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FACTORS AFFECTING STRANDING OF JUVENILE SALMONIDS BY WAKES FROM SHIP PASSAGE IN THE LOWER COLUMBIA RIVER†

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ABSTRACT

The effects of deep-draft vessel traffic in confined riverine channels on shorelines and fish are of widespread concern. In the Pacific Northwest of the United States, wakes and subsequent beach run-up from ships transiting the Lower Columbia River have been observed to strand juvenile salmon and other fish. As part of a before-and-after study to assess stranding effects that may be associated with channel deepening, we measured 19 variables from observations of 126 vessel passages at three low-slope beaches and used multiple logistic regression to discern the significant factors influencing the frequency of stranding. Subyearling Chinook salmon were 82% of the fish stranded over all sites and seasons. Given a low-slope beach, stranding frequencies for juvenile salmon were significantly related to river location, salmon density in the shallows, a proxy for ship kinetic energy, tidal height and two interactions. The beach types selected for our study do not include all the beach types along the Lower Columbia River so that the stranding probabilities described here cannot be extrapolated river-wide. A more sophisticated modelling effort, informed by additional field data, is needed to assess salmon losses by stranding for the entire lower river. Such modelling needs to include river-scale factors such as beach type, berms, proximity to navigation channel, and perhaps, proximity to tributaries that act as sources of outmigrating juvenile salmon. At both river and beach scales, no one factor produces stranding; rather interactions among several conditions produce a stranding event and give stranding its episodic nature. Published in 2010 by John Wiley & Sons, Ltd.

KEY WORDS: stranding; deep-draft vessels; juvenile salmonids; wakes; Lower Columbia River

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INTRODUCTION

The effects of vessel traffic in confined riverine channels on shorelines and fish are of concern in several parts of the world (Huesig *et al*., 1999; Arlinghaus *et al*., 2002; Maynord, 2003; Wolter and Arlinghaus, 2003; Maynord, 2004). In the Pacific Northwest of the United States, 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 (Hinton and Emmett, 1994; Bauersfeld, 1977; Ackerman, 2002). Fish stranding is an episodic event that occurs on certain beaches under certain combinations of deep-draft vessel passage, shoreline structure and ambient conditions.

Because several salmon stocks in the Columbia River are threatened and endangered, proposed deepening of the Columbia River navigation channel raised concerns about the potential effects of the deepening project on juvenile salmon stranding. As part of a before-and-after study to assess stranding effects that may be associated with channel deepening (Pearson *et al*., 2006), we also measured covariables to understand the factors leading to fish stranding. Here we report on the ship and ambient factors influencing the occurrence of juvenile salmon stranding.

Along the LCR, three prior studies documented fish stranding caused by wakes from deep-draft vessels (Hinton and Emmett, 1994; Bauersfeld, 1977; Ackerman, 2002). These three studies suggest that under certain conditions, deep-draft vessels (but not small vessels) can produce wakes that strand juvenile salmon. The factors hypothesized to influence the occurrence of stranding include river and beach factors, wake properties, ship characteristics and ambient river and biological conditions. River and beach factors are related to the physical structure of the river channel, shallows and shoreline and include low beach slopes, short distances from channel to beach and exposure of beach to wakes (no sheltering islands or bars). Wake properties include wave height, drawdown height and distance, run-up height and distance and run-up speed. Ship characteristics include size (draft, length and beam) and speed. Ambient river conditions include river stage and tidal height at time of passage. Because seasonal decreases in fish availability were previously seen to reduce stranding occurrence (Bauersfeld, 1977), ambient biological conditions need to include the availability of fish in the shallow nearshore zone along the beach.

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In this study, we collected data that coupled ship characteristics, river conditions and fish availability to the occurrence of stranding. This approach not only produced data to compare fish stranding before and after channel deepening but also yielded data to discern the significant factors leading to ship stranding. The aim of this paper is to report the results of multiple logistic regression to discern the significant factors influencing the frequency of stranding at three low-slope beaches in the LCR.

MATERIALS AND METHODS

Study sites

During study design, 12 potential study sites on the Columbia River were considered and narrowed to three candidate sites (Figure 1), selected on the following basis: (a) known for previous juvenile salmon stranding, (b) gently sloping beaches, (c) exposure to ship wakes from the navigation channel and (d) evidence of fairly stable beach morphology. We collected data during the field sampling on beach slope, sediment grain-size composition and infiltration rates at each beach to characterize beach structure.

County Line Park (RK 85) is near the boundary between Wahkiakum and Cowlitz Counties on the north (Washington) side of the Columbia River. The beach is backed by riprap, especially on the downstream end where it extends below the ordinary high water mark. The beach is the narrowest 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 riprap. County Line Park has the steepest beach slope (~4.0%), fastest water infiltration rate, and coarsest sediment, with over 90% of the sediment collected composed of medium sand or larger particle sizes. Being the closest of the three sites to the ocean, it has the largest tidal amplitude, with a mean range of 1.4 m.

Barlow Point (RK 103) is located on the north (Washington) side of the Columbia River. At low tide, the expansive shore (over 100 m from the waterline to the backshore) is covered with rippled bedding characteristic of tidal flats. This beach is the widest and most gradually sloping of the three 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 and redirects wave energy so that some waves travel laterally, generally in the downstream direction. At the downstream end of the beach, patches of vegetation (Carex sp.) occur at mid-tide level. Barlow Point has the most gradual beach slope (~2.2%), slowest water infiltration rate, and finest average sediment

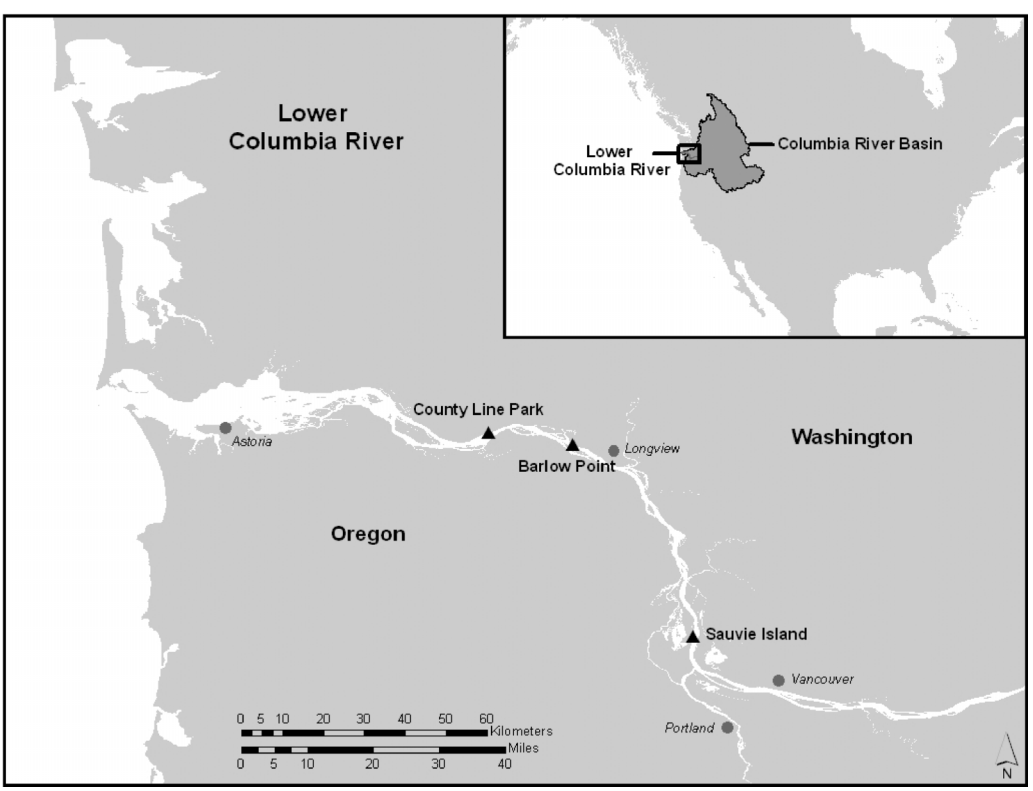

Figure 1. Locations of the three study sites on the Columbia River; (1) County Line Park, (2) Barlow Point and (3) Sauvie Island

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grain size. Over 90% of the sediment collected from Barlow Point was composed of fine sand or smaller particle sizes. Barlow Point has a mean tidal range of 1 m.

Sauvie Island (RK 162) is located on the south (Oregon) side of the river. Some vegetation (shrub willow and grasses) is emergent on the beach face, located ~75 m landward of the waterline. The beach is terminated at each end by an erosional bank. Sauvie Island's physical characteristics were intermediate between Barlow Point and Country Line Park with respect to beach slope (~2.5%), infiltration rate and sediment grain size (71.7% was medium sand and coarser). This site had a mean tidal range of 0.6 m.

Field observations and data collection

The basic unit of observation was the passage of an individual deep-draft vessel by a study beach and the recording of the subsequent number and species of fish stranded, if any. To obtain sufficient numbers of observations, we attempted to observe a minimum of 15 vessels at each site, during each of three major seasons of juvenile salmonid occurrence (i.e. summer, winter and spring) (i.e. $\approx$15 vessels $\times$ 3 sites $\times$ 3 periods = 135 observations). The order in which the sites were visited was randomized for each sampling trip. Observations were limited to deep-draft vessels (e.g. bulk carriers, oil tankers, car carriers and container ships) because smaller vessels and barges were observed previously not to produce stranding (Hinton and Emmett, 1994; Ackerman, 2002).

During each ship passage, characteristics of the vessel were recorded including the 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 time of passage, weather conditions, vessel behaviour and other vessel traffic in the area were also recorded. After returning from the beaches, information on ship length, draft, beam and load condition were gathered from either the Columbia River Pilots (CRP) or from the U.S. Coast Guard, Port State Information Exchange, Vessel Search web portal (http://cgmix.uscg.mil/PSIX/PSIX2/VesselSearch.asp).

Two types of instruments to measure ship wakes were installed at each site. A wave run-up gauge captured information on wave extent up the beach as well as speed of run-up and drawdown. This 33-m long instrument was positioned perpendicular to the waterline and just above the beach substrate. Electric relays activated by floats along the length of the instrument were connected to a data logger which recorded times of water submersion as the waves passed over the instrument. Post-processing of the time sequence of the contacts between the instrument and the waves permitted estimation of wave speed and distance travelled.

Two wave staff gauges were also used to record wave characteristics. The wave staffs had capacitive-type water-level sensors in a 3-m long staff and housing (http://www.oceansensorsystems.com/). Each gauge was mounted on a post driven into the sediment. The tip of the staff was set ~15 cm above the substrate. Each staff was connected to a laptop computer. During each passage event, data were recorded from prior to ship arrival to 20 min after passage. Voltage output was converted to water elevation using a direct scaling algorithm and normalized to a still water level by subtracting the mean of the 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. Plots of the data were made showing the short- and long-period waves produced by the vessel passage. Videotaping was also used to measure drawdown, run-up and run-up speed. To measure the total extent of wave excursion across the beach, stakes were placed at the maximum points of drawdown and run-up and then the distance between these points was measured with a tape measure.

For vessel speed, two observers recorded the time it took for the vessel to travel 200 m between two pair of gunsite stakes. The average time of the two observers was used. This method measures speed over ground which probably differs from speed through the water.

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 examined 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 dGPS unit. Their condition (dead or alive) and relative position (at waterline or not) were noted. 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 passage events. At the start of each sampling period, the beach was surveyed and stranded fish removed.

The potential for stranding must depend, in part, on the presence of fish. To monitor relative fish abundance, fish were sampled with a beach seine up to three times each day at the beach under observation. A standard Puget Sound floating beach seine (Simenstad *et al.*, 1991) was used to collect fish for the fish density index. Seining occurred in the area immediately downstream of the stranding survey area. 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 0.8–1.2 m at the deepest point. The net was hauled evenly and gradually pursed as it reached the waterline. Fish were removed from

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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). A fish density index was computed based on numbers of fish caught and area swept by the beach seine.

Statistical methods

The response variable of interest was the occurrence or not of a fish stranding event. A stranding event was defined as at least one salmonid fry or smolt being stranded on a beach following a ship passage event. The actual number of fish stranded was not considered important in this effort to identify the factors that caused stranding events. Generalized linear models (McCullagh and Nelder, 1983) were used to model this binary response (i.e. $1 = \text{stranding}$, $0 = \text{no stranding}$) using a logistic-link function and binomial ($n = 1$) error structure.

The objective of the statistical analysis was to identify ship characteristics associated with stranding events. To this end, hierarchical regression procedures were used, where indicators for site and season were first entered into the model. The logistic model treated location 1 (i.e. Barlow Point) as the base condition with adjustments for the other two locations. Next, other ambient factors, including tidal stage (ebbing, flooding, low slack and high slack), tidal height, river flow, current velocity (knots, estimated from a nearby gauging station) and alternative indicators of fish availability (i.e. Chinook salmon density index or salmonid density index) were considered. Finally, 11 variables reflecting ship characteristics were considered (Table I). The majority of vessel measurements are directly interpretable; two require explanation.

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

$$\mathrm{KE} = \frac{1}{2}mv^2 \tag{1}$$

where m is the mass and v is velocity. 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, although we have called this factor kinetic energy, it is actually a proxy for kinetic energy, whereby

$$\mathrm{KE}' = \frac{\left[\text{Block factor} \times (\text{Ship speed})^2\right]}{1 \times 10^{-8}} \tag{2}$$

where block factor is the ship length × beam × draft, as provided by the CRP.

Model selection was based on analysis of deviance (McCullagh and Nelder, 1983) at an $\alpha = 0.05$ significance level and verified by Akaike information criterion (AIC) (Burnham and Anderson, 1998; Burnham and Anderson, 2002). Main effects were retained in the model when nonsignificant if they were present in an interaction term that was significant ($P < 0.05$).

RESULTS

Wake properties

The wake waves generated by a ship making headway in a channel are of several types (Maynord, 2003; Maynord, 2004). The short-period waves generated at the bow of the

Table I. Descriptors of vessel characteristics used in the logistic modelling of the number of stranding events

Variable	Unit of measurement	Description
Ship type	Categorical	Type of deep-draft vessel (car carrier, bulk carrier, oil tanker, container vessel or other)
Ship direction	Binary	Upstream or downstream travel
Ship condition	Categorical	Indicator for unloaded, partially loaded or loaded vessel
Ship distance	Categorical	Five ordered levels of distance from vessel to shore (i.e. near, near-middle, middle, middle-far, far)
Ship time	sec	Duration of vessel passage in front of site
Ship speed	knots	Vessel speed over ground
Draft	m	Depth of vessel below waterline
Beam	m	Vessel maximum width
Length	m	Vessel length
Ship block coefficient	m^3	Draft × Beam × Length, 1st-order approximation of water displacement of vessel
Kinetic energy proxy		Block coefficient × Speed^2 × 10^{-8} , 1st-order approximation for energy imparted by the vessel as it moves through the water

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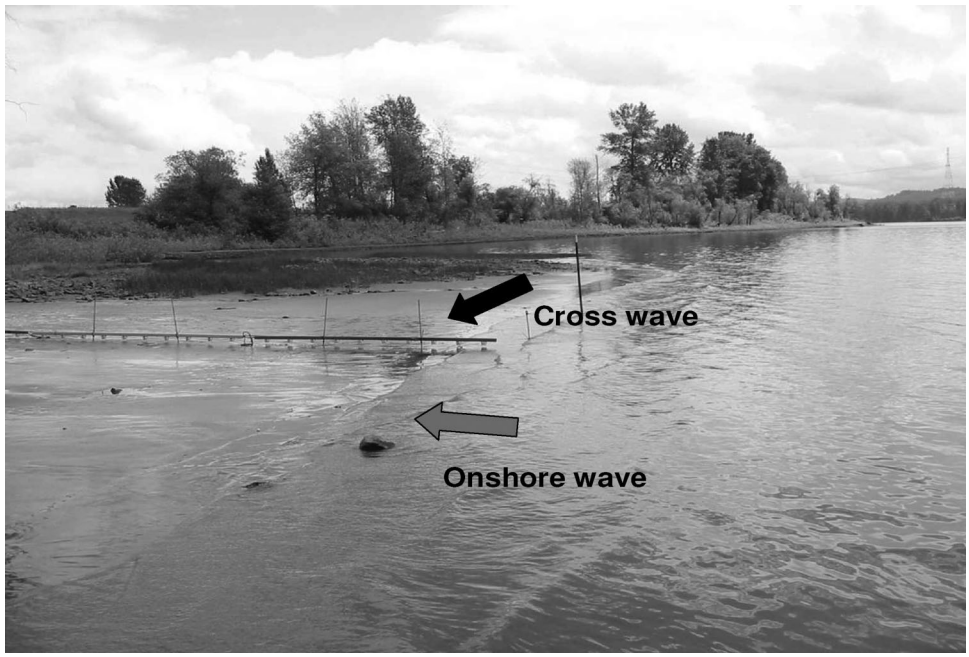

Figure 2. Beach at Barlow Point with directions of onshore wave (grey arrow) and cross wave (black arrow). Also depicted are the wave staff gauge and wave run-up gauge

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 confined channel, long-period waves exhibiting drawdown and subsequent run-up or surge may also develop. These long-period waves travel along the shoreline at the speed of the ship and are the waves that strand fish.

At all sites, but particularly at Barlow Point, cross waves were also observed. The onshore wave was one that travelled from the channel up the beach face (Figure 2). Cross waves travelled along the beach face and typically met shore waves, sometimes muting their energy. Cross waves were seen in areas with complex shoreline structure, for example, the Reno Mat that armours the shoreline at Barlow Point and rip-rap at County Line Park. Cross waves made the measurement of run-up speed difficult, as they were often strong enough to disrupt the wave run-up gauge.

A time plot of a typical wake event clearly shows the drawdown and run-up surges (Figure 3). The drawdown 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. Field measurements of the total wave excursion (across the beach face) ranged from 3 to 78 m for the three beaches. Run-up and drawdown distances tended to be slightly different, with a mean run-up of 9.3 m and drawdown of 12.6 m. Similarly, the vertical extent of wave run-up and drawdown was measured and analysed. The maximum vertical extent ranged from about 0.1 m to over 0.7 m, with a mean of 0.25 m across all beaches.

Stranding by location, season and ship type

During the three seasons of sampling, we observed a total of 126 vessels (Table II). Of these, 46 vessel passages resulted in stranding events. Barlow Point had the highest proportion of stranding events (26 of 49; 53.1%), followed by Sauvie Island (14 of 38; 36.8%) and County Line Park (6 of 39; 15.4%). There was a significant difference in the rate of stranding between the three sites ($P = 0.0013$).

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 ($P = 0.040$), this effect is most evident at Barlow Point ($P = 0.007$), 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. At these sites, the proportion of

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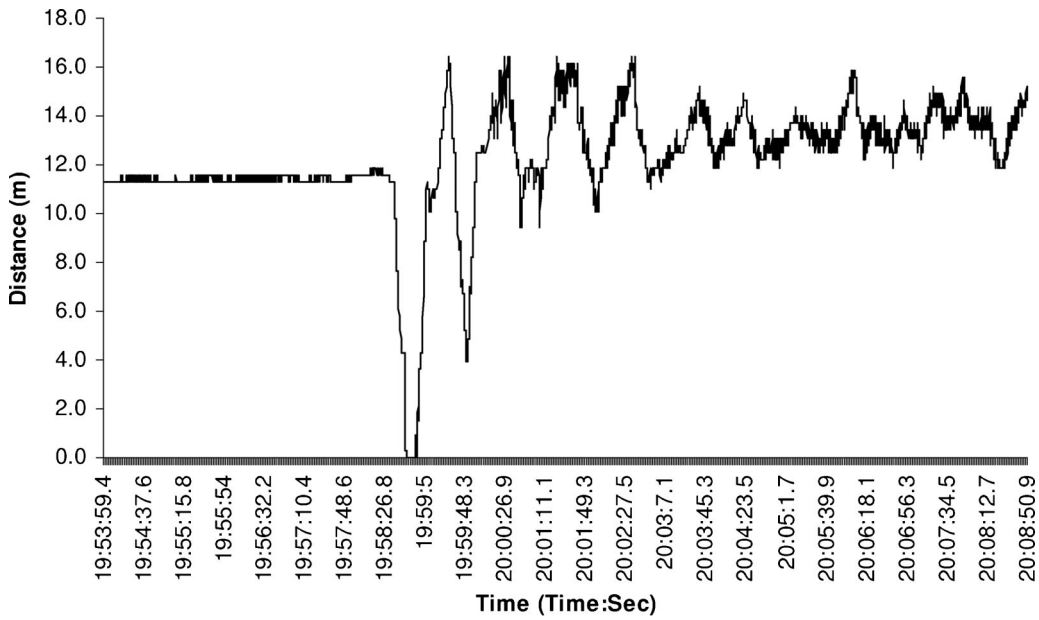

Figure 3. Wave run-up gauge plot showing the full extent of drawdown and run-up over the 15-min sampling event

stranding events was similar during all seasons. As will be seen later, when fish availability is taken into account, season is no longer a significant factor.

Most observed vessel passages were bulk carriers, with car carriers being the next most common type of vessel observed. 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. Oil tankers comprised 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). Data obtained from the CRP on individual ships showed that ships ranged in length from 91.4 to 290 m (300–950 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).

Table II. Ship passage observed at each study site and by season and the incidence of stranding events (in parentheses)

Site	Season Summer	Winter	Spring	Total
County Line Park	17 (3)	14 (1)	8 (2)	39 (6)
Barlow Point	23 (7)	14 (9)	12 (10)	49 (26)
Sauvie Island	14 (4)	12 (5)	12 (5)	38 (14)
Total	54 (14)	40 (15)	32 (17)	126 (46)

The river conditions measured for each passage event included tidal height, river flow or discharge, and river velocity. River discharge ranged from −2833 to12 742 m^3/s (−100 000 to 450 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 resulted from a flooding tide reversing the flow in the LCR. Because of unusually high run-off, greater discharge and velocity occurred during the spring sampling period [mean of 9260 m^3/s (327 000 cfs) over all sampling days] than the other sampling periods. Winter mean was 2888 m^3/s (102 000 cfs); summer mean was 4361 m^3/s (154 000 cfs). Stranding events were observed up to the maximum river discharge and velocity in our study.

Beach-scale distribution of stranding

There were a total of 46 stranding events during the study period (all sites, all seasons). Stranding occurred in similar locations for all seasons for Barlow Point and Sauvie Island. At the Barlow Point site, fish tended to strand in an area where strong cross-waves and an eddy occurred (Figure 4). Also at this site, fish were stranded towards the downstream end of the site (upper portion of map) in vegetation patches. Stranding at County Line Park, though less frequent, 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 aggregated at the far end of the site where ship wakes extended up the beach into a depression.

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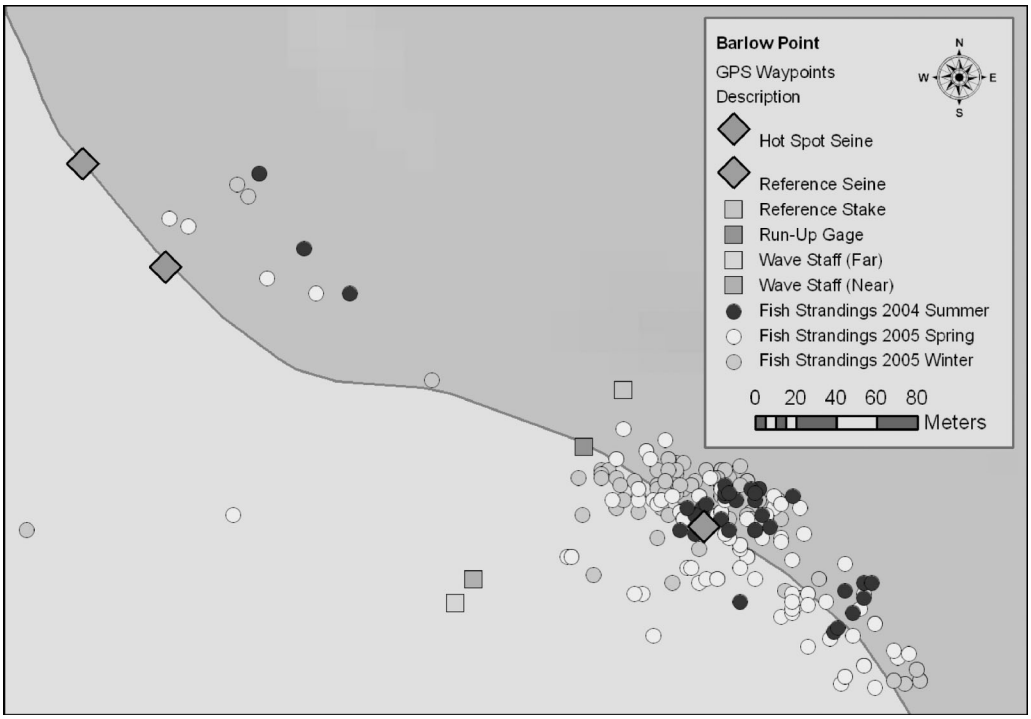

Figure 4. Barlow Point stranding locations. Shoreline represented by the mean high tide

Composition of stranded fish

Stranding numbers ranged from 1 to over 100 stranded fish per event, with an average of 11.3 fish stranded per stranding event (only events resulting in stranding were used in this calculation). Average number of fish stranded per stranding event at County Line Park, Barlow Point and Sauvie Island were 7.3, 14.9 and 5.6, respectively. Overall, 52% of the stranding events had between 1–5 fish, 67% of the stranding events had between 1–10 fish and 91% of the events had $\leq$20 fish. The predominant fish stranded (82%) over all sites and seasons were Chinook salmon subyearlings. Threespine stickleback were the only other fish stranded in moderate to large numbers. Most other fish species were rarely stranded.

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. Sampling trip (i.e. the site-date combination) was used as a blocking factor. Fish comprising $<$1% of the catch were not examined. The proportions vary significantly across sampling type (i.e. seine net versus strandings) for Chinook salmon ($P = 0.0121$), American shad ($P = 0.0323$), and possibly for peamouth chub ($P = 0.0866$). Chinook salmon occurred in greater proportion among the stranded fish (81.9%) than among the seined fish (49.1%). Other fish were found in equal or lesser proportions among the stranded than the seined fish.

Logistic modelling

Initial analyses examined the correlation between the incidence of fish stranding and the individual covariates. Of the many covariates considered on a single-factor basis, only ship draft ($P = 0.1026$), season ($P = 0.2192$), tidal stage (e.g. ebb or flood) ($P = 0.2947$) and ship distance ($P = 0.5277$) were not significantly related to stranding occurrence (Table III). The binary nature of the response precludes illustrating the model fits to the original data. Instead, nonparametric moving average curves for the proportion of stranding events versus the fitted logistic curves can be plotted. As anticipated, as the index of fish availability increased, so did the rate of fish stranding (Figure 5). Similarly, as kinetic energy increased, so did the probability of a stranding event occurring (Figure 6). The kinetic energy manifests itself by the strength of the resulting wave as measured by wave height and run-up distance. Therefore, it was not surprising that a strong relationship was found between the total wave distance and the probability of stranding (Figure 7).

Subsequent model building included indicator variables for location effects, salmonid seine index for fish availability, but not seasonal effects. Stepwise regression proceeded to identify kinetic energy and tidal height as additional variables significant at $P \leq 0.05$. The final stage of the analysis considered interaction terms for the variables already in the model. Two interaction terms, kinetic

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Table III. 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	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 load 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

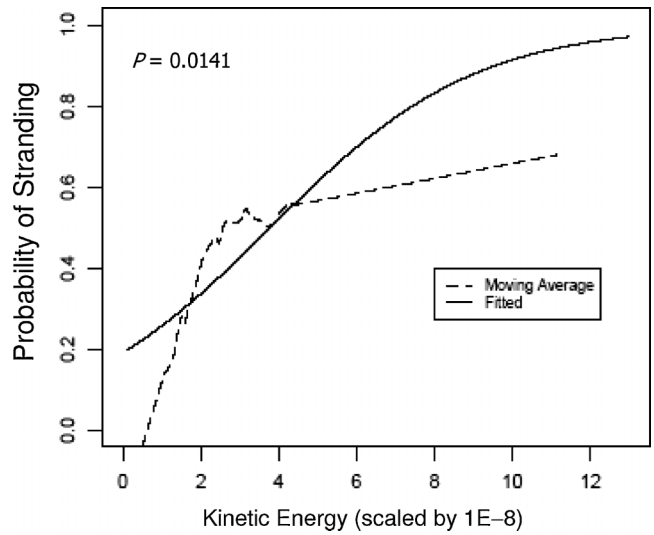

Figure 6. The fitted logistic curve (solid line) for the probability of stranding versus kinetic energy (scaled by 10^{-8}), and a nonparametric moving average curve (dashed line) for the proportion of strandings versus kinetic energy. Data pooled across all seasons and sites

energy × tidal height and tidal height × salmonid seine index were found to be significant ($P < 0.05$) and were added to the model (Table IV). The final model was of the form:

$$\begin{aligned}\ln\left(\frac{p_i}{1-p_i}\right) &= \beta_0 + \beta_{1i}(\text{Location}_i) + \beta_2(\text{Kinetic energy}) \\ &+\beta_3(\text{Tidal height}) + \beta_4(\text{Salmonid density}) \\ &+\beta_5(\text{Kinetic energy} \times \text{Tidal height}) \\ &+\beta_6(\text{Tidal height} \times \text{Salmonid density})\end{aligned} \tag{3}$$

where the coefficients are provided in Table IV. The overall model was highly significant $\left(P\left(F_{7,91} \geq 5.6783\right) = 0.000018\right)$.

The fitted model included few surprises. It was anticipated that site-specific differences in beach topography, distance and profile to the shipping channel, salmonid habitat, etc., would result in inherent differences in the propensity for stranding. Fish availability and the susceptibility of a beach to stranding, as measured by tidal height, would also be expected to modify the rate of stranding from one trial to

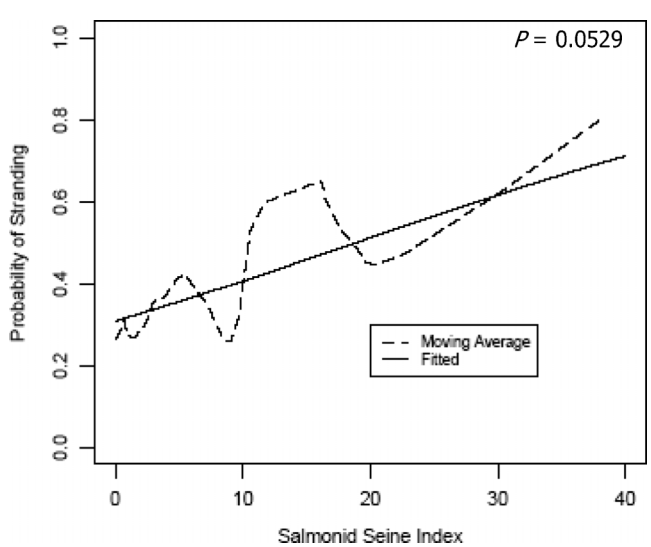

Figure 5. The fitted logistic curve (solid line) for the probability of stranding versus salmonid seine index, and a nonparametric moving average curve (dashed line) for the proportion of stranding versus salmonid seine index. Data pooled across all seasons and sites

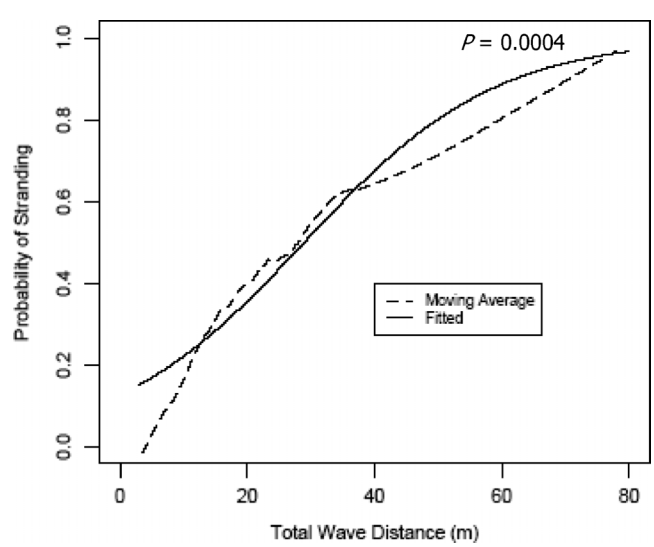

Figure 7. The fitted logistic curve (solid line) for the probability of stranding versus total wave distance, and a nonparametric moving average curve (dashed line) for the proportion of strandings versus total wave distance (horizontal). Data pooled across all seasons and sites

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Table IV. Coefficients from final logistic model fit to the stranding data

Independent variable	Coefficient	Standard error
Intercept	−1.0945	1.1843
Location 2 (County Line Park)	−3.1547	0.9856
Location 3 (Sauvie Island)	−1.3672	0.6063
Kinetic energy (scaled)	1.2334	0.4011
Tidal height	−0.2310	0.4828
Salmonid density	−0.0714	0.0589
Kinetic energy × Tidal height	−0.2554	0.1357
Tidal height × Kinetic energy	0.0736	0.0358

another, above and beyond site differences. More interesting is that the constructed variable, kinetic energy, supplanted the individual influences of ship length, beam, depth and speed. It can nevertheless be interpreted from the definition of kinetic energy that the log odds ratio changes linearly with ship displacement but changes exponentially with ship speed. Doubling ship speed changes the log odds ratio by a factor of four while doubling displacement changes the odds ratio by a factor of two.

DISCUSSION

By design, our study only examined factors related to ship characteristics, ambient conditions and fish availability. The sites chosen for this study were selected because they had a history of fish stranding. All the sites studied were low slope beaches (<5%) with relatively short distances between the navigation channel and the beach and no bars or islands between the channel and the beach. The results of Bauersfeld (1977) show that stranding does not occur at high river flows when the river stage is at 7–8 feet (2.1–2.4 m) at the Rainer gauge. Our study purposefully did not include high flows that inundate the beaches. The highest river flow in our study was 12 742 m^3/s (450 000 cfs) and stranding did occur at this flow.

Our logistic regression analysis has led to an increased understanding of the mechanisms that produce the stranding of concern here. Single-factor and multivariate regression analyses were undertaken to assess the roles and linkages between ambient conditions and ship or wake characteristics that produce stranding events. It is now clear that no single factor appears to be the cause of juvenile salmon stranding. The fitted logistic model (3) indicates that ship kinetic energy (which accounts for ship size and speed), tidal height and fish availability, along with unique beach characteristics, are primary factors in stranding occurrence, given a low-slope beach and proximity to the navigation channel.

Site effects were a significant factor. Although the sites studied represent only low-slope beaches, each has distinct differences. 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. At County Line, infiltration rate may be high enough that infiltration could affect the speed of wash-back. Sauvie Island has aspects between the other two sites but is closer to County Line in many respects.

The video observations indicate that 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. 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 wave patterns were complex. 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 structure, where the shoreline had a berm. It is in this area where stranding occurrence was the highest. This phenomenon was observed at both Sauvie Island and County Line Park, though not to the same extent as at Barlow Point. The role of fine-scale beach structures in stranding merits further study.

The kinetic energy proxy was a significant main effect and represents the amount of energy imparted by the ship as it moved through the water. The logarithm of the total wave excursion across the beach was significantly related to the kinetic energy proxy as well as location and tidal height (Pearson *et al.* 2006). Increasing the size and speed of the vessel increased the extent of drawdown and run-up. It is important to note that higher speed by itself does not necessarily increase stranding rate. A larger vessel with deeper draft can have a higher kinetic energy that a smaller, lower draft vessel moving at higher speed. In modelling to relate ship-induced currents and displacement of juvenile fish in European waterways, Wolter *et al.* (2004) derived their predictors of return velocity from the kinetic energy of ships and concluded that navigation-induced currents decreased the suitability of channel habitats for small fish.

Tidal height was also a significant factor influencing stranding rate. All other factors being equal, lower tidal heights tend to increase stranding rates. Wave height was found to decrease with increasing tidal height (Pearson *et al.* 2006).

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Although fish composition changed over time and with each location, salmon (specifically Chinook) were present in all sampling seasons, and the salmonid density index was found to be a significant factor in stranding. Outmigrating juvenile Chinook salmon clearly use the shallow margins of the river. Tiffan *et al.* (2006) found subyearling Chinook salmon in the upper Columbia River to be most abundant in low water velocities, in water shallower than 1 m, and close to shore (within 25 m of shore).

Although habitat use appears to increase the vulnerability of juvenile Chinook to stranding, other aspects of the species biology and behaviour may also play a role. Comparison of seined fish with stranded fish showed Chinook salmon were stranded more often than seined. Other fish were stranded at equal or lower frequencies than were 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 behaviour or some combination of both. For example, a rheotactic response by Chinook salmon during drawdown may aggregate the fish at the water's edge, and the aggregation may then be carried up the beach by the run-up wave. The finding that total wave excursion across the beach is significantly related to the probability of stranding also suggests swimming ability and behaviour may play a role. Investigation of swimming speed and other behavioural factors may lead to greater understanding of stranding mechanisms and the increased predisposition to stranding among juvenile Chinook salmon.

Although the mechanisms of stranding are still not completely understood, the factors identified in the logistic analysis (3) are consistent with what is known about biological and physical processes of fish stranding, 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. Given that the beach has low slope and the navigation channel is confined and close, the kinetic energy 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 at the time of the event. Wave excursion or total distance from drawdown to run-up provides the physical event that strands fish. Increasing juvenile salmonid density in the nearshore increases the probability of stranding and remains a significant factor even after location is taken into account.

The multiple logistic regression model (3) does not account for all the variability in the data so the involvement of other, yet unspecified, factors is clear. The multivariate regression equation, the video observations of cross waves, and the presence of stranding hot spots all indicate that fine-scale site characteristics at a specific location play a prominent role in structuring the processes that modify the onshore wave climate and lead to fish stranding. Another potential factor is the occurrence and morphology of berms in the shallows in front of the beach (Maynord, 2004).

Some implications

The beach types selected for our study do not include all the beach types along the LCR so that the stranding probabilities described here cannot be extrapolated river-wide. A more sophisticated modelling effort, hopefully informed by additional field data from other beach types, would be needed. Such modelling would need to include such river-scale factors as beach type, berms, proximity to navigation channel, and perhaps, proximity to tributaries that act as sources of outmigrating juvenile salmon.

It is premature to offer suggestions concerning ways to reduce stranding occurrence along the LCR. The logistic regression equation (3) offers a means to examine how changes in ship operations (i.e. speed) might influence stranding occurrence. The kinetic energy variable in our model is a function of the square of vessel speed; consequently, relatively small changes in ship speed could result in significant changes in the incidences of stranding. Our observations on fine-scale beach structure should not be taken as recommendations for their modification without further study. For European waterways, Arlinghaus *et al.* (2002) suggests increasing channel complexity by providing side-channel habitat may reduce effects of ship traffic on fish fauna. Increasing side-channel habitat is certainly a well-established strategy for salmon recovery in the Pacific Northwest. It remains to be seen whether such mitigation can both increase rearing habitat and mitigate stranding effects. In the LCR, many of the shallow-sloped sandy beaches are a result of previous dredging operations. Restoring some of these manmade beaches to natural conditions may therefore be part of the solution to the fish stranding problem.

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