

Chapter 5.—Application of the SHOALS Survey System to Fisheries Investigations in the Columbia River

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Abstract

We used a Scanning Hydrographic Operational Airborne LiDAR (Light Detection and Ranging) Survey (SHOALS) system to collect high-resolution bathymetry for 33 km of the Hanford Reach. Data were used in conjunction with hydrodynamic and predictive habitat models within a GIS (Geographical Information System) framework to evaluate the effects of a varying hydrograph on juvenile fall Chinook salmon rearing habitat and risk from stranding and entrapment. Furthermore, we were able to estimate the number of juvenile fish that were stranded and entrapped in pools when operations at Priest Rapids Dam caused rapid decreases in river flows. Our findings were ultimately used to estimate impacts of power generation operations at Priest Rapids Dam and develop long-term policy and operational guidelines to protect juvenile fall Chinook salmon during the spring rearing period.

Introduction

The Hanford Reach is the only unimpounded section of the Columbia River between Bonneville Dam and the Canadian border (fig. 1). Because the Hanford Reach retains many of the riverine processes that no longer exist in the impounded Columbia River, it supports the largest population of fall Chinook salmon *Oncorhynchus tshawytscha* in the Columbia River Basin (Huntington et al., 1996; Dauble and Watson, 1997). These fish are part of the “Upriver Bright” fall Chinook stock and are a primary contributor to ocean and freshwater sport, commercial, and in-river tribal fisheries. They also are a component of the international Pacific Salmon Treaty between the United States and Canada and their status affects management decisions throughout the West Coast (Wolf and Wagner, 1998; Wolf, 1999). Fall Chinook salmon are unique in that they spawn and rear in mainstem habitats rather than in tributaries like many other anadromous salmonids. Each year the Hanford Reach produces an estimated 13–39 million juvenile salmon (Paul Hoffarth,

Washington Department of Fish and Wildlife (WDFW), unpublished data), which rear along shallow mainstem shorelines for 2–4 months before migrating seaward during the summer.

Flows through the Hanford Reach are regulated by upstream hydroelectric dams of which Priest Rapids Dam at the head of the Reach exerts the greatest local influence. Changes in discharge at Priest Rapids Dam to meet power demand, termed power peaking, can cause tail-water elevations to fluctuate more than 3 vertical meters in 6 h. These fluctuations can potentially change the amount of rearing habitat available to juvenile fall Chinook salmon on a daily and hourly basis. Sharp decreases in flow also strand fall Chinook salmon in substrate and in disconnected pools when water rapidly recedes from low-gradient shoreline habitats, causing significant mortality of young salmon (Wagner et al., 1999).

In 1998, we initiated a study to examine the effects of flow fluctuations on juvenile fall Chinook salmon rearing habitat and susceptibility to stranding, entrapment, and level of survival. However, to make inferences ranging from the scale of the individual fish to the scale of the reach presented a unique challenge that required high-resolution data over a broad spatial area. To address this challenge, we collected LiDAR (Light Detection and Ranging) data from 33 km of river using a Scanning Hydrographic Operational Airborne LiDAR Survey (SHOALS) system (Guenther et al., 1996; Lillycrop et al., 1996; Parson et al., 1996). The resulting detailed riverbed bathymetry was used in conjunction with one- and two-dimensional hydrodynamic modeling, predictive statistical models, and a spatially explicit analysis to predict the effects of flow changes on rearing habitat. Furthermore, we were able to quantify the effects of a variable hydrograph from Priest Rapids Dam on juvenile fall Chinook salmon stranding and entrapment to ultimately derive estimates of mortality over the course of an entire rearing season. The use of remote sensing coupled with direct monitoring provided information to support policy discussions and decisions leading to broad agreements and decreased impacts to this principal salmon population.

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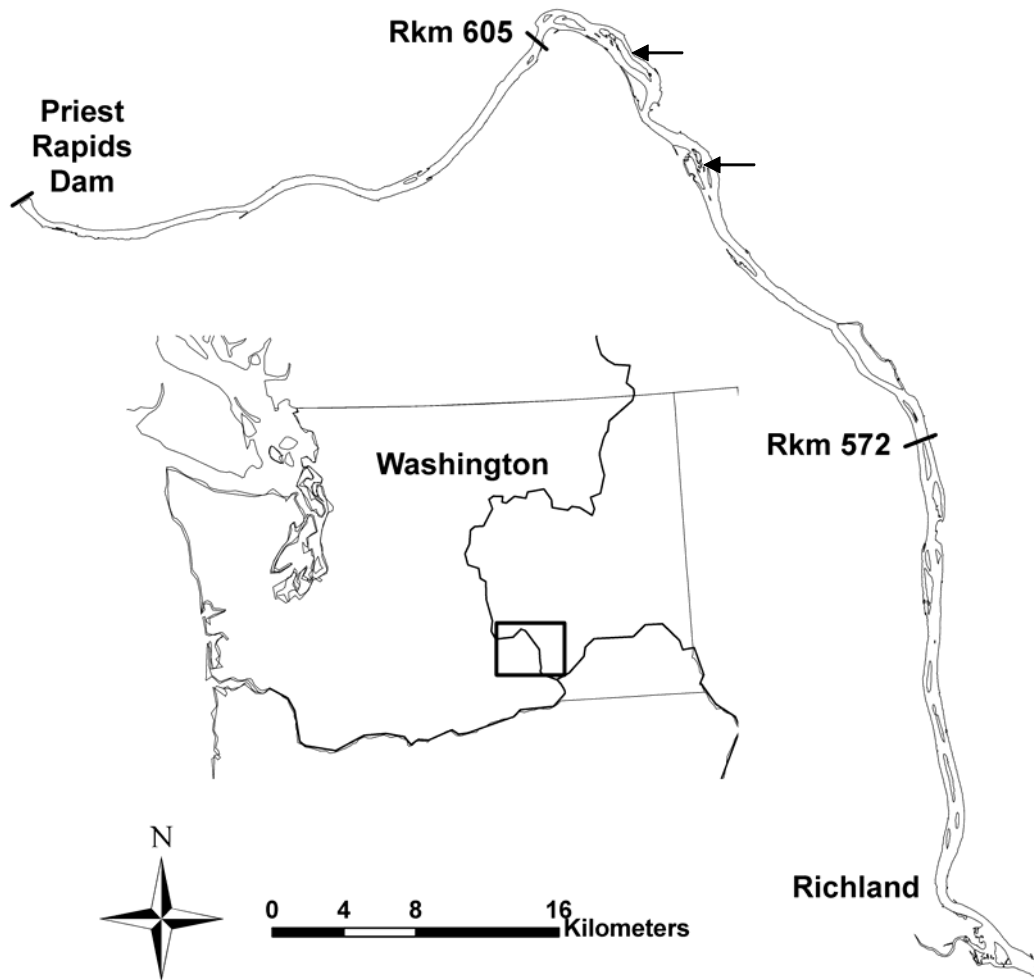


Figure 1. The Hanford Reach of the Columbia River in Washington showing the river kilometers (Rkm) that delineated our study area.

Study Area

The Hanford Reach extends 90 km from Richland, Washington, upstream to Priest Rapids Dam (fig. 1). We restricted our study to a 33-km area between river kilometers (kilometers from the mouth, Rkm) 572 and 605 because this area supports large numbers of rearing juvenile fall Chinook salmon and contains a range of geomorphic and hydraulic features. Steep bluffs bound the northern and northeastern side of the river in the upper half of the study area, and there are numerous alluvial islands. The average channel width is about 0.7 km, depths typically are less than 10 m, and the longitudinal elevation change along the channel is less than 1 m/km. The bed is composed primarily of gravel and cobble size sediment (Dauble and Geist, 2000). The riparian community is relatively sparse and is composed predominantly of forbs, grasses, and a few shrubs and trees (Fickeisen et al., 1980).

Methods

SHOALS Survey

We required a high-resolution, digital elevation model of the study area for two-dimensional hydrodynamic modeling and a geographic information system (GIS)-based analysis of juvenile fall Chinook salmon rearing, stranding, and entrapment areas. For this reason, we contracted with the U.S. Army Corps of Engineers to conduct a SHOALS survey of 33 km of the Hanford Reach between Rkm 572 and 605 during the first week of August 1998. The SHOALS system we used was able to rapidly collect highly accurate elevation data over a large area both above and below the water surface (Guenther et al., 1996; Lillycrop et al., 1996; Parson et al., 1996). A LiDAR surveying unit was attached to the bottom of a helicopter whose position and altitude were determined using

a kinematic global positioning system (GPS). Kinematic GPS base stations were established at three locations over National Geodetic Survey benchmarks to reference all data to known elevations and geographic positions. Surveys were flown at an altitude of 200 m above the river to obtain a density of one sample point for every 16 m² (4×4 m cell). Horizontal accuracy of positions was ≤ 1 m, and vertical accuracy was ≤ 12 cm (Lillycrop et al., 1996).

We limited our SHOALS survey to shoreline areas because they contain important rearing habitats for juvenile fall Chinook salmon (Becker, 1973; Dauble et al., 1989). We surveyed the area between shorelines created at flows of 50 and 400 kcfs, which encompass the range of flows typical during the fall Chinook salmon rearing period. The survey area bounded by these flows was determined from a one-dimensional flow model (MASS1) developed for the Hanford Reach (Richmond and Perkins, 1998). MASS1 is a steady-state model that estimates water-surface elevations and mean cross-sectional velocities for a given input flow. We had hydrosystem operators reduce Columbia River flows to 50 kcfs in the Hanford Reach during our SHOALS survey to dewater as much of the river channel as possible to avoid problems associated with measuring elevations in water less than 1 m deep.

The SHOALS survey collected more than 2.2 million riverbed points, which were incorporated in GIS to create a bathymetric coverage of the study area. Because dense vegetation such as bushes and trees caused false elevations in our data, we manually removed these from the dataset and interpolated ground elevations for those areas. Video records collected during the survey confirmed the locations of dense vegetation. Because our survey did not cover the center of the river channel, we completed our bathymetric coverage using riverbed elevations collected every 27 m along cross sections spaced every 0.4 km throughout the study area (U.S. Army Corps of Engineers, unpublished data).

Rearing Habitat

The amount of rearing habitat available to juvenile fall Chinook salmon was estimated for a range of flows from Priest Rapids Dam. We defined suitable rearing habitat as having lateral bed slopes $< 40\%$ and water velocities < 0.4 m/s. These variables were the best predictors of fish presence in our spatially explicit analysis. We used a logistic regression model to predict the probability that fall Chinook salmon would occupy habitat cells (4×4 m created in GIS) that contained lateral bed slopes ranging from 0 to 40% (in 10% increments) and with water velocities ranging from 0 to 0.4 m/s (in 0.1 m/s increments; Tiffan et al., 2002). Cells with probabilities > 0.5 were deemed to contain suitable rearing habitat. The

lateral bed slope of each cell was calculated in GIS as a grid-based two-dimensional slope and was expressed as a percent (Burrough, 1986; Environmental Systems Research Institute, Inc., 1998). Depth-averaged water velocities were estimated for each cell under a range of flows likely to be encountered by rearing fall Chinook salmon. We modeled water velocities at 36 steady-state flows ranging from 50 to 400 kcfs in 10-kcfs increments using a two-dimensional hydrodynamic model (RIVER_2D; Ghanem et al., 1996; Tiffan et al., 2002). The hydrodynamic model also enabled us to identify topographic depressions in rearing areas that could potentially entrap fish when these depressions became disconnected from the main river channel. We calculated the total area of disconnected pools that were created in the study area when flows were decreased by 20 and 30 kcfs increments from each flow modeled. These are the daily-flow-reduction increments currently allowed by fishery managers to minimize the stranding and entrapment of juvenile fall Chinook salmon when mean daily discharge is less than 110 kcfs.

Stranding and Entrapment

SHOALS bathymetry data were used in conjunction with the MASS1 unsteady flow model to estimate shoreline locations for flows ranging from 40 to 400 kcfs in 10-kcfs increments. These were used to estimate the area of the riverbed dewatered by each 10-kcfs reduction in flow to guide the sampling and analysis of the juvenile fall Chinook salmon stranding and entrapment (Nugent et al., 2002a). Following flow reduction events, circular plots (344.4 m²) were randomly selected and sampled within the wetted area of a 40-kcfs flow band that bounded the affected area (Nugent et al., 2002a). Within each sample plot, field crews counted the number of alive and dead juvenile fall Chinook salmon that were stranded or entrapped in pools. Other data recorded at the sites included bird activity (i.e., tracks), entrapment water temperatures, dominant and subdominant substrate size and embeddedness (Platts et al., 1983), and vegetation density (absent, sparse, medium, or dense; Nugent et al., 2002a and 2002b).

The total number of juvenile fall Chinook salmon mortalities due to stranding/entrapment was estimated for the study area. We enumerated the number of dead fish in each sample plot and accounted for the number of plots in each flow band, the area of the flow band, the number of flow reductions that occurred during the study period, and the attenuation of the amplitude of the fluctuations in river flows as the flows move down through the Hanford Reach. A statistical analysis of these data was performed to estimate mortality and associated confidence intervals for the 1999 and 2000 sampling years (Nugent et al., 2002a and 2002b).

Results

Rearing Habitat

Our approach enabled us to make the first quantitative estimates of the amount of juvenile fall Chinook salmon rearing that exists at different flows in the Hanford Reach. We found the amount of juvenile fall Chinook salmon rearing habitat generally decreased as flows increased (fig. 2). Habitat area ranged from a high of 275 ha at a flow of 50 kcfs to a low of 125 ha at a flow of 400 kcfs. We summed the lengths of shoreline that contained suitable rearing habitat cells to determine what percent of the total shoreline was available to rearing fall Chinook salmon. The percentage of suitable shorelines also decreased as flow increased. For the entire study area, the percent of suitable shoreline ranged from 77 to 97% over the range of flows we modeled.

Our spatially explicit analysis also allowed us to identify how rearing habitat was distributed throughout the study area and how habitat area changed with flow fluctuations. Figure 3 provides a graphical example of available rearing area at Rkm 587. The steeper shoreline on the right side of the river contains less suitable area than the islands on the left side of the river where the velocities and lateral slopes are lower. Fish abundance generally was higher in habitats with high suitability than in lower quality habitats. Our evaluation showed that habitat area can change up to 8% daily under flow fluctuations currently allowed at Priest Rapids Dam.

Stranding and Entrapment

The area of disconnected pools that could potentially strand juvenile fall Chinook salmon in the Hanford Reach also varies with river flow. We were able to identify specific flows from which additional reductions caused the formation of a significant amount of entrapment pool area. We also were able to identify the areas that pose the greatest risk of entrapment to juvenile fall Chinook salmon both in terms of the size and number of entrapments created by different flow reductions. Figure 2 shows the amount of area potentially dewatered within each 10 kcfs-flow fluctuation zone for our study area. The area of shoreline exposed by flow fluctuations at lower river elevations (50–120 kcfs) is much larger than at higher fluctuation zones. However, the amount of shoreline exposed at some flow levels actually increases with increasing river elevations (i.e., 170–180 kcfs) suggesting steep banks may give way to flats or flood terraces. The extent of steep banks and flood terraces vary with river kilometer.

For the first time, we were able to estimate the stranding/entrapment-related mortality of juvenile fall Chinook salmon due to flow fluctuations over 36 km of river. We estimated 126,695 (95% CI = 50,724 – 200,666) fish were lost to stranding and entrapment in 1999, and an additional 381,897 (95% CI = 1,026 – 764,141) fish were placed at risk of mortality. In 2000, we estimated 72,362 (95% CI = 34,270 – 110,454) juvenile fall Chinook salmon mortalities were caused by stranding and entrapment with an additional 255,222 (95% CI = 17,743 – 492,701) fish placed at risk of mortality (Nugent et al., 2002a and 2002b).

Discussion

The SHOALS system enabled us to collect high-resolution bathymetry over a broad, complex geographic area in the Hanford Reach that supported the development of hydrodynamic models to estimate fish habitat attributes such as water velocity, depth, flow direction and turbulence, and meso-habitat features. These in turn were used to assess the amount and suitability of habitat under different flow scenarios. The approach we describe will enable fishery scientists to predict the effects of different river operations and management actions on fish habitat use and survival.

Our use of the SHOALS system represents the first use of this technology in the Columbia River Basin. Since that time, the remainder of the Hanford Reach was surveyed with the “next generation” SHOALS technology (Compact Hydrographic Airborne Rapid Total Survey (CHARTS); Heslin and Lillycrop, 2003), and about 160 km of Hells Canyon on the Snake River was surveyed with a LiDAR system (Idaho Power Company, 2002). A number of factors contributed to the success of the SHOALS survey of the Hanford Reach and should be considered in other applications. First, we were able to have river flows reduced to their minimum levels for the survey. This ensured that all shoreline rearing areas were dewatered, which improved the quality of our data. Second, terrestrial vegetation is relatively sparse so the false elevations these produced were removed without too much effort. However, vegetation density may be of greater concern in other applications, in which the advantages of vegetation-penetrating LiDAR may need to be weighed against those of water-penetrating LiDAR. Finally, a number of geographic and elevation benchmarks existed along the river that facilitated accurate geo-referencing of our data.

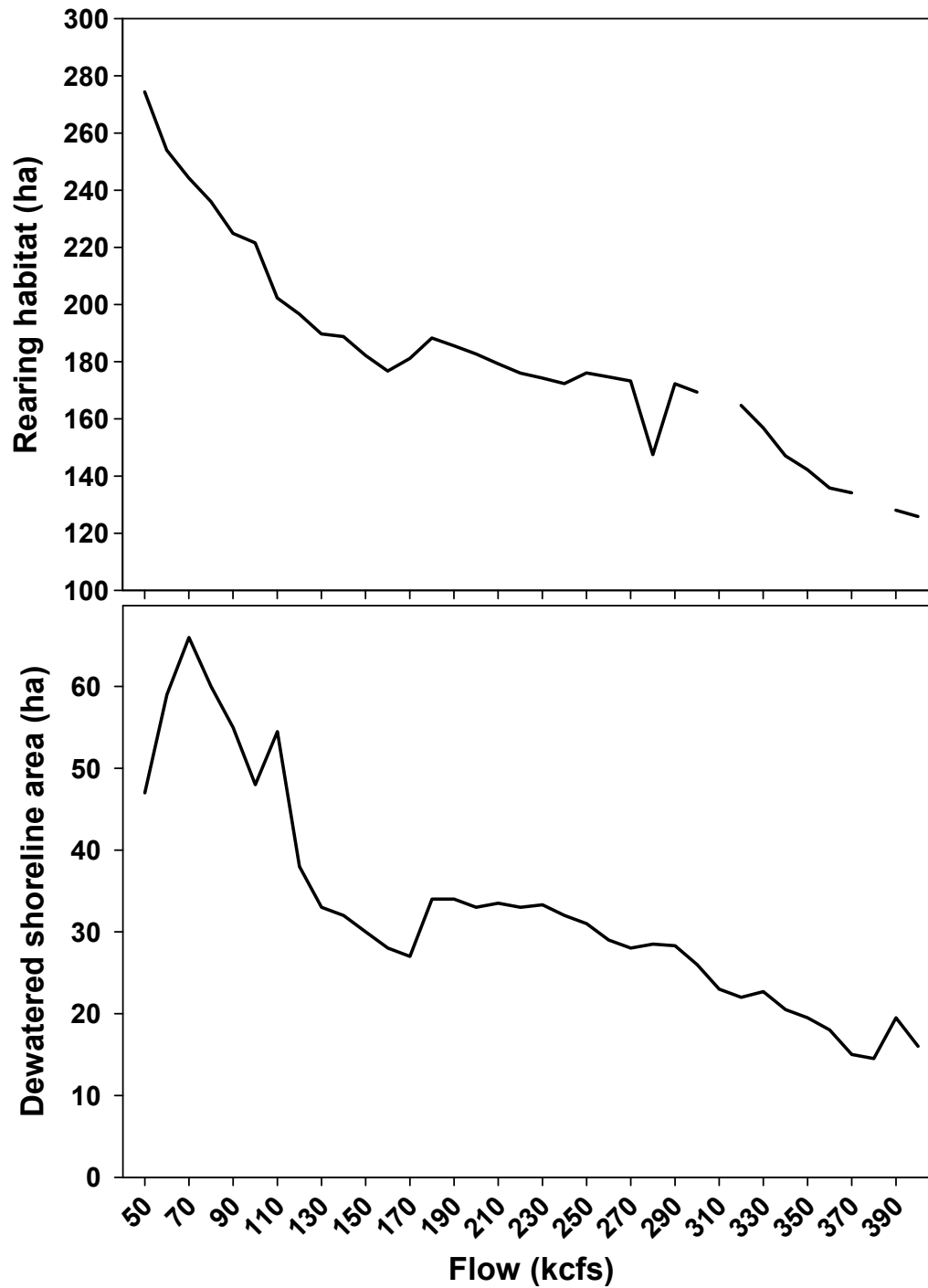


Figure 2. The amount of juvenile fall Chinook salmon rearing habitat (top panel) estimated at various flows in the Hanford Reach of the Columbia River. The bottom panel shows the amount of shoreline area that is dewatered by reducing flows in 10-kcfs increments from the flows shown on the X axis. Data are presented for that portion of the Hanford Reach between river kilometers 572 to 605 that was surveyed with the SHOALS system.

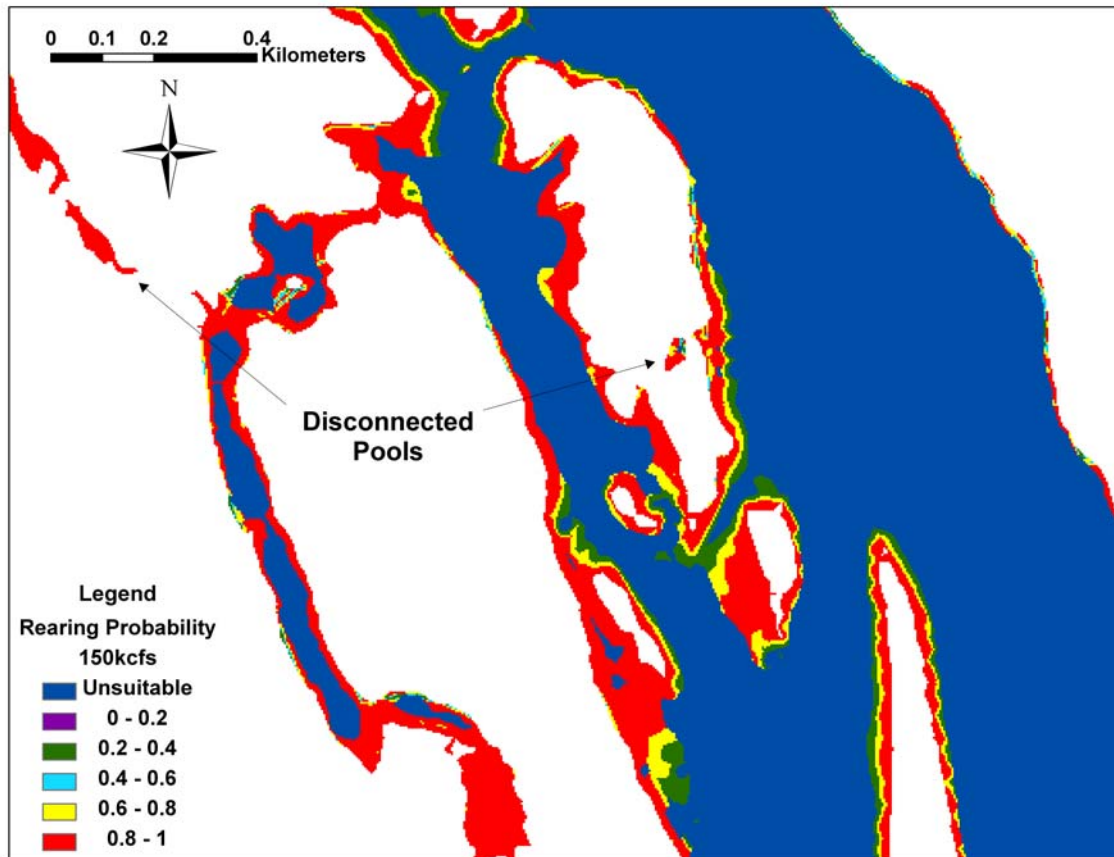


Figure 3. A GIS display of subyearling fall Chinook rearing area and entrapment pools at Rkm 587 in the Hanford Reach study area at a modeled flow of 150 kcfs. High probability areas (red and yellow) represent suitable rearing habitat. The dark blue represents unsuitable habitat where the water was too deep or fast for rearing.

Our analysis of juvenile fall Chinook salmon rearing habitat demonstrates the utility of combining remotely sensed bathymetry data with hydrodynamic modeling and a predictive statistical model to quantify habitat over at a large spatial scale. A GIS-based analysis enabled us to use our logistic regression model (developed at the scale of the individual fish) to make inferences at the landscape scale. This made it possible to quantify suitable habitat beyond the local field sampling unit and identify important rearing areas such as at 100F and Locke islands (fig. 1) by virtue of the greater distribution of suitable habitat found there compared to other areas. This type of analysis also enables one to quantify the distribution and connectivity of habitats in situations where actual field assessments of habitat are not possible. For example, Tiffan et al. (2006a) quantified changes in juvenile fall Chinook salmon rearing and migratory habitat in John Day Reservoir of the Columbia River under two different drawdown scenarios. This would not have been possible without the modeling approach we describe here. Being able to take a landscape level view of habitat changes due

to natural or anthropogenic causes is critically important for fishes, particularly migratory species such as salmon that move over great distances.

The geographic bathymetry data we collected with the SHOALS system facilitated a spatially explicit analysis using GIS. However, we were only able to consider important rearing habitat variables that could be incorporated into GIS, which limited our ability to fully characterize juvenile fall Chinook salmon rearing habitat. Incorporating lateral bed slope and water velocity in GIS was relatively easy because these variables could be estimated for the entire study area. In contrast, the transient nature of temperature and other time-varying determinants of habitat use by juvenile fall Chinook salmon (Tiffan et al., 2006b) could not easily be included in GIS-based analyses. Another variable that was not included was submerged terrestrial and aquatic vegetation. This multi-dimensional variable (e.g., height, density, area) also would be difficult to include in a spatially explicit analysis of a study area the size of ours. The compatibility habitat variables with GIS should be considered in future assessments using similar methodologies.

One of the consequences to juvenile fall Chinook salmon of changing habitat conditions caused by fluctuating flows in the Hanford Reach is stranding or entrapment in disconnected pools (Wagner et al., 1999). Consequently, mortality of stranded and entrapped fish is often high depending on pool size, drainage rate, exposure to lethal temperatures due to solar warming, exposure to predators, and time to reflooding and liberation. Our collection of high-resolution bathymetry data allowed us for the first time to evaluate the impacts of daily flow fluctuations from Priest Rapids Dam and generate seasonal mortality estimates. Using a one-dimensional hydrodynamic model to estimate shoreline locations at any given flow, we were able to calculate the area dewatered by incremental decreases in flow. Deploying field crews was necessary to collect field samples in order to extrapolate mortality estimates. GIS coverages of dewatered areas caused by flow drops were invaluable in refining search areas for field crews and creating randomized sampling strategies. However, a significant challenge we encountered was effectively sampling 36 km of river with a small number of field crews. This is likely to be a recurring problem in other broad-scale habitat assessments where limited effort is available for field verification of fish habitat use or operational effects. In such instances, a random stratified sampling approach would be beneficial.

Our data collection and analyses ultimately led to the implementation of a long-term protection plan for juvenile fall Chinook salmon in the Hanford Reach. In 1999, the first “Interim Agreement for the Hanford Reach Fall Chinook Population” was negotiated (Wolf, 1999) with the Grant County Public Utility District which operates the Priest River Dam. A Policy Team consisting of the “Joint Fisheries Managers” worked for over a year-and-a-half with the SHOALS data and study results to develop a plan to reduce stranding and the mortality associated with rapid flow fluctuations. These discussions consisted of a system-wide operations review due to the constraint on specific actions Grant County and the Priest Rapids Dam operations could implement. Subsequently, annual interim plans were updated based on new information. Ultimately, a long-term plan was derived and associated with the Vernita Bar Agreement—an agreement to protect pre-emergent juveniles. This combined plan now provides a single management framework for protecting spawning adults, pre-emergent, rearing, and outmigrating juveniles (Hoffarth, 2004). This plan specifies the operational constraints that operators of Priest Rapids Dam must abide by to limit fluctuations that would minimize stranding and entrapment events. Specific monitoring protocols are defined with integrated feedback mechanisms that inform hydro and fishery managers of the efficacy of the protection program. This adaptive management approach facilitates in-season operational corrections and policy decisions when field monitoring finds that juvenile fall Chinook salmon are adversely affected. This study provides

a model of how remote sensing technology can be used to lay the foundation for an effective monitoring program. Such monitoring programs form a critical link between the status of natural resources and the policy makers tasked with protecting those resources.

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