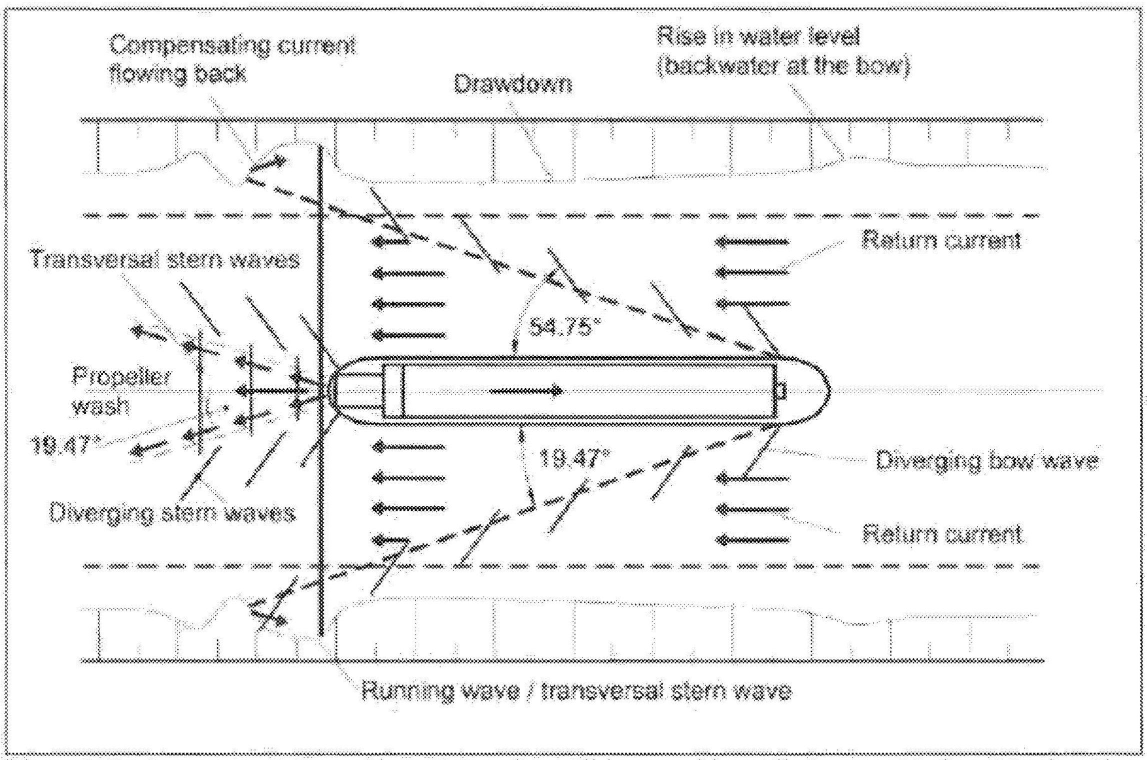

Figure 2. Surface-water deformation and shoreline effects caused by a displacement hull making headway in a confined channel (graphic reprinted from BAW 2005)

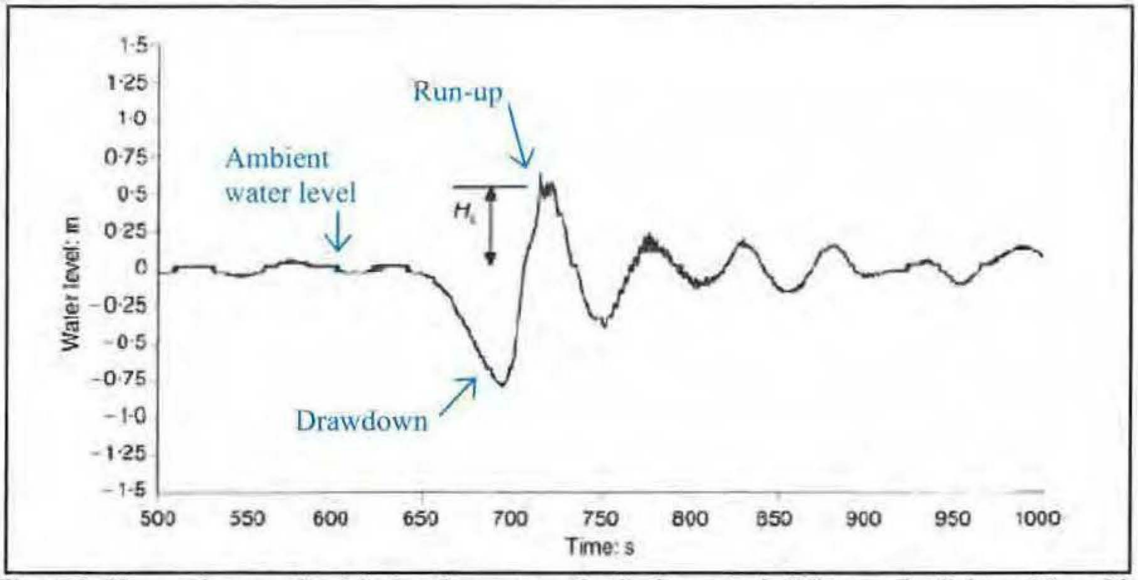

Figure 3. Changes in water level during the passage of a displacement hull in a confined channel (graphic reprinted from Maynord 2004)

As illustrated in Figure 3, the transversal stern wave is capable of moving a large volume of water rapidly up a shoreline face. Fish present in the shallow margin can become entrained by this surge and deposited high above the ambient water level once the wave recedes, infiltrates the substrate, or encounters debris/vegetation (Wolter et al. 2004, Pearson et al. 2006, Krieter et al. 2012). Although some small, fast-moving vessels can cause drawdown and surge (Krieter et al. 2012), stranding events in the lower Columbia River typically involve large, deep-draft vessels such as container ships, bulk carriers, oil tankers, and vehicle carriers (Bauersfeld 1977, Hinton and Emmett 1994, Ackerman 2002, Pearson et al. 2006).

2. OVERVIEW OF WAKE STRANDING IN THE LOWER COLUMBIA RIVER

Wake stranding in the Columbia River has been a topic of study for nearly 40 years. Field studies have been conducted by the Washington Department of Fisheries (WDF) (Bauersfeld 1977), the National Marine Fisheries Service (NMFS) (Hinton and Emmett 1994), SP Cramer and Associates (Ackerman 2002), and the Pacific Northwest National Laboratory (Pearson et al. 2006). Brief summaries of each of these investigations and other analyses based on them are included below, and sites where stranding was studied by Pearson et al. (2006) are shown on Figure 4.

2.1 WASHINGTON DEPARTMENT OF FISHERIES, FIELD STUDY (BAUERSFELD 1977)

The WDF (Bauersfeld 1977) was the first to formally document wake stranding of juvenile salmon in the Columbia River. In the spring of 1974 and the spring and summer of 1975, observations were made at six sites between RM 57 and 97. A total of 216 vessel passages were recorded, of which half produced stranding events. Wakes which stranded fish were limited to those generated by large, deep-draft vessels. Beaches where stranding occurred were all classified as having low slopes, sandy substrates, and fine-scale morphological features (e.g., inlets, coves) that constricted wave action and forced water onshore. In addition, stranding potential varied by season, with the fewest fish stranded during the summer.

In total, Bauersfeld (1977) documented the stranding of 2,297 Chinook salmon, 66 chum salmon, 25 coho salmon, and 9 unidentified trout. Stranded fish were small, with more than half of the Chinook measuring between 30 and 45 mm FL.

2.2 NATIONAL MARINE FISHERIES SERVICE, FIELD STUDY (HINTON AND EMMETT 1994)

From April through September 1992 and March through July 1993, the NMFS sampled eight sites several times a month between RM 38.3 and 92 where stranding had been documented by Bauersfeld (1977) (Hinton and Emmett 1994). The authors characterized the morphology of each beach and made detailed observations related to physical parameters associated with each vessel passage.

In total, 145 deep-draft vessel passages were observed, most of which produced wakes which were described as capable of stranding fish. Although juvenile Chinook salmon were detected in shallow nearshore habitats at the study sites through beach seining, stranding was only observed following five passages, each of which included a single juvenile Chinook salmon (size range between 38 and 73 mm FL). The authors concluded that stranding was the result of complex interactions dependent upon a suite of physical and environmental criteria, but was not a common event or source of significant mortality, as had been suggested by Bauersfeld (1977). They speculated that the high incidence of stranding observed by Bauersfeld (1977) could have been influenced by dissolved gas supersaturated (>100 percent) river water caused by spilling of water at upstream hydropower dams during that study period. Dissolved gas levels above 106 percent are known to decrease juvenile Chinook salmon swimming performance (Schiewe 1974 *in* Hinton and Emmett 1994).

2.3 SP Cramer and Associates, Inc., Field Study (Ackerman 2002)

Under contract to the Portland District of the USACE, SP Cramer and Associates sampled three sites where Bauersfeld (1977) and Hinton and Emmett (1994) had observed wake stranding of juvenile salmon: County Line Park (RM 51.5), Barlow Point (RM 61.5), and Sauvie Island (RM 96.5) (Figure 4) (Ackermann 2002). Shoreline surveys were conducted during late June and early July, and again in late July and early August.

In total, 21 juvenile Chinook salmon and 162 other small fish were stranded by 56 vessel passages. Juvenile Chinook salmon ranged in size from 53 to 90 mm FL, although one fish with injuries measured 136 mm. Stranding events were found to occur when deep-draft vessels (draft greater than 25 ft) traveled within close proximity to low-slope beaches, with vessel size and speed influencing wake amplitude. In addition, tidal stage was cited as a factor likely to influence wake dynamics. Overall, these findings supported many of the observations made by both Bauersfeld (1977) and Hinton and Emmett (1994), and confirmed that juvenile salmon could be stranded by vessel wakes in the lower Columbia.

2.4 Pacific Northwest National Laboratory, Field Study (Pearson et al. 2006)

Under contract to the Portland District of the USACE, the Pacific Northwest National Laboratory (Pearson et al. 2006) conducted the most intensive investigation of wake stranding in the lower Columbia River, to date. The study was designed to develop an impact-assessment model for predicting stranding risk following proposed deepening of the Columbia River navigation channel. Sampling was conducted between the summer of 2004 and the spring of 2005. Study sites were the same as those used by Ackermann (2002), Hinton and Emmett (1994), and Bauersfeld (1977): County Line Park, Barlow Point, and Sauvie Island. The authors observed vessel passage at each site and collected a variety of data to address 19 potential risk-factors amongst parameters related to shoreline morphology, vessel metrics, wake metrics, and fish presence.

In total, 126 ship passages were observed amongst the three sites, of which 46 resulted in the stranding of 520 fish. The majority (425 fish, 82 percent) of stranded fish were small subyearling (age-0+) Chinook salmon. A total of eight juvenile chum salmon and seven juvenile coho salmon were stranded amongst all events. Although yearling (age-1+) Chinook salmon and juvenile steelhead were detected in beach seine nets in very low numbers, neither were observed in stranding events. Although the lengths of stranded fish were not published in the final report, they are assumed to represent the same size range as those which were detected in beach seine surveys (~35 to 80 mm).

The majority (57 percent) of stranding events observed by Pearson et al. (2006) occurred at Barlow Point. Barlow Point also had the highest proportion of stranding events to vessel passages, where 49 ships produced 26 stranding events (53 percent), compared to 14 events out of 38 passages (37 percent) at Sauvie Island and six events out of 39 passages (15 percent) at County Line Park. There was no difference in stranding between seasons (winter, spring, summer) at County Line Park or at Sauvie Island, but stranding at Barlow Point during the summer was significantly lower than during the winter or spring.

Although beach-seine surveys determined that juvenile salmon were evenly distributed across each of the sampling sites, the authors found that stranding events typically occurred in specific "hot spots" where fine-scale morphological features enabled wave energy to congregate, transport, and trap fish. This effect was especially pronounced at Barlow Point, where the majority of stranding events were clustered in the upstream extent of the site and "heavily influenced by complex waves."

Based on their field observations, the authors performed single- and multi-variable regression analyses to discern which ambient conditions and ship/wake characteristics influenced stranding potential. The authors concluded that stranding represented a complex and episodic process related to a multitude of interdependent factors, including site location, a ship's kinetic energy (a function of ship size and speed), tidal height, wave excursion (the maximum drawdown distance plus the maximum run-up distance), and the presence of fish in the shallow nearshore.

2.5 Entrix, Inc., Vessel-Traffic Analysis (Pearson and Skalski 2007)

A modeling analysis was conducted by Pearson and Skalski (2007) to determine how an increase in deep-draft vehicle carriers transiting to the Port of Vancouver could influence the potential for wake stranding to occur in the lower Columbia River. The study used the dataset and logistical regression model from Pearson et al. (2006) and did not involve any new field effort. The study involved predicting stranding at three previously studied sites.

After reviewing this report, Grette Associates had serious concerns about the appropriateness of the methodology and the predictions. Therefore, we requested that Dr. Vladimir Shepsis of Coast and Harbor Engineering conduct an initial review of the document. His brief initial review is provided below.

> It is our opinion that the statistical models and framework published by Pearson, 2006 (and used by 2007 report), was a first approximation for developing a methodology for evaluating fish stranding due to vessel wakes at three specific sites along the Columbia River. The reports provide valuable information and entertain innovative ideas that potentially may be applicable for developing a methodology. However, the statistical relationships of the framework as presented in Pearson's 2006 publication and used by the 2007 study are questionable and may not be appropriate for any realistic estimates of fish stranding at the sites. Our initial review of the framework, used by 2007 study, has identified inconsistencies with interpretation and application of various aspects of vessel hydrodynamics and uncertainties with defining reliable statistical relationships between governing factors. For example, the 2007 report defines block coefficient as the product of multiplying three vessel dimensions: length, beam, and draft and includes a constant scaling factor of 10^{-8}. The actual definition of block coefficient includes the mass of displaced water (sometimes it is defined by ship deadweight). If the calculation of block coefficient were conducted properly, using the mass of displaced water, the statistical

relationships between kinetic energy and stranding factors would have been of a different shape and the regression coefficients that were used for calculations of stranding fish would be much different.

The Pearson study also misinterpreted vessel speed. Vessel wakes as well as drawdown effect depends on vessel speed relative to still water, as opposed to ground speed. These two speeds (relative to still water and to the ground) may be significantly different, depending on current direction and velocities. It appears that the vessel speed data that were used in the 2007 report are based on the ground speed of passing vessels only. It is likely that if the report properly accounts for vessel speed the stranding predictions would differ dramatically from those presented in the report.

2.6 Entrix, Inc., Port of Vancouver, Geospatial Analysis (Pearson et al. 2008)

To estimate the potential for wake stranding to occur at the landscape scale, Pearson et al. (2008) categorized shorelines throughout the lower Columbia River using physical criteria associated with susceptibility. The analysis was based on the understanding that ship wakes only result in stranding when multiple criteria are met in concert; wake stranding does not typically occur in association with one criterion alone (Hinton and Emmett 1994, Ackerman 2002, Pearson et al. 2006). This study used the dataset generated by Pearson et al. (2006) and did not involve any new field effort.

A geographic information system (GIS) was used to characterize a series of transects spaced at 200 m (0.12 mile) between RM 0 and 104 (n=1,634: 827 along the Washington bank and 807 along the Oregon bank). Stranding susceptibility was based on criteria established in previous field studies, including the presence of a confined channel (where the cross-sectional area of the hull is large relative to the cross-sectional area of the channel), close-proximity of the sailing line to shore, exposure of the shoreline to the navigation channel, shallow (<10 percent) beach-slopes, presence of an offshore berm shoreward of the 18-ft depth contour, and presence of fine-scale shoreline features (bank faces, vegetation, debris, riprap, etc.). Through a series of screening steps, each transect was classified as posing either a low, medium, or high risk of stranding juvenile salmon. Beaches with the highest risk represented very low slopes (<3 percent), close proximity to the sailing line, and presence of offshore berms shoreward of the 6-ft contour.

This analysis demonstrated that not all shorelines in this portion of the Columbia River pose a stranding risk to juvenile salmon. Between RM 0 and 22, shorelines were found to be too far distant from the sailing line for wake energy to pose a stranding risk. Between RM 22 and 104, only 31 percent of transects (n=506) met the joint criteria for sailing-line proximity and exposure (non-shielded), and approximately 16 percent (n=269) met the additional criteria for an above-minimal susceptibility based on beach slope. When berm depth was considered, only four percent of the total transects (n=65) had the highest potential susceptibility to stranding, with low beach slopes (<2.5%) and berms at or below the 6-ft contour. Overall, the results of this analysis identify 33 miles of disconnected shoreline reaches that exhibit physical characteristics predicted to have an above-minimal risk of stranding (Figure 4). The majority of shorelines in the lower Columbia River do not pose a stranding risk to juvenile salmon. These results are discussed further in Section 4

This analysis provided a general assessment of stranding risk based on a suite of basic morphological criteria. Pearson et al. (2008) did not include information regarding fish abundance or distribution to refine their estimates of stranding susceptibility. The authors cautioned that because fish availability varies substantially by season and habitat, this study is best viewed as a systematic analysis for identifying physical characteristics which could influence stranding, but that it should not be used as a definitive risk analysis.

Figure 4. Areas within the Lower Columbia River identified by Pearson et al. (2008) as having an above-minimal (yellow segments) and the most extreme (pink segments) risk of wake stranding (totaling approximately 33 miles of shoreline); also shown are the three primary stranding study sites. (Graphic © Google 2015)

2.7 U.S. Army Corps of Engineers, Channel-Deepening Analysis (Pearson 2011)

Pearson (2011) developed stranding probabilities for juvenile salmon due to wake stranding in association with the deepening of the Columbia River navigation channel. The modeling analysis examined four different scenarios of vessel traffic in the deepened channel based on the dataset and logistical regression model developed by Pearson et al. (2006). No new field work was conducted and no fish abundance data were included in the analysis.

The analysis determined that when vessel draft, length, and speed remained similar to metrics associated with the -40 ft CRD channel, stranding probability in the -43 ft CRD channel decreased. When vessel draft was increased to the maximum capacity afforded by the deepened channel, but ship speed remained constant, stranding probability also decreased. The author determined that, all other factors being equal, stranding was influenced more by vessel speed than by vessel draft. Overall, changes in stranding probability for all ship types were anticipated to be small (less than 6 percent) or undetectable between the -40- and -43 ft CRD channels.

2.8 Factors Affecting Stranding of Juvenile Salmonids (Pearson and Skalski 2011)

Pearson and Skalski (2011) is the published version of the derivation of the logistical regression model developed by Pearson et al. (2006). This publication was based on the dataset generated by Pearson et al. (2006) (see Section 2.4), and did not involve any new field effort.

As described previously, authors concluded that stranding represented a complex and episodic process related to a multitude of interdependent factors, including site location, a ship's kinetic energy (a function of ship size and speed), tidal height, wave excursion (the maximum drawdown distance plus the maximum run-up distance), and the presence of fish in the shallow nearshore. The authors note the focus on these factors (ship characteristics, ambient conditions, and fish availability) was by design, as was the decision to choose study sites with a history of stranding, and to avoid sampling during conditions were stranding is known not occur (e.g., high periods).

The authors caution against wider extrapolation of the stranding dataset and model river-wide, as the beach types selected (with a history of stranding) are not representative of all beach types in the lower Columbia River.

2.9 U.S. Geological Survey, Review of Channel-Deepening Analysis (Kock et al. 2013)

Under contract to the USACE, the USGS conducted a review of the Pearson (2011) modeling analysis (Kock et al. 2013). The authors determined that the model and methodology used by Pearson was appropriate in design, suitable for estimating stranding probability, and arrived at credible results. They confirmed that Pearson (2011) had identified the importance of environmental and biological factors related to fish stranding, but noted that the model was limited spatially in relevance to the three study sites (County Line Park, Barlow Point, and Sauvie Island) and did not allow for an assessment of stranding throughout the lower Columbia River.

2.10 Summary of Conclusions of Previous Studies

Wake stranding has been documented at specific locations in the lower Columbia River. However, the potential for a ship wake to result in a stranding event depends on a variety of interdependent factors:

- Not all juvenile salmonids are susceptible to stranding. The majority of stranding events include small subyearling Chinook salmon. Subyearling chum and coho salmon have been stranded by ship wakes in the lower Columbia, but in very low numbers compared to subyearling Chinook salmon.
- Juvenile sockeye, juvenile pink, yearling Chinook salmon, and yearling coho salmon, and juvenile steelhead trout are not typically susceptible to stranding risk.
- Wake stranding events are generally limited by season to the winter, spring, and early summer, when subyearling Chinook salmon are present in the shallow river margin. Subyearling Chinook salmon are largely absent from the shallow river margin during the late summer and fall and are thus not exposed to stranding risk during that time.
- Stranding represents a complex and episodic process related to a multitude of interdependent factors, including site location, a ship's kinetic energy, tidal height, wave excursion, and the presence of fish in the shallow margin. No single factor determines the potential for stranding to occur.
- The majority of shorelines in the Columbia River do not pose a stranding risk to subyearling Chinook salmon. Shorelines between RM 0 and 22 are not susceptible to stranding, and those between RM 22 and 25 represent only minimal susceptibility. Of the shorelines between RM 25 and 104, about four percent were classified as highest risk.
- Fine-scale morphological features which enable wave energy to congregate, transport, and trap fish typically pose an increased potential for a shoreline to strand subyearling Chinook salmon.
- Decreases in stranding probability was anticipated to be small or undetectable for all ship types once the federal navigation channel was deepened from -40 ft CRD to -43 ft CRD.

3. SUBYEARLING CHINOOK SALMON AND EULACHON SUSCEPTIBILITY TO STRANDING IN THE LOWER COLUMBIA RIVER

3.1 SUBYEARLING CHINOOK SALMON

As discussed in Section 2, ship wakes primarily result in stranding when small subyearling Chinook salmon are present in the shallow margin, and the majority of shorelines where wake stranding may occur are within the tidal freshwater region, which extends from roughly RM 34 to Vancouver Washington and above (Figure 4). Therefore, information about habitat associations and timing of subyearling Chinook salmon in the tidal freshwater region can inform which Evolutionary Significant Units (ESUs) could be exposed to stranding risk in this area.

3.1.1 Swimming Speed

Swimming speeds for fish are classified by Bell (1991) as "cruising," "sustained," and "darting." Cruising speed can be maintained for hours, sustained for minutes, and darting for seconds. In relation to wake stranding, it is expected that cruising and sustained swimming speeds are the rates at which juvenile salmon would react to wave energy, since the gradual rate of drawdown and run-up are likely to illicit a rheotaxis response where fish point into the current and hold position, and not one of flight or avoidance. The transport of juvenile Chinook salmon up a beach face could therefore occur when wave run-up velocity exceeds the sustained swimming ability (Wolter et al. 2004).

Sustained swimming speeds for juvenile Chinook, coho, pink, chum, and sockeye salmon are included in Table 1. Based on the findings of multiple investigators, swimming ability amongst these species are similar and largely dependent upon fish length. In general, small fry (~30 to 40 mm) are capable of maintaining speeds up to approximately 0.5 ft/sec, larger fry (~40 to 50 mm) up to 1.5 ft/sec, and small juveniles (76 to 95 mm) up to 1.9 ft/sec. For subyearling Chinook salmon, entrainment of fry and small juveniles could occur when wave run-up velocities exceed 1.5 ft/sec and 1.9 ft/sec, respectively.

Table 1. Swimming speeds of juvenile salmon

Salmon Species	Fish Length (in), (mm)	Sustained Swimming Speed (ft/sec)
Coho	1.3 (33)	0.4 – 0.5[1]
	2 (50)	0.5 – 1.2[3]
	3 – 3.75 (76 – 95)	1.4 – 1.8[2]
Chinook	1 – 1.8 (25 – 46)	0.5 – 1[1]
	1.25 – 1.5 (32 – 38)	1 – 1.5[4]
Pink	1.3 (33)	0.4 – 0.5[1]
Chum	1.5 (38)	0.4 – 0.6[1]
Sockeye	3 (76)	1.9[1]

[1] Furniss et al. 2006
[2] Powers et al. 1997
[3] Bell 1991
[4] Kerr 1953

Pearson et al. (2006) measured wave run-up velocity for most deep-draft vessel passage events. For those measurements taken with a video camera2, wake waves traveled up the beach face at between approximately 1.4 and 10.8 ft/sec, with an overall mean wave speed of approximately 3.8 ft/sec. This velocity exceeds the sustained swimming ability of juvenile salmon presented in Table 1. However, as discussed in Section 2, wake stranding represents a complex and episodic process related to a multitude of interdependent factors, of which the potential for a wave to entrain a fish is one.

3.1.2 Presence in the Shallow Margin by ESU

Differences in life history define when and at what size juvenile Chinook salmon will outmigrate and correspond to either a stream- or ocean-type rearing strategy. Juvenile Chinook salmon life histories are complex and variable among and within populations, but in general stream-type juveniles spend their first winter in freshwater and outmigrate as yearlings (age-1+), while ocean-type juveniles outmigrate to the estuary soon after hatching and spend their first winter at sea as subyearlings (age-0+).

Spring- and summer-run Chinook salmon generally represent the stream-type strategy while fall-run Chinook salmon represent the ocean-type strategy, although these relationships are not exclusive. For example, Chinook salmon from the Upper Willamette, spring-run ESU and the Snake River fall-run ESU each represent stocks where both ocean- and stream-type rearing strategies co-occur.

In general, habitat use and timing of Chinook salmon outmigration periods vary by age group. Most yearling fish outmigrate in the spring, during which time they utilize deepwater areas. In addition, subyearling outmigrants from the Snake River fall-run ESU are typically larger than other subyearlings (>99 mm), and like yearling fish are most likely to use deepwater areas.

[2] Pearson et al. (2006) measured wave run-up velocity with a video camera and a wave gage. Because the video camera proved to be more reliable and logistically sound than the gage, only data from video recordings was considered here.

Unlike yearling fish, Snake River fall-run Chinook salmon outmigrate over a longer period, which extends from the spring through the fall (see Table 4 in Section 3.1.3).

By contrast, smaller subyearling outmigrants use shallower water areas closer to shore. Collectively, subyearlings from several ESUs could be present in the lower Columbia year round, and in general their habitat use shifts from the very shallow margins to shallow water and eventually to deep water areas as fish size increases throughout the outmigration period.

Roegner et al. (2012, 2013) collected subyearling Chinook salmon with beach seines at sites throughout the lower Columbia River (Figure 5). For the purpose of considering stranding risk, this analysis focuses on results downstream from RM 104 to approximately RM 22. This includes study sites across two sets of reaches considered (and combined) in Roegner et al. 2013: Reaches C and D are roughly RM 33 to RM 74, reaches E and F are roughly RM 74 to RM 108. Within those reach combinations, beach seine sites were located between roughly RM 34 to 70, and RM 86 to 102, respectively.

The authors performed genetic-stock analyses to assign subyearling fish to their ESU of origin[3] and to determine the proportional presence of each ESU in the nearshore by month/season (Tables 2 and 3). Six of the eight Columbia Basin ESUs were represented in captured subyearlings, three of which are listed as threatened under the ESA.

In the lower reaches (C and D), genetic stock analyses indicate that in all seasons, fall-run Chinook salmon from the Lower Columbia River ESU make up the vast majority (generally greater than 91 percent) of all Chinook salmon present in shallow water areas of the tidal freshwater region (Figure 6).

In the upper reaches (E and F), fall-run Chinook salmon from the Lower Columbia River ESU make at least half to more than three quarters of subyearling Chinook salmon in shallow water areas in all seasons (Figure 7). In the winter, fry from the Upper Willamette River ESU comprise approximately one-third of these fish, with almost all of the remaining being fall-run Lower Columbia River Chinook (Figure 7). However, based on the reach data for March (Table 3) the high proportion of Upper Willamette River ESU Chinook salmon is likely localized to Reach F. This reach includes the mouth of the Willamette River and areas immediately downstream where this ESU would disperse to while exiting the Willamette River and increase their abundance locally. In the summer and fall period, Upper Columbia summer/fall run ESU fish comprise approximately one-third of the fingerling population in reaches E and F (Figure 7). This greater proportion of Upper Columbia summer/fall run ESU

[3] Roegner et al. 2012, 2013, and Teel et al. 2014 use different terminology for ESUs than those considered under the ESA. In ESA parlance, "Lower Columbia River Chinook ESU" includes the Roegner et al. categories "West Cascade Tributaries fall, West Cascade Tributary spring, and Spring Creek group fall". For this stranding analysis, this ESU divided only by fall and spring life history types. The Roegner categories also combine the Middle Columbia (not listed) and Upper Columbia (listed) spring-run ESUs, which were detected very rarely. Other minor differences in terminology exist – this analysis uses the ESU names as described by NOAA Fisheries for ESA management and recovery purposes as described on the NOAA Fisheries website http://www.westcoast.fisheries.noaa.gov/protected_species/salmon_steelhead/salmon_and_steelhead_listings/salmon_and_steelhead_listings.html.

fish in reaches E and F compared to reaches C and D farther downstream is likely due to their generally moving to deeper waters over the course of their outmigration, as it typical for subyearling Chinook salmon. Therefore, they are present near the shoreline in reaches E and F while relatively small but move away from the shoreline as they grow on their migration to reaches C and D farther downstream.

For most juvenile Chinook salmon, travel through the tidal freshwater region to the lower estuary is direct, on the order of days or weeks. Variations in migration rates are related, in part, to size (a function of swimming ability) and season (a function of river discharge). In addition, both yearling and subyearling Chinook salmon may extend their outmigrations by loitering within off-channel habitats, although occupation of these areas is typically brief (one to two tidal cycles). Overall, juvenile Chinook salmon generally move through the tidal freshwater region and do not hold or occupy areas within it for extended periods.

In summary, subyearling Chinook salmon can occur within the tidal freshwater region year-round, but presence in the shallow margin is limited largely to the spring, with low relative abundance in the winter and summer. Based on genetic-stock analyses, the majority of subyearling Chinook salmon present in the shallow nearshore during all seasons originate from the Lower Columbia River ESU, and of those, the majority represent fall-run stocks (Figure 6).

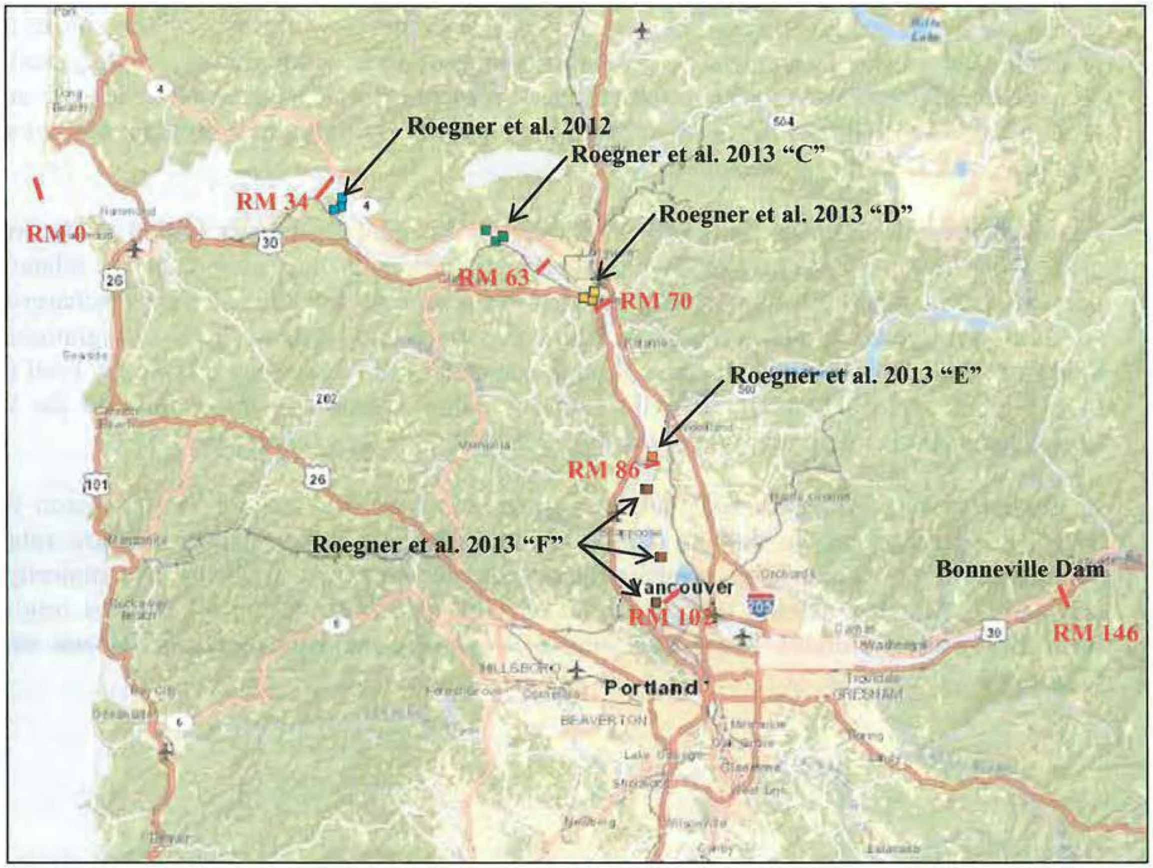

Figure 5. The sampling sites of Roegner et al. (2012, 2013) were located between RM 34 and 70 of the Columbia River, which is within the lower portion of the tidal freshwater region (RM 34 to 146) of the estuary.

Table 2. Genetic-stock composition of subyearling Chinook salmon captured in the lower portion of the tidal freshwater region of the Columbia River estuary by month (gray shading, Roegner et al. 2013) and season (no shading, Roegner et al. 2012), between approximately RM 34 and 70 (see Figure 5). ESU names in bold font denote listing as threatened or endangered under the ESA. Composition in catch listed as '<0.01' represents a reported value of 0.005 to 0.009; reported values less than 0.004 are listed as '0.'

	Month/ Season	**January[3]**	**Winter[4]**	**March**		**May**		**Spring[4]**	**July**		**Sept/Nov**		**Summer/Fall[4]**
	Sampling Location	**Reach 'C'+'D'**	**Tidal freshwater**	**Reach 'C'**	**Reach 'D'**	**Reach 'C'**	**Reach 'D'**	**Tidal freshwater**	**Reach 'C'**	**Reach 'D'**	**Reach 'C'**	**Reach 'D'**	**Tidal freshwater**
ESU (run component)	n=fry n=fingerling	*n=102* *n=0*	*n=83* *n=0*	*n=81* *n=0*	*n=198* *n=0*	*n=135* *n=33*	*n=138* *n=42*	*n=218* *n=318*	*n=25* *n=103*	*n=58* *n=122*	*n=0* *n=76*	*n=0* *n=56*	*n=57* *n=291*
Lower Columbia (fall[1])	fry	0.60	0.87	0.95	0.95	0.94	0.95	0.95	0.93	0.89	--	--	1.00
	fingerling	--	--	--	--	0.94	0.96	0.95	0.83	0.95	0.93	0.94	0.89
Lower Columbia (spring[1])	fry	0.39	0.12	0.05	0.03	<0.01	0.02	0.02	0.04	0.05	--	--	0
	fingerling	--	--	--	--	0.06	0.04	<0.01	0.05	<0.01	0.04	0.03	0.02
Upper Willamette	fry	0.01	<0.01	0	<0.01	0.02	<0.01	0	0	0	--	--	0
	fingerling	--	--	--	--	0	0	0	0	0	0.01	0.02	0
Deschutes River summer/fall-run	fry	0	0	0	0	0	0	0	0	0	--	--	0
	fingerling		--	--	--	0	0	0	0	0.02	0	0	0
Middle and **Upper Columbia spring-run[2]**	fry	0	0	0	0	0	0	0	0	0	--	--	0
	fingerling	--	--	--	--	0	0	0	0	0	0	0	0
Upper Columbia summer/fall-run	fry	0	0	0	0.01	0	0.02	0.01	0	0.03	--	--	0
	fingerling	--	--	--	--	0	0	0.03	0.11	0.02	0	0.02	0.08
Snake River fall-run	fry	0	0	0	0	0	0	<0.01	0.04	0.02	--	--	0
	fingerling	--	--	--	--	0	0	0	0	0	0	0	0.02
Snake River spring/summer-run	fry	0	0	0	0	0	0	0	0	0	--	--	0
	fingerling	--	--	--	--	0	0	0	0	0	0	0	0

[1] Lower Columbia fall-run and Lower Columbia spring-run represent the same ESU.
[2] Stocks from the Middle Columbia and Upper Columbia spring-runs represent two distinct ESUs but were not genetically differentiated. Only fish from the Upper Columbia ESU are listed as threatened under the ESA.
[3] Roegner et al. (2013) combined sampling from sites in reach C and D to determine the fry proportion for January.
[4] Roegner et al. (2012) defined seasons as: November–February = 'Winter'; March–June = 'Spring'; July–October = 'Summer/Fall'

Table 3. Genetic-stock composition of subyearling Chinook salmon captured in the middle portion of the tidal freshwater region of the Columbia River estuary by month (Roegner et al. 2013), between approximately RM 86 and 102 (see Figure 5). ESU names in bold font denote listing as threatened or endangered under the ESA. Composition in catch listed as '<0.01' represents a reported value of 0.005 to 0.009; reported values less than 0.004 are listed as '0.'

	Month/ Season	January[3]	March		May		July		Sept/Nov	
	Sampling Location	Reach 'E'+'F'	Reach 'E'	Reach 'F'	Reach 'E'	Reach 'F'	Reach 'E'	Reach 'F'	Reach 'E'	Reach 'F'
ESU (run component)	n=fry n=fingerling	*n=59* *n=0*	*n=108* *n=0*	*n=91* *n=0*	*n=116* *n=64*	*n=82* *n=94*	*n=54* *n=122*	*n=0* *n=175*	*n=0* *n=107*	*n=0* *n=51*
Lower Columbia (fall[1])	fry	0.55	0.95	0.54	0.79	0.70	0.86	--	--	--
	fingerling	--	--	--	0.94	0.95	0.46	0.43	0.78	0.38
Lower Columbia (spring[1])	fry	0.04	0	0.08	0	0.04	0.04	--	--	--
	fingerling	--	--	--	0	0.03	0.02	0.03	0.03	0.11
Upper Willamette	fry	0.39	0.03	0.35	0	0	0	--	--	--
	fingerling	--	--	--	0.04	0	0	0	0.04	0.18
Deschutes River summer/fall-run	fry	0	0.02	0	0	0	0.02	--	--	--
	fingerling		--	--	0	0	0.05	0.05	0	0.07
Middle and Upper Columbia spring-run[2]	fry	0	0	0	0	0	0	--	--	--
	fingerling	--	--	--	0	0	0	0	0	0
Upper Columbia summer/fall-run	fry	0	0	0	0.17	0.19	0.08	--	--	--
	fingerling	--	--	--	0.02	0	0.46	0.43	0.14	0.23
Snake River fall-run	fry	0.02	0	0.03	0.04	0.01	0	--	--	--
	fingerling	--	--	--	0	0	0.01	0.06	<0.01	0.03
Snake River spring/summer-run	fry	0	0	0	0	0	0	--	--	--
	fingerling	--	--	--	0	0	0	0	0	0

[1] Lower Columbia fall-run and Lower Columbia spring-run represent the same ESU.
[2] Stocks from the Middle Columbia and Upper Columbia spring-runs represent two distinct ESUs but were not genetically differentiated. Only fish from the Upper Columbia ESU are listed as threatened under the ESA.
[3] Roegner et al. (2013) combined sampling from sites in reach E and F to determine the fry proportion for January.

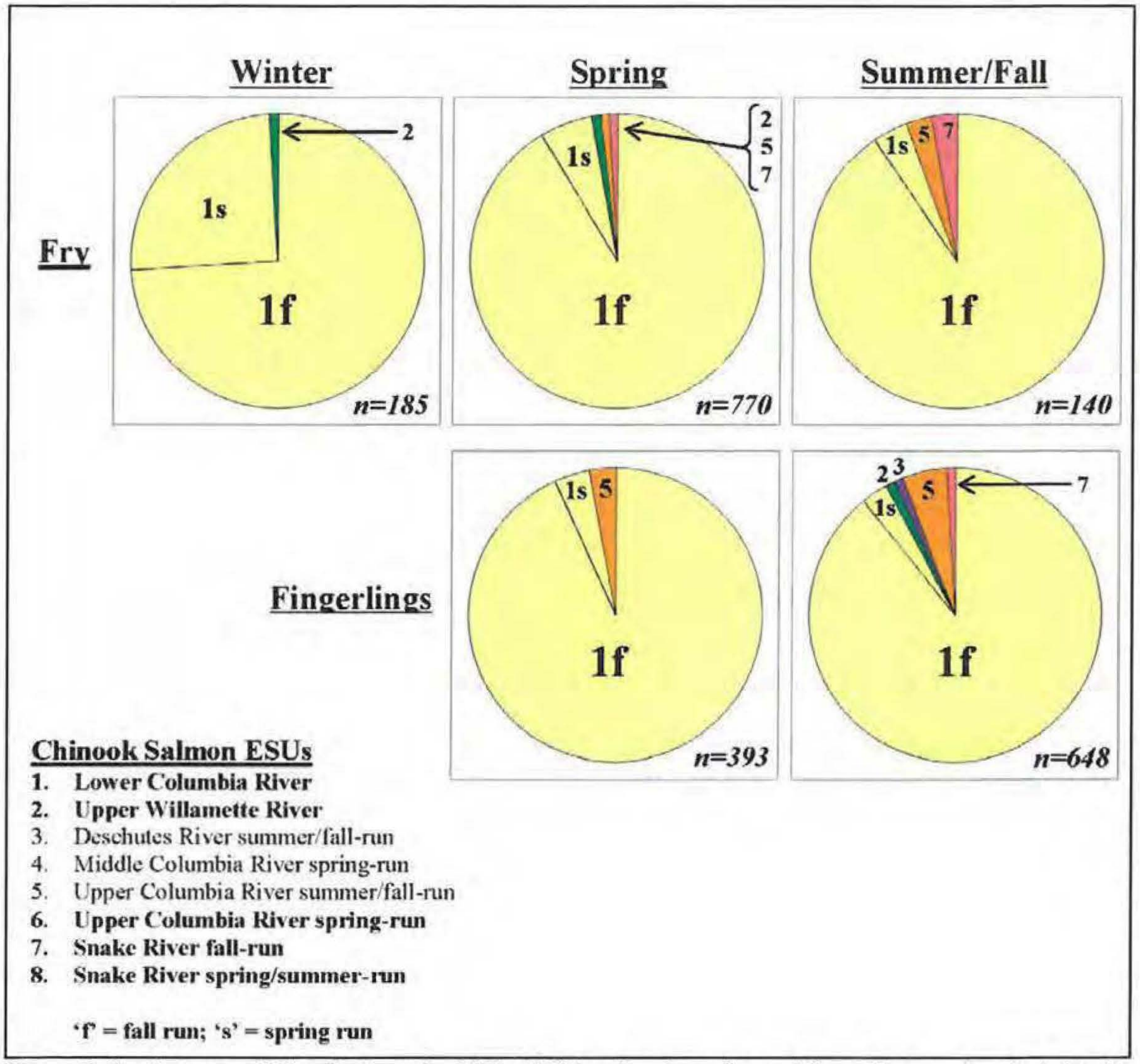

Figure 6. Spatiotemporal distributions, by ESU, of Chinook salmon fry and fingerlings captured at sites in the lower portion of the tidal freshwater region of the Columbia River estuary, between approximately RM 34 and 70 (data from Roegner et al. 2012, 2013). Chinook salmon ESU names in bold font denote listing as threatened or endangered under the ESA.

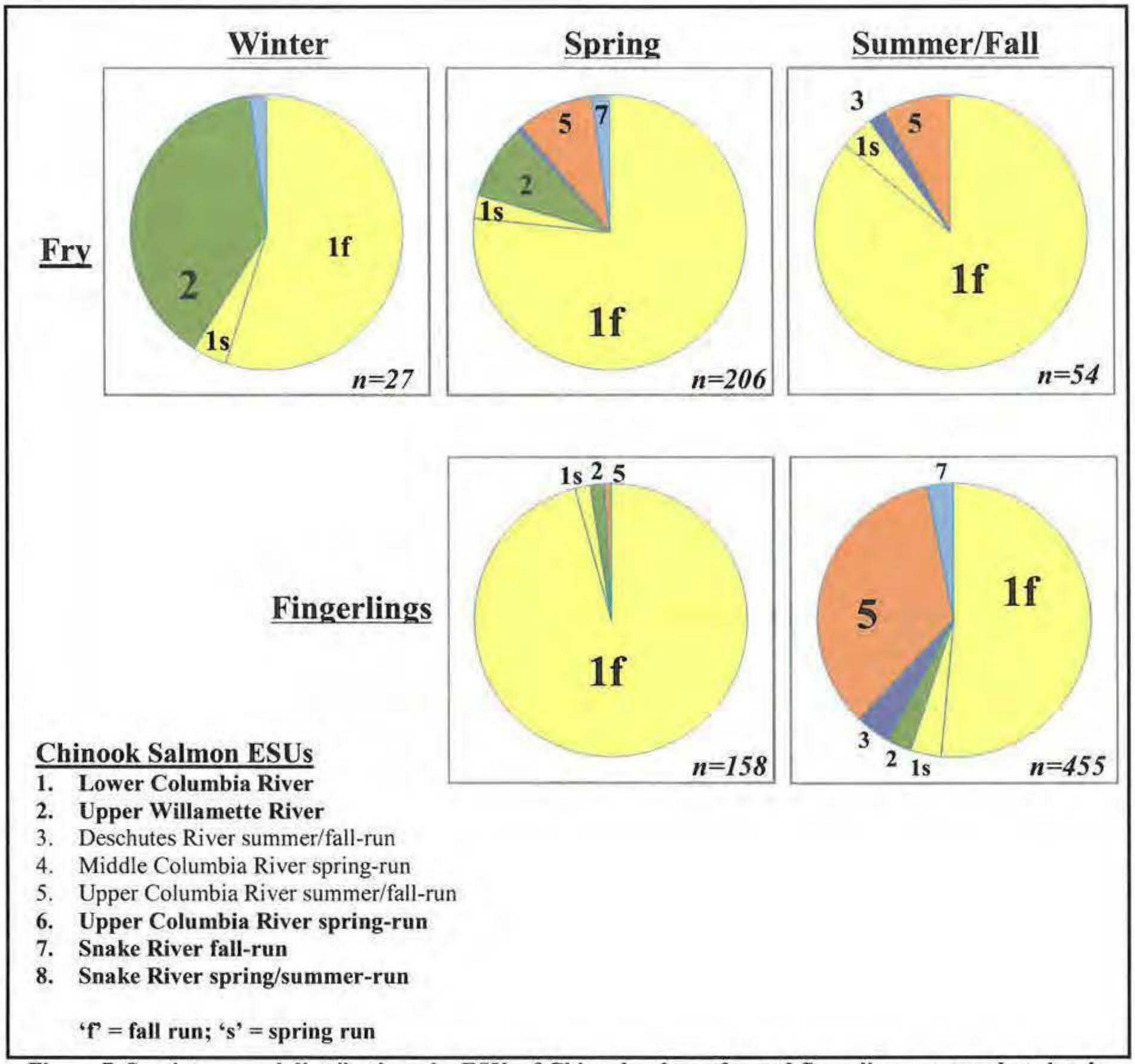

Figure 7. Spatiotemporal distributions, by ESU, of Chinook salmon fry and fingerlings captured at sites in the middle portion of the tidal freshwater region of the Columbia River estuary, between approximately RM 86 and 102 (data from Roegner et al. 2013 as reported in Teel et al. 2014 [reaches combined]). Chinook salmon ESU names in bold font denote listing as threatened or endangered under the ESA.

3.1.3 Stranding Susceptibility by ESU

Field studies have demonstrated that in order for subyearling Chinook salmon to be exposed to stranding potential, they must be present in the shallow margin when ship wakes interact with the bankline (Bauersfeld 1977, Hinton and Emmett 1994, Pearson et al. 2006) (see Section 2). The distribution of subyearling Chinook salmon in the shallow margin varies seasonally, with differences in water temperature, river level, and fish length all influencing habitat preferences (McCabe et al. 1986, Dawley et al. 1986, Healy 1991, Bottom et al. 2005, Bottom et al. 2008). Bottom et al. (2008) found that the presence of subyearling Chinook salmon in nearshore areas declined in July, once surface-water temperatures at sampling sites exceeded 19°C. The authors concluded that high temperatures reduced the availability of shallow-water habitat by mid-summer and shifted occupation to deepwater areas during the late-summer and fall. Further, as the water level of the Columbia River decreases in the late summer and early fall, subyearling Chinook salmon may have limited or no access to the shallowest shoreline areas that were used earlier in the spring (Figure 8).

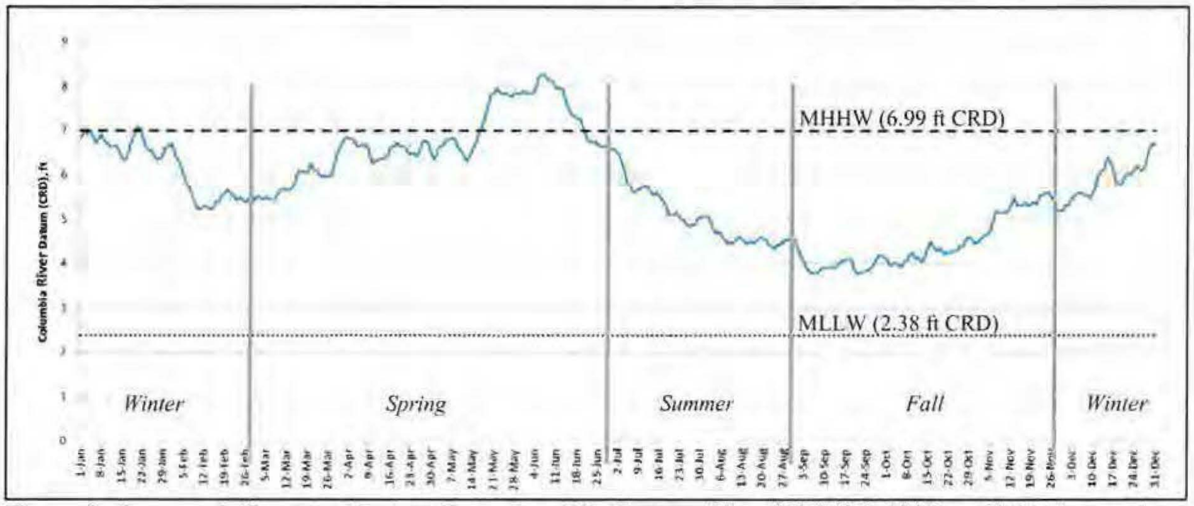

Figure 8. Average daily water level at Longview, Washington (Site #9440422), 2003 to 2012. Seasonal notations are consistent with those in Table 1.

A shift away from the shallow margin to deeper habitat is also associated with the attainment of fingerling size. This has been observed during concurrent sampling where subyearling Chinook salmon occupying shallow-water areas were generally smaller than those subyearlings captured from adjacent deepwater channels (Dawley et al. 1986, McCabe et al. 1986, Weitkamp et al. 2012). Additionally, fish length influences habitat preference by season. In the winter and early spring, mean length is typically consistent with fry (<60 mm), in spring and summer it is more typically consistent with small fingerlings (60 to 80 mm), and in the fall it is more typically consistent with larger fingerlings (80 to 120 mm) (Bottom et al. 2008, Johnson et al. 2011). Fish length influences habitat associations and outmigration pathways, with small fry and fingerlings occupying shallow margin areas and larger fish moving through deepwater channels (Dawley et al. 1986, McCabe et al. 1986, Bottom et al. 2008, Roegner et al. 2012, Roegner et al. 2013, Weitkamp et al. 2012). For instance, McCabe et al. (1986) determined that this habitat transition occurred when fish approached 99 mm.

Based on the above discussion, a summary of expected presence in the different habitat zones between RM 34 and 102, by ESU, is included in Table 4. The river extent is based on the lower- and upper-most beach seine locations within Reaches C and F, which represent the tidal freshwater portion of the river below RM 104.

Table 4. Summary of expected presence in the different habitat zones between RM 34 and 102 of the tidal freshwater region for juvenile Chinook salmon from all Columbia River ESUs.

		Expected Presence[1]							
		Winter[2]		Spring[2]		Summer[2]		Fall[2]	
ESU (outmigrant age class)	ESA Listing Status	Shallower[3]	Deeper[4]	Shallower	Deeper	Shallower	Deeper	Shallower	Deeper
Lower Columbia River (subyearling and yearling)	Threatened	...[5]	...	X	X	...	X		...
Upper Willamette River (subyearling and yearling)	Threatened	...[6]	...	...	X				...
Deschutes River summer/fall-run (subyearling)[6]	Not Listed			...	X	...	X		...
Middle Columbia River spring-run (yearling)[6]	Not Listed				X				
Upper Columbia River summer/fall-run (subyearling and yearling)[7]	Not Listed			...	X	...	X		...
Upper Columbia River spring-run (yearling)	Endangered				X				
Snake River fall-run (subyearling and yearling)	Threatened			...	X	...	X		...
Snake River spring/summer-run (yearling)	Threatened				X				

[1] Information referenced from Roegner et al. (2012, 2013), Columbia River DART (2013), and Bottom et al (2008)
[2] Seasons are based on Roegner et al. (2012, 2013): December–February = 'Winter'; March–June = 'Spring'; July –August = 'Summer'; and September–November = 'Fall'
[3] Refers generally to shallow, nearshore water, e.g. 0-6 ft depth.
[4] Refers generally to deeper water, e.g. 6 ft and deeper.
[5] The use of '...' denotes low relative abundance within each ESU, X denotes higher relative abundance more typical of standard outmigration periods.
[6] Localized presence is higher in the Shallow water near and immediately downstream of the mouth of the Willamette River, but not generally within the tidal freshwater region.
[7] ESUs that are not listed are included here for context

Subyearling Chinook salmon documented in stranding events have been limited to those of fry and fingerling size, typically between 30 and 90 mm (Bauersfeld 1977, Hinton and Emmett 1995, Ackerman 2002, Pearson et al. 2006). This size range is consistent with those fish which have a strong association to shallow nearshore areas (see Table 4). Based on genetic-stock analyses from the shallow nearshore (Figures 6 and 7) and seasonal expectations for presence in the habitat zones (Table 4), exposure to stranding risk is expected to primarily concern small subyearlings from fall-run stocks of the Lower Columbia River ESU during the winter, spring, and early summer. In addition, minor proportions of the Upper Willamette River ESU may be exposed to stranding risk during the winter and spring (particularly upstream of RM 74). The Upper Columbia summer/fall-run ESU (not ESA-listed) also could be exposed to limited stranding risk upstream of RM 74 during the spring and early summer. All other ESUs are expected to be at very low risk of stranding due to their near absence from the shallow water shoreline during seasons where stranding occurs.

3.2 EULACHON

Eulachon are small ocean-going fish that occur in offshore marine waters and return to tidal portions of rivers to spawn. Eulachon are broadcast spawners, and spawning events typically occur over coarse, sandy substrates or pea-sized gravels (WDFW and ODFW 2001, Willson et al. 2006). Females produce between 20,000 and 60,000 eggs which are distributed downstream by river currents (Willson et al. 2006, WDFW and ODFW 2008, Gustafson et al. 2010). Once fertilized, eggs reveal a sticky membrane that adheres to sand grains, causing the egg to sink to the river bottom and become covered by the substrate (Wilson et al. 2006, Gustafson et al. 2010). Larvae typically hatch and emerge from the substrate within 30-40 days of spawning (Smith and Saalfield 1955 *in* Gustafson et al. 2010). Upon emergence, larvae drift rapidly downstream to salt water and rear in nearshore marine areas.

3.2.1 Stranding Susceptibility of Eulachon

Based on the stranding susceptibility criteria described above in Section 2, eulachon would only be exposed to stranding risk while present in shallow margin habitats of the Columbia River mainstem above RM 22; there is no potential for stranding to occur within the tributaries. The susceptibility of eulachon to stranding risk is thus described below as a function of habitat usage of the shallow margin of the Columbia River mainstem.

Adults preferentially spawn in coarse, clean sand or gravel (Cowlitz Indian Tribe 2012). As reviewed in Willson et al. (2006), spawning can occur at various depths, and has been documented at up to 20 feet in the Columbia River (Smith and Saalfield *in* Willson et al. 2006) and 25 feet in the Fraser River in British Columbia (Hart and McHugh *in* Willson et al. 2006). The eggs adhere to these substrates which weigh them down and make them susceptible to bedload transport away from spawning areas. Sampling within sand waves of the lower Cowlitz, Kalama, and Grays rivers revealed viable eggs and larvae beneath as much as 24 inches of substrate (Cowlitz Indian Tribe 2012). This reveals that even though the majority of spawning takes place within the upper tributaries, egg incubation and larval emergence could also occur in the lower portions of tributaries and, to some extent, the Columbia River mainstem. Although the relative importance of the Columbia River mainstem for spawning is not clear, areas of sand-wave bed forms may support egg incubation.

Assuming that some portion of adult eulachon spawn in the Columbia River mainstem, they are not likely to so in the shallow margin where fish are susceptible to stranding because this area is not typically characterized by moderate to fast moving water over coarse substrates. Therefore, one can infer a very low susceptibility to stranding risk. Further, adult eulachon are strong swimmers; any adult eulachon which may occur in the shallow margin (spawning or in transit) are unlikely to be entrained by onshore waves. Overall, adult eulachon do not appear to be at risk of wake stranding in the lower Columbia River.

Fertilized eulachon eggs are expected to settle out of the water column in areas where active currents occur, rather than in slow-moving peripheral waters. Dynamic areas of the Columbia River mainstem are considered especially well-suited for the incubation of eulachon eggs because active currents maintain elevated dissolved oxygen levels and limit the stability of benthic habitat to potential predators. Incubation in the river mainstem is supported by larval sampling surveys which have detected the majority of emergent eulachon larvae in deep- to mid-water portions of the Columbia River. Therefore, the majority of eulachon eggs are expected to occur in deepwater areas of the river mainstem where they are unlikely to be at risk of stranding.

Larval eulachon are poor swimmers which rely on hydraulic processes to facilitate downstream transport. The majority of eulachon larvae are expected to emerge from dynamic, deepwater areas of the Columbia River mainstem and be rapidly dispersed downstream within mid- to deep-water portions of the river. Therefore, it is unlikely that larvae would occur within shallow nearshore habitats. Based on absence from the shallow margin, eulachon larvae are not considered to be susceptible to wake stranding.

Overall, eulachon are not expected to be susceptible or exposed to wake stranding risk in the lower Columbia River. This is supported by the fact that eulachon were not observed either stranded or in beach seines conducted by Pearson et al. (2006).

4. DISCUSSION

4.1 Stranding Susceptibility in the Columbia River between RM 0 and 104

Pearson et al. (2008) examined the characteristics of the Columbia River shoreline from RM 0 to RM 104 by measuring along transects overlain on bathymetric data and aerial photographs. The transects were spaced 200 meters apart yielding a total of 1634 transects. Based on the analysis the majority of the shorelines in the lower Columbia River were concluded to not pose a stranding risk to subyearling Chinook salmon (Pearson et al. 2008). Further, they concluded that between RM 0 and 22, shorelines were too far distant from the sailing line (Columbia River channel) for wake energy to pose a stranding risk.

Pearson et al. (2008) determined that 16 percent (269 transects) of the transects met the criteria for sailing-line proximity (i.e., sites are close enough to the shoreline for the vessel wake to have the energy necessary to cause stranding), exposure to vessel wakes (i.e., the transect is not shielded from wave energy by islands or other features), and had a beach slope flatter than 10 percent (i.e., the beach was flatter enough to potentially strand fish). These 269 transects define a set of non-contiguous beaches that total 33 miles of shoreline (illustrated as the pink and yellow beach segments on Figure 4), that was predicted to have at least some potential to strand fish when vessel wakes interacted with the shoreline. The conclusion that these beaches have a risk of stranding is a very conservative (i.e., more likely to predict stranding occurs when it does not occur than vice versa) due to the inclusion of the 10 percent slope criterion. Pearson et al. (2006) did not study any sites that had this "steep" of a beach. County Line Park had a slope of about 4 percent, Barlow Point had a slope of about 2.2 percent and Sauvie Island had a slope of about 2.5 percent. Pearson et al. (2008) presents information from previous studies showing that fish are more typically stranded on beaches with slopes flatter than about 5 or 6 percent and not all of the very flat beaches strand fish (Figure 2 in Pearson et al. 2008). Therefore, we conclude that the 33 miles of shorelines identified above includes many beaches that have very limited to no stranding risk due to the inclusion of the very conservative 10 percent criterion.

When Pearson et al. (2008) included in their criteria the presence of underwater berms (a ridge or complex beach feature that affects how the waves interact with the beach) and only considered transects with very flat slopes (<2.5 percent), 4 percent of the total transects (65 transects) had the highest predicted potential susceptibility to stranding. Four percent of the 208 miles of shoreline study means that approximately 8 miles of shoreline were predicted to have the most extreme susceptibility to stranding based on including two more criteria. The beaches with the most extreme risk of stranding, as defined by Pearson et al. 2008, are illustrated on Figure 4 as the pink beach segments.

(Pearson et al. 2006) noted that much of the stranding at Barlow Point occurred in an area where strong cross-waves and an eddy formed when the waves ran up the beach. Other researchers (Hinton and Emmett 1994, Bauersfeld 1977 noted the importance of fine-scale beach features (e.g., coves, inlets, and shoreline depressions) in redirecting wave energy to congregate, transport, and trap fish. Collectively these observations suggest that the approximately 8 miles of beaches identified as having high susceptibility to stranding as identified by Pearson et al. (2008) likely need to have such fine-scale features for the predicted high occurrence of stranding to actually occur. Pearson et al. (2008) used video available from other researchers to examine what fine-scale features (specifically looking for rip-rap, gabions, piers etc.) were present near their study transects. They did not draw conclusions about what was seen or use the observations to develop another criteria to further refine their predictions of stranding susceptibility for the transects studied.

It is important to consider fine-scale beach morphology because based on the results of the stranding studies (particularly at Barlow Point) we know that even at a site that has characteristics that based on Pearson et al. (2008) suggest a high susceptibility to stranding over much of the site, actual standing only occurs in a subset of the site in "hotspots". Stranding at hotspots is best illustrated at Barlow Point (Figure 9). In contrast to the wider distribution of stranding events at Sauvie Island (Figure 10) and County Line Park (Figure 11), the majority of stranding events at Barlow Point were clustered at a very small upstream hot spot. The magnitude of stranding at Barlow Point suggests that something more complex and unique is happening there than at either the Sauvie Island or County Line Park study sites. To a lesser extent, stranding events at Sauvie Island and County Line Park were associated with hot spots, but stranding at these sites were grouped more according to season (Pearson et al. 2006) (Figures 10 and 11). This is likely due to differences in water levels during different times of the year altering the location of the water's edge and also modifying beach morphology. At all the sites the hotspot stranding patterns occurred despite the generally even distribution of fish across these sites as determined by beach seine net sampling during the study (Pearson et al. 2008). This means that stranding susceptibility on a single beach can vary greatly over a very short distance and is likely associated with the fine-scale features of the beach.

Hotspot stranding is also important because it affects the conclusions of studies (e.g., Pearson et al. 2006) that have derived relationships between physical parameters (e.g., beach slope). Such studies and the relationship derived from them are based on stranding observations dominated by a small subset of the Barlow Point study site (the hotspot).

Coast and Harbor Engineering (2016) conducted a focused review of the morphology at the precise locations where stranding occurred at the Barlow Point, County Line Park, and Sauvie Island study sites to further evaluate how site morphology and the resulting hydraulics relate to the patterns of stranding that were observed by Pearson et al. (2006). Coast and Harbor (2016) found that beaches with a wide upper beach and a small and/or steeply sloped lower beach had a low potential for fish stranding due to the dissipation of wake energy. Shorelines with a wide and flat lower beach with no or very small upper beach (typically with an armored backshore) do not have a mechanism for dissipating wake energy. As a result, this type of shoreline morphology has a higher potential for stranding fish. County Line Park (RM 51.5) and Sauvie Island (RM 96.5) both represent morphologies with a lower potential for stranding (compared to Barlow Point) while the morphology of Barlow Point is associated with a very high risk of stranding (Coast and Harbor Engineering 2016).

In addition to overall beach morphology as described above, Coast and Harbor (2016) identifies that the location of the Barlow Point stranding hotspot on an outside bend of the river likely further contributes to the stranding at this site. Essentially, the hotspot is located at a focused point for energy based on how the ships turn offshore. This configuration focuses wave energy, likely increasing the effect of the vessel wakes.

The beach characteristics that Coast and Harbor (2016) identified as contributing to high stranding risk are additional criteria that can be applied to refine the understanding of areas previously defined as having a high susceptibility to stranding based on the criteria of Pearson et al. (2008). Additionally, the results of Coast and Harbor (2016) help explain why stranding hotspots occur and builds on the observations that that fine-scale beach morphology is a primary driver determining if a shoreline will strand fish.

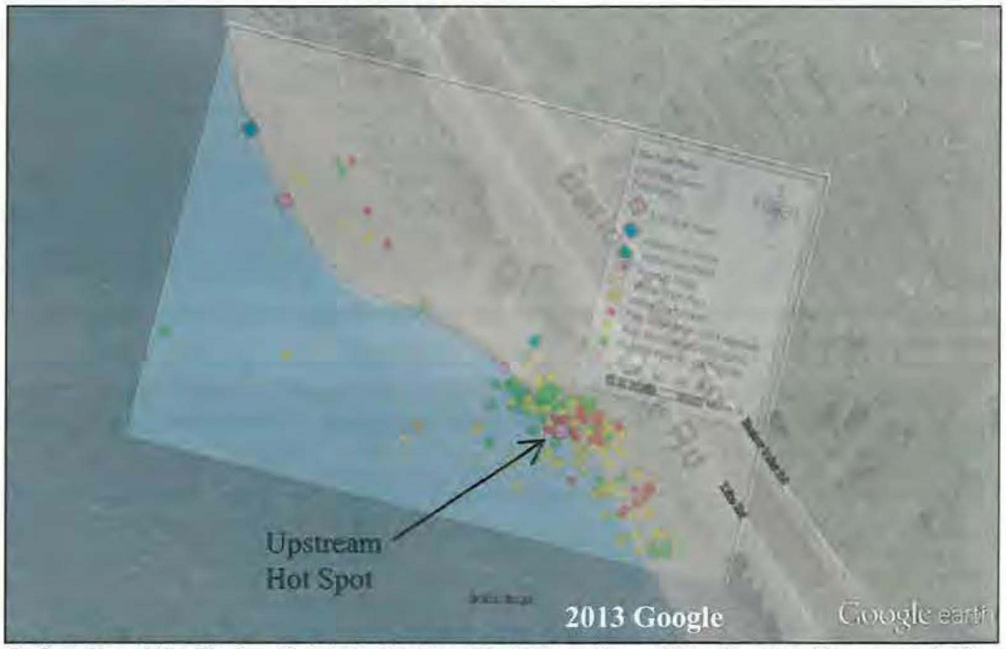

Figure 9. Overlay of the Barlow Point study site with the locations of beach-seine sites, wave staffs, run-up gauge, and seasonal stranding observations (for all fish) (graphic reprinted from Pearson et al. 2006; aerial photography from Google Earth 2013)

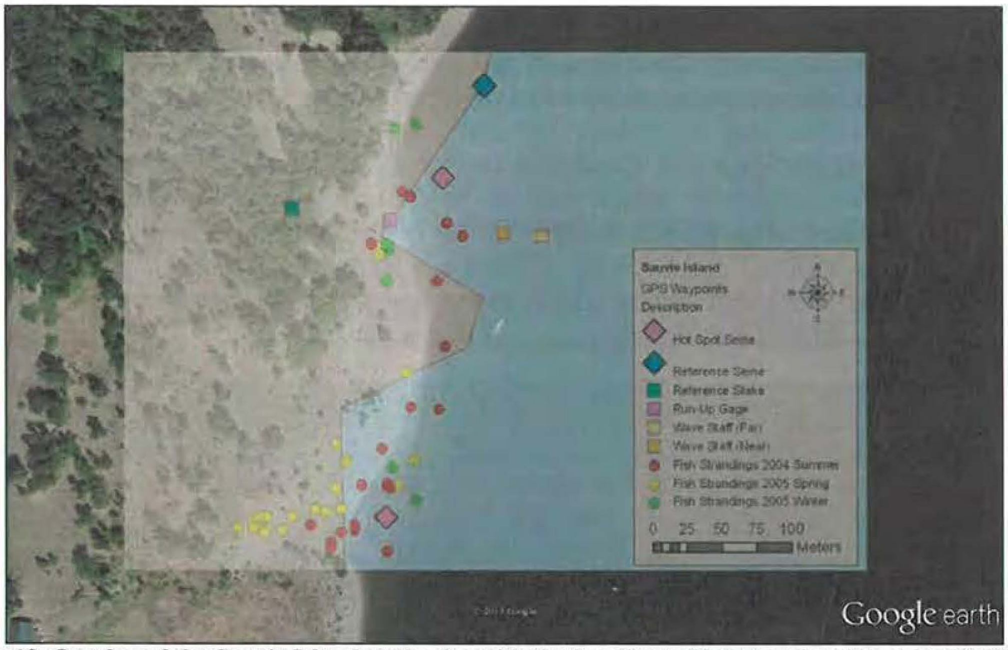

Figure 10. Overlay of the Sauvie Island study site with the locations of beach-seine sites, wave staffs, run-up gauge, and seasonal stranding observations (for all fish) (graphic reprinted from Pearson et al. 2006; aerial photography from Google Earth 2013)

Figure 11. Overlay of the County Line Park study site with the locations of beach-seine sites, wave staffs, run-up gauge, and seasonal stranding observations (for all fish) (graphic reprinted from Pearson et al. 2006; aerial photography from Google Earth 2013)

5. SUMMARY OF CONCLUSIONS

Section 2

- Wake stranding occurs on a small subset of the shoreline beaches of the vessel corridor not over a broad length of shoreline. Pearson et al. (2008) predicted that 16% or about 33 miles of non-contiguous beaches had some potential to strand fish. When additional beach morphology criteria were included Person et al. (2008) predicted that about 4% or about 8 miles of beaches had a high susceptibility to stranding.
- Stranding hotspots are determined by the morphological characteristics of the beach, not by the aggregation of the fish to a specific stranding-susceptible habitat.
- The seasonal abundance of small chinook in shallow shoreline habitat varies by season as does the numbers of fish stranded.
- Additional fine-scale morphological features, that control wave effects at the shoreline, appear to be necessary for there to be a stranding "hotspot" on a beach (Baursfeld 1977, Pearson et al. 2006).
- Further with respect to stranding of Chinook salmon, only small (35mm to 80mm) fish of one age group (0+ subyearlings) is at risk of stranding and only when present in shallow water.

Section 3

- The subyearling Chinook salmon that are subject to stranding are primarily from one ESU, (Lower Columbia River). The Upper Willamette River Chinook ESU is at a lower risk of standing because it is close to shore (and subject to being stranded) in fewer areas where there is a risk of stranding.
- Eulachon appear to be at limited risk of stranding by vessel wakes based on the analysis provide above, and were not detected in the most intensive stranding study that has been conducted (Pearson et al. (2006).
- Subyearling chinook salmon present in the shallow water margin of the Columbia River are on a "rearing migration" moving slowly downstream rather than holding in one location for months. This means that an individual fish is subject to stranding risk intermittently not continually on it path to the ocean.
- Based on genetic analysis, small subyearling Chinook salmon in shallow water areas susceptible to wake stranding are primarily comprised of fall-run stocks of the Lower Columbia River ESU.
- In the lower portion of the tidal freshwater area (RM 34 to RM 70) subyearling Chinook of the Lower Columbia River ESU are more than 90 percent of the subyearling Chinook salmon present along the shallow water shorelines of the Columbia River.
- In the middle portion of the of tidal freshwater area (RM 86 to RM 102), subyearling Chinook of the Lower Columbia River ESU are about 60 percent of the subyearling

Chinook salmon present along the shallow water shorelines of the Columbia River during winter and about 75 percent of those present in spring.

- In the middle portion of the of tidal freshwater area (RM 86 to RM 102), subyearling Chinook of the Upper Willamette River ESU are about 40 percent of the subyearling Chinook salmon present along the shallow water shorelines of the Columbia River during winter and about 10 percent of those present in spring.

Section 4

- The beach characteristics that Coast and Harbor (2016) identified as contributing to high stranding risk are additional criteria that can be applied to refine the understanding of areas previously defined as having a high susceptibility to stranding based on the criteria of Pearson et al. (2008). Additionally, the results of Coast and Harbor (2016) help explain why stranding hotspots occur and builds on the observations that that fine-scale beach morphology is a primary driver determining if a shoreline will strand fish.

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