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Pacific Northwest National Laboratory
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February 2006

Prepared for
the U.S. Army Corps of Engineers, Portland District
Portland, Oregon
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Marine Sciences Laboratory
Sequim, Washington

February 2006

Final Report

Prepared for
the U.S. Army Corps of Engineers, Portland District
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under a Related Services Agreement
with the U.S. Department of Energy
Contract DE-AC05-76RL01830

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Abstract

Ship wakes produced by deep-draft vessels transiting the lower Columbia River have been observed to cause stranding of juvenile salmon. Proposed deepening of the Columbia River navigation channel has raised concerns about the potential impact of the deepening project on juvenile salmon. The Portland District of the U.S. Army Corps of Engineers requested that the Pacific Northwest National Laboratory design and conduct a study to assess stranding impacts that may be associated with channel deepening. The basic study design was a multivariate analysis of covariance of field observations and measurements under a statistical design for a before-and-after impact comparison. We have summarized field activities and statistical analyses for the "before" component of the study here. Stranding occurred at all three sampling sites and during all three sampling seasons (summer 2004, winter 2005, and spring 2005), for a total of 46 stranding events during 126 observed vessel passages. The highest occurrence of stranding occurred at Barlow Point, Washington, where 53% of the observed events resulted in stranding. Other sites included Sauvie Island, Oregon (37%) and County Line Park, Washington (15%). To develop an appropriate impact assessment model that accounted for relevant covariates, regression analyses were conducted to determine the relationships between stranding probability and other factors. Nineteen independent variables were considered as potential factors affecting the incidence of juvenile salmon stranding, including tidal stage, tidal height, river flow, current velocity, ship type, ship direction, ship condition (loaded/unloaded), ship speed, ship size, and a proxy variable for ship kinetic energy. In addition to the ambient and ship characteristics listed above, site, season, and fish density were also considered. Although no single factor appears as the primary factor for stranding, statistical analyses of the covariates resulted in the following equations:

- Stranding Probability ~ Location + Kinetic Energy Proxy + Tidal Height + Salmonid Density + Kinetic energy proxy × Tidal Height + Tidal Height × Salmonid Density
- Stranding Probability ~ Location + Total Wave Distance + Salmonid Density Index
- Log(Total Wave Height) ~ Ship Block + Tidal Height + Location + Ship Speed
- Log(Total Wave Excursion Across the Beach) ~ Location + Kinetic Energy Proxy + Tidal Height

The above equations form the basis for a conceptual model of the factors leading to salmon stranding. The equations also form the basis for an approach for assessing impacts of dredging under the before/after study design.

Executive Summary

Ship wakes produced by deep-draft vessels transiting the lower Columbia River have been observed to cause stranding of juvenile salmon. Proposed deepening of the Columbia River navigation channel has raised concerns about the potential impact of the deepening project on juvenile salmon stranding. The Portland District of the U.S. Army Corps of Engineers requested that the Pacific Northwest National Laboratory design and conduct a study to assess stranding impacts that may be associated with channel deepening. The basic study design is a multivariate analysis of covariance of field observations and measurements under a statistical design for a before-and-after impact comparison. The report presented here is a summary of field activities and statistical analyses for the “before” component of the study.

Three previous studies have documented fish stranding caused by wakes from deep draft vessels along the Lower Columbia River (Bauersfeld 1977, Hinton and Emmett 1994, Ackerman 2002). The studies suggest that under certain conditions, deep-draft vessels (but not small vessels) can produce wakes that strand juvenile salmon. The factors that are thought to influence the occurrence of stranding include

- fish availability in the shallow nearshore zone along the beach
- nearshore ship-wake properties and wave run-up characteristics (wave height and period as well as direction, speed, and extent of wave draw-down and run-up on the beach)
- river elevation (river stage and tidal height)
- beach characteristics (slope, distance to navigation channel).

The overall goal of this study is to assess the impact of the channel-deepening project on juvenile salmon stranding along the Lower Columbia River. The specific question is whether the channel deepening project changes the risk that wakes of deep-draft vessels will increase stranding of juvenile salmon. The two objectives of the study are to

- assess the effect of channel deepening on the risk (probability) of juvenile salmon stranding with a before-and-after comparison
- determine the properties of ship wakes and resulting wave run-up generated by passing deep-draft vessels before and after channel deepening, and relate these properties to ship characteristics and shoreline conditions with factors analysis.

The basic design to assess stranding impacts is a multivariate analysis of covariance of field observations and measurements under a statistical design for a before-and-after impact comparison. The statistical analysis will test for the main effect of a period (i.e., “before” [2004 and 2005] channel deepening versus “after” channel deepening [estimated to be 2007]) after accounting for covariate effects (fish availability, wake characteristics, and other factors). Analysis of covariance will be used to assess period effects after adjusting pre- and post-periods to common conditions.

The work undertaken thus far included a planning phase (early 2004), a pilot study (spring 2004), and the "before" sampling (summer 2004, winter 2005, and spring 2005). Methods were largely developed during the pilot study, with additional modifications made during the first sampling period of the extended study.

Study sites for both the before and after phases are Barlow Point, Washington (Rive Mile [RM] 62), County Line Park, Washington (RM 51), and Sauvie Island, Oregon (RM 97). All beaches have a low slope (<5%) and are on the mainstem of the river. Substrate ranges from very fine sand (Barlow Point) to coarse sand (County Line Park).

We collected and analyzed data in four categories: site and ambient river characteristics, ship characteristics, wake characteristics, and fish characteristics (fish availability index and fish stranded). From the data, we developed 19 independent variables to be considered as potential factors affecting the incidence of juvenile salmon stranding, including tidal stage, tidal height, river flow, current velocity, ship type, ship direction, ship condition (loaded/unloaded), ship speed, ship size (length, beam, draft), and a proxy for ship kinetic energy. The proxy for kinetic energy was the ship block coefficient (length X beam X draft) multiplied by the square of the ship speed. A physics-based measure of kinetic energy is $KE = ½ mv^2$, where m = mass and v = velocity. Because we did not have a measurement for ship mass, we used a proxy variable related to displacement, which, in turn, is related to mass. In addition to the ambient and ship characteristics listed above, site, season, and fish density were also considered.

Stranding occurred at all sites and during all three sampling seasons (summer 2004, winter 2005, and spring 2005), for a total of 46 stranding events during 126 observed vessel passages. The highest occurrence of stranding occurred at Barlow Point, Washington, where 53% of the observed passages resulted in stranding. Stranding occurred with less frequency at Sauvie Island (37% of the observed passages resulted in stranding) and County Line Park (15% of the observed passages resulted in stranding). The sites were found to differ significantly in stranding occurrence, and there was no significant seasonal effect when site was accounted for.

Several ship types were observed, including car carriers, bulk carriers, tankers, and container ships. All of the observed passages used in the analysis of stranding were made by deep-draft vessels, as previous studies and field observations during the pilot study showed that other vessels produce small wakes. Ship and wake characteristics were evaluated to further understand how ship wakes are produced and interact with local bathymetry in the lower Columbia River.

The before-and-after comparison needed to account for covariates so that the comparison will not be confounded by changes in the covariates between the before and after phases. One covariate obvious during the design phase was fish availability, which received attention during design and dedicated sampling during the before-phase sampling. Other potential covariates were expected to be among the ambient conditions (e.g., tidal height, river flow) and among the ship and wake characteristics. However, precisely which of the several ambient conditions and ship and wake characteristics would be appropriate covariates was not evident during design or even the pilot-phase sampling.

Single-variable and multivariate regression analyses were used to discern which ambient conditions and ship or wake characteristics would be appropriate covariates. First, we examined the incidence of stranding events versus the ambient conditions and ship characteristics. Second, we examined the incidence of stranding events versus ambient conditions and wave characteristics. Third, we examined wave characteristics versus ambient conditions and ship characteristics. No single factor appears to be the cause for juvenile salmon stranding. Statistical analyses of the covariates resulted in the following multivariate equations:

- Stranding Probability ~ Location + Kinetic Energy Proxy + Tidal Height + Salmonid Density Index + Kinetic Energy Proxy × Tidal Height + Tidal Height × Salmonid Density Index.
- Stranding Probability ~ Location + Total Wave Excursion + Salmonid Density Index.
- Log(Wave Height) ~ Ship Block Coefficient + Tidal Height + Location + Ship Speed.
- Log(Wave Excursion) ~ Kinetic Energy Proxy + Tidal Height + Location

The covariates in the above equations are described below:

Stranding: probability that fish are stranded on a beach by a ship wake

Location: study site (Barlow Point, County Line Park, Sauvie Island)

Kinetic Energy Proxy: $KE' = [\text{Block Coefficient} \times (\text{Speed})^2]/1 \times 10^{-8}$

Tidal Height: predicted tidal height at the time of ship passage (from local tide chart)

Salmonid Density Index: salmonid (*Oncorhynchus* sp.) density in beach seine hauls; the Fish Availability Index for salmonds.

Total Wave Excursion: maximum distance across the beach of the draw-down and run-up of the onshore wave

Ship Block Coefficient: ship length x beam x draft, as provided by the Columbia River Pilots

Ship Speed: speed over ground in knots.

These equations indicate that location, a proxy for ship kinetic energy (which accounts for ship size and speed), tidal height, total wave excursion, and an index of salmon density along the beach are the primary factors in stranding occurrences. We have created a conceptual model to illustrate how these significant factors and interactions are linked together (Figure i).

Although the mechanisms of stranding are still not completely understood, the linkages in this model are all statistically significant, are consistent with what is known about biological and physical processes, and represent a substantial advance in our understanding of fish stranding by ship wakes. It is now clear that no single factor governs the process of stranding. Rather, a series of interlinked factors act together to produce stranding during a ship passage. The kinetic energy proxy derived from the size and speed of the vessel provides the energy producing the wake. Tidal height influences both the fish availability and the interaction of the wake with the beach at each site. Increasing total distance from draw-down to run-up is the wake characteristic that increases the probability of stranding. Increasing juvenile salmonid density in the nearshore increases the probability of stranding and remains a significant factor even after the location is taken into account. The multivariate regression equations, the video observations of waves, and presence of stranding "hot spots" all indicate that fine-scale site characteristics at a specific location play a dominant role in structuring the processes that produce the onshore wave and subsequent fish stranding.

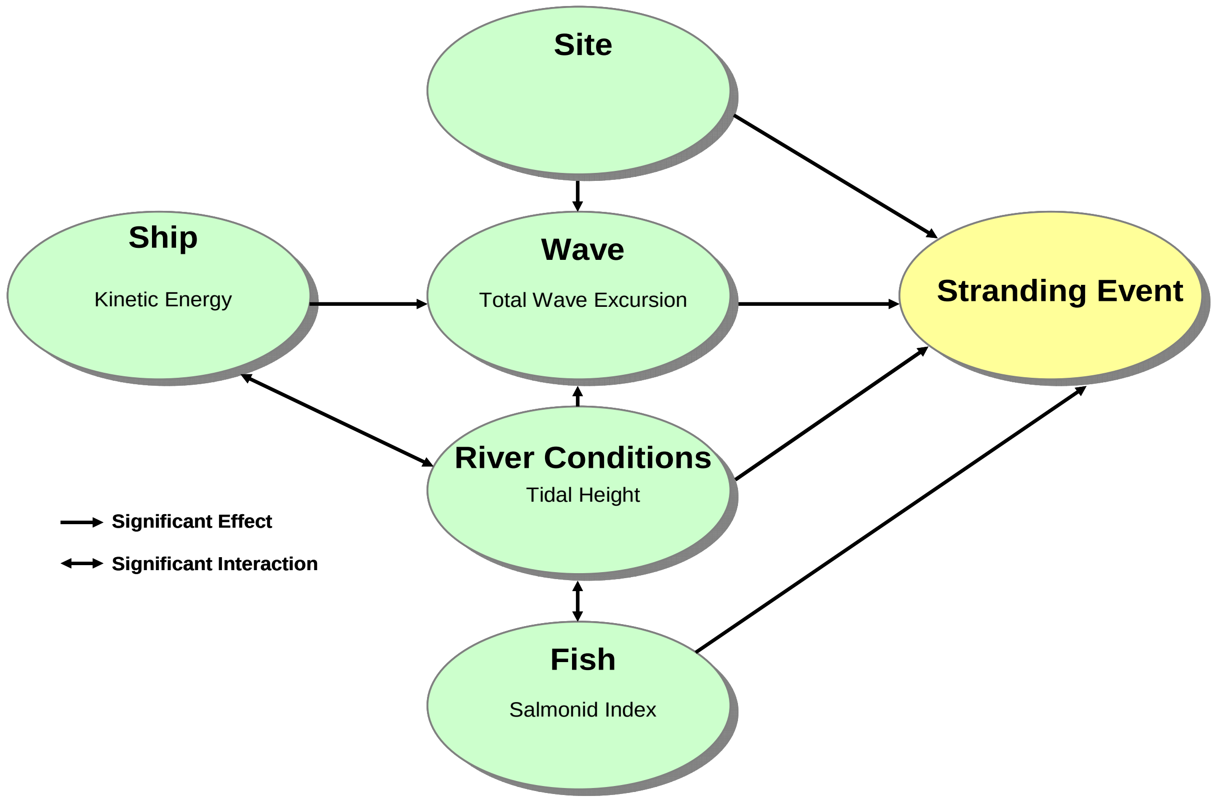

Figure i. Conceptual Model Illustrating Statistically Significant Factors and Linkages

The purpose of the before-and-after impact assessment is to determine whether the probability of juvenile salmon stranding will increase once the lower Columbia River is deepened (“post-dredging”). There are two questions to be examined:

1. For similar ambient river conditions, fish availability, and vessel conditions, does the probability of stranding relative to pre-deepening conditions increase after channel deepening?
2. If yes to the above question, then do the patterns of use by deeper-draft vessels change after deepening and, holding other factors equal, is greater probability of stranding associated with such changes compared with pre-deepening conditions?

The post-deepening impact assessment will examine both questions using the above multivariate regression equations derived from the pre-deepening data. For juvenile salmon stranding by ship wakes, we recommend the impact assessment decision process illustrated in Figure ii.

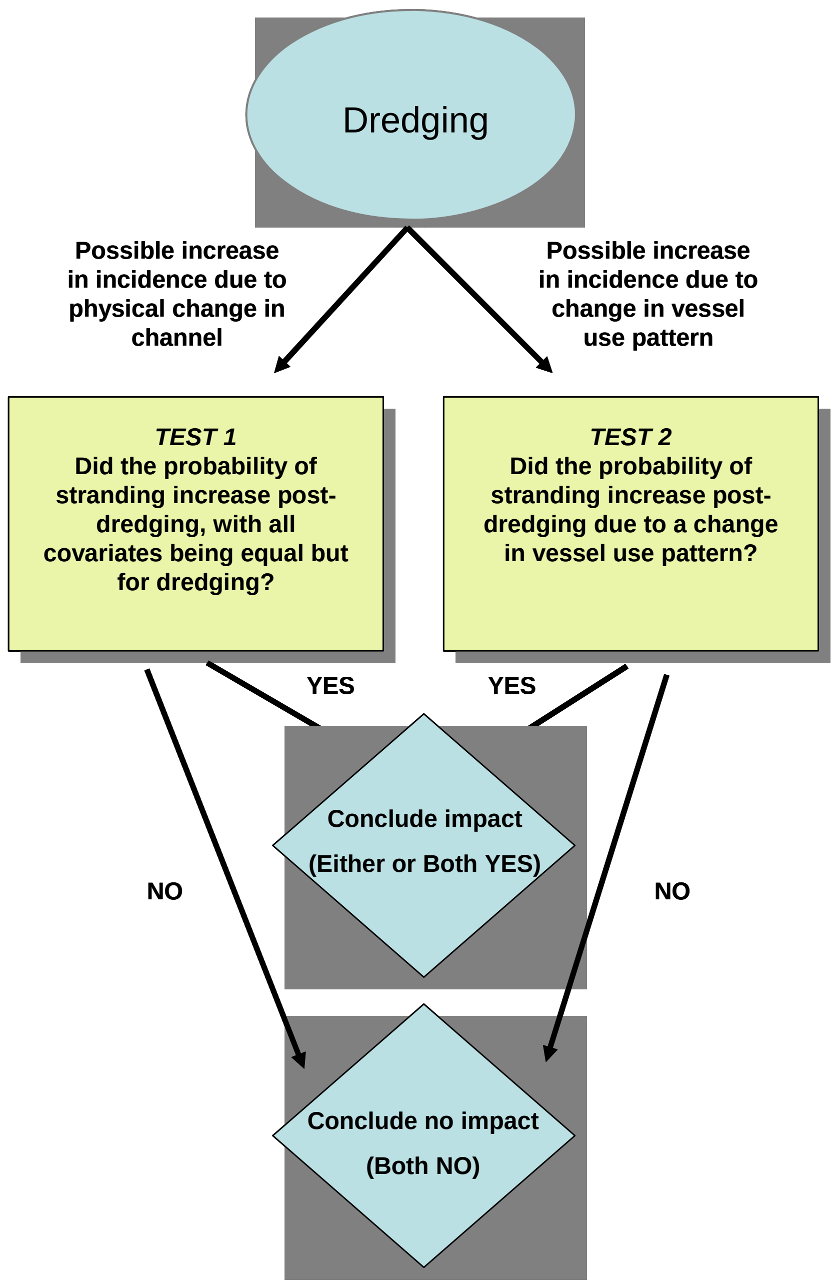

Figure ii. Schematic of the Decision Rules for Assessing Impact of Channel Deepening on the Incidence of Juvenile Salmon Stranding

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Glossary

ANOVA	analysis of variance
BP	Barlow Point
CL	County Line
Corps	U.S. Army Corps of Engineers
CPU	central processing unit
CRP	Columbia River Pilots
CV	coefficient of variation
dGPS	differential global positioning system
DIDSON	Dual-frequency Identification Sonar
FAI	Fish Availability Index
Fd	Froude number
GPS	global positioning system
KE	kinetic energy
LCR	Lower Columbia River
MLLW	mean lower low water
NAVEFF	Navigation Effects model
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
PCA	principal component analysis
PNNL	Pacific Northwest National Laboratory
RM	river mile
SI	Sauvie Island
USGS	US Geological Survey

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1.0 Introduction

1.1 Background

Wakes and subsequent beach run-up (swash) from deep-draft vessels transiting the Lower Columbia River (LCR) have been observed to strand juvenile salmon and other fish (Bauersfeld 1977, Hinton and Emmett 1994, Ackerman 2002). Proposed deepening of the Columbia River navigation channel has raised concerns about the potential impact of the deepening project on juvenile salmon stranding. The Portland District of the U.S. Army Corps of Engineers (Corps) requested that the Pacific Northwest National Laboratory (PNNL) design and conduct a study to assess stranding impacts that may be associated with channel deepening. The basic study design calls for conducting a before-and-after comparison while taking into account several covariables in the biological and physical processes leading to stranding. Two sets of such covariables encompass fish availability and wake characteristics in the nearshore area of the study sites. A separate work plan (Pearson et al. 2004) was the outcome of the design phase of this stranding study and provides more detail on the study design, technical approaches, and statistical analyses. This document serves as a summary report of the "before" phase of the study by describing field activities and providing results from activities undertaken in 2004 and 2005.

The Corps maintains the Federal Navigation Channel in the Columbia River through operations and maintenance dredging. Currently, the navigation channel is maintained to a depth of 40 ft. The Corps has proposed improvements to the main navigation channel that include deepening the channel to 43 ft. A deeper channel would lessen existing depth constraints to vessel movement, thereby improving access to the ports of the LCR for deep-draft vessels.

As a result of formal consultation under Section 7 of the Endangered Species Act, the National Marine Fisheries Service (NMFS) issued a Biological Opinion on the Corps' Columbia River Channel Improvements Project in May 2002 (NMFS 2002). The conclusion of the Opinion was that "the proposed action is not likely to jeopardize the continued existence of the 13 ESA-listed species potentially affected by the Project, or result in the destruction or adverse modification of designated critical habitat." However, the Opinion included terms and conditions to be implemented by the Corps. One such term and condition in the Opinion called for a before-and-after study of stranding. Another stated that "the Corps shall minimize effects from stranding through the following actions." The one action applicable to this study is paraphrased below:

> *Develop and implement a stranding study to evaluate parameters that influence stranding. Potential factors include river cross-sectional area, velocity, water level, bank configuration, location along river, slope of bank, ship traffic past site, and type, size, draft, and speed of vessel.*

Three prior studies have documented fish stranding caused by wakes from deep-draft vessels along the LCR (Bauersfeld 1977, Hinton and Emmett 1994, Ackerman 2002). Each of these three studies is qualitative in some aspects of its approach, while at the same time providing new information that increases understanding of fish stranding and making recommendations for future research. The sum of the three studies above suggests that under certain conditions, deep-draft vessels (but not small vessels) can produce wakes that strand juvenile salmon. The factors that influence the occurrence of stranding include the following:

- fish availability in the shallow nearshore zone along the beach
- nearshore ship-wake properties and wave run-up characteristics (wave height and period, as well as direction, speed, and extent of wave draw-down and run-up on the beach)
- river elevation (river stage and tidal height)
- beach characteristics (slope, distance to navigation channel).

Ship-wake properties are related to vessel size and speed and characteristics of the channel, prompting the need for comprehensive vessel and wake data collection. An analysis to compare pre-deepening stranding with post-deepening stranding needs to take into account fish availability along the beach, as well as the physical processes that result when ship wakes interact with gently sloping beaches. Thus, beach seining was proposed and used to provide an index of the availability of fish in the nearshore zone. To better characterize the factors that promote fish stranding, the present study measured vessel range and speed, the characteristics of waves resulting from vessel passage, and the extent of wave run-up on the beach. To better understand the wake properties, the study used the considerable body of theoretical and field research on the development of vessel wakes conducted by the Corps on the Upper Mississippi River-Illinois Waterway system. Measured wake and run-up data were used in conjunction with a physics-based numerical model, and field data were compared with model predictions to determine whether predictive models could be further developed specifically for use in other LCR reaches. Data collection was designed to support a statistical multivariate covariance analysis that will ultimately account for known confounding factors in comparing fish stranding before and after channel deepening.

1.2 Objectives

The overall goal of this study is to assess the impact of the channel-deepening project on juvenile salmon stranding along the LCR. The specific question is whether channel deepening changes the risk that wakes of deep-draft vessels will increase stranding of juvenile salmon. The two objectives of the study are to

1. assess the effect of channel deepening on the risk of juvenile salmon stranding with a before-and-after comparison
2. determine the properties of ship wakes and resulting wave run-up generated by passing deep-draft vessels before and after channel deepening, and relate these properties to ship characteristics and shoreline conditions with factors analysis.

Quantifying the total fish losses from stranding (loss determination) along the Columbia River cannot be supported by the statistical design proposed in the work plan (Pearson et al. 2004). Loss determination will require a substantially different statistical sampling design than the before-and-after comparison. The tasks outlined in the work plan provide information that will be useful in the design of a full loss determination. Also, loss determination should be conducted after channel deepening. Data collected before channel deepening may not be perceived as representative of post-deepening conditions.

1.3 Study Design and General Approach

The basic design to assess stranding impacts is a multivariate analysis of covariance of field observations and measurements under a statistical design for a before-and-after impact comparison. The statistical analysis will test for the main effect of a period (i.e., before [2004 and 2005] channel deepening versus after channel deepening [estimated 2007 or later]), after accounting for covariate effects (fish availability, wake characteristics, and other factors). Analysis of covariance will be used to assess period effects after adjusting pre- and post-periods to common conditions. Figure 1 illustrates the basis for the analysis under idealized conditions. Any difference in the amplitude of the regression lines after adjustment for covariate effects would be attributed to channel deepening effects. In practice, multivariate regression is used to assess treatment effects instead of the univariate regressions illustrated in Figure 1. A more complete discussion of the statistical modeling approach to assess impacts appears in Section 7.

The general approach to the fieldwork contains two interrelated elements. The first element consists of physical monitoring at beaches to measure and characterize vessel wakes during ship passage. This element is used to identify key parameters to characterize wakes, to compare these wake parameters pre- and post-channel deepening, and to provide covariates for the analysis of covariance. Ship-wake properties are measured with an electronic wave staff gage, and wave run-up is measured using a linear run-up gage designed and constructed by PNNL and video camera and video analysis software. Observations of ship characteristics also provide data to relate ship and wake properties. The second element is biological sampling. Beach seining is used to estimate fish presence and abundance and to provide covariates for comparing stranding between pre- and post-channel deepening. The biological sampling includes observations to provide a fish availability index (FAI). Together, these two elements provide the necessary data for statistical analysis to determine whether the channel deepening has, or has not, increased the risk of juvenile salmonid fish stranding in the LCR.

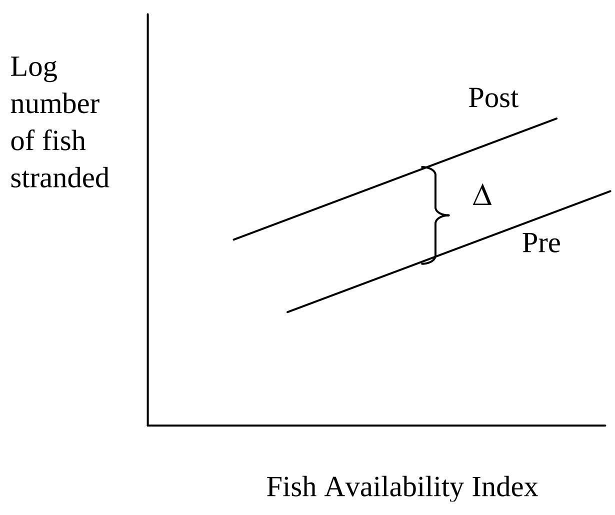


Figure 1. Profiles for Numbers of Fish Stranded as a Function of the Fish Availability Index and Pre- and Post-channel Dredging. Value of Δ is an estimate of the fractional increase in stranding due to direct and indirect effects of channel improvement.

The assessment of the effects of channel deepening on stranding of juvenile salmon will evaluate both physical and biological responses. Statistical analyses include regression analysis to relate ship wake run-up and other wake properties to ship characteristics and river elevation for both pre-deepening and post-deepening. Multivariate analysis of covariance is used to assess whether the risk of juvenile salmon stranding changes after deepening, adjusting for fish availability, run-up characteristics, and river elevation. Together, the assessments of the potential changes in physical and biological variables are used to infer the degree and extent of any changes due to channel deepening. If increased fish stranding is observed after channel deepening, it might be hypothesized that the extent of swash caused by ship wakes has also increased. Therefore, assessments of the changes in ship-wake properties and fish stranding before and after channel deepening provide supporting and confirmatory evidence if additional stranding occurs (see Section 7, Discussion).

1.4 Work Plan and Task Breakdown

The work plan (Pearson et al. 2004) presented to the Corps provided a task breakdown and proposed methods organized under four phases, described below.

1.4.1 Phase I. Design and Planning (January Through May 2004)

The objective of Phase I was to develop an appropriate statistical design and sampling scheme for "before and after" field studies. Three sites were selected where stranding was known to occur—a characteristic necessary to before-and-after comparison (see Section 2, Study Sites). The product of Phase I was a written plan for the fieldwork and data analysis (submitted January 2004).

1.4.2 Phase II. Pilot Study, Including Preliminary Testing of Prototype Run-up Gage and DIDSON Acoustic Camera (March Through June 2004)

Field deployments of various technologies proposed for the study were needed to validate equipment and refine methods. Development of the work plan led to the conclusion that a Dual-frequency Identification Sonar (DIDSON) acoustic camera might provide a less intrusive sampling method to capture fish availability. As part of Phase II, the DIDSON was evaluated along with other acoustic technologies. Additionally, the measurement of wave run-up or swash required instrumentation that needed to be tailored to riverine environments; this equipment was field-tested during this phase.

1.4.3 Phase III. Extended Field Sampling Pre-Channel Deepening (June 2004 Through May 2005)

We monitored three fixed sites (Sauvie Island, Oregon, and Barlow Point and County Line Park, Washington) (Section 2, Study Sites) during each of three outmigration periods (winter, spring, and summer). This work was initiated in summer 2004 (June through September) during the summer outmigration period and continued through May of 2005 (February and March for the winter sampling period, and April and May for the spring period). The basic unit of observation was the passage of an individual deep-draft vessel by a study beach and the subsequent number of fish stranded. Also, wake characteristics and fish availability were measured.

1.4.4 Phase IV. Extended Field Sampling Post-Channel Deepening (Estimated at 2007 or After)

Eventually, nearshore ship-wake properties and stranding will be measured over three outmigration periods, at all three sites, and comparisons between pre- and post-deepening will be made. Phase IV work is scheduled to commence in 2007, after channel deepening.

Phases I and II were completed and Phase III was initiated during FY04. Phase II was competed in FY2005. The work plan was the output of Phase I, and this report provides the results relating to the activities in Phase II and Phase III. Essentially, this report summarizes the pre-deepening field sampling activities and results.

2.0 Study Sites

In July 2003, as part of the planning process, approximately 12 potential study sites were considered and narrowed to 3 candidate sites, selected on the following basis:

- All sites are known to have previously had juvenile salmon stranding (for the before-and-after comparison, it is important to select sites where the events of interest are known to occur)
- All sites should have gently sloping beaches (previous work indicates this beach type is prone to stranding)
- All sites should be exposed to ship wakes from the navigation channel
- All sites should have evidence of fairly stable beach morphology.

Three candidate sites were visited in July 2003 by representatives from PNNL, the Corps, National Oceanic and Atmospheric Administration (NOAA) Fisheries, US Fish and Wildlife, the Port of Portland, the Washington Department of Fish and Wildlife, the Oregon Department of Fish and Wildlife, the Washington Department of Ecology, and the University of Washington to confirm the sites' suitability for the project. The three selected sites are the same LCR sites studied by Ackerman (2002) (Figure 2). Photographs of the sites appear in Appendix A.

As part of the field sampling, we collected data on beach slope, sediment grain-size composition, and infiltration rates at each beach to characterize beach structure (Table 1). Using a tripod, stadia rod, and range finder capable of calculating percentage of slope, we measured beach slope along a reference line at each site during each sampling period (Section 4.2, Materials and Methods, provides a complete discussion of site layout). We measured the relative infiltration rate of each site using a 0.5-m long, 10-cm diameter PVC pipe, driven 10-cm into the sediment and gradually filled with 4.5 gal of water at each of three locations per site. We recorded the time of infiltration for the known quantity of water, as it drained completely through the sediment at the base of the pipe. We performed this procedure at approximately the same elevation at each location, and approximated the midwater tide level at each site. In addition, we collected sediment grain-size samples from each site during each sampling period (composite samples of ~90 g at each site from low, medium, and high tide marks at each of three locations at the site). Samples were stored on ice and shipped within 5-days of collection for analysis. Particle size determinations were made by Columbia Analytical Services following standard Puget Sound Estuary Program protocols (Table 2.)

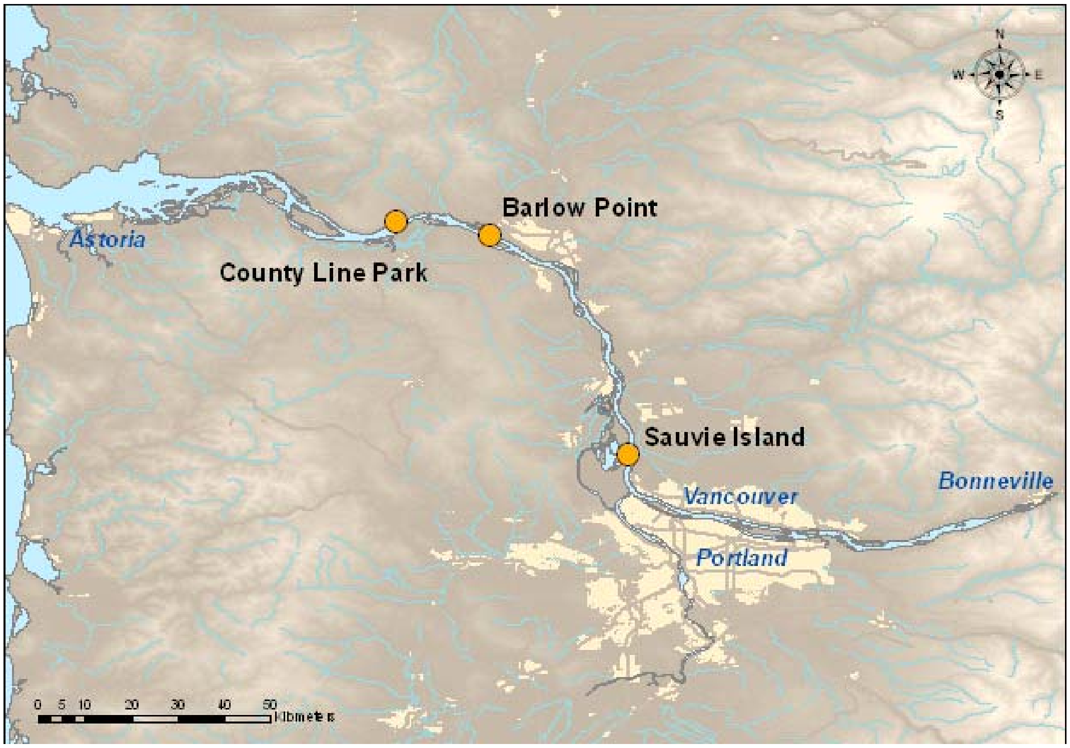


Figure 2. Study Site Locations, Including 1) Sauvie Island, 2) Barlow Point, and 3) County Line Park

Table 1. Physical Characteristics of the Three Study Sites: Sauvie Island, County Line Park, and Barlow Point

Site	River Mile	Tidal Datum	Average Infiltration Rate (l/m)	Season	Beach Slope (%)
Barlow Point	62	Longview, WA	0.11	Summer Winter Spring	2.3 2.1 2.2
County Line Park	51	Eagle Cliff, WA	2.45	Summer Winter Spring	4.1 4.1 3.9
Sauvie Island	97	St. Helens, OR	0.94	Summer Winter Spring	2.6 2.1 2.8

Table 2. Grain Size Analysis From the Three Sampling Sites During the Three Sampling Periods

Site	Season	Gravel	Very Coarse Sand	Coarse Sand	Med. Sand	Fine Sand	Very Fine Sand	Silt	Clay
Barlow Point	Summer	0.02	0.14	1.23	4.82	44.16	38.63	8.75	0.35
	Winter	0.04	0.04	0.24	4.11	41.83	45.30	6.60	0.05
	Spring	0.00	0.03	0.29	6.63	47.38	40.17	5.55	0.13
County Line Park	Summer	4.86	13.02	48.10	24.33	5.59	2.9	0.57	0.07
	Winter	0.73	5.98	54.57	32.00	4.95	1.25	0.12	0.02
	Spring	2.15	5.63	51.95	33.55	5.60	1.72	0.28	0.02
Sauvie Island	Summer	2.55	8.42	16.52	44.20	22.10	3.77	1.43	0.1
	Winter	0.78	3.08	11.64	47.97	30.20	4.53	0.55	0.01
	Spring	0.26	0.73	3.84	47.60	39.90	6.08	1.53	0.14

Note: Categories with the highest proportions are underlined.

2.1 County Line Park, Washington (RM 51)

The site is near the boundary between Wahkiakum and Cowlitz Counties on the north (Washington) side of the river. The survey reach extends 200 m east of the parking area at County Line Park. The beach is backed by riprap which protects State Route 4 and, at the downstream end, the County Line Park camping area, from erosion (Figure A-1). The beach is the narrowest (from the ordinary water line to the rip-rapped and vegetated backshore) of the three in the study. Additionally, the channel deepens very quickly at this site, producing stronger nearshore currents than at the other sites. Much of the beach is covered by debris that has sloughed off the rip-rap. County Line Park has the steepest beach slope (~4.0%), fastest water infiltration rate (Table 1), and coarsest sediment, with over 90% of the sediment collected composed of medium sand or larger particle sizes (Table 2). Tidal elevations were calculated from the Eagle Cliff datum; County Line Park, being the furthest downstream of the sampling sites, also has the largest tidal amplitude, with a mean range of 1.4 m (4.5 ft).

2.2 Barlow Point, Washington (RM 62)

This site is located on the north (Washington) side of the river. The survey reach is over 300 m long (Figures A-2 and A-3). At low tide, the expansive shore (over 100 m from the waterline to the backshore) is covered with rippled bedding characteristic of tidal flats (Figure A-4). This beach is the widest and most gradually sloping of the study beaches. The upper part of the beach on the upstream end is protected from erosion by a gabion structure referred to as "Reno Mat." The mat is wetted at high tide (Figure A-3) and redirects wave energy so that it travels laterally along the mat, generally in the downstream direction. At the downstream end of the beach, patches of vegetation (likely *Carex* sp.) occur at mid-tide level. Barlow Point has the most gradual beach slope (~2.2%), slowest water infiltration rate (Table 1), and finest average sediment grain size (Table 2). Over 90% the sediment collected from Barlow Point was composed of fine sand or smaller particle sizes. Tidal elevations were determined from the Longview, Washington, datum; Barlow Point has a mean tidal range of 1 m (3.3 ft).

2.3 Sauvie Island, Oregon (RM 97)

This site is located on the Oregon side of the river. The survey reach is ~300 m long. Some vegetation (shrub alder and grasses) is emergent on the beach face and is located ~75 m landward of the ordinary water line (Figure A-5). The reach is terminated at each end by an erosional bank and narrower beach face (Figure A-6). Sauvie Island's physical characteristics were intermediate between Barlow Point and Country Line Park with respect to beach slope (~2.5%), infiltration rate (Table 1), and sediment grain size (Table 2). Tidal elevations were determined from the St. Helens tidal datum, located downstream of the site; the mean tide range at St. Helens, is 0.6 m (2.0 ft).

3.0 Pilot Study

3.1 Introduction

Pilot field studies conducted at a single survey site (Sauvie Island) on the Columbia River during March 24–26, April 1, and April 21–22, 2004, evaluated the field sampling protocols and statistical design proposed in Phase I and detailed in Phase III. Many aspects of the extended field-sampling plan (Phases III and IV) were tested during the day and night, including run-up gage measurements, wave-sensor measurements, vessel characterization, monitoring of fish-stranding events, and development of the best technique for FAI measurements. The available literature related to wake generation in navigational channels was reviewed and used to guide the placement of the instrumentation.

3.2 Fish Availability Index

The statistical design for the before-and-after comparison uses the FAI in the nearshore area of a site to prevent the comparison from being confounded by changes in fish availability with time. Bauersfeld (1977) and Hinton and Emmett (1994) conducted beach seining to assess nearshore fish availability, and Ackerman (2002) recommended beach seining to assess fish availability in future stranding studies. It was recognized that beach seining is an intrusive sampling method and may itself confound stranding observations that closely follow seining activities.

In developing the work plan, it became clear that a less intrusive alternative to seining could be of advantage and that the use of the DIDSON acoustic camera might provide that alternative. The DIDSON has been used successfully in other fishery applications, including the identity, abundance, and behavior of juvenile salmon and their potential predators at a Washington State ferry terminal (Williams et al. 2003). The DIDSON camera, developed by engineers at the University of Washington Applied Physics Laboratory (http://www.apl.washington.edu/ programs/DIDSON/DIDSON.html), uses multi-channel acoustic reflections, rather than light, to create images of fish and other objects. The DIDSON can capture near-video-quality images, regardless of visibility. Therefore, the camera is especially useful at night and in turbid water. The pilot study included trials with the DIDSON camera to assess its potential effectiveness before undertaking the full study.

The results of the pilot study trials with the beach seine, acoustic camera, and split beam hydroacoustics did not lead us to recommend acoustic technology for this shallow-water application. The extremely shallow water of the study site caused difficulties with target recognition for the DIDSON camera. In response, we tried a narrow split-beam transducer, but this acoustic device also did not provide acceptable results. Limitations with push nets and snorkeling did not lead us to recommend those two techniques, either. Push nets do not sample larger fish or demersal fish in the water column. Snorkeling will not provide consistent observations in shallow, turbid water.

We recommended beach seining as the most practical basis for the FAI. Beach seining at the downstream end of the stranding survey area will be done to minimize disruption of the stranding data, because the fish of interest are more likely to be moving downstream than moving upstream (Figure 3).

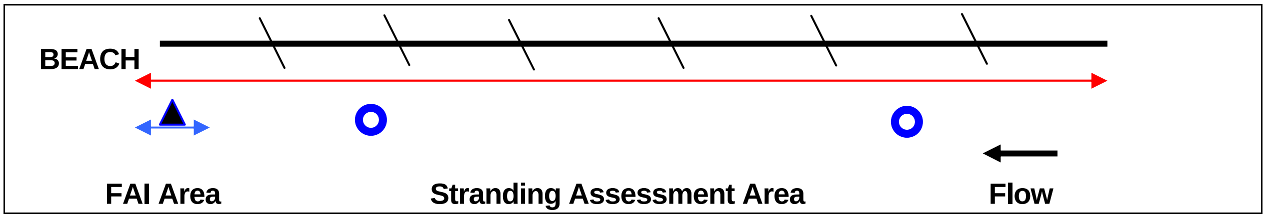


Figure 3. Schematic of FAI Relative to Flow and Stranding Assessment Area. The triangle represents the main seining site and the circles are supplemental seining sites, corresponding to fish stranding "hot spots."

Sampling for the FAI at the beginning, middle, and end of a study day is necessary because we probably will not know the vessel passage schedule precisely enough to do it before each passage event. Finally, spreading the three seine sets over the day rather than concentrating them at one time of the day increases the accuracy of the FAI for the same cost. In addition, we proposed to collect two more seine samples along the stranding assessment area at the end of a study day. These supplemental samples are to be chosen based on known fish stranding locales (stranding "hot spots"). They will provide additional data for the FAI and enable us to address the assumption that fish index data from seining at the designated location at the downstream end of the stranding assessment area is representative or proportional to the whole stranding assessment area.

Abundance data from beach-seining efforts will be used to estimate the FAI. Size information gathered from onshore stranding observations and seining efforts will indicate any differences in length between stranded fish and fish captured offshore of the beach. Information from seining efforts will also allow comparison of the ratio of wild to hatchery fish of the nearshore population with the ratio of those that are stranded, as well as the relative proportion of a given species in both the seined and stranded populations.

3.3 Fish-Stranding Measurements

During the pilot study, procedures for determining the number of fish stranded were tested. A strip-transect sampling technique was initially recommended. However, field crews were capable of covering 100% of the beach, from high water mark to standing water mark, after a vessel passed, and therefore, a full beach survey was recommended.

In general, stranding surveys of the beach are conducted upon arrival at the site and immediately following vessel passage and cessation of the wake impingement on shore. The start and end times for each survey are recorded. When fish are found, they are identified to species, salmonids are classified as native or hatchery stock (as determined by adipose fin clips), and length is measured. Live fish are placed in a bucket of river water for holding prior to being measured and released downstream. Dead fish are removed from the beach.

3.4 Wake Properties

The wake-waves generated by a ship making headway in a channel are of several types. The short-period waves generated at the bow of the vessel, along with the transverse stern wave, are developed as a result of the near-normal pressure distribution along the hull. The bow wave is formed as the water is accelerated along the flared portion of the bow and elevates the surface above the still-water level. Along the sides of the vessel, the accelerated water is lowered in accordance with Bernoulli's principle, which requires that pressure decrease as velocity increases. The transverse stern wave is formed by the return pressure and separation at the stern of the vessel.

If the vessel is in a channel, long-period waves characterized as draw-down and the following run-up or surge wave may also develop. These waves are observed if the draft of the vessel is greater than about half of the channel depth and a considerable portion of the water in the channel is displaced as the vessel proceeds. A large volume of water is pushed up at the bow of the vessel with an exaggerated lowering of water level along the sides (Figure A-7). The wave travels along the shoreline at the speed of the ship and may provide a significant lowering of the water followed by an up-rush. Depending on the slope of the channel flanks, the draw-down and run-up may affect a large portion of the shore perpendicular to the waterline.

Wave run-up has been measured on marine beaches with linear arrays of capacitance sensors that are triggered by high-salinity seawater. However, capacitance sensors are problematic in low-salinity riverine environments. PNNL developed an in-house prototype wave run-up gage, which is intended to measure three parameters: 1) the extent of wave run-up across the beach face, 2) the speed of run-up, and 3) the rate at which the wave withdraws or falls as the water sinks into the sediment. The device consists of a rigid horizontal frame to which floats are attached at 0.3-m (1-ft) intervals (Figure A-8). The run-up gage is laid across the beach face, perpendicular to the beach, and just above the beach surface. As the run-up wave lifts each float, the movement activates a series of reed switches (Figure A-9). A data logger records the events. The device is assembled in 3.1-m (10-ft) sections to cover a portion of the beach at a sampling site. Field trials at beaches near the PNNL Marine Sciences Laboratory examined the mechanical operation of an approximate 3.1-m (10-ft) section and the effectiveness of the data logger in recording the run-up characteristics. The field trials in March indicated that better anchoring for the run-up gage was needed. Improved anchoring was used in subsequent field work. The run-up gage was scaled up to cover a distance of ~30.5 m (100 ft) for the extended field sampling. Part of the device was deployed below the water line to measure the horizontal distance over which both draw-down and run-up occur.

Additionally, commercially available wave staffs from Ocean Sensor Systems were used to measure wave height and changes in water elevation along the shoreline (http://www.oceansensorsystems.com). We deployed two 3-m long staffs (Figure A-10, far right). These staffs are fast, capacitive-type water-level sensors. They operate from 5.5 volts to 40 volts, and output to the RS232 serial port on a laptop PC. We used the interface software provided by Ocean Sensor Systems.

3.5 Analysis and Modeling

The pilot study included analysis and modeling of wake properties generated by deep-draft vessels. The short- and long-period ship-generated waves on the LCR were evaluated using empirically developed relationships available in the engineering literature. The short-period waves from passing vessels, commonly observed as wake, were estimated using the method of Kriebel et al. (2003). The authors evaluated laboratory and field data of waves generated by a variety of ship types and sailing conditions and developed relationships that were shown to be superior to those previously available in the literature. The draw-down and subsequent run-up generated by large displacement ships in confined navigation channels were estimated using empirical relationships developed by Maynord (1996, 2003) for the upper Mississippi River and the Sabine-Neches Waterway. During the pilot study, qualitative observations revealed that the draw-down, run-up, and wakes generated by large ships passing the Willow Bar site on Sauvie Island were dramatic and were judged to be of the order of magnitude predicted by the models.

Because the ship-wave estimation methods depend on empirical data, they should not be used outside of the range of conditions over which they were developed without confirmation. If the field studies provide sufficient confirmation of the methods, they may be used to estimate generated vessel waves for other known ships transiting the LCR. The following steps are being taken to confirm the wave estimation procedures before they are used to predict wakes on the LCR:

1. Measure ship-generated waves using one or more wave staffs at the Sauvie Island, Barlow Point, and County Line Park study sites

   Measurements were made during the field work in Phase III for as many ship passages as possible. Other parameters of interest are beach slope, sediment characteristics, river current, river stage, tidal elevation, water depth, channel cross-section, ship speed and other ship characteristics (length, draft, displacement, hull shape, entry length) as available.

2. Measure the resulting draw-down and run-up from the ship passage

   We used measured or reported vessel characteristics and speed, as well as empirical data collected from passing vessels to calculate wave characteristics. We will compare the measured short- and long-period waves with those predicted from the Kriebel et al (2003) and Maynord (1996, 2003) methods.

We collected the following information on ship-wake properties and wave run-up for vessels passing during the survey:

- extent of beach run-up and draw-down (run-up gage)
- nearshore ship wake period (wave sensor)
- nearshore ship wake height (wave sensor)

- river stage: Flow stage information, both volume and current, for the river below the confluence with the Willamette River (USGS Beaver Army Terminal Gaging Station, RM 53.8) was obtained from the US Geological Survey (USGS) website: http://waterdata.usgs.gov
- tidal height: Tide predictions available through the "Tides and Currents" computer software program were used to estimate tide levels for the LCR.

Eventually, nearshore ship-wake properties and run-up will be measured at a variety of river stages (i.e., river elevations) over three outmigration periods, and comparisons between pre- and post-deepening at comparable river elevations will be made. Regression techniques will be used to characterize the relationship between wake properties, run-up, and river elevation and to assess whether channel deepening altered that relationship. The data collected from each vessel will be used to establish the wake-river elevation relationship. Nearshore wake properties will also be described as a function of vessel characteristics. The vessel characteristics found most helpful in predicting nearshore wake properties will be used as covariates in subsequent modeling efforts of fish-stranding numbers.

3.6 Pilot Study Recommendations for Data Collection During Extended Sampling

As mentioned previously, to account for the anticipated variability between fish-stranding events, several potential covariates will be measured for each vessel that passes, including vessel speed, draft, size, and direction of travel; nearshore wake properties, including wave height, period, direction, and resulting wave run-up; fish abundance; and river elevation. Water-quality parameters, including temperature, salinity, dissolved oxygen, and pH were also measured; water clarity (secchi depth) cannot be measured because of low light levels at night and the shallow depths where sampling occurs. A summary of the data collected during the 2004-2005 field sampling appears in Table 3.

Table 3. Summary of Data being Collected for the Extended Study of Stranding of Juvenile Salmon along the Lower Columbia River

Parameter	Collection Method/Source	Use of Data
Ship direction	Observation	Wake properties
Ship speed	Transit time over known distance	Wake properties
Distance from shore	Range finder, navigational chart	Wake properties
Ship name	Read from ship, confirm with Columbia River Pilots	Wake properties
Vessel type	Record type as: Bulk carrier, Car carrier, Oil tanker, Container ship, other	Wake properties
Ship characteristics (Draft, Beam, Length)	Confirm from Pilots records	Wake properties
Ship wake measurement	Wave staff gages	Relate to run-up
Channel bathymetry	COE data, Navigation chart	Wave transformation
Beach and nearshore slope	Transit measurement	Wave transformation
Wake run-up	MSL Run-up gage and video camera	Relate to stranding and ship characteristics
Beach material	Grain size analysis and field observation	Beach infiltration rate estimates
Beach permeability/drainage	Drainage test	Beach infiltration rate estimates
Stranding	Survey and count stranded fish on arrival at site and after each ship passage	Presence, abundance, and size distribution, of stranded fish
Positions	Geographic positions to be determined by dGPS.	Document positions of all measurements, strandings, and instruments
Fish in nearshore	Beach seining	Fish Availability Index, species, size, hatchery or wild
Water temperature	YSI Sonde multi-parameter probe	Fish conditions
River stage and flow	USGS Station at Beaver Army Terminal, Quincy, OR, www.usgs.gov	Wake properties
Tidal height	Tide prediction tables	Wake properties
Weather conditions	Record each 4 hours	Wake properties
Dissolved gas (Bonneville)	Columbia River Data Access in Real Time. www.cqs.washington.edu/dart/dart.html	Fish conditions
Dissolved gas (on site)	In-situ dissolved oxygen measurement	Fish conditions
Salmon release data	DART web site: www.cqs.washington.edu/dart/dart.html	Fish outmigration timing

4.0 Extended Sampling for Pre-Deepening Phase

4.1 Introduction

Extended sampling for the "before" component of the study comprised three sampling periods: summer, winter, and spring. The basic unit of observation was the passage of an individual deep-draft vessel by a study beach and the subsequent number and species of fish stranded, if any. Additional data regarding vessel characteristics, river condition, and fish availability were collected according to Table 3. To obtain sufficient numbers of observations, we attempted to observe a minimum of 14 vessels at each site; thus the entire study ("before" component) was to yield a total of 126 potential stranding events (14 vessels x 3 sites x 3 outmigration periods = 126 observations). Observations were limited to deep-draft vessels (e.g., bulk carriers, oil tankers, car carriers, and container ships), because smaller vessels and barges have not previously produced significant stranding, and initial observations in 2004 revealed small vessels produced wakes without draw-down. The order in which the sites were visited was randomly selected for each trip.

4.2 Materials and Methods

Methods and materials for the extended sampling initiated during summer 2004 were largely developed during the pilot study. Some refinement of sampling procedures occurred early in the summer field work and again in the winter sampling season. A full discussion of statistical analyses and the methods used relative to fish stranding was provided in the work plan (Pearson et al. 2004). The FAI was used in conjunction with records of observed stranding and vessel-passage characteristics to assess the characteristics most likely to cause fish stranding.

4.2.1 Vessel Characteristics

During ship passage, the characteristics of the vessel were recorded on a field form. These included: site, date, time of passage, weather conditions, direction of passage, ship name, ship type (e.g., car carrier, container), whether the ship was loaded or unloaded, its relative position in the channel (near, mid, far), and the vessel's speed. Additional notes regarding gage operation, vessel behavior, other vessel traffic in the area, and any other information of relevance were also made on this data sheet.

Vessel speed was measured by recording the time it took the vessel to travel 200 m. Gun-site stakes were installed upon arrival at the site; these stakes were set 200 m apart and were oriented in the same direction using a compass. Field personnel communicated via radio to start and stop the measurement, and an average of the two times collected by two observers was used. The time of passage and the vessel type were later given to the Columbia River Pilots (CRP) to retrieve positive identification on vessels. Vessel characteristics (e.g., length, draft, beam) were also gathered from the CRP or US Coast Guard Port State Information Exchange Vessel Search web portal (http://cgmix.uscg.mil/PSIX/PSIX2/VesselSearch.asp) for confirmation.

4.2.2 Wake Measurements

Two types of instruments to measure ship wakes were installed at each site during each sampling event: wave run-up gage and wave staff gage. Additionally, during the winter and spring sampling periods, a digital video camera was used to measure wave run-up speed. These instruments collectively measured a variety of wave characteristics, as discussed above in Sections 3.4 and 3.5. The placement of the gages varied slightly between sampling events; however, exact positions were noted using global positioning systems (GPS). Field measurements from a known reference stake were also collected.

4.2.2.1 Wave Run-Up Gage

The wave run-up gage captured wave extent and speed of run-up and draw-down. This 33-m long instrument is composed of 10 sections of equal length, set just above the substrate (the base of the float shields ~10 cm above the sand) at the mid-tide level of the beach (Figures 4 and A-8 through A-10). Placement was determined prior to installation by estimating minimum and maximum tide height during the sampling event. Placement was intended to maximize beach coverage (thus data collection) during the tidal cycle, though both the Sauvie Island and Barlow Point beaches were too broad at low tide to allow for full beach coverage. The gage was held in place by screw-anchors to prevent movement during wake events.

Once connected, the sections of the gage can each send 1000 mV of current when all floats are triggered (submerged). The gage was connected via cabling to a battery and a data logger, which wrote to a computer card. During vessel passage, the wave run-up gage data logger was manually activated as the ship neared the site. Once wave action ceased, the data logger was stopped. Data were downloaded to a permanent storage medium at the end of each sampling day using a laptop computer.

Post-processing of the wave run-up records involved filtering out errant readings and plotting the event. Qualitative observations were made regarding the condition of the record, as some records were partial or otherwise imperfect. Wave run-up gage plots show the voltage expressed during the event over time. Each 1000 mV corresponds to one section of the run-up gage, or ~3.1 m (10 ft).

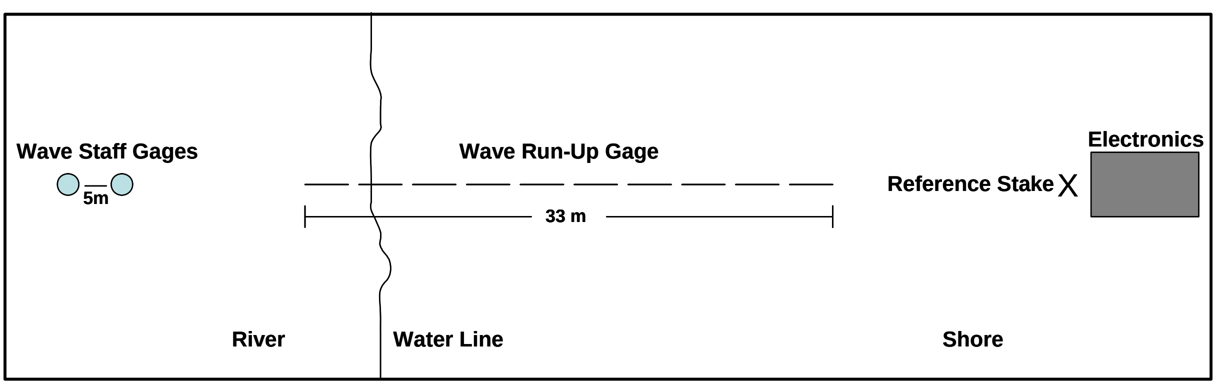


Figure 4. Plan-View Schematic of Gage Placement and Site Set-Up at a Stranding Study Site

When the gage was positioned optimally on the beach for a given tide height, the maximum extent of the draw-down and run-up were captured. Because of the large amplitude of the tidal cycle on the LCR and the difficulty in repositioning the gage once installed, many records did not capture the full extent of the wave event. However, even partial measurements from the wave run-up gage allowed for estimation of run-up velocity. The initial run-up was evaluated to determine speed of the wave. The calculation was done from visual examination of the plots by determining the extent of the run-up and the time between the beginning and end points of the wave.

4.2.2.2 Wave Staff Gage

Two wave staff gages set 5-m apart (extending perpendicular from the beach) were used to record wave characteristics (Figures 4 and A-10). The wave staffs are capacitive-type water-level sensors, and each consists of a 3-m long staff and housing (http://www.oceansensorsystems.com). These gages were placed at the deepest extent possible (Figure A-10) and were mounted on posts driven into the sediment. The tip of each staff was set ~15 cm above the substrate, with actual distance noted for each staff. Each staff was connected to a laptop computer and a 12-V battery via a cable (maximum extent is ~95 m), which was secured at several locations across the beach for stability during vessel passage. During each event, the staff-gage software was manually started in advance of the vessel passage to record stable conditions. Data were recorded for ~20 min after vessel passage until waves subsided and water elevation returned to near normal. Data were saved to a compact disk at the end of the field day.

Post-processing of the wave staff records involved filtering errant readings and plotting the event. Qualitative observations were made regarding the condition of the record, as some records were partial or otherwise imperfect. Voltage output was converted to elevation using a direct scaling algorithm, and plots of the near and far wave staffs were compared. In all cases in which both gages returned data, the plots were virtually identical, except for a slight phase shift, which accounts for the 5-m separation in installation. The deeper wave staff was selected for further processing, because it was less frequently subject to dewatering by the draw-down and low tide. If only one gage record was useable, it was used for the processing and considered to adequately represent the waves.

The raw data readings from the single gage selected were normalized to the still-water level by subtracting the mean of that entire time series from each successive measurement. The data were then filtered using a 60-point (6 sec) moving average to filter the short-period waves and emphasize the long-period waves. The 3 seconds at the beginning and end of each record was discarded since they were not averaged with all 60 points. Plots of the data were made on a single graph which showed the short- and long-period waves produced by the vessel passage. Examples are provided below in the results section.

4.2.2.3 Video Camera

A digital video camera was mounted on a t-post and tripod at the water line to capture wave events. Stakes were installed parallel (at a distance of ~20 m) to the camera's view at 5-m intervals so that the video would capture wave speed over a known distance. An additional stake was placed perpendicular to the camera so that any cross waves could be evaluated. The camera was manually started prior to vessel passage. A narrative of the approaching vessel, site, date, time and conditions, and a time-date stamp were used to validate vessel passage. Once the vessel passed, the camera ran until the waves subsided. The camera was moved with the tide to ensure similar positioning for all events.

In the lab, video was transferred from the tapes to a PC using Pinnacle Studio Deluxe version 8 movie-making software (Pinnacle Systems 2002). We watched the first part of each scene to confirm the ship name and time of vessel passage. The part of the event containing the wave draw-down and run-up was identified and a segment containing these features was recorded to the PC using the Studio software. In some cases, the run-up was either not identifiable or so slight as to not be measurable, in which case additional video was recorded to the computer to show that nothing measurable happened before secondary waves began.

Once the video clips were transferred to the computer, they were analyzed to determine the wave run-up speed using internal video analysis software. This software was designed for a separate project, but was modified to measure the speed of the wave as it passed between the stakes. As the wave crossed the first stake, a built-in timer was manually started; this timer was stopped as the wave crossed the farthest measurable stake. The distance measured could be adjusted depending upon the extent of the wave excursion (5 m, 10 m, or 15 m), though most of the measurements were made using the 5-m increment. The software calculated the time (m/sec) based upon user input for distance. Video clips were reviewed in slow motion and each wave was measured three times to arrive at an average speed measurement. The average speed for each event was entered into a spreadsheet.

4.2.2.4 Field Measurements of Wake Run-up Event

As a backup to the run-up gage, stakes and tape measures were used to obtain the maximum extent of run-up and draw-down. Prior to vessel passage, the still-water line was marked with a stake. As the vessel passed, the maximum extent of the wave draw-down and run-up were also marked with stakes. These three stakes were then measured from the reference point (geo-referenced) to get measurements of draw-down and run-up across the beach, as well as the sum of the two (total wave excursion).

4.2.3 Water Quality

Water quality measurements were taken with each beach seine using a hand-held YSI Sonde (Model 556, Yellow Springs Instruments 2001). The probe was held in the middle of the water column, ~0.5 m deep, in all cases. Temperature, dissolved oxygen, pH, and salinity were measured, recorded to a data sheet in the field, and entered into a spreadsheet in the laboratory.

4.2.4 Fish Availability Index

Fish were collected with a beach seine five times per sampling day, as noted above. Reference sites and fish hot spots remained the same throughout the sampling period. A standard Puget Sound floating beach seine (Simenstad et al. 1991) was used to collect fish for the FAI. Depending upon water depth, the net was set parallel to the beach approximately 30 m from shore. The depth of the water at deployment varied, but was generally 0.8 m to 1.2 m at the deepest point. The net was hauled evenly and gradually pursed as it reached the waterline. Fish were removed from the net and placed in buckets with fresh river water until processed. Fish were identified to species, counted, and measured (fork length for salmonids, total length for other species, in mm), up to 20 fish per species, per size class. To minimize handling, salmonids were placed in a glass graduated cylinder filled with river water for identification and measurement. Data were recorded on a field form and later entered into a spreadsheet for analysis.

4.2.5 Fish Stranding

After a vessel passed and wave action subsided, the field crew walked the beach looking for stranded fish. The line demarking maximum extent of wave-run up was covered first, as most fish tended to be stranded there, with subsequent passes on the river side of the high-water mark. Stranded fish were flagged by the observer. Fish were identified, their lengths measured, and their positions recorded in a handheld GPS unit. Their condition (dead or alive) and relative position (at water line or not) were noted along with any miscellaneous information. Alive fish were removed from the beach as soon as possible and placed in a holding bucket before being returned to the river; dead fish were removed from the beach to prevent confusion in subsequent events.

4.3 Results

Summary statistics and analyses for measured variables are provided below. Additional figures and data tables can be found in Appendixes B-D. A more thorough description of model development and analyses using multivariate analysis of covariance is discussed in Section 7.

Summer 2004 was the first of the “before” sampling periods. Field sampling began in June and ended in September 2004, with a total of four sampling trips. The first field trip used daytime observations and subsequent field trips used nighttime observations, because literature indicated higher stranding rates at night during the summer (Hinton and Emmet 1994). Two week-long winter sampling trips (February 8-13 and March 16–22, 2005) totaled 13 sampling days. For the spring sampling period, we spent a total of 14 field days at the three sites. The first trip was from April 11–16 and the second was from May 16–23, 2005. For both the winter and spring sampling periods, all observations were made during the daytime. The period of observation was 8 hours, though the field crew was often on site longer and therefore included observation of all ships that passed while they were present.

4.3.1 Ship Passages

During the three sampling periods, we observed a total of 126 vessels (Table 4). Although we did realize our total observation goal, we were unable to capture 14 events at each site during each period. Sauvie Island proved to be the most difficult site at which to obtain observations, possibly because it is upstream of the ports of Longview and Kalama, Washington. Ship passages were sporadic, with as many as 8 per observation period; several observation periods had 0 to 2 ships pass during the time of measurement (8 hrs minimum). For each vessel passage, data were compiled in a spreadsheet; Table 5 shows an example of the summary data available for a ship.

Table 4. Ship Passages Observed at Each Site During Each Sampling Period

Site	Observed Ship Passages			
	Summer	Winter	Spring	All
Barlow Point	23	14	12	49
County Line Park	17	14	8	39
Sauvie Island	14	12	12	38
All	54	40	32	126

Table 5. Summary Data for an Individual Vessel Observation

Summary of Event	
Period	Before
Season	Summer
Site	CLP
Diel Phase	Night
Date	08/09/04
Time	1950
Vessel Name	____________
Vessel Type	Bulk Carrier
Direction	Downstream
Condition	Loaded
Position in Channel	Far
Speed Over Ground	13.15 kts.
Stranded Fish	0
Tide Height at Eagle Cliff Datum (MLLW)	3.0 ft.
River Stage at Beaver Army Terminal (RM 53)	107,000 CFS
Current Velocity at Beaver Army Terminal (RM 53)	-0.17 ft./sec.
Duration of Event	14 mins., recorded
Maximum Draw-Down (wave gage)	36 ft.
Maximum Run-Up (wave gage)	14 ft.
Distance Between Draw-Down and Run-Up (wave gage)	50 ft.
Speed of Draw-Down	1.67 ft./sec.
Speed of Run-Up	1.46 ft./sec.

Of the total observed passages, 46 vessel passages resulted in stranding events (Figure 5). Barlow Point had the highest number of observed vessel passages (49) and the highest proportion of stranding events (26 of 49, 53% of passages). County Line Park and Sauvie Island had a similar number of observed passages (39 and 38, respectively), but Sauvie Island had a higher incidence of stranding with 14 events (37% of passages). We observed only six stranding events at County Line Park (15% of passages). There is a significant difference in stranding occurrence between the three sites (p = 0.001, chi-square test).

Stranding occurred at all times of day and during all seasons. A total of 80 passages were observed during the day, with 40% of those resulting in stranding events. 46 vessel passages were observed at night, with 30% resulting in stranding events. There was no significant difference between day and night stranding occurrence (p = 0.283, chi-square test, Figure 6). Due to seasonal differences in river flow and fish movement, season was hypothesized to be a factor in stranding occurrence. Although overall there was a significant season effect (p = 0.040, chi-square test), this effect is most evident at Barlow Point (p = 0.007, chi-square test), most likely because of the lower proportion of events that resulted in stranding during the summer period (7 of 23) than during the winter (9 of 14) and spring (10 of 12) sampling periods. At County Line Park and Sauvie Island, season is not significant in stranding occurrence (Table 6). At these sites, the proportion of stranding events was similar during all seasons.

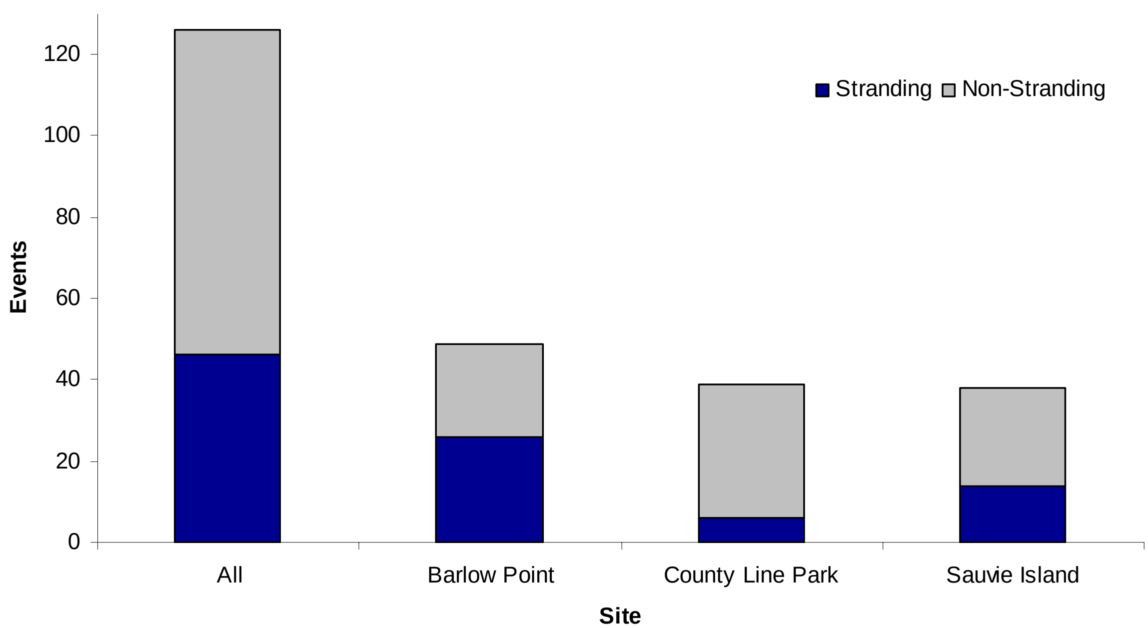


Figure 5. Stranding Events by Study Site and for all Sites (Left), Where the Total Number of Observances Is 126 and the Total Number of Observed Stranding Events Is 46

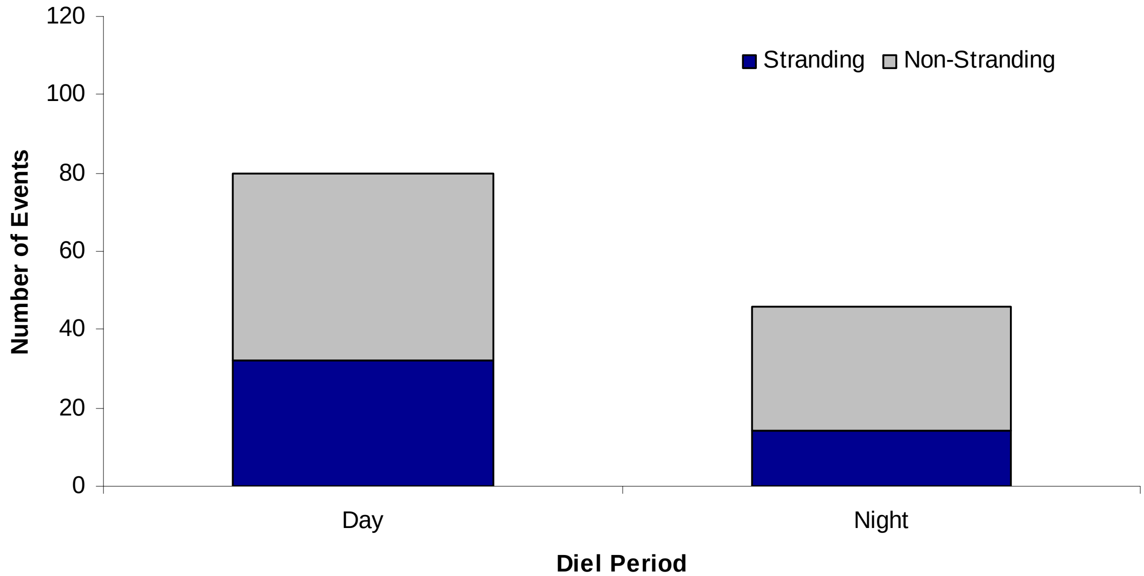


Figure 6. Stranding Events by Diel Period

Table 6. Chi-Square Test Results for Seasonal Effect at Each Study Site

Site	Proportion of Events Resulting in Stranding	p-value
Barlow Point	53%	0.007
County Line Park	15%	0.505
Sauvie Island	37%	0.722

4.3.2 Vessel Characteristics

Most observed vessel passages were bulk carriers, with car carriers being the next most common type of vessel observed (Figure 7). Other deep-draft vessel types included oil tankers, container ships, and other vessels such as military ships and research vessels. In some cases, the type of vessel could not be identified; in these cases, the vessel was considered “other” for analysis. Chi-square analysis showed vessel type to be marginally non-significant in stranding ($p = 0.099$). It is important to note that oil tankers produced the highest proportion of stranding occurrences (7 of 10 observed passages resulted in stranding). This was the only vessel type for which stranding occurred in more than 50% of the vessel passages.

Equal numbers of deep-draft vessels were observed going upstream and downstream ($n = 63$ in both cases). There was a significant difference ($p = 0.026$, chi-square test) in stranding occurrence between upstream- and downstream-bound vessels.

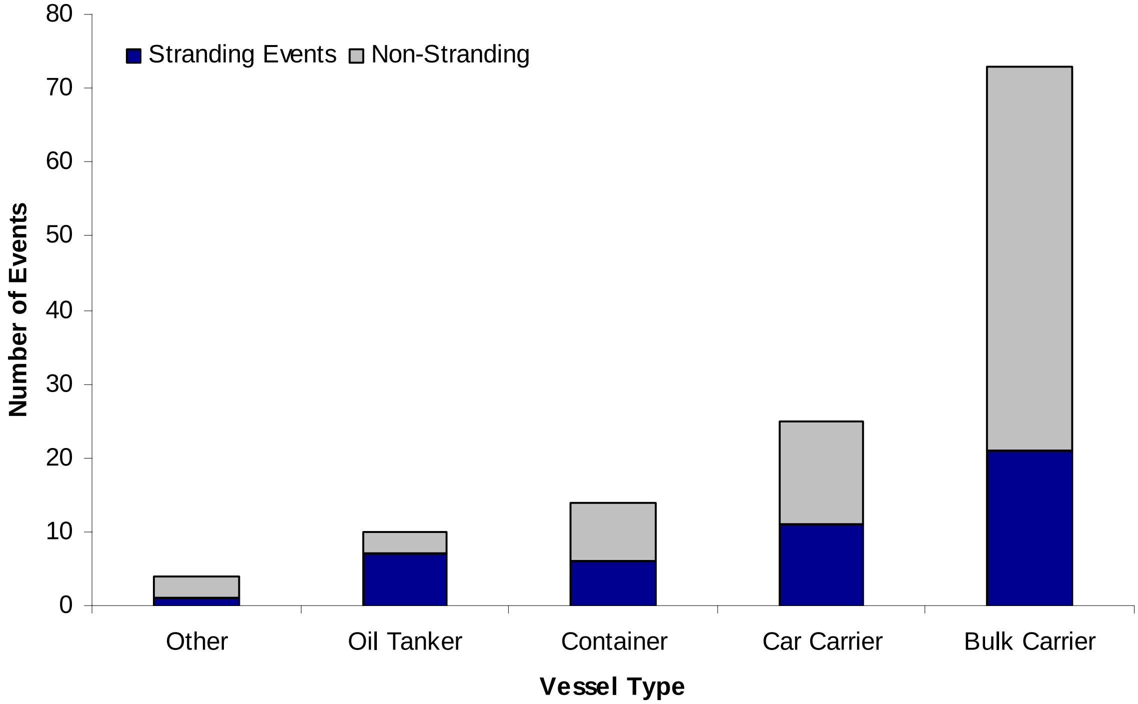


Figure 7. Number of Stranding Events Observed by Vessel Type for all Sites and Seasons

Vessel speed was analyzed in relation to stranding events (Figure 8). Speed over ground was used for calculations, though speed through the water likely differed from this measurement due to tides and currents. Stranding occurred during passages at a range of speeds; when the data were parsed out by site and season a similar result was seen.

Data on individual ships were obtained from the Columbia River Pilots. Ship beam, length, draft and block coefficient (beam x length x draft) were plotted with stranding events. Ships ranged in length from 91.4 m to 290 m (300 ft to 950 ft), with an average of 191 m (626 ft). The draft for all vessels was under 12.1 m (40 ft), though several had drafts of 11.8 m (39 ft). There was no direct relationship between ship size and stranding occurrence.

Because ship wake is a function of vessel size and vessel speed, we evaluated a kinetic energy proxy in relation to fish stranding (Figure 9). Kinetic energy (KE) is the energy of motion and is defined as follows:

$$KE = \frac{1}{2} mv^2 \qquad (1)$$

where m is the mass and v is velocity.

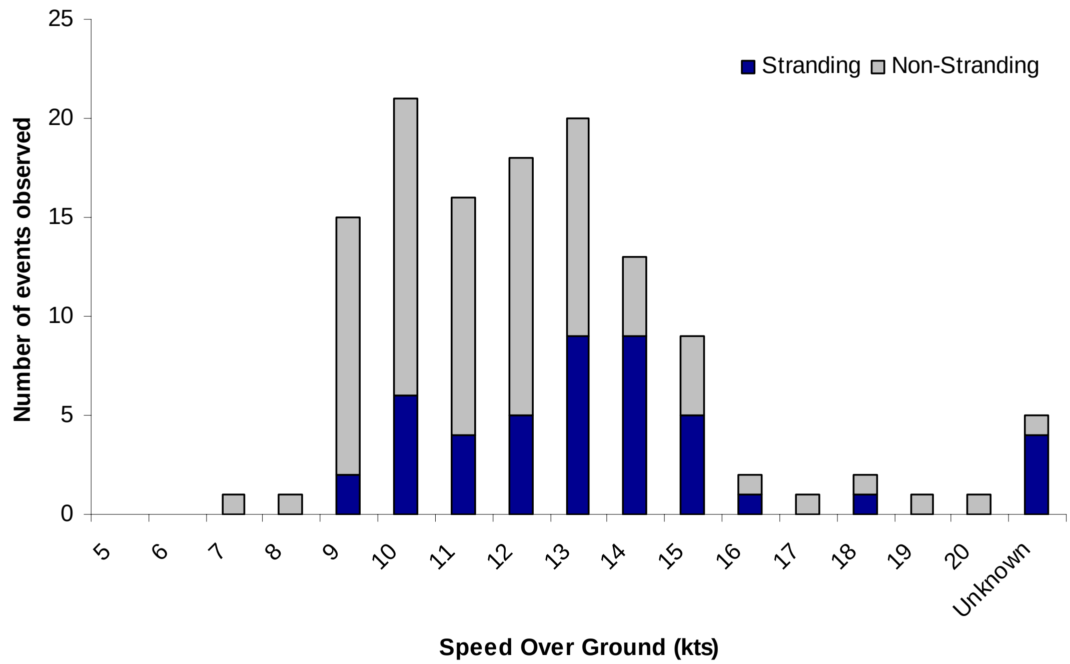


Figure 8. Stranding Events by Vessel Speed for all Sites and Dates

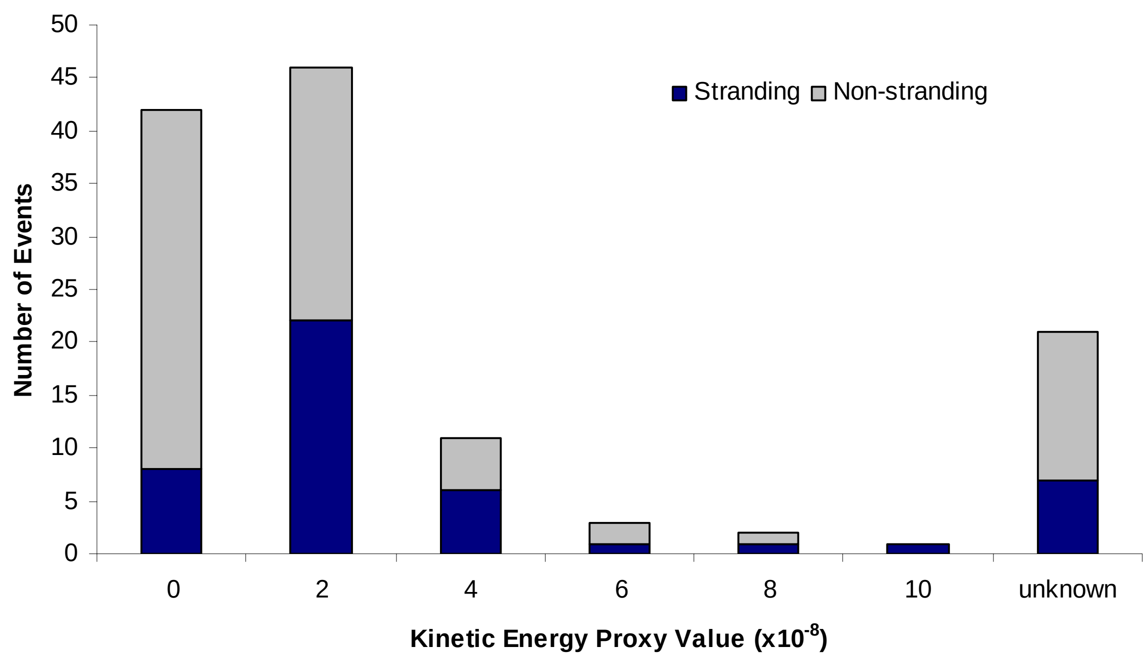


Figure 9. Stranding Events by Kinetic Energy Proxy

Because we did not have a direct measure of mass, we used the ship block factor, which is related to displacement, to arrive at a proxy. Therefore, though we have called this factor kinetic energy, it is actually a proxy for kinetic energy, whereby

$$KE' = [\text{Block Factor x (Ship Speed)}^2]/1 \text{ x } 10^{-8} \qquad (2)$$

where block factor is the ship length x beam x draft, as provided by the Columbia River Pilots. Kinetic energy is significant with regard to fish stranding ($p = 0.042$, chi-square) when all sites and sampling periods are pooled.

4.3.3 River Characteristics

A number of characteristics related to river condition were obtained for each observation. These included tidal height, river flow or discharge (cfs), and river velocity (ft/sec). River discharge ranged from -100,000 cfs to 450,000 cfs during the study period. River velocity ranged from -0.3 to 1.2 m/sec (-1 to 4 ft/sec) (negative discharge and velocity result from a rising tide reversing the flow in the LCR). Greater discharge and velocity occurred during the spring sampling period (mean of 327,000 cfs over all sampling days) than the other sampling periods (winter mean was 102,000 cfs; summer mean was 154,000 cfs) as a result of unusually high run-off. Stranding events were observed over a range of river discharge and velocity levels.

Tidal height was also considered as a variable for stranding occurrence (Figure 10). Each of the study sites was subjected to a different tidal regime, given position on the river. County Line Park, the most downstream site, had the highest mean tide range (1.4 m [4.5 ft] mean lower low water, or MLLW), whereas Sauvie Island had the lowest mean tide range (0.6 m or 2.0 ft, MLLW) being the farthest from the river mouth. For all sampling periods and sites, tidal height is significant ($p = 0.024$, chi-square test); however, when each site is analyzed individually, only Barlow Point shows tidal height to be significant ($p = 0.026$). At this site, tides from 0 m to 0.3 m (0.0 ft to 1.0 ft) had the highest proportion of stranding events. It is important to note that season and river flow influence tides considerably and that predicted tides were used in these analyses.

4.3.4 Wake Description

For each event, plots of ship wakes were created from gage data. In general, a ship wake consisted of a draw-down event followed by a run-up event, with smaller waves being generated after the initial run-up. A full description of wake generation and prediction can be found in Section 5. Although the first run-up tended to be the most extreme, several events had later waves that reached farther up the beach than did the initial run-up. Most events continued for 15 to 20 min before wave action subsided to ambient conditions; occasionally an event would continue for 40 min or more. On several occasions, a second vessel passed before the first event ended. These occurrences were noted in the field notes.

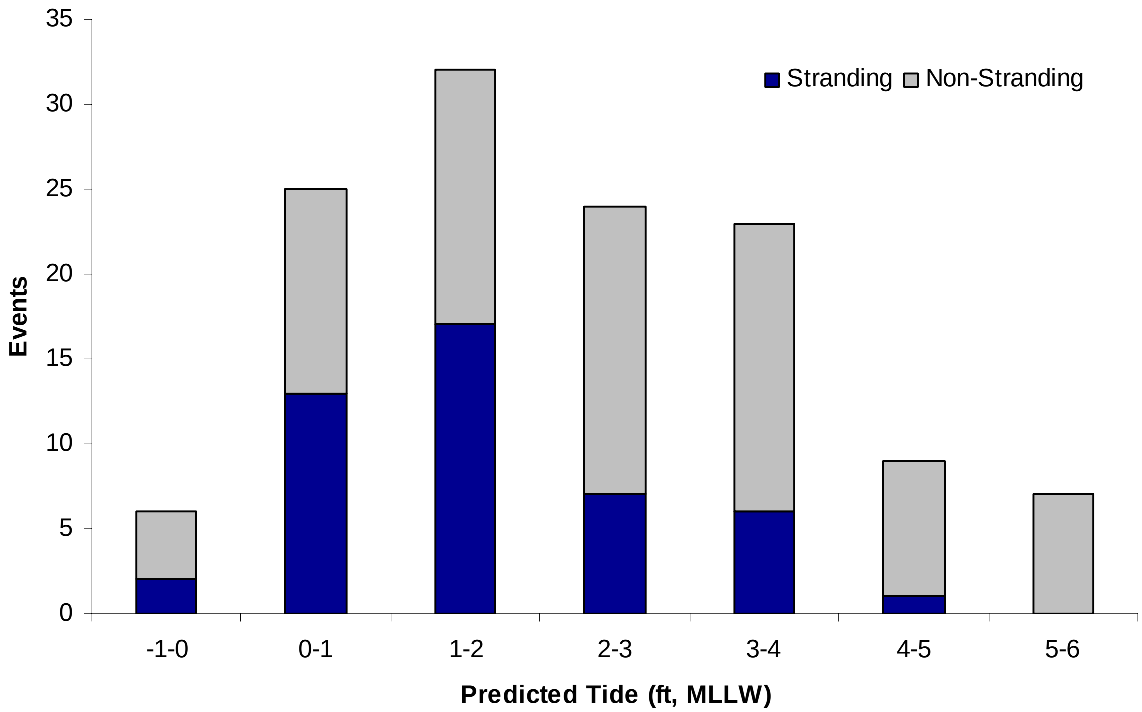


Figure 10. Stranding Events by Tide Height for all Sites and Seasons

At all sites, but particularly at Barlow Point, cross waves were observed. The anticipated ship-wake wave (onshore wave) was one that traveled from the channel up the beach face (Figure 11). The cross waves traveled across the beach face and typically met oncoming waves, which muted their force (Figure 12). Cross waves were seen in areas with complex shoreline structure, for example the Reno mat at Barlow Point and rip rap at County Line Park. Cross waves made the measurement of wakes difficult, as they were often strong enough to disrupt the wave run-up gage. Video footage taken during events captured the nature of these waves. The generation of cross waves may have contributed to fish stranding. Because this phenomenon was unpredictable, it was difficult to measure, though such waves were observed repeatedly by the field crew.

Figure 13 shows a typical wake event. The draw-down and run-up surge generated by the vessel passage are discernable to the left of the plot, as well as the arrival of short-period wake-waves at about the same time as the second surge. In this case, the event lasted about 10 min before the wave action subsided.

For some records, the run-up is followed by a series of evenly spaced wave maxima with periods of about 70 sec. These oscillations extend, with diminishing amplitude, for the entire record length of up to 40 min. The period of oscillation of the wave is consistent with that of a shallow-water wave reflected from bank to bank across the channel. Other investigators have shown records with a few wave cycles that may be indicative of reflections (Maynord 2003). None, however, have lasted as long, nor have others drawn the relationship to cross-channel oscillation. Wake records at all sites show evidence of reflections, but the channel cross-sections at Barlow Point and County Line Park are more complicated by side channels and shallow areas than is the Sauvie Island site, where this pattern is most visible.

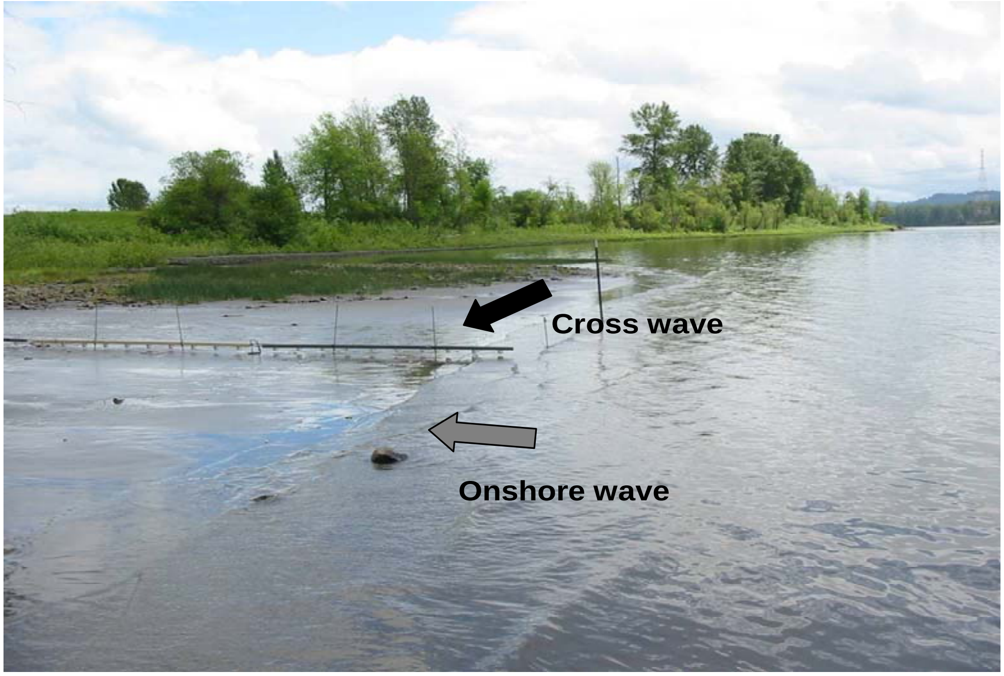


Figure 11. Beach Stretch Showing Direction of Onshore Wave (gray arrow) and Cross Wave (black arrow)

Figure 12. Example of Cross Wave at County Line Park, Coming Across the Beach Rather Than Up the Beach

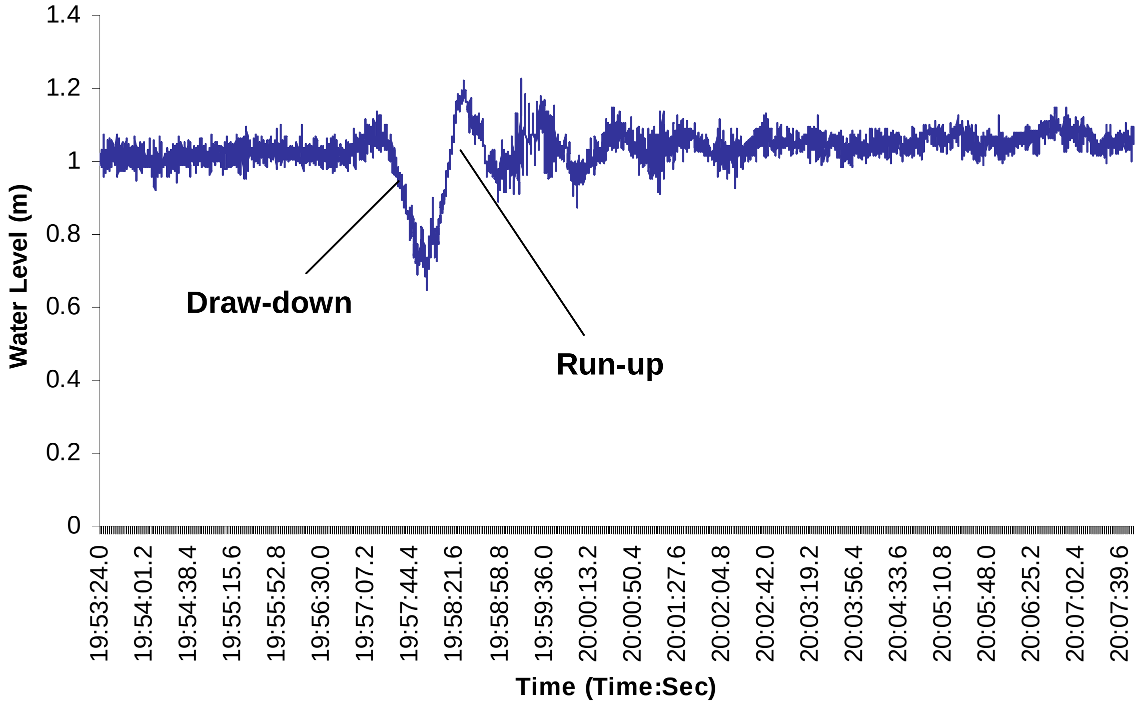


Figure 13. Record From Wave Staff Gage Showing Wake Event Through Time

Figure 14 shows a successful plot of the wave-run up gage. Few records showed the full extent of the event because of the positioning of the instrument on the beach. From the plots, average wave speed was determined. For example, for the initial wake set in the event shown below (Figure 14), the draw-down velocity was 0.51 m/sec (1.67 ft/sec) and the run-up velocity was 0.45 m/sec (1.48 ft/sec). Steeper waves indicate higher velocity, though many wake events resulted in cross waves or confused waves, which interfered with the function of the gage.

For the successful events, distance of the wave excursion could also be measured. However, the run-up and draw-down measurements from the wave run-up gage records differed from those taken in the field using stakes and a tape measure. For example, for the event shown in Figure 14, the apparent distance of the excursion from the wave run-up gage record was 16.1 m. The field measurement for the same event showed a total excursion of 28.7 m. Because the gage is placed several centimeters above the substrate (Section 4.2, Materials and Methods), and the floats are tripped only when there is enough water beneath them (~12 cm), the actual extent of run-up and draw-down as measured in the field by marking the water lines is likely to differ from that recorded by the gage. Therefore, the field measurements are a more reliable and accurate means of measuring wave excursion across the beach.

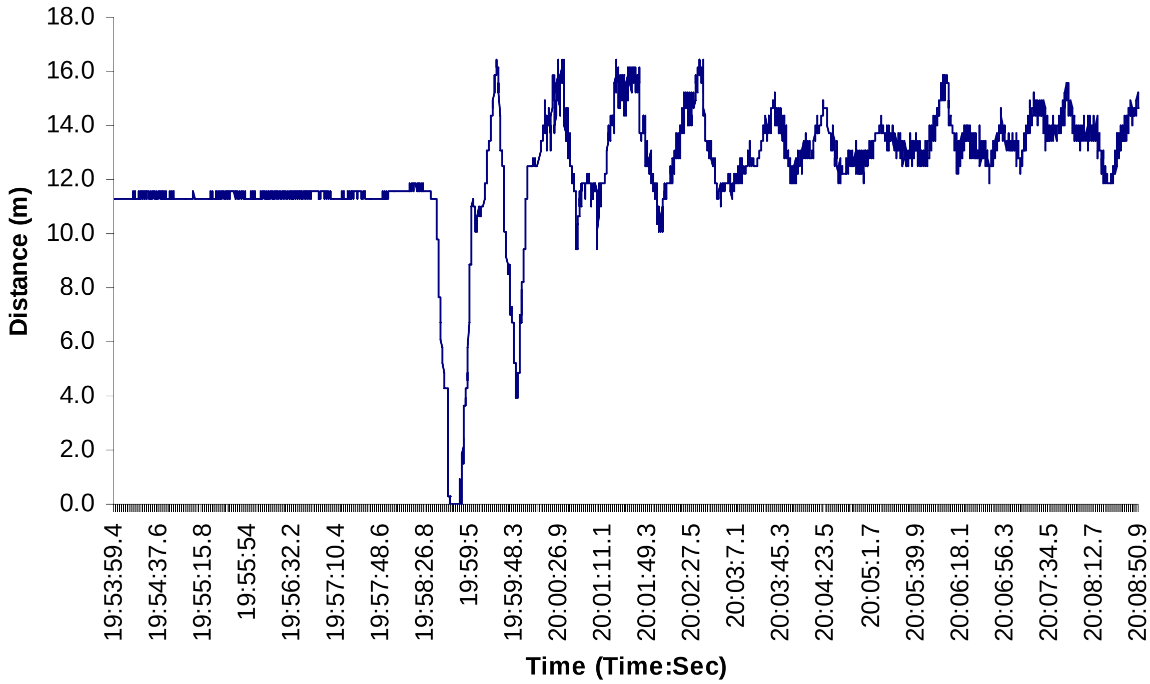


Figure 14. Wave Run-up Gage Plot Showing the Full Extent of Draw-down and Run-up Over the 15-Minute Sampling Event.

4.3.5 Wake Characteristics

A number of variables relating to ship wake were evaluated and are defined in Table 7. These measurements were derived from the wake plots or were measured directly in the field, as noted. Field measurements of the total wave excursion (across the beach face) ranged from 3 m to 78 m. Run-up and draw-down distances tended to be approximately equal, with a mean run-up of 9.3 m and draw-down of 12.6 m. When binned by distance of excursion (Figure 15), distance of total wave excursion appears to be a significant factor ($p = 0.004$, chi-square test).

Similarly, the vertical extent of wave run-up and draw-down was measured and analyzed. The maximum vertical extent ranged from <0.1 m to over 0.7 m, with a mean of 0.25 m. There does not appear to be a clear relationship between vertical extent of ship wakes and fish stranding (Figure 16) and chi-square analysis shows no significant difference in stranding occurrence between ranges of vertical extent ($p = 0.138$, Unknown category removed for analysis).

Table 7. Descriptions of Wake-Related Variables

Variable	Source/Unit of Measurement	Description
Run-up distance	Measured with tape, m	Horizontal distance from normal water line to furthest extent of run-up, measured by flagging the normal water line prior to ship passage and the highest extent of run-up during the vessel passage and measuring the distance between the 2 flags (e.g., 15 m)
Draw-down distance	Measured with tape, m	Horizontal distance from normal water line to furthest extent of draw-down, measured by flagging the normal water line prior to ship passage and the lowest extent of draw-down during the vessel passage and measuring the distance between the 2 flags (e.g., 10 m)
Total Wave Excursion	Measured with tape, m	Maximum distance between run-up and draw-down (sum of 2 measurements, e.g., 25 m)
Run-up Velocity	Camera, m/s	Speed of wave (m/sec) as it crosses between 2 points of known distance from each other (2.5 m, 5 m, or 10 m, depending upon event)
Run-up Velocity	Run-up gage, m/s	Speed of wave (m/sec) during a run-up event using the wave run-up gage. Value was determined by taking a trough and peak of one wave and dividing the maximum distance by the time elapsed.
Wash-back Velocity	Run-up gage, m/s	Speed of wave (m/sec) during a draw-down event using the wave run-up gage. Value was determined by taking a peak and trough of one wave and dividing the maximum distance by the time elapsed.
Vertical draw-down height	Staff gage, m	Vertical distance (-) of wave from the mean
Vertical run-up height	Staff gage, m	Vertical distance (+) of wave from the mean, from the first wave following the draw-down
Maximum Vertical Extent	Staff gage, m	Vertical distance (+) of wave from the mean, from the largest wave of an event

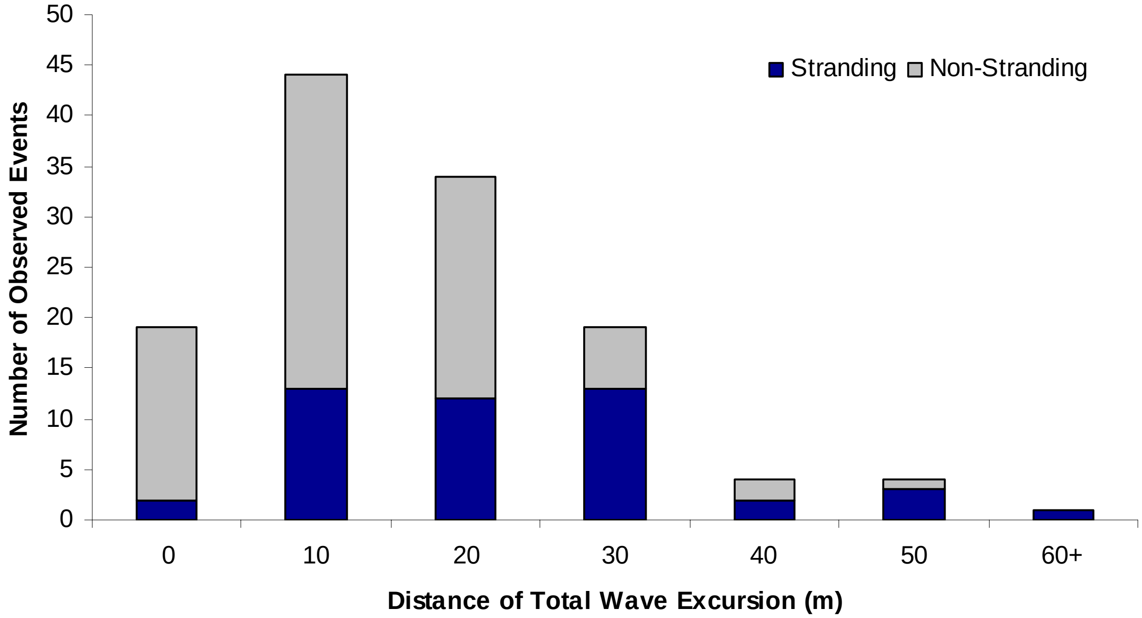


Figure 15. Stranding Events by Distance of Total Wave Excursion Across the Beach Face. Categories refer to a range, e.g., 0 = 0.1 to 9.9; 10 = 10.0 to 19.9; 20 = 20.0 to 29.9.

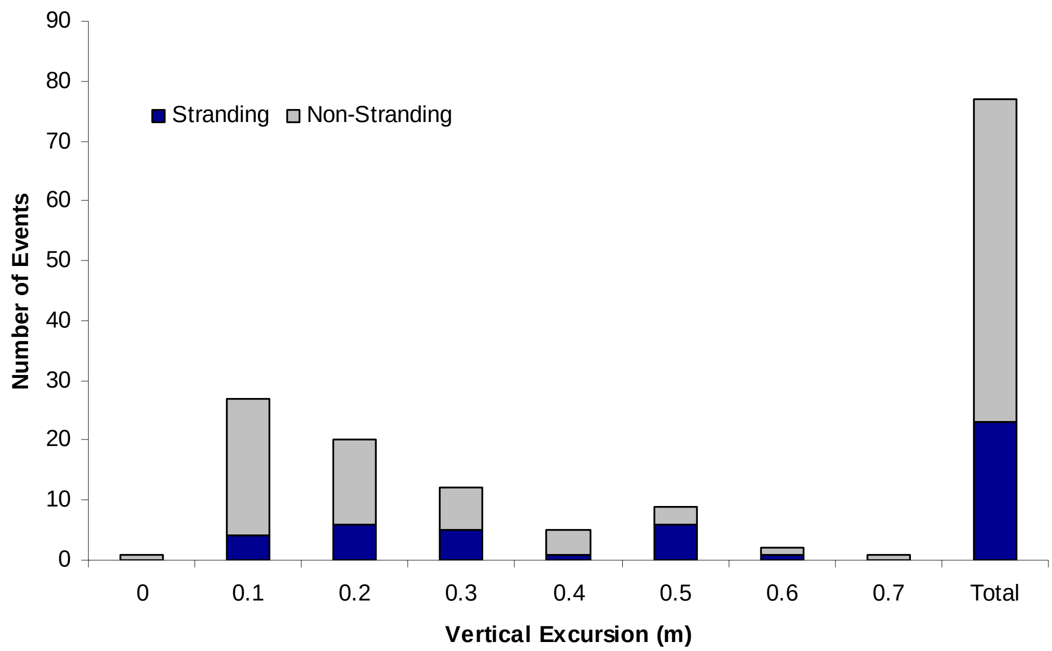


Figure 16. Stranding Events by Vertical Extent of Ship Wakes. Unknown events are those in which gage measurements could not be obtained.

Wave velocity was measured using two methods: run-up gage and camera. The camera was used only during the winter and spring sampling periods. To compare the two methods, regression analysis was used (Figure 17). For events in which acceptable records exist for both methods (n = 12), the run-up speed as captured by the video method is higher (video mean for 12 events is 1.13 m/sec, whereas mean gage speed for same events is 0.95 m/sec). The results of a t-test show this difference to be non-significant ($p = 0.407$, two-tailed t-test). It is important to note that the wave run-up gage is placed several centimeters above the substrate (Section 4.2, Materials and Methods) and the floats are tripped only when there is enough water beneath them (~12 cm). Therefore, the speed of the approaching wave is measured differently than when the camera is used and may be underestimated.

4.3.6 Water Quality

Water quality was within normal expectation and similar throughout each sampling period at all sites (Table 8).

4.3.7 Fish Availability Index

4.3.7.1 Species Composition

A total of 197 beach seine hauls were made during the “before” study period. With the exception of one seine during the spring sampling period, fish were present in all seines; over 20 species of fish were collected (Table 9). Seven species comprised more than 1% of the total catch (Figure 18); other species were considered rare. Table 10 shows average densities per species for each site and season. It is important to note that observed mortality from beach seines was much lower than predicted at 0.5%.

Chinook salmon were the most abundant species collected, especially during the winter and spring sampling periods when they made up about 85% of the total catch (compared with 9% in the summer). Threespine stickleback and banded killifish were also ubiquitous, being found at all sites during all sampling periods. Threespine stickleback were especially numerous during the summer, comprising almost 40% of the catch. Banded killifish, though more abundant during the summer sampling period, were found in small numbers during all sampling periods. Peamouth chub, American shad, and yellow perch were also common, though were not found during the winter sampling period. During the summer, peamouth chub made up 31% of the total catch. Chum, although comprising 1.6% of the total catch, were only present during the winter and spring sampling periods.

Several of the fish species, including American shad, peamouth chub, banded killifish, threespine stickleback, Chinook, and coho, were represented by more than one age/size class. For salmonids, catch data were separated by two age classes, 0+ and 1+, though only 0+ fish made up a significant proportion of the catch. Mean lengths for prominent species are shown in Figure 19 by season.

As explained in the preliminary analysis (Section 4.3.9, Statistical Analysis of Summer Fish Data) differences in fish composition among sites were evident (Figure 20). The location on the river and geomorphology at each site may contribute to these differences.

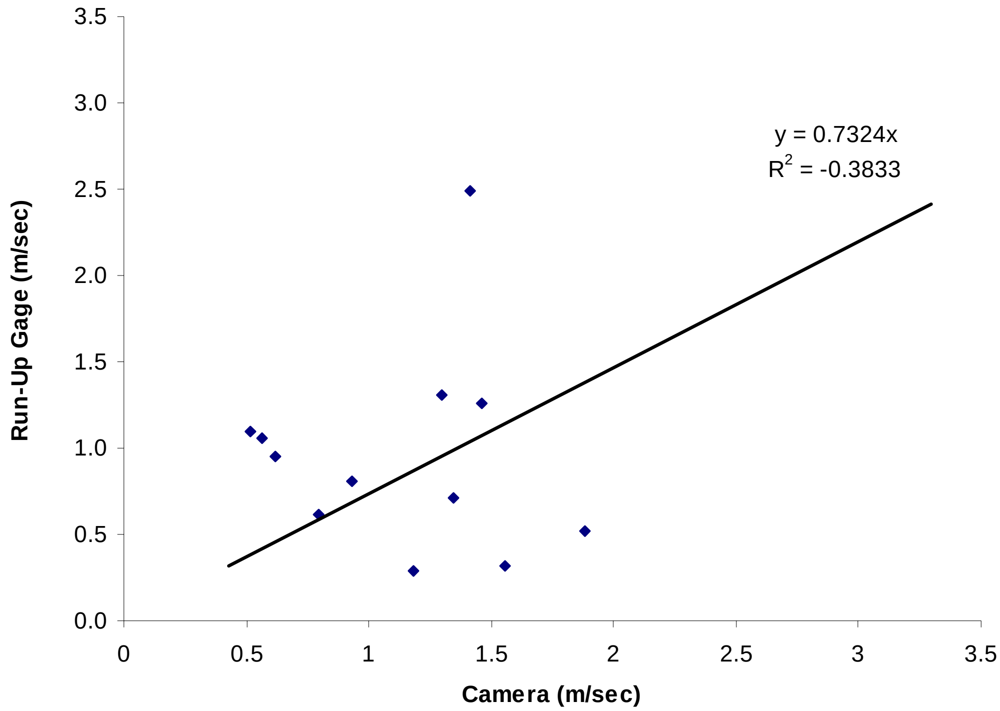


Figure 17. Regression Comparing Events in Which Both the Camera and Run-up Gage Captured Run-up Velocity

Table 8. Summary of Water Quality Data for Sampling Sites During the Three Sampling Periods

	Summer			Winter			Spring		
	BP	CLP	SI	BP	CLP	SI	BP	CLP	SI
Temperature									
Mean	22.0	21.5	22.0	7.1	6.9	6.6	9.7	11.5	13.0
Min	21.2	19.5	19.5	4.5	4.9	4.5	8.6	9.0	9.8
Max	22.4	23.0	23.7	8.8	8.3	10.4	10.8	15.1	15.7
Dissolved Oxygen									
Mean	7.3	7.3	7.4	11.8	11.7	11.8	10.3	9.5	9.6
Min	6.5	6.1	6.3	10.8	11.1	11.0	9.9	7.3	8.5
Max	7.8	9.0	8.9	12.8	12.7	12.6	10.7	11.1	10.9
Salinity									
Mean	0.06	0.06	0.06	0.07	0.07	0.08	0.06	0.04	0.07
Min	0.06	0.05	0.05	0.07	0.07	0.06	0.05	0.02	0.06
Max	0.06	0.07	0.07	0.08	0.08	0.08	0.07	0.06	0.08
pH									
Mean	6.8	7.4	7.2	7.8	7.8	7.8	8.0	7.9	8.1
Min	6.2	7.1	6.3	7.0	7.7	7.7	7.9	6.6	7.8
Max	7.5	7.8	7.9	8.4	7.8	8.0	8.3	8.2	8.5

Table 9. Species of Fish Collected in Beach Seines for All Sampling Sites and Dates

Common Name	**Scientific Name**	**Total # Caught**	**% of Total Catch**
Chinook (0+)	*Oncorhynchus tshawytscha*	8395	49.1
Threespine Stickleback	*Gasterosteus aculeatus*	3701	21.6
Peamouth Chub	*Mylocheilus caurinus*	2580	15.1
American Shad	*Alosa sapidissima*	1102	6.4
Yellow perch	*Perca flavescens*	388	2.3
Chum	*Oncorhynchus keta*	277	1.6
Banded Killifish	*Fundulus diaphanous*	231	1.4
Chinook (1+)	*Oncorhynchus tshawytscha*	100	0.6
Starry Flounder	*Platichthys stellatus*	75	0.4
Mountain whitefish	*Prosopium williamsoni*	72	0.4
Sculpin	*Cottus* spp.	50	0.3
Coho	*Oncorhynchus kisutch*	38	0.2
Northern Pikeminnow	*Ptychocheilus oregonensis*	25	0.1
UID Trout	*Oncorhynchus* spp.	13	0.1
Bass (fry)	*Micropterus* spp.	11	0.1
Red-sided Shiner	*Richardsonius balteatus*	8	0.0
Large Scale Sucker	*Catostomus macrocheilus*	8	0.0
Lepomis sp.	*Lepomis* spp.	7	0.0
UID salmonid	*Oncorhynchus* spp.	5	0.0
Crappie	*Pomoxis* spp.	5	0.0
Steelhead	*Oncorhynchus mykiss*	3	0.0
Cutthroat	*Oncorhynchus clarkii*	1	0.0
Common carp	*Cyprinus carpio*	1	0.0
Total		17096	

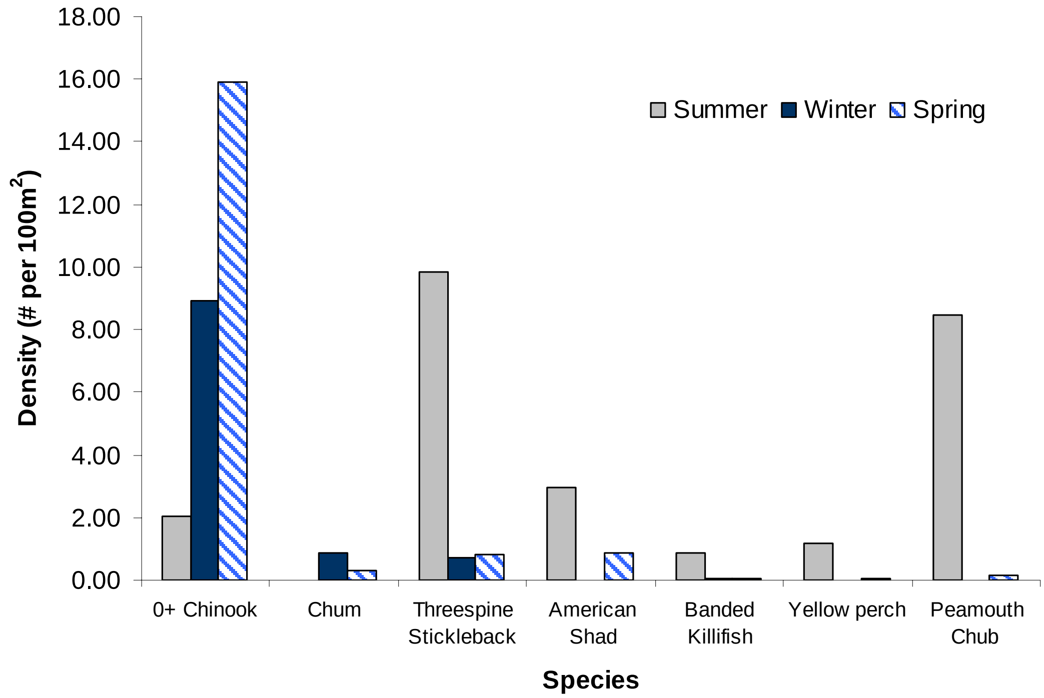


Figure 18. Fish Species Composition (Density) by Season for All Sites. Only species comprising more than 1% of the total catch are shown.

Table 10. Average Densities (# of fish/100 m^2) of Fish Species Found in Beach Seines by Season and Site

	Summer			Winter			Spring		
	BP	**CLP**	**SI**	**BP**	**CLP**	**SI**	**BP**	**CLP**	**SI**
0+ Chinook	2.10	3.02	0.98	17.71	5.91	3.12	14.46	13.85	19.49
1+ Chinook				0.01	0.01	0.08	0.11	0.48	0.35
Chum				0.11	2.13	0.30	0.09	0.69	0.07
Coho					0.66		0.01	0.13	0.01
Cutthroat								0.03	
Steelhead							0.01	0.05	0.01
UID Trout							0.12	0.04	
UID salmonid	0.00	0.01			0.01				0.01
Mountain whitefish		0.03	0.01				0.53		0.10
Threespine Stickleback	4.61	7.52	17.44	0.18	1.64	0.36	1.34	1.01	0.08
American Shad	4.84		1.04				0.88	1.36	0.29
Banded Killifish	0.21	2.40	0.05	0.03	0.05	0.06	0.07	0.02	0.10
Red-sided Shiner			0.01				0.06	0.01	
Common carp			0.01						
Yellow perch	0.00		2.36				0.05		
Bass (fry)		0.01	0.09						
Lepomis sp.	0.01		0.01	0.01			0.01		0.02
Crappie	0.01		0.03						
Peamouth Chub	3.55	4.11	17.73				0.22	0.03	0.21
Large Scale Sucker	0.02		0.02			0.01		0.01	
Northern Pikeminnow	0.01	0.04	0.10				0.01	0.07	0.04
Sculpin	0.02	1.02	0.03			0.01			
Starry Flounder	0.30	0.18	0.03	0.01	0.02		0.06	0.02	0.01

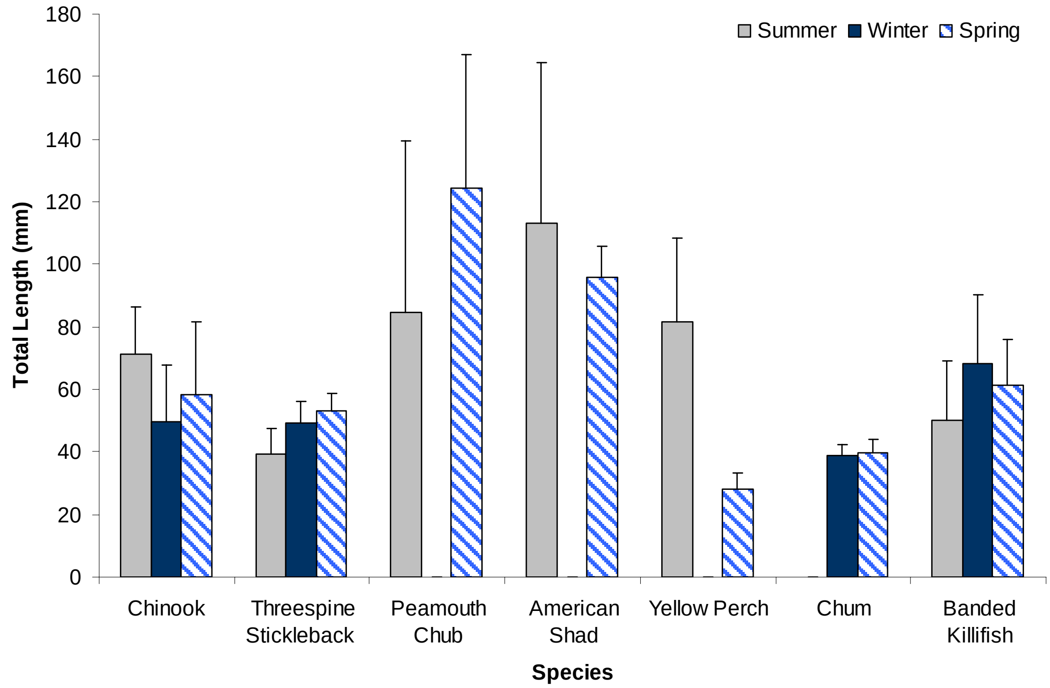


Figure 19. Mean Fish Size (total length) for Common Species by Season. Error bars represent standard deviation of the mean.

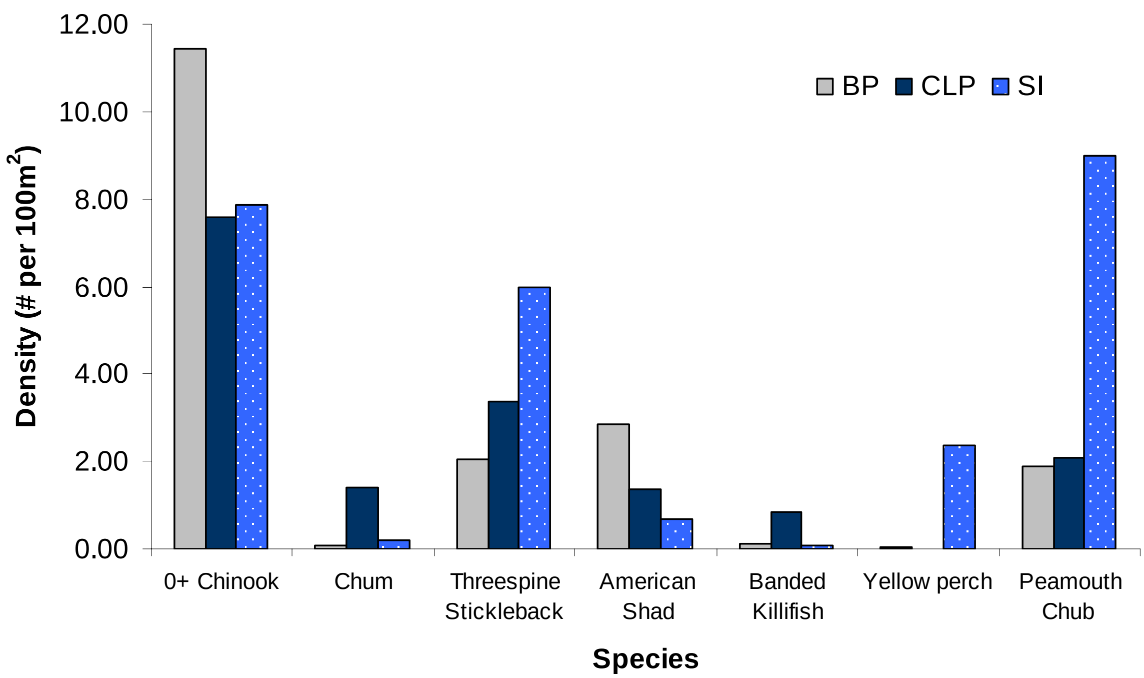


Figure 20. Fish Species Composition (density) by Site for All Seasons

Chinook

Chinook salmon were present in all but 13 seine hauls (10 from the summer, 2 from the winter and 1 from the spring sampling events). Chinook were the only salmon species found in the summer sampling period, though coho, chum, and trout species were found during the winter and spring sampling periods. The spring sampling period had the highest densities of salmonids, especially Chinook in the seines. During the winter sampling period, Barlow Point had substantially more Chinook per seine than did the other sites.

Sampling during the winter and spring periods was done monthly (February through May), allowing for a comparison of Chinook catch over time during peak outmigration. Although February catches were comparable with those from the summer sampling period (average of 18 per haul), the number of Chinook in the beach seines increased substantially in March (average of 65 per haul) and peaked in May with an average of 84 Chinook per seine haul. Additionally, during these two sampling periods, attention was paid to discerning hatchery origin in Chinook (adipose fin clips). Adipose-clipped fish were termed "marked," whereas others were termed "unmarked" (Figure 21). Clipped fish tended to be bigger than unclipped fish and more uniform in size (Figure 22). February Chinook were all unclipped and small in size, some of them still bearing the yolk sac.

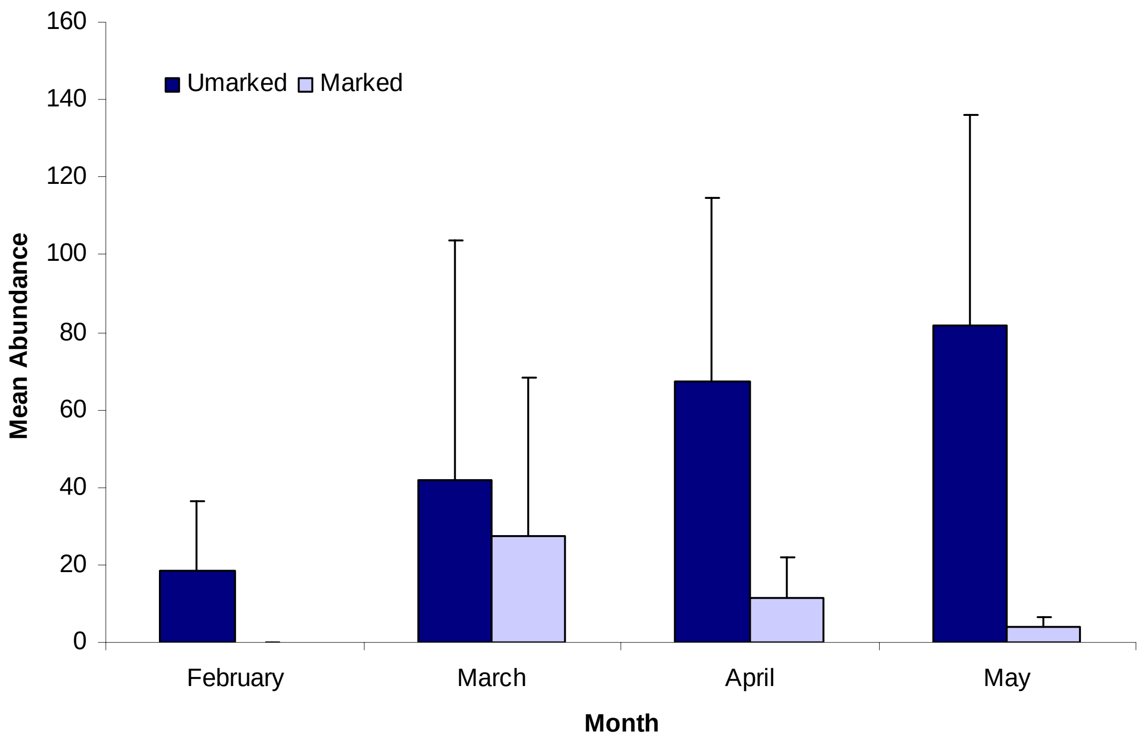


Figure 21. Comparison of Mean Abundance of Marked and Unmarked Chinook by Month for All Sites. Error bars show standard deviation.

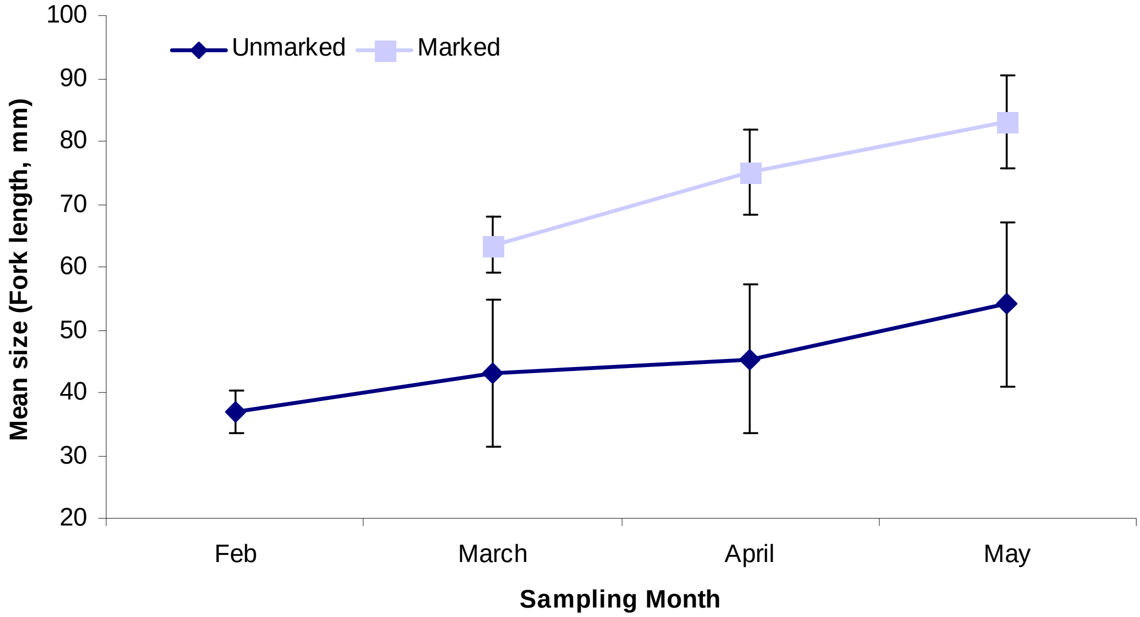


Figure 22. Mean Size of Subyearling Chinook Through Time. Error bars represent standard deviation.

4.3.8 Statistical Analysis of Summer Fish Data

We analyzed fish availability data after one sampling period to ensure the methods would adequately reflect the fish assemblage in the river. This analysis was performed on the summer dataset so that changes for the winter and spring seasons could be implemented, if needed. The seine data were analyzed to a) assess any diel trends (e.g., change in abundance with time during daily sampling), b) estimate sampling variance, c) compare the fish species composition among sites, d) determine whether fish abundance decreased over the sampling period, and e) compare the species composition of the seines for the reference areas versus the "hot spots."

4.3.8.1 Diel Trends

The "start," "middle," and "end" (reference seines 1, 2, and 3, respectively) beach seine data were analyzed for the summer nighttime samples. Ten days of data across the three study locations were analyzed to assess any diel pattern in catch. Counts of subyearling Chinook salmon and total catch (i.e., subyearling Chinook, threespine stickleback, peamouth chub, and banded killifish) were analyzed using a two-way analysis of variance (ANOVA). Blocks were defined by survey day and treatments by time of seining.

There was no significant difference in mean catch between sampling times for either subyearling Chinook ($p = 0.9259$) or total catch ($p = 0.6690$). In addition, an interclass correlation coefficient was calculated to assess whether there was a pattern to the catch numbers across the three sampling times $(\hat{\rho}_I = -0.0321)$.

The estimated correlation is essentially zero, suggesting no consistent diel trend in catches, simply random variation.

The results of the analyses suggest no preferred time to collect the reference beach seine data. The mean catch was not different between sampling times, nor was there a constant diel trend over the 8-hr sampling period. The best characterization of the fish population at risk in this circumstance is the average daily catch.

4.3.8.2 Estimates of Variance of Fish Availability

The ANOVAs also provide estimates of sampling variance, (i.e., the unassignable variance due neither to treatments nor blocks). The average catch for subyearling Chinook was $\bar{x}$ = 1.9943 with a variance of $\hat{\sigma}^2$ = 2.2324 for a coefficient of variation (CV) in catch of $\mathrm{CV}\left(x_i\right) = \hat{\sigma}/\bar{x}$ = 0.7492. The CV for the nightly mean catch is then estimated to be

$$\mathrm{CV}(\bar{x}) = \frac{\sqrt{\frac{\hat{\sigma}^2}{3}}}{\bar{x}} = 0.4325. \qquad (3)$$

Hence, for subyearling Chinook, the nightly mean abundance is estimated with an approximate precision of $\pm 86.5\%$ about the true mean, 95% of the time. The average total catch per beach seine was $\bar{x}$ = 11.1827 with a variance of $\hat{\sigma}^2$ = 6140.40. This translates to a CV of 7.0073 for the catch data. Mean nightly catch then has a CV of

$$\frac{\sqrt{\frac{\hat{\sigma}^2}{3}}}{\bar{x}} = 4.0457. \qquad (4)$$

In other words, you can expect to be within $\pm 808\%$ of the true abundance, 95% of the time. Hence, with three nightly beach seines, the index of total fish abundance is estimated with great uncertainty. Fortunately, the precision for the salmonid index is much better than the index of total fish availability.

4.3.8.3 Fish Community Comparison

A principal component analysis (PCA) was performed on the beach seine catch data. For each nighttime survey, mean catch by species (i.e., Chinook, threespine stickleback, peamouth chub, and banded killifish) was calculated across the “start,” “middle,” and “end” seines. The catch data for each species were then standardized across nights and locations by the general equation

$$Z_i = \frac{x_i - x}{\sqrt{s^2}}. \qquad (5)$$

Standardization results in PCA focused more on interspecies composition rather than on the absolute abundance of fish species. A bivariate plot of the first two principal components (i.e., PC1 and PC2) was used to graphically depict the species composition at each site and replicate night of sampling (Figure 23).

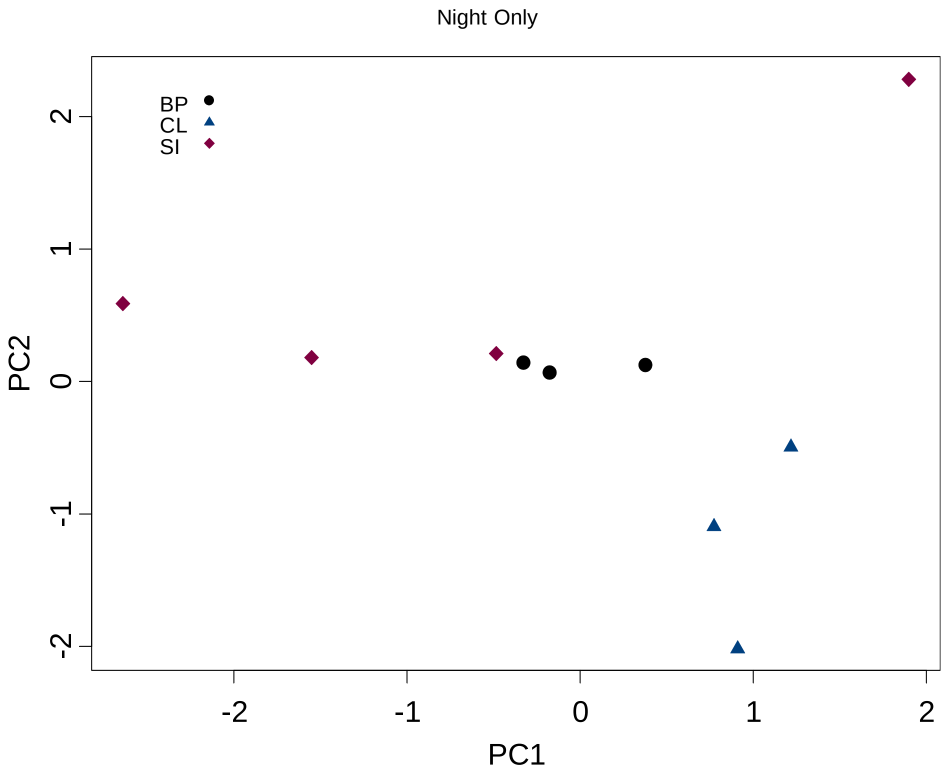


Figure 23. Bivariate Principal Component Plot for Fish Species Composition from Beach Seine Samples at Barlow Point (BP), County Line Park (CL), and Sauvie Island (SI).

Multivariate analysis of variance was subsequently used, based on PC1 and PC2 values to test for significant differences in fish community composition between the three study locations.

The first two principal components of the beach seine fish composition data explained 76.7% of the overall variability in the data. Examination of the PCA bi-plot indicates the replicate catches at a study site tend to be segregated by location. Catches at Barlow Point are located at mid-plot, catches at County Line Park in the lower right corner, and Sauvie Island catches are widely scattered across the top half of the plot. Catches at Barlow Point were the most consistent across replicate nights, whereas Sauvie Island had the greatest variability in species composition. The PC1 contrasts Chinook, peamouth chub, and banded killifish versus threespine stickleback composition. Negative values of PC1 indicate more sticklebacks, whereas positive values show more of the other species present. The PC2 contrasts threespine stickleback and peamouth chub versus banded killifish. Negative values for PC2 indicates more killifish, whereas positive values indicate more of the other two fish species.

The multivariate analyses of variance based on PC1 and PC2 values found a significant difference ($p = 0.0821$) in species composition between the three study areas. Hence, the visual separation seen in Figure 12 is supported by statistical inference.

4.3.8.4 Comparison of Reference Versus Hot spot Seine Samples

Beach seining was conducted at a reference site immediately downstream of the survey reach and after the survey day at two sites within the survey reach. The sites within the survey reach were selected based on observations during the pilot study that revealed that fish stranding tended to be concentrated at these “hot spots.”

Two methods were used in comparing fish catch at “hot spots” and reference areas. A PCA was used to compare community composition between reference and “hot spot” areas. Bivariate PCA plots graphically compared community composition (i.e., four primary species) between reference, hot spot 1, and hot spot 2 areas at each location. Multivariate analysis tested whether sampling areas had the same multivariate fish composition. Two-way ANOVAs (night-by-seining locations) were used to compare Chinook-0 and total species abundance between reference, hot spot 1, and hot spot 2 locations at each study site.

A PCA was used to reduce the dimensionality of the species composition data. The first two principal components expand 67.8% of the total variability. Figure 24 presents the bivariate PCA plots for each study site. The first principal component contrasts threespine stickleback abundance versus Chinook-0 and banded killifish abundance. Negative values indicate more stickleback, whereas positive values indicate presence of more of the other two species. The second principal component contrasts peamouth chub abundance versus threespine stickleback and banded killifish abundance. Negative values indicate more peamouth chub, whereas positive values indicate greater abundance of the other two species. Species composition did not differ between reference, hot spot 1, and hot spot 2 areas at any of the study sites ($p = 0.8377$ at Barlow Point, $p = 0.2396$ at County Line Park, $p = 0.9066$ at Sauvie Island).

Analysis of variance found no difference in the number of Chinook-0 caught at reference, hot spot 1, and hot spot 2 locations at any study site ($p = 0.8481$ at Barlow Point, $p = 0.4113$ at County Line Park, $p = 0.2616$ at Sauvie Island). Total fish catch (i.e., four primary species) was not different between seine locations at Barlow Point ($p = 0.7564$) and County Line Park ($p = 0.2139$), but was different at Sauvie Island ($p = 0.0402$). These results indicate that the species compositions in the downstream reference areas are representative of those in the "hot spots" for each site.

4.3.9 Fish Stranding Events

As shown above, we observed a total of 46 stranding events during the study period (all sites, all seasons). Positions of fish strandings are shown at each site in Figures 25-27. Stranding occurred in similar locations for all seasons. County Line Park had the least number of stranding events and stranded fish. At the Barlow Point site, fish tended to strand in an area where strong cross-waves and an eddy occurred. Also at this site, fish were stranded toward the downstream end of the site (upper portion of map) in vegetation patches. Stranding at County Line Park tended to be widespread at the site, but varied by season, possibly as a result of changes in geomorphology with seasonal river conditions. Stranding at Sauvie Island also tended to be widespread, though stranded fish congregated at the far end of the site where ship wakes extended up the beach in a depression.

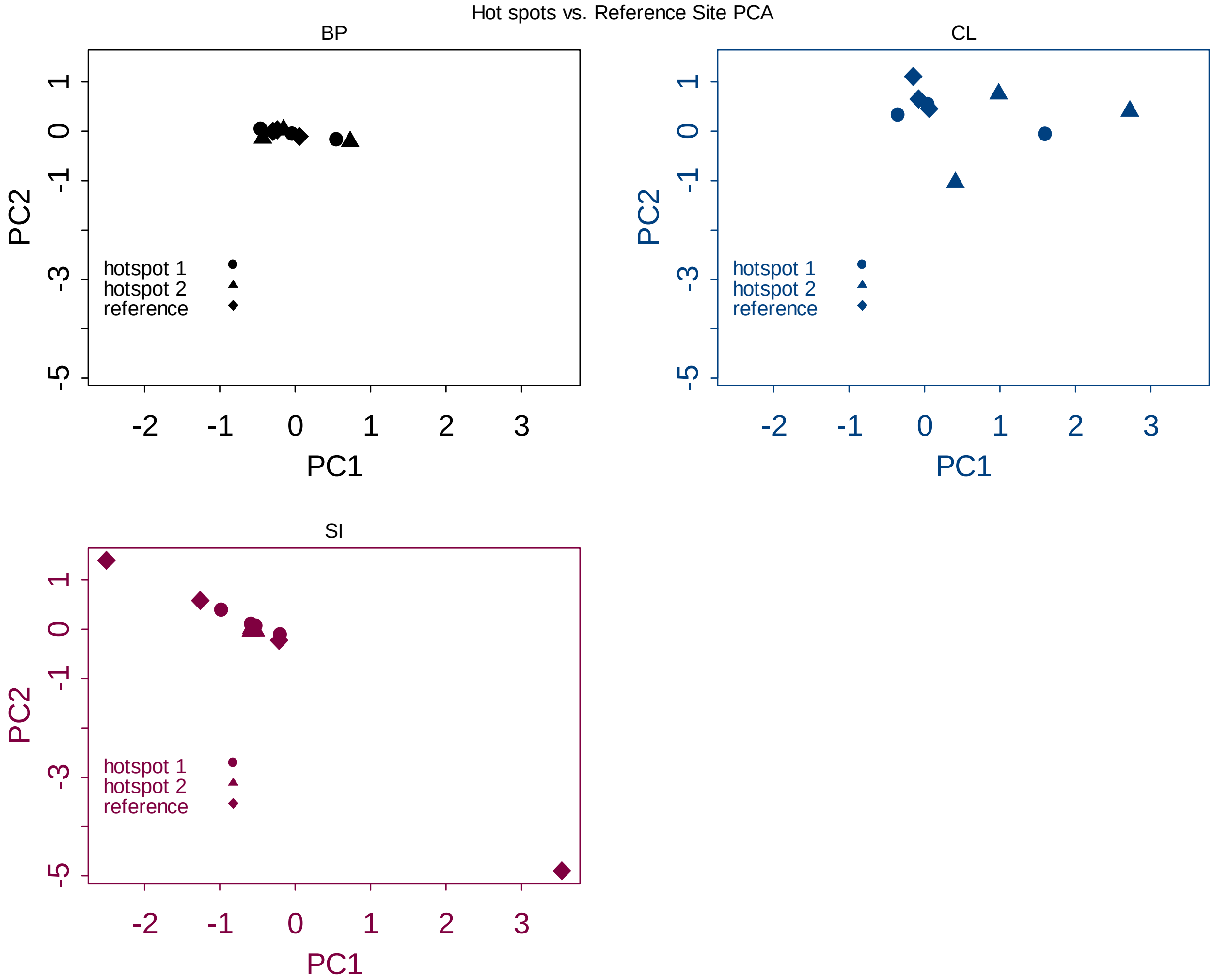


Figure 24. Bivariate PCA Plots for Reference, Hot Spot 1, and Hot Spot 2 Seine Locations at Barlow Point (upper left) County Line Park (upper right), and Sauvie Island (lower left)

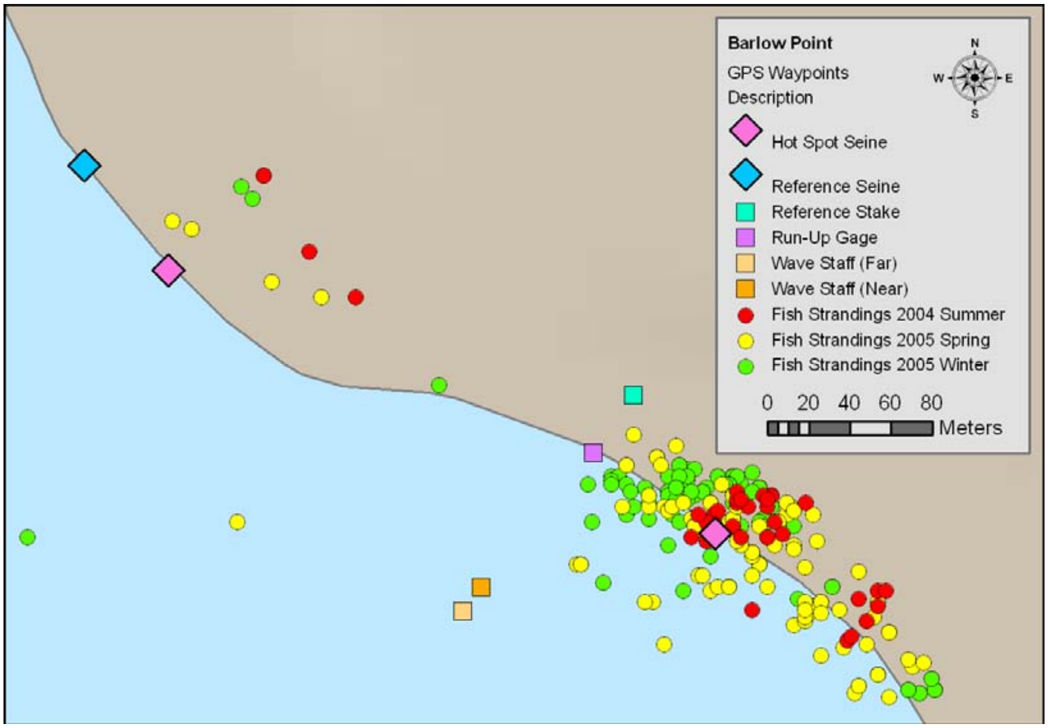


Figure 25. Barlow Point Stranding Locations

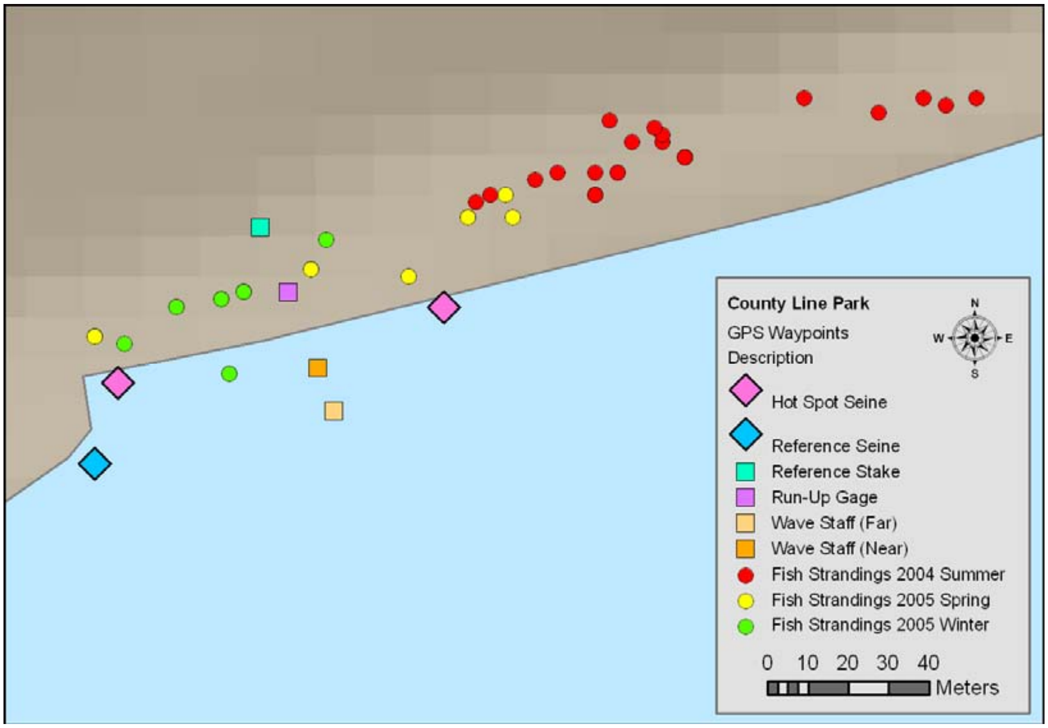


Figure 26. County Line Park Stranding Locations

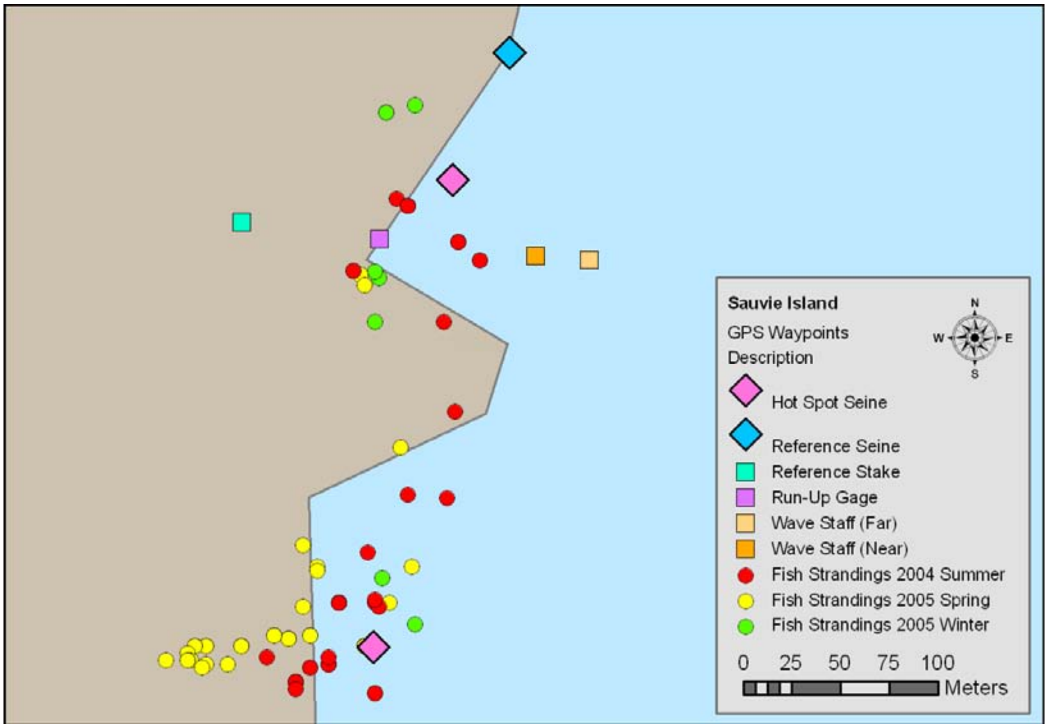


Figure 27. Sauvie Island Stranding Location

Stranding events ranged from 1 to over 100 stranded fish per event, with an average of 11.3 fish stranded per event (only events resulting in stranding were used in this calculation). Data for individual sites are provided in Table 11.

The predominant fish stranded were Chinook salmon subyearlings (Table 12). Threespine stickleback were the only other fish stranded in moderate numbers. Most other fish species were rarely stranded.

4.3.10 Species Composition in Stranded Fish and Available Fish

The hypothesis that the proportion of the seine catch made up of a given species is the same as the proportion of the strandings made up of that species was tested via logistic regression for seven species (Table 13). Trip (i.e., the site-date combination) was used as a blocking factor. Fish comprising <1% of the catch were not examined. It appears that the proportions vary significantly across sampling type (i.e., seine net versus strandings) for Chinook ($p = 0.0121$), American shad ($p = 0.0323$), and possibly for peamouth chub ($p = 0.0866$). Table 14 shows the proportion of each species stranded and caught in seines.

Table 11. Stranding Events and Mean Number of Fish Stranded at Each Site

Site	Number of Events	Mean Number of Stranded Fish
Barlow Point	26	14.9
County Line Park	6	7.3
Sauvie Island	14	5.6

Table 12. Stranded Fish by Species for Each Site

Site	BP		CLP		SI	
Species	**# Stranded**	**%**	**# Stranded**	**%**	**# Stranded**	**%**
0+ Chinook	351	90.7%	30	68.2%	45	50.6%
1+ Chinook	0	0.0%	0	0.0%	0	0.0%
Chum	1	0.3%	4	9.1%	3	3.4%
Coho	3	0.8%	4	9.1%	0	0.0%
UID salmonid	1	0.3%	0	0.0%	0	0.0%
Mountain whitefish	8	2.1%	0	0.0%	0	0.0%
Threespine Stickleback	7	1.8%	0	0.0%	33	37.1%
American Shad	3	0.8%	0	0.0%	1	1.1%
Banded Killifish	3	0.8%	4	9.1%	0	0.0%
Yellow perch	0	0.0%	0	0.0%	2	2.2%
Bass (fry)	1	0.3%	2	4.5%	2	2.2%
Lepomis sp.	1	0.3%	0	0.0%	0	0.0%
Crappie	0	0.0%	0	0.0%	1	1.1%
Peamouth Chub	8	2.1%	0	0.0%	1	1.1%
Starry Flounder	0	0.0%	0	0.0%	1	1.1%
Total	387		44		89	

Note: Percentage refers to the proportion of an individual species to all fish stranded at that site.

Table 13. Results from Species Composition Analyses, Sorted by p-Value

Species	$F_{1,194}$	p-value
Chinook 0+	6.4229	0.0121
American Shad	4.6499	0.0323
Peamouth Chub	2.9671	0.0866
Banded Killifish	1.4822	0.2249
Chum	0.3000	0.5845
Threespine Stickleback	0.0897	0.7649
Yellow Perch	0.0109	0.9168
Note: For each species, the hypothesis tested is that of equal proportions of the catch (seine) and strandings for a given species.		

Table 14. Comparison of Fish Species by Percent of Total Catch and Percent of Total Stranded

Species	% of Stranded	% of Catch
0+ Chinook	81.9	49.1
1+ Chinook	0.0	0.6
Chum	1.5	1.6
Coho	1.3	0.2
UID Trout	0.0	0.1
UID salmonid	0.2	0.0
Mountain whitefish	1.5	0.4
Threespine Stickleback	7.7	21.6
American Shad	0.8	6.4
Banded Killifish	1.3	1.4
Yellow perch	0.4	2.3
Bass (fry)	1.0	0.1
Lepomis sp.	0.2	0.0
Crappie	0.2	0.0
Peamouth Chub	1.7	15.1
Northern Pike Minnow	0.0	0.1
Sculpin	0.0	0.3
Starry Flounder	0.2	0.4
Note: Only Chinook (0+) were stranded at higher rates using logistic regression; American shad were found to strand at lower rates than that at which they were seined.		

5.0 Methods of Ship-Generated Wave Prediction

5.1 Description of Wakes

The wake waves generated by a ship making headway in a channel are of several types. The short-period waves generated at the bow of the vessel along with the transverse stern wave are developed as a result of the near-normal pressure distribution along the hull. The bow wave is formed as the water is accelerated along the flared portion of the bow and elevates the surface above the still-water level. Along the sides of the vessel, the accelerated water is lowered in accordance with Bernoulli's principal, which requires that pressure decrease as velocity increases. The transverse stern wave is formed by the return pressure and separation at the stern of the vessel.

If the vessel is in a channel, long-period waves characterized as draw-down and the following run-up, or surge wave, may also be developed. These waves are observed if the draft of the vessel is greater than about half of the channel depth and a considerable portion of the water in the channel is displaced as the vessel proceeds. A large volume of water is pushed up at the bow of the vessel with an exaggerated lowering of water level along the sides. The wave travels along the shoreline at the speed of the ship and may provide a significant lowering of the water level at the shore followed by an up-rush return flow. Because the draw-down is forced by the ship displacement and the return flow is a free oscillation and is subject to the frictional influences of the shoreline, the draw-down tends to be exaggerated relative to the run-up. Depending on the slope of the channel flanks, the draw-down and up-rush may affect a large portion of the shore perpendicular to the waterline.

The observation and measurement of water-surface-elevation change during a ship passage in a channel are complicated by the superposition of all of the waveforms present, including those formed by the ship as well as the ambient waves due to local wind generation. Because of the importance to channel safety, maintenance, and environmental impacts, ship wakes and their effects have been subjects of a large number of studies. Sorensen (1997) provides an annotated bibliography of studies to 1991; more recent references are found in Maynord (2003).

Sophisticated numerical models based on the Boussinesq or the Navier-Stokes equations have recently been developed and show great promise for accurately representing the wake-wave field, along with animations of the progressive waves generated by ships (Nwogu 1993). These codes are very data intensive, however, requiring detailed information on ship characteristics and bathymetric information to develop a computational grid. They also require large computer resources, such as massive parallel processors or super computers. Because such detailed information is seldom available and is very expensive to gather, empirical methods have been developed that relate ship operating conditions, channel geometry, and vessel hull-form characteristics to estimate short- and long-period waves.

5.2 Prediction of Short-Period Ship Wakes

Because of its importance in channel design and maintenance, and because it is a safety and environmental issue, the generation of ship wakes in channels has received a considerable amount of attention in the literature. Sorensen (1997) evaluated eight empirical methods of wake-height prediction and recommended a method that was slightly modified from one previously presented in Weggel and Sorensen (1986). Though widely used, the Weggel and Sorensen method was recently shown by Kriebel et al. (2003) to be a relatively poor predictor of ship-generated wave characteristics.

The short-period wave pattern generated by a moving vessel is shown in Figure 28. At the bow of the vessel, a symmetrical set of diverging waves is generated that move obliquely out from the sailing line, and a single set of transverse waves that move in the direction of the sailing line are generated at the stern. The distance from the sailing line is indicated by point y.

The highest waves in the pattern are found along the locus of cusp lines on either side of the vessel where the diverging bow wave constructively interferes with the transverse stern wave. This line forms at an angle of 19°28′ to the sailing line in deep water (e.g., when the water depth is greater than twice the draft [d/T ≥ 2]) and increases in shallow water.

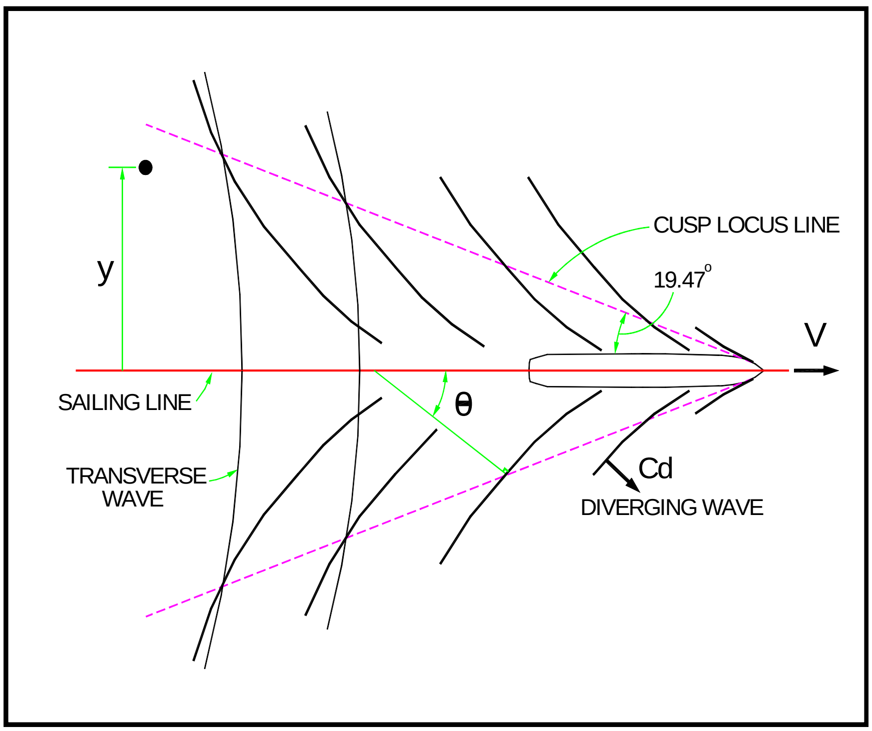


Figure 28. General Short-Period Wake Pattern Produced by a Moving Vessel

The dominant vessel-generated short-period waves, as they travel out from the sailing line, are the diverging waves. These are the waves formed by the constructive interference of the bow wave and the transverse-stern wave. The diverging waves travel at an angle that varies from 35°16′ for deep water to 0°, for a depth-based Froude number (Fd) of unity. Weggel and Sorensen (1986) have shown from experimental data that, for Fd <1, the angle can be expressed as

$$\theta = 35.27(1 - e^{12(F-1)}) \tag{6}$$

where Fd is the depth-based Froude number relating vessel speed (V) to the celerity (e.g., wave speed) of a shallow-water wave.

$$F_d = \frac{V}{\sqrt{gd}} \tag{7}$$

Wave speed is predicted by

$$C = V\cos\theta. \tag{8}$$

Displacement vessels are limited to speeds less than the critical Froude number (e.g., Fd <1.0), because they cannot exceed the speed of the bow wave. Fast ferries and planing hull vessels, however, can span the range from sub- to super-critical speeds. The maximum divergent wave is usually produced at Fd ~0.90 for both displacement and planing hull vessels. In confined navigation channels, displacement vessels typically travel at maximum speeds of 0.7 to 0.9 Fd. For an ~12.2-m (40–ft) channel depth, Equation 8 predicts a speed of 15.1 and 19.4 kts, corresponding to an Fd of 0.7 and 0.9, respectively. If the channel were deepened to ~13 m (43 ft), the *potential* speed could increase to 15.6 and 20.1 knots for the indicated Froude numbers.

For a given hull form, the wave height also varies with ship speed (V), distance from the sailing line (y), and water depth (d). As both the diverging and transverse waves move away from the vessel, their wave energy decreases due to diffraction, with a consequent decrease in height. Theory predicts that the wave height at the cusp point decreases at a rate that is inversely proportional to the cube root of the distance from the bow, whereas the transverse wave heights at the sailing line should decrease at a rate that is inversely proportional to the square root of the distance from the bow (Havelock 1908). These considerations were used by Kriebel et al. (2003) to develop their empirical relationships.

Recordings of wake-waves show that the wave height increases to a maximum in three to four wavelengths followed by a gradual decrease over the remainder of the record. A typical record of short-period wake may last for several minutes before the waves die out completely.

Figure 29 shows the effects of ship speed and water depth on the generated wake wave at increasing distance from the sailing centerline and for the same hull form. The records were made in a laboratory using scale models (1:96). The wave time series on the left is in relatively deep water and with ship speed 1.16 m/sec (3.8 ft/sec). The record shows a wake wave that builds up and decays over time. The records on the right are for slower ship speed but in much shallower water, and illustrate the draw-down and run-up of the water surface.

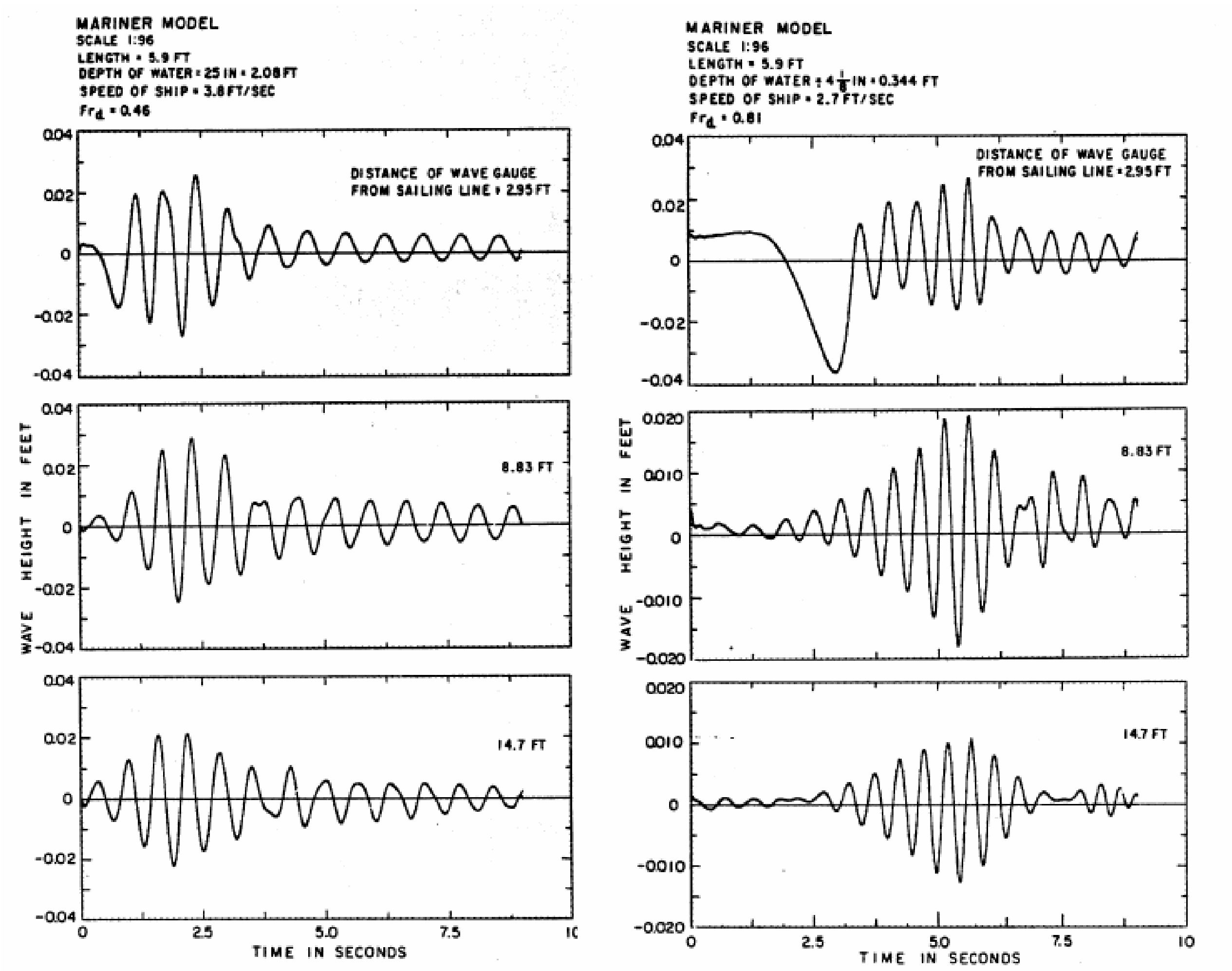


Figure 29. Water Level Records From Scale Model Studies of Ship-Generated Waves (Kriebel et al. 2003)

Kriebel et al. (2003) examined 2100 data records, collected at full and reduced scale from 12 characteristic ship types. Results of the analysis indicate that the variation of wave height, H, with distance from the sailing line, y, is best described by a $-1/3$ power relationship.

$$\frac{gH}{V^2} = C\left(\frac{y}{L}\right)^{-1/3} \tag{9}$$

Where g is gravity, and the coefficient, C, varies with hull form, depth ratio (T/d) and either depth or length Froude number.

Froude depth can be described by the following equation:

$$(F_d = \frac{V}{\sqrt{gd}} \tag{10}$$

Similarly, Froude length can be determined as follows:

$$F_L = \frac{V}{\sqrt{gL}} \tag{11}$$

Of the 2100 records reviewed, Kriebel et al. (2003) selected between 1200 and 1300 that provided sufficient details concerning wave and ship characteristics to be useful in developing a revised empirical equation. Following the relationship suggested above, the equations from Kriebel et al. (2003) are as follows:

$$\frac{gH}{V^2} = \beta(F_* - 0.1)^2\left(\frac{y}{L}\right)^{-1/3} \tag{12}$$

where

$$F_* = F_L \exp\left(\alpha\frac{T}{d}\right) \tag{13}$$

$$\alpha = 2.5(1 - C_b) \tag{14}$$

$$\beta = 1 + 8\tanh^3\left(0.45\left(\frac{L}{L_e} - 2\right)\right). \tag{15}$$

Most of the parameters are defined above but some require further explanation.

The function, F_*, is referred to by Kriebel et al. (2003) as a "Universal Froude Number," which is closely related to the variability of $\frac{gH}{V^2}$. The single empirical coefficient, α, is dependent on ship hull form; α is large for slender hulls and small for blocky hulls. Two parameters appear to be most significant in determining the variation of α: the entry length, L_e, defined as the length of the curved bow section to the start of the parallel middle body, and the block coefficient, C_b, defined as the ship volume relative to a block with volume L x B x T. Evaluation of the available data showed a linear relationship between α and C_b (Figure 30).

Experimental data for a given ship indicated that $\frac{gH}{V^2}$ increased with F_*, and the shape of the curve indicated that the relationship was quadratic or higher. Distinct variations were observed for different hull forms, and trial and error led to a best-fit relationship between β and $\frac{L}{L_e}$, as shown in Figure 31 and described by the relationship above.

The equations provided in Kriebel et al. (2003), referred to as KSJ equations, are considered preliminary, because there are plans to further investigate the relationship of the variables with additional data. The predictive skill of Equation 12 is shown in Figure 32, which displays the evaluated data relative to the line of perfect agreement. Comparison with the large data set obtained by Kriebel et al., this relationship has much greater predictive capability than that proposed by Sorensen (1997). Later studies by Sorensen attempted to include an empirical hull-shape factor into the wave-height calculation but results were not compelling.

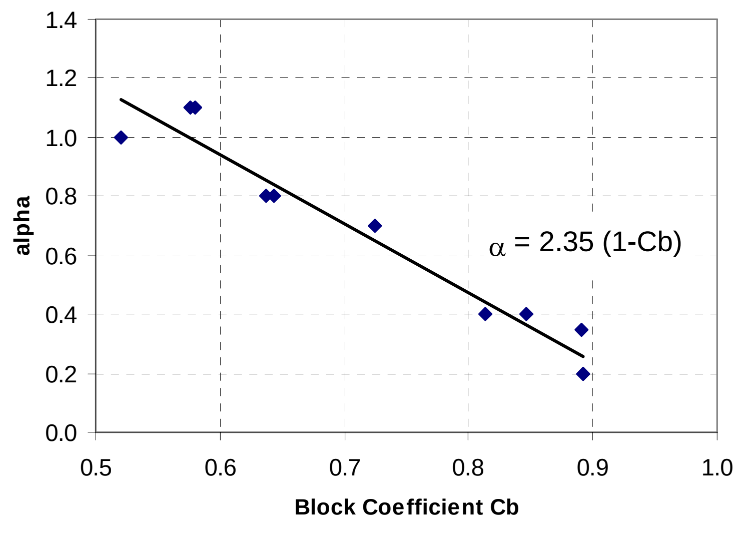


Figure 30. Relationship Between α and C_b Determined From Regression of Available Data (Kriebel et al. 2003). Fast ships with "fine form" have block coefficients <0.65; slow ships with "full form" have block coefficients greater than 0.75.

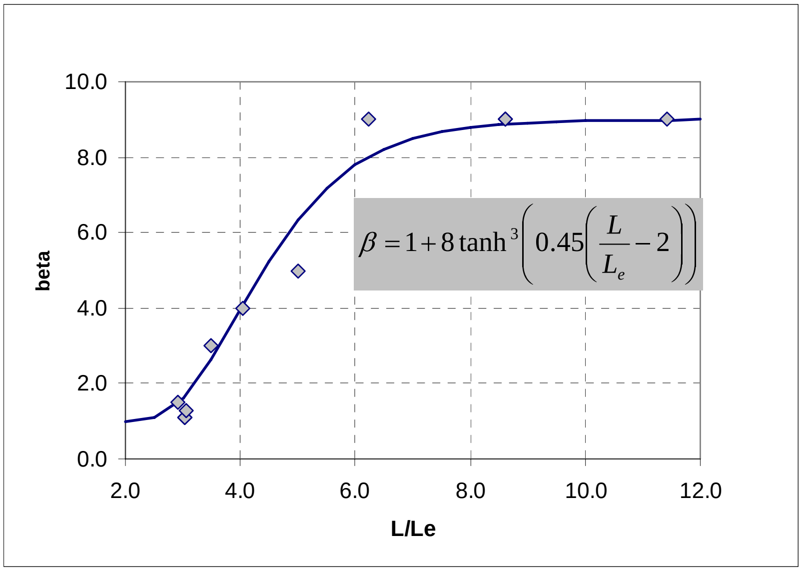


Figure 31. Empirical Shape Factor Related to Hull Form, in This Case, the Ratio Between Entrance Length to Total Waterline Length

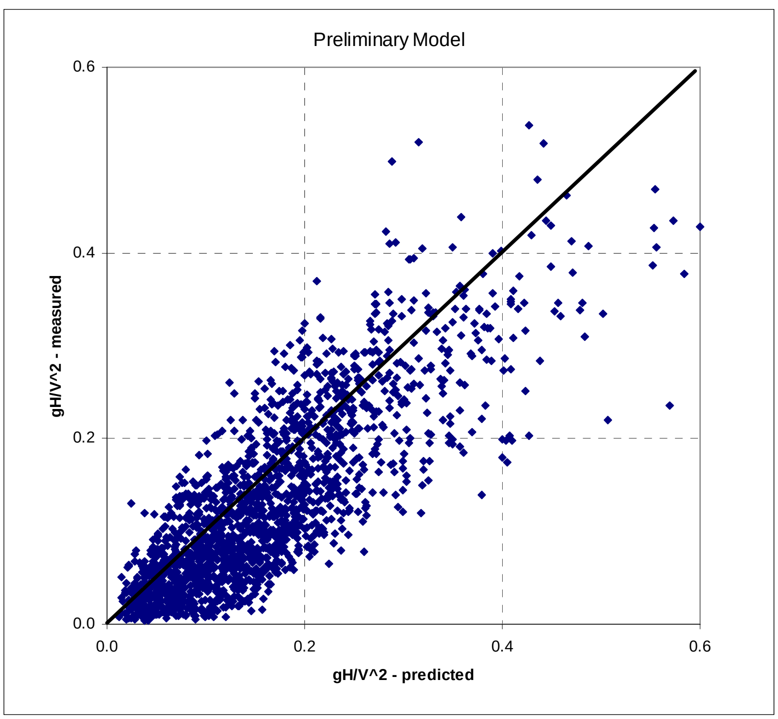


Figure 32. Comparison of Predicted Non-dimensional Wake Height to Measured Values (Laboratory and Field) Using Equations of Kriebel et al. (2003). The solid line indicates perfect agreement.

Equation 12 can be rearranged to solve for wake-wave height to evaluate the importance of the various terms.

$$H = \frac{V^2}{g}\left[\frac{V}{\sqrt{gL}}\exp\left(\alpha\frac{T}{d}\right) - 0.1\right]^2 \beta\left(\frac{y}{L}\right)^{1/3} \tag{16}$$

Equation 16 shows that velocity is very important in controlling wake wave height since it enters the predictive equation to greater the second power.

5.3 Implications of the KSJ Development

A spreadsheet was developed using the KSJ equations to predict short-period wake-wave height at selected distances from the ship sailing line.

The magnitude of entry length (L_e) is often not readily available and must be assigned an estimated value based on characteristics of the ship class or by observation. Most streamlined ships have β values of 1 to 2, whereas more blunt vessels, such as tankers, have β up to 9. The former corresponds to an entry length extending over ~30% of the total ship length, whereas the latter corresponds to an entry length of ~7.5% of total length.

The value of α may also be problematical, because the block coefficient (C_b) is not often known. As shown in Figure 30, blunt hulls, typical of cargo ships have lower values of α, on the order of 0.2 to 0.4. Once α and β are determined, the calculation of F_* and H are straightforward. The lack of accurate information, however, may introduce scatter into the wave estimate.

As an example, the predicted wake heights are shown in Table 15 for a 575-ft (175.3-m) long ship with a 23.5-m (77-ft) beam traveling at 14 knots. The height of the wake wave is determined at y = 300 ft (e.g., at the edge of the maintained channel) for three conditions, as shown, with all other parameters held constant.

If the first condition is considered the "base case" using a nominal channel depth of 40 ft (12.2 m), increasing channel depth and vessel draft each by 3 feet (0.9 m) while operating at the same speed (14 kts) will increase the expected wake wave by 0.3%. Increasing channel depth by 3 ft (0.9 m), from 40 to 43 ft, while maintaining the same draft and operating speed will reduce the wake by nearly 10% relative to the base case. The final line shows the effect of ship speed *reduction* from 14 kts to 12 kts, which results in prediction of nearly a 60% decrease in wake height. The results in Table 15 show trends and sensitivity of predicted wave height based on the adjustment of selected parameters in the KSJ equations. The predicted wave under actual operating conditions should be compared with measured data to test the accuracy of the method for the prototype conditions. Table 15 summarizes the wave estimates based on a few conditions of variable speed, draft, and channel depth. A large number of such sensitivity experiments were conducted using the spreadsheet program but are not shown here.

Table 15. Sensitivity Analysis Comparing Wake-Wave Height for Indicated Combined Values of Vessel Draft, Channel Depth and Vessel Speed

Variables	Wake Height, H, at y = 300 ft	Percent Change in Wake Height
T = 38 ft, D = 40 ft, V = 14 kts	3.59 ft	-
T = 41 ft, D = 43 ft, V = 14 kts	3.60 ft	0.3 % Increase
T = 38 ft, D = 43 ft, V = 14 kts	3.28 ft	8.6 % Decrease
T = 38 ft, D = 40 ft, V = 12 kts	1.53 ft	57.3% Decrease

5.4 Evaluation of Ship Generated Draw-down and Run-up

The method of wake wave prediction proposed by Kriebel et al. (2003) applies only to the short-period waves generated by a moving large displacement vessel. Based on primarily laboratory data, it predicts that speed is the most important variable in controlling wake-wave height. In confined channels, large vessels also generate long waves with periods of more than a minute, which are characterized by a draw-down and subsequent run-up.

As large displacement vessels pass through confined channels, they may displace a significant portion of the volume of water within the channel. This displacement creates a mound of water ahead of the vessel and a draw-down of water along its sides. At the shoreline, the draw-down is seen as a drop in the water level to some minimum below the still-water level. The following surge or run-up onto the shore is the rise to the maximum water level as the water returns following vessel passage. Both draw-down and surge are measured from the average ambient or still-water level. The draw-down is a forced wave that moves along the shore at the speed of the vessel, whereas the surge is a return-flow event. The magnitude of the draw-down and surge depend on the channel and beach geometry, the speed of the vessel, distance from the sailing line, and the size (beam, draft, length) of the vessel relative to the channel cross-section, e.g., the blocking ratio. In some channels, the long-period wave persists for a considerable time (e.g., more than 30 min) after ship passage due to reflection from the channel sides.

Empirical methods for calculating the draw-down and surge (run-up) in confined navigational channels have been developed by Maynord and others at the Army Engineer, Engineering Research and Development Center (ERDC), Vicksburg, Mississippi, and are documented in a number of Coastal and Hydraulics Laboratory technical reports. Much of the model development and documentation was conducted for the Rock Island District for the Upper Mississippi River-Illinois Waterway and are available in a series of environmental reports. The primary references used here are Maynord (1996) and Maynord (2003).

The draw-down observed at the shoreline can be calculated using the Navigation Effects (NAVEFF) numerical model developed by Maynord (1996). The program was translated from the QuickBASIC 4.5 to VisualBASIC and adapted to an EXCEL spreadsheet. The example file inputs were tested to confirm that the program returned the expected output. The program was then run to evaluate the predicted draw-down under various speeds and sailing locations relative to the channel centerline. Initial program testing to evaluate the sensitivity of draw-down to various parameters was made for the Sauvie Island (Willow Bar) site. Later, the program was applied to the other sites.

The Willow Bar study location is on the left bank of the LCR at river mile 119 (RM 119). General characteristics are shown in Figure 33. Sediment characteristics, ground water stage, beach vegetation cover and type, and local beach morphology features may also be important in predicting local draw-down and surge.

A series of NAVEFF input files was generated to examine the predicted effect of ship speed on draw-down. The lowering of the water surface below the still-water level is shown in the dark blue line of Figure 34 as a function of ship speed. The effect of ship speed indicates that, for a given ship, speed is the dominant factor influencing draw-down. The model predicts that draw-down increases from about -0.5 ft at 14 kts to about -2 ft at 18 kts.

Figure 33. Willow Bar, Sauvie Island Survey Site. The channel cross-section A-A' was used in the NAVEFF calculations.

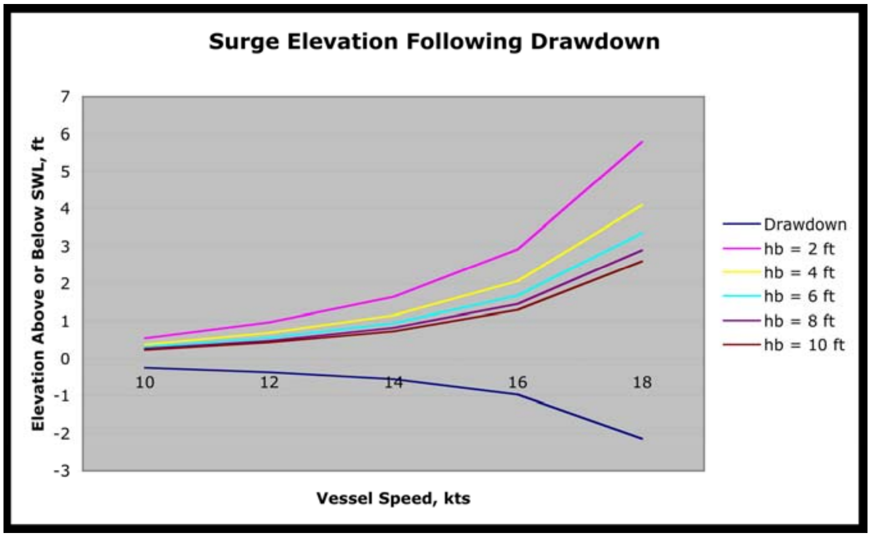


Figure 34. Predicted Draw-down and Run-up at the Shore for Indicated Speed and Berm Depth

The surge elevation following draw-down is calculated using the following empirical relationship (Maynord 2003):

$$\frac{H_s}{h_b} = 0.26\left(\frac{d}{h_b}\right)^{0.6}\left(\frac{V}{\sqrt{gh_b}}\right)^{1.8} \tag{17}$$

where H_s = surge height (run-up) above the still-water level
h_b = berm depth – depth at the channel edge
d = draw-down determined from NAVEFF
V = ship speed
g = gravity.

The surge height, H_s is seen to be proportional to ship speed, V, to the 1.8 power. Small changes in speed can be expected to generate large changes in surge elevation.

The berm depth, h_b, in the Sabine-Neches Waterway is constant and relatively well-defined, because the channel was dredged in the river bottom to form a sort of groove along which the barges and ships pass. The berm depth is relatively easy to distinguish under these conditions. In the LCR, the determination of berm depth is more problematical. A number of berm depths were used in the numerical experiments to examine the effect it has on surge. Figure 34 shows the run-up estimates for the indicated values of speed and berm depth. The nearly exponential change in draw-down and surge with speed is evident. Figure 34 also shows that, as a first estimate, the surge elevation is nearly the same as the preceding draw-down. The values of the predicted water-level changes are likely to be different from those that would be measured in the field, because the estimation method makes many simplifying assumptions, but the model results can be used to show the sensitivity of the parameters of interest to the relative magnitude of the water-level change.

Figure 35 shows the change in predicted draw-down at the shoreline for a ship sailing off the channel centerline toward the left side of the channel. A 1-kt current was used in the calculation. The red lines on the right and left represent the channel centerline and left side (300 ft from center) respectively. At a given location in the channel, the draw-down increases rapidly with speed, as expected. At speeds under 14 kts, however, the predicted draw-down is relatively small and does not change appreciably with position in the channel.

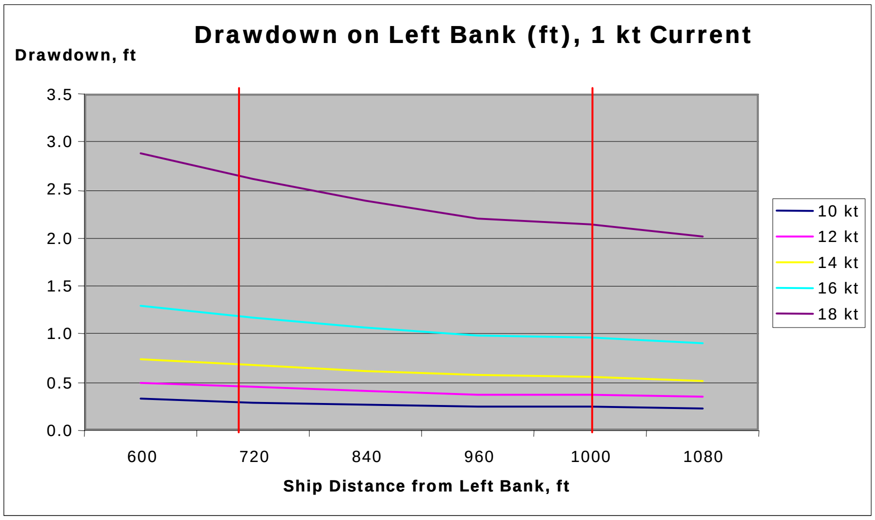


Figure 35. Predicted Draw-down at the Shoreline for Off-centerline Courses and for Various Ship Speeds

5.5 Conclusions From Modeling

The following conclusions can be reached from the preceding analysis of the ship-wave generation near the Willow Bar site:

- The empirical method of Kriebel et al. (2003) for predicting the short waves generated by ships provides a better fit to the available laboratory and the limited field data than do previous estimation techniques.
- Channel deepening from 40 to 43 ft will have little effect on individual ship-wave generation, all else remaining equal.
- Increased ship draft in the deeper channel to a bottom clearance in the existing channel will have little effect on ship-wave generation, all else remaining equal.

- Ship speed is expected to have the greatest effect on ship-wave generation, including short-period waves, draw-down, and run-up.

The empirical methods of ship-wave prediction were developed by assessing the important variables that influence wave generation and by fitting the curves to measured data. They are applicable only within the limits of the verification data and should not be applied outside of those limits. Additional field data that can be used to evaluate the appropriateness of the method for the proposed site and ship conditions should be collected to determine the confidence to be placed in the empirical estimates. The following sections evaluate the wave-height data that were collected at the three study sites along the Columbia River.

5.6 Wake-wave Record-Processing Procedure

For most field deployments, two wave staffs were placed perpendicular to the shoreline, with one about 5 m (15 ft) farther offshore. The field crew tried to place the staff in water of sufficient depth and at such a tidal stage such that the variation caused by wave passage occurred in the center two-thirds of the staff. Each staff was attached by mounting brackets to a metal rod firmly driven into the sandy bottom. To determine the deployment depth, the distance from the bottom of the staff to the sediment-water interface was measured and added to the mean still-water level recorded by the staff gage. The staff was connected to a computer at the shore station through a fixed cable and RS232 connection and was set to record at a data rate of 10 Hz. The voltage signal was converted to water level and arrayed on an Excel spreadsheet; plots were made of the signals from both staffs to evaluate differences between water levels. A typical row wave height recording from both wave staffs is shown in Figure 36.

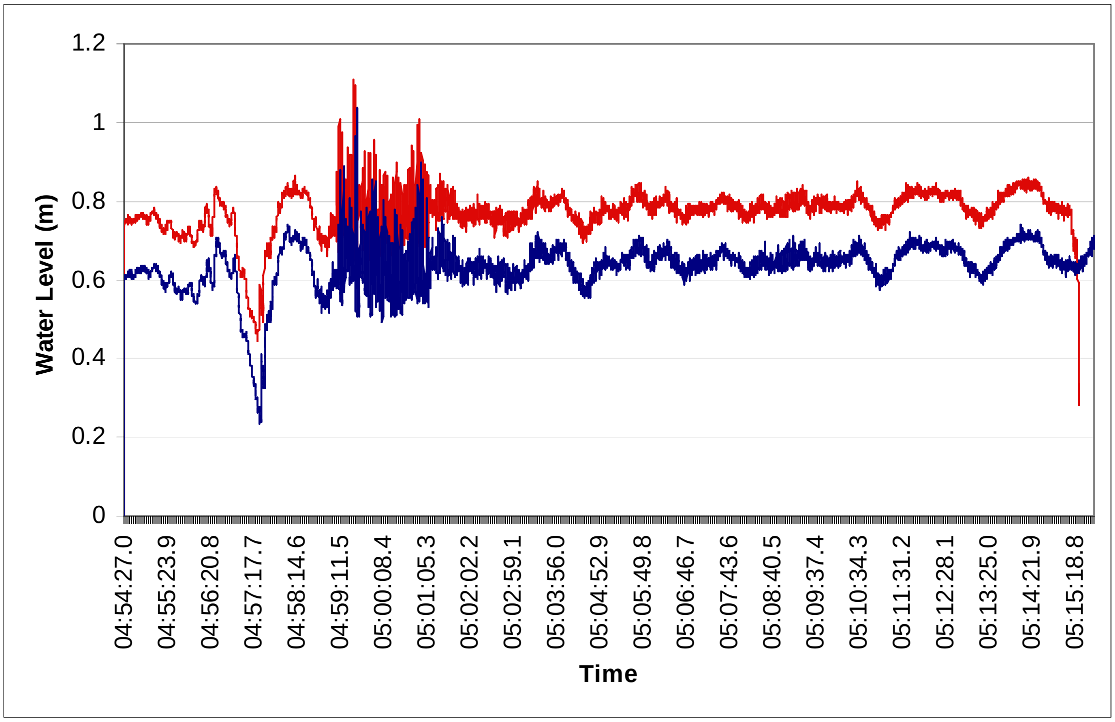


Figure 36. Raw Data Record of Waves From an Oil Tanker Recorded on Two Wave Staffs at Sauvie Island On 16 August 2004

A review of the raw water-level record indicates that when both staffs operated normally, the outputs were essentially identical in amplitude, with only a small phase lag between staffs related to the 15-ft separation. If both wave gages recorded a complete data record, the deeper one was selected for further processing because the shallower staff was more likely to “bottom out” during the draw-down coinciding with the deep-draft ship passage. If only one staff recorded data, as happened on only a few occasions, the data from that staff were used. For a few deployments, only one staff was used to save time setting up the equipment.

Other environmental and physical information collected on site or obtained to assist in the analysis included the following:

- Ship dimensions – The ship name and time of passage was noted by the field crew. Following their return, the compiled list was submitted by e-mail to the Columbia River Pilots Association, who supplied the length, beam, and draft of the vessels. Because Pilots bill the ship operators based on draft, both the pilots and the ship’s crew corroborate this information. The type of ship (oil tanker, car carrier, bulk carrier, container vessel, other) was also noted by the field crew and confirmed by the Pilots.
- Ship speed – Ship speed over the ground was determined by timing the passage of the vessel between two fixed points a known distance apart along a straight portion of the study reach.
- Tide, water level. and current – Water level was obtained from the tide prediction tables and from the USGS river gage at the Beaver Army Terminal, Quincy, Oregon, at RM 53.8. The gaging station also supplies floe velocity and river volume. Flow velocity was used to compute ship speed through the water.
- Water depth and channel cross-section – Information on the channel depth and cross-sections at the survey sites was obtained from Portland District hydrographic channel surveys. Bathymetry for County Line Park, near RM 51 was obtained from soundings along the Eureka Bar Reach; Barlow Point, near RM 61 from the Walker Island Reach; and Sauvie Island, near RM 96 from the Willow Bar Reach.

5.7 Wave Data Processing

The record shown in Figure 36 clearly shows a draw-down of the water level, a run-up above the mean water level, and the arrival of short-period wake-waves following passage of the ship. Short-period waves of relatively low amplitude can be seen before the draw-down event and, following the arrival of the pulse of short-period waves, the water surface returns to small amplitude waves.

The deeper wave staff, in this case the pink (upper) record, was selected for processing. It was “demeaned” by averaging the entire record and subtracting the average from each individual measurement to determine the water fluctuation around the still-water level; and filtered using a 60-point moving average to better show the long-period wave. The record that results from this processing is shown in Figure 37, which shows a 12-minute record from the wave staff, beginning 2 min before the draw-down minimum, and continuing for an additional 10 min.

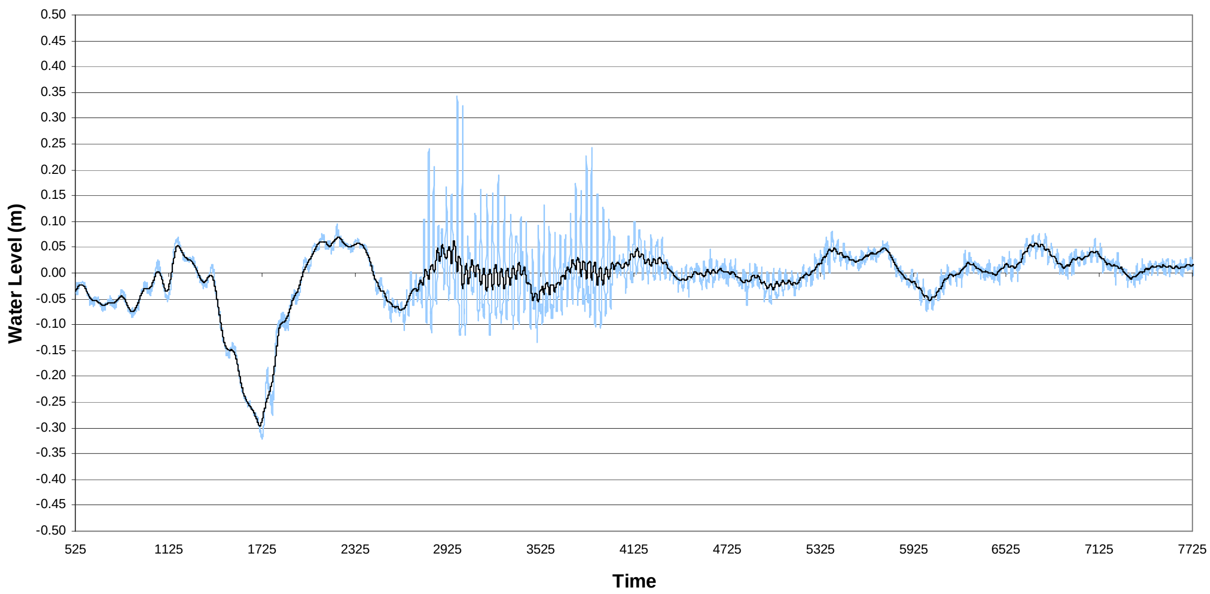


Figure 37. Processed Wave Record for Passage of an Oil Tanker Ship at Sauvie Island. Time line is recorded each 1/10 second and shows a 12-minute record.

The dark line is the filtered record showing the long-period draw-down and run-up, whereas the lighter line is short-period wave height. Most large displacement vessels generate a draw-down and following run-up with a pattern similar to that shown in Figure 37, though the degree of draw-down and run-up varies by ship, operating conditions, and site. When the draw-down pattern is observed, the depression of the water level below the still-water level during the long-period event is always greater than the following run-up above the still-water level. The draw-down may be three to five times the run-up height. The initial long-period surge is almost always of greatest trough-to-crest distance compared with subsequent long-period oscillations. In the record selected, the long-period wave shows only one surge but, in some records, a long-period oscillation is evident at decreasing amplitude for as long as 30 min when the recorder was turned off. The period of oscillation corresponds to that of a shallow-water wave oscillating across the navigation channel.

The periods of the long-period waves generated by the vessels are between ~40 sec to as long as ~116 sec between the first and second trough. The longest periods were observed at Barlow Point where the slope of the beach is small.

The arrival of the short-period bow and transverse-stern waves are clearly visible in the lighter lines of the record in Figure 37, which have not been filtered and are recorded at a frequency of 10 Hz. Though the short-period waves in this record appear to arrive for about 2 min duration, other records have a more abbreviated signal with as few as five large, short-period waves before returning to nearly background conditions.

During the study, 75 wave records were obtained from the three sites; Sauvie Island (22), Barlow Point (26), and County Line Park (27). Each of the raw wave records was processed as described above. The short-period wave height and period were obtained by locating the arrival of the wake-wave and measuring and averaging the total wave height (trough to crest) of the five largest waves in the record. These were usually, but not always, successive waves in the record. The average wave period was determined by measuring the time for 10 successive wave crests. Wave gages were deployed in various water depths, which affects the wave height as a result of shoaling. All waves were transformed to the corresponding height in water depth of 1.5 m (4.9 ft) using linear wave theory (Dally et al. 1984).

The NAVEFF program of Maynord (1996) was used to determine the draw-down for each of the sites, and the method of Maynord (2003) was used to estimate the run-up. The total long-period wave height (trough to crest) was obtained by summing the measured draw-down and run-up and comparing it with the modeled values. Ship speed used in the computation was corrected for river flow velocity and ship direction; it was, therefore, speed through the water. The regression relationship between measured and modeled values had an r^2 of ~0.15, indicating a very poor prediction. A comparison between the predicted short-period wake-wave using KSJ equations and the measured short-period wave gave a similar r^2. It seems apparent that these models do not perform well for predicting draw-down and run-up or for short-period wake-waves for ships passing the measurement sites on the LCR. Both methods depend heavily on empirical coefficients to combine physical factors that are important in the wave generation and propagation. Such empirical relationships often work well under the conditions for which they were developed (e.g., Mississippi River, Sabine-Neches Waterway, unrestricted channels) but often do not perform well outside of that environment.

Alternative regression relationships between independent variables (or combinations of variables) are considered to be important to wave generation and the observed short- and long-period wave heights. The independent variables selected to compare with wave height were as follows:

- Relative draft equal to total depth divided by vessel draft (d/T) – A non-dimensional factor used by Kriebel et al. (2003), representing the area of channel taken by the vessel
- Draft Froude number (V/(gT)1/2) – A non-dimensional relationship that incorporates speed as well as draft
- Block volume (LxBxT) – The total submerged volume displaced by the block of the vessel
- Keel clearance Froude number (V/[g(d-T)]1/2) – A non-dimensional number that uses the vessel keel clearance as the length scale.

Measured values of both long-period wave height (draw-down plus run-up) and short-period wake-wave height were used to develop regression equations and r^2 values using data at each site. The most favorable relationship was obtained between wave and block volume for long-period waves at the Sauvie Island site (Figure 38).

The r^2 values for the other regression relationships for all long- and short-wave measurements are given in Tables 16 and 17 respectively.

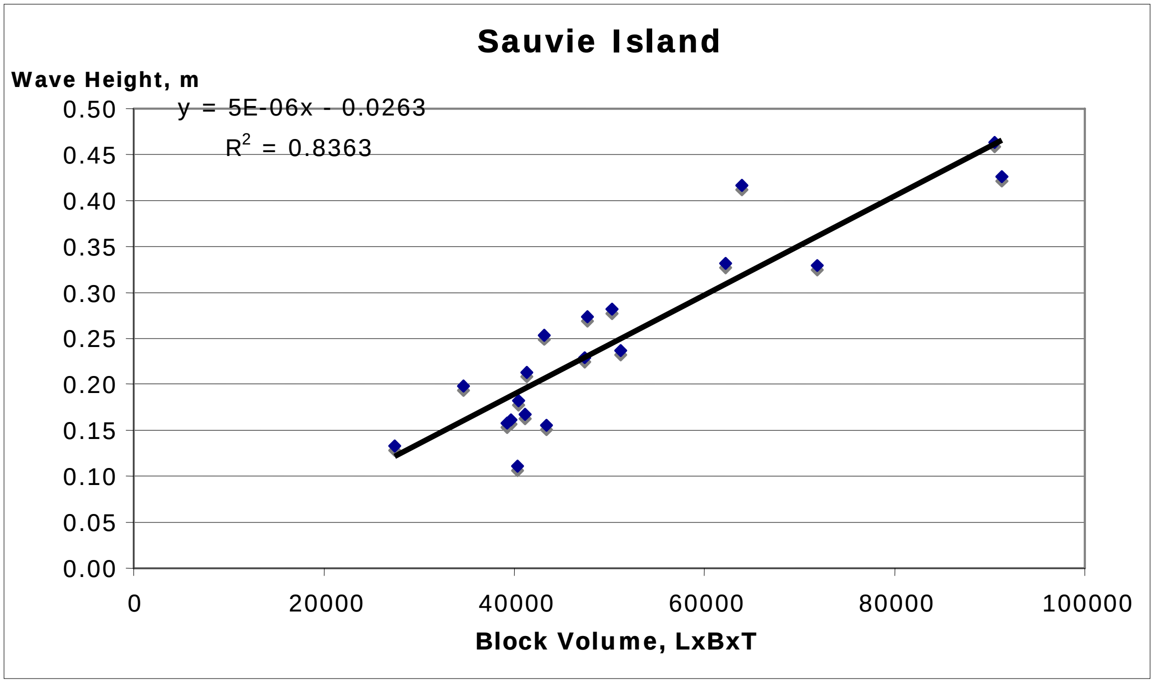


Figure 38. Linear Regression Relationship Between Long Wave Height (Draw-Down Plus Run-Up) and Vessel Block Volume at the Sauvie Island Study Site

Table 16. r^2 Values Resulting From Regression of the Indicated Value Against Long-Period, Vessel-Generated Surge-Wave Height at the Site Indicated

	Relative Draft d/T	Draft Froude Number $V/(gT)^{1/2}$	Block Volume LxBxT	Keel Clearance Froude Number $V/[g(d-T)]^{1/2}$
Sauvie Island	0.38	0	0.84	0.44
Barlow Point	0.01	0	0.10	0.02
County Line Park	0.15	0.05	0.19	0.28

Table 17. r^2 Values Resulting From Regression of the Indicated Value Against Short-Period Vessel-Generated Wake-Wave Height at the Site Indicated

	Relative Draft d/T	Draft Froude Number $V/(gT)^{1/2}$	Block Volume LxBxT	Keel Clearance Froude Number $V/[g(d-T)]^{1/2}$
Sauvie Island	0.19	0	0.26	0.18
Barlow Point	0	0.03	0.11	0.05
County Line Park	0	0.09	0.18	0.18

.

The results displayed in Tables 16 and 17 indicate that ship variables and differences between sites play large roles in the generation and propagation of surge and wake-waves. It may be possible to reduce some of the variability by using other parameters or by combining parameters, but it is apparent that the physical process is not captured by these relationships.

There were 15 occurrences when the same ship was observed multiple times, but only 8 of these provided measured data that allowed comparison of wave conditions for the passage. These results are provided in Table 18. Only one vessel was observed three times. The multiple observations do not provide sufficient data for a statistical evaluation. Considerable variability can be observed between passages at various sites, further emphasizing that site characteristics may be controlling factors.

Table 18. Comparison of Vessel Wake for Multiple Observations of the Same Ship

Ship	**Date**	**Site**	**Direction**	**L**	**B**	**D**	**Vessel speed**	**Surge wave height in 1.5 m water depth**	**Surge wave period**	**Wake-wave height in 1.5 m water depth**	**Wake-wave period**
Units				**ft**	**ft**	**ft**	**m/s**	**m**	**s**	**m**	**s**
A	08/09/04	CLP	Downstream	558	89	33.3	5.07	0.216	80	0.372	4.01
A	02/10/05	BP	Downstream	558	89	n/a	6.35	0.27	97.7	0.159	3.26
B	**08/16/04**	**SI**	**Upstream**	**650**	**96**	**35.2**	**5.05**	**0.332**	**92.4**	**0.345**	**3.31**
B	**08/30/04**	**BP**	**Downstream**	**650**	**96**	**27**	**7.28**	**0.218**	**81.4**	**0.191**	**2.21**
B	**05/16/05**	**SI**	**Downstream**	**650**	**96**	**27**	**5.52**	**0.273**	**71.1**	**0.32**	**2.85**
C	06/29/04	CLP	Upstream	568	90	28	6.36	0.295	80.1	0.151	4.05
C	06/30/04	BP	Downstream	568	90	27	7.29	0.121	110.7	0.164	3.59
D	07/20/04	SI	Upstream	950	106	32	6.87	0.426	97.7	0.551	3.68
D	**07/21/04**	**CLP**	**Downstream**	**950**	**106**	**33.4**	**8.85**	**0.418**	**62**	**0.375**	**3.53**
E	02/08/05	SI	Downstream	623	106	21	6.14	0.158	46.2	0.261	3.72
E	**02/11/05**	**BP**	**Downstream**	**623**	**106**	**39**	**4.65**	**0.145**	**116.8**	**0.206**	**3.96**
F	08/10/04	CLP	Upstream	640	106	26.1	6.69	0.503	39.3	0.304	1.97
F	**08/13/04**	**SI**	**Downstream**	**640**	**106**	**37.4**	**5.1**	**0.329**	**56**	**0.204**	**3.26**
G	**03/21/05**	**CLP**	**Downstream**	**599**	**106**	**25**	**7.22**	**0.336**	**73.8**	**0.284**	**3.71**
G	**05/18/05**	**SI**	**Downstream**	**599**	**106**	**24**	**5.35**	**0.254**	**59.3**	**0.319**	**2.78**
H	08/15/04	SI	Downstream	650	102	25.3	3.99	0.229	71.2	0.126	2.95
H	**02/11/05**	**BP**	**Upstream**	**650**	**102**	**25**	**6.4**	**0.423**	**104.7**	**0.391**	**3.88**
Bold = stranding events.											

5.8 Conclusions

Methods for predicting the magnitudes of ship-generated wake-waves, consisting of long-period draw-down and run-up, have been developed for confined channels. Additional methods for predicting the short-period bow and transverse-stern wake have been developed primarily from scale model tests. Though these methods show promise for the conditions under which they were developed, they do not accurately predict the components of ship wake observed at the three study sites along the Columbia River. Both prediction methods rely heavily on empirical relationships, which combine physical parameters into non-dimensional numbers with coefficients and exponents determined from observation. Neither of the methods adequately accounts for factors that are likely to be important during wave propagation, such as bottom slope, distance from the site, bottom friction, and possible non-linear wave effects, to name a few.

6.0 Multivariate Analysis of Covariance

6.1 Introduction

The before-and-after comparison needs to account for covariates so that any changes in the covariates between before and after time periods will not later confound analysis. One obvious covariate during the design phase was fish availability, which received attention during design and before-phase sampling. Other potential covariates were expected to be among the ambient conditions (e.g., tidal height, river flow) and among the ship and wake characteristics. However, precisely which of the several ambient conditions and ship and wake characteristics would be appropriate covariates was not evident during design or even during the pilot-phase sampling.

Single-variable and multivariate regression analyses were used to discern which ambient conditions and ship or wake characteristics would be appropriate covariates. First, we examined the incidence of stranding events versus the ambient conditions and ship characteristics. Second, we examined the incidence of stranding events versus ambient conditions and wave characteristics. Third, we examined wave characteristics versus ambient conditions and ship characteristics.

6.2 Incidence of Stranding Versus Ambient Conditions and Ship Characteristics

Nineteen independent variables were considered as potential factors affecting the incidence of smolt stranding. Four variables reflecting ambient conditions were considered:

- tidal stage: ebbing, flooding, low slack, and high slack
- tidal height
- river flow
- current velocity (knots)

Current velocity measured in m/sec was also available, but mirrored the values of current velocity in knots, so only the velocity measured in knots was used. Eleven variables reflecting ship characteristics were considered, including several constructed from other variables:

- ship type: five types of vessels (car carrier, bulk carrier, oil tanker, container vessel, and other)
- ship direction: upstream or downstream
- ship condition: unloaded, partially loaded, and loaded
- ship distance: five levels of distance of the vessel from shore (near, near-middle, middle, middle-far, and far)
- ship time: duration of vessel passage (sec)
- ship speed over ground (knots)
- ship draft
- ship beam
- ship length
- ship block coefficient: draft×beam×length
- kinetic energy proxy: block × (ship speed)2/1 × 10−8

Two measures of ship speed over ground were available: one measured in knots and the other in m/sec. Because the difference in speed measures was only one of units, only the measurement in knots was used. The derived variable kinetic energy proxy was scaled by 10^{-8} to facilitate interpretation of model parameters.

In addition to the ambient and ship characteristics listed above, site, season, and fish density were also considered. Site (i.e., “location”) was included as an indicator variable for the three study sites (BP, CL, and SI). Season was included as an indicator variable for the three seasons studied (summer, winter, and spring). Both a Chinook seine index and a more inclusive salmonid seine index were considered as measures of fish density.

Not all variables were measured for each passage trial. Thus, the degrees of freedom in the following models vary more than expected simply due to the type of covariates.

6.2.1 Single-variable Regressions

Single-variable logit regression models were analyzed to identify factors that may be related to stranding incidence. The results are summarized in Table 19 (also see Appendix B-1). Table 19 suggests that season ($p = 0.2192$), tidal stage ($p = 0.2947$), and ship distance ($p = 0.5277$) are not significantly related to stranding incidence, and that the remaining variables may be related to incidence. Tidal height ($p = 0.0045$), location ($p = 0.0055$), and ship time ($p = 0.0071$) are particularly indicated. Multivariate analyses considering the effects of these and other variables are explained below. Graphs showing the relationship between incidence of stranding and location (Figure 39), tidal height (Figure 40), ship time (Figure 41), kinetic energy (Figure 42), and salmonid density index (Figure 43) are shown below. Figure 39 shows a plot of the proportion of the stranding at the three different locations.

6.2.2 Multivariate Regressions

Several multiple regressions using combinations of ambient factors, ship characteristics, and fish density were considered. Because of the differing beach morphology and hydrology at the three locations, the location variable is included in all the following analyses.

With the location effect accounted for, the significance of each of the other variables was tested; the resulting p-values are shown in Table 20, with the individual analysis of deviance tables in Appendix B-2. It appears from Table 20 that most of the ship covariates (ship time, force or kinetic energy proxy, speed, beam, block coefficient, type, length, direction, and draft) may be related to the incidence of stranding, even when location is accounted for. Figures 44 through 47 show the fitted single-logistic curves, together with a non-parametric moving-average curve showing the proportion of the stranding versus the covariate. As previously described, the variable kinetic energy (which is rather a proxy for kinetic energy) is a function of the variables ship speed, and block coefficient (beam, length, and draft) and it is reasonable to expect that inclusion of kinetic energy in the model will obviate the need for these other ship variables. This is shown to be the case in Table 21, which gives the p-values for alternative variables when both location and kinetic energy are accounted for.

Table 19. Summary of Single-Variable Logit-Regression Analyses, With Covariates Ranked by Their p-Value

Independent Variable	p-value
Tidal Height	0.0045
Location	0.0055
Ship Time	0.0071
Ship Beam	0.0138
Kinetic Energy Proxy	0.0141
Ship Speed	0.0166
Current Velocity	0.0206
Ship Block	0.0262
Ship Direction	0.0364
Chinook Seine Index Count	0.0529
River Flow	0.0700
Ship Condition	0.0731
Ship Type	0.0782
Salmonid Seine Index Count	0.0821
Ship Length	0.0948
Ship Draft	0.1026
Season	0.2192
Tidal Stage	0.2947
Ship Distance	0.5277

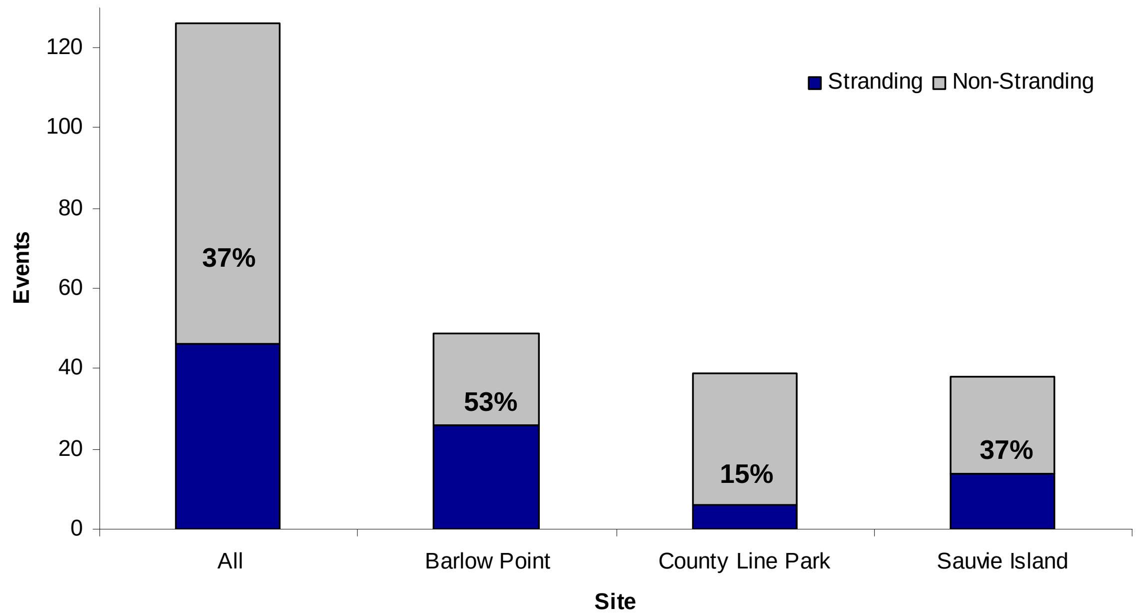


Figure 39. Proportion of Stranding Events by Site, for All Seasons

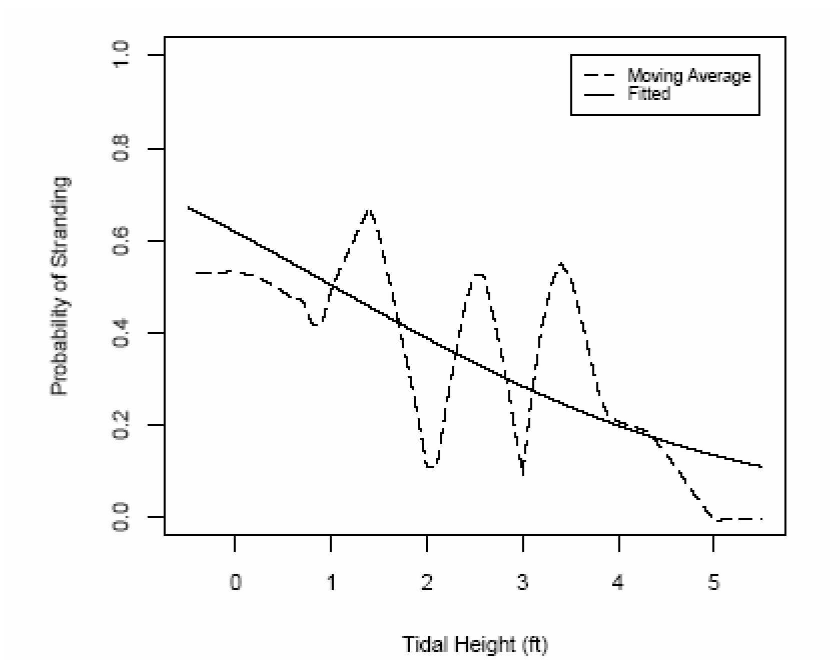


Figure 40. The Fitted Logistic Curve (solid line) of the Probability of Stranding Versus Tidal Height, and a Non-Parametric Moving Average Curve (dotted line) of the Proportion of Strandings Versus Tidal Height

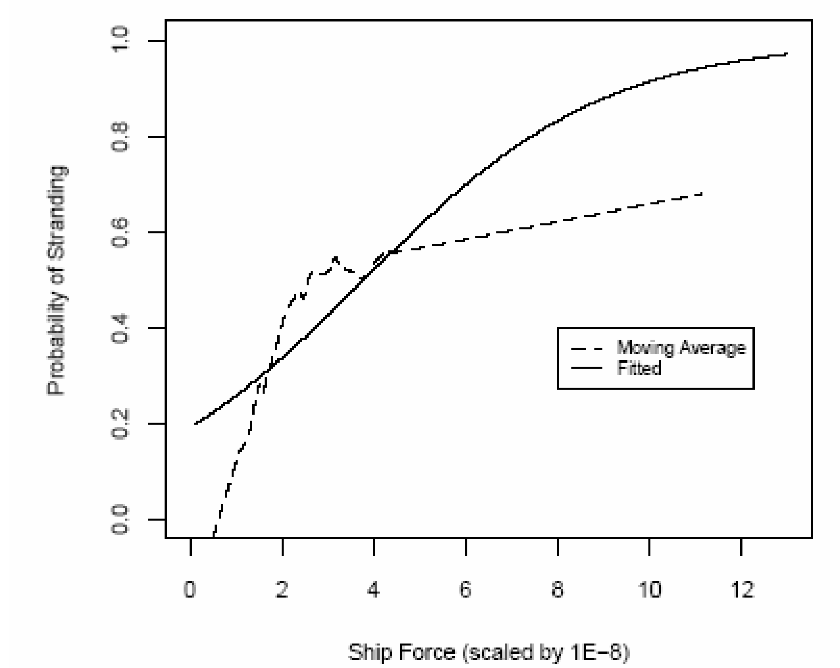


Figure 41. The Fitted Logistic Curve (solid line) of the Probability of Stranding Versus a Proxy for Ship Kinetic Energy (scaled by 10^{-8}), and a Non-Parametric Moving Average Curve (dotted line) of the Proportion of Strandings Versus Ship Time

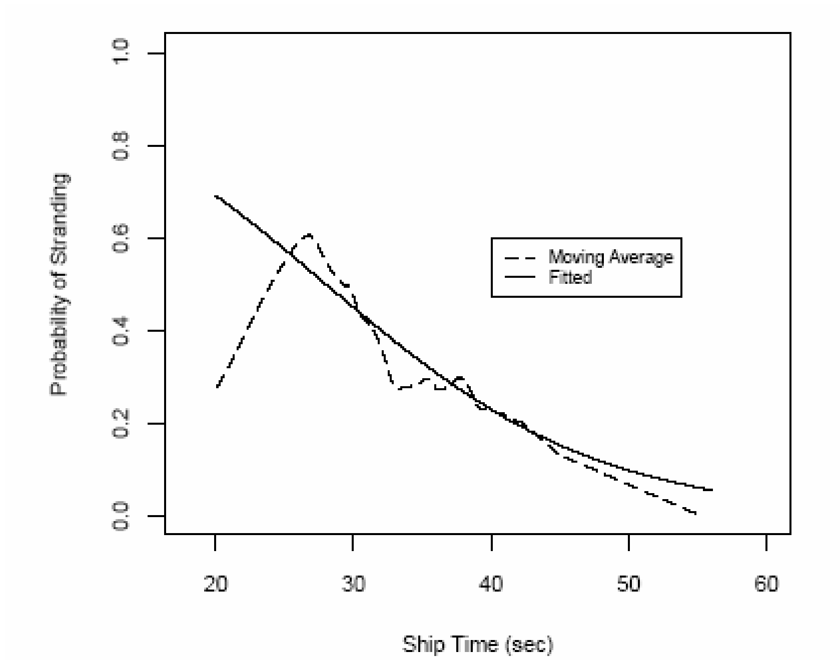


Figure 42. The Fitted Logistic Curve (solid line) of the Probability of Stranding Versus Ship Time, and a Non-Parametric Moving Average Curve (dotted line) of the Proportion of Stranding Versus Kinetic Energy

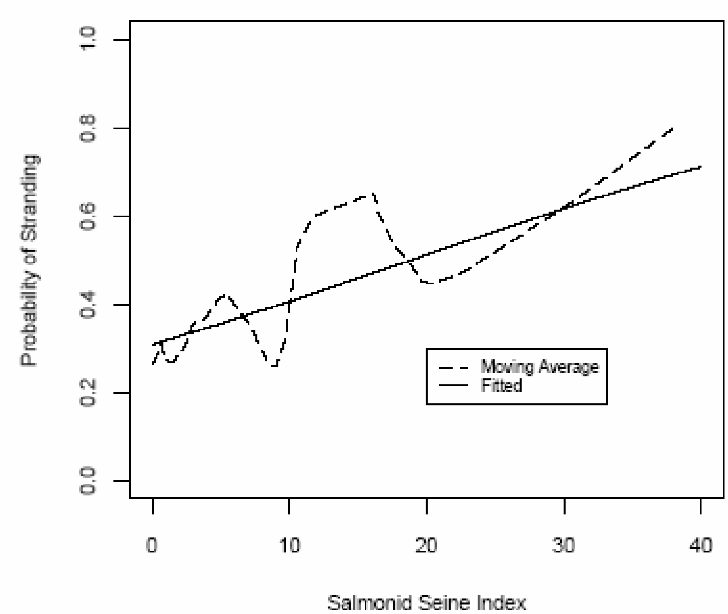


Figure 43. The Fitted Logistic Curve (solid line) of the Probability of Stranding Versus Salmonid Seine Index, and a Non-Parametric Moving Average Curve (dotted line) of the Proportion of Strandings Versus Salmonid Seine Index

Table 20. Summary of Added Significance of Individual Covariates in Two-Variable Logit-Regression Analyses With Location Accounted For

Independent Variable	p-value
Ship Time	0.0004
Kinetic Energy Proxy	0.0008
Ship Speed	0.0009
Ship Beam	0.0020
Ship Block	0.0074
Ship Type	0.0146
Tidal Height	0.0267
Ship Length	0.0268
Ship Direction	0.0281
Current Velocity	0.0363
Ship Draft	0.0399
Salmonid Seine Index Count	0.0420
Chinook Seine Index Count	0.0441
Ship Condition	0.0661
River Flow	0.1260
Season	0.1488
Ship Distance	0.2750
Tidal Stage	0.6944
Note: The covariates are ranked by their p-values.	

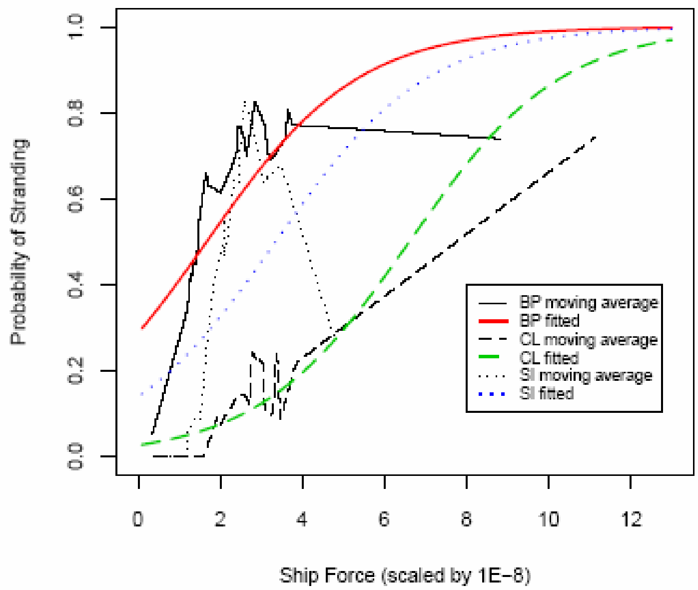


Figure 44. The Fitted Logistic Curves of the Probability of Stranding Versus Kinetic Energy (scaled by 10^{-8}), and Non-Parametric Moving Average Curves of the Proportion of Strandings Versus Kinetic Energy (scaled), Each for the Three Locations. The logistic curves vary significantly with location (p-value for equal lines: $p[F_{2,95} \geq 8.1798] = 0.0005$).

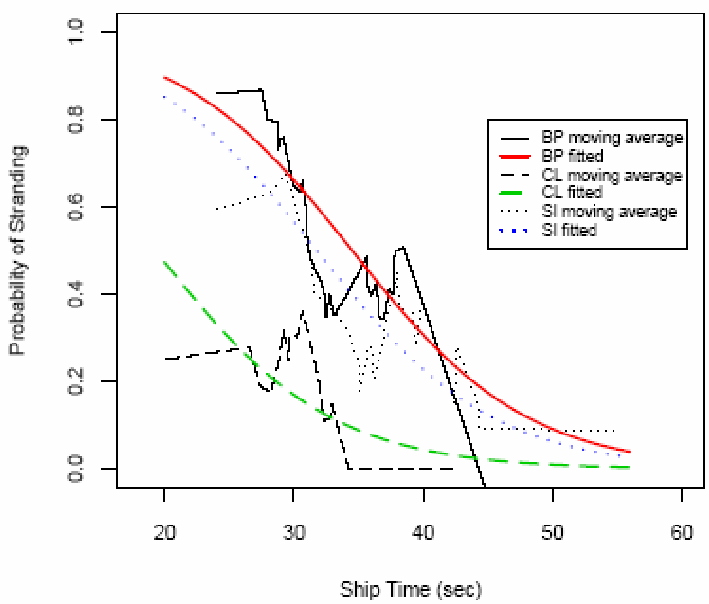


Figure 45. The Fitted Logistic Curves of the Probability of Stranding Versus Ship Time, and Non-Parametric Moving Average Curves of the Proportion of Strandings Versus Ship Time, Each for the Three Locations. The logistic curves vary significantly with location (p-value for equal lines: $p[F_{2,109} \geq 7.6829] = 0.0008$).

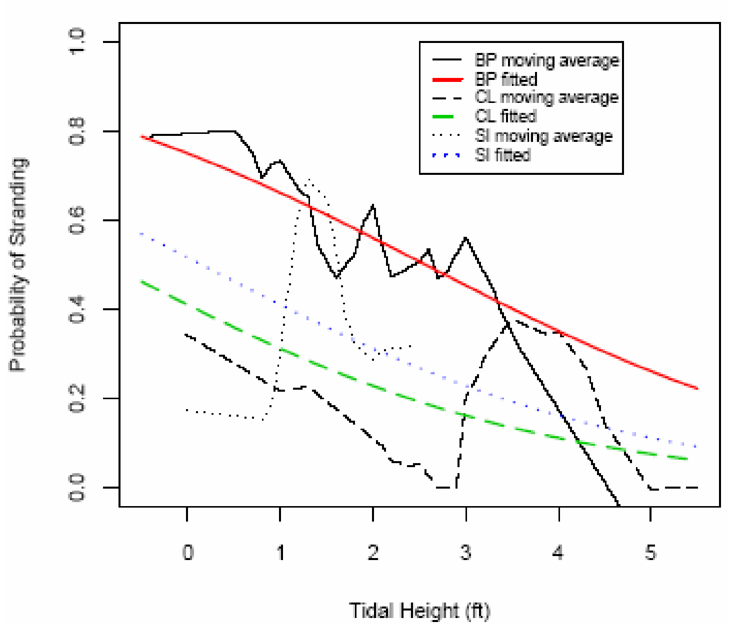


Figure 46. The Fitted Logistic Curves of the Probability of Stranding Versus Tidal Height, and Non-Parametric Moving Average Curves of the Proportion of Strandings Versus Tidal Height, Each for the Three Locations. The logistic curves vary significantly with location (p-value for equal lines: $p[F_{2,114} \geq 3.7640] = 0.0261$).

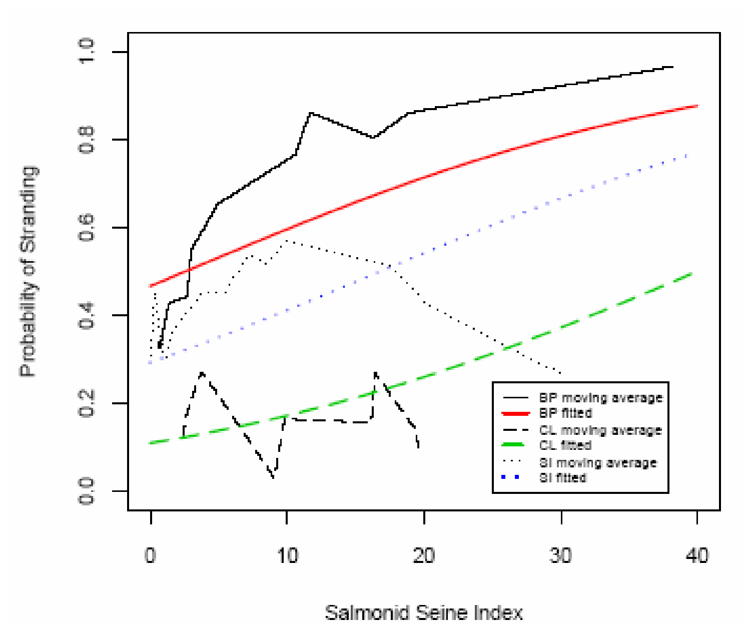


Figure 47. The Fitted Logistic Curves of the Probability of Stranding Versus Salmonid Seine Index, and Non-Parametric Moving Average Curves of the Proportion of Strandings Versus Salmonid Index, Each for the Three Locations. The logistic curves vary significantly with location [p-value for equal lines: $p[F_{2,114} \geq 6.0485] = 0.0032$).

Table 21. Summary of Trivariate Logit-Regression Analyses, With Covariates Ranked By Their p-Value, Given That Location and Kinetic Energy Are Accounted For

Independent Variable	p-value
Tidal Height	0.0729
Salmonid Seine Index	0.0806
Chinook Seine Index	0.0979
Season	0.1108
Ship Time	0.1285
Ship Type	0.1512
Ship Speed	0.1730
Ship Direction	0.9247
Ship Beam	0.2955
Current Velocity (Knots)	0.4484
Ship Condition	0.5321
River Flow	0.5905
Ship Distance From Shore	0.6657
Ship Block Coefficient	0.6835
Ship Length	0.6891
Tidal Stage	0.7823
Ship Draft	0.8307

From Table 21, it is apparent that with both location and kinetic energy accounted for, the remaining variables that may be related to the incidence of smolt stranding are tidal height ($p = 0.0729$), the salmonid density index ($p = 0.0806$), and the Chinook seine index ($p = 0.0979$).

There is some evidence that season, ship time, ship type, and ship speed may be related to smolt stranding, as well. The significance of added contributions of the different variables when location, kinetic energy proxy, and tidal height were already accounted for was examined, and the associated p-values are listed in Table 22.

Table 22 suggests that with location, kinetic energy proxy, and tidal height accounted for, no other variables may be sufficiently related to smolt stranding incidence to warrant inclusion in the model. Although ship time is weakly indicated ($p = 0.1288$), because it is closely related to the derived variable kinetic energy, it is not included as a fourth variable. Ship speed is not considered for a similar reason. The contribution of the salmonid index of fish density is considered below.

Table 22. Summary of Multivariate Logit-Regression Analyses, With Covariates Ranked by Their p-Value Given That Location, Kinetic Energy, and Tidal Height Are Accounted For

Independent Variable	p-value
Ship Time	0.1288
Ship Speed	0.1742
Salmonid Seine Index	0.1748
Ship Type	0.1845
Chinook Seine Index	0.2070
Ship Direction	0.2321
Season	0.2421
Ship Beam	0.2917
Tidal Stage	0.5094
Ship Condition	0.6399
Ship Distance From Shore	0.6539
River Flow	0.7352
Ship Length	0.7455
Ship Block Coefficient	0.7596
Ship Draft	0.8193
Current Velocity (knots)	0.8572

6.2.3 Interaction Effects

Possible interaction effects between location and either kinetic energy, tidal height, or salmonid index were considered. For each, it was concluded that the interaction effect of location with the other variable was non-significant, implying that although the effect of the amplitude of the values of the three variables varies with site, a change in these variables has the same effect on stranding incidence at each of the three sites ($p = 0.8000$, $p = 0.1103$, and $p = 0.3084$, respectively, for the interaction effect between location and kinetic energy, tidal height, and salmonid density) (Tables 23 through 25). The analysis of deviance tables that follow show the added contributions of each term (variable), given that the variables listed above it in the table are already in the model. Thus, the listed F-statistics test the significance of the variable relative to the model that includes the previously listed variables, rather than to the model with all terms listed in the table.

Interaction effects between kinetic energy and tidal height were also considered (Table 26). It appears that there is a significant interaction effect between kinetic energy and tidal height ($F_{1,92} = 3.2555$, $p = 0.0745$). This indicates that the effect of a given increase in kinetic energy varies with tidal height, although the effect of the increase is the same at the three different locations.

Table 23. Analysis of Deviance Table Examining the Effect of the Interaction Between Location and Kinetic Energy

Source	DF	DEV	MDEV	F	P
Total $_{Corr}$	98	132.775			
Location	2	12.870	6.435		
Kinetic energy proxy	1	13.489	13.489		
Tidal Height	1	3.597	3.597		
Salmonid Density	1	2.026	2.026	$F_{1,93}$ = 1.8697	0.1748
Location X Kinetic energy	2	0.493	0.247	$F_{2,91}$ = 0.2237	0.8000
Error	91	100.280	1.102		

Notes:
- The F1,93 statistic for salmonid density tests the significance of the added contribution of salmonid density when location, kinetic energy proxy, and tidal height are accounted for.
- The $F_{2,91}$ statistic for the interaction term (location × kinetic energy) tests the significance of the added contribution of the interaction term when the preceding four variables are accounted for.
- Overall Model $p(F_{7,91}) \geq 4.2100 = 0.0005$, $r^2 = 0.2446$.

Table 24. Analysis of Deviance Table Examining Effect of Interaction Between Location and Tidal Height

Source	DF	DEV	MDEV	F	P
Total $_{Corr}$	98	132.775			
Location	2	12.870	6.435		
Kinetic energy	1	13.489	13.489		
Tidal Height	1	3.597	3.597		
Salmonid Density	1	2.026	2.026	$F_{1,93}$ = 1.8697	0.1748
Location X Tidal Height	2	4.767	2.384	$F_{2,91}$ = 2.2592	0.1103
Error	91	96.006	16.001		

Note: Overall Model $p(F_{7,91}) \geq 4.9761 = 0.000085$, $r^2 = 0.2768$.

Table 25. Analysis of Deviance Table Examining Effect of Interaction Between Location and Salmonid Density

Source	DF	DEV	MDEV	F	P
Total $_{Corr}$	98	132.775			
Location	2	12.870	6.435		
Kinetic energy	1	13.489	13.489		
Tidal Height	1	3.597	3.597		
Salmonid Density	1	2.026	2.026	$F_{1,93}$ = 1.8697	0.1748
Location X Salmonid Density	2	2.572	1.286	$F_{2,91}$ = 1.1917	0.3084
Error	91	98.201	1.079		

Note: Overall Model p(F7,91) ≥4.5743 = 0.00021, $r^2 = 0.2603$.

Table 26. Analysis of Deviance Table Examining Effect of Interaction Between Kinetic Energy and Tidal Height

Source	DF	DEV	MDEV	F	P
Total $_{Corr}$	98	132.775			
Location	2	12.870	6.435		
Kinetic energy	1	13.489	13.489		
Tidal Height	1	3.597	3.597		
Salmonid Density	1	2.026	2.026	$F_{1,93}$ = 1.8697	0.1748
Kinetic Energy Proxy x Tidal Height	1	3.444	3.444	$F_{2,91}$ = 3.2555	0.0745
Error	91	97.328	1.058		
Note: Overall Model p($F_{6,92}$) ≥5.5813) = 0.000057, r^2 = 0.2669.					

A possible interaction effect between kinetic energy and salmonid density (instead of tidal height) was also considered; the interaction effect between kinetic energy and salmonid density was found to be insignificant (p[$F_{1,92}$ ≥1.1658] = 0.2831, r^2 = 0.2504). Also, a possible interaction between tidal height and salmonid density was considered, in addition to the interaction between kinetic energy and tidal height; the interaction effect between tidal height and salmonid density was found to be significant (p = 0.0297). The analysis of deviance table for this model is below (Table 27).

The model in Table 27 accounts for the largest amount of variation in incidence of stranding (r^2 = 0.3042) among the models considered, and is biologically reasonable. Because of these considerations and the significance of the interaction between tidal height and salmonid density, this model was selected as the final model.

Table 27. Analysis of Deviance Table Examining Effect of Interaction Between Tidal Height and Salmonid Density

Source	DF	DEV	MDEV	F	P
Total $_{Corr}$	98	132.775			
Location	2	12.870	6.435		
Kinetic Energy Proxy	1	13.489	13.489		
Tidal Height	1	3.597	3.597		
Salmonid Density	1	2.026	2.026	$F_{1,93}$ = 1.8697	0.1748
Kinetic Energy Proxy X Tidal Height	1	3.444	3.444	$F_{1,92}$ = 3.2555	0.0745
Tidal Height X Salmonid Density	1	4.954	4.954	$F_{1,91}$ = 4.8803	0.0745
Error	91	97.374	1.015		
Note: Overall Model p($F_{7,91}$) ≥5.6783) = 0.000018, r^2 = 0.3042.					

In summary, the final model has the following form:

Stranding~ Location + Kinetic Energy Proxy + Tidal Height + Salmonid Density + Kinetic Energy Proxy × Tidal Height + Tidal Height × Salmonid Density.

The coefficients of the terms in the final model are given in Table 28.

Table 28. Coefficients from Final Logistic Model of Regression 1: Stranding~ Location + Kinetic Energy Proxy + Tidal Height + Salmonid Density + Kinetic Energy Proxy×Tidal Height + Tidal Height×Salmonid Density

Independent Variable	Coefficient	S.E.
Intercept	-1.0945	1.1843
Location 2 (CL)	-3.1547	0.9856
Location 3 (CL)	-1.3672	0.6063
Kinetic Energy Proxy (scaled)	1.2334	0.4011
Tidal Height	-0.2310	0.4828
Salmonid Density	-0.0714	0.0589
Kinetic Energy Proxy (scaled) x Tidal Height	-0.2554	0.1357
Tidal Height x Salmonid Density	0.0736	0.0358

6.3 Incidence of Stranding Versus Ambient Conditions and Wave Characteristics

6.3.1 Single-Variable Regressions

Seventeen single-variable regressions were analyzed independently to identify potential factors affecting incidence of stranding. Four variables reflecting ambient conditions were considered:

- Tidal Stage: indicator variable for four tidal stages (ebbing, flooding, low slack, and high slack)
- Tidal Height
- River Flow
- Current Velocity (knots)

Current velocity measured in m/sec was also available, but mirrored the values of current velocity in knots, so only the velocity measured in knots was used. Nine variables reflecting wave characteristics were considered, including several constructed from other variables:

- Run-up Distance
- Draw-down Distance
- Total Wave Excursion: run-up distance plus draw-down distance (horizontal)
- Maximum Run-up Height
- Maximum Draw-down Height
- Maximum Water Level
- Run-up Velocity (measured with gage)
- Run-up Velocity (measured with camera)
- Wash-back Velocity (measured with gage)

The two measures of run-up velocity do not appear related, so both measures were considered. Some measures of wave characteristics were unavailable for a large number of records, in particular run-up velocity and washback velocity, and to a lesser extent, maximum run-up and draw-down heights. In addition to the ambient and wave characteristics listed above, site, season, and fish density were also considered. Site (i.e., "location") was included as an indicator variable for the three study sites (BP, CL, and SI). Season was included as an indicator variable for the three seasons studied (summer, winter, and spring). Both a Chinook seine index and a more inclusive salmonid seine index were considered as measures of fish density. The results for the 17 single-variable regressions are shown in Table 29.

Table 29. Summary of Single-Variable Logit-Regression Analyses, With Covariates Ranked by Their p-Value

Independent Variable	p-value
Total Wave Distance	0.0004
Draw-Down Distance	0.0006
Run-Up Distance	0.0016
Tidal Height	0.0045
Location	0.0055
River Flow	0.0700
Current Velocity (knots)	0.0206
Maximum Draw-down Height	0.0393
Chinook Seine Index	0.0529
Salmonid Seine Index	0.0821
Maximum Run-up Height	0.0956
Run-up Velocity	0.1509
Season	0.2192
Tidal Stage	0.2947
Maximum Water Level	0.3368
Washback Velocity	0.7118
Run-up velocity (camera)	0.9943

Several factors appear unrelated to incidence of stranding from Table 29: season, tidal stage, maximum water level, wash-back velocity, and run-up velocity (camera). Run-up velocity (gage) is not strongly indicated, but is considered further. Of the remaining nine covariates, five had p-values <0.01: total wave distance ($p = 0.0004$), draw-down distance ($p = 0.0006$), run-up distance ($p = 0.0016$), tidal height ($p = 0.0045$), and location (i.e., site; $p = 0.0055$). The remaining variables are indicated at slightly lower levels of significance (Table 19; Appendix B-3). The three measures of wave velocity (run-up velocity with camera, run-up velocity with gage, and wash-back velocity) may appear insignificant because of the large number of missing values among these data. A graph showing the fitted logistic curve relating incidence of stranding to total wave distance is given below (Figure 48). The fitted single-variable logistic curve is shown, together with a non-parametric moving average curve showing the proportion of the stranding versus the covariate. Figures 39 and 40 show the relationship between stranding incidence and location and tidal height, respectively.

6.3.2 Multivariate Regressions

Based on the results shown in Table 29, certain factors were considered in multivariate regressions. Because of varying topography and hydrology across sites, location was included in all multivariate regressions. With the location effect accounted for, the significance of each of the other variables was examined; the resulting p-values are shown in Table 30.

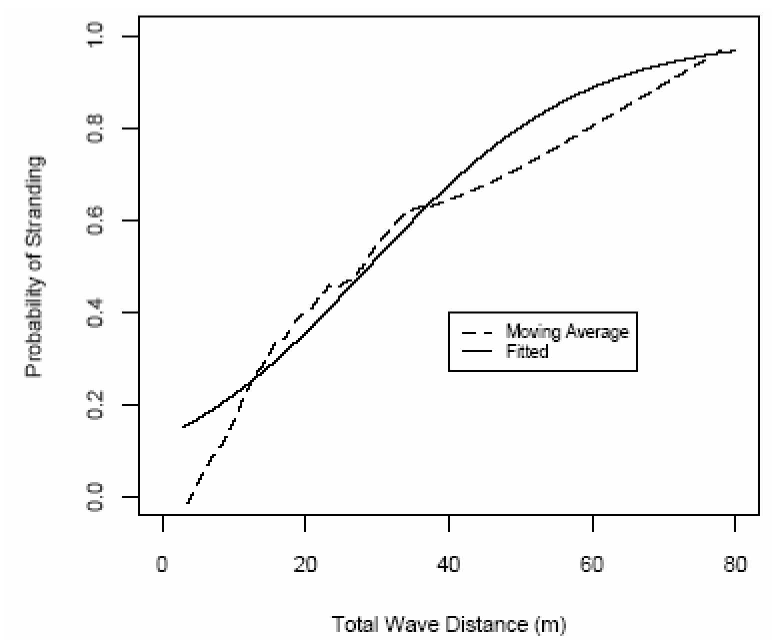


Figure 48. The Fitted Logistic Curve (solid line) of the Probability of Stranding Versus Total Wave Distance, and a Non-Parametric Moving Average Curve (dotted line) of the Proportion of Strandings Versus Total Wave Distance (horizontal)

Table 30. Summary of Added Significance of Individual Covariates in Two-Variable Logit-Regression Analyses With Location Accounted For

Independent Variable	**p-value**
Total Wave Distance	0.0003
Draw-down distance	0.0005
Run-up distance	0.0008
Maximum draw-down Height	0.0023
Maximum Run-up Height	0.0041
Tidal Height	0.0267
Current Velocity (knots)	0.0363
Salmonid Seine Index	0.0420
Chinook Seine Index	0.0441
Run-up Velocity (gage)	0.1158
River Flow	0.1260
Season	0.1488
Maximum Water Level	0.2073
Run-up Velocity (camera)	0.4778
Washback Velocity	0.6015
Tidal Stage	0.6994
Note: The covariates are ranked by their p-values.	

Table 30 indicates that measures of both horizontal wave distance (total wave distance, draw-down distance, and run-up distance) and (vertical) wave height (maximum draw-down height and maximum run-up height) are significant ($p < 0.01$ for each factor individually), even when location is accounted for. Additionally, tidal height ($p = 0.0267$), current velocity ($p = 0.0363$), and both fish density measures ($p < 0.05$ for each individually) are also significant when location is accounted for. Run-up velocity (gage), river flow, and season may be significant factors.

Because total wave distance is just the sum of the run-up distance and the draw-down distance, total wave distance was considered in future models, with both run-up distance and draw-down distance omitted. Similarly, because the two measures of fish density are closely related (Figure 49) and because the salmonid index ($p = 0.0420$) is slightly more significant than the Chinook index ($p = 0.0441$), only the salmonid index is used in future regressions. Figures 47 and 50 show graphs of the fitted logistic models that include both location and either total wave distance or salmonid index, respectively. The plots show the fitted logistic curves for the three locations, together with a non-parametric moving average curve showing the proportion of stranding versus the covariate, again for each of the three locations.

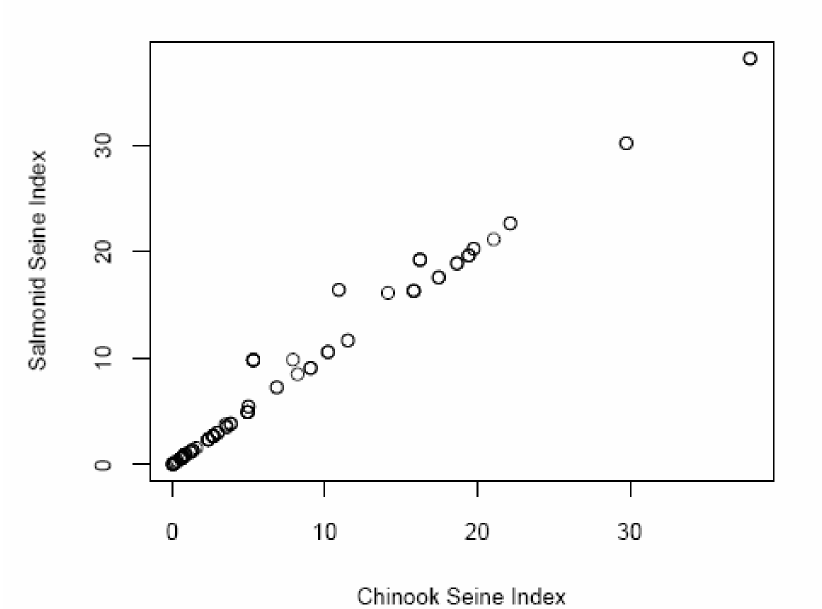


Figure 49**.** Scatterplot of the Two Measures of Fish Density, Across All Locations

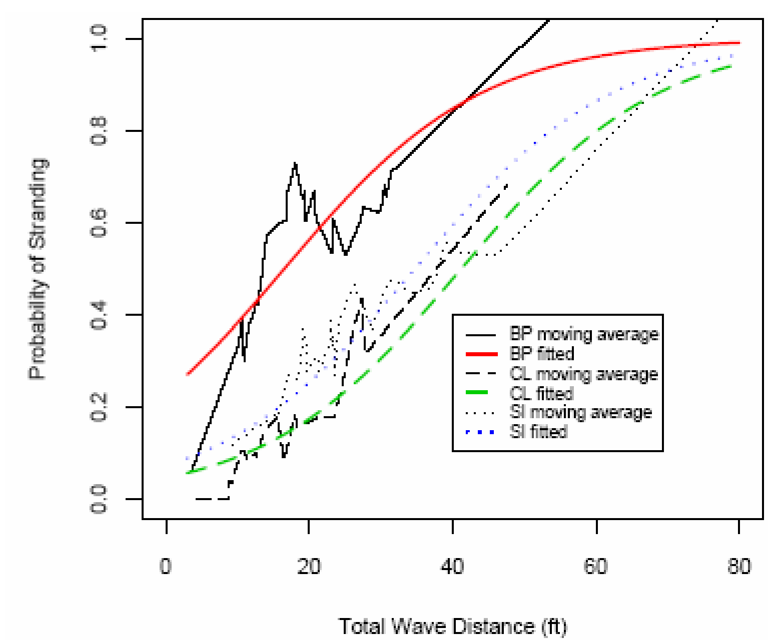


Figure 50. Fitted Logistic Curves of the Probability of Stranding Versus Total Wave Distance, and a Non-Parametric Moving Average Curve of the Proportion of Strandings Versus Total Wave Distance, Each for the Three Locations. The logistic curves vary significantly with location (p-value for equal lines: $p[F_{2,113} \geq 6.0208] = 0.0033$).

Total wave distance appears to be a key factor, and models that include location, total wave distance, and other variables were considered. With both total wave distance and location included, salmonid index ($p = 0.0013$), season ($p = 0.0082$), tidal height ($p = 0.0327$), and river flow ($p = 0.0397$) were all indicated as significant (Appendix B-4). With location, total wave distance, and salmonid index all included ($r^2 = 0.2616$), no other factor was found to be significant at the 10% level. Run-up velocity (gage) was found to be marginally related to stranding incidence ($p = 0.1735$) when location, total wave distance, and salmonid index were accounted for. However, inclusion of run-up velocity in the model decreased the amount of variation explained ($r^2 = 0.2436$), possibly a result of the large number of missing values in the run-up velocity data. Thus, neither run-up velocity nor other variables were considered further.

6.3.3 Interaction Effects

Several models examining possible interaction effects among location, total wave distance, and salmonid index were considered (Tables 31 and 32). In an analysis of the interaction between location and total wave distance (accounting for salmonid density), it was concluded that although the effect on stranding by the absolute value of the total wave distance varied across sites ($p = 0.0003$), the effect of a given increase in total wave distance was the same at each location ($p = 0.7777$) (Table 31). Similarly, in examining the interaction between location and salmonid density (accounting for wave distance), it was concluded that although the effect on stranding at different sites varied with fish density ($p = 0.0013$), a given change in fish density also had the same effect at each location ($p = 0.3354$) (Table 32). A possible interaction between total wave distance and salmonid density was considered, and found to be insignificant ($p[F_{1,111} \geq 0.1238] = 0.7256$).

After examining alternative models, the model selected includes the main effects of location, total wave distance, and salmonid density, with no interaction effects:

Stranding ~ Location + Total Wave Distance + Salmonid Density Index.

This main effect, trivariate model is significant ($p[F_{4,112} \geq 9.922] = 6.57 \times 10^{-7}$ for the overall model), and explains 26.2% of the variability in smolt stranding incidence ($r^2 = 0.2616$). Both total wave distance and salmonid density appear to be related to smolt stranding, but the relationship varies at the different sites. Parameters of the logistic model are listed in Table 33.

Table 31. Analysis of Deviance Table Examining Effect of Interaction Between Location and Total Wave Distance When Salmonid Density Is Accounted For

Source	DF	DEV	MDEV	F	P
Total $_{Corr}$	116	156.813			
Location	2	13.644	6.822		
Total Wave Distance	1	16.087	16.087	$F_{1,113} = 14.3045$	0.0003
Salmonid Density	1	11.297	11.297	$F_{1,113} = 10.9278$	0.0013
Location X Total Wave Distance	2	0.528	0.264	$F_{2,110} = 0.2520$	0.7777
Error	110	115.256	1.048		

Notes:

- The F-statistic for total wave distance tests the significance of the effect of total wave distance given that location is already accounted for, but without salmonid density in the model.
- Overall Model $p(F6,110) \geq 6.6103 = 5.47 \times 10^{-6}$, $r^2 = 0.2650$.

Table 32. Analysis of Deviance Table Examining Effect of Interaction Between Location and Salmonid Density When Total Wave Distance Is Accounted For

Source	DF	DEV	MDEV	F	P
Total $_{Corr}$	116	156.813			
Location	2	13.644	6.822		
Total Wave Distance	1	16.087	16.087	$F_{1,113}$ = 14.3045	0.0003
Salmonid Density	1	11.297	11.297	$F_{1,113}$ = 10.9278	0.0013
Location X Salmonid Density	2	2.277	1.139	$F_{2,110}$ = 1.1033	0.3354
Error	110	113.506	1.032		
Note: Overall Model p(F6,110) ≥6.9949) = 2.55 × 10^{-6}, r^2 = 0.2762.					

Table 33. Coefficients from Final Logistic Model of Regression 2: Stranding _ Location + Total Wave Distance + Salmonid Density.

Independent Variable	Coefficient	S.E.
Intercept	-2.2883	0.6506
Location 2 (CL)	-2.0106	0.6129
Location 3 (SI)	-1.5336	0.5668
Total Wave Distance	0.0933	0.0227
Salmonid Density Index	0.0879	0.0289

6.4 Wave Height Versus Ship Characteristics and Ambient Conditions

Wave height (maximum run-up height plus maximum draw-down height) was used as a descriptor of wave characteristics. Relationships between wave height and several measures of ship characteristics and ambient conditions were examined using both simple linear regression and multivariate normal regression. Wave height was analyzed on the log scale to better fit regression assumptions.
Eighteen independent variables were considered as potential factors affecting wave height.
Five variables reflecting ambient conditions were considered:

- Tidal Stage (4 levels): ebbing, flooding, low slack, and high slack
- Tidal Stage (2 levels): ebbing or low slack, and flooding or high slack
- Tidal Height
- River Flow
- Current Velocity (knots)

Two forms of tidal stage indicator variables were considered because wave height appeared to be similar for ebbing and low slack tides, and also for flooding and high slack tides. Current velocity measured in m/sec was also available, but mirrored the values of current velocity in knots, so only the velocity measured in knots was used. Eleven variables reflecting ship characteristics were considered, including several constructed from other variables:

- Ship Type: indicator variable for five types of vessel (car carrier, bulk carrier, oil tanker, container vessel, and other)
- Ship Direction: indicator variable for upstream or downstream
- Ship Condition: indicator variable for unloaded, partially loaded, and loaded
- Ship Distance: indicator variable for five levels of distance of the vessel from shore (near, near-middle, middle, middle-far, and far)
- Ship Time: duration of vessel passage (sec)
- Ship Speed over ground (knots)
- Ship Draft
- Ship Beam
- Ship Length
- Ship Block Coefficient: Draft × Beam × Length
- Kinetic Energy Proxy: Block × (Speed)2 /1 × 10^{-8}

Two measures of ship speed over ground were available: one measured in knots and the other in m/sec. Because the difference in speed measures was only one of units, only the measurement in knots was used. The derived variable kinetic energy proxy was scaled by 10^{-8} to facilitate interpretation of model parameters.

In addition to the ambient and ship characteristics listed above, site (i.e., location) and season were also considered. Location was included as an indicator variable for the three study sites (BP, CL, and SI). Season was included as an indicator variable for the three seasons studied (summer, winter, and spring). Not all variables were measured for each passage trial. Thus, the degrees of freedom in the following models vary more than expected simply due to the type of covariates.

6.4.1 Single-Variate Regressions

It appears that season ($p = 0.2585$), ship direction ($p = 0.3196$), and the four-level measure of tidal stage ($p = 0.4188$) were not significant. There is marginal evidence that tidal height ($p = 0.1178$) and river flow ($p = 0.1235$) are related to wave height. The other variables considered are all indicated as being related to wave height, in particular the ship block coefficient ($p = 1 \times 10^{-5}$), kinetic energy ($p = 0.0001$), ship length ($p = 0.0002$), and ship type ($p = 0.0006$).

Figure 51 shows the pattern of wave heights across location. Figures 52 through 54 show the relationship between wave height and ship block coefficient, tidal height, and ship speed, respectively. The curves are fitted values from simple linear regressions summarized in Table 34. Figures 55 through 57 show the observed and predicted wave height values for the three different study sites versus ship block, tidal height, and ship speed, respectively.

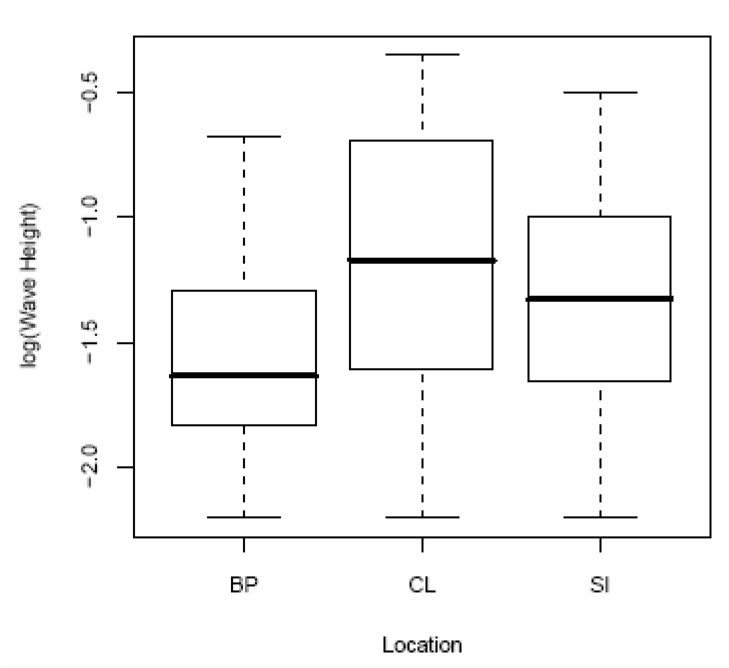


Figure 51. Wave Height (Log Scale) by Location

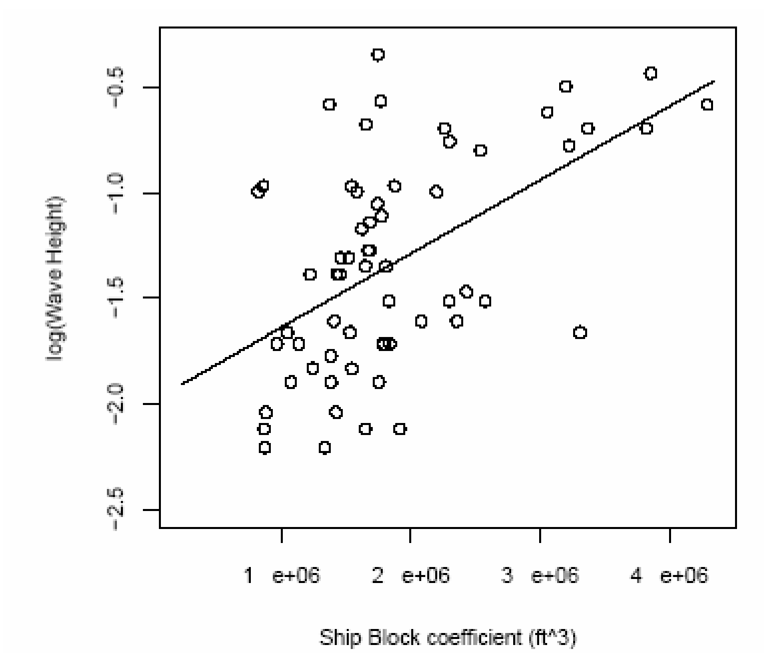


Figure 52. The Observed Values (points) and Fitted Values (line) of Wave Height (log scale) Versus Ship Block Coefficient

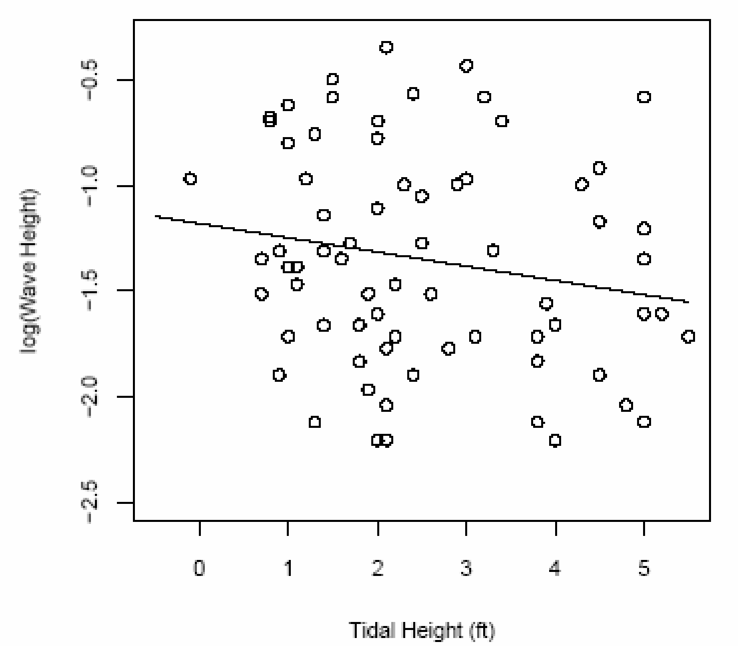


Figure 53. The Observed Values (points) and Fitted Values (line) of Wave Height (log scale) Versus Tidal Height

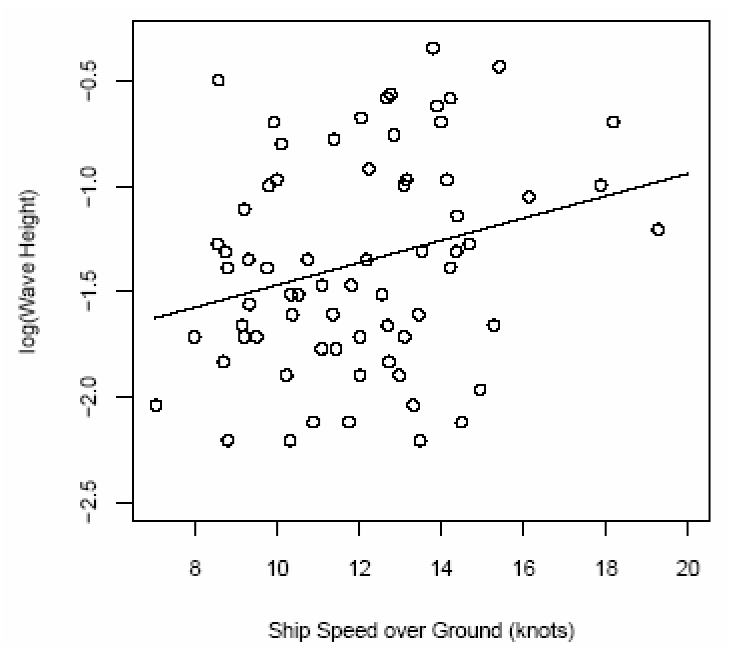


Figure 54. The Observed Values (points) and Fitted Values (line) of Wave Height (log scale) Versus Ship Speed Over Ground (in knots)

Table 34. Summary of Significance of Individual Covariates in Single-Variable Regression Analyses.

Independent Variable	p-value
Ship Block Coefficient	1e-05
Kinetic energy	0.0001
Ship Length	0.0002
Ship Type	0.0006
Ship Beam	0.0023
Ship Draft	0.0027
Ship Distance	0.0242
Ship Speed	0.0278
Ship Time	0.0350
Ship Condition	0.0398
Location	0.0433
Current Velocity (knots)	0.0486
Tidal Stage (2 levels)	0.0932
Tidal Height	0.1178
River Flow	0.1235
Season	0.2585
Ship Direction	0.3196
Tidal Stage	0.4188
Note: The covariates are ranked by their p-values.	

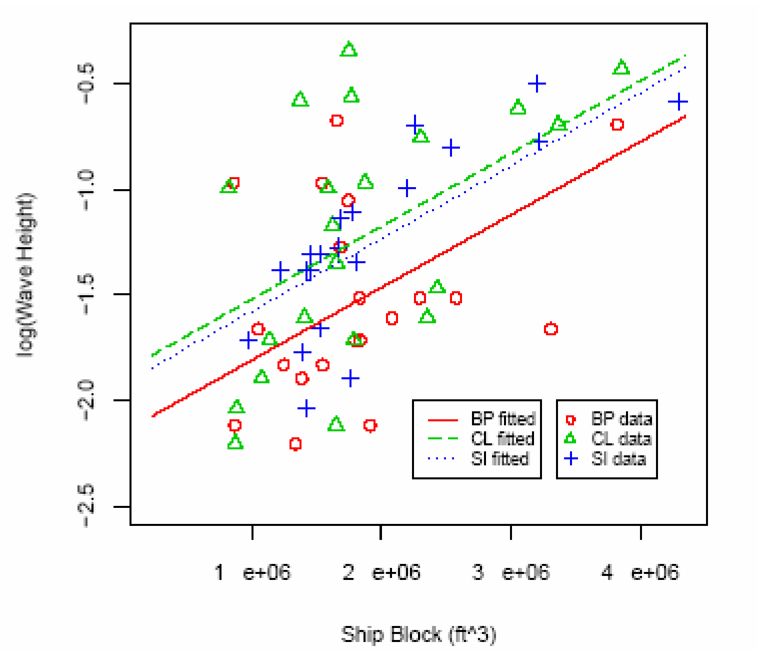


Figure 55. The Observed Values (points) and Fitted Values (line) of Wave Height (log scale) Versus Ship Block Coefficient for the Three Different Study Sites. The fitted curves vary with location (p-value for equal lines: p[$F_{2,57} \geq 2.635$] = 0.0804).

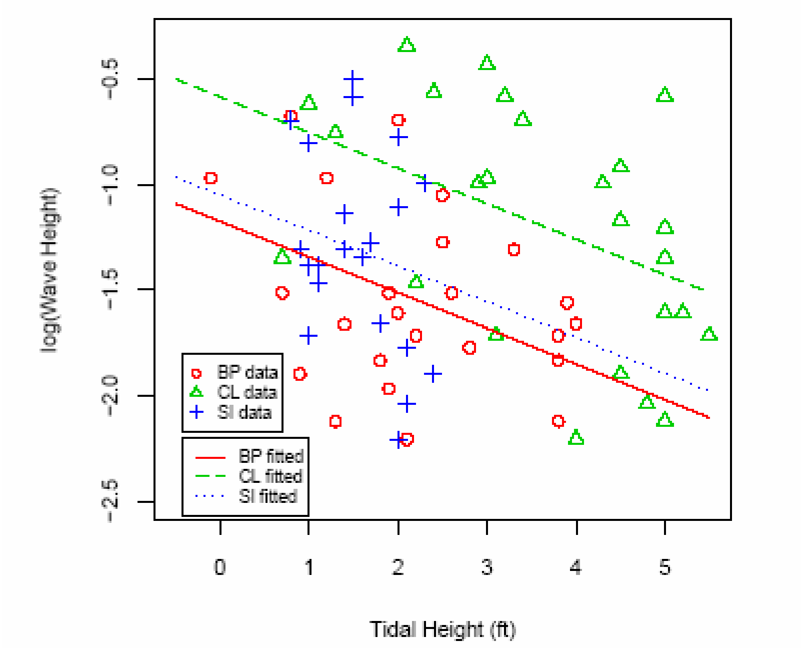


Figure 56. The Observed Values (points) and Fitted Values (line) of Wave Height (log scale) Versus Tidal Height for the Three Different Study Sites. The fitted curves vary with location (p-value for equal lines: $p[F_{2,67} \geq 8.0014] = 0.0008$).

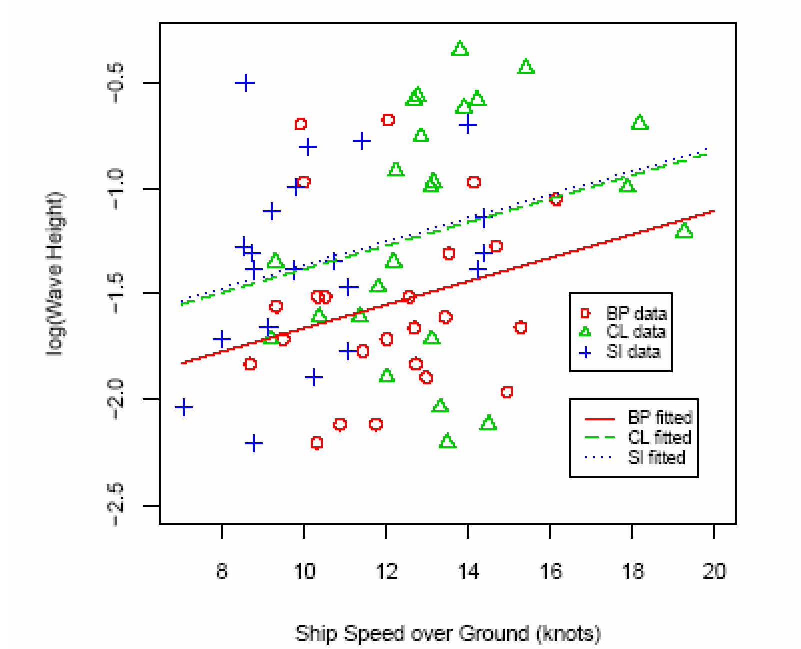


Figure 57. The Observed Values (points) and Fitted Values (line) of Wave Height (log scale) Versus Ship Speed Over Ground (in knots) for the Three Different Study Sites. The fitted curves vary with location (p-value for equal lines: $p[F_{2,65} \geq 2.9186] = 0.0611$).

6.4.2 Multivariate Regressions

The block coefficient appears to be the most significant single variable (Table 34), so it is included in the multivariate regressions. Beam, length, draft, and kinetic energy are all related to the block coefficient, so no multivariate model includes both block and one of these other four variables. The significance of the added contribution of the remaining variables, given that block coefficient is accounted for, is summarized in Table 35.

With block coefficient accounted for, it appears that tidal height ($p = 0.0360$), ship speed ($p = 0.0455$), current velocity ($p = 0.0615$), river flow ($p = 0.0779$), location ($p = 0.0804$), and ship time ($p = 0.0870$) are all possibly significantly related to wave height. Season ($p = 0.1657$) may be slightly related to wave height, but such a relationship may occur through the relationship between season and current velocity or river flow. Ship type ($p = 0.4549$) and condition ($p = 0.6616$) no longer appear related to wave height when block coefficient is accounted for; nor does the two-level measure of tidal stage ($p = 0.9562$), possibly because most trials occurred at ebbing or low slack tides.

Tidal height appears to be the most significant factor in affecting wave height, once the ship block coefficient is taken into account. However, because of the differing tidal regimes at the three study sites, inclusion of tidal height should be accompanied by location, as well. The added contribution of location, given block and tidal height, is significant ($p[F_{2,56} \geq 9.9860] = 0.0002$); all future models considered included ship block coefficient, tidal height, and location. The significance of the added contribution of the remaining variables is summarized in Table 36.

With block, tidal height, and location all accounted for, only ship speed ($p = 0.0532$) and ship time ($p = 0.0683$) appear significant. Ship speed is inversely related to ship time, so only one of these factors should be considered. Because ship speed appears slightly more significant, it is included. No other variable had a significant effect on wave height, when block, tidal height, location, and ship speed were all accounted for (Table 37).

Table 35. Summary of Significance of Individual Covariates in Bivariate Regression Analyses, With Ship Block Coefficient Accounted For

Independent Variable	**p-value**
Tidal Height	0.0360
Ship Speed	0.0455
Current Velocity (knots)	0.0615
River Flow	0.0779
Location	0.0804
Ship Time	0.0870
Season	0.1657
Ship Direction	0.3686
Ship Type	0.4549
Ship Distance	0.5653
Ship Condition	0.6616
Tidal Stage (4 levels)	0.8934
Tidal Stage (2 levels)	0.9562

Note: The covariates are ranked by their p-values.

Table 36. Summary of Significance of Individual Covariates in Multivariate Regression Analyses, With Ship Block Coefficient, Tidal Height, and Location Accounted For

Independent Variable	p-value
Ship Speed	0.0532
Ship Time	0.0683
Ship Direction	0.3010
Ship Distance	0.3680
Ship Type	0.4052
Ship Condition	0.5919
Current velocity (knots)	0.6282
River Flow	0.6610
Season	0.6799
Tidal Stage (4 levels)	0.8003
Tidal Stage (2 levels)	0.9430
Note: The covariates are ranked by their p-values.	

Table 37. Summary of Significance of Individual Covariates in Multivariate Regression Analyses, With Ship Block Coefficient, Tidal Height, Location, and Ship Speed Accounted For

Independent Variable	p-value
Ship Type	0.4684
Ship Direction	0.6933
Ship Condition	0.5617
Ship Distance	0.5143
River Flow	0.9743
Tidal Stage (4 levels)	0.6502
Current Velocity (knots)	0.9047
Season	0.8129
Tidal Stage (2 levels)	0.8153
Note: The covariates are ranked by their p-values.	

6.4.3 Interaction Effects

Possible interaction effects among block, tidal height, location, and speed were considered; the results from these analyses are summarized in Table 38.

It appears from Table 38 that no interaction effect is significant. Thus, the final model has the form:

Log(Wave Height) ~ Ship Block + Tidal Height + Location + Ship Speed.

The coefficients for the model are given in Table 39.

Table 38. Summary of Analyses of Interaction Effects Among Ship Block Coefficient, Tidal Height, Location, and Speed, With All Four Main Effects Included in Each Model.

Interaction Effect	F-statistic	P-Value
Ship Block x Location	$F_{2,51} = 1.7773$	0.1794
Ship Block x Ship Speed	$F_{1,52} = 1.5616$	0.2170
Ship Block x Tidal Height	$F_{1,52} = 0.1931$	0.6622
Tidal Height x Location	$F_{2,51} = 0.3249$	0.7241
Tidal Height x Ship Speed	$F_{1,52} = 0.0606$	0.8066
Location x Ship Speed	$F_{2,51} = 0.0891$	0.9149
Note: The covariates are ranked by their p-values.		

Table 39. Coefficients From Final Model of Regression 3: Log(Wave Height) ~ Ship Block + Tidal Height + Location + Ship Speed

Independent Variable	Coefficient	S.E.
Intercept	-2.281	0.3325
Ship Block	3.276e-07	6.642e-08
Tidal Height	-0.1886	0.0456
Location 2 (CL)	0.5214	0.1415
Location 3 (SI)	0.2122	0.1260
Ship Speed	0.0454	0.0230

Notes:
- Ship Speed is measured in knots.
- Overall model $p(F_{5,53} \geq 12.1079) = 7.6 \times 10^{-8}$, $r^2 = 0.5332$.

6.5 Wave Excursion vs. Ship Characteristics and Ambient Conditions

Wave excursion (maximum run-up distance plus maximum draw-down distance across the beach) was used as a descriptor of wave characteristics. Relationships between wave excursion and several measures of ship characteristics and ambient conditions were examined using both simple linear regression and multivariate normal regression. Wave excursion was analyzed on the log scale to better fit regression assumptions (Table 40).

The resulting model has the form:

Log(Wave Excursion) ~ Kinetic Energy + Tidal Height + Site.

Table 40. Coefficients From the Model of Regression 4: Log(Wave Excursion) ~ Kinetic Energy + Tidal Height + Site, $r^2 = 0.415$.

Independent Variable	Coefficient	S.E.	p-value
Intercept	1.289	0.0514	<0.001
Kinetic Energy Proxy	0.000714	0.000117	<0.001
Tidal Height	-0.0341	0.0168	0.046
BP	-0.153	0.0500	0.003
CL	-0.259	0.0614	<0.001

7.0 Discussion

The pilot study and extended pre-deepening field sampling proved the value of the experimental design and generally confirmed the appropriateness of the approaches and equipment in evaluating the complexities associated with ship wakes and fish stranding.

7.1 Sites

The study observed stranding at all three sites. This observation validates their selection under the criterion for a before-and-after study that the variable of interest must be known to occur at the sampling locations. Physically, the three sites were also selected based on their low slope, and all have an average slope of <5%. Although the sites represent low-slope beaches on the river scale, each has distinct differences at the fine scale of local beaches.

Barlow Point has the lowest slope and the finest sand with slowest infiltration rate. In fact, the infiltration rate is so low at Barrow Point that little or no infiltration may occur during the time it takes for a wave to run-up and wash-back. In contrast, County Line has the highest slope with the coarsest sand and highest infiltration. At County Line, infiltration rate may be high enough that infiltration could affect the speed of wash-back. Sauvie Island is between the other two sites but is closer to County Line in many respects.

Perhaps more important than infiltration is the local-scale shoreline structure at each site. The differential GPS (dGPS) waypoints taken at the location of each stranded fish enabled the critical observation that fish were consistently stranded at one or two specific locations and not evenly distributed over the beach (Figures 25 through 27). Also, these “hot spot” locations are characterized by distinct beach morphologies that interact with onshore waves in dynamic and complex ways. Field observations and video records validated that these "hot spots" were indeed areas where complex waves occurred. At Barlow Point, for example, the area at the upstream end of the site where the majority of stranding occurred was heavily influenced by complex waves. Onshore waves from ship wakes interacted with the shoreline structure (Reno mat) upstream of the site. These waves propagated along the Reno mat as cross waves, and finally broke at the end of the Reno mat, where the shoreline structure had a berm. It is in this area where stranding occurrence was the highest. This effect was observed at both Sauvie Island and County Line Park, though not to the same extent as at Barlow Point.

7.2 Fish Availability Index

Biologically, the sites differed in the fish species composition. However, the species of interest, Chinook salmon and other salmonids, were found at all sites during all seasons. The FAI based on beach seining in downstream reference areas immediately adjacent to the survey areas proved appropriate.

The DIDSON camera and narrow-beam sonar are known to work well elsewhere but did not reliably discern fish in the extremely shallow (<1 m) areas that were surveyed in this study. The observed sensitivity of the seines to change among the sites and over time indicated that the seines were an appropriate approach to indexing fish availability in the before-and-after design of the overall project. Also, limited mortality to Chinook salmon occurred during seining and catch-processing.

The beach seine and resulting FAI provided adequate quantitative data. Although fish composition changed over time and with each location, salmon (specifically Chinook) were present in all sampling seasons and the FAI (salmonid density) was found to be a significant factor in stranding. Additionally, a comparison of seined fish with stranded fish showed Chinook were stranded more often than seined. Other fish were stranded at equal or lower frequencies than seined. Wolter and Arlinghaus (2003) concluded from studies of wake impacts along European rivers that impacts on fish communities occurred when the run-up velocity exceeded the swimming abilities of fish. The differences between seined and stranded fish may be related to differences in swimming ability or behavior or some combination of both. The finding that total wave excursion across the beach is a significant factor in probability of stranding also suggests swimming ability and behavior may play a role. For example, a rheotactic response by Chinook salmon during draw-down may aggregate the fish at the water's edge, and the aggregation may then be carried up the beach by the run-up wave. Investigation of swimming speed and other behavioral factors is warranted to further understand the increased predisposition to stranding among Chinook.

7.3 Wake Characteristics and Instrumentation

For measurement of wake characteristics, the wave staff gages proved adequate, whereas the wave run-up gage proved to have some difficulties. The addition of the video recording helped offset some of the problems associated with the wave run-up gage and provided additional information otherwise not possible. First, the two wave staff gages deployed 5 m apart adequately captured the wave height dynamics; for cases in which only a single gage was used, the nature of the wave was still characterized successfully, given that only a slight phase shift was evident between the two gages (attributable to the 5-m difference in placement location). The wave staff-gage records were of fine enough detail to detect the long-period oscillations not seen elsewhere in studies of this nature. At beaches with low slope, such as Sauvie Island and Barlow Point, the width of the beach at low tide created difficulty in placing the gages for maximum effect while also ensuring the electronics stayed dry. The cable length (~95 m) and water depth proved somewhat limiting and resulted in several events in which the gages were dry at draw-down or low tide; a longer cable may alleviate some of the problems; however, the shore-based installation precluded placement in water depths greater than 1.5 m, which is less than the mean tide range at some sites.

The best use of the run-up gage was that of estimating the speed of run-up and wash-back, which were obtained when the wave crests of the onshore wave were parallel to the shoreline and the gage was in optimal position. To maximize such sampling, the wave run-up gage needed to be placed at the water line; however, as the tidal height changed, the gage would be in a sub-optimal location, limiting its ability to capture the full extent of the wave. Reinstalling the gage as the tide moved was impractical, because during installation, passage and stranding observations would be missed.

When the wave climate became complex, the run-up gage did not yield speed measurements. Waves moving across (rather than onto) the beach occurred during certain wake events (see Figure 10 and discussion of cross waves in Section 4.3.4). Such cross waves lifted all the wave run-up gage floats simultaneously and disrupted the ability of the data record to support speed calculations. The lack of reliability with the wave run-up gage led to modification of methods for measuring run-up velocity.

Video observations were included to augment measurements of wave velocity. The video camera proved reliable and logistically sound. Unlike the wave run-up gage, the camera could be moved with the tide to be in optimal position for each event; thus, the number of unsuccessful recordings was fewer with the camera than with the run-up gage. Error in the interpretation of video records was minimized by using software intended for quantitative analysis. Although the video camera captured cross waves for qualitative description, the ability to quantify cross waves was limited due to angle of view. Additionally, the use of the camera at night has not been tested, though portable or infrared lights may enable night-video observations.

Wake measurement was augmented by staking the points of maximum draw-down and maximum run-up, thereby capturing the full across-beach extent of these end points.

7.4 Multivariate Regression Equations and Conceptual Models

One overall objective of the study was to determine the relationships among factors that influence the probability of stranding. This analysis would have two outcomes: 1) a determination of factors that need to be considered in the before-and-after comparison, and 2) an increased understanding of the mechanisms that produce stranding. During the design phase, the need to address fish availability was obvious, but the roles and linkages among other potential factors were not. Figure 58 is the original conceptual model the study team conceived after the summer field season. The indicated factors were derived from the literature, the pilot study, the summer field season, and other field observations. The strength of each component was unknown, though all factors were suggested to have some causal relationship to stranding.

Single factor and multivariate regression analyses of the full set of before data were undertaken to assess statistically those roles and linkages and to discern which ambient conditions and ship or wake characteristics would be appropriate covariates. It is now clear that no single factor appears to be the cause for juvenile salmon stranding. Statistical analyses of the covariates resulted in the following multivariate equations:

- Stranding Probability ~ Location + Kinetic Energy Proxy + Tidal Height + Salmonid Density Index + Kinetic Energy Proxy × Tidal Height + Tidal Height × Salmonid Density Index.
- Stranding Probability ~ Location + Total Wave Excursion + Salmonid Density Index.
- Log(Wave Height) ~ Ship Block Coefficient + Tidal Height + Location + Ship Speed.
- Log(Wave Excursion) ~ Kinetic Energy Proxy + Tidal Height + Location

These equations indicate that location, a proxy for ship kinetic energy (which accounts for ship size and speed), tidal height, total wave excursion, and an index of salmon density along the beach are the primary factors in stranding occurrences. Figure 59 is the conceptual model developed as a result of our complete "before" field study and the statistical analyses.

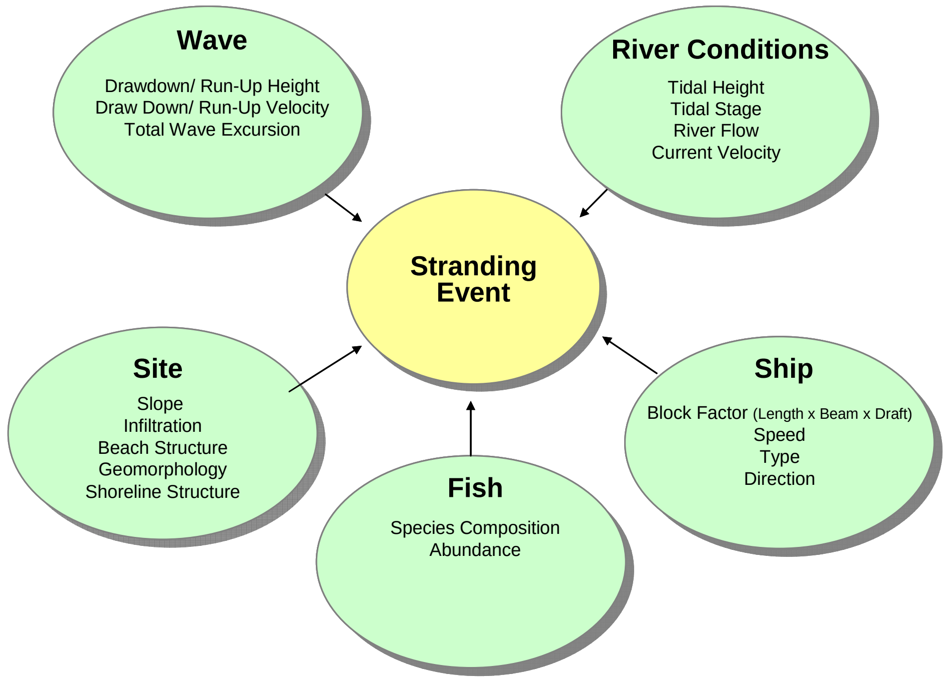


Figure 58. Original Conceptual Model of Stranding

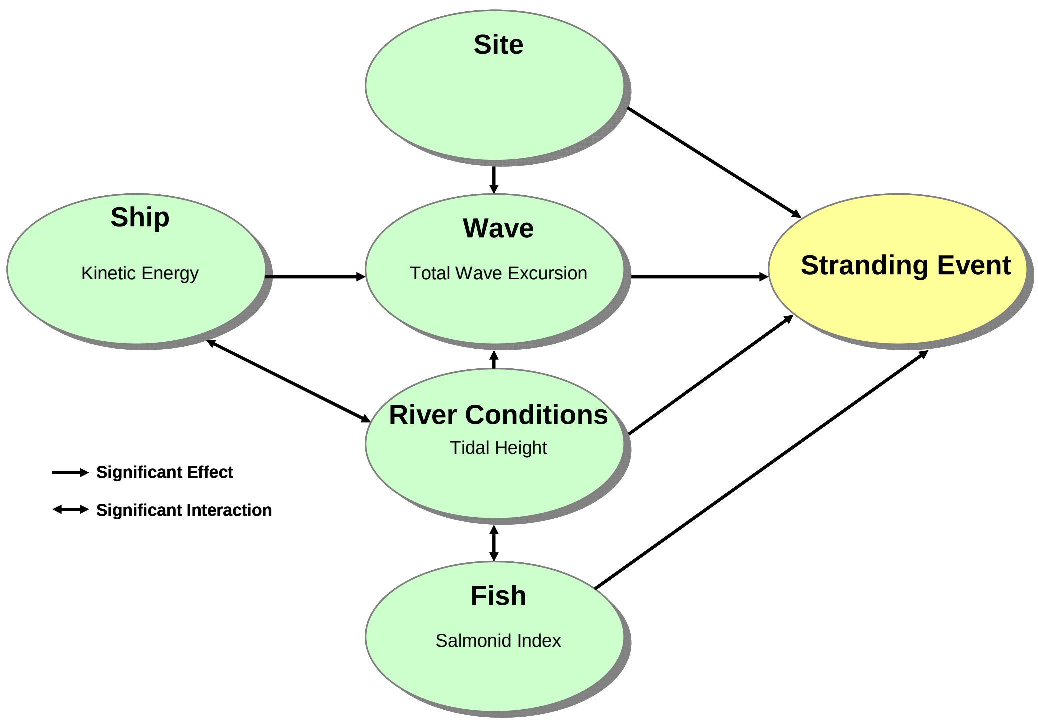


Figure 59. Current Conceptual Model, With Statistically Significant Factors and Linkages

Although the mechanisms of stranding are still not completely understood, the linkages in this model are all statistically significant, are consistent with what is known about biological and physical processes, and represent a substantial advance in our understanding of fish stranding by ship wakes. Rather than any single factor, a series of interlinked factors act together to produce stranding during a ship passage. The kinetic energy proxy derived from the size and speed of the vessel provides the energy producing the wake. Tidal height influences both the fish availability and the interaction of the wake with the beach at each site. Increasing total distance from draw-down to run-up is the wake characteristic that increases the probability of stranding. Increasing juvenile salmonid density in the nearshore increases the probability of stranding and remains a significant factor even after the location is taken into account. The multivariate regression equations, the video observations of waves, and the presence of stranding hot spots all indicate that fine-scale site characteristics at a specific location play a dominant role in structuring the processes that produce the onshore wave and subsequent fish stranding.

7.5 Assessment of Impacts of Channel Deepening

The purpose of the before-and-after impact assessment is to determine whether the probability of juvenile salmon stranding will increase once the LCR is deepened ("post-dredging"). There are two questions to be examined:

1. For similar ambient river conditions, fish availability, and vessel conditions, does the probability of stranding relative to pre-deepening conditions increase after channel deepening?
2. If yes to the above question, then do the patterns of use by deeper-draft vessels change after deepening and, holding other factors equal, is there a greater probability of stranding associated with such changes compared with pre-deepening conditions?

The post-deepening impact assessment will examine both questions using the above multivariate regression equations derived from the before data. For juvenile salmon stranding by ship wakes, we recommend the impact assessment decision process outlined in Figure 60 and described below.

7.5.1 Test of the Physical Effects of Channel Deepening on the Incidence of Juvenile Salmon Stranding (Test 1)

A logistic regression model was constructed using the pre-deepening surveys of the form

$$\ln\left(\frac{\hat{p}_i}{1-\hat{p}_i}\right) = \underset{\sim}{\beta}'\underset{\sim}{x}_i \qquad (19)$$

or

$$\hat{p}_i = \frac{e^{\underset{\sim}{\beta}'\underset{\sim}{x}_i}}{1+e^{\underset{\sim}{\beta}'\underset{\sim}{x}_i}} \quad \text{(Model 1)} \qquad (20)$$

where $\hat{p}_i$ is the estimated probability of smolt stranding for the *i*th trial, $\underset{\sim}{x}_i$ is the vector of covariates for the *i*th trial, and $\underset{\sim}{\beta}$ is the vector of regression coefficients.

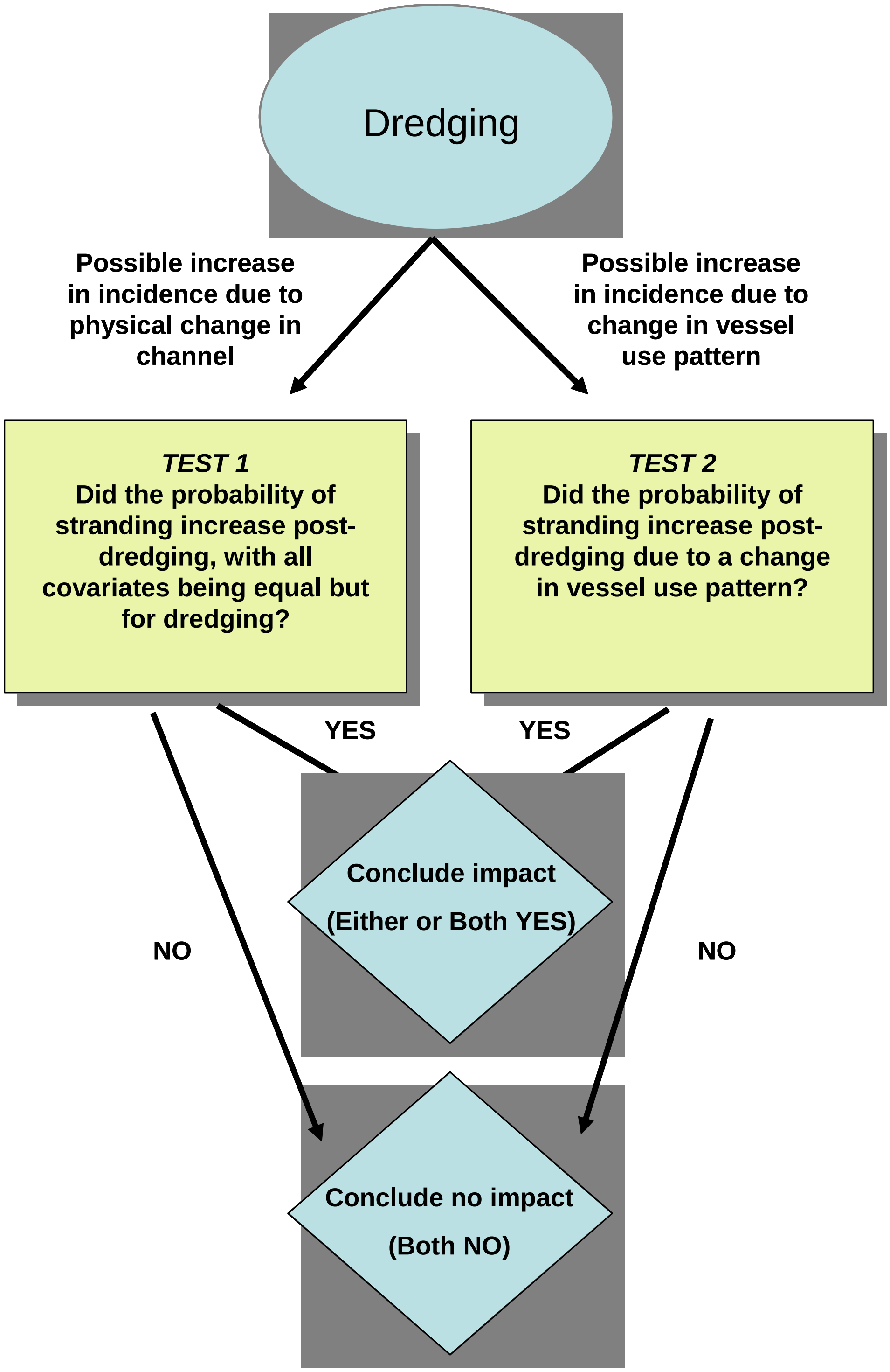


Figure 60. Schematic of the Decision Rules for Assessing Impact of Channel Deepening on the Incidence of Smolt Stranding

The incidence of stranding post-dredging will be compared with the predictions based on the pre-deepening Model 1. Correcting for the specific covariate values observed during a post-deepening trial, the probability of stranding will be calculated using the pre-deepening model. The test of impact is based on assessing whether the incidence of stranding actually observed post-deepening is greater than that predicted by the pre-deepening logistic Model 1. The null hypotheses can be written as

$$\mathrm{H_o}: \quad E\left(I_{\mathrm{Post},i}\right) \leq E\left(I_{\mathrm{Pre},i}\right) \tag{21}$$

versus

$$\mathrm{H_a}: \quad E\left(I_{\mathrm{Post},i}\right) > E\left(I_{\mathrm{Pre},i}\right), \tag{22}$$

where

$$I_i = \begin{cases} 1 & \text{if stranding occured in the } i\text{th trial} \\ 0 & \text{otherwise.} \end{cases}$$

The test statistic comparing observed and expected outcomes can be written as a *Z*-statistic for a single trial, where

$$Z_i = \frac{I_{\mathrm{Post},i} - \hat{p}_i}{\sqrt{\mathrm{Var}\left(\hat{p}_i\right)}} \quad \text{(Model 2)} \tag{23}$$

A similar test will be computed for each post-deepening trial. The overall test results will be compiled as a chi-square statistic, where

$$\chi^2_{2k} = \sum_{i=1}^{k}\left(-2\ln P_i\right) \qquad \text{(Model 3)} \tag{24}$$

for $P_i = P\left(Z \geq Z_i\right); i = 1, \ldots, k$. The test statistic is a chi-square random variable with 2*k* degrees of freedom. The null hypotheses of no impact will be rejected if

$$P\left(\chi^2 > \chi^2_{2k}\right) \leq 0.10 \tag{25}$$

for an α = 0.10, one-tailed test of impact.

Note:

$$\operatorname{Var}(\hat{p}_i) = \operatorname{Var}\left(\frac{e^{\underset{\sim}{\beta}'\underset{\sim}{x}_i}}{1+e^{\underset{\sim}{\beta}'\underset{\sim}{x}_i}}\right) \qquad \text{(Model 4)} \qquad (26)$$

$$\approx \left(\frac{1}{1+e^{\underset{\sim}{\beta}'\underset{\sim}{x}_i}}\right)^2 \left(e^{\underset{\sim}{x}_i'\underset{\sim}{\Sigma}\underset{\sim}{x}_i} - 1\right)$$

and where $\underset{\sim}{\Sigma}$ is the variance-covariance matrix of the logistic regression parameters.

This logistic regression analysis is necessary because neither the pre-deepening nor the post-deepening trials were randomly selected. The regression model is used instead to correct for extraneous factors that were not eliminated by a process of randomization affecting stranding.

An alternative assessment approach might include a comparison of the multiple regression models constructed separately for the pre-dredging and post-dredging periods. However, large complex multiple regression models may make direct comparisons difficult or impractical to interpret.

7.5.2 Test of the Effect of Changes in Vessel Use Pattern on the Frequency of Juvenile Salmon Stranding (Test 2)

A change in the frequency or size class of the vessels post-dredging would have an effect on the incidence of stranding in and of itself. This source of impact will be assessed in two fashions:

1. Comparison of the size frequency of vessels pre- and post-dredging (i.e. draft, displacement, length, etc.).
2. Comparison of the predicted frequency of stranding events pre- and post-dredging.

7.5.3 Comparison of Size Frequency of Vessels

Using Port of Portland and Port of Longview records, data on vessel type, displacement, and other factors, will be compared on an annual basis for the years 2004 (pre-dredging) and 2007 (post-dredging). Kolmogorov-Smirnov (Conover 1980, pp. 373-376) tests of equal distributions will be performed comparing pre- and post-dredging vessel distributions.

This test alone will not determine a change in the frequency of stranding events, only a change in vessel-use pattern between phases of the study. However, these results may provide some explanation for a change in stranding frequency, should it occur.

7.5.4 Comparison of Predicted Frequency of Stranding Pre- Versus Post-Dredging

During each of the pre- and post-dredging phases of the monitoring program, a logistic regression model (Model 1, Equation 20) will be developed to describe the incidence of stranding as a function of ambient river conditions, fish availability, and vessel characteristics. If *TEST 1* rejects the null hypothesis of no impact, two separate models will be developed—one for each phase of the monitoring. If *TEST 1* does not reject the null hypothesis of no impact, a common logistic model will be used to describe both monitoring phases.

Using the distribution of vessel characteristics compiled in Section 4.3, the predicted incidence of stranding events at the three monitoring sites will be calculated under pre- and post-dredging vessel-use patterns. The total number of stranding events predicted per monitoring phase will be calculated as follows:

$$\hat{I}_{Total} = \sum_{j=1}^{3}\sum_{i=1}^{k} f(\underset{\sim}{x}_i)\, p_{ij}(\underset{\sim}{x}_i) \quad \text{(Model 5)} \tag{27}$$

where $\underset{\sim}{x}_i$ is the vector of vessel characteristics for the ith vessel (i = 1,…, k), $f(\underset{\sim}{x}_i)$ is the frequency of vessels with characteristics ($\underset{\sim}{x}_i$), and $p_{ij}(\underset{\sim}{x}_i)$ is the predicted probability of a stranding event for a vessel with characteristics ($\underset{\sim}{x}_i$) at the *j*th location (*j* = 1, 2, 3).

The set of one-tailed hypotheses will be tests of the form

$$H_o : I_{Total-Post} \le I_{Total-Pre} \tag{28}$$

versus

$$H_a : I_{Total-Post} > I_{Total-Pre} \tag{29}$$

using an asymptote Z-statistic of the form

$$\hat{Z} = \frac{\hat{I}_{Total-Post} - \hat{I}_{Total-Pre}}{\sqrt{\mathrm{Var}(\hat{I}_{Total-Post}) + \mathrm{Var}(\hat{I}_{Total-Pre})}} \quad \text{(Model 6)} \tag{30}$$

where H_o will be rejected if $P(Z > \hat{Z}) \le 0.10$

The variance of $\hat{I}_{Total}$ can be expressed as

$$\mathrm{Var}(\hat{I}_{Total}) = \sum_{j=1}^{3}\sum_{i=1}^{k} f(\underset{\sim}{x}_i)^2\,\mathrm{Var}(\hat{p}_{ij}) + 2\sum_{j=1}^{3}\sum_{i>j}^{k} f(\underset{\sim}{x}_i)\, f(\underset{\sim}{x}_i')\mathrm{Cov}(\hat{p}_{ij}, \hat{p}_{ij}') \,. \tag{31}$$

8.0 Conclusions and Recommendations

The results of the design phase, the pilot study, and the pre-deepening sampling lead us to several conclusions and recommendations concerning the design and conduct of the overall study:

- The three sites chosen during the design remained appropriate for the before-deepening sampling and should be retained for the after-deepening sampling. Stranding occurred at all three sites. Location proved to a major factor in the probability of stranding.

- Beach seining proved effective in providing an index of fish availability, and we recommend that three seines in the downstream reference area continue as the basis for the FAI. The present seining approach should be applied in the same way during the after-deepening phase. The DIDSON camera and narrow-beam sonar are known to work well elsewhere but did not reliably discern fish in the extremely shallow (<1-m) areas surveyed in this study.

- The wave staff gage performed adequately and should be employed in the after-deepening measurements. The two wave staff gages deployed 5 m apart captured the wave-height dynamics that a single gage would have missed. We recommend continuing with two gages.

- The video monitoring approach performed more reliably and provided more kinds of information than did the wave run-up gage. When complex waves were generated, along-shore waves lifted all the floats simultaneously and disrupted the ability of the data recorder to support speed calculations. We recommend consideration be given to discontinuing the use of the wave run-up gage in favor of increasing the use of video monitoring. The current stake approach to measuring maximum wave excursion across the beach should be continued.

- For surveys of stranded fish, the field crew was able to perform 100% surveys of stranded fish at all sites at all samplings, day and night. The statistical sub-sampling design developed for stranded fish surveys did not need to be implemented. Taking the dGPS positions of stranded fish enables the discernment of fine-scale patterns in fish stranding that suggest that fine-scale interactions of wake characteristics with beach morphology may contribute to stranding. We recommend that 100% beach surveys along with dGPS positioning of stranded fish continue.

Concerning characterization of the study sites, the major findings of the before sampling include the following:

- The three study sites all have beach slopes of <5% but differ in beach morphology, grain size, and infiltration rate.

- County Line has the highest slope (about 4%), predominantly coarse sand, and the highest infiltration rate.

- Barrow Point has the lowest slope (about 2%), predominantly fine and very fine sand, and the lowest infiltration rate.

- Sauvie Island is between the other two sites with a low slope (almost 3%), predominantly medium sand, and moderate infiltration rate.

- The water-quality values for temperature, salinity, dissolved oxygen, and pH did not vary among the sites and were all with normal expectation.

- The beach characteristics varied only slightly with seasons. We recommend continued collection of data on slope, grain size, and infiltration rate at a rate of one assessment per seasonal sampling period.

Concerning the fish fauna and FAI, the major findings of the before sampling were as follows:

- Fish were captured in almost all seines at all sites both day and night.

- The four most abundant fish in the seines in order from most to least were juvenile Chinook salmon, threespine sticklebacks, peamouth chub, and American shad. Juvenile Chinook salmon were almost 50% of the total catch of seined fish for all seasons. In winter and spring, juvenile Chinook were over 85% of the seined catch. Juvenile Chinook salmon observed in this study were predominantly unmarked.

- Fish species composition in the reference area seines varied among the sites and among seasons.

- The density of subyearling Chinook decreased significantly over the summer with the rate of decrease differing among the sites. The over-summer decline in Chinook density is consistent with the 2004 timing of outmigration of fall Chinook at the Bonneville Dam.

- The lack of a diel trend in Chinook and total fish abundance among the times of sampling within a sampling day indicates that the three sampling times (start, middle, and end) are appropriate.

- Neither fish species composition in seines nor subyearling Chinook density differed significantly among the reference and two hot spots within the survey areas at any site. Total fish density did not differ significantly among reference and two hot spots within the survey areas at Barrow Point and County Line but did at Sauvie Island.

- The differences in fish species composition at the river scale but not at the site scale are of great advantage in a before-and-after study. The ability to detect change in Chinook density at different sites over time is also of great advantage in a before-and-after study.

Concerning wake and wave run-up characteristics, the major findings of the pre-deepening field sampling were as follows:

- Four types of deep-draft vessels (bulk carriers, container ships, oil tankers, and car carriers) produced wakes leading to both draw-down and run-up on the beach. Tugs and small passenger vessels did not produce wakes leading to any significant draw-down and little run-up.

- Different types of deep-draft vessels produce wakes leading to different patterns of draw-down and run-up.

- The sustained presence of long-period waves following the initial draw-down and run-up was documented for probably the first time in these types of studies.

- Average draw-down distance was 12.6 m; average run-up distance, 9.4 m; and average maximum excursion across the beach was 21.9 m.

Concerning fish stranding events, the major findings of the pre-deepening field sampling were as follows:

- Of 126 observed passages of deep-draft vessels, 46, or 36%, led to fish stranding.

- Fish stranding occurrence varied significantly with site. Barlow Point had the highest number of observed vessel passages (49) and the highest proportion of stranding events (26 of 49, or 53% of passages). County Line Park and Sauvie Island had a similar number of observed passages (39 and 38, respectively), but Sauvie Island had a higher incidence of stranding with 14 events (37% of passages). We observed only six stranding events at County Line Park (15% of passages).

- Fish stranding occurrence did not vary with season at Sauvie Island or County Line Park but did at Barlow Point.

- During summer 2004, all stranding events occurred during night passages and none occurred during day passages. This finding is consistent with other studies for the summer period (Bauersfeld 1977, Hinton and Emmett 1994, Ackerman 2002).

- Fish stranding was observed with four vessel types (bulk carriers, container ships, oil tankers, and car carriers but not tugs). The frequency of stranding events differed significantly by vessel type. The order from highest frequency was tanker, container ship, car carrier, and bulk carrier.

- Fish stranding was localized in one or two hot spots at the three study sites. Such localization appeared to be related to interactions between the incoming wakes and the particular beach morphology at a site.

- The observations suggest two scales for stranding events: a river scale governed by low slope and proximity to the navigation channel, and a beach or site scale governed by a complex set of fine-scale interactions between wake properties, beach morphology, and tidal height, along with fish distribution and behavior.

- Some fish, including juvenile Chinook salmon, occurred among the stranded fish at a significantly higher percentage of total fish than they occurred among the available fish as a percentage of total fish captured in the seines. This difference may be related to swimming abilities and behavior of the different fish species.

Concerning the factors analyses to determine the relationships among the factors that influence the probability of stranding, the major findings of the pre-deepening study were as follows:

- Based on single factor and multivariate regression analyses of the full set of before-deepening data, clearly there is no single factor for juvenile salmon stranding. Several factors interlinked together to produce stranding.

- Statistical analyses of the covariates resulted in the following multivariate equations:
  1. Stranding Probability ~ Location + Kinetic Energy Proxy + Tidal Height + Salmonid Density Index + Kinetic Energy Proxy × Tidal Height + Tidal Height × Salmonid Density Index.
  2. Stranding Probability ~ Location + Total Wave Excursion + Salmonid Density Index.
  3. Log(Wave Height) ~ Ship Block Coefficient + Tidal Height + Location + Ship Speed.
  4. Log(Wave Excursion) ~ Kinetic Energy Proxy + Tidal Height + Location

- Location, a proxy for ship kinetic energy (which accounts for ship size and speed), tidal height, total wave excursion, and an index of salmon density along the beach are the primary factors in stranding occurrences.

  The kinetic energy proxy derived from the size and speed of the vessel provides the energy producing the wake.

  Tidal height influences both the fish availability and the interaction of the wake with the beach at each site.

  Longer total distance from draw-down to run-up is the wake characteristic that increases the probability of stranding.

  Higher juvenile salmonid density in the nearshore increases the probability of stranding and remains a significant factor even after the location is taken into account.

- The multivariate regression equations, the video observations of waves, and presence of stranding "hot spots" all indicate that fine-scale site characteristics at a specific location play a dominant role in structuring the processes that produce the onshore wave and subsequent fish stranding.

Concerning the impact assessment to be accomplished following the post-deepening sampling, we offer the following:

- The decision rules for the before-and-after impact assessment need to be specified before the data are collected post-deepening.

- A detailed analysis and decision procedure should be followed that addresses two questions:

  Does the probability of stranding increase post-deepening, holding constant all relevant factors other than dredging?

  Do the patterns of use by deeper-draft vessels change after deepening and, holding other factors equal, is there greater probability of stranding associated with such changes compared with pre-deepening conditions?

The multivariate equations from the before-deepening phase will be used with the after-deepening data to address these two questions.

9.0 Literature Cited

Ackerman, NA. 2002. *Effects of vessel wake stranding of juvenile salmonids in the Lower Columbia River, 2002 – A pilot study*. Produced by SP Cramer & Associates, Inc., Sandy, Oregon, for the US Army Corps of Engineers, Portland District, Portland, Oregon.

Bauersfeld, K. 1977. *Effects of peaking (stranding) of Columbia River dams on juvenile anadromous fishes below the Dalles Dam, 1974 and 1975.* State of Washington Department of Fisheries, Technical Report No. 31. Report to the U.S. Army Corps of Engineers, Contract DACW 57-74-C-0094, 32 p. plus appendices. (Available from U.S. Army Corps. of Engineers, Portland District, P.O. Box 2946, Portland OR 97208.)

Conover, WJ. 1980. *Practical Nonparametric Statistics.* Wiley & Sons, New York, N.Y. 493 pp.

Dally, W. R., Dean, R. G., and Dalrymple, R. A. 1984. *Modeling Wave Transformation in the Surf Zone* Miscellaneous Paper CERC-84-8, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Hinton, SA and RL Emmett. 1994. *Juvenile salmonid stranding in the Lower Columbia River, 1992 and 1993.* NOAA Technical Memorandum NMFS-NWFSC-20. Prepared by the National Marine Fisheries Service, Northwest Fisheries Science Center, Coast Zone and Estuaries Studies Division, Seattle, Washington.

Kriebel, D, W Seelig and C Judge. 2003. *A Unified Description of Ship-Generated Waves*. Proceedings of the PIANC Passing Vessel Workshop, Portland, Oregon. October 28-30, 2003.

Maynord, ST. 1996 *Return Velocity and Drawdown in Navigable Waterways.* Coastal and Hydraulics Laboratory, US Army Engineer Research and Development Center, Vicksburg, MS, Technical Report HL-96-7. 89pp.

Maynord, ST. 2003. *Ship Effects Before and After Deepening of Sabine-Neches Waterway, Port Arthur, Texas.* Coastal and Hydraulics Laboratory, US Army Engineer Research and Development Center, Vicksburg, MS, Final Report ERDC/CHL TR-03-15. 84pp.

NMFS—National Marine Fisheries Service. 2002. *Endangered Species Act – Section 7 Consultation and Magnuson-Stevens Act Essential Fish Habitat Consultation. Biological Opinion: Columbia River Federal Navigation Channel Improvements Project.* Prepared for the US Army Corps of Engineers, Portland District, Portland, Oregon by the National Marine Fisheries Service, Northwest Region, Seattle, Washington.

Nwogu, O., 1993. *Alternative form of Boussinesq equations for nearshore wave propagation*, J. Waterway, Port, Coastal, and Ocean Engineering, 119, 618—638.

Pearson, WH, GE Johnson, MC Miller, SL Sargeant, and JR Skalski. 2004. *Study of Stranding of Juvenile Salmon Along the Lower Columbia River*, Draft Work Plan, Version 2, Submitted to US Army

Corps of Engineers, Portland District by Pacific Northwest National Laboratory, Marine Sciences Laboratory, Sequim, Washington

Simenstad, CA, CT Tanner, RM Thom, and LL Conquest. 1991. *Estuarine Habitat Assessment Protocol.* U.S. Environmental Protection Agency, Region 10, Seattle, Washington.

Sorensen, R.M.. 1997. *Interim Report for the Upper Mississippi River – Illinois Waterway System Navigation Study, Prediction of Vessel-Generated Waves with Reference to Vessels Common to the Upper Mississippi River System*. USACE Rock Island District, St. Louis District, and St. Paul District.

Weggel, J.R., and Sorensen, R.M. 1986. *Ship Wave Prediction for Port and Channel Design.* Proceedings, Ports 86 Conference, ASCE, Oakland, CA., pp. 794-814.

Williams, GD, RM Thom, DK Shreffler, JA Southard, LK O'Rourke, SL Sargeant, VI Cullinan, R Mourund, and M. Stamey. 2003. *Assessing Overwater Structure-Related Predation Risk on Juvenile Salmon: Field Observations and Recommended Protocols.* PNNL-SA-39451. Pacific Northwest National Laboratory, Marine Sciences Laboratory, Sequim, Washington.

Wolter, C and R Arlinghaus. 2003. *Navigation impacts on freshawater fish assemblages: the ecological relevance of swimming performance*. Reviews in Fish Biology and Fisheries: 13, 63-89

Appendix A

Photographs

Figure A-1. County Line Park looking upstream. In addition to the large root wad, there are numerous local scour features around sloughed rip-rap.

Figure A-2. Barlow Point survey reach.

Figure A-3. Barlow Point, upstream end of site. The upper part of the beach is protected by a gabion structure known as “Reno mat.”

Figure A-4. Sand Flats at Barlow Point. Ripples on the beach are characteristic of a tidal flat. The pencil and footprints indicate scale.

Figure A-5. Sauvie Island survey reach, looking upstream.

Figure A-6. Sauvie Island, downstream termination of the survey reach.

Figure A-7. Vessel passage depicting bow-wake.

Figure A-8. Wave run-up gage, as installed at Barlow Point site

Figure A-9. Waves triggering floats on the wave run-up gage. The two floats at the right in the picture are activated in this photo.

Figure A-10. Site layout, with wave run-up gage to left of photo and wave staff gages offshore to right of photo.

Appendix B

Statistical Analyses/ANODEV Tables

B-1

ANODEV tables for single-factor models for Regression 1

	Source	DF	DEV	MDEV	F	P
Location	Total_{Corr}	117	157.81			
	Location	2	13.67	6.853	$F_{2,115} = 5.4532$	0.0055
	Error	115	144.14	1.2534		

	Source	DF	DEV	MDEV	F	P
Season	Total_{Corr}	117	157.807			
	Season	2	4.111	2.0555	$F_{2,115} = 1.5380$	0.2192
	Error	115	153.696	1.3365		

	Source	DF	DEV	MDEV	F	P
River Flow	Total_{Corr}	117	157.807			
	Flow	1	4.422	4.422	$F_{1,116} = 3.3442$	0.0700
	Error	116	153.385	1.3223		

	Source	DF	DEV	MDEV	F	P
Tidal Stage	Total_{Corr}	117	157.807			
	Stage	3	5.029	1.676	$F_{3,114} = 1.2508$	0.2947
	Error	114	152.778	1.3402		

	Source	DF	DEV	MDEV	F	P
Tidal Height	Total_{Corr}	117	157.807			
	Height	1	10.659	10.659	$F_{1,116} = 8.4027$	0.0045
	Error	116	147.148	1.2685		

	Source	DF	DEV	MDEV	F	P
Current Velocity (knots)	Total_{Corr}	117	157.807			
	Velocity	1	7.158	7.158	$F_{1,116} = 5.5117$	0.0206
	Error	116	150.649	1.2987		

	Source	DF	DEV	MDEV	F	P
Ship Type	$Total_{Corr}$	116	155.909			
	Type	4	11.161	2.9025	$F_{4,112} = 2.2458$	0.0686
	Error	112	144.748	1.2924		
Ship Direction	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	117	157.807			
	Direction	1	5.873	5.873	$F_{1,116} = 4.4840$	0.0363
	Error	116	151.934	1.3098		
Ship Condition	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	109	145.286			
	Condition	2	6.934	3.467	$F_{2,107} = 2.6813$	0.0731
	Error	107	138.352	1.2930		
Ship Distance	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	116	155.91			
	Distance	4	4.33	1.0825	$F_{4,112} = 0.7998$	0.5278
	Error	112	151.58	1.3534		
Ship Time	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	112	149.125			
	Time	1	9.478	9.478	$F_{1,111} = 7.5337$	0.0071
	Error	111	139.647	1.2581		
Ship Speed (knots)	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	112	149.125			
	Speed	1	7.547	7.547	$F_{1,111} = 5.917$	0.0166
	Error	111	141.578	1.2755		
Ship Draft	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	103	141.043			
	Draft	1	3.654	3.654	$F_{1,102} = 2.7128$	0.1026
	Error	102	137.389	1.3470		
Ship Beam	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	110	149.88			
	Beam	1	8.14	8.14	$F_{1,109} = 6.2598$	0.0138
	Error	109	141.74	1.3004		
Ship Length	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	110	149.882			
	Length	1	3.807	3.807	$F_{1,109} = 2.8408$	0.0948
	Error	109	146.075	1.3401		

	Source	DF	DEV	MDEV	F	P
Ship Block	Total_{Corr}	103	141.043			
	Block	1	6.699	6.699	$F_{1,102} = 5.0862$	0.0263
	Error	102	134.344	1.3171		
Ship Force	Source	DF	DEV	MDEV	F	P
	Total_{Corr}	98	132.755			
	Force	1	8.037	8.037	$F_{1,97} = 6.2509$	0.0141
	Error	97	124.717	1.2857		
Chinook Index	Source	DF	DEV	MDEV	F	P
	Total_{Corr}	117	157.807			
	Chinook	1	5.038	5.038	$F_{1,116} = 3.8255$	0.0529
	Error	116	152.768	1.3170		
Salmonid Index	Source	DF	DEV	MDEV	F	P
	Total_{Corr}	117	157.807			
	Salmonid	1	4.077	4.077	$F_{1,116} = 3.0764$	0.0821
	Error	116	153.730	1.3253		

ANODEV tables for bivariate models for Regression 1

	Source	DF	DEV	MDEV	F	P
Season	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	117	157.807			
	Location	2	13.670	6.853		
	Season	2	4.779	2.3895	$F_{2,113} = 1.9376$	0.1488
	Error	113	139.357	1.2332		
River Flow	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	117	157.807			
	Location	2	13.670	6.853		
	Flow	1	2.942	2.942	$F_{1,114} = 2.3754$	0.1260
	Error	114	141.194	1.2385		
Tidal Stage	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	117	157.807			
	Location	2	13.670	6.853		
	Stage	3	1.816	0.6053	$F_{1,112} = 0.4764$	0.6994
	Error	112	142.320	1.2707		
Tidal Height	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	117	157.807			
	Location	2	13.670	6.853		
	Height	1	6.104	6.104	$F_{1,114} = 5.0412$	0.0268
	Error	114	138.033	1.2108		
Current Velocity (knots)	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	117	157.807			
	Location	2	13.670	6.853		
	Velocity	1	5.46	5.46	$F_{1,114} = 4.4884$	0.0363
	Error	114	138.68	1.2165		

Ship Type	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	116	155.909			
	Location	2	12.931	6.4655		
	Type	4	15.123	3.7808	$F_{1,110} = 3.2528$	0.0146
	Error	110	127.855	1.1623		

Ship Direction	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	117	157.807			
	Location	2	13.670	6.852		
	Direction	1	5.998	5.998	$F_{1,114} = 4.9499$	0.0281
	Error	114	138.138	1.2117		

Ship Condition	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	109	145.286			
	Location	2	11.268	5.634		
	Condition	2	6.757	3.3785	$F_{1,105} = 2.7875$	0.0661
	Error	105	127.261	1.0021		

Ship Distance	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	116	155.909			
	Location	2	12.931	6.4655		
	Distance	4	6.448	1.612	$F_{1,110} = 1.2988$	0.2750
	Error	110	136.530	1.2412		

Ship Time	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	112	149.125			
	Location	2	11.800	5.9000		
	Time	1	14.931	14.931	$F_{1,109} = 13.2971$	0.0004
	Error	109	122.394	1.1229		

Ship Speed (knots)	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	112	149.125			
	Location	2	11.800	5.9000		
	Speed	1	13.28	13.28	$F_{1,109} = 11.6693$	0.0009
	Error	109	124.05	1.1381		

Ship Draft	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	103	141.043			
	Location	2	14.929	7.4645		
	Draft	1	5.239	5.239	$F_{1,100} = 4.3342$	0.0399
	Error	100	120.875	1.2088		

Ship Beam	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	110	149.882			
	Location	2	17.242	8.621		
	Beam	1	11.390	11.390	$F_{1,107} = 10.0514$	0.0020
	Error	107	121.249	1.1332		

Ship Length	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	110	149.882			
	Location	2	17.242	8.621		
	Length	1	5.970	5.970	$F_{1,107} = 5.0430$	0.0268
	Error	107	126.670	1.1838		

Ship Draft	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	103	141.043			
	Location	2	14.929	7.4645		
	Draft	1	8.764	8.764	$F_{1,100} = 7.4682$	0.0074
	Error	100	117.350	1.1735		

Ship Force	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	98	132.755			
	Location	2	12.870	6.435		
	Force	1	13.489	13.489	$F_{1,95} = 12.0443$	0.0008
	Error	95	106.395	1.1199		

Chinook Index	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	117	157.807			
	Location	2	13.670	6.852		
	Chinook	1	5.054	5.054	$F_{1,114} = 4.1425$	0.0441
	Error	114	139.083	1.2200		

Salmonid Index	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	117	157.807			
	Location	2	13.670	6.852		
	Salmonid	1	5.155	5.155	$F_{1,114} = 4.2284$	0.0420
	Error	114	138.982	1.2191		

B-3

ANODEV tables for single-factor models for Regression 2

	Source	DF	DEV	MDEV	F	P
Location	$Total_{Corr}$	117	157.81			
	Location	2	13.67	6.853	$F_{2,115} = 5.4532$	0.0055
	Error	115	144.14	1.2534		
Season	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	117	157.807			
	Season	2	4.111	2.0555	$F_{2,115} = 1.5380$	0.2192
	Error	115	153.696	1.3365		
River Flow	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	117	157.807			
	Flow	1	4.422	4.422	$F_{1,116} = 3.3442$	0.0700
	Error	116	153.385	1.3223		
Tidal Stage	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	117	157.807			
	Stage	3	5.029	1.676	$F_{3,114} = 1.2508$	0.2947
	Error	114	152.778	1.3402		
Tidal Height	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	117	157.807			
	Height	1	10.659	10.659	$F_{1,116} = 8.4027$	0.0045
	Error	116	147.148	1.2685		
Current Velocity (knots)	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	117	157.807			
	Velocity	1	7.158	7.158	$F_{1,116} = 5.5117$	0.0206
	Error	116	150.649	1.2987		

	Source	DF	DEV	MDEV	F	P
Run-up Distance	$Total_{Corr}$	116	156.813			
	Run-up	1	13.105	13.105	$F_{1,115} = 10.4868$	0.0016
	Error	115	143.708	1.2496		
Draw-down Distance	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	116	156.81			
	Draw-down	1	15.32	15.32	$F_{1,115} = 12.4518$	0.0006
	Error	115	141.49	1.2303		
Total Wave Distance	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	116	156.813			
	Wave	1	16.189	16.189	$F_{1,115} = 13.2395$	0.0004
	Error	115	140.624	1.2228		
Run-up Velocity (camera)	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	45	63.770			
	Camera	1	7.6×10^{-5}	7.6×10^{-5}	$F_{1,44} = 5.3 \times 10^{-5}$	0.9943
	Error	44	63.769	1.4493		
Run-up Velocity (gage)	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	27	35.165			
	Gage	1	2.733	2.733	$F_{1,26} = 2.1908$	0.1509
	Error	26	32.432	1.2474		
Wash-back Velocity	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	32	42.010			
	Wash-back	1	0.188	0.188	$F_{1,31} = 0.1390$	0.7118
	Error	31	41.822	1.3491		
Maximum Draw-down Height	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	70	90.840			
	Draw-down	1	5.462	5.462	$F_{1,69} = 4.4138$	0.0393
	Error	69	85.379	1.2374		
Maximum Run-up Height	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	70	90.840			
	Run-up	1	3.608	3.608	$F_{1,69} = 2.8543$	0.0956
	Error	69	87.232	1.2642		
Maximum Water Level	Source	DF	DEV	MDEV	F	P
	$Total_{Corr}$	73	93.253			
	Level	1	1.196	1.196	$F_{1,72} = 0.9351$	0.3368
	Error	72	92.057	1.2786		

B-4

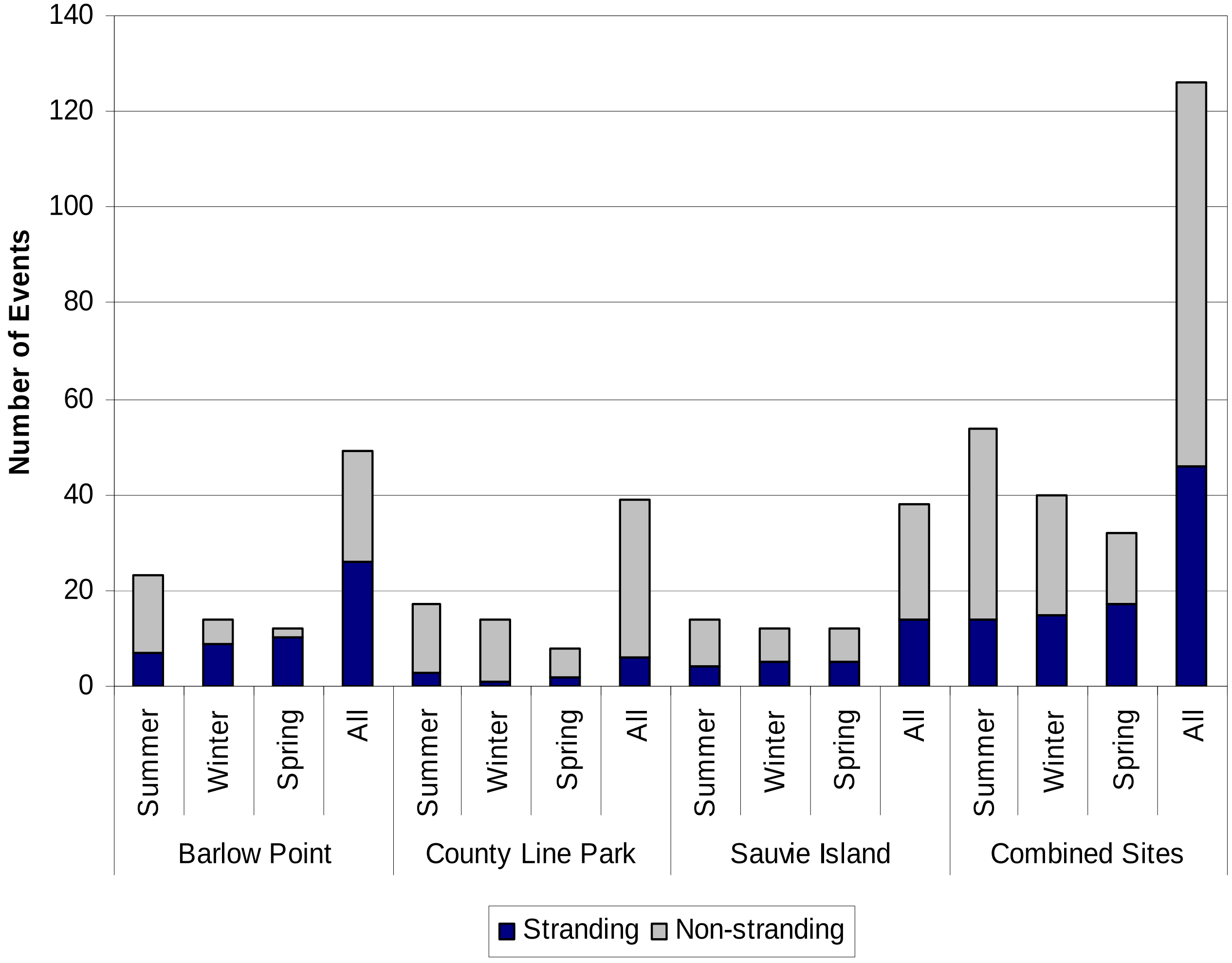
Select ANODEV tables for trivariate models for Regression 2

	Source	DF	DEV	MDEV	F	P
Season	Total_{Corr}	116	156.813			
	Location	2	13.644	6.822		
	Wave	1	16.087	16.087		
	Season	2	10.544	5.272	$F_{2,111} = 5.0215$	0.0082
	Error	111	116.538	1.0499		
River Flow	Source	DF	DEV	MDEV	F	P
	Total_{Corr}	116	156.813			
	Location	2	13.644	6.822		
	Wave	1	16.087	16.087		
	Flow	1	4.731	4.731	$F_{1,112} = 4.3308$	0.0397
	Error	112	122.350	1.0924		
Tidal Height	Source	DF	DEV	MDEV	F	P
	Total_{Corr}	116	156.813			
	Location	2	13.644	6.822		
	Wave	1	16.087	16.087		
	Height	1	5.091	5.091	$F_{1,112} = 4.6741$	0.0327
	Error	112	121.991	1.0892		
Salmonid Index	Source	DF	DEV	MDEV	F	P
	Total_{Corr}	116	156.813			
	Location	2	13.644	6.822		
	Wave	1	16.087	16.087		
	Salmonid	1	11.297	11.297	$F_{1,112} = 10.9278$	0.0013
	Error	112	115.784	1.0338		

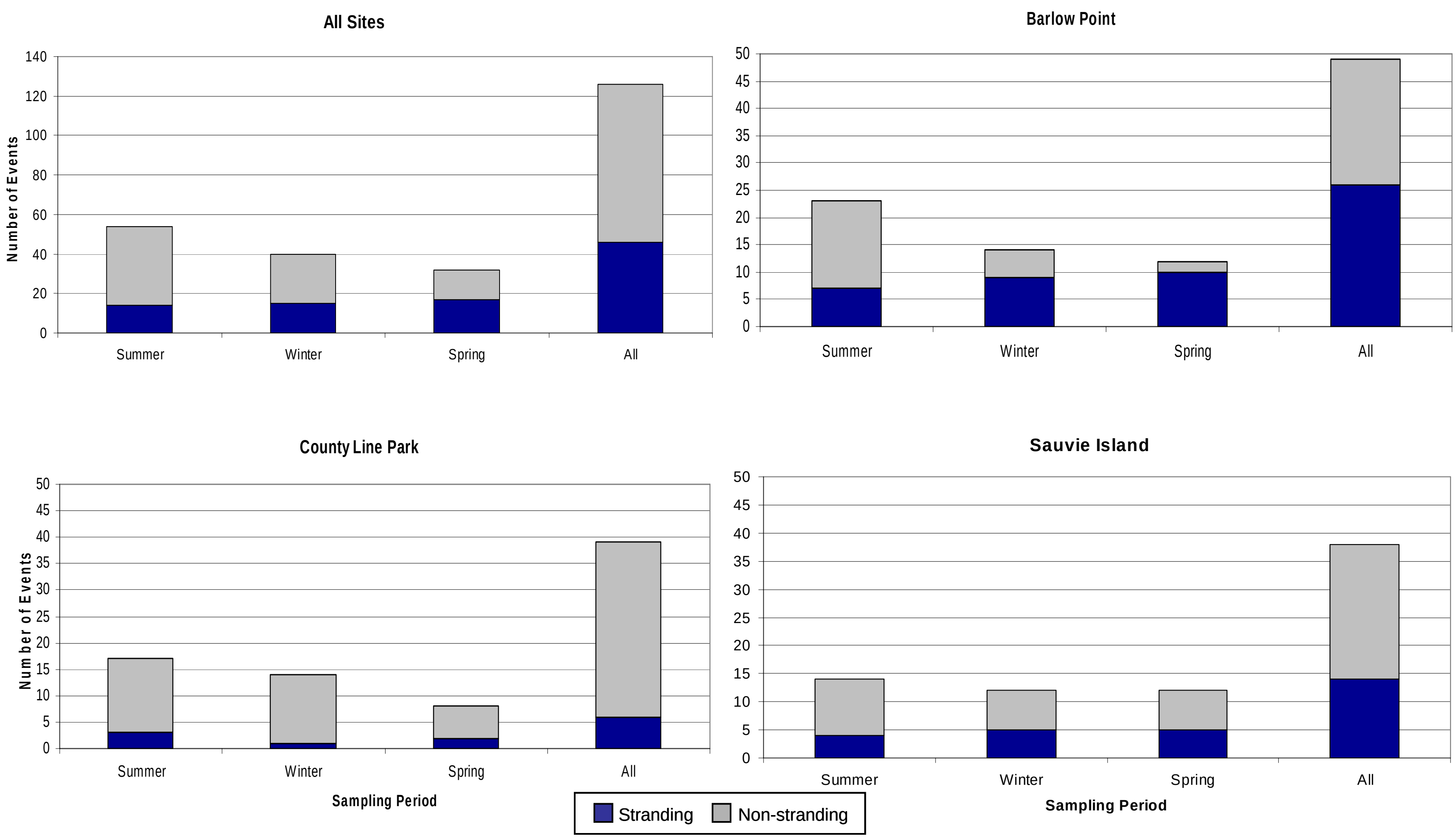
Appendix C

Stranding Plots

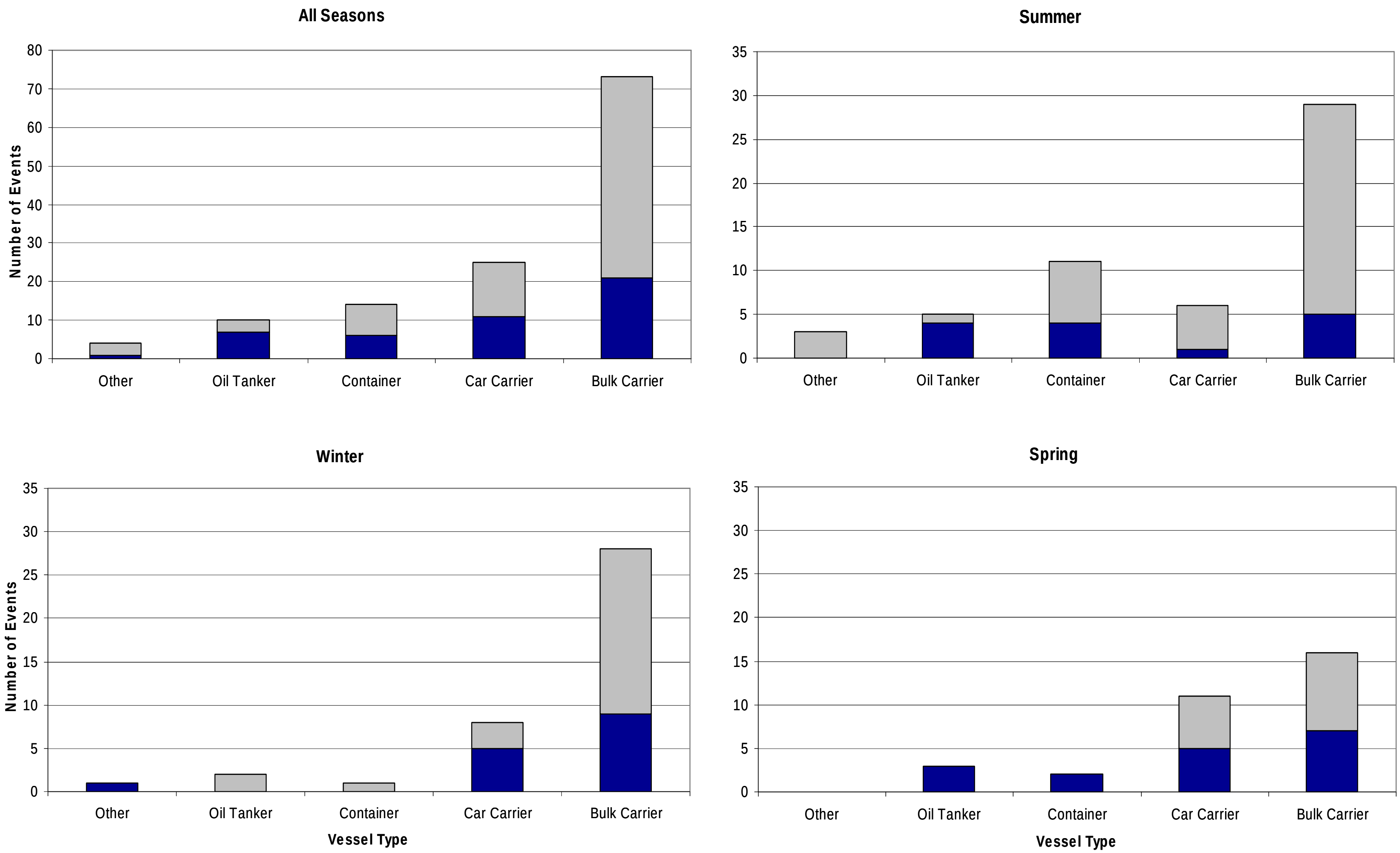
C-1 Stranding Events by Sampling Period and Study Site



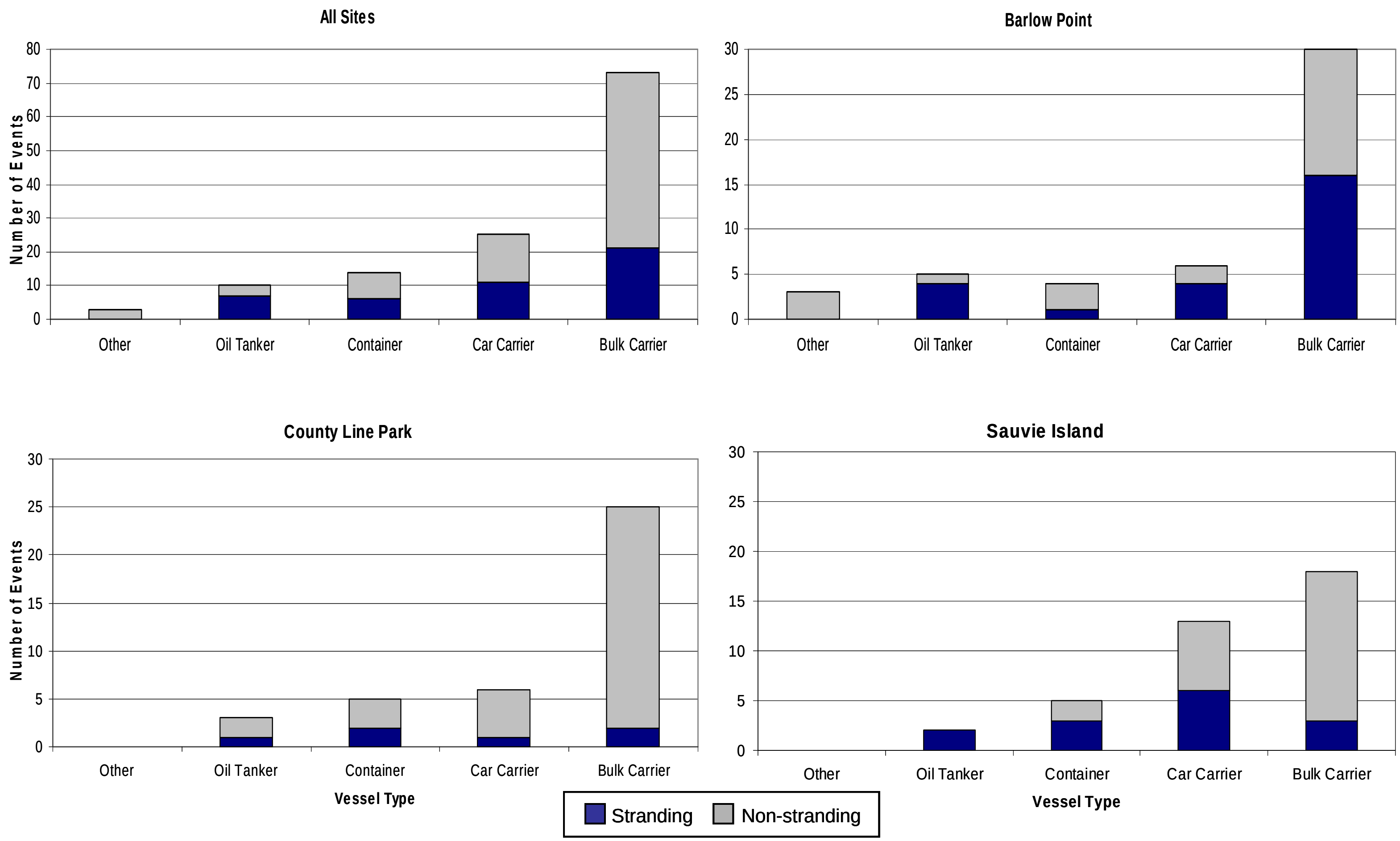
C-2 Stranding by Sampling Period



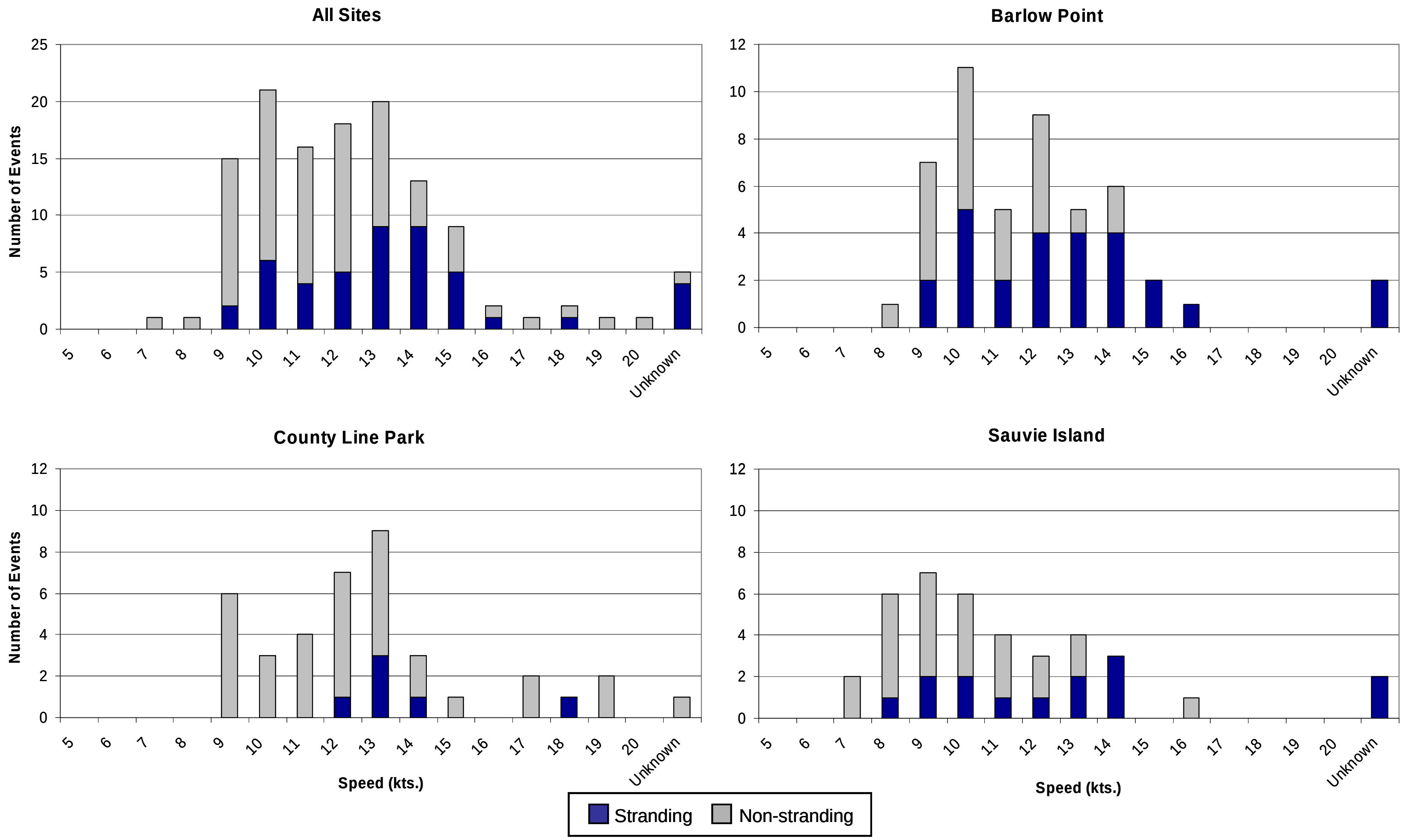
C-3 Stranding by Vessel Type for Each Season



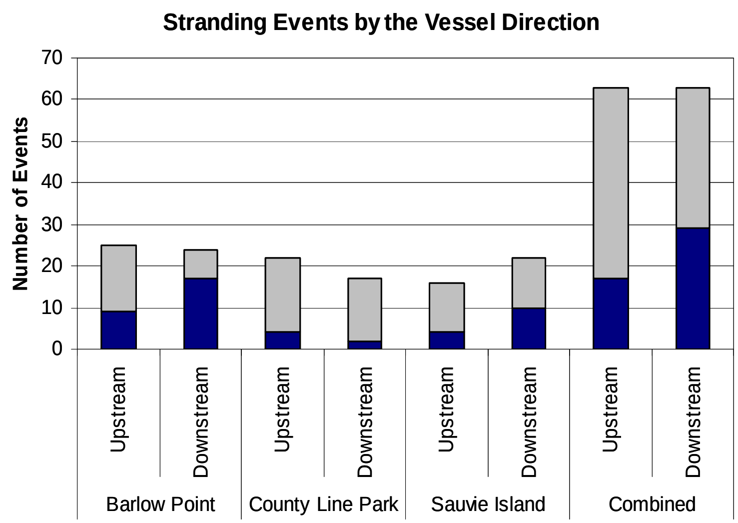
C-4 Stranding by Vessel Type for Each Site

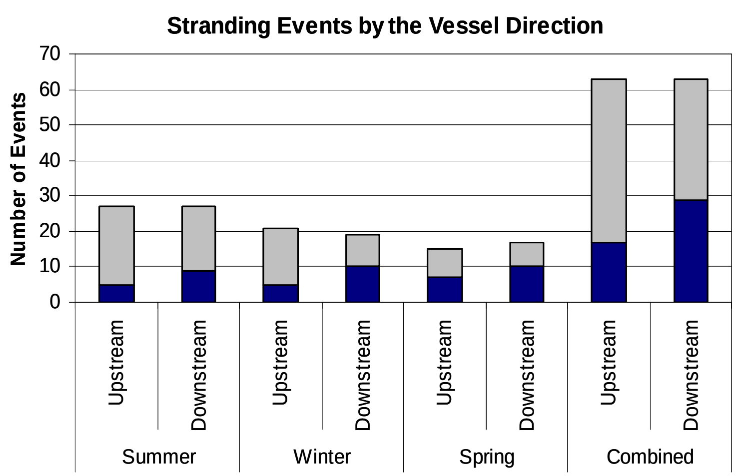


C-5 Stranding by Vessel Speed



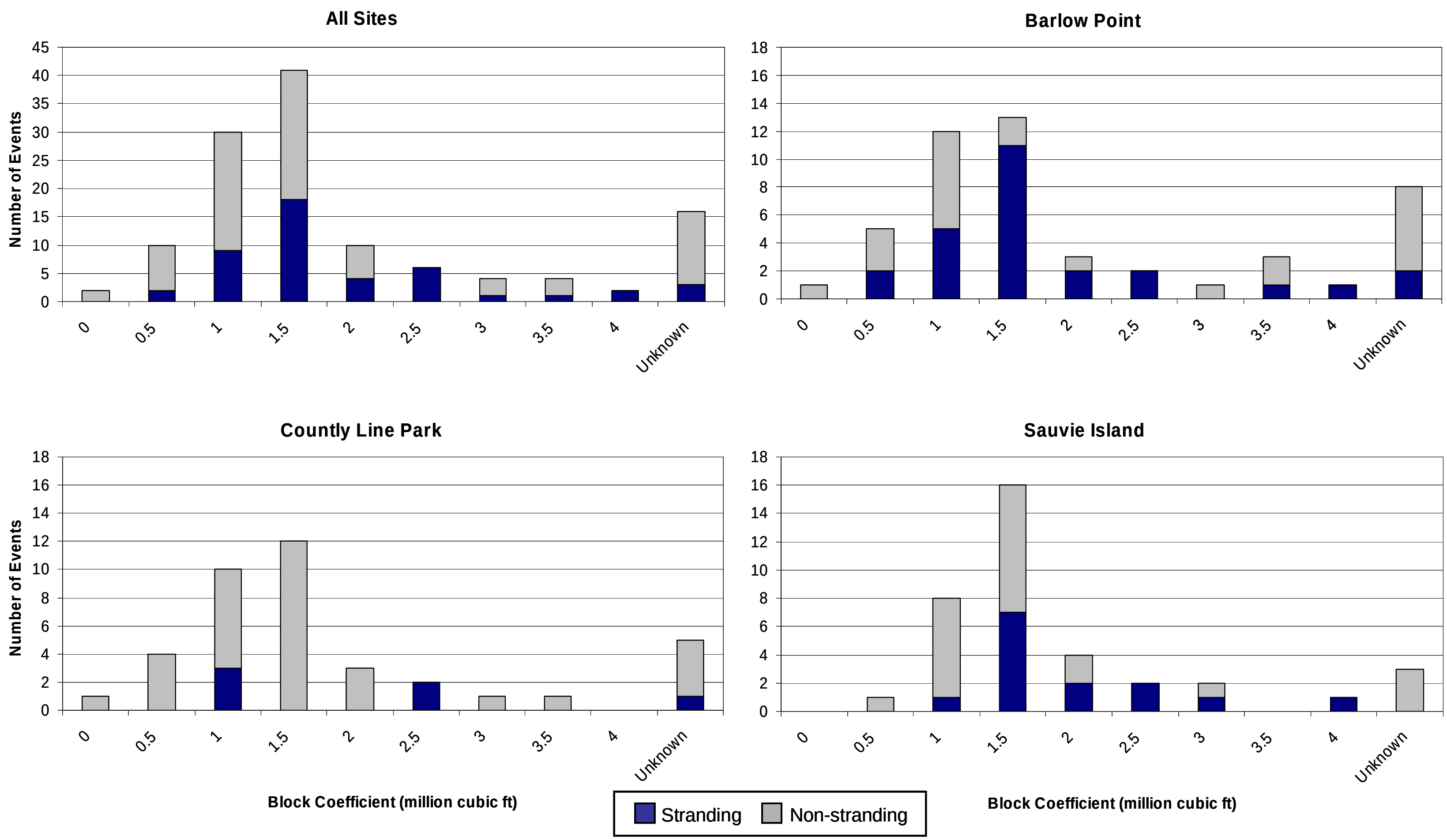
C-6 Stranding by Vessel Direction by Site and Season



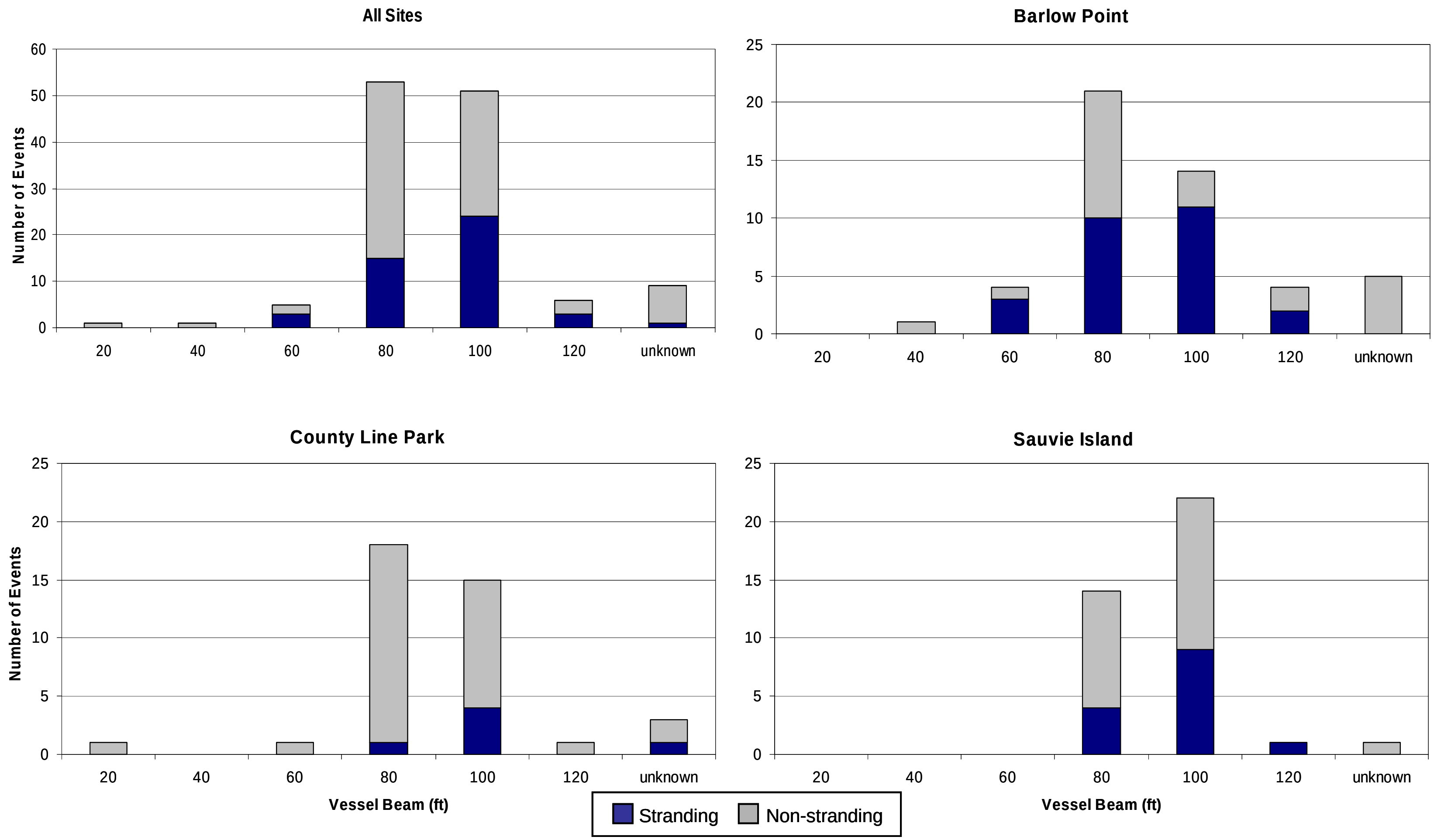


Stranding Non-stranding

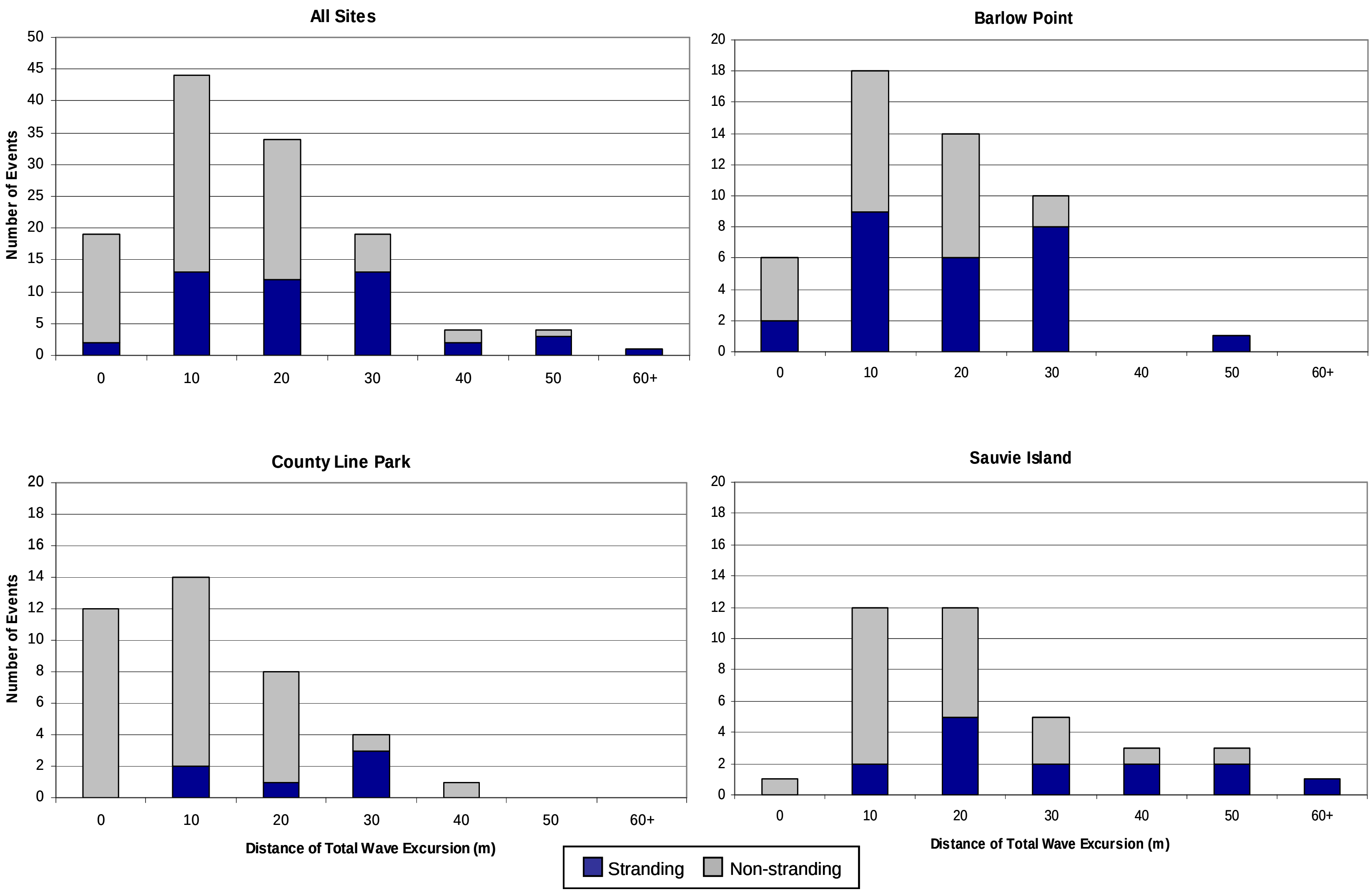
C-7 Stranding by Ship Block Coefficient for Each Site



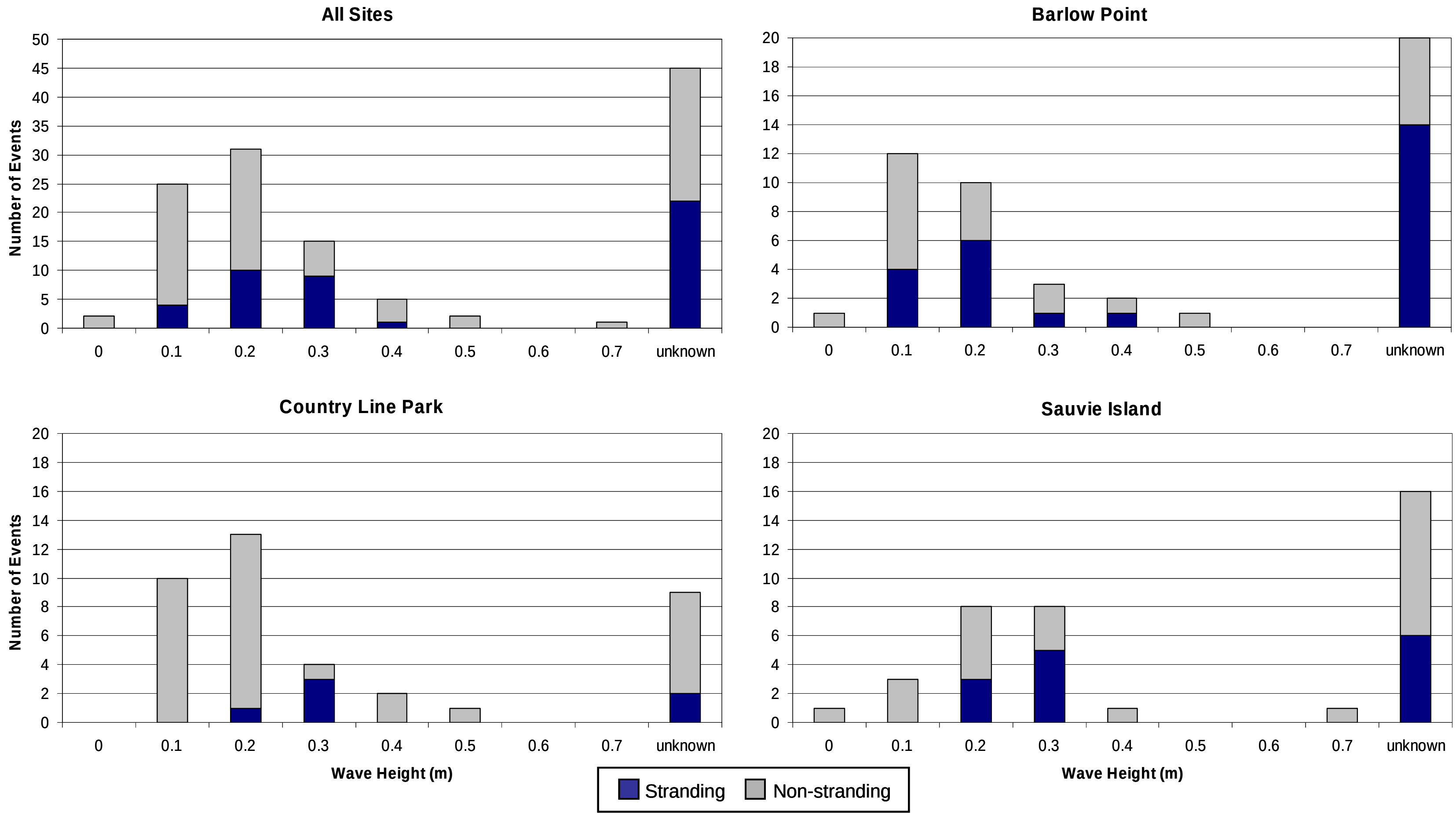
C-8 Stranding by Vessel Beam for Each Site



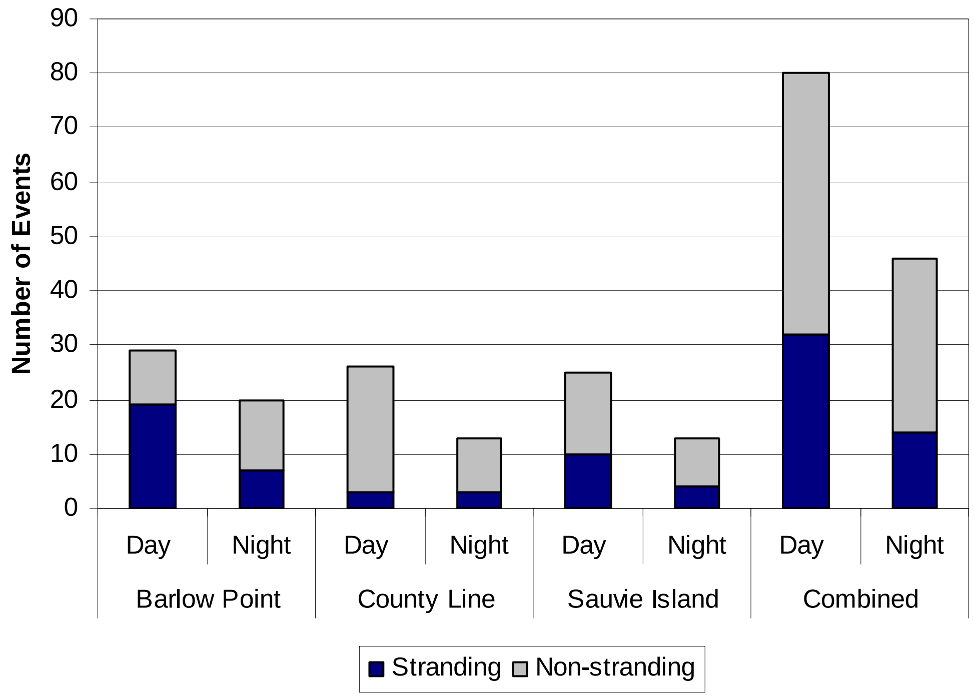
C-9 Stranding by Total Wave Excursion for Each Site



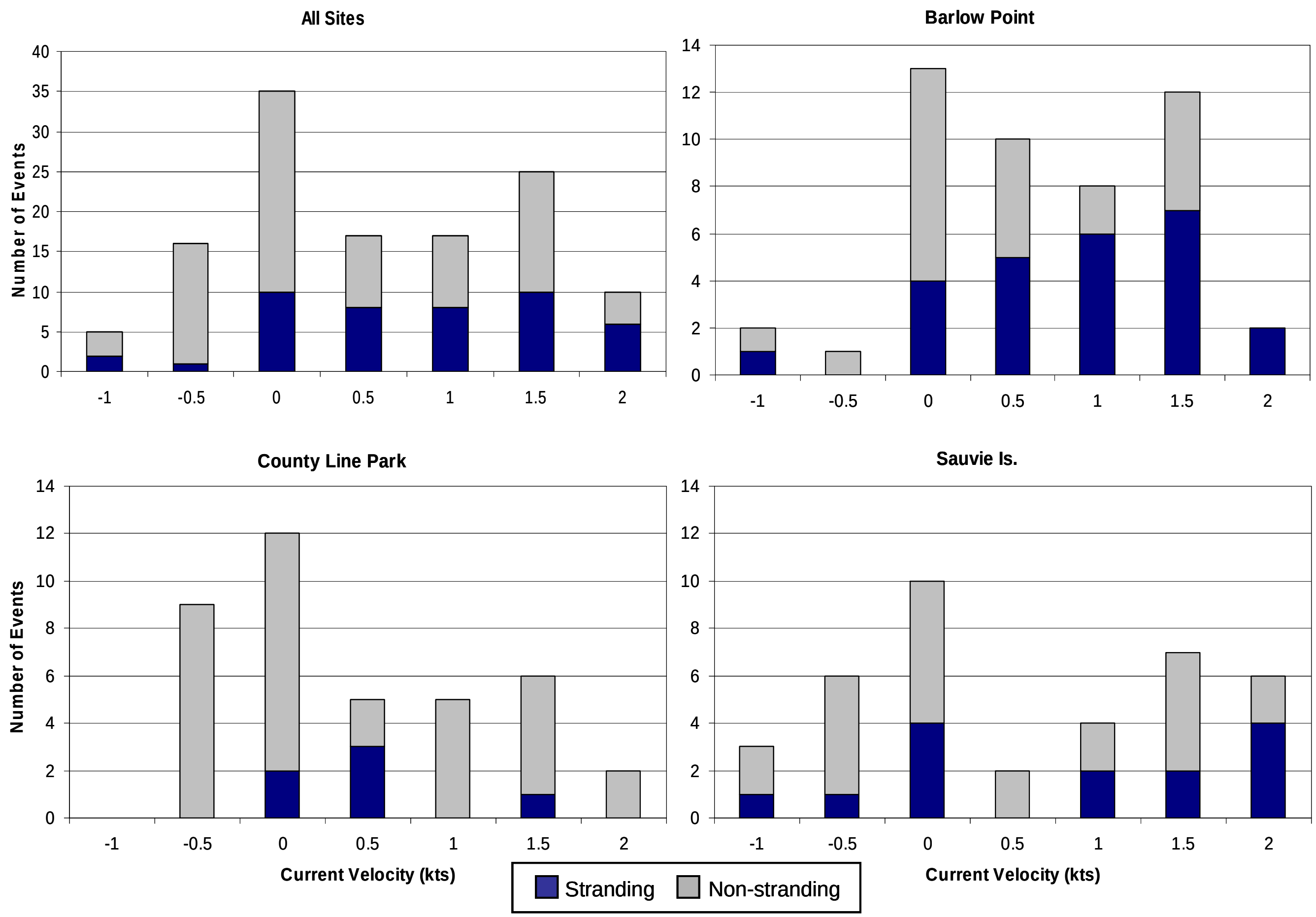
C-10 Stranding by Maximum Wave Height for Each Site



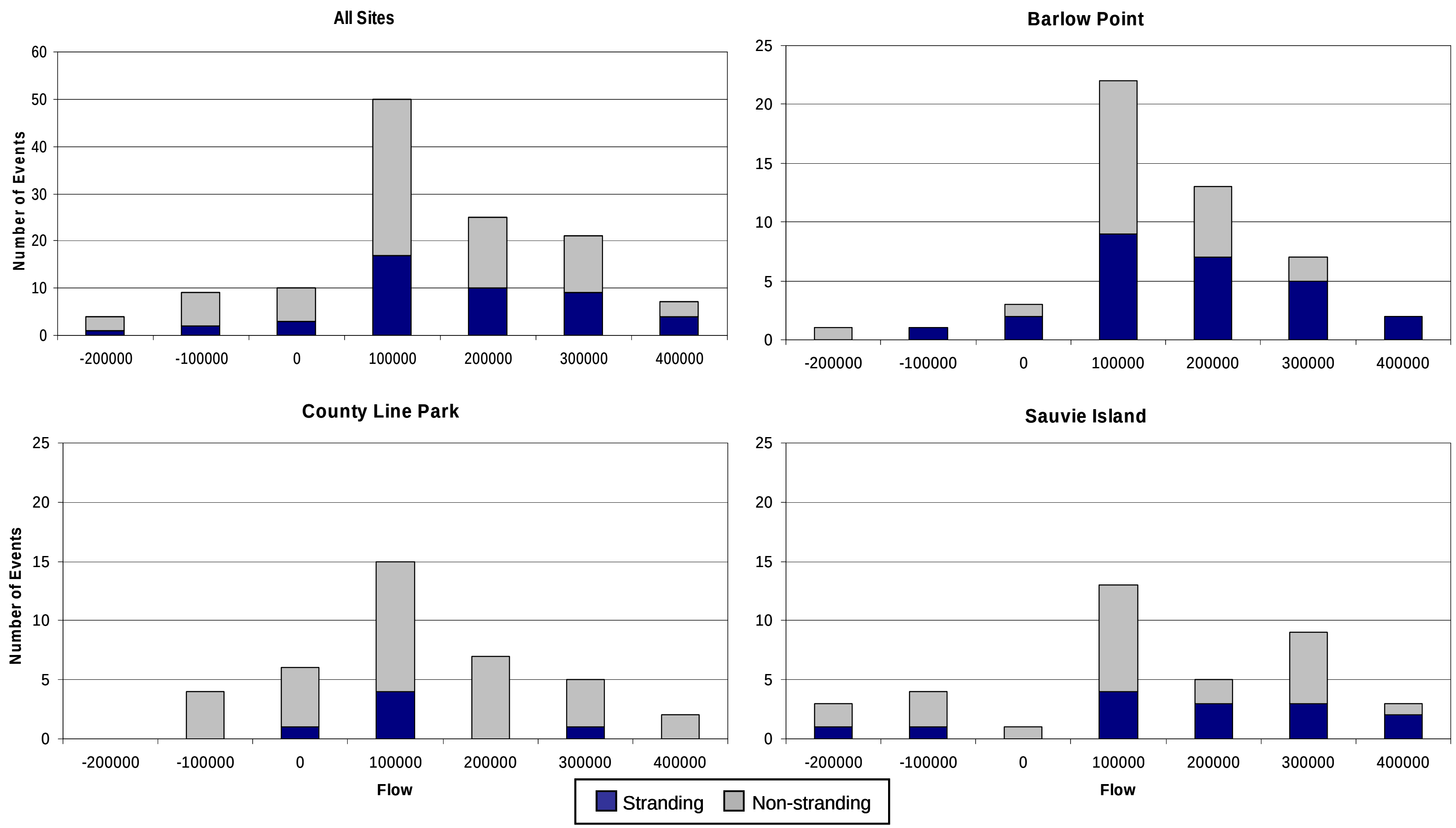
C-11 Stranding by Time of Day for Each Site



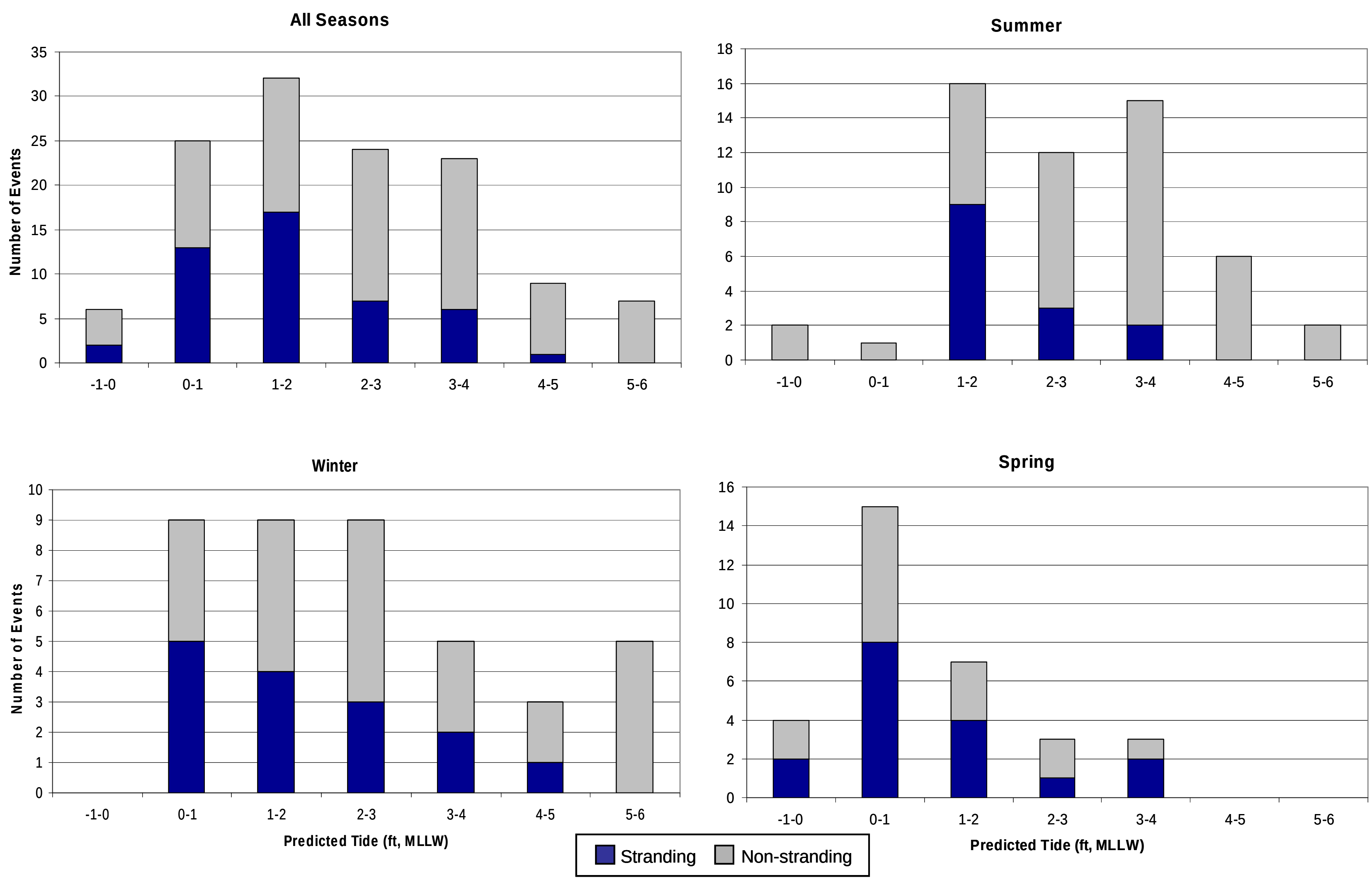
C-12 Stranding by River Velocity for Each Site



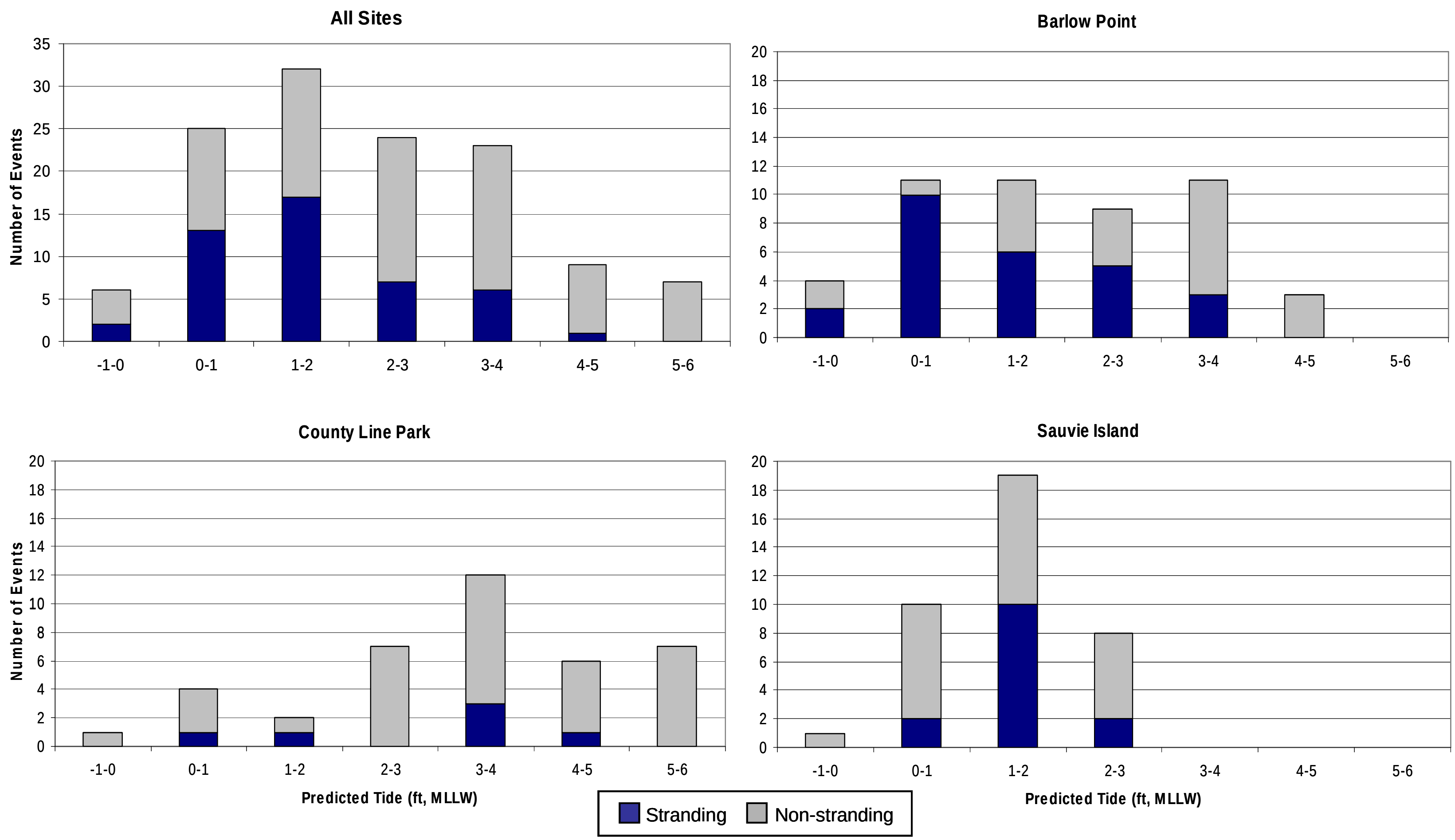
C-13 Stranding by River Flow for Each Site



C-14 Stranding by Tidal Height for Each Season



C-15 Stranding by Tidal Height for Each Site



Appendix D

Data

D-1. Basic Identifiers

Basic Identifiers								River Characteristics				
Deep Draft Passage #	Date	Location	Diel Sampling Phase	Phase	Season	Field Trip	Data Collection Trial #	River Flow (Quincy, OR)	Tidal Stage	Tidal Height, ft.	Current Velocity (Qunicy, OR)	
		County Line= CL Barlow = BP Sauvie = SI		Before (B) or After (A) Deepening	Sp=spring, Su=summer, Win=winter			cubic ft/sec		SI=St. Helens, BP=Longview, CLP=Eagle Cliff	f/s	Kts
1	06/29/04	CL	Day	B	Su	1	3	205,000	Flooding	3.00	0.85	0.503
2	06/29/04	CL	Day	B	Su	1	4	205,000	Flooding	3.20	0.8	0.474
3	06/29/04	CL	Day	B	Su	1	6	205,000	Ebbing	3.00	1.72	1.018
4	06/29/04	CL	Day	B	Su	1	7	205,000	Ebbing	2.50	2.51	1.486
5	06/30/04	BP	Day	B	Su	1	8	204,000	Flooding	-0.50	3.1	1.835
6	06/30/04	BP	Day	B	Su	1	13	204,000	Flooding	3.20	0.82	0.485
7	06/30/04	BP	Day	B	Su	1	14	204,000	Ebbing	3.20	1.35	0.799
8	07/01/04	SI	Day	B	Su	1	16	211,000	Low Slack	-0.50	0.99	0.586
9	07/19/04	BP	Night	B	Su	2	19	125,000	Ebbing	2.00	2.86	1.693
10	07/19/04	BP	Night	B	Su	2	20	125,000	Ebbing	1.90	2.68	1.587
11	07/20/04	BP	Night	B	Su	2	21	147,000	Low Slack	1.30	0.81	0.480
12	07/20/04	BP	Night	B	Su	2	22	147,000	Flooding	1.40	0.2	0.118
13	07/20/04	SI	Night	B	Su	2	25	147,000	Ebbing	2.00	1.82	1.077
14	07/21/04	CL	Night	B	Su	2	26	137,000	Ebbing	3.40	1.64	0.971
15	07/21/04	CL	Night	B	Su	2	27	137,000	Ebbing	3.00	2.26	1.338
16	07/22/04	CL	Night	B	Su	2	28	132,000	Flooding	5.00	-0.61	-0.361
17	08/09/04	CL	Night	B	Su	3	29	107,000	Flooding	3.00	-0.17	-0.101
18	08/09/04	CL	Night	B	Su	3	30	107,000	High Slack	5.00	-0.27	-0.161
19	08/10/04	CL	Night	B	Su	3	31	129,000	Ebbing	1.00	0.86	0.507
20	08/10/04	CL	Night	B	Su	3	32	129,000	Flooding	2.40	0.39	0.233
21	08/10/04	CL	Night	B	Su	3	33	129,000	Flooding	3.00	0.25	0.146
22	08/10/04	CL	Night	B	Su	3	34	129,000	Flooding	4.00	-0.24	-0.141
23	08/11/04	CL	Night	B	Su	3	35	153,000	Ebbing	4.80	-0.04	-0.023
24	08/11/04	CL	Night	B	Su	3	36	153,000	Ebbing	4.50	0.35	0.206
25	08/11/04	CL	Night	B	Su	3	37	153,000	Ebbing	4.50	0.43	0.253

Basic Identifiers								River Characteristics				
Deep Draft Passage #	Date	Location	Diel Sampling Phase	Phase	Season	Field Trip	Data Collection Trial #	River Flow (Quincy, OR)	Tidal Stage	Tidal Height, ft.	Current Velocity (Qunicy, OR)	
26	08/11/04	CL	Night	B	Su	3	38	153,000	Ebbing	3.20	0.74	0.440
27	08/11/04	BP	Night	B	Su	3	39	153,000	Ebbing	2.00	0.69	0.406
28	08/11/04	BP	Night	B	Su	3	40	153,000	Ebbing	1.80	0.62	0.370
29	08/12/04	BP	Night	B	Su	3	41	172,000	Ebbing	3.60	0.40	0.235
30	08/12/04	BP	Night	B	Su	3	42	172,000	Ebbing	3.00	0.70	0.413
31	08/13/04	SI	Night	B	Su	3	43	154,000	Ebbing	1.50	0.63	0.374
32	08/13/04	SI	Night	B	Su	3	44	154,000	Ebbing	1.00	0.19	0.114
33	08/14/04	SI	Night	B	Su	3	45	145,000	Ebbing	1.80	0.72	0.424
34	08/14/04	SI	Night	B	Su	3	46	145,000	Ebbing	0.00	0.02	0.009
35	08/15/04	SI	Night	B	Su	3	47	122,000	High Slack	2.10	0.27	0.159
36	08/15/04	SI	Night	B	Su	3	48	122,000	Ebbing	2.00	0.34	0.204
37	08/15/04	SI	Night	B	Su	3	49	122,000	Ebbing	1.70	0.74	0.440
38	08/15/04	SI	Night	B	Su	3	50	122,000	Ebbing	1.50	0.77	0.458
39	08/15/04	SI	Night	B	Su	3	51	122,000	Ebbing	1.10	0.64	0.381
40	08/16/04	SI	Night	B	Su	3	52	121,000	Flooding	1.00	-0.45	-0.267
41	08/16/04	SI	Night	B	Su	3	53	121,000	Flooding	2.00	-0.26	-0.153
42	08/16/04	SI	Night	B	Su	3	54	121,000	High Slack	2.30	0.02	0.009
43	08/29/04	BP	Night	B	Su	4	55	174,000	Ebbing	3.00	0.85	0.502
44	08/29/04	BP	Night	B	Su	4	56	174,000	Ebbing	2.10	0.91	0.538
45	08/29/04	BP	Night	B	Su	4	57	174,000	Ebbing	1.90	0.95	0.563
46	08/29/04	BP	Night	B	Su	4	58	174,000	Ebbing	1.60	0.91	0.541
47	08/30/04	BP	Night	B	Su	4	59	163,000	High Slack	4.30	-0.13	-0.078
48	08/30/04	BP	Night	B	Su	4	60	163,000	Ebbing	4.00	0.48	0.287
49	08/30/04	BP	Night	B	Su	4	61	163,000	Ebbing	3.80	0.31	0.186
50	08/30/04	BP	Night	B	Su	4	62	163,000	Ebbing	3.80	0.51	0.300
51	08/30/04	BP	Night	B	Su	4	63	163,000	Ebbing	2.50	0.93	0.549
52	08/30/04	BP	Night	B	Su	4	64	163,000	Ebbing	2.50	0.93	0.550
53	08/30/04	BP	Night	B	Su	4	65	163,000	Ebbing	1.20	1.01	0.595
54	08/30/04	BP	Night	B	Su	4	66	163,000	Ebbing	1.20	0.98	0.577

Basic Identifiers								River Characteristics				
Deep Draft Passage #	Date	Location	Diel Sampling Phase	Phase	Season	Field Trip	Data Collection Trial #	River Flow (Quincy,OR)	Tidal Stage	Tidal Height, ft.	Current Velocity (Qunicy, OR)	
55	02/08/05	SI	Day	B	Win	1	1	98,600	Ebbing	1.00	0.89	0.527
56	02/08/05	SI	Day	B	Win	1	2	-116,000	Flooding	1.60	-0.98	-0.580
57	02/08/05	SI	Day	B	Win	1	3	-94,400	Flooding	2.10	-0.79	-0.468
58	02/08/05	SI	Day	B	Win	1	4	-51,900	Flooding	2.40	-0.44	-0.260
59	02/08/05	SI	Day	B	Win	1	5	-51,900	Flooding	2.40	-0.44	-0.260
60	02/09/05	SI	Day	B	Win	1	6	-20,100	Low Slack	0.70	-0.18	-0.107
61	02/09/05	SI	Day	B	Win	1	7	-101,000	Low Slack	0.70	-0.87	-0.515
62	02/09/05	SI	Day	B	Win	1	8	-119,000	Flooding	1.70	-1.00	-0.592
63	02/10/05	BP	Day	B	Win	1	9	255,000	Low Slack	0.90	2.39	1.415
64	02/10/05	BP	Day	B	Win	1	10	-93,500	Flooding	2.70	-0.8	-0.474
65	02/10/05	BP	Day	B	Win	1	11	-109,000	Flooding	3.90	-0.92	-0.545
66	02/10/05	BP	Day	B	Win	1	12	12,200	High Slack	4.80	0.1	0.059
67	02/11/05	BP	Day	B	Win	1	13	276,000	Ebbing	3.40	2.5	1.480
68	02/11/05	BP	Day	B	Win	1	14	303,000	Ebbing	2.20	2.81	1.664
69	02/11/05	BP	Day	B	Win	1	15	340,000	Ebbing	1.30	3.2	1.894
70	02/11/05	BP	Day	B	Win	1	16	267,000	Low Slack	0.70	2.5	1.480
71	02/11/05	BP	Day	B	Win	1	17	234,000	Low Slack	0.70	2.17	1.285
72	02/11/05	BP	Day	B	Win	1	18	75,700	Flooding	0.80	0.68	0.403
73	02/12/05	CL	Day	B	Win	1	19	70,400	Flooding	2.50	0.63	0.373
74	02/12/05	CL	Day	B	Win	1	20	-46,000	Flooding	5.20	-0.39	-0.231
75	02/12/05	CL	Day	B	Win	1	21	-55,000	High Slack	5.50	-0.47	-0.278
76	02/13/05	CL	Day	B	Win	1	22	300,000	Low Slack	0.70	2.84	1.681
77	02/13/05	CL	Day	B	Win	1	23	59,700	Flooding	2.70	0.54	0.320
78	02/13/05	CL	Day	B	Win	1	24	11,800	Flooding	3.90	0.1	0.059
79	03/16/05	BP	Day	B	Win	2	25	273,000	Ebbing	1.00	2.57	1.521
80	03/17/05	BP	Day	B	Win	2	26	75,100	High Slack	3.80	0.67	0.397
81	03/17/05	BP	Day	B	Win	2	27	289,000	Ebbing	1.40	2.74	1.622
82	03/17/05	BP	Day	B	Win	2	28	210,000	Low Slack	0.50	2	1.184
83	03/18/05	SI	Day	B	Win	2	29	261,000	Ebbing	1.00	2.49	1.474
84	03/18/05	SI	Day	B	Win	2	30	231,000	Ebbing	0.70	2.21	1.308
85	03/19/05	SI	Day	B	Win	2	31	265,000	Ebbing	1.10	2.5	1.480

Basic Identifiers								River Characteristics				
Deep Draft Passage #	Date	Location	Diel Sampling Phase	Phase	Season	Field Trip	Data Collection Trial #	River Flow (Quincy, OR)	Tidal Stage	Tidal Height, ft.	Current Velocity (Qunicy, OR)	
86	03/20/05	SI	Day	B	Win	2	32	276,000	Ebbing	1.30	2.57	1.521
87	03/21/05	CL	Day	B	Win	2	33	105,000	Flooding	3.10	0.95	0.562
88	03/21/05	CL	Day	B	Win	2	34	3,920	High Slack	5.00	0.03	0.018
89	03/21/05	CL	Day	B	Win	2	35	25,400	High Slack	5.00	0.22	0.130
90	03/21/05	CL	Day	B	Win	2	36	179,000	Ebbing	4.30	1.6	0.947
91	03/21/05	CL	Day	B	Win	2	37	271,000	Ebbing	2.90	2.5	1.480
92	03/21/05	CL	Day	B	Win	2	38	297,000	Ebbing	2.20	2.76	1.634
93	03/22/05	CL	Day	B	Win	2	39	-37,700	Flooding	4.50	-0.33	-0.195
94	03/22/05	CL	Day	B	Win	2	40	-79,300	Flooding	5.00	-0.69	-0.408
95	04/11/05	CL	Day	B	Sp	1	1	46,400	Flooding	3.50	0.41	0.243
96	04/12/05	CL	Day	B	Sp	1	2	362,000	Ebbing	1.30	3.35	1.983
97	04/12/05	CL	Day	B	Sp	1	3	357,000	Ebbing	0.60	3.31	1.960
98	04/12/05	CL	Day	B	Sp	1	4	324,000	Low Slack	-0.03	3.07	1.817
99	04/12/05	CL	Day	B	Sp	1	5	236,000	Flooding	0.50	2.21	1.308
100	04/13/05	BP	Day	B	Sp	1	6	335,000	Ebbing	0.40	3.17	1.877
101	04/13/05	BP	Day	B	Sp	1	7	321,000	Low Slack	0.00	3.04	1.800
102	04/13/05	BP	Day	B	Sp	1	8	191,000	Flooding	0.30	1.76	1.042
103	04/13/05	BP	Day	B	Sp	1	9	116,000	Flooding	0.90	1.05	0.622
104	04/14/05	BP	Day	B	Sp	1	10	258,000	Ebbing	3.30	2.33	1.379
105	04/14/05	BP	Day	B	Sp	1	11	314,000	Ebbing	2.60	2.88	1.705
106	04/14/05	BP	Day	B	Sp	1	12	232,000	Low Slack	0.20	2.2	1.302
107	04/15/05	SI	Day	B	Sp	1	13	330,000	Ebbing	0.90	3.13	1.853
108	04/16/05	SI	Day	B	Sp	1	14	302,000	Ebbing	1.20	2.87	1.699
109	04/16/05	SI	Day	B	Sp	1	15	300,000	Ebbing	0.90	2.83	1.675
110	05/16/05	SI	Day	B	Sp	2	16	374,000	Ebbing	1.40	3.4	2.013
111	05/16/05	SI	Day	B	Sp	2	17	373,000	Ebbing	0.80	3.44	2.036
112	05/16/05	SI	Day	B	Sp	2	18	377,000	Ebbing	0.70	3.49	2.066
113	05/17/05	SI	Day	B	Sp	2	19	359,000	Ebbing	1.00	3.32	1.965
114	05/17/05	SI	Day	B	Sp	2	20	356,000	Ebbing	0.90	3.3	1.954

Basic Identifiers								River Characteristics				
Deep Draft Passage Trial #	Date	Location	Diel Sampling Phase	Phase	Season	Field Trip	Data Collection Trial #	River Flow (Quincy, RM 53.8)	Tidal Stage	Tidal Height, ft.	Current Velocity (Qunicy, OR RM 53.8)	
115	05/18/05	SI	Day	B	Sp	2	21	410,000	Ebbing	1.50	3.64	2.155
116	05/18/05	SI	Day	B	Sp	2	22	414,000	Ebbing	1.40	3.69	2.184
117	05/19/05	SI	Day	B	Sp	2	23	300,000	Flooding	0.60	2.59	1.533
118	05/19/05	SI	Day	B	Sp	2	24	414,000	Ebbing	1.20	3.64	2.155
119	05/20/05	CL	Day	B	Sp	2	25	447,000	Low Slack	0.80	4.01	2.374
120	05/20/05	CL	Day	B	Sp	2	26	358,000	Flooding	2.10	3.17	1.877
121	05/20/05	CL	Day	B	Sp	2	27	427,000	Ebbing	3.00	3.75	2.220
122	05/22/05	BP	Day	B	Sp	2	28	451,000	Low Slack	-0.10	4.08	2.415
123	05/22/05	BP	Day	B	Sp	2	29	229,000	Flooding	2.80	1.93	1.143
124	05/23/05	BP	Day	B	Sp	2	30	450,000	Ebbing	0.90	4.02	2.380
125	05/23/05	BP	Day	B	Sp	2	31	363,000	Low Slack	-0.40	3.26	1.930
126	05/23/05	BP	Day	B	Sp	2	32	345,000	Low Slack	-0.10	3.08	1.823

D-2. Vessel Characteristics

Basic Identifiers			**Vessel Characteristics**											
Deep Draft Passage #	Location	Date	Name	Vessel Type	Vessel Direction	Condition	Distance from Shore	Time (s)	Vessel Speed over Ground		Vessel Draft	Vessel Beam	Vessel Length	Block Coefficient
	County Line= CL Barlow = BP Sauvie = SI		not included in report		U= upriver D=downriver	Unloaded, Partially loaded, Loaded	N=Near M=Middle F=Far		meters/sec	knots	ft	ft	ft	
1	CL	06/29/04		Car Carrier	U	Unloaded	M	16.4	6.10	11.85	28.0	90	568	1431360
2	CL	06/29/04		Bulk Carrier	U	Loaded	M	18.34	5.45	10.60	28.0	90	614	1547280
3	CL	06/29/04		Bulk Carrier	D	Loaded	M	15.57	6.42	12.48	33.2	85	579	1632313.91
4	CL	06/29/04		Car Carrier	D	Unloaded	M	9.8	10.20	19.83	27.0	106	656	1877472
5	BP	06/30/04		Container Ship	D	Partially	F	15.35	6.51	12.66	35.0	122	902	3851540
6	BP	06/30/04		Bulk Carrier	U	Loaded	F	20.53	4.87	9.47				
7	BP	06/30/04		Car Carrier	D	Unloaded	F	12.99	7.70	14.96	27.0	90	568	1380240
8	SI	07/01/04		Car Carrier	D	Unloaded	F	14.35	6.97	13.55				
9	BP	07/19/04		Bulk Carrier	D		F	28.9	6.92	13.45	35.1	100	593	2080244
10	BP	07/19/04		Oil Tanker	U		F	37.63	5.31	10.33	32.3	99	574	1832638.5
11	BP	07/20/04		Bulk Carrier	D		F	26.51	7.54	14.66	30.8	95	609	1783669.65
12	BP	07/20/04		Bulk Carrier	D		M	25.44	7.86	15.28	21.0	95	525	1047375
13	SI	07/20/04		Container Ship	U	Loaded	N	34.12	5.86	11.39	32.0	106	950	3222400
14	CL	07/21/04		Container Ship	D	Unloaded	N	21.38	9.35	18.18	33.4	106	950	3365394
15	CL	07/21/04		Container Ship	U	Partially	M	25.22	7.93	15.41	35.0	122	903	3855810
16	CL	07/22/04		Bulk Carrier	D	Loaded	M	20.17	9.92	19.27				
17	CL	08/09/04		Bulk Carrier	D	Loaded	F	29.57	6.76	13.15	30.0	106	590	1876200
18	CL	08/09/04		Bulk Carrier	D	Unloaded	M-F	31.93	6.26	12.18	33.3	89	558	1651261.5
19	CL	08/10/04		Container Ship	U	Loaded	N	27.97	7.15	13.90	30.3	106	950	3054231
20	CL	08/10/04		Bulk Carrier	U	Unloaded	M	30.45	6.57	12.77	26.1	106	640	1769267.2
21	CL	08/10/04		Container Ship	D	Loaded	M	38.95	5.13	9.98	34.4	106	907	3309207.64
22	CL	08/10/04		Bulk Carrier	U	Unloaded	F	28.81	6.94	13.49	20.5	75	567	871762.5
23	CL	08/11/04		Bulk Carrier	U	Unloaded	F	29.19	6.85	13.32	21.0	85	494	881790
24	CL	08/11/04		Bulk Carrier	U	Partially	M-F	32.33	6.19	12.02	24.3	85	520	1075386
25	CL	08/11/04		Bulk Carrier	D	Loaded	M	31.77	6.30	12.24				
26	CL	08/11/04		Oil Tanker	U	Loaded	M	30.66	6.52	12.68				

Basic Identifiers			Vessel Characteristics											
Deep Draft Passage #	Location	Date	Name	Vessel Type	Vessel Direction	Condition	Distance from Shore	Time (s)	Vessel Speed over Ground		Vessel Draft	Vessel Beam	Vessel Length	Block Coefficient
27	BP	08/11/04		Container Ship	U	Loaded	M	39.19	5.10	9.92	34.8	122	902	3824029
28	BP	08/11/04		Bulk Carrier	U	Partially	N-M	44.72	4.47	8.69	23.1	93	580	1244935
29	BP	08/12/04		Bulk Carrier	U	Unloaded	M	37.8	5.29	10.28				
30	BP	08/12/04		Other	U	Unknown	M	37.34	5.36	10.41				
31	SI	08/13/04		Container Ship	D	Loaded	N				39.0	122	902	4291716
32	SI	08/13/04		Bulk Carrier	D	Loaded	F	38.45	5.20	10.11	37.4	106	640	2538573
33	SI	08/14/04		Bulk Carrier	D	Loaded	F	42.55	4.70	9.14	31.1	85	580	1532244
34	SI	08/14/04		Bulk Carrier	D		M	39.15	5.11	9.93	25.4	85	504	1088993
35	SI	08/15/04		Car Carrier	U	Loaded	N-M	55.13	3.63	7.05	25.1	100	568	1424544
36	SI	08/15/04		Bulk Carrier	U	Loaded	M-F	42.25	4.73	9.20	35.8	89	558	1775417
37	SI	08/15/04		Container Ship	D	Unloaded	N-M	45.47	4.40	8.55	25.3	102	650	1674075
38	SI	08/15/04		Container Ship	U	Loaded	N	45.4	4.41	8.56	33.3	106	907	3196722
39	SI	08/15/04		Bulk Carrier	D	Unloaded	M	35.04	5.71	11.09	??	84	556	
40	SI	08/16/04		Bulk Carrier	U	Unloaded	M	48.69	4.11	7.98	19.5	89	558	968409
41	SI	08/16/04		Bulk Carrier	U	Partially	M	44.22	4.52	8.79		106	738	
42	SI	08/16/04		Tanker	U	Loaded	M	39.67	5.04	9.80	35.2	96	651	2197984
43	BP	08/29/04		Bulk Carrier	U	Unloaded	M	32.75	6.11	11.87	21.2	88	558	1039532
44	BP	08/29/04		Bulk Carrier	U	Unloaded	M	37.69	5.31	10.31	22.3	100	600	1335000
45	BP	08/29/04		Dredge	D	Unloaded	M	26	7.69	14.95				
46	BP	08/29/04		Oil Tanker	D	Loaded	M-F	32.44	6.17	11.98	22.0	82	495	892980
47	BP	08/30/04		Research Ves.	D	Unloaded	M	31.26	6.40	12.44	16.0	51	274	223584
48	BP	08/30/04		Container Ship	U	Loaded	M	30.63	6.53	12.69	34.4	106	907	3309208
49	BP	08/30/04		Bulk Carrier	U	Loaded	F	33.1	6.04	11.75	33.8	96	589	1912884
50	BP	08/30/04		Bulk Carrier	D	Loaded	M	32.36	6.18	12.01	36.8	85	575	1796156
51	BP	08/30/04		Car Carrier	D	Unloaded	M-F	24.09	8.30	16.14	27.0	106	610	1745820
52	BP	08/30/04		Bulk Carrier	D	Loaded	M	26.46	7.56	14.69	27.0	96	650	1684800
53	BP	08/30/04		Oil Tanker	U	Loaded	F	38.9	5.14	9.99	16.2	83	640	858950
54	BP	08/30/04		Bulk Carrier	D	Loaded	N	27.97	7.15	13.90	29.5	106	738	2307726
55	SI	02/08/05		Bulk Carrier	U	Unloaded	M	44.23	4.52	8.79	24.0	85	600	1224000
56	SI	02/08/05		Car Carrier	D	Loaded	M	36.20	5.52	10.74	26.0	106	656	1807936
57	SI	02/08/05		Bulk Carrier	D	Unloaded	F	35.10	5.70	11.08	21.0	106	623	1386798

Basic Identifiers			Vessel Characteristics												
Deep Draft Passage #	Location	Date	Name	Vessel Type	Vessel Direction	Condition	Distance from Shore	Time (s)	Vessel Speed over Ground		Vessel Draft	Vessel Beam	Vessel Length	Block Coefficient
58	SI	02/08/05		Car Carrier	D	Unloaded	F	36.00	5.56	10.80	26.0	106	655	1805180
59	SI	02/08/05		Car Carrier	U	Loaded	N	38.00	5.26	10.23	26.6	106	623	1756611
60	SI	02/09/05		Bulk Carrier	U	Unloaded	M	44.85	4.46	8.67	29.8	102	623	1893671
61	SI	02/09/05		Bulk Carrier	D	Unloaded	M	31.45	6.36	12.36	26.6	102	600	1627920
62	SI	02/09/05		Car Carrier	D	Unloaded	M	39.47	5.07	9.85	25.0	106	623	1650950
63	BP	02/10/05		Bulk Carrier	U	Unloaded	F	39.47	5.07	9.85	21.0	102	623	1334466
64	BP	02/10/05		Bulk Carrier	D	Loaded	F	36.44	5.49	10.67	35.5	75	567	1509638
65	BP	02/10/05		Bulk Carrier	D	Loaded	M	41.73	4.79	9.32		89	558	
66	BP	02/10/05		Bulk Carrier	U	Unloaded	M	35.69	5.60	10.89	21.0	92	588	1136016
67	BP	02/11/05			D						36.0	132	915	4348080
68	BP	02/11/05		Bulk Carrier	U	Unloaded	F	40.94	4.89	9.50	23.5	106	738	1838358
69	BP	02/11/05		Bulk Carrier	U	Unloaded	F	35.72	5.60	10.88	20.7	85	494	869193
70	BP	02/11/05		Bulk Carrier	D	Loaded	M	36.96	5.41	10.52	39.0	106	623	2575482
71	BP	02/11/05		Bulk Carrier	U	Unloaded	F	40.46	4.94	9.61	20.0	76	617	937840
72	BP	02/11/05		Bulk Carrier	U	Loaded	M	32.27	6.20	12.05	25.0	102	650	1657500
73	CL	02/12/05		Bulk Carrier	U	Unloaded	M	39.81	5.02	9.77	25.0	90	574	1291500
74	CL	02/12/05		Bulk Carrier	U	Unloaded	M	37.49	5.33	10.37	23.0	102	600	1407600
75	CL	02/12/05		Car Carrier	D	Unloaded	N	42.30	4.73	9.19	27.0	106	625	1788750
76	CL	02/13/05		Bulk Carrier	U	Unloaded	M	41.80	4.78	9.30		89	554	
77	CL	02/13/05		Bulk Carrier	U	Unloaded	F	40.66	4.92	9.56		93	581	
78	CL	02/13/05		Bulk Carrier	D	Loaded	M	40.45	4.94	9.61	32.8	26	504	429811
79	BP	03/16/05		Bulk Carrier	U	Unloaded	F	35.98	5.56	10.80	20.6	89	564	1034038
80	BP	03/17/05		Bulk Carrier	D	Loaded	M	30.53	6.55	12.73	30.0	90	573	1547100
81	BP	03/17/05		Bulk Carrier	U	Unloaded	F	38.48	5.20	10.10	19.0	85	494	797810
82	BP	03/17/05		Car Carrier	D		M				23.0	90	541	1119870
83	SI	03/18/05		Bulk Carrier	U	Unloaded	F	39.89	5.01	9.75	22.0	106	623	1452836
84	SI	03/18/05		Bulk Carrier	D	Loaded	F	31.30	6.39	12.42	39.2	106	653	2713346
85	SI	03/19/05		Bulk Carrier	D	Unloaded	M	27.33	7.32	14.22	24.7	94	615	1427907
86	SI	03/20/05		Car Carrier	D	Unloaded	M				26.0	106	653	1799668
87	CL	03/21/05		Bulk Carrier	U	Unloaded	M	29.65	6.75	13.11	23.0	89	555	1136085

Basic Identifiers			Vessel Characteristics											
Deep Draft Passage #	Location	Date	Name	Vessel Type	Vessel Direction	Condition	Distance from Shore	Time (s)	Vessel Speed over Ground		Vessel Draft	Vessel Beam	Vessel Length	Block Coefficient
88	CL	03/21/05		Bulk Carrier	U	Unloaded	M	26.81	7.46	14.50	21.3	106	731	1650452
89	CL	03/21/05		Bulk Carrier	D	Unloaded	N	27.33	7.32	14.22	31.9	85	506	1372019
90	CL	03/21/05		Car Carrier	U	Partially	M	29.70	6.73	13.09	25.0	106	599	1587350
91	CL	03/21/05		Bulk Carrier	D	Unloaded	F	21.74	9.20	17.88	18.4	85	525	821100
92	CL	03/21/05		Container Ship	D	Loaded	M	32.91	6.08	11.81	37.4	98	663	2430028
93	CL	03/22/05		Oil Tanker	U	Loaded	M				26.0	96	651	1624896
94	CL	03/22/05		Oil Tanker	U	Loaded	F	34.23	5.84	11.36	37.0	106	600	2353200
95	CL	04/11/05		Bulk Carrier	U	Partially	M	29.69	6.74	13.09	25.9	106	656	1800982
96	CL	04/12/05		Bulk Carrier	D	Loaded	M	30.26	6.61	12.85	37.8	100	609	2302020
97	CL	04/12/05		Bulk Carrier	D	Loaded	M	26.56	7.53	14.64	33.9	93	580	1828566
98	CL	04/12/05		Bulk Carrier	U	Unloaded	M	35.83	5.58	10.85	19.2	89	555	948384
99	CL	04/12/05		Bulk Carrier	U	Loaded	M	32.88	6.08	11.82	28.5	91	554	1436799
100	BP	04/13/05		Bulk Carrier	D	Partially	M	29.17	6.86	13.33	25.8	106	656	1794029
101	BP	04/13/05		Oil Tanker	U	Loaded	F	36.48	5.48	10.66	33.5	79	485	1283553
102	BP	04/13/05		Bulk Carrier	D	Loaded	M	32.5	6.15	11.96	39.9	102	623	2535485
103	BP	04/13/05		Bulk Carrier	U	Unloaded	F	29.95	6.68	12.98	21.0	106	623	1386798
104	BP	04/14/05		Bulk Carrier	D	Loaded	M	28.74	6.96	13.53		93	581	
105	BP	04/14/05		Bulk Carrier	D	Loaded	M	30.94	6.46	12.56	37.8	100	607	2294460
106	BP	04/14/05		Oil Tanker	D	Partially	M	27.05	7.39	14.37		79	485	
107	SI	04/15/05		Car Carrier	D	Partially	M	24.05	8.32	16.16	25.0	105	586	1538250
108	SI	04/16/05		Car Carrier	U	Loaded	N	29.38	6.70	13.03	27.5	106	621	1810215
109	SI	04/16/05		Bulk Carrier	D	Loaded	M	27.92	7.16	13.92	38.5	103	623	2470507
110	SI	05/16/05		Oil Tanker	D	Loaded	M	27.02	7.40	14.39	27	96	650	1684800
111	SI	05/16/05		Container Ship	D	Loaded	M	27.78	7.20	13.99	33.9	98	680	2259096
112	SI	05/16/05		Bulk Carrier	U	Unloaded	N	42.43	4.71	9.16	25	92	617	1419100
113	SI	05/17/05		Car Carrier	U	Unloaded	M	38.09	5.25	10.21	25.3	106	599	1606398
114	SI	05/17/05		Car Carrier	D	Partially	M	44.48	4.50	8.74	26	98	573	1460004
115	SI	05/18/05		Bulk Carrier	U	Unloaded	M	35.75	5.59	10.87	19	89	558	943578
116	SI	05/18/05		Car Carrier	D	Partially	M	27.05	7.39	14.37	24	106	599	1523856
117	SI	05/19/05		Bulk Carrier	D	Loaded	M	31.65	6.32	12.28	36.7	92	617	2083239

Basic Identifiers			Vessel Characteristics											
Deep Draft Passage Trial #	Location	Date	Name	Vessel Type	Vessel Direction	Condition	Distance from Shore	Time (s)	Vessel Speed over Ground		Vessel Draft	Vessel Beam	Vessel Length	Block Coefficient
118	SI	05/19/05		Car Carrier	U	Loaded	M	33.25	6.02	11.69	27	106	625	1788750
119	CL	05/20/05		Bulk Carrier	D	Loaded	M	29.4	6.80	13.22	33.7	89	555	1664612
120	CL	05/20/05		Car Carrier	U	Loaded	M	28.18	7.10	13.80	28	106	590	1751120
121	CL	05/20/05		Car Carrier	D	Partially	M	22.66	8.83	17.16	25	106	625	1656250
122	BP	05/22/05		Car Carrier	U	Partially	F	27.5	7.27	14.14	26.7	98	590	1543794
123	BP	05/22/05		Bulk Carrier	U	Loaded	F	33.98	5.89	11.44				0
124	BP	05/23/05		Container Ship	D	Partially	M	25.56	7.82	15.21	31.5	132	915	3804570
125	BP	05/23/05		Car Carrier	U	Loaded	F	30.99	6.45	12.54	27.5	84	555	1282050
126	BP	05/23/05		Car Carrier	U	Loaded	M	28.8	6.94	13.50	29	106	588	1807512

D-3 Wave Characteristics

Basic Identifiers			Wave Characteristics								
Deep Draft Passage #	Location	Date	Run-up distance	Draw-down distance	Total Dist – Run-up to Draw-down	Run-up Velocity	Run-up Velocity	Wash-back Velocity	Maximum draw-down height	Maximum run-up height	Maximum Water Level
	County Line= CL Barlow = BP Sauvie = SI		m	m	m	camera m/s	run-up gage, m/s	run-up gage m/s	staff gage m	staff gage m	staff gage m
1	CL	06/29/04			15.1				-0.18	0.11	0.19
2	CL	06/29/04			20.55		0.064	0.101	-0.20	0.12	0.22
3	CL	06/29/04			9.5				-0.11	0.05	0.13
4	CL	06/29/04			34.5		0.357	0.274	-0.25	0.21	0.27
5	BP	06/30/04			27				n/a	n/a	n/a
6	BP	06/30/04			23				-0.10	n/a	0.12
7	BP	06/30/04			20.6				-0.07	0.05	0.13
8	SI	07/01/04	6.2	6.8	13			0.314	n/a	n/a	0.76
9	BP	07/19/04	5.1	4.3	9.4				-0.15*	0.05	0.15
10	BP	07/19/04	6.65	6.2	12.85				-0.15*	0.07	0.23
11	BP	07/20/04	17.9	18	35.9				n/a	n/a	n/a
12	BP	07/20/04	8.8	12.3	21.1			0.500	-0.13	0.06	0.23
13	SI	07/20/04	22	28.9	50.9		0.360	0.960	-0.36	0.10	0.49
14	CL	07/21/04	10.3	14.9	25.2				-0.33	0.17	0.35
15	CL	07/21/04	24.6	23	47.6		0.107	0.799	-0.43*	0.22	0.46
16	CL	07/22/04	9.3	11.8	21.1		0.320	0.774	-0.21	0.09	0.19
17	CL	08/09/04	13.3	15.4	28.7		0.509	0.445	-0.27*	0.11	0.17
18	CL	08/09/04	7.8	8.7	16.5				-0.18	0.08	0.34
19	CL	08/10/04	14.6	18.9	33.5				-0.40*	0.14	0.28
20	CL	08/10/04	8	19.8	27.8		0.616	0.475	-0.44	0.13	0.27
21	CL	08/10/04	6.1	6.6	12.7		0.305	0.393	n/a	n/a	0.25
22	CL	08/10/04	5.4	2.9	8.3		0.018	0.030	-0.08	0.03	0.20
23	CL	08/11/04	5.4	3.8	9.2				-0.07	0.06	0.15
24	CL	08/11/04	6	6.8	12.8				-0.08	0.07	0.20
25	CL	08/11/04	9.5	14	23.5				-0.25	0.15	0.17
26	CL	08/11/04	8.3	29.1	37.4		0.796	0.814	-0.40	0.16	0.53
27	BP	08/11/04	5.6	24.9	30.5				-0.35	0.15	0.34

Basic Identifiers			**Wave Characteristics**								
Deep Draft Passage #	Location	Date	Run-up distance	Draw-down distance	Total Dist – Run-up to Draw-down	Run-up Velocity	Run-up Velocity	Wash-back Velocity	Maximum draw-down height	Maximum run-up height	Maximum Water Level
28	BP	08/11/04	3.6	5.9	9.5				-0.11	0.05	0.25
29	BP	08/12/04	8.1	12.6	20.7				n/a	n/a	n/a
30	BP	08/12/04	5.9	6.4	12.3			0.701	n/a	n/a	0.46
31	SI	08/13/04	27	30.7	57.7				-0.40*	0.16	0.28
32	SI	08/13/04	13	28.5	41.5				-0.25*	0.20	0.30
33	SI	08/14/04	7.7	7	14.7			0.396	-0.11	0.08	0.30
34	SI	08/14/04	6.1	13.4	19.5				n/a	n/a	n/a
35	SI	08/15/04	7.8	15.2	23		0.482	0.485	-0.12	0.01	0.12
36	SI	08/15/04	17	17.3	34.3		0.969	0.335	-0.27	0.06	0.38
37	SI	08/15/04	8.9	17.4	26.3				-0.18	0.10	n/a
38	SI	08/15/04	21.8	27.1	48.9			0.604	-0.38*	0.23	0.39
39	SI	08/15/04	4.8	8.8	13.6				-0.13	0.10	0.27
40	SI	08/16/04	7.7	10.9	18.6				-0.11	0.07	0.24
41	SI	08/16/04	6.3	5.7	12				-0.07	0.04	0.07
42	SI	08/16/04	25.9	29.3	55.2				-0.30	0.07	0.34
43	BP	08/29/04	3.5	6.7	10.2				n/a	n/a	n/a
44	BP	08/29/04	3.2	6.8	10				-0.08	0.03	0.15
45	BP	08/29/04	6.8	11.3	18.1				-0.07	0.07	0.27
46	BP	08/29/04	11.2	7.9	19.1				n/a	n/a	n/a
47	BP	08/30/04	1.8	1.8	3.6				n/a	n/a	0.13
48	BP	08/30/04	10	13.4	23.4		0.143	0.482	-0.12	0.07	0.57
49	BP	08/30/04	11.4	16.2	27.6		0.140	0.384	-0.06	0.06	0.24
50	BP	08/30/04	10.7	19.1	29.8			0.408	-0.14	0.04	0.11
51	BP	08/30/04	11.9	23.2	35.1				-0.20	0.15	0.20
52	BP	08/30/04	11	20.5	31.5				-0.15	0.13	0.22
53	BP	08/30/04	13.4	19	32.4				-0.19*	0.19	0.28
54	BP	08/30/04	13.4	19	32.4				n/a	n/a	n/a
55	SI	2/8/2005	10.7	8.5	19.2				-0.17	0.08	0.14
56	SI	2/8/2005	8.5	14.5	23	0.561	1.060	1.720	-0.18	0.08	0.12
57	SI	2/8/2005	15.1	8.2	23.3	0.576			-0.10	0.07	0.25

Basic Identifiers			Wave Characteristics								
Deep Draft Passage #	Location	Date	Run-up distance	Draw-down distance	Total Dist – Run-up to Draw-down	Run-up Velocity	Run-up Velocity	Wash-back Velocity	Maximum draw-down height	Maximum run-up height	Maximum Water Level
58	SI	2/8/2005	29	49	78	2.251					
59	SI	2/8/2005							-0.12	0.03	0.28
60	SI	2/9/2005	17.7	21.3	39	0.516	1.100	3.290			
61	SI	2/9/2005	19.1	18.1	37.2		1.190	1.070			
62	SI	2/9/2005	8.3	7.5	15.8	0.616	0.950	0.330			
63	BP	2/10/2005	3.8	5.5	9.3						
64	BP	2/10/2005	11.3	15.8	27.1	0.755					
65	BP	2/10/2005	10.1	9.4	19.5				-0.15	0.06	0.07
66	BP	2/10/2005	4.2	3.8	8				n/a	n/a	0.12
67	BP	2/11/2005	10.8	19.4	30.2	0.646					
68	BP	2/11/2005	4.1	9.4	13.5		0.530	0.269	-0.12	0.06	0.17
69	BP	2/11/2005	3.4	7.5	10.9	0.681			-0.07	0.05	0.30
70	BP	2/11/2005	5.4	6.2	11.6				-0.17*	0.05	0.23
71	BP	2/11/2005	6.2	7.9	14.1	0.556					
72	BP	2/11/2005	14.7	19.8	34.5	1.885	0.515	2.200	-0.47	0.04	0.43
73	CL	2/12/2005	5.3	5.9	11.2		0.297	0.833			
74	CL	2/12/2005	2.3	4.2	6.5				-0.12	0.08	0.27
75	CL	2/12/2005	2.1	2.3	4.4				0.12	0.06	0.20
76	CL	2/13/2005	-4	12	8				0.18	0.08	0.28
77	CL	2/13/2005	4.7	4	8.7						
78	CL	2/13/2005	4.1	4.7	8.8						
79	BP	3/16/2005	4.2	8.3	12.5						
80	BP	3/17/2005	6.5	10.5	17	0.795			-0.08	0.08	0.15
81	BP	3/17/2005	2.2	4.8	7						
82	BP	3/17/2005	10	15	25						
83	SI	3/18/2005	9.4	14	23.4	1.107			-0.17	0.08	0.24
84	SI	3/18/2005	15.9	15.8	31.7	0.987					
85	SI	3/19/2005	10.7	18.2	28.9	1.349	0.707	0.769	-0.17	0.08	0.28
86	SI	3/20/2005	13.5	10.5	23.5						

Basic Identifiers			Wave Characteristics								
Deep Draft Passage #	Location	Date	Run-up distance	Draw-down distance	Total Dist – Run-up to Draw-down	Run-up Velocity	Run-up Velocity	Wash-back Velocity	Maximum draw-down height	Maximum run-up height	Maximum Water Level
87	CL	3/21/2005	8.6	4.5	13.1	3.299			-0.13	0.05	0.10
88	CL	3/21/2005	1.7	4.1	5.8				-0.06	0.06	0.10
89	CL	3/21/2005	7	19	26	1.180			-0.36	0.20	0.27
90	CL	3/21/2005	7.5	12	19.5	1.374			-0.19	0.18	0.30
91	CL	3/21/2005	9.6	8.8	18.4	0.607			-0.17	0.20	0.50
92	CL	3/21/2005	2.5	5	7.5	0.832			-0.15	0.08	0.16
93	CL	3/22/2005	4.6	9	13.6	1.222			-0.18	0.13	0.26
94	CL	3/22/2005	2.1	2.6	4.7	0.836			-0.13	0.07	0.12
95	CL	4/11/2005	7.1	5.5	12.6	0.980					
96	CL	4/12/2005	8.5	7.1	15.6	0.934	0.804	7.619	-0.24*	0.23	0.28
97	CL	4/12/2005	18.7	17.9	36.6	1.458	1.264	3.333			
98	CL	4/12/2005	2.3	3.9	6.2	0.999					
99	CL	4/12/2005	6.7	11.3	18	1.688					
100	BP	4/13/2005	10.8	6.1	16.9						
101	BP	4/13/2005	6.5	16.7	23.2	0.910					
102	BP	4/13/2005	13	14.6	27.6	0.786					
103	BP	4/13/2005	6.4	7.4	13.8	0.872			-0.12	0.03	0.21
104	BP	4/14/2005	9.5	11.4	20.9	0.796	0.612	1.750	-0.15	0.12	0.14
105	BP	4/14/2005	9.3	10	19.3				-0.12	0.10	0.11
106	BP	4/14/2005	5.5	10.4	15.9	0.430					
107	SI	4/15/2005	8.2	11.4	19.6	1.298	1.306	1.468			
108	SI	4/16/2005	11.1	10	21.1	0.662					
109	SI	4/16/2005	24.4	22	46.4	2.080					
110	SI	5/16/2005	9.4	13.6	23	1.182	0.287	0.370	-0.20	0.12	0.30
111	SI	5/16/2005	12.9	17.5	30.4	1.709			-0.27	0.23	0.30
112	SI	5/16/2005	5.8	11.1	16.9	1.253					
113	SI	5/17/2005	9.2	15	24.2						
114	SI	5/17/2005	10.4	11	21.4	1.557	0.316	0.513	-0.15	0.12	0.30
115	SI	5/18/2005	4.9	4.4	9.3	1.102					
116	SI	5/18/2005	7.5	8.1	15.6	1.749			-0.16	0.11	0.28
117	SI	5/19/2005	6.1	3.9	10	1.696					

Basic Identifiers			Wave Characteristics								
Deep Draft Passage #	Location	Date	Run-up distance	Draw-down distance	Total Dist – Run-up to Draw-down	Run-up Velocity	Run-up Velocity	Wash-back Velocity	Maximum draw-down height	Maximum run-up height	Maximum Water Level
118	SI	5/19/2005	8.2	14.7	22.9						
119	CL	5/20/2005	3.2	7.9	11.1	0.775					
120	CL	5/20/2005	10.3	17.1	27.4		0.748	1.355	-0.47	0.24	0.43
121	CL	5/20/2005	4.2	6.4	10.6						
122	BP	5/22/2005	9.3	21.4	30.7	1.415			-0.25	0.13	0.30
123	BP	5/22/2005	3.5	7.2	10.7				-0.10	0.07	0.12
124	BP	5/23/2005	30.9	27.6	58.5	1.413	2.486	4.182			
125	BP	5/23/2005	13.4	11.8	25.2	1.000					
126	BP	5/23/2005	13.4	18.6	32	1.303					

D-4 Stranding Estimates By Species

	Stranding Estimates by Species														
Deep Draft Passage #	Chinook 0+	Coho 0+	Chum	Three-spine Stickleback	Peamouth Chub	Banded Killifish	Bass Fry	American Shad	Yellow Perch	Mountain Whitefish	Starry Flounder	Crappie	Sunfish / Bluegill	UID	Total
1															0
2															0
3															0
4															0
5															0
6															0
7															0
8															0
9															0
10	5			1						1					7
11	8				1	1									10
12	2			1											3
13															0
14	15														15
15															0
16															0
17															0
18															0
19	1						2								3
20															0
21															0
22															0
23															0
24															0
25															0
26	1					4									5
27															0
28															0
29															0
30															0

	Stranding Estimates by Species														
Deep Draft Passage	Chinook 0+	Coho 0+	Chum	Three-spine Stickleback	Peamouth Chub	Banded Killifish	Bass Fry	American Shad	Yellow Perch	Mountain Whitefish	Starry Flounder	Crappie	Sunfish / Bluegill	UID	Total
31				11				1	1		1				14
32				13	1		1		1			1			17
33															0
34															0
35															0
36															0
37															0
38							1								1
39															0
40															0
41															0
42				8											8
43															0
44															0
45															0
46							1	1							2
47															0
48															0
49															0
50															0
51				2				1					1		4
52	2			2	6			1							11
53															0
54				1											1
55															0
56															0
57															0
58	3														3
59															0
60															0

	Stranding Estimates by Species														
Deep Draft Passage #	Chinook 0+	Coho 0+	Chum	Three-spine Stickleback	Peamouth Chub	Banded Killifish	Bass Fry	American Shad	Yellow Perch	Mountain Whitefish	Starry Flounder	Crappie	Sunfish / Bluegill	UID	Total
61															0
62	1														1
63	1														1
64	3														3
65															0
66															0
67	44					1									45
68	2					1									3
69															0
70	4														4
71															0
72	19														19
73															0
74															0
75															0
76															0
77															0
78															0
79															0
80	14														14
81	10														10
82	122														122
83															0
84	3														3
85	1														1
86			1												1
87															0
88															0
89															0
90	4	4	3												11

	Stranding Estimates by Species														
Deep Draft Passage #	Chinook 0+	Coho 0+	Chum	Three-spine Stickleback	Peamouth Chub	Banded Killifish	Bass Fry	American Shad	Yellow Perch	Mountain Whitefish	Starry Flounder	Crappie	Sunfish / Bluegill	UID	Total
91															0
92															0
93															0
94															0
95	3														3
96															0
97	6		1												7
98															0
99															0
100	16		1												17
101	16	1													17
102	16														16
103	5	1													6
104	39	1													40
105	5														5
106	12													1	13
107															0
108	2														2
109															0
110	1														1
111	25		2	1											28
112															0
113															0
114															0
115															0
116	5														5
117															0
118	4														4
119															0
120															0

	Stranding Estimates by Species														
Deep Draft Passage #	Chinook 0+	Coho 0+	Chum	Three-spine Stickleback	Peamouth Chub	Banded Killifish	Bass Fry	American Shad	Yellow Perch	Mountain Whitefish	Starry Flounder	Crappie	Sunfish / Bluegill	UID	Total
121															0
122	5														5
123															0
124	1				1					6					8
125															0
126										1					1

D-5 Seine Data (Density estimates are fish per 100 m^2)

Date	Location	Sampling Period	ID	Area	0+ Chinook	1+ Chinook	Chum	Coho	Cutthroat	Steelhead	Trout	UID Salmonid	Mountain whitefish	Threespine Stickleback	American Shad	Banded Killifish
		summer=su winter=win spring=sp	Location at each site	Area swept	2											
06/29/04	CL	su	Ref 1	600	23							1		599		2
06/29/04	CL	su	Ref 2	518	8											22
06/29/04	CL	su	Ref 3	600	3									2		22
06/29/04	CL	su	Hotspot 1	600	25									1		1
06/29/04	CL	su	Hotspot 2	600	14									10		1
06/30/04	BP	su	Ref 1	660	89									431		7
06/30/04	BP	su	Ref 2	743	38							1		36		18
06/30/04	BP	su	Ref 3	645	5									3		2
06/30/04	BP	su	Hotspot 1	788	12									2		6
06/30/04	BP	su	Hotspot 2	788	17									1		2
07/01/04	SI	su	Ref 1	743	31											
07/01/04	SI	su	Ref 2	788	39								1	2		
07/01/04	SI	su	Ref 3	788	14									1		1
07/01/04	SI	su	Hotspot 1	900	5											
07/01/04	SI	su	Hotspot 2	870	10											
07/19/04	BP	su	Ref 1	823	12											1
07/20/04	BP	su	Ref 2	705	17									2	56	
07/20/04	BP	su	Ref 3	788	14									2	11	
07/20/04	BP	su	Hotspot 1	675	25									2	17	
07/20/04	BP	su	Hotspot 2	675	30									11	9	
07/20/04	SI	su	Ref 1	350	16									2		
07/21/04	SI	su	Ref 2	500	7										43	
07/21/04	SI	su	Ref 3	563	9									36	17	
07/21/04	SI	su	Hotspot 1	563	6									20	11	
07/21/04	SI	su	Hotspot 2	450	0									34	3	
07/21/04	CL	su	Ref 1	150	2									43		
07/22/04	CL	su	Ref 2	146	10									1		6
07/22/04	CL	su	Ref 3	200	2									3		1
07/22/04	CL	su	Hotspot 1	300	21									6		6

Date	Location	Sampling Period	ID	Blue gill/sunfish/pumpkinseed	Crappie	All Peamouth Chub	Large Scale Sucker	Northern Pike Minnow	Sculpin (Prickly)	Starry Flounder	Other UID
06/29/04	CL	su	Ref 1			11					
06/29/04	CL	su	Ref 2			3					
06/29/04	CL	su	Ref 3			0					
06/29/04	CL	su	Hotspot 1			0					
06/29/04	CL	su	Hotspot 2			0					
06/30/04	BP	su	Ref 1			5				6	
06/30/04	BP	su	Ref 2			13				5	
06/30/04	BP	su	Ref 3			13	1				
06/30/04	BP	su	Hotspot 1			6					
06/30/04	BP	su	Hotspot 2			9					
07/01/04	SI	su	Ref 1			17					
07/01/04	SI	su	Ref 2			13	1	1			
07/01/04	SI	su	Ref 3	1		18					
07/01/04	SI	su	Hotspot 1			77		2			
07/01/04	SI	su	Hotspot 2			10				1	
07/19/04	BP	su	Ref 1			20				2	
07/20/04	BP	su	Ref 2			26			4	10	
07/20/04	BP	su	Ref 3			43					
07/20/04	BP	su	Hotspot 1			41					
07/20/04	BP	su	Hotspot 2			47					
07/20/04	SI	su	Ref 1			1233					
07/21/04	SI	su	Ref 2			26				1	
07/21/04	SI	su	Ref 3		1	47			1		
07/21/04	SI	su	Hotspot 1			34					
07/21/04	SI	su	Hotspot 2			24	1				
07/21/04	CL	su	Ref 1			2					
07/22/04	CL	su	Ref 2			0			7		
07/22/04	CL	su	Ref 3			18		1			
07/22/04	CL	su	Hotspot 1			46					

Date	Location	Sampling Period	ID	Area	0+ Chinook	1+ Chinook	Chum	Coho	Cutthroat	Steelhead	Trout	UID Salmonid	Mountain whitefish	Threespine Stickleback	American Shad	Banded Killifish
07/22/04	CL	su	Hotspot 2	300	4									31		
08/09/04	CL	su	Ref 1	350	2											2
08/09/04	CL	su	Ref 2	400	3											
08/10/04	CL	su	Ref 3	200	6									2		28
08/10/04	CL	su	Hotspot 1	200	5									3		4
08/10/04	CL	su	Hotspot 2	338	41								1	3		10
08/10/04	CL	su	Ref 1	400	5											
08/10/04	CL	su	Ref 2	300	2											
08/11/04	CL	su	Ref 3	200	7									2		16
08/11/04	CL	su	Hotspot 1	450	3											6
08/11/04	CL	su	Hotspot 2	470	26								1	4		19
08/11/04	BP	su	Ref 1	563	3										80	1
08/12/04	BP	su	Ref 2	563	9									1		
08/12/04	BP	su	Ref 3	563	7									13	45	
08/12/04	BP	su	Hotspot 1	450	8									9	14	
08/12/04	BP	su	Hotspot 2	563	9									9	10	
08/12/04	BP	su	Ref 1	563	7									3	20	1
08/13/04	BP	su	Ref 2	675	7										39	
08/13/04	BP	su	Ref 3	563	16									14	79	1
08/13/14	BP	su	Hotspot 1	675	19									79	29	1
08/13/04	BP	su	Hotspot 2	563	5									28	26	
08/13/04	SI	su	Ref 1	300	5									3	1	1
08/14/04	SI	su	Ref 2	563	0									49	1	
08/14/04	SI	su	Ref 3	563	2									22	7	
08/14/04	SI	su	Hotspot 1	675	1									6	1	
08/14/04	SI	su	Hotspot 2	338	0									8		
08/14/04	SI	su	Ref 1	450	0									1	6	
08/15/04	SI	su	Ref 2	338	1									58	4	
08/15/04	SI	su	Ref 3	394	2									1037		
08/15/04	SI	su	Hotspot 1	563	1									25	1	
08/15/04	SI	su	Hotspot 2	450	0									9		
08/15/04	SI	su	Ref 1	450	1									3	2	

Date	Location	Sampling Period	ID	Blue gill/sunfish/pumpkinseed	Crappie	All Peamouth Chub	Large Scale Sucker	Northern Pike Minnow	Sculpin (Prickly)	Starry Flounder	Other UID
07/22/04	CL	su	Hotspot 2			93					
08/09/04	CL	su	Ref 1			7					
08/09/04	CL	su	Ref 2			6					
08/10/04	CL	su	Ref 3			4			11	3	1
08/10/04	CL	su	Hotspot 1			1			6	1	3
08/10/04	CL	su	Hotspot 2			27			2	2	
08/10/04	CL	su	Ref 1			0		1			
08/10/04	CL	su	Ref 2			3			1	1	
08/11/04	CL	su	Ref 3			3			11		
08/11/04	CL	su	Hotspot 1			5					
08/11/04	CL	su	Hotspot 2			26			3	3	
08/11/04	BP	su	Ref 1			15					
08/12/04	BP	su	Ref 2			9				1	
08/12/04	BP	su	Ref 3			5				4	
08/12/04	BP	su	Hotspot 1		1	18				4	
08/12/04	BP	su	Hotspot 2			6				3	
08/12/04	BP	su	Ref 1			113				1	
08/13/04	BP	su	Ref 2			13	1			1	
08/13/04	BP	su	Ref 3			13				1	
08/13/14	BP	su	Hotspot 1			44					
08/13/04	BP	su	Hotspot 2			36	1				
08/13/04	SI	su	Ref 1			67					
08/14/04	SI	su	Ref 2		1	40	1	1	1		
08/14/04	SI	su	Ref 3			1		2			
08/14/04	SI	su	Hotspot 1			4		1			
08/14/04	SI	su	Hotspot 2		1	9					
08/14/04	SI	su	Ref 1			19		1			
08/15/04	SI	su	Ref 2			10		2	1		
08/15/04	SI	su	Ref 3			0					
08/15/04	SI	su	Hotspot 1			7		1			
08/15/04	SI	su	Hotspot 2			12		1		1	
08/15/04	SI	su	Ref 1			9					

Date	Location	Sampling Period	ID	Area	0+ Chinook	1+ Chinook	Chum	Coho	Cutthroat	Steelhead	Trout	UID Salmonid	Mountain whitefish	Threespine Stickleback	American Shad	Banded Killifish
08/16/04	SI	su	Ref 2	360	0									211	6	1
08/16/04	SI	su	Ref 3	450	0									141		1
08/16/04	SI	su	Hotspot 1	450	0									83	5	1
08/16/04	SI	su	Hotspot 2	450	0									20	18	
08/29/04	BP	su	Ref 1	600	5									11	97	
08/29/04	BP	su	Ref 2	563	1									17	30	
08/30/04	BP	su	Ref 3	400	6									20	12	
08/30/04	BP	su	Hotspot 1	400	2									16	7	
08/30/04	BP	su	Hotspot 2	500	0									2	3	
08/30/04	BP	su	Ref 1	675	7									68	155	
08/31/04	BP	su	Ref 2	600	2									5	49	
02/09/05	SI	win	Ref 1	675	25											1
02/09/05	SI	win	Ref 2	675	1											1
02/09/05	SI	win	Ref 3	675	5											
02/09/05	SI	win	Hotspot 1	675	4											3
02/09/05	SI	win	Hotspot 2	675	5									27		
02/08/05	SI	win	Ref 1	675	4											
02/08/05	SI	win	Ref 2	675												1
02/08/05	SI	win	Ref 3	675	11											
02/08/05	SI	win	Hotspot 1	675	12											1
02/08/05	SI	win	Hotspot 2	675	1	4										
02/10/05	BP	win	Ref 1	675	20											
02/10/05	BP	win	Ref 2	788	12											1
02/10/05	BP	win	Ref 3	500	21									1		
02/10/05	BP	win	Hotspot 1	500	25											
02/10/05	BP	win	Hotspot 2	675	15	1										
02/11/05	BP	win	Ref 1	675	14											
02/11/05	BP	win	Ref 2	823	58									1		
02/11/05	BP	win	Ref 3	675	29											1
02/11/05	BP	win	Hotspot 1	675	57											
02/11/05	BP	win	Hotspot 2	675	16											
02/12/05	CL	win	Rer 1	200	1									1		

Date	Location	Sampling Period	ID	Blue gill/sunfish/pumpkinseed	Crappie	All Peamouth Chub	Large Scale Sucker	Northern Pike Minnow	Sculpin (Prickly)	Starry Flounder	Other UID
08/16/04	SI	su	Ref 2			0		1		1	
08/16/04	SI	su	Ref 3		1	1					
08/16/04	SI	su	Hotspot 1			6					
08/16/04	SI	su	Hotspot 2			12					
08/29/04	BP	su	Ref 1	1		14				2	
08/29/04	BP	su	Ref 2			17				2	
08/30/04	BP	su	Ref 3			15					
08/30/04	BP	su	Hotspot 1			10				2	
08/30/04	BP	su	Hotspot 2	1		23					
08/30/04	BP	su	Ref 1			0					
08/31/04	BP	su	Ref 2			7		1		5	
02/09/05	SI	win	Ref 1								
02/09/05	SI	win	Ref 2								
02/09/05	SI	win	Ref 3								
02/09/05	SI	win	Hotspot 1								
02/09/05	SI	win	Hotspot 2								
02/08/05	SI	win	Ref 1				1				
02/08/05	SI	win	Ref 2						1		
02/08/05	SI	win	Ref 3								
02/08/05	SI	win	Hotspot 1								
02/08/05	SI	win	Hotspot 2								
02/10/05	BP	win	Ref 1								
02/10/05	BP	win	Ref 2								
02/10/05	BP	win	Ref 3								
02/10/05	BP	win	Hotspot 1								
02/10/05	BP	win	Hotspot 2								
02/11/05	BP	win	Ref 1								
02/11/05	BP	win	Ref 2								
02/11/05	BP	win	Ref 3								
02/11/05	BP	win	Hotspot 1								
02/11/05	BP	win	Hotspot 2	1							
02/12/05	CL	win	Ref 1								

Date	Location	Sampling Period	ID	Area	0+ Chinook	1+ Chinook	Chum	Coho	Cutthroat	Steelhead	Trout	UID Salmonid	Mountain whitefish	Threespine Stickleback	American Shad	Banded Killifish
02/12/05	CL	win	Ref 2	450	65									48		
02/12/05	CL	win	Ref 3	375	27									1		
02/12/05	CL	win	Hotspot 1													
02/12/05	CL	win	Hotspot 2													
02/13/05	CL	win	Ref 1	270												
02/13/05	CL	win	Ref 2	563	6									1		
02/13/05	CL	win	Ref 3	300	3											
02/13/05	CL	win	Hotspot 1	400	8									1		1
02/13/05	CL	win	Hotspot 2	400	35											1
03/16/05	BP	win	Ref 1	788	131									2		
03/16/05	BP	win	Ref 2	675	199									1		
03/16/05	BP	win	Ref 3	450	73		2							2		
03/16/05	BP	win	Hotspot 1													
03/16/05	BP	win	Hotspot 2													
03/17/05	BP	win	Ref 1	675	81											
03/17/05	BP	win	Ref 2	675	249		4									
03/17/05	BP	win	Ref 3	338	88									5		
03/17/05	BP	win	Hotspot 1	338	418		3							1		1
03/17/05	BP	win	Hotspot 2	338	59									1		
03/18/05	SI	win	Ref 1	788	57											
03/18/05	SI	win	Ref 2	675	26		4									
03/18/05	SI	win	Ref 3	563	45		8							1		1
03/18/05	SI	win	Hotspot 1	563	26		2							1		
03/18/05	SI	win	Hotspot 2	675	9		1							11		
03/19/05	SI	win	Ref 1	675	8											
03/19/05	SI	win	Ref 2	675	6		1									
03/19/05	SI	win	Ref 3	675	27		1									
03/19/05	SI	win	Hotspot 1	563	27									10		
03/19/05	SI	win	Hotspot 2	675	46	7								1		
03/20/05	SI	win	Ref 1													
03/20/05	SI	win	Ref 2	563	36	1	16									
03/20/05	SI	win	Ref 3	563	53		5									

Date	Location	Sampling Period	ID	Blue gill/sunfish/pumpkinseed	Crappie	All Peamouth Chub	Large Scale Sucker	Northern Pike Minnow	Sculpin (Prickly)	Starry Flounder	Other UID
02/12/05	CL	win	Ref 2								
02/12/05	CL	win	Ref 3								
02/12/05	CL	win	Hotspot 1								
02/12/05	CL	win	Hotspot 2								
02/13/05	CL	win	Ref 1								
02/13/05	CL	win	Ref 2								
02/13/05	CL	win	Ref 3								
02/13/05	CL	win	Hotspot 1								
02/13/05	CL	win	Hotspot 2								
03/16/05	BP	win	Ref 1								
03/16/05	BP	win	Ref 2								
03/16/05	BP	win	Ref 3							1	
03/16/05	BP	win	Hotspot 1								
03/16/05	BP	win	Hotspot 2								
03/17/05	BP	win	Ref 1								
03/17/05	BP	win	Ref 2								
03/17/05	BP	win	Ref 3								
03/17/05	BP	win	Hotspot 1								
03/17/05	BP	win	Hotspot 2								
03/18/05	SI	win	Ref 1								
03/18/05	SI	win	Ref 2								
03/18/05	SI	win	Ref 3						1		
03/18/05	SI	win	Hotspot 1								
03/18/05	SI	win	Hotspot 2								
03/19/05	SI	win	Ref 1								
03/19/05	SI	win	Ref 2								
03/19/05	SI	win	Ref 3								
03/19/05	SI	win	Hotspot 1								
03/19/05	SI	win	Hotspot 2								
03/20/05	SI	win	Ref 1								
03/20/05	SI	win	Ref 2								
03/20/05	SI	win	Ref 3								

Date	Location	Sampling Period	ID	Area	0+ Chinook	1+ Chinook	Chum	Coho	Cutthroat	Steelhead	Trout	UID Salmonid	Mountain whitefish	Threespine Stickleback	American Shad	Banded Killifish
03/20/05	SI	win	Hotspot 1													
03/20/05	SI	win	Hotspot 2													
03/21/05	CL	win	REF 1	450	1		12									
03/21/05	CL	win	REF 2	100	19		13	8								
03/21/05	CL	win	REF 3	338	23		31	6						2		
03/21/05	CL	win	Hotspot 1	300	11		1									
03/21/05	CL	win	Hotspot 2	450	33		2					1		41		
03/22/05	CL	win	REF 1	563	23		7	3						1		1
03/22/05	CL	win	REF 2	100	6											
03/22/05	CL	win	REF 3	400	2	1		1						21		
03/22/05	CL	win	Hotspot 1	788	73		25	4						8		1
03/22/05	CL	win	Hotspot 2	675	98		56	5						10		1
04/11/05	CL	sp	REF 1	225				0								
04/11/05	CL	sp	REF 2	450	46		3	0						4		1
04/11/05	CL	sp	REF 3	270	9	2		0								
04/11/05	CL	sp	Hotspot 1	500	45	2	5	2								
04/11/05	CL	sp	Hotspot 2	500	175		25	0								
04/12/05	CL	sp	REF 1	180	1			0	1							
04/12/05	CL	sp	REF 2	225	31	8		0						5		
04/12/05	CL	sp	REF 3	338	15	8	2	4								
04/12/05	CL	sp	Hotspot 1	563	64		7	0						1		
04/12/05	CL	sp	Hotspot 2	450	174	2	18	3						1		
04/13/05	BP	sp	REF 1	788	175	1	4	0								
04/13/05	BP	sp	REF 2	788	107	2	2	1							1	1
04/13/05	BP	sp	REF 3	675	152	4	2	0						2	10	2
04/13/05	BP	sp	Hotspot 1	675	92		2	0						7	1	
04/13/05	BP	sp	Hotspot 2	675	44			0						5	1	
04/14/05	BP	sp	REF 1	675	88			0						26		1
04/14/05	BP	sp	REF 2	675	67	1		0						1	1	
04/14/05	BP	sp	REF 3	450	138	2		0						2	5	
04/14/05	BP	sp	Hotspot 1	450	146	1	1	0								
04/14/05	BP	sp	Hotspot 2	563	86	1	1	0						21		1

Date	Location	Sampling Period	ID	Blue gill/sunfish/pumpkinseed	Crappie	All Peamouth Chub	Large Scale Sucker	Northern Pike Minnow	Sculpin (Prickly)	Starry Flounder	Other UID
03/20/05	SI	win	Hotspot 1								
03/20/05	SI	win	Hotspot 2								
03/21/05	CL	win	REF 1								
03/21/05	CL	win	REF 2								
03/21/05	CL	win	REF 3								
03/21/05	CL	win	Hotspot 1								
03/21/05	CL	win	Hotspot 2							2	
03/22/05	CL	win	REF 1								
03/22/05	CL	win	REF 2								
03/22/05	CL	win	REF 3								
03/22/05	CL	win	Hotspot 1								
03/22/05	CL	win	Hotspot 2								
04/11/05	CL	sp	REF 1								
04/11/05	CL	sp	REF 2							1	
04/11/05	CL	sp	REF 3								
04/11/05	CL	sp	Hotspot 1								
04/11/05	CL	sp	Hotspot 2								1
04/12/05	CL	sp	REF 1								
04/12/05	CL	sp	REF 2								
04/12/05	CL	sp	REF 3								
04/12/05	CL	sp	Hotspot 1							1	
04/12/05	CL	sp	Hotspot 2								
04/13/05	BP	sp	REF 1								
04/13/05	BP	sp	REF 2								
04/13/05	BP	sp	REF 3								
04/13/05	BP	sp	Hotspot 1							3	
04/13/05	BP	sp	Hotspot 2								
04/14/05	BP	sp	REF 1							1	
04/14/05	BP	sp	REF 2								
04/14/05	BP	sp	REF 3							1	
04/14/05	BP	sp	Hotspot 1								
04/14/05	BP	sp	Hotspot 2								

Date	Location	Sampling Period	ID	Area	0+ Chinook	1+ Chinook	Chum	Coho	Cutthroat	Steelhead	Trout	UID Salmonid	Mountain whitefish	Threespine Stickleback	American Shad	Banded Killifish
04/15/05	SI	sp	REF 1					0								
04/15/05	SI	sp	REF 2	563	52			0		1						
04/15/05	SI	sp	REF 3	450	88	2	1	0								1
04/15/05	SI	sp	Hotspot 1	675	28	1		0								
04/15/05	SI	sp	Hotspot 2	675	26	2		0								
04/16/05	SI	sp	REF 1	563	43	1		0								
04/16/05	SI	sp	REF 2	563	23			0								1
04/16/05	SI	sp	REF 3	675	58		4	0						12		
04/16/05	SI	sp	Hotspot 1	675	42	1		0						1		
04/16/05	SI	sp	Hotspot 2	500	38		6	0								
05/16/05	SI	sp	REF 1	788	96	1		0					1			
05/16/05	SI	sp	REF 2	700	122			0					3			
05/16/05	SI	sp	REF 3	675	83			0								
05/16/05	SI	sp	Hotspot 1	400	72	1		0						1	2	
05/16/05	SI	sp	Hotspot 2	300	127	1		1					2		1	
05/17/05	SI	sp	REF 1	500	134	1		0						1		
05/17/05	SI	sp	REF 2	563	153	2		0					1			2
05/17/05	SI	sp	REF 3	675	138	3		0								
05/17/05	SI	sp	Hotspot 1	675	222	3		0					1		1	
05/17/05	SI	sp	Hotspot 2	450	205	4		0							4	
05/18/05	SI	sp	REF 1	563	147	1		0					1			1
05/18/05	SI	sp	REF 2	563	83	1		0					1		4	1
05/18/05	SI	sp	REF 3	563	67	2		0					1		2	
05/18/05	SI	sp	Hotspot 1	400	139	7		0					2			2
05/18/05	SI	sp	Hotspot 2	350	104	2		0								2
05/19/05	SI	sp	REF 1	563	21			0				1			3	2
05/19/05	SI	sp	REF 2	563	47	1		0				1	2		2	
05/19/05	SI	sp	REF 3	450	58	2		0								1
05/19/05	SI	sp	Hotspot 1	300	126	7		0							13	
05/19/05	SI	sp	Hotspot 2	338	185			0							1	
05/20/05	CL	sp	REF 1	450	26	1		0						1	1	1
05/20/05	CL	sp	REF 2	113	24			0		1				3		

Date	Location	Sampling Period	ID	Blue gill/sunfish/pumpkinseed	Crappie	All Peamouth Chub	Large Scale Sucker	Northern Pike Minnow	Sculpin (Prickly)	Starry Flounder	Other UID
04/15/05	SI	sp	REF 1								
04/15/05	SI	sp	REF 2								
04/15/05	SI	sp	REF 3								
04/15/05	SI	sp	Hotspot 1								
04/15/05	SI	sp	Hotspot 2								
04/16/05	SI	sp	REF 1								
04/16/05	SI	sp	REF 2								
04/16/05	SI	sp	REF 3								
04/16/05	SI	sp	Hotspot 1								
04/16/05	SI	sp	Hotspot 2								
05/16/05	SI	sp	REF 1			2					
05/16/05	SI	sp	REF 2			1					
05/16/05	SI	sp	REF 3			1					
05/16/05	SI	sp	Hotspot 1								
05/16/05	SI	sp	Hotspot 2								
05/17/05	SI	sp	REF 1			1		2		1	
05/17/05	SI	sp	REF 2					1			
05/17/05	SI	sp	REF 3								
05/17/05	SI	sp	Hotspot 1								
05/17/05	SI	sp	Hotspot 2								
05/18/05	SI	sp	REF 1								
05/18/05	SI	sp	REF 2			7					
05/18/05	SI	sp	REF 3			4		1			
05/18/05	SI	sp	Hotspot 1	1		1		1			
05/18/05	SI	sp	Hotspot 2			1					
05/19/05	SI	sp	REF 1								
05/19/05	SI	sp	REF 2			2					
05/19/05	SI	sp	REF 3	1		3		1			
05/19/05	SI	sp	Hotspot 1								
05/19/05	SI	sp	Hotspot 2			6					
05/20/05	CL	sp	REF 1								
05/20/05	CL	sp	REF 2								

ate	Location	Sampling Period	ID	Area	0+ Chinook	1+ Chinook	Chum	Coho	Cutthroat	Steelhead	Trout	UID Salmonid	Mountain whitefish	Threespine Stickleback	American Shad	Banded Killifish
05/20/05	CL	sp	REF 3	100	12			0						1		
05/20/05	CL	sp	Hotspot 1	450	77			0						41	1	
05/20/05	CL	sp	Hotspot 2	225	121			0			1			3	35	
05/21/05	CL	sp	REF 1	400	24	1		0			1				28	
05/21/05	CL	sp	REF 2	270	12	2		0						1	4	
05/21/05	CL	sp	REF 3	40	1			0								
05/21/05	CL	sp	Hotspot 1					0								
05/21/05	CL	sp	Hotspot 2					0								
05/22/05	BP	sp	REF 1	563	96			0			1		9			4
05/22/05	BP	sp	REF 2	675	60	1		0			1		12	70	20	
05/22/05	BP	sp	REF 3	563	35			0					4	1		
05/22/05	BP	sp	Hotspot 1	225	17			0			1		2	3	6	
05/22/05	BP	sp	Hotspot 2	450	77			0					6	4	18	
05/23/05	BP	sp	REF 1	450	70			0					8	3	4	
05/23/05	BP	sp	REF 2	450	55			0			5		6	13	14	
05/23/05	BP	sp	REF 3	563	37			0							3	
05/23/05	BP	sp	Hotspot 1	563	17			0		1	1					
05/23/05	BP	sp	Hotspot 2	563	85	1		0			2		7	1	2	

Date	Location	Sampling Period	ID	Blue gill/sunfish/pumpkinseed	Crappie	All Peamouth Chub	Large Scale Sucker	Northern Pike Minnow	Sculpin (Prickly)	Starry Flounder	Other UID
05/20/05	CL	sp	REF 3					1			
05/20/05	CL	sp	Hotspot 1					1			
05/20/05	CL	sp	Hotspot 2								
05/21/05	CL	sp	REF 1			2	1				
05/21/05	CL	sp	REF 2								
05/21/05	CL	sp	REF 3								
05/21/05	CL	sp	Hotspot 1								
05/21/05	CL	sp	Hotspot 2								
05/22/05	BP	sp	REF 1								
05/22/05	BP	sp	REF 2			2					
05/22/05	BP	sp	REF 3								
05/22/05	BP	sp	Hotspot 1			4				1	
05/22/05	BP	sp	Hotspot 2			1					
05/23/05	BP	sp	REF 1			6		1			
05/23/05	BP	sp	REF 2			3					
05/23/05	BP	sp	REF 3								
05/23/05	BP	sp	Hotspot 1								
05/23/05	BP	sp	Hotspot 2	1		1					

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