RESOURCE SELECTION STUDIES IN THE COLUMBIA AND SNAKE RIVERS: RECENT APPLICATIONS AND FUTURE NEEDS

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Abstract: Resource selection models are being developed and used, often in conjunction with predictive hydraulic models, to address critical questions about the management of juvenile Pacific salmon (*Oncorhynchus* spp.) and resident fishes in the Columbia and Snake rivers (Northwestern USA). Research in these large rivers has been "application-oriented," and model results are used by policy-makers and managers to plan water budgets and construction near dams that influence the survival of juvenile salmonids. Two specific studies are reviewed: In the first case, we developed a model to predict habitat use by juvenile fall chinook salmon in the Hanford Reach, one of the few unimpounded reaches of the Columbia River. This model has been used to predict the area of suitable rearing habitat and potential stranding habitat for juvenile salmonids during variable river flows. In the second case, we described how resource selection models are being developed using radio-tagged predators and juvenile salmon, particularly in dam tailraces. Resource selection models have been useful, although some situations may require individual-based or hybrid models to capture density-dependent interactions or complex behaviors. Radio tags that enable the collection of frequent (15-minute intervals, e.g.) data on the depth and temperature of fish over long periods (months) may become valuable in future resource selection models.

Key words: resource selection, models, Columbia River, salmon, predation, Snake River, stranding, northern pikeminnow

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Fishery issues in the Columbia River Basin (Northwestern USA) are largely focused around the recovery of anadromous salmonids (*Oncorhynchus* spp.), which have declined dramatically during the last 150 years (Lichatowich 1999). Thirteen stocks of salmon and steelhead (*O.* mykiss) are listed as threatened or endangered under the federal Endangered Species Act. The causes for their are hotly debated, but loss of habitat due to land use practices (logging, mining, urbanization, etc.) and damming of the mainstem Columbia and Snake rivers, which impedes both juvenile and adult migration, are commonly considered to be major factors (National Research Council 1996; Lichatowich 1999). Dams and water management practices in these large mainstem rivers have resulted in altered hydrographs, increased water temperatures, reduced water velocities, and other changes that disrupt the patterns of migrating salmon. Recovery of salmon populations is a high priority in the Columbia River Basin because salmon are very important to the economy, culture, and society of this area. Thus, results of large research projects and modeling studies are being used to make decisions about seasonal water management, fish passage designs at dams, predation on juvenile salmonids by fish and birds, and the impact of dams on downriver spawning habitats, which will hopefully lead to salmon recovery.

Until recently, fish habitat assessments have relied on physical habitat models, such as PHABSIM (Bovee 1982). PHABSIM incorporates one-dimensional flow models and biological models to predict habitat availability in terms of weighted usable area (WUA). However, PHABSIM has the drawback of simplistic hydraulic assumptions and often requires a major field effort (Ghanem et al. 1996). Recent technological advances in remote sensing and computers make it possible to use more refined tools (e.g., two-dimensional hydrodynamic models, geographic information systems [GIS]) to provide detailed and realistic habitat assessments with less effort (Leclerc et al. 1995). Logistic regression is becoming more widely used in aquatic resource selection studies, particularly when the response variable is dichotomous (Murtaugh 1988; Beauchamp et al. 1992; Yu et al. 1995; Kruse et al. 1997). Applications of logistic regression in conjunction with hydrodynamic modeling and GIS have been demonstrated by Guay et al. (2000) and Tiffan et al. (2002). This can provide a powerful approach to investigating resource selection, especially when lotic habitats are modeled in an unsteady state.

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Most fish habitat assessments in this basin and other regions involve model-building for individual species, usually disregarding inter- and intra-specific interactions such as competition, predation, or aggregation. This approach may work in many applications, but species interactions, and the need to consider spatial scales associated with these interactions, may require new approaches and flexible models. For example, managing predator-prey interactions in a dam tailrace may require an understanding of the hydraulics of the tailrace, fish passage patterns, fish densities in different areas, and seasonal variations in these factors (Petersen and DeAngelis 1992; Isaak and Bjornn 1996; Martinelli and Shively 1997). The mixture of physical characteristics and species interactions may make it difficult to model and predict distribution patterns and feeding behavior of fish species in large rivers such as the Columbia or Snake rivers.

In this paper, we discuss two specific examples of resource selection modeling being conducted in the Columbia River and its largest tributary, the Snake River. The first example considers juvenile salmonids in the Hanford Reach of the Columbia River and their response to a hydraulic environment that is highly variable over short time periods. The second example reviews some of our efforts to develop useful models of predation on juvenile salmonids. Suggestions are offered for future work using various models and new types of data. We emphasize our own research in these areas, and do not attempt to review all the studies or data with respect to resource selection modeling in this large basin. Our intention is to present examples and discuss some new, potential data sources, with the hopes of spurring an exchange of ideas among researchers in other rivers, or those with new analytical methods.

STRANDING OF JUVENILE FALL CHINOOK SALMON IN THE HANFORD REACH

The Hanford Reach is the only unimpounded section of the Columbia River between Bonneville Dam and the Canadian border, and supports the largest population of fall chinook salmon (*Oncorhynchus tshawytscha*) in the Columbia River Basin (Huntington et al. 1996; Dauble and Watson 1997). Each year the Hanford Reach produces an estimated 20-25 million subyearling salmon (Paul Hoffarth, Washington Department of Fish and Wildlife (WDFW), unpublished data), which rear along shallow main-stem shorelines for 2-4 months before migrating seaward during the summer.

Upstream hydroelectric dams regulate flows through the Hanford Reach; 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 tailwater elevations to fluctuate more than three vertical meters in 6 h (U.S. Geological Survey (USGS), gage station 12472800, unpublished data). These fluctuations can potentially change the amount of rearing habitat available to subyearling 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, which can result in significant mortality of young salmon (Wagner et al. 1999). The objective of this study was to develop a predictive model to quantify the effects of flow fluctuations on the amount of subyearling fall chinook salmon rearing habitat and stranding area.

Our approach included remote sensing to collect riverbed bathymetry, two-dimensional hydrodynamic modeling, development of a predictive statistical model, and a spatially-explicit analysis. High-resolution bathymetric data was collected during a Light Detection and Ranging (LIDAR) survey of 33 km of the Hanford Reach. This served as a platform for conducting hydrodynamic modeling and for calculating lateral bank slopes. We used a two-dimensional hydrodynamic model (RIVER_2D; Ghanem et al. 1996) to estimate depth-averaged water velocities and wetted area for 36 steady-state flows ranging from 1,416 to 11,328 m^3/s. Bathymetric data, estimated water velocities and depths, and other physical habitat data were put into a GIS for subsequent analysis.

We developed a resource selection function (RSF) to determine the relationship between subyearling fall chinook salmon presence and physical habitat. Fish were collected in shoreline habitats using point electrofishing (Persat and Copp 1990), and the physical habitat was measured at each sampling point. We constructed a multivariate logistic regression model (Hosmer and Lemeshow 2000) to predict the probability, P_i, of subyearling fall chinook salmon presence in i nearshore habitat cells given habitat characteristics of each cell. P_i can be expressed as:

$$P_i = \frac{e^{g(x)}}{1 + e^{g(x)}}$$

where $g(x)$ is the linear combination of parameter estimates of the predictor variables. Univariate analyses were first conducted to determine the significance of each variable before proceeding with a backward elimination process to arrive at the final multivariate model (Hosmer and Lemeshow 2000). Because the assumption of linearity between the predictor and the logit (Demaris 1992) was violated for gradient and velocity variables, they were modeled as design variables following Hosmer and Lemeshow (2000) and Hardy (1993). We only considered habitat variables that were compatible with a GIS, which included water velocity, depth, distance to shore, substrate, lateral slope, and sample site location. The location of each sampling site (river kilometer location) was included to account for spatial autocorrelation in our data (Legendre 1993; Knapp and Preisler 1999). The fit of our final model was evaluated using the Hosmer-Lemeshow statistic (Hosmer and Lemeshow 2000) and its performance was evaluated using cross-validation (SAS 1998). Cross-validation classifications were tested against those expected by chance by means of Cohen's *kappa* statistic (Titus et al. 1984).

We predicted the quantity of subyearling fall chinook salmon habitat in our study area at different river discharges by analyzing the GIS data with the logistic regression model. Habitat attributes of each GIS cell were used in the logistic regression model to obtain the probability of fish presence in each cell. Habitat cells with probabilities greater than or equal to 0.5 were considered suitable for rearing subyearling fall chinook salmon, and their areas were summed to determine the total amount of potential rearing area at each flow. Finally, the area of disconnected pools that could strand fish were summed for each 566 m^3/s and 850 m^3/s decrease from each flow modeled, which are reductions currently allowed under an interagency protection plan for juvenile fall chinook salmon.

Lateral slope and velocity were the only variables included in our final logistic regression model, which was represented by $g(x) = -3.19 + 2.23V_1 + 2.45V_2 + 1.96V_3 + 2.66S_1 + 2.42S_2 + 2.28S_3 + 1.04S_4$. Variables $V_{1\text{-}3}$ represented velocities of 0-0.1, 0.1-0.2, and 0.2-0.4 m/s, respectively, and variables $S_{1\text{-}4}$ represented slopes of 0-10, 10-20, 20-30, and 30-40%, respectively. Velocities >0.4 m/s and slopes >40% served as reference categories. The Hosmer-Lemeshow statistic for our final model, 0.7613 (P = 0.9931, 6 df), indicated a good fit to the data. The correct cross-validation classification of fish presence and absence in rearing habitats was 76% using a probability level of 0.5. The *kappa* statistic indicated that correct classifications were 41% better than those expected by chance and that they were significantly different from zero (*kappa* = 0.41; 95% CI = 0.29-0.54; P < 0.0001). The number of subyearling fall chinook salmon caught or observed in rearing habitats during shoreline electrofishing increased as the probability of fish presence increased. With the exception of three observations, catches greater than 100 fish were only associated with probabilities greater than 0.8.

Our estimates of the amount of subyearling fall chinook salmon rearing habitat generally decreased as flows increased. The greatest decreases occurred as flows increased from 1,416 m^3/s to about 4,531 m^3/s and from 9,062 m^3/s to 10,195 m^3/s (Figure 1). The percentage of suitable shoreline for rearing also declined with increasing flow, and ranged from 77% 11,328 m^3/s to 97% at 1,416 m^3/s. The inverse relationship between rearing habitat and flow results from shallower near-shore slopes and reduced water velocities at lower flows contributing to higher estimates of suitable habitat. In contrast, at higher flows water velocities were generally greater and the shorelines were located on steeper banks (higher lateral slopes) due to fuller river channels. In addition, many of the islands that provided rearing area at low flows were submerged at high discharges.

The consequence of this flow habitat relationship is that low-flow years may support more rearing fish in the Hanford Reach than higher-flow years because of the increase in available habitat. For example, the mean flow for May (typically the month of peak abundance) 2001 was 1,812 m^3/s, whereas in 1999 and 2000 it was about 4,701 m^3/s for both years. This resulted in an additional 70 ha (39% increase) of rearing area available to subyearling fall chinook salmon in our study area in 2001. This may have contributed to the catch of 37,023 subyearling fall chinook salmon in index beach-seine sites in 2001 compared to the catches of 7,269 in 1999 and 5,262 in 2000 (Paul Hoffarth, WDFW, unpublished data).

The area of disconnected pools that could potentially strand subyearling fall chinook salmon in the Hanford Reach also varied with river discharge. The amount of stranding area increased as flows rose from 1,416 m^3/s to 3,682 m^3/s and then sharply declined as flows increased to 5,381 m^3/s (Figure 1). We determined the amount of stranding area formed during 566 m^3/s and 850 m^3/s decreases from each river flow modeled. A 566 m^3/s drop in flow produced the greatest amount of stranding area at flows ranging from 3,965 m^3/s to 5,381 m^3/s (Figure 1). Flow reductions of 850 m^3/s resulted in the creation of the most stranding area between flows of 5,381 m^3/s and 5,664 m^3/s (Figure 1).

Our approach allowed us to identify the extent to which stranding pools are created over a range of flow reductions. Wagner et al. (1999), studying stranding in the Hanford Reach, found that most (99%) subyearling fish were stranded in pools rather than on exposed substrate. The potential for high stranding-related mortality prompted fishery and hydroelectric managers to implement protective measures for Hanford Reach fall chinook salmon in 1999. Under the current program, hydroelectric operations are not constrained when average weekly flows exceed 4,814 m^3/s, except that a minimum hourly flow of 4,248 m^3/s has to be maintained at Priest Rapids Dam.

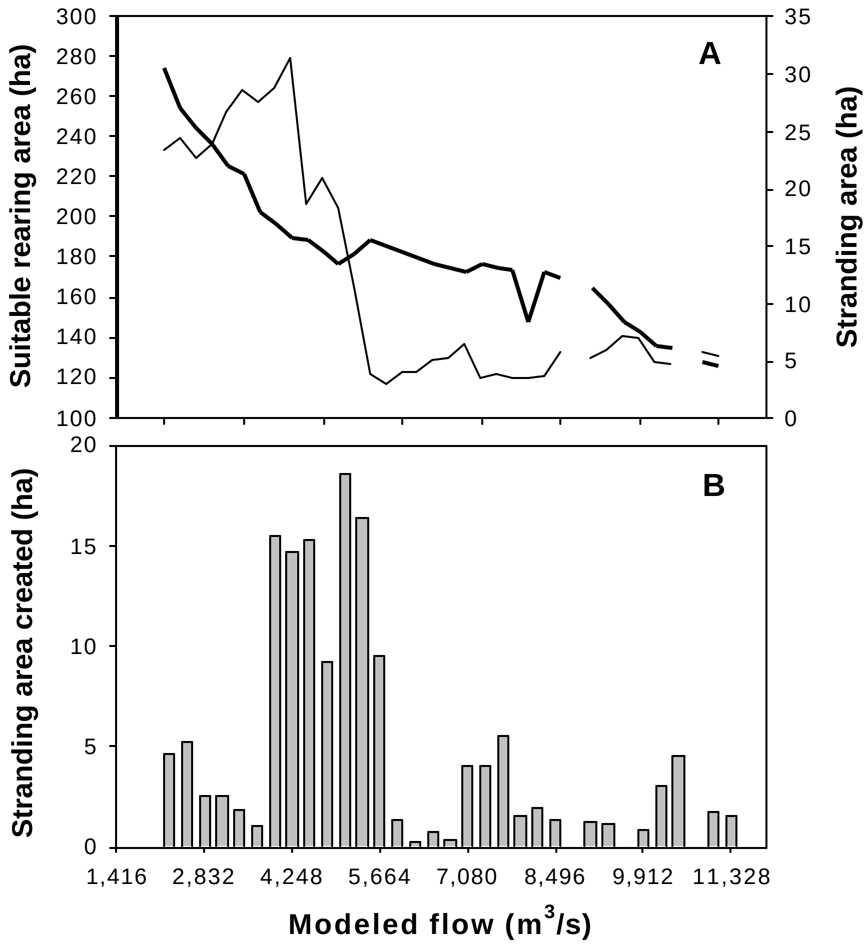

Figure 1. The relationship between the amount of suitable rearing area (heavy line, panel A) and stranding area (light line, panel A) for subyearling fall chinook salmon and modeled steady-state flows. Panel B shows the net stranding area created from 850-m^3/s reductions in flows in the Hanford Reach. Bars are additive in 850-m^3/s increments.

However, our analysis suggests that decreases in flow may still be a significant stranding threat to subyearling fall chinook salmon at flows up to 5,664 m^3/s. For example, on April 26, 2000, the flow at Priest Rapids Dam dropped from 7,958 m^3/s to 4,276 m^3/s in 8 h, which created 26 ha of stranding area (Figure 1). On the next day, over 1,900 subyearling fall chinook salmon were found stranded in seven small pools whose total area was less than 0.2 ha (Paul Hoffarth, WDFW, unpublished data). This represented a fraction of the total number of fish that may have been entrapped throughout the Hanford Reach from this flow reduction. In spite of current protective measures, an estimated 1.6 million subyearling fall chinook salmon died because of stranding in 2001 (Paul Hoffarth, WDFW, unpublished data).

DEVELOPING PREDATOR-PREY MODELS IN THE COLUMBIA AND SNAKE RIVERS

Along with passage mortality at dams, predation is the major source of mortality for juvenile salmonids in the mainstem Columbia and Snake rivers (Ward et al. 1995; Collis et al. 2001). Northern pikeminnow (*Ptychocheilus oregonensis*), which are large fish in the minnow family (Cyprinidae), are believed to be the most important predator in many parts of the system, and a management program has been in place since 1991 in an effort to reduce predation losses caused by this species (Beamesderfer et al. 1996). Predation by northern pikeminnow, smallmouth bass (*Micropterus dolomieui*), walleye (*Stizostedion vitreum vitreum*), and channel catfish (*Ictalurus punctatus*) may be particularly intense in the forebay and tailrace zones of large mainstem dams (Vigg et al. 1991; Ward et al. 1995). A variety of models and techniques have been developed to estimate the magnitude of predation (Rieman et al. 1991; Ward et al. 1995; Beamesderfer et al. 1996), although questions remain about the mechanisms and appropriate scales that have been implemented in these models (Petersen and DeAngelis 2000; DeAngelis and Petersen 2001; J. Anderson, University of Washington, unpublished manuscript). Resource managers within the region require estimates about the magnitude and location of predation losses, and mechanisms that might limit predation mortality so they can make decisions concerning predator control, hatchery release practices, potential temperature effects, and physical modifications near dams. Resource selection models are one type of model that has been applied, and continues to be developed, although the complex nature of the predator-prey interaction may require modeling approaches that can incorporate such variables as prey and predator densities. In this section, we summarize some of these complex predator-prey behaviors, describe recent modeling approaches, and offer a few opinions about the future directions of management models.

The behavior of predators in the two river systems has been described in numerous laboratory and field studies (Vigg et al. 1991; Tabor et al. 1993; Petersen and Gadomski 1994; Shively et al. 1996; many others). Here we discuss a few behaviors that may be particularly crucial for predator-prey modeling, emphasizing studies on northern pikeminnow. Predation on juvenile salmonids by northern pikeminnow, and likely other predators, appears to be strongly responsive to changes in salmonid density, whether the density change occurs at a dam, reservoir, or free-flowing part of the river system (Petersen and DeAngelis 1992; Tabor et al. 1993; Shively et al. 1996). Temporal and spatial changes in salmonid density may cause rapid changes as predators switch from non-salmonid to salmonid prey. Northern pikeminnows have been shown to feed on salmonids during discrete "bouts," which usually last for quite short periods of time (Petersen and DeAngelis 1992). Predator movements are also sensitive to a variety of variables, including changes in local prey density (Shively et al. 1996), dam operations (Faler et al. 1988; Isaak and Bjornn 1996; Martinelli and Shively 1997), reproductive state (Beamesderfer 1992; Martinelli and Shively 1997), and other factors that change drastically throughout the river system. Finally, there is some evidence of contagious distributions (aggregations) by northern pikeminnow, which may be a response to either physical conditions or prey patches (Petersen 2001).

A variety of studies have been conducted to describe the behavior of juvenile salmonids as they migrate downriver through the Columbia and Snake rivers, although much of this work has not been incorporated into predation models. Habitat and radio-telemetry studies suggest that most predators are shoreline-oriented (Martinelli and Shively 1997; J.H. Petersen, unpublished data). Juvenile salmonids are also found near shorelines in relatively shallow water except for some stocks that move offshore when they begin active downriver migration (Dauble et al. 1989). Predators such as northern pikeminnow often have mixed diets of salmonids, other fish, and benthic prey (Poe et al. 1991; Petersen and Ward 1999; Zimmerman 1999), suggesting that salmonids are temporally and spatially patchy. The exception to this pattern occurs in dam tailraces where predators often have a diet that is >90% juvenile salmonids for several months (Poe et al. 1991). The condition of juvenile salmonids may also influence their vulnerability to predators in the system (Mesa et al. 1994). Disease, physical stress from dam passage, and acute thermal stress are some factors that have been examined, at least in the laboratory, for their impacts on juvenile salmonid vulnerability (e.g., Gadomski et al. 1994; Mesa et al. 1998, 2002).

Models that include RSFs have been developed independently for predators and juvenile salmonids in a variety of habitats of the Columbia and Snake rivers (Table 1). The models that have been developed for juvenile salmon migrants have been largely based on local density data (point electroshocking, e.g.), and are associated with habitat variables within a GIS context (Tiffan et al. 2002; J. H. Petersen, unpublished analysis). One of these models is described in detail in the previous section. Predator RSF models have been developed for northern pikeminnow in free-flowing (C. A. Barfoot and J.H. Petersen, manuscript in preparation) and dam tailrace habitats (Petersen et al. 2001), although these models have not been rigorously tested and applied in management decision-making. RSF models for both predators and juvenile salmonid prey tend to have similar predictive variables (Table 1). The principal advantage of these types of models is that they can be driven by hydraulic models of the river system, thus providing a fairly well-accepted tool for predicting changes in physical conditions (depth and water velocity especially) and thus predator-prey distributions. Combined predator-prey RSF models are feasible for the same river reach, but have not at this time been implemented. Disadvantages of RSF models for predator-prey systems in large rivers include the relatively high cost of field data in many cases (LIDAR flights, long-term radio-telemetry studies) and their lack of consideration of density-dependent processes.

Individual-based models (IBMs) of predator-prey systems are an alternative to RSF models, because IBMs have the potential to include density-dependent processes. IBM's keep track of individual members or subclasses (e.g., size groups) of a population through a period of time, describing, for example, feeding encounters, capture success, predation risk, and growth (DeAngelis and Gross 1992). The principal advantages of IBM's are their ability to include density-dependent processes and the fact that they can consider the "state" of individual animals (satiation, e.g.). Individual-based models of northern pikeminnow and juvenile salmonids have been developed and used to examine questions about the predator's feeding rate in response to prey density (functional response) and light, the role of predator and prey sizes, salmonid response to dissolved gas, and the importance of spatial scale for estimating predation rates and losses (Petersen and DeAngelis 1992, 2000; Petersen and Gadomski 1994; DeAngelis and Petersen 2001; Scheibe and Richmond 2002). These models have provided insight into feeding patterns on juvenile salmonids and the need to consider the size of model cells, but they have not been used in applied management scenarios. Many authors have noted that IBM's are theoretically appealing, however they have the disadvantages of being complex and requiring large datasets to develop and parameterize. Other approaches to modeling predator-prey interactions in the Columbia and Snake rivers have been used, but the RSF and IBM approaches can be implemented in a spatially explicit framework, which is often necessary for specific management questions.

This review of RSF and individual-based modeling approaches for predator-prey interactions is not meant to promote one over the other, but shows some of the weaknesses and strengths of the two methods. For example, the strong response of predators to dynamic changes in prey density may be difficult, but perhaps not impossible, to implement into an RSF approach and the RSF models are simpler than IBMs. Well-developed IBMs may prove to be most useful in analyzing "patterns" of habitat selection as was recently demonstrated by Railsback and Harvey (2002) with small-stream salmonids. Habitat selection patterns confirmed with an IBM might then be compared to observed field data or compared to predicted patterns from an RSF model. The behavior of fish predators in the Columbia River is moderately well understood, having been studied intensively for about the last 25 years, so IBM's could be developed. There also appears to be opportunities to improve our understanding of the fine-scale behavior of predators and their prey in this system using conventional fisheries techniques and telemetry methods that allow researchers to track individual fish (Faler et al. 1988; Isaak and Bjornn 1996; Martinelli and Shively 1997). For example, we recently (2002) conducted a study in the tailrace of The Dalles Dam where two predator species (northern pikeminnow and smallmouth bass) were tagged and tracked concurrently with radio-tagged juvenile salmonid prey. From this information we hope to build a better understanding of predator movements in response to local hydraulic conditions, season, river flow, and the migration pathways of salmonid prey.

DISCUSSION

Spatially-explicit models, whether they are based on RSFs or a set of fish behavior rules, are needed for decision-making by a variety of agencies with purview over salmon and management issues in the Columbia River and its tributaries. In addition to the two examples that we have described, recent work has been done on the fine-scaled patterns of adult salmon spawning in both the Hanford Reach and in the lower Columbia River (Geist et al. 2000; Garland et al. 2002). Optimal siting for the outfalls of juvenile salmonid bypass systems at several large dams is often based on expected predator behaviors in response to local water velocity and distances from structures (Shively et al. 1996). The successful development of juvenile salmon fish passage structures at dams is partially based on an understanding of how juvenile fish will respond to forebay flow patterns upstream of the dam during their approach to the structures. Since mainstem dams are unique structures, models that can predict approach patterns of juvenile salmon in a forebay may reduce the need for expensive prototypes. Predicting the impacts of reservoir drawdowns or dam breaching could also be made with spatially-explicit models that estimate the quality of local habitat and how they would change. Finally, complex models that predict how water temperature varies in these large rivers might be necessary if temperature refugia are important for migrating adult or juvenile salmon.

Table 1. Resource selection models that have been developed for predators and juvenile salmonid prey in the Columbia or Snake rivers. Symbols indicate either a significant (X; $P < 0.05$) independent variable or a variable that was tested and found to be not significant (NS; $P > 0.05$); blanks indicate the variable was not tested. X / NS is a mixed result when multiple models were fit. NPM = northern pikeminnow; SMB = Smallmouth bass.

	Near-dam habitats		Reservoir or free-flowing habitats	
Independent variable	Juvenile chinook salmon in dam forebay[1]	NPM in dam tailrace[1]	Juvenile chinook salmon[2]	NPM and SMB[3]
Water velocity	X	X	X	X
Water depth	X	X	NS	X
Direction of water flow	X / NS			
Distance to shore or structure	X	X	NS	X
Substrate type		X	NS	X / NS
Lateral slope of shore			X	
Season				X
Type of model	Logistic	Logistic	Logistic	Logistic

[1] J.H. Petersen, unpublished analyses
[2] Tiffan et al. 2002
[3] C. A. Barfoot and J. H. Petersen, manuscript in preparation

Advances in the application of RSF in large rivers should involve the responses of individual fish to a greater range of independent variables. Movements between habitat patches, responses to migratory prey or predators, and density-dependent behaviors are some of the mechanisms that may need consideration (Lima and Zollner 1996; Johnson et al. 2002). Improving our predictions about habitat "quality" and extrapolating model results to river reaches or populations, which is necessary for many management applications, will require incorporation of behaviors that describe individual movement. Lima and Zollner (1996) concluded that a major impediment to the development of better landscape-level models has been the different spatial scales at which animal movement and habitat selection have been studied. Considerations of the scale of habitat patches and the "state" of animals (satiation/hunger, e.g.) may be necessary to improve models. Radio-telemetry, to describe fish movement and distribution, and hydraulic models of river flows are two tools that can be combined to address some of these questions. Patch and scale analyses can be conducted on animal movement data collected from radio-tagged individuals (Petersen and DeAngelis 2000; DeAngelis and Petersen 2001; Johnson et al. 2002).

Advances in miniature electronics, remote sensing, and data acquisition have increased our ability to collect information about resource selection by fish in large rivers. Miniature electronics have resulted in temperature-sensing radio transmitters suitable for use in fish as small as 120 mm fork length. These tags make it possible to obtain thermal histories on migrating juvenile salmon, identify areas of thermal refugia, and develop resource selection functions that include local temperature change. Tiffan et al. (In press) used these tags to measure the thermal exposure of juvenile fall chinook salmon migrating through a lower Snake River reservoir during the summer. Another example is the use of acoustic tags to locate fish in three dimensions within a body of water. We have recently used the three-dimensional locations of juvenile salmon and modeled water velocities to better understand the approach paths selected by fish within the complex environment upstream of dams (Cash et al. 2002). Improvements in airborne (LIDAR) and satellite-based remote sensing allow application of resource selection functions over a broad spatial scale. This is particularly useful when resource selection is being studied at the landscape or population level. However, at this scale, the physical habitat data that feed into the resource selection function may come at a high cost for high-resolution data. Depending on objectives, it is now computationally possible to construct hydrodynamic models in one, two, or three dimensions, and in steady or unsteady states, at a larger scale than was previously feasible. When supported with the appropriate level of expertise to interpret the results, they can provide descriptions of flow useful at a landscape or population level.

Finally, relative survival estimates of juvenile salmonids that pass dams through different migrational pathways are becoming available (Counihan et al. In review), and these survival estimates could be used in model calibration or for testing specific hypotheses. Because of the high value placed on the recovery of salmon in the Pacific Northwest, a variety of large-scale fisheries studies are possible – our challenge will be in designing fruitful studies and building useful models that can predict patterns and aid in managing salmon recovery.

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