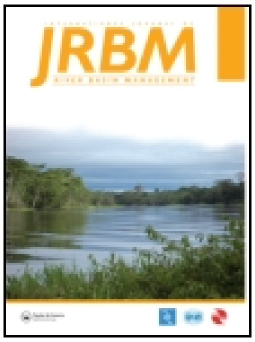

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Validation of chinook fry behavior-based escape cover modeling in the lower Klamath River

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ABSTRACT

An emerging trend in the state-of-the-art instream flow assessment applications is the use of three-dimensional channel topography coupled with two-dimensional hydrodynamic models. These components are most often integrated with biological response functions for depth, velocity, and substrate to simulate physical habitat for target species and life stages. These approaches typically involve the simple extension of the one-dimensional conceptual habitat models represented by the Physical Habitat Simulation System (PHABSIM) developed by the U.S. Fish and Wildlife Service (Stalnaker, 1995). However, as demonstrated in this paper, the physical habitat based template represented by high-resolution channel topography and two-dimensional hydrodynamic model outputs can extend these simple conceptual models of habitat to incorporate additional behavior-based decision rules. The approach demonstrated in this paper evaluates the spatial suitability of physical habitat for chinook fry based on the incorporation of behavioral rule sets associated with instream object cover (i.e., velocity refuges) and in-water escape cover type and distance. Simulation results are compared to simplistic based physical habitat simulations using only depth, velocity, and substrate and validated against independent fish observation data. Results demonstrate that the functional relationship between predicted habitat and discharge utilized in many instream flow assessments is significantly different when the additional behavior-based decision rules are applied.

Keywords: Behavior-based habitat modeling; instream flows; two-dimensional hydraulics; habitat model validation.

1 Introduction

An important focus of the emerging state-of-the-art in instream flow assessments is the development, testing, and application of methodologies that can assess the requirements of overlapping multidisciplinary components while meeting long-term monitoring and assessment needs required under adaptive management paradigms (Goodwin and Hardy, 1999; Annear *et al.*, 2004; NRC, 2005). This often dictates that data acquisition and analyses must span spatial scales from microhabitat, to mesohabitat, to the reach level, and finally to the broader spatial and temporal domains at the watershed level. This has forced current trends in research and applications toward more integrated data collection efforts and linkages between simulation tools often involving use of GIS. This trend in the use of GIS and integrated analysis systems provides an expanded set of modeling capabilities upon which more complex and integrated assessment and monitoring frameworks can be developed (Hardy, 1998; Hardy and Addley, 1999; Goodwin and Hardy, 1999).

Historical applications of physical habitat based modeling of fry salmonid habitat has been criticized for generating ‘irrational results’ that suggest that stream systems should be practically dewatered in order to maximize fry habitat. This arises in many studies based on the generated habitat versus discharge relationships that show substantial available habitat at irrationally low flows, reduced habitat over intermediate flows and then increases

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in habitat again at higher discharges (e.g., Orth and Maughan, 1982; Mathur *et al.*, 1985; Shirvell, 1986; Scott and Shirvell, 1987). These types of functional relationships between available habitat and discharge are counterintuitive to fisheries scientists' implicit understanding of how river systems function (see Annear *et al.*, 2004). Furthermore, utilization of these types of habitat relationships to set target instream flows that 'maximize' fry habitat result in flow regimes that are deleterious to overall aquatic ecosystem process and fail to maintain adequate ranges in flow variability embodied by the natural flow paradigm (Poff *et al.*, 1997; NRC, 2005).

Perhaps the primary factor for the irrational results obtained for salmonid fry modeling of physical habitat is the simplistic representation of the conceptual physical habitat models for these life stages. These models are usually based on biological response functions confined to depth, velocity, and substrate/cover functions. Although existing habitat simulation models such as the Physical Habitat Simulation System (Milhous *et al.*, 1989) have incorporated the use of adjacent stream attributes (e.g., conditional velocity and escape cover coding), their reliance on one-dimensional cross sections to represent the stream habitat is significantly constrained by restriction of the analyses to the lateral dimension on specific cross sections.

In this paper, we focus on the use of behavior-based decision rules derived from empirical measurements of chinook salmon (*Oncorhynchus tschawytscha*) fry for their affinity with escape cover and functional cover. The approach taken in this paper extends the commonly applied conceptual models of physical habitat based on depth, velocity, and substrate/cover by incorporating escape and functional cover relationships within a spatially explicit modeling domain of the river channel. In this context, escape cover is defined as any substrate, structural, or vegetative component or feature located within the water, or out of the water, but within 0.5 meters of the water surface, that an observed fish seeks out, or may seek out, for concealment, hiding, etc., in response to fright or threat. Functional cover refers to cover components (e.g., water velocity shelter) that influence a fish's daily activities (feeding, resting, etc.), and to which fish may select or orientate (Hardin *et al.*, 2005).

The modeling approach takes advantage of the high spatial resolution of the three-dimensional river channel topography, integrated results from substrate and vegetation mapping using GIS, and solutions derived from two-dimensional hydrodynamic modeling to develop a conceptual physical habitat model that incorporates attributes of adjacent stream properties at spatial scales consistent with observed reaction scales of the target species and life stage (i.e., fry). In essence, the developed conceptual habitat model evaluates the suitability of a stream location for chinook fry conditioned on the adjacent properties of the channel in terms of escape and functional cover types and escape cover distance. This research effort also highlights the use of field observations of fish distributions within multiple study sites and different flow rates to empirically validate the physical habitat modeling results.

2 Methods

2.1 River reach segmentation, habitat mapping and study site selection

The main stem Klamath River, California (Figure 1) was divided into river segments primarily based on the junctions of major

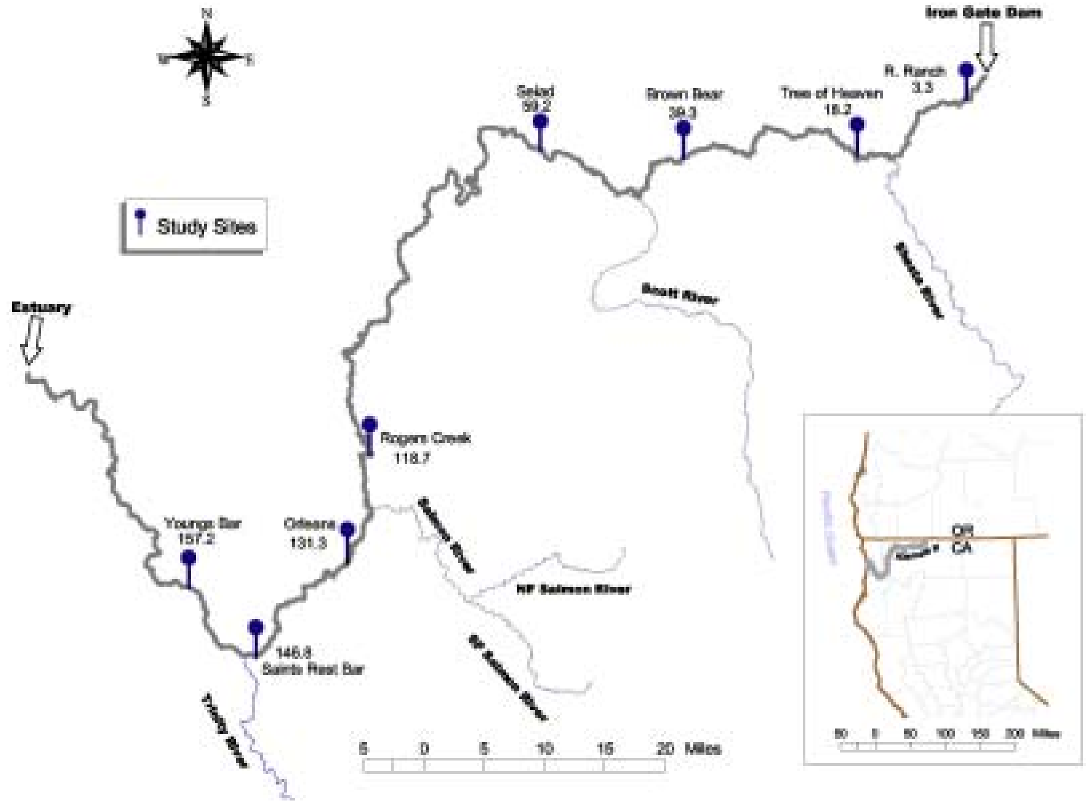

Figure 1 Study site locations and associated river miles within the main stem Klamath River.

Table 1 Criteria used to define mesohabitat types in the Klamath River.

Criteria	Mesohabitat Types				
	Pool	Run	Low slope	Moderate slope	Steep slope
Gradient[a]	–	$< 0.3\%$	$< 0.3\%$	0.3%–0.8%	$> 0.8\%$
Channel Width	–	Confined	Relatively unconfined	Moderately confined	Confined
Backwater	Yes	No	No	No	No
Substrate	Fines, sand, gravel	–	Gravel, small cobble	Large cobble, small boulders	Small and large boulders
Standing Waves	None	< 0.15 meters	< 0.15 meters	0.15 to 0.30 meters	> 0.30 meters

[a] Gradient = vertical drop/horizontal distance ×100.

tributary systems, and represented by generally homogeneous conditions of flow volumes and overall channel characteristics. Field-based mapping by the U.S. Fish and Wildlife Service of all mesohabitat types from Iron Gate Dam to the estuary was undertaken. Each mesohabitat unit was counted and assigned to a specific mesohabitat classification as defined in Table 1. GPS coordinates were determined for the start/end of each mesohabitat and the maximum water depth recorded with an acoustic bottom sounder. A laser range finder was used to determine lengths and widths of each mesohabitat unit. In addition, main channel, side channels, and split channel classifications were made. Whenever a split or side channel condition was encountered, mesohabitat mapping was conducted for the main channel and each side/split channel separately.

Within each river segment, habitat mapping results were used to select study sites such that all major habitat features available at the reach scale were present within the study site. At each study site, three to four control points were established as a control network. Points were placed in a non-linear alignment so that triangulations between points could be carried out to rectify coordinate positions. These points were used as horizontal and vertical control in the photogrammetry block adjustment process as described below. These control points permitted the rectification of all subsequent data collected at each study site to a standard map projection using GIS.

2.2 *Characterization of channel topography, substrate, and vegetation mapping*

Low elevation high-resolution aerial photograph stereo pairs (1:2400) were obtained at each study site during low flows to maximize the exposure of channel topographies. The stereo pairs were scanned at 12 μm (0.15 m/pixel) and the interior orientation of each image was set using reported camera calibration parameters. Standard soft-copy photogrammetry analysis techniques of the stereo pairs were used to derive digital terrain models (DTMs) for above water areas at each study site. The ground control points in combination with between image tie-points were used to perform a least-squares block bundle adjustment of all images. Statistics from this process were reviewed for accuracy with an allowable maximum Root Mean Square Error (RMS) of 1.0 or less. The resulting DTM's had coordinate accuracies in the range of 0.03–0.09 meters based on comparisons with known survey points within each study site. In some instances, where topographies in the stereo photography were obscured by riparian vegetation, the topography was delineated using standard survey techniques with a total station. Topographic sampling in these cases was approached using a systematic irregular sampling strategy that focused on delineating changes in the plan form topography. Digital orthophotographs were produced for each study site and used as a base map to overlay fish observations, substrate/cover mapping, hydrodynamic modeling (including computational meshes), topography contours, and fish habitat modeling results.

The hydro-acoustic mapping of the underwater channel topography was undertaken with a boat-mounted real time kinematic differentially corrected survey grade GPS system integrated with a scientific grade acoustic bottom profiling system. An acoustic doppler current profiling system (ADP) for measurement of the 3-dimensional velocity vectors throughout the water column was also integrated into the instrument package. The hydro-acoustic mapping was conducted at a discharge that was greater than the discharge at which the aerial photogrammetry was collected to ensure an overlap between the DTMs generated from these data sets and to minimize the potential for missing topographies where the acoustic mapping was limited by water depths at the stream margins.

The DTM data derived from the softcopy photogrammetry and the hydro-acoustic mapping were integrated with conventional survey data to generate a single spatially explicit terrain model for each study site. A smooth (gradually varying radius) stream centerline was overlaid on the DTM for a study site and used to create a curvilinear orthogonal mesh for use in the hydraulic modeling. The hydraulic model computational meshes at all sites contained nodes every 1.6 meters across the river and 1.7 meters in the longitudinal direction (i.e., up and down the river).

Substrate and vegetation distributions were mapped at each study site by delineating polygons on the color aerial photograph while traversing each study site. Where under water substrate could not be delineated by direct visual observation, snorkeling and underwater video were utilized. The field-derived distribution of substrate and vegetation were digitized in the laboratory and these polygon data were overlaid onto the orthophotographs using GIS in order to assign these attributes at each node of the computational mesh. This also permitted the assignment of spatially variable roughness values within each computational mesh for use in the hydraulic modeling. For each substrate or vegetation type, we associated an estimated hydraulic roughness height based on the particle size (or largest particle size when mixed substrates were delineated) or vegetation type in each substrate/vegetation category. In the case of substrates, the hydraulic roughness was based on a drag coefficient calculated from the roughness length (particle size) of each substrate category. In the case of vegetation, roughness was assigned according the morphometry and density of the vegetation delineated within a polygon (i.e., grass versus willows). Roughness values were assigned from published values in the literature (Chow, 1959; Arcement and Schneider, 1989). The three-dimensional representation of the R-Ranch study site is provided in Figure 2 and illustrates the integrated topography and hydraulic model solutions discussed next.

2.3 Hydraulic modeling

The hydraulic model was initially developed by the USGS and the technical description and underlying equations can be found in Nelson (1996), Thompson *et al.* (1998), Nelson *et al.* (1995), McLean *et al.* (1999) and Topping *et al.* (2000). The model solves the two-dimensional vertically averaged flow equations on an orthogonal curvilinear grid. It uses a spatially variable, scalar kinematic eddy viscosity turbulence closure that emphasizes the vertical diffusion of momentum. The model was written to accommodate spatially variable channel roughness and was modified in this project to enhance the wetting-drying algorithm and initial condition capabilities. These modifications were made to enhance computational efficiency during the iterative process of model calibration and improve overall simulation results. The model relies on 3-dimensional riverbed topography, flow rate, and stage (i.e., water surface elevations) boundary conditions to calculate flow, velocities, water surface elevations and boundary shear stresses in the channel.

At each study site, three sets of water surface and discharge estimates were measured for use in calibration of the hydrodynamic model. At each site the model was calibrated to measured water surfaces at the highest calibration flow by adjusting the roughness associated with the computational nodes. The roughness height assigned to specific nodes for substrate/vegetation was increased or decreased by a constant percentage globally over the computational mesh until the modeled water surface matched the measured water surface at the high calibration flow. The calibrated roughness was then used in subsequent simulations to verify model performance at the medium and low calibration flows. Water surface modeling results were generally within 1 to 5 centimeters over the entire spatial domain of each study site. Measured velocity readings were used to compare the simulated flow patterns and magnitudes to ensure modeled velocities were realistic when compared with observed flow fields. Where necessary, adjustments to the computational mesh and/or spatial roughness were made to achieve agreement between simulated and observed velocities.

2.4 Site-specific habitat suitability criteria

Habitat use data for chinook fry ($<$ 55 mm total length) were collected from the main stem Klamath River from Iron Gate Dam downstream to the Seiad study site during 1998 and 1999. A total of 2,498 observations were made for water depth, 2,252 for average water velocity, and 2,300 for substrate and escape/functional

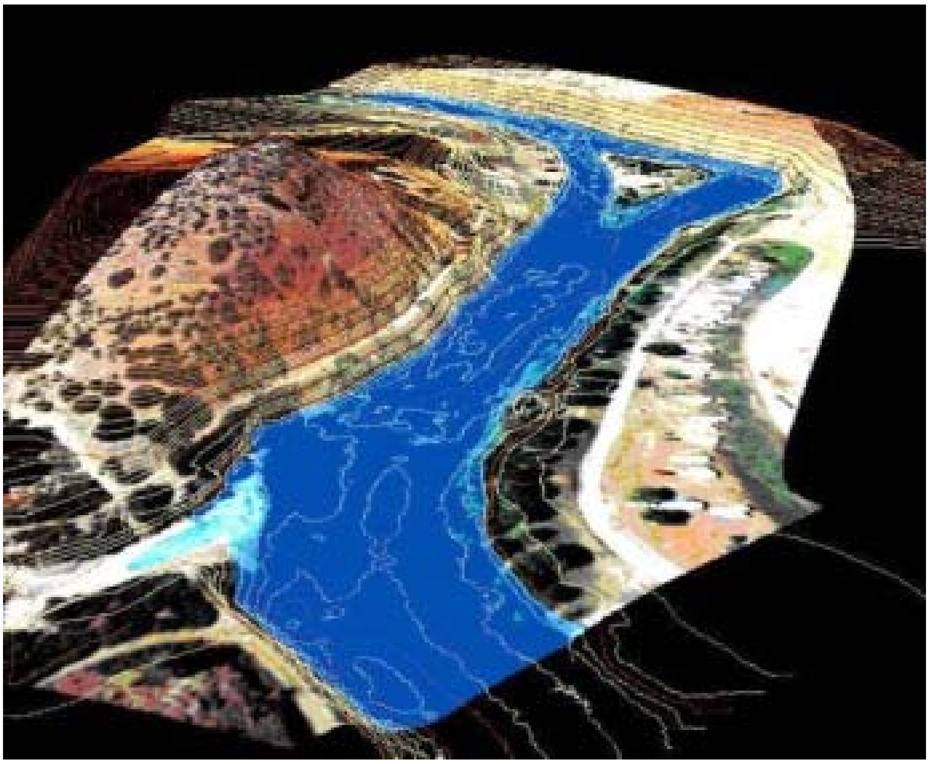

Figure 2 R-Ranch study site showing integrated three-dimensional channel topography and hydraulic model solutions (depth contours).

cover. Habitat Suitability Criteria (HSC) were developed for water depth and velocity, functional cover type, escape cover type, and distance to escape cover (Figures 3 through 5). The behavioral dependency for escape cover type and the distance to escape cover is illustrated in Figure 5. The data reflect the relatively small proportion of chinook fry found in association with substrate specific cover compared to the overwhelming number of observations associated with vegetation cover types. The data in Figure 5 also reflect the close association of chinook fry to escape cover where over 90 percent of all observations are within 0.6 meters of escape cover. These data suggest escape cover type and its proximity to the fish's focal point are key behavioral attributes necessary to model physical habitat quality and quantity and have been evaluated in this paper.

The habitat use field observations also demonstrated that chinook fry are closely associated with functional cover capable of producing a velocity wake (i.e., object cover). Chinook fry were not found to be associated with in-water or out-of-water overhead cover.

An independent empirical-based field assessment was undertaken to confirm chinook fry habitat use or distribution longitudinally and laterally within the river. This assessment examined fry distribution in respect to presence or absence of escape cover as well. This was accomplished through a combination of sampling techniques including direct and indirect (i.e., videography) underwater observations and electrofishing techniques. Direct underwater observations and electrofishing were used along the stream margin and longitudinal transects using underwater videography were used within the main river channel.

HSC for water depth and velocity were derived from the binned frequency data (0.06 meters for depth and 0.06 meters/second for velocity) using a three-point running mean to smooth to frequency distributions. No more than three iterations were utilized in the smoothing process. Escape cover

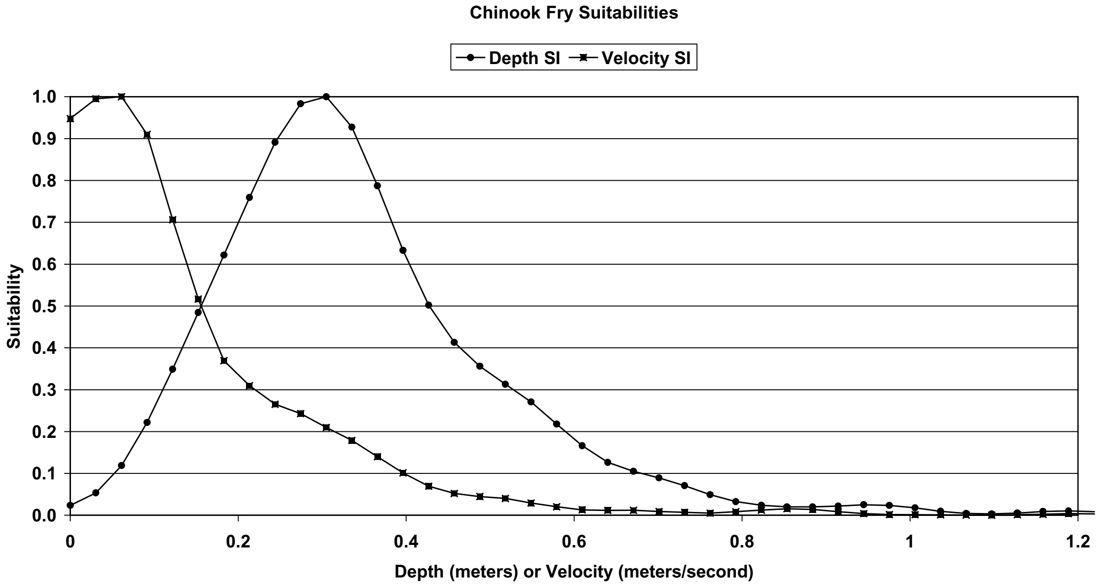

Figure 3 Habitat suitability criteria for chinook fry depth and velocity.

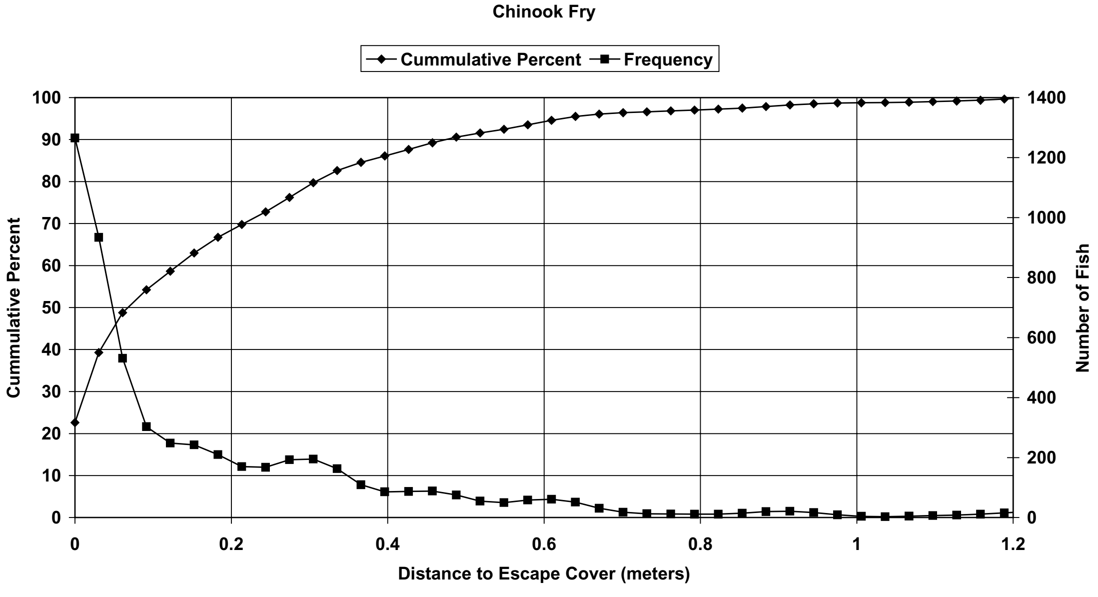

Figure 4 Habitat suitability criteria for chinook fry distance to escape cover.

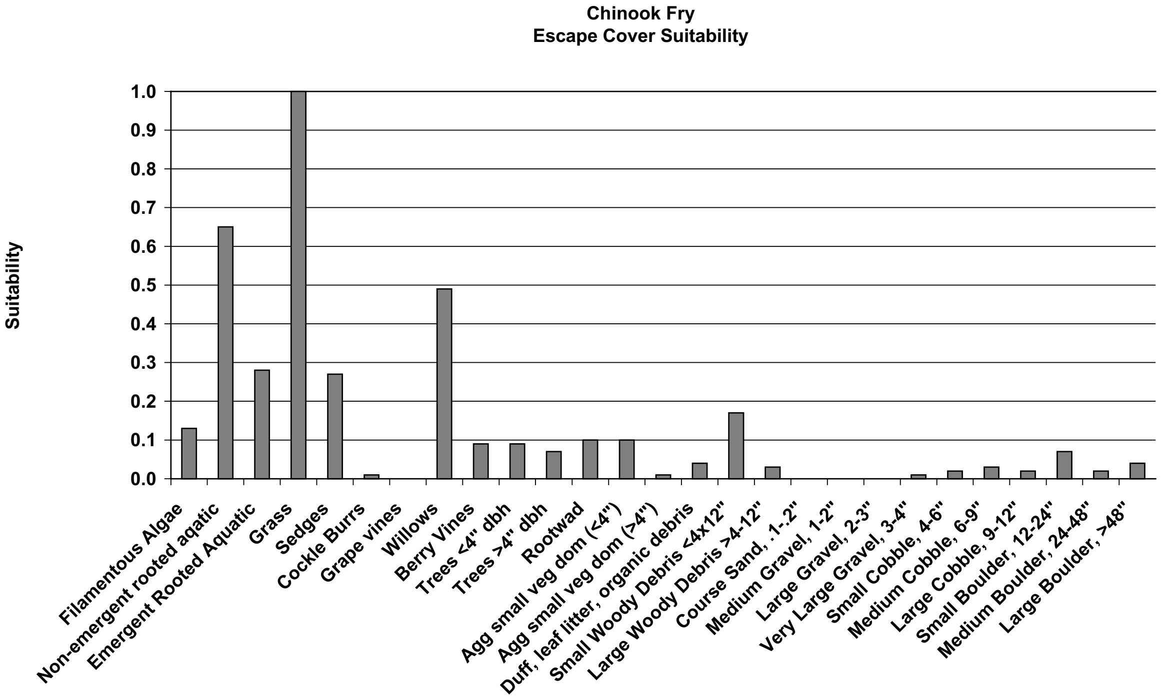

Figure 5 Habitat suitability criteria for chinook fry escape cover.

and functional cover HSC were calculated by normalizing the observed frequency distributions.

Based on the cumulative frequency of distance to escape cover (Figure 4) that shows $\sim$ 95 percent of all fish were observed within 0.6 m (2 ft) of escape cover, a 0.6 meter distance to escape cover criteria was selected for use in the modeling.

An escape cover minimum depth threshold was established to ensure sufficient depth existed to allow access by fry to the escape cover at a given flow rate. This value was based on the water depth HSC, that shows depths less than this have associated suitabilities less than 0.2 and were considered unusable for escape cover for modeling purposes.

2.5 *Fish observation data*

State, federal, and tribal biologists in support of this research undertook field observations of chinook fry locations within study sites. These data delineated the spatial location of chinook fry and the flow rate at which the data were collected. Several flow rates were typically sampled at each study location over the course of the field studies. The number of fish observations varied by date and study site. Validation data reported in this paper consisted of 102 fish at the R-Ranch study site, 34 fish at the Trees of Heaven study site, and 7 fish at the Seiad study site. These observation data were used to overlay the fish locations on the orthophotos at each study site for specific flow rates associated with the observations and compare against the predicted habitat quality (i.e., combined suitability) derived from the habitat modeling at similar flow rates. These comparisons represented the validation step in the modeling process.

2.6 *Conceptual habitat models*

In physical habitat modeling, an appropriate hydraulic model is applied to determine characteristics of the stream in terms of depth and velocity as a function of discharge. The hydraulic properties in conjunction with substrate/vegetation information are integrated with habitat suitability curves to produce a measure of available habitat as a function of discharge. Given the 0.6 meter criteria for distance to escape cover (see Figure 4), the simulated hydraulic properties for the computational meshes were utilized to generate habitat computational meshes at a 0.6 meter grid spacing using bi-linear interpolation for bed elevations, depths and velocities. GIS was then used to overlay the original substrate/vegetation polygons and to assign these attributes to each computational node for the habitat computational grids. This allowed for the calculation of habitat on a spatial scale consistent with the most limiting biological criteria. At a given flow rate, the integrated data sets included the x and y location, area for the node, simulated/interpolated bed elevation, depth, mean column velocity, and the substrate/vegetation attribute of the node.

An algorithm was developed to compute available habitat in the form of combined suitability ($\mathrm{CB_{SI}}$) using the attribute data at each node and the HSC described previously. The first conceptual habitat model implemented utilized only depth, velocity, and functional cover (FC) as ‘substrate’ and represents the ‘classical’ habitat modeling approach used in instream flow assessments:

$$\mathrm{CB_{SI}} = (\mathrm{Depth_{SI}} * \mathrm{Velocity_{SI}} * \mathrm{FC_{SI}})^{1/3}$$

In comparison, a behavior-based model was developed that evaluates the habitat at a given node in light of adjacent node properties that reflect the observed behavioral dependencies on escape cover type and distance to escape cover as follows:

For a given node location:

1. Compute the component suitability for depth ($\mathrm{Depth_{SI}}$) and velocity ($\mathrm{Velocity_{SI}}$) using the HSC functions for these variables. If either component suitability is zero, this node has a

combined suitability of zero, and so move to the next node. If both the depth and velocity suitability components are non-zero then;

2. Search one set of adjacent node locations (within the threshold 'Distance to Cover') for all escape cover types with non-zero suitability. If none are found, then increase the search to the next band of nodes still within the distance to cover threshold. If no suitable escape cover nodes are found within the threshold distance for cover then the current node location has no habitat value. Otherwise,
3. For each escape cover node, the depth at this flow rate is checked to ensure that it is greater than or equal to the escape cover minimum depth threshold (i.e., set at 0.12 meters for fry in this study). All nodes not meeting the criteria are then excluded. For any remaining nodes, the velocity is checked against the velocity HSC to ensure the node location is below the maximum allowable velocity. The highest suitability of any remaining nodes is then assigned as the Escape Cover Suitability (EC_{SI}) for the given node location. Then,
4. One node in the upstream direction is examined and the associated Functional Cover suitability (FC_{SI}) is computed.
5. The final combined suitability (CB_{SI}) of the given node is then computed as:

$$CB_{SI} = (Depth_{SI} * Velocity_{SI} * FC_{SI})^{1/3} * EC_{SI}$$

The simulated combined suitability at all nodes associated with a particular flow rate was used to generate contours of predicted suitable habitat between 0.00001 and 1.0 to overlay the spatial distribution of habitat at each study site. Setting the lower threshold at 0.00001 eliminated essentially non-suitable conditions from the contour overlays of habitat. Finally, it should be noted that fish observation data contain observation data not utilized in the development of site-specific HSC and therefore represent true validation data.

3 Results and discussion

Figure 6 shows the spatial distribution and quality of habitat (i.e., combined suitability) based on the behavior-based conceptual model at three different stations at the flow rates indicated in the figure legend. Chinook fry observation data have been overlaid in each figure to allow a comparison between modeling results and actual habitat use.

These results demonstrate the validity of the behavior-based conceptual habitat model over a range of discharges and study sites. They also demonstrate that the model effectively excludes suitable habitat within the main channel consistent with the lack of observed fry in those areas during the independent fish collection efforts noted above. Two factors account for the exclusion

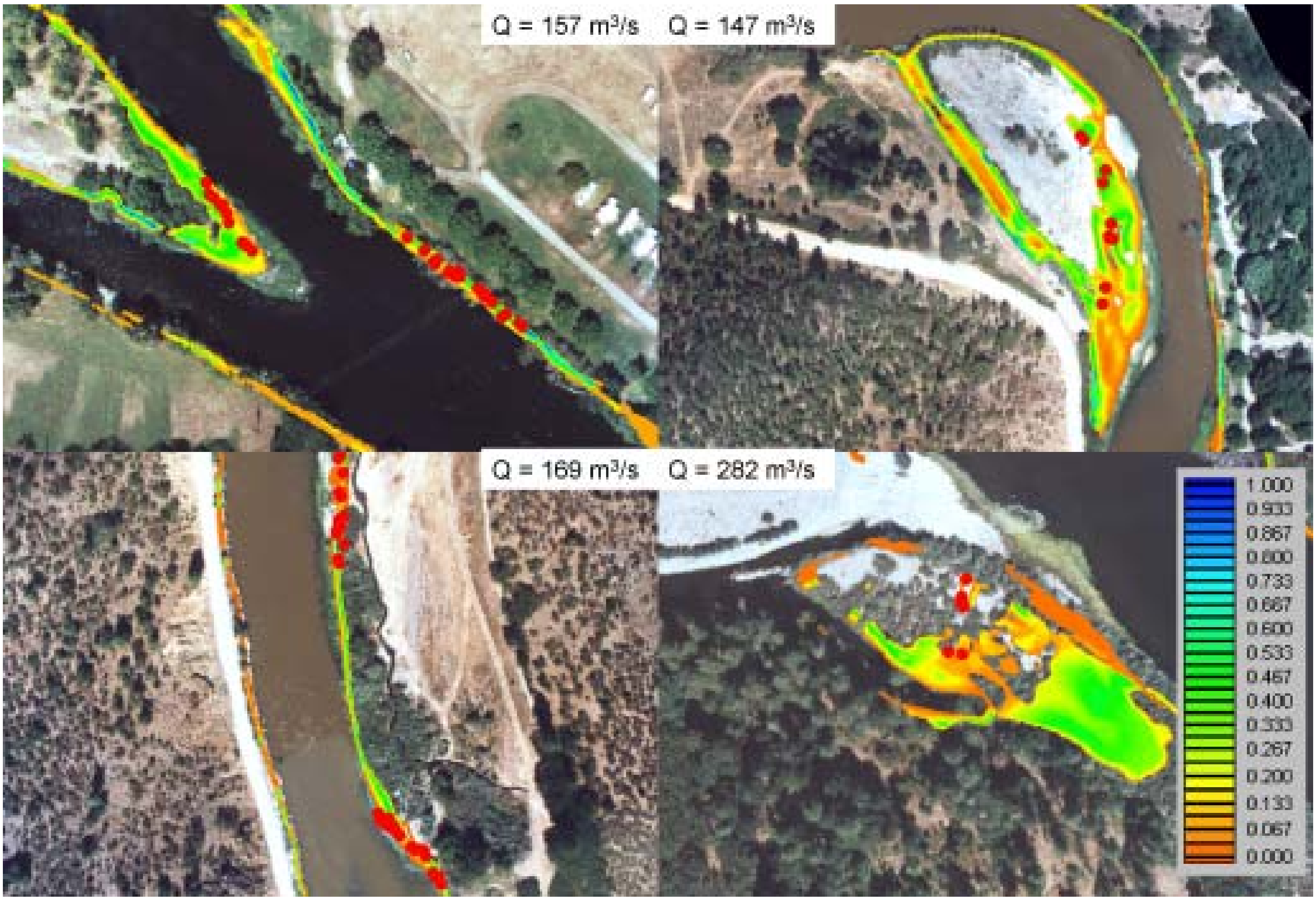

Figure 6 Predicted spatial distribution and quality of available habitat at study sites R-Ranch (top left) at 147 m^3/s, Trees of Heaven (top right) at 147 m^3/s and 169 m^3/s (bottom left), and Seaid (bottom right) at 282 m^3/s. The combined suitability of habitat is shown in the lower left and in the imagery if the river is visible then the combined suitability is zero.

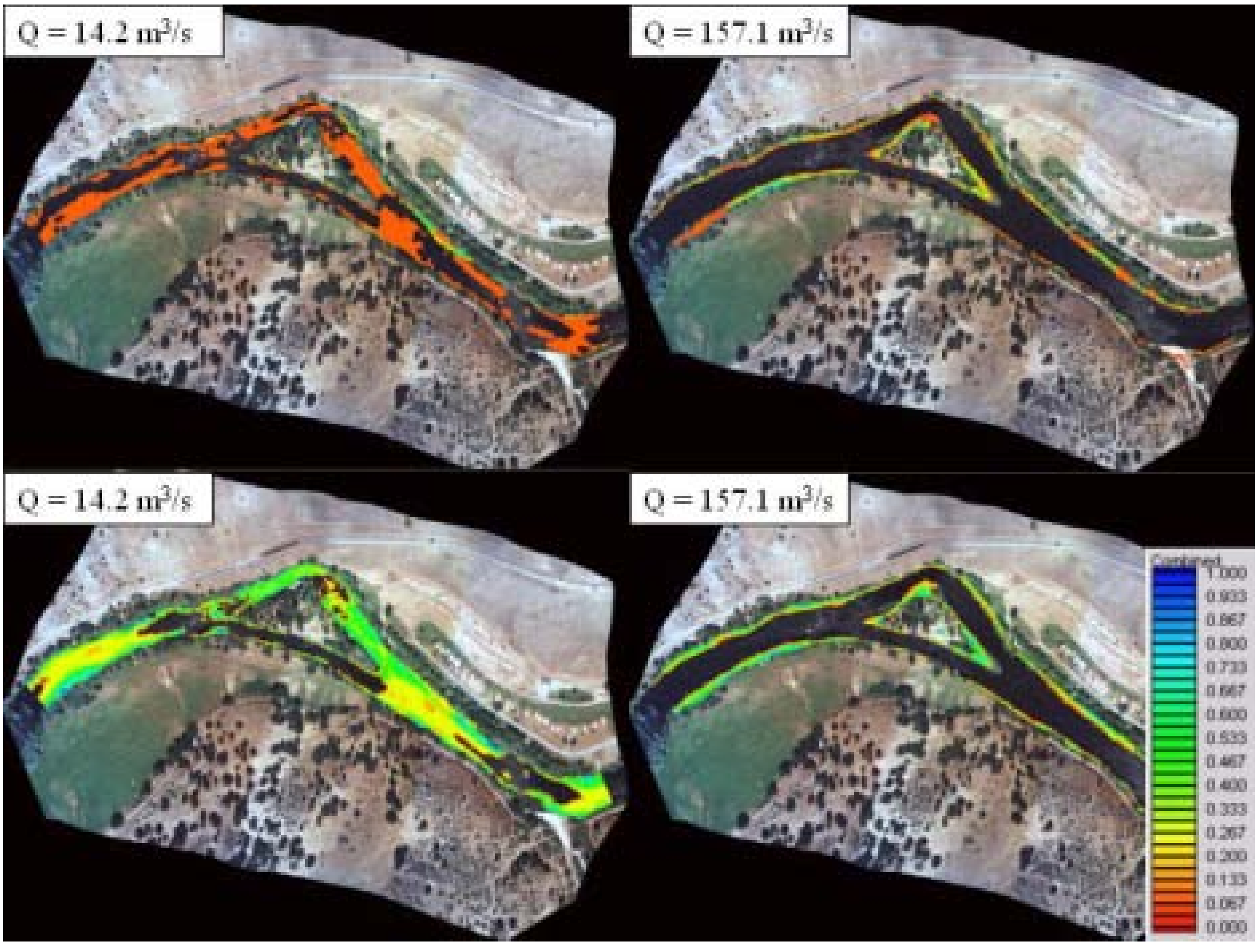

Figure 7 Predicted spatial distribution and quality of available habitat at the R-Ranch study site. The top row contains results from the behavior-based habitat model at 14.2 (left) and 157.1 (right) m^3/s. The bottom row shows results for these same discharges based on the simple depth, velocity, and substrate-based habitat model for these same flow rates. The combined suitability of habitat is shown in the lower left and in the imagery if the river is visible then the combined suitability is zero.

of habitat within the main channel. First, velocities are generally outside the range of suitable habitat conditions (see Figure 3) while the stream margins at these discharges remain in contact with suitable escape cover habitat (see Figure 4). This is illustrated in Figure 7 where simulated habitat using the behavior-based habitat model at the R-Ranch study site at 14.2 and 157.1 m^3/s are compared against the more simplistic depth, velocity, and substrate-based conceptual habitat model.

At the lower discharge (left side) the simplistic habitat model shows moderately high habitat availability throughout most of the main channel except in the steepest part where the velocities exceed the suitability criteria. In contrast, the behavioral model shows both reduced spatial availability and very low overall habitat quality (i.e., $\sim$ 0.01 combined suitabilities). At the higher discharge, both models show similar spatial patterns. However, the behavior-based conceptual habitat model still reflects lower combined suitabilities due to a lack of wetted area in contact with suitable escape cover. These computational differences result in dramatically different magnitudes of predicted habitat availability as well as fundamentally different relationships between available habitat and discharge as shown in Figure 8.

The simplistic depth, velocity, and substrate-based model produces the ‘classical’ decay in available habitat for fry life stages with increasing discharge that has been criticized by fisheries biologists since the inception of the science of instream flows. In contrast, the incorporation of escape cover and functional cover dependencies produces a habitat versus flow relationship that makes more institutive sense for this particular river system. For example, the flow rates at which the behavior-based habitat model predictions first reach a maximum ($\sim$ 80 m^3/s) are within flow magnitudes of the estimated unimpaired flows during the chinook fry rearing period. These results underscore that the choice of the conceptual habitat modeling approach can significantly impact modeling results and therefore the decision process when the relationships illustrated in Figure 8 are utilized in the instream flow assessment process.

It should be noted that fish habitat utilization is not expected to always occur in the highest combined suitability habitats for a variety of reasons (e.g., predation, temperature, food availability, presence of predators, etc.). However, it is expected that fish distributions should be spatially distributed in a ‘presence or absence’ manner associated with useable (i.e., combined suitability $\gg$ 0.0) versus non-usable (i.e., combined suitability $\sim$ 0.0) habitats. Results from this study show that over 80 percent of the observed fry were spatially located in areas with combined suitabilities that ranged between 0.75 and 1.0, and less than

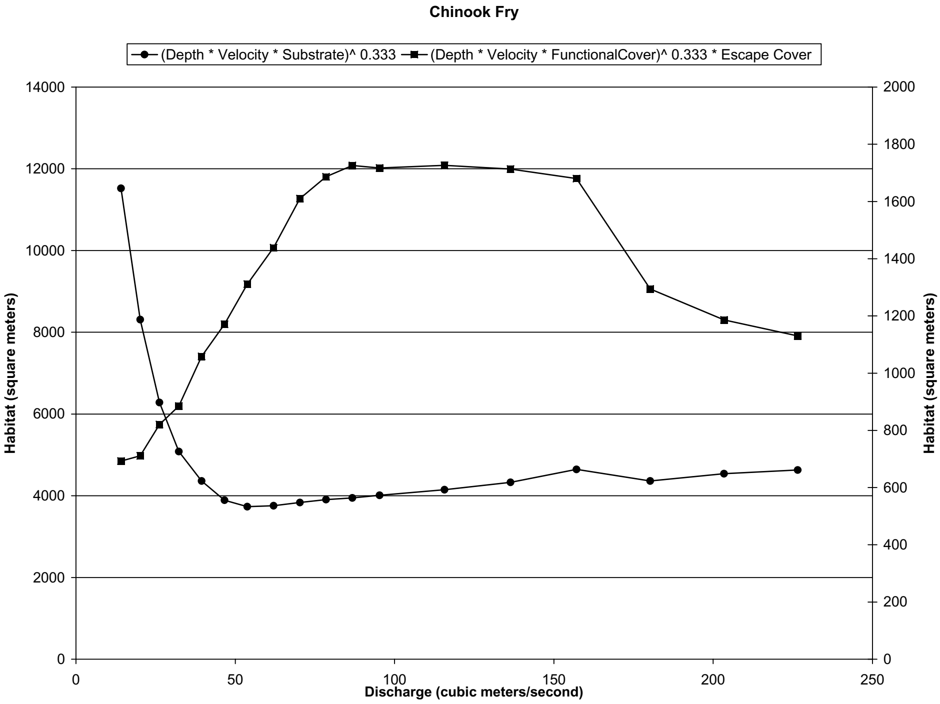

Figure 8 Relationship between total available habitat and discharge based on two different conceptual habitat models.

5 percent fell in areas with combined habitat suitabilities below 0.25. Based on the modeling results for this study, and in particular the spatial agreement between predicted suitable habitat and observed fish locations, we place a high degree of confidence in the behavior-based modeling approach.

The results of this study demonstrate that the particular conceptual habitat model formulation can have a dramatic affect on the fundamental relationship between available habitat and discharge used in instream flow assessments. Fortunately, given the state-of-the-art in field sampling technologies, advanced hydrodynamic models, and development of behavior-based habitat modeling demonstrated in this paper, more realistic assessments of the physical habitat requirements for fry life stages can be achieved. This type of modeling approach for fry life stages of salmonids with known behavioral affinity for escape and functional cover should provide resource managers increased confidence when incorporating these life stages into the decision making process while evaluating alternative flow strategies for water resource systems.

4 Conclusions

Typical modeling approaches for fry physical habitat based on depth, velocity and substrate typically produce modeling results that fisheries biologists find irrational (see Figure 8). This shortcoming has often resulted in fry not being incorporated into the instream flow assessment process, or when included, result in a high degree of unreliability for decision makers faced with evaluating alternative flow strategies. However, these limitations in the modeling approach can be overcome by incorporation of known behavioral dependencies for escape and functional cover attributes. This can be accomplished by taking advantage of high spatial resolution topographies obtained from existing techniques for data collection, hydrodynamic models, and implementation of more advanced habitat modeling algorithms as demonstrated in this study. Utilization of fish observation data to validate conceptual habitat modeling results greatly increases the confidence and reliability of the models when utilized in instream flow assessments.

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