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Comparison of spawning habitat predictions of PHABSIM and River2D models*

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ABSTRACT
This study compared the predictions of two instream flow habitat models, the Physical Habitat Simulation System (PHABSIM) and River2D, with regards to spawning habitat for chinook salmon, *Oncorhynchus tschawytscha*, and steelhead trout, *Oncorhynchus mykiss*. Spawning habitat was simulated with both models for eight sites in the Sacramento River, five sites in the American River and one site in the Merced River, California, using habitat suitability criteria developed from data collected on redds in each of these rivers. For four out of five cases, both models correctly predicted that the combined suitability, calculated as the product of the depth, velocity and substrate suitabilities, of occupied locations was significantly greater than the combined suitability of unoccupied locations. There was little difference in the flow-habitat relationships for each site and set of habitat suitability criteria predicted by the two models. The use of River2D, rather than PHABSIM, is still warranted given its ability to model complex flow conditions which cannot be simulated with PHABSIM.

Keywords: Instream Flow Incremental Methodology; IFIM; chinook salmon (*Oncorhynchus tschawytscha)*; Physical Habitat Simulation system; PHABSIM; Two-dimensional habitat modeling.

1 Introduction

By applying life stage specific habitat suitability criteria for depth, velocity, substrate and cover, the Physical Habitat Simulation system (PHABSIM) predicts depth and velocity across channel transects and combines these predictions with substrate or cover data into a habitat index known as weighted useable area (WUA) (Bovee, 1982; Milhous *et al.*, 1989). The WUA output is generally simulated for river reaches over a range of stream flows. Alternatively, two-dimensional (2-D) hydraulic and habitat models can be used to predict depth and velocity laterally and longitudinally throughout a length of river channel at a range of stream flows, and combine them with substrate or cover to predict the WUA for the site. Two-dimensional models have been suggested as a improvement and replacement for PHABSIM (Ghanem *et al.*, 1996; Leclerc *et al.*, 1995).

There are a number of potential advantages of using a 2-D model, versus PHABSIM. The use of a 2-D model avoids problems of where to place transects within a mesohabitat unit (Williams, 1996), since all of the mesohabitat unit is modeled with a 2-D model. Two-dimensional models have the potential to model depths and velocities in complex channels over a range of flows more accurately than PHABSIM because they take into account local bed topography and roughness, and explicitly use mechanistic processes (conservation of mass and momentum), rather than the reduced Manning's formulation and an empirical velocity adjustment factor (Leclerc *et al.*, 1995). Two-dimensional models can explicitly handle complex habitats, including transverse flows, across-channel variation in water surface elevations, and flow contractions/expansions, which cannot be modeled explicitly with PHABSIM (Ghanem *et al.*, 1996). Two-dimensional models can perform better than PHABSIM at representing patchy microhabitat features, such as gravel patches. The data can be collected with a stratified sampling scheme, with higher intensity sampling in areas with more complex or more quickly varying microhabitat features, and lower intensity sampling in areas with uniformly varying bed topography and uniform substrate. Bed topography and substrate mapping data can be collected at a very low flow, with the only data needed at high flow being discharge and water surface elevations at the top and bottom of the site and randomly sampled velocities for validation purposes.

In this paper, we evaluate whether the two-dimensional model used, River2D, (Steffler and Blackburn, 2001) is better than PHABSIM at predicting chinook salmon (*Oncorhynchus tschawytscha*) spawning habitat, and whether there are differences between PHABSIM and River2D in flow-habitat relationships for chinook salmon and steelhead (*Oncorhynchus mykiss*) spawning.

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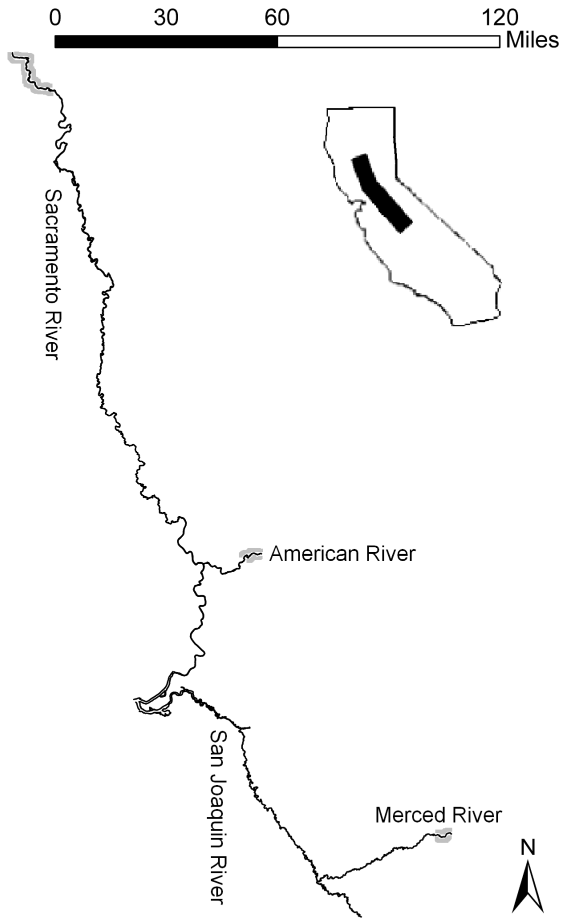


Figure 1 Location of the Sacramento, Merced and American Rivers, California. Shaded areas are the study reaches used to compare the spawning habitat predictions of the PHABSIM and River2D models.

Table 1 Characteristics of study sites. Three of the Sacramento River sites were modeled for two conditions – with boards in and out at the Anderson-Cottonwood Irrigation District (ACID) Dam. Stage at the study sites was up to 2 m higher with the ACID Dam boards in, versus with the boards out. The Merced site was simulated for 11 flows, one of the American River sites (El Manto) was simulated for 35 flows, and the Sacramento sites and the rest of the American River sites were simulated for 30 flows. The lower end of the simulated flow range for the El Manto site was 14.2 m^3/s.

River	Number of sites	Number of transects/ site	Length of site (channel widths)	Range of simulated flows (m^3/s)
Sacramento	8	1–10	0.33–1.88	92.0–877.8
American	5	2–7	2.43–10.43	28.3–311.5
Merced	1	6	2.03	5.7–19.8

2 Study sites

The Merced, American and Sacramento Rivers, located in the Central Valley of California, have a mean annual flow of 18.7, 106 and 275.8 m^3/s, respectively. This study was conducted in a 16-km reach of the Merced River, a 9-km reach of the American River, and a 47-km reach of the Sacramento River (Figure 1). PHABSIM and River2D were used to model one site on the Merced River, five sites on the American River and eight sites on the Sacramento River (Table 1). Three of the Sacramento River sites, located upstream of the Anderson-Cottonwood Irrigation District (ACID) Dam, were modeled for two conditions, with boards in or out at the ACID Dam. Stage at the sites was as much as 2 m higher with the boards in at the ACID, versus with the boards out.

3 Methods

3.1 Field measurements

To model spawning habitat in the study sites, depth, velocity and substrate data were collected on 34 PHABSIM transects in the Sacramento River, 27 PHABSIM transects in the American River, and 6 PHABSIM transects in the Merced River, and substrate and bed topography data were collected for 2-dimensional hydraulic and habitat models for all 14 sites. For the PHABSIM transects, lateral cell boundaries were established systematically or where depth, velocity or substrate changed. Dominant substrate was visually assessed as the 2.5 to 5.0 cm size range of particles which comprised more than fifty percent of the surface area. For example, if more than fifty percent of the area was comprised of 5.0 to 10.0 cm particle sizes, the dominant substrate was classified as 5.0 to 10.0 cm. The midpoint of the dominant substrate size range would be an approximation of the D50 particle size. The substrate size classes used are shown in Figures 2 to 5. Depth, velocity and substrate data were collected in October 1996 at a flow of 11.95 m^3/s for the Merced River PHABSIM transects, in July to December 1998 at flows of 84.4 to 114.2 m^3/s for the American River PHABSIM transects, and in June to September 1997 at flows of 216.0 to 427.5 m^3/s for the Sacramento River PHABSIM transects. Water surface elevations and, for the Merced River, flows were measured at four to six flows for each PHABSIM transect. These flows ranged from 2.21 to 29.6 m^3/s for the Merced River during August to October 1996 (Gallagher and Gard, 1999), from 29.4 to 316.4 m^3/s for the American River during April to December 1998, and from 128.6 to 1192.5 m^3/s for the Sacramento River during May 1997 to March 1999 (Gard and Ballard, 2003). Flows for the American and Sacramento Rivers were determined from gage readings.

The downstream-most and upstream-most PHABSIM transects were used for, respectively, the bottom and top of each River2D site. The remaining PHABSIM transects were used to establish a portion of the bed topography and substrate distribution of each River2D site. Data to develop the rest of the bed topography and substrate distribution of the River2D sites were collected with a total station for all of the Merced River site and the dry and shallow portions of the American and Sacramento River sites, generally in sets of points going across the channel. Data for the bed topography and substrate distribution of the deep (greater than 1 m depth) portions of the American and Sacramento River sites were collected with an Acoustic Doppler Current Profiler (ADCP) and underwater video (Gard and Ballard, 2003). The average density of points from all sources (PHABSIM transects, ADCP and total station) used to develop the bed topography for the River2D model was 2.65 points/100 m^2 (Table 2). The stage-discharge relationship for the downstream-most PHABSIM transect and the flows at the upstream boundary were used as inputs to the River2D model of each site, while the water surface elevation measured at the highest flow at the remaining PHABSIM transects were used to calibrate the River2D model of each site by adjusting the bed roughnesses of the site until the water surface elevations predicted by River2D matched the measured water surface elevations.

To develop chinook salmon spawning habitat suitability criteria, depth, velocity and substrate data were collected on fall-run chinook salmon redds in the Merced, American and Sacramento Rivers and on late-fall-run and winter-run chinook salmon redds in the Sacramento River (Table 3). The methods used to collect habitat suitability criteria for the Merced and American Rivers are given in Gard (1998), while the methods used to collect habitat suitability criteria for the Sacramento River are given in Gard and Ballard (2003). Horizontal surveying was used to determine the location of redds in the Merced River site in 1996 and in two of the American River sites on December 14–17, 1998, and a Global Positioning System (GPS) receiver was used to determine the location of redds in all of the Sacramento River sites (occupied *n* values in Tables 4 and 5).

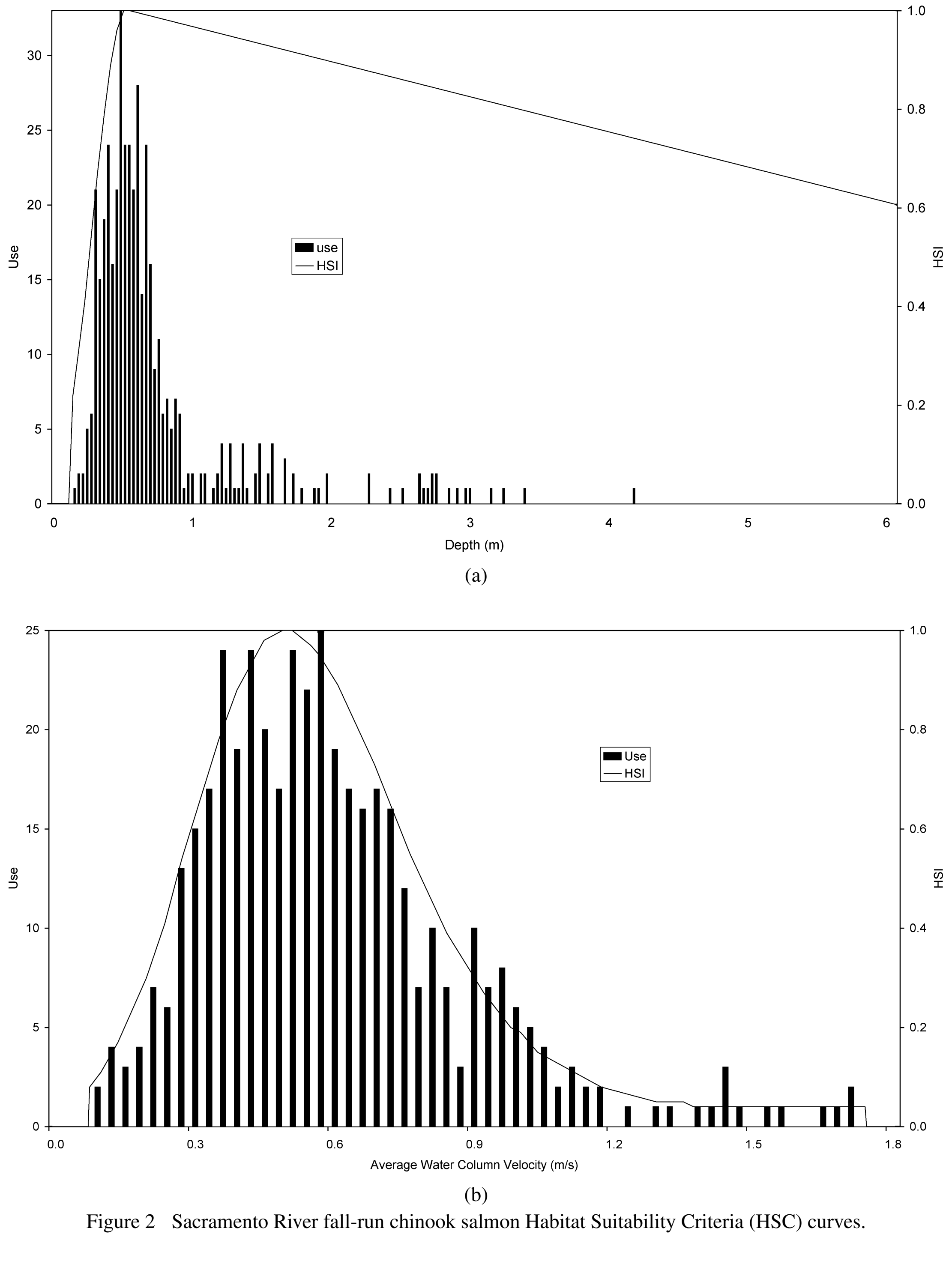
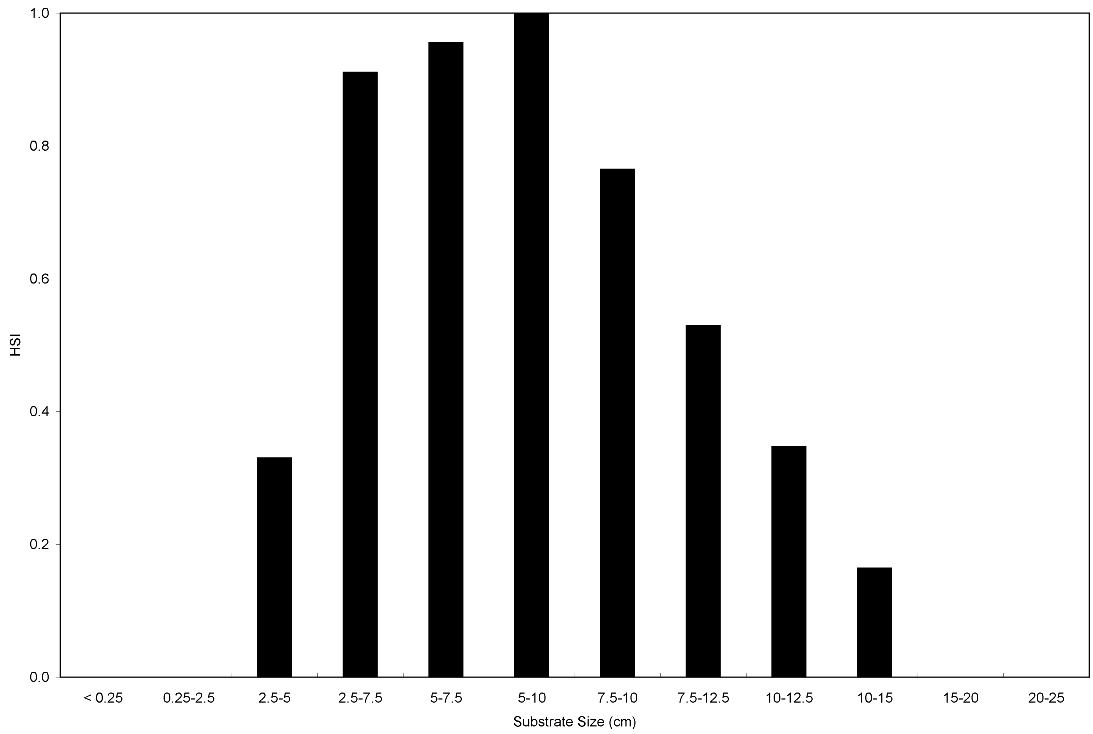


Figure 2 Sacramento River fall-run chinook salmon Habitat Suitability Criteria (HSC) curves.



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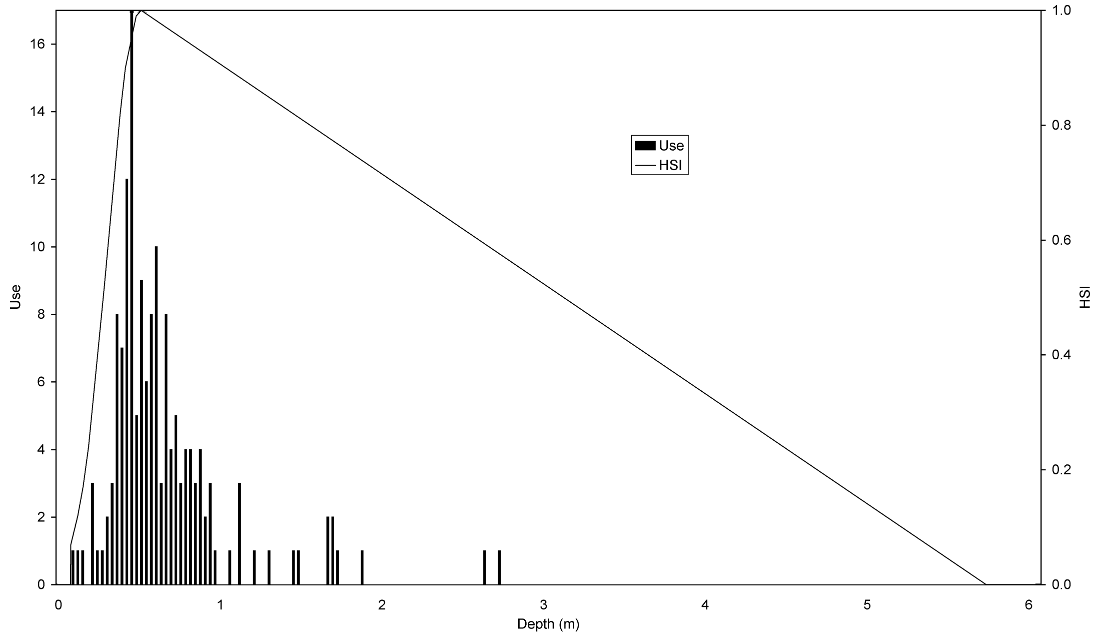


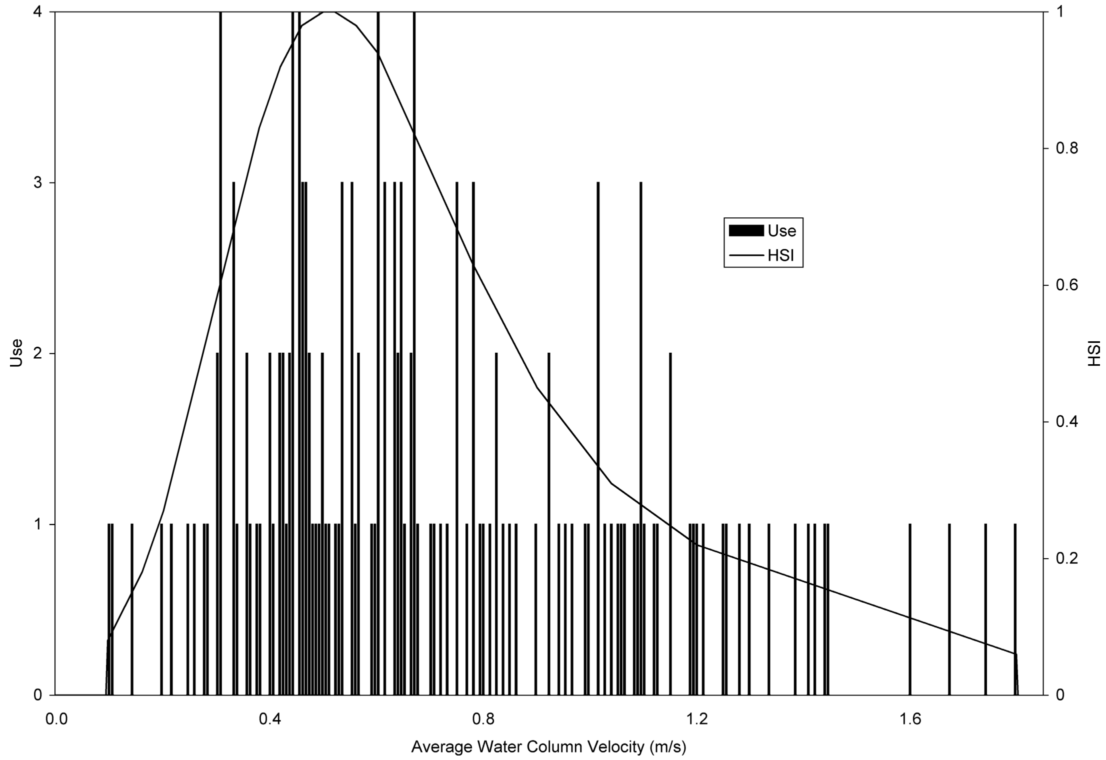
(a)

Figure 3 Sacramento River late-fall-run chinook salmon Habitat Suitability Criteria (HSC) curves.

3.2 Habitat modeling

Average water column velocities, water surface elevations, riverbed elevations, cell substrate categories, and site discharges were entered into PHABSIM to create hydraulic models for each transect. PHABSIM hydraulic data were calibrated following procedures in Milhous *et al.* (1989). These procedures involve the development of stage-discharge relationships using three possible techniques: a log-log linear rating curve, Manning's equation, or a step-backwater method. The calibrated files for each site were used in PHABSIM to simulate hydraulic characteristics for the range of flows in Table 1, and for the average flows each year from the beginning of spawning through the end of redd data collection (Table 6).

The River2D model solves the two-dimensional, depth averaged St. Venant equations expressed in conservative form (Steffler and Blackburn, 2002). The River2D model uses a finite



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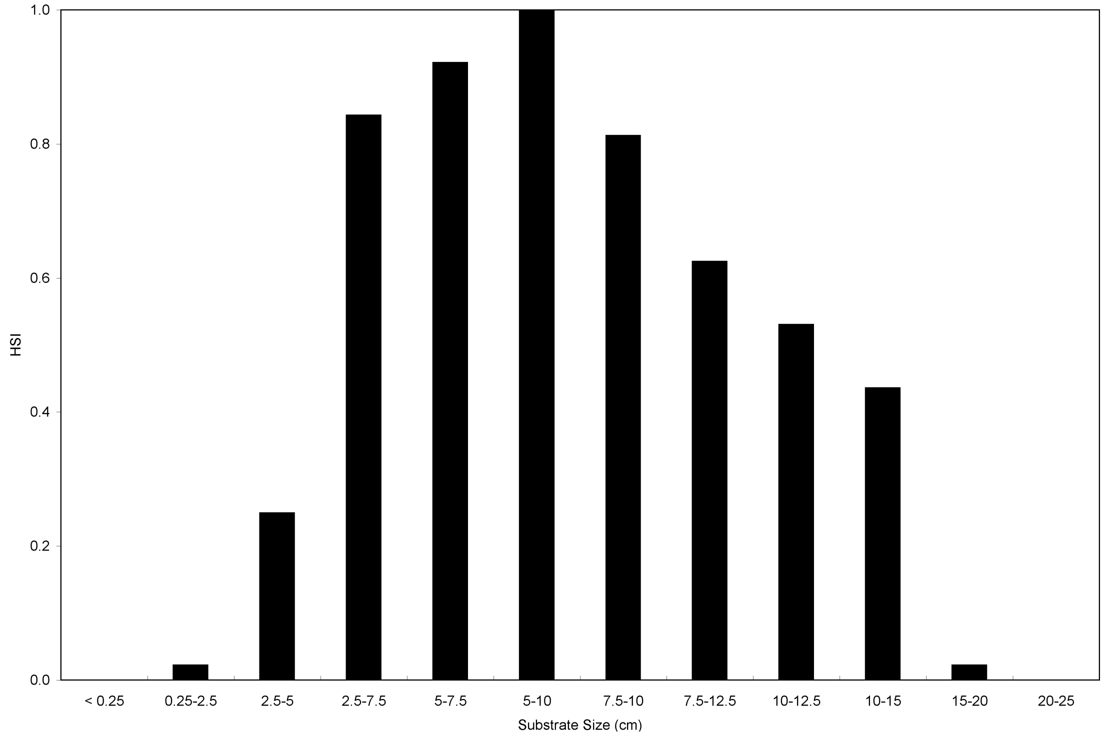

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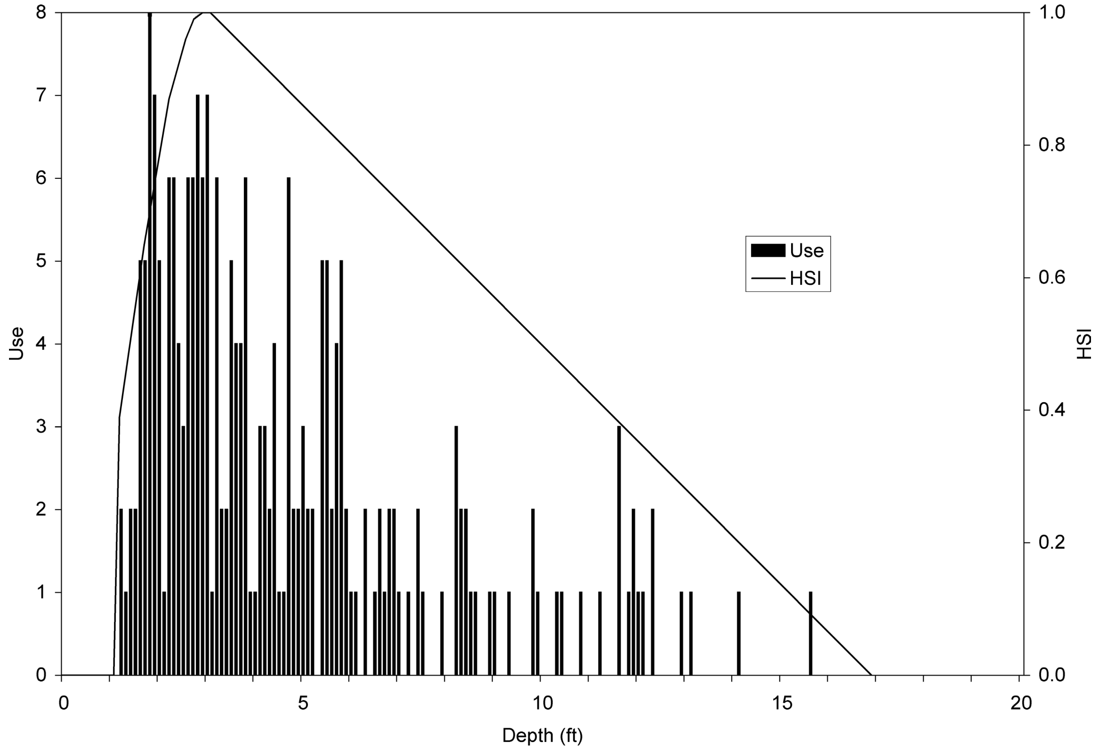
Figure 3 (*Continued*)

element numerical method based on the Streamline Upwind Petrov-Galerkin weighted residual formulation, using a Newton Raphson iterative method (Steffler and Blackburn, 2002). The River2D model achieves turbulence closure through the use of a Boussinesq type eddy viscosity formulation (Steffler and Blackburn, 2002). The basis for the current form of RIVER2D is given in Ghanem *et al.* (1995).

Bed topography, bed roughness and substrate distribution data were entered into River2D to create hydraulic models for each site. To minimize the effects of inflow boundary condition specifications, a one-channel-width upstream artificial extension was added to each site by translating the cross-sectional topography at the top of the site upstream parallel to the top PHABSIM transect, with a bedslope equal to the water surface elevation slope



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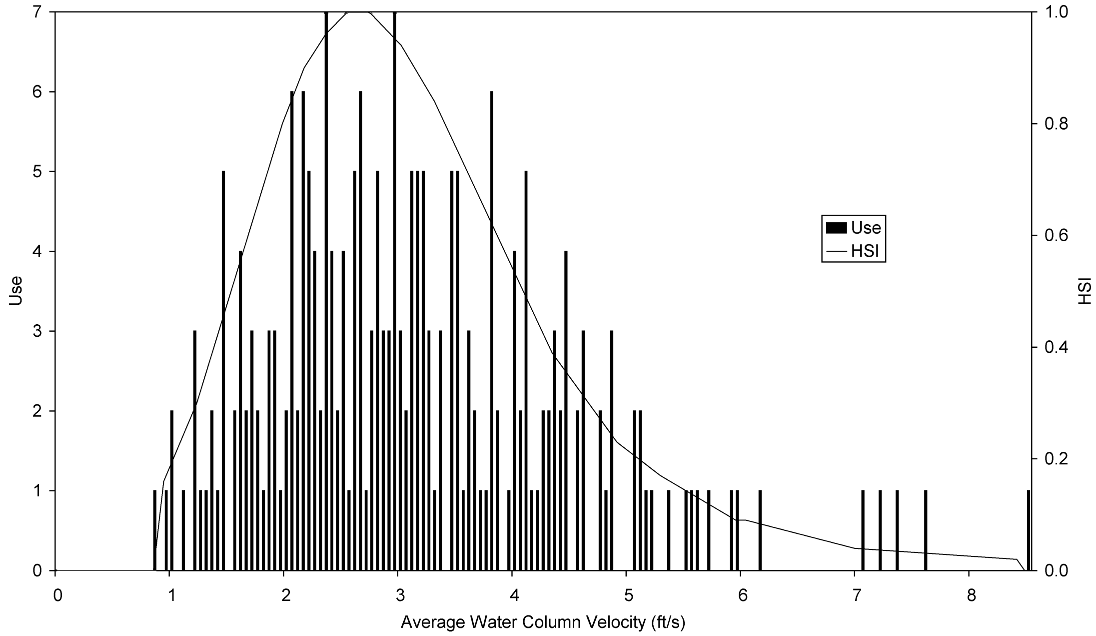

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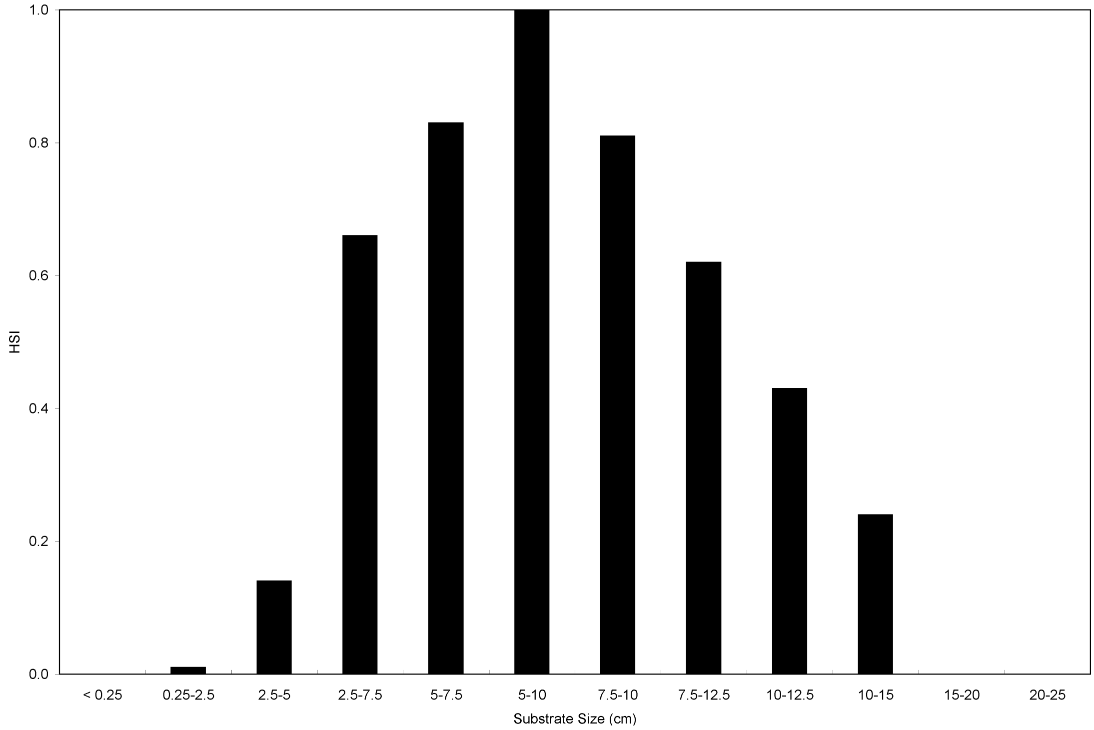
Figure 4 Sacramento River winter-run chinook salmon Habitat Suitability Criteria (HSC) curves.

at the top of the site. The River2D model distributes flow across the inflow boundary proportional to depth, resulting in the fastest velocity being at the thalweg. The River2D model used a triangular irregular network (TIN) grid, with grid elements ranging in size from 13 m in areas with uniform topography to 0.7 m in areas with rapidly varying topography (Figure 6). The grid element sizes were selected to minimize the elevation error between the TIN and the underlying bed topography data, while taking into account computational limitations of large numbers of grid elements. The number of grid elements, from site to site, ranged from 5,475 to 24,488. River2D hydraulic data were calibrated by adjusting bed roughnesses until simulated water surface elevations matched measured water surface elevations. The initial values of bed roughness for the River2D model were set equal to five times the midpoint of the substrate range, i.e. a substrate range of 5 to 10 cm would have an initial bed roughness of 0.4 m (7.5 cm × 5). Five times the average particle size is approximately the same as 2 to 3 times the d85 particle size, which is recommended as an estimate of bed roughness height (Yalin 1977). The bed roughnesses were adjusted by applying a fixed multiplier



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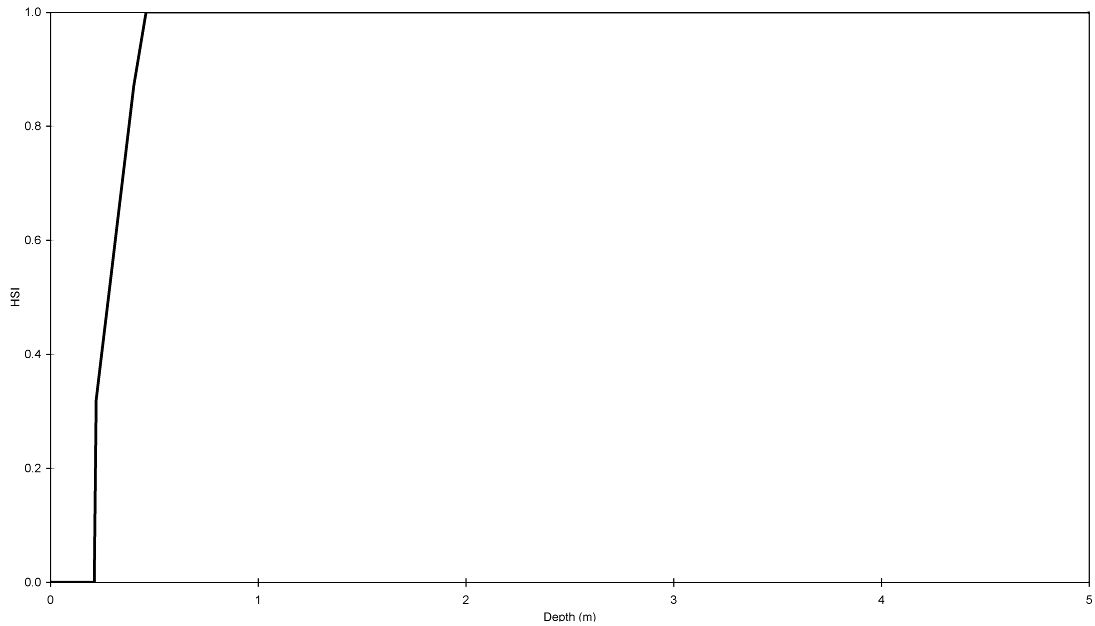
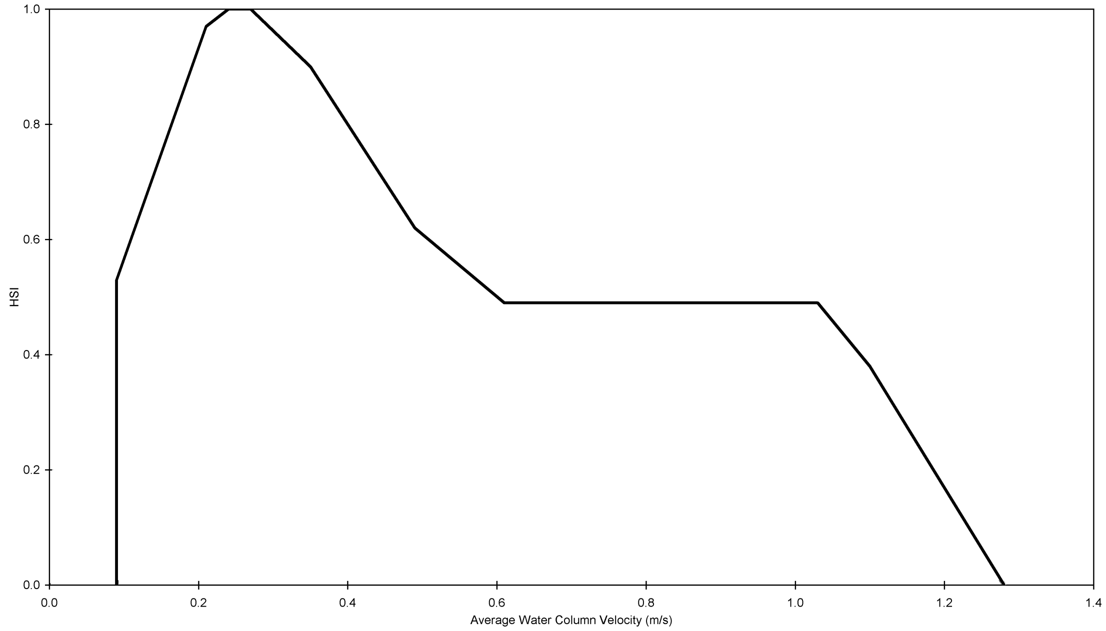


(a)

Figure 5 Steelhead Habitat Suitability Criteria (HSC) curves used to simulate steelhead spawning habitat in the Sacramento and Lower American Rivers.

to all of the bed roughnesses. The values of all other River2D hydraulic parameters were left at their default values (upwinding coefficient = 0.5, minimum groundwater depth = 0.1 m, groundwater transmissivity = 0.1 m^2/s, groundwater storativity = 1, and eddy viscosity parameters epsilon1 = 0.01 m^2/s, epsilon2 = 0.5 m^2/s and epsilon3 = 0.1 m^2/s). The upwinding coefficient is used in River2D's Petrov-Galerkin finite element scheme, the groundwater parameters are used for River2D's wetting/drying algorithm, and the eddy viscosity parameters are used in River2D's transverse shear model (Steffler and Blackburn, 2002). The calibrated files for each site were used in River2D to simulate hydraulic characteristics for the range of flows in Table 1, and for the average flows each year from the beginning of spawning through to the end of redd data collection (Table 6).

Habitat suitability curves (HSC) are used in PHABSIM and River2D to translate hydraulic and structural elements of rivers into indices of habitat quality called combined suitability indices (CSI), calculated as the product of the depth, velocity and



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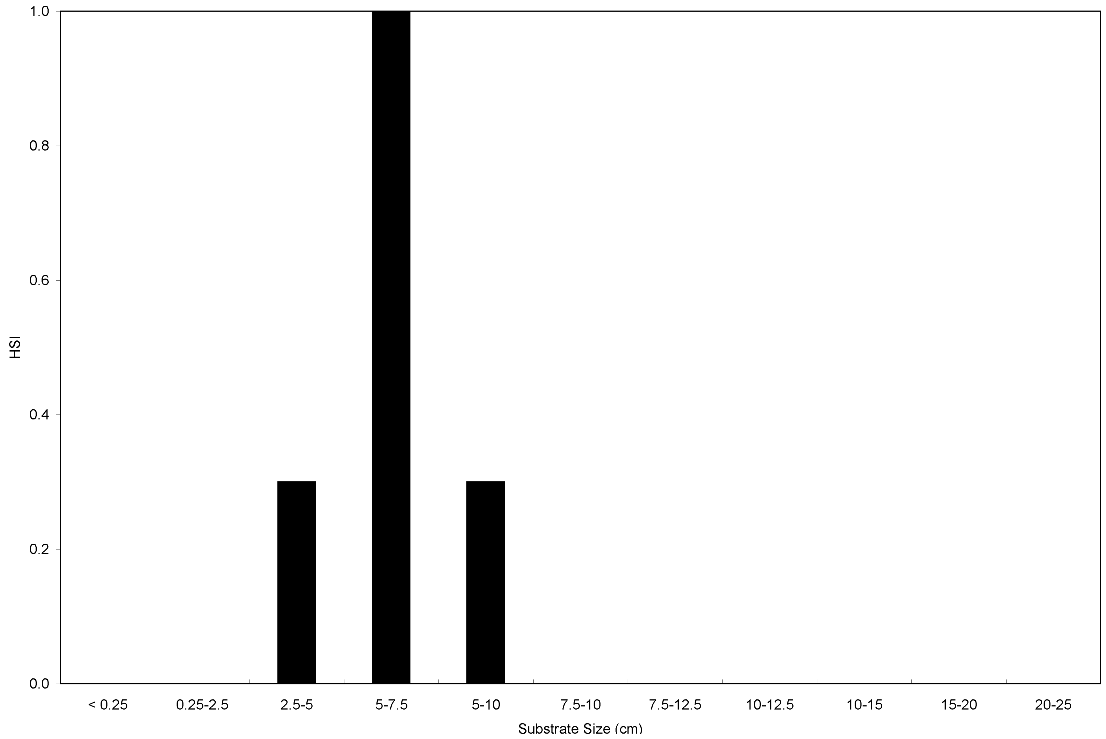

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Figure 5 (*Continued*)

Table 2 Study site data collection. There is only one value for the range of point densities for the Merced River since there was only one study site on that river.

River	Range of point densities (points/100 m^2)	Number of points per reach
Sacramento	0.90–4.16	4717
American	1.03–1.24	4784
Merced	3.41	367

substrate suitabilities. The habitat suitability criteria data for the Merced and Lower American Rivers in Table 3 were used to develop HSC for fall-run chinook salmon in the Merced and Lower American Rivers (Gard, 1998). The habitat suitability criteria data in Table 3 for the Sacramento River were used to develop HSC for fall-run, late-fall-run and winter-run chinook salmon in the Sacramento River (Figures 2 to 4) using the techniques in Gard (1998). Habitat suitability criteria for steelhead (Figure 5) were developed from depth and velocity

Table 3 Habitat suitability criteria data collected as part of this study. Flows are the range of flows during data collection. Spawning criteria for late-fall chinook salmon were developed using the data from this study and data collected on 79 redds by the California Department of Fish and Game on Jan 1–Mar 3 1986–1988 at flows of 89.2 to 162.8 m^3/s.

River	Race	Number of Redds	Data collection dates	Flow (m^3/s)
Sacramento	Fall-run	437	Oct 23–Nov 25 1995–1999	130.4–176.8
Sacramento	Late-fall-run	77	Feb 27–Mar 29 2001	90.2–117.0
Sacramento	Winter-run	227	May 26–Jul 15 1996–2001	297.2–563.8
American	Fall-run	218	Nov 6–7 1996	78.6
Merced	Fall-run	186	Nov 12–14 1996	7.79

data collected on steelhead redds in the Lower American River by the California Department of Fish and Game and substrate data collected on steelhead redds in the Trinity River by the U.S. Fish and Wildlife Service using the methods in Gard (1998).

The calibrated PHABSIM and River2D hydraulic simulations were used with the above HSC to generate flow-habitat relationships for fall-run chinook salmon spawning in the Sacramento, American and Merced River sites, for steelhead spawning in the Sacramento and American River sites, and for late-fall-run and winter-run chinook salmon spawning in the Sacramento River sites. The calibrated PHABSIM hydraulic simulations for the flows in Table 6 were used with the chinook salmon HSC to calculate the CSI values predicted by PHABSIM for occupied (cells with redds) and unoccupied cells for each site and year where redd locations were determined. For unoccupied cells, all wetted cells

Table 4 Results of Mann-Whitney U Tests for PHABSIM occupied versus unoccupied cells.

River	Race	Occupied *n*	Unoccupied *n*	Occupied median	Unoccupied median	*p*-value
Merced	Fall	28	221	0.10	0.00	0.011
American	Fall	103	497	0.23	0.01	0.003
Sacramento	Fall	71	3081	0.31	0.01	< 0.000001
Sacramento	Late-fall	22	1906	0.26	0.17	0.16
Sacramento	Winter	51	6164	0.29	0.00	< 0.000001

Table 5 Results of Mann-Whitney U Tests for 2-D model occupied versus unoccupied locations.

River	Race	Occupied n	Unoccupied *n*	Occupied median	Unoccupied median	*p*-value
Merced	Fall	33	220	0.54	0.27	0.001
American	Fall	184	458	0.04	0.00	0.000003
Sacramento	Fall	74	3080	0.11	0.03	0.000026
Sacramento	Late-fall	16	1906	0.07	0.14	0.313
Sacramento	Winter	58	6164	0.14	0.01	0.000062

Table 6 Time period and average chinook salmon spawning river discharge (m^3/s) for the Merced, Lower American and Sacramento Rivers. Data are only given for years in which redd locations were recorded for study sites. The range of flows for the Sacramento River sites reflects the different flows present at different sites due to tributary inflow within the reach and differences from site to site in the final date of redd data collection.

	Race	1996	1997	1998	1999	2000	2001
Merced	Fall						
Time period		10/23–11/14					
Average		8.4					
American	Fall						
Time period				11/11–12/17			
Average				87.4			
Sacramento	Fall						
Time period			10/9–11/20			10/7–11/4	
Average			127.9–130.3			173.3–177.8	
Sacramento	Late-						
Time period	fall						1/6–3/29
Average							108.1–117.0
Sacramento	Winter						
Time period				5/15–6/23	4/15–7/14	4/15–7/10	4/15–6/21
Average				445.4–469.4	288.6–308.5	308.1–324.0	281.2

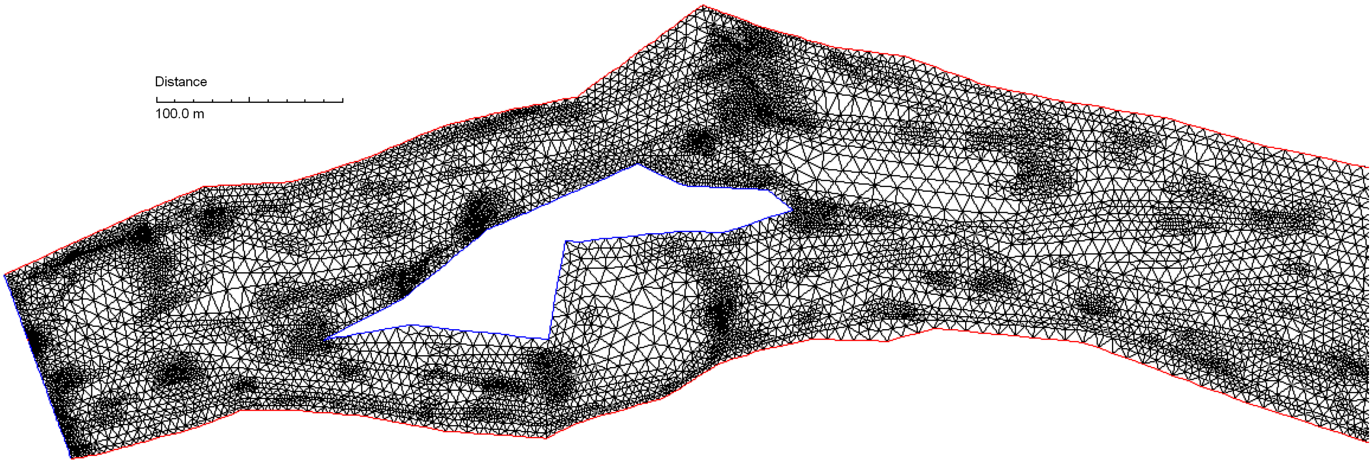


Figure 6 Example of triangular irregular element mesh used to perform the two-dimensional hydraulic modeling of the American River.

were used. Similarly, the calibrated River2D simulations for the flows in Table 6 were used with the same chinook salmon HSC to calculate the CSI values predicted by River2D for occupied and unoccupied locations for each site and year where redd locations were determined. Unoccupied locations were randomly selected which met the following criteria: they were farther than one m from an occupied location, and they were wetted. The number of unoccupied River2D locations (Table 5) was chosen to be similar to the number of unoccupied PHABSIM cells (Table 4). The number of occupied River2D locations (Table 5) differs from the number of occupied PHABSIM cells (Table 4) for the following reasons: 1) some PHABSIM cells contained more than one redd, while each occupied River2D location only contained one redd; 2) some portions of the River2D sites were not represented by any of the PHABSIM transects; and 3) redds located upstream of the uppermost PHABSIM transect, but within the portion of the channel represented by the uppermost PHABSIM transect, would be located within PHABSIM cells but would be upstream of the River2D site. Model type (River2D versus PHABSIM) came into the analysis of CSI because the analysis used the CSI calculated by the two models based on the depths, velocities and substrates predicted by each model at the redd locations, rather than the CSI that could be calculated from the measured depths, velocities and substrates. The River2D model calculates CSI using the depths and velocities from the hydraulic simulation, substrate data from a channel index file, and the HSC. The key differences between the models tested in this paper are that PHABSIM is a one-dimensional model that simulates velocities using Manning's n values, while River2D is a two-dimensional model that simulates velocities using conservation of mass and momentum. During the habitat calculations, substrate is assigned to each River2D node based on the nearest substrate datapoint in the channel index file (either longitudinally or laterally), while PHABSIM, with longitudinal cells, assigns substrate values based on the nearest vertical longitudinally.

3.3 Data analysis

Mann-Whitney U tests (Wilkinson, 1990) were used to determine for each river, and, in the case of the Sacramento River, for each race of chinook salmon, if there was a significant difference in the CSI predicted by PHABSIM for occupied versus unoccupied cells, and if there was a significant difference in the CSI predicted by River2D for occupied versus unoccupied locations. This test is analagous to the transferability test described by Thomas and Bovee (1993). Kolmogorov-Smirnov tests (Steel and Torrie, 1980) were performed for each site for each set of suitability criteria to detemine if there was a significant difference between the PHABSIM and River2D flow-habitat relationships. Separate Kolmogorov-Smirnov tests were performed for the three Sacramento River sites upstream of the ACID dam for the two conditions simulated (boards in or out at the ACID Dam). As a result, there were a total of 55 Kolmogorov-Smirnov tests ([3 Sacramento River sites above ACID Dam $\times$ 2 conditions + 5 Sacramento River sites below ACID Dam] $\times$ 4 HSC sets + 5 American River sites $\times$ 2 HSC sets + 1 Merced River site $\times$ 1 HSC set).

4 Results

Velocity validation statistics of the River2D hydraulic model are given in Table 7, while a graphical example of the validation results are shown in Figure 7. Typical results of the River2D habitat model are shown in Figure 8. The CSI of occupied locations predicted by both PHABSIM (Table 4) and River2D (Table 5) was significantly greater than the CSI of unoccupied locations at $p = 0.05$ (Mann-Whitney U test) for fall-run chinook salmon spawning for all three rivers and for winter-run chinook salmon spawning in the Sacramento River. However, the CSI of occupied locations predicted by both PHABSIM and River2D were not significantly different from the CSI of unoccupied locations at p = 0.05 (Mann-Whitney U test) for late-fall-run chinook salmon spawning in the Sacramento River. The number of occupied cells and locations for late-fall-run (Tables 4 and 5) was lower than for the other Mann-Whitney U tests. The median CSI predicted for redd locations by River2D was greater than that predicted by PHABSIM for the Merced River, but was less for the American and Sacramento Rivers (Tables 4 and 5). The percentage of occupied locations where River2D predicted a CSI of 0 was less than

Table 7 River2D hydraulic modeling validation results. The errors were calculated as the absolute value of the difference between the measured and simulated velocities.

River	Site number	Mean error (m/s) for velocities < 0.91 m/s	Mean error (%) for velocities > 0.91 m/s
Sacramento	1	0.31	24%
Sacramento	2	0.17	17%
Sacramento	3	0.14	16%
Sacramento	4	0.52	30%
Sacramento	5	0.29	15%
Sacramento	6	0.22	13%
Sacramento	7	0.48	13%
Sacramento	8	0.34	20%
American	1	0.63	38%
American	2	0.25	27%
American	3	0.27	17%
American	4	0.35	24%
American	5	0.31	22%
Merced	1	0.17	26%

the percentage of occupied cells where PHABSIM predicted a CSI of 0 for fall-run chinook salmon spawning in all three rivers, but was greater for late-fall-run and winter-run chinook salmon spawning (Tables 7 and 8). For both PHABSIM and River2D, a substrate which was too large or small was the cause of most of the occupied locations which were predicted to have a CSI of 0 (Tables 7 and 8).

The Kolomogorov-Smirnov D statistics for the comparisons of PHABSIM and River2D flowhabitat relationships (Figure 9) ranged from 0.007 (Figure 10C) to 0.41 (Figure 10A), with a median value of 0.07 (Figure 10B). Only one PHABSIM flow-habitat relationship (Figure 10A) was significantly different from the River2D flow habitat relationship at $p = 0.05$. Even though the differences between the PHABSIM and River2D flow habitat relationships were almost allways not statistically significantly different, differences in the flow habitat relationships between the two model could result in different flow management decisions. For example, a comparison with a relatively low Kolomogorov-Smirnov D statistic of 0.03 (Figure 10D) has a maximum amount of spawning habitat at 85.0 m^3/s for PHABSIM, versus at 118.9 m^3/s with River2D, a 40 percent higher flow.

5 Discussion

Errors in the habitat predictions for occupied locations for PHABSIM can be due to longitudinal variation in depth, velocity and substrate (Gallagher and Gard, 1999) or due to the velocity distribution across the channel changing with flow. Errors in the habitat predictions for occupied locations for River2D can be due to inadequate detail in mapping substrate distribution, insufficient data collected to correctly map the bed topography of the site, or effects of the bed topography upstream of the study site not being included in the model. For the Sacramento River sites, a substantial proportion of the error for both the PHABSIM and

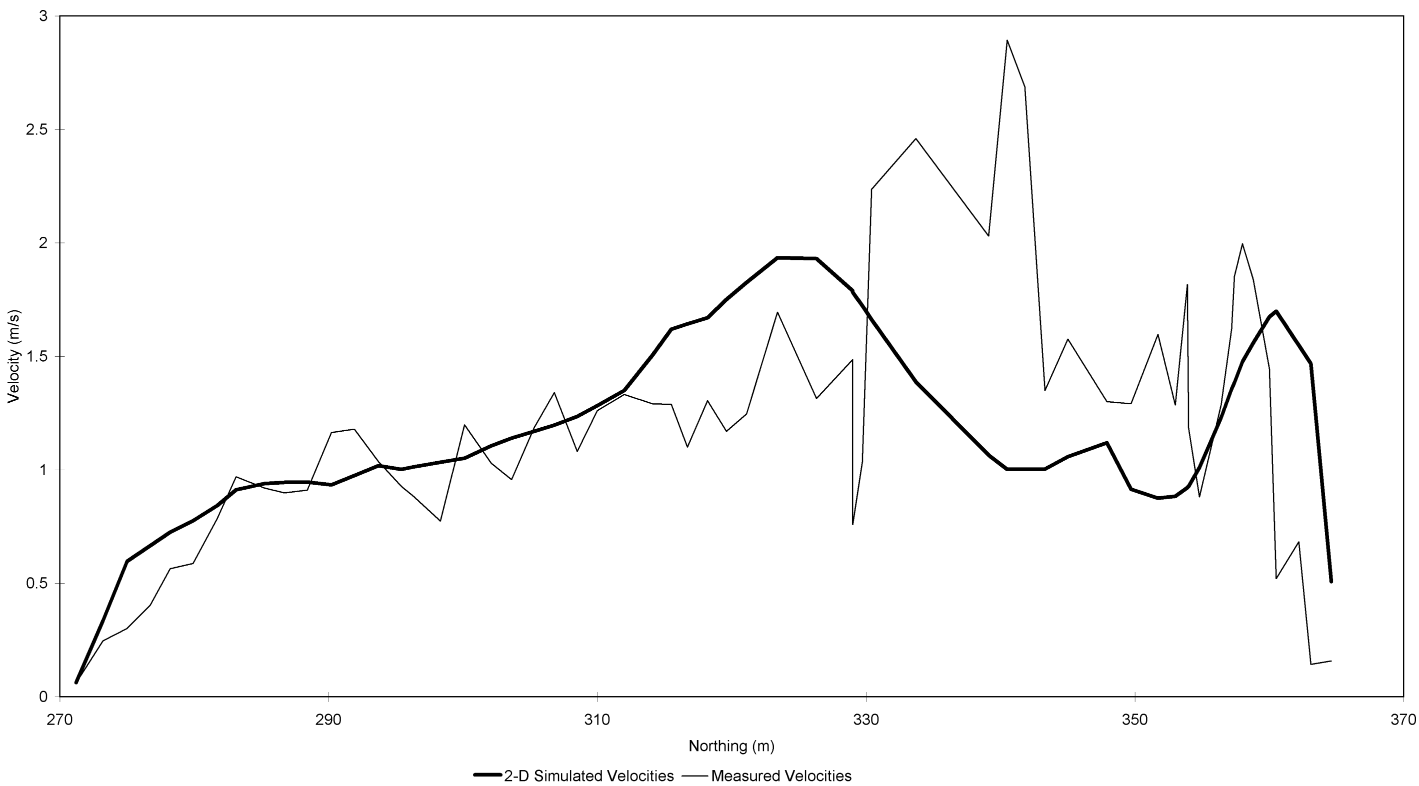


Figure 7 Example of River2D validation for one of the transects of the American River site illustrated in Figure 6 at a flow of 88.2 m^3/s.

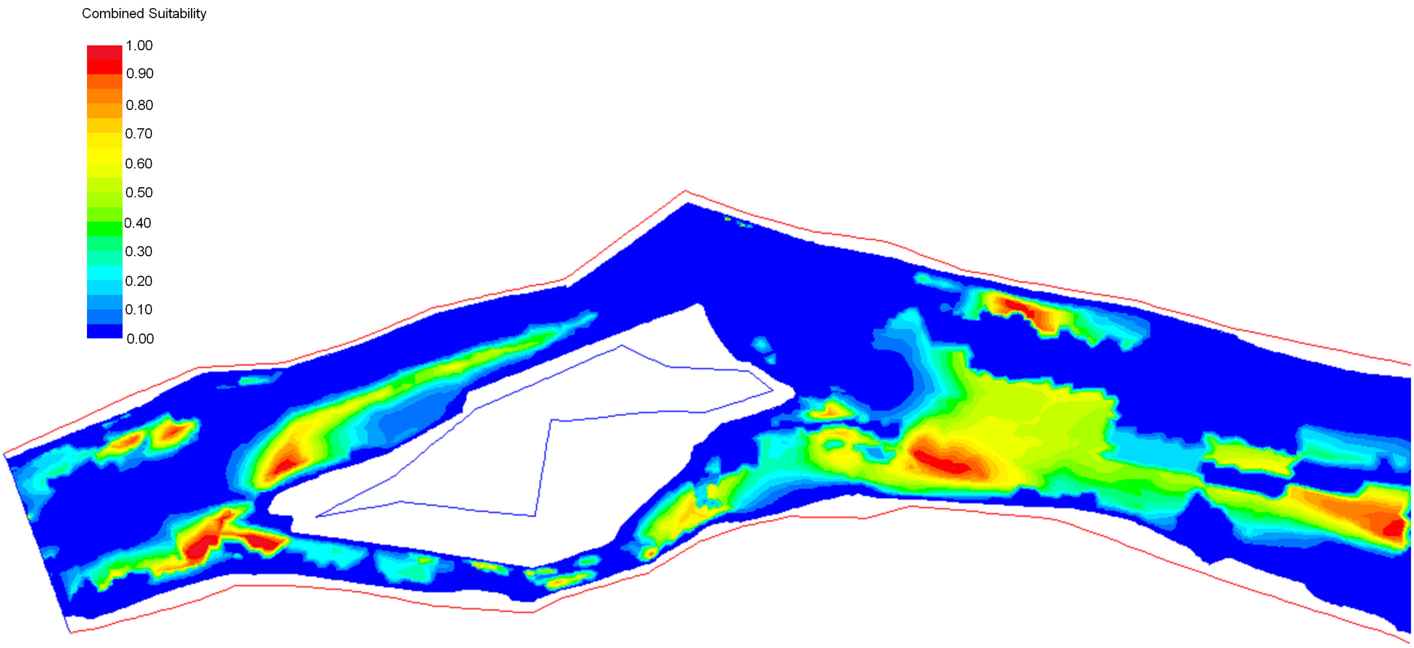


Figure 8 Example of River2D output of CSI for fall-run chinook salmon spawning at a flow of 87.8 m^3/s for the American River site illustrated in Figure 6.

Table 8 Characteristics of occupied cells predicted by PHABSIM. The numbers in the last five columns are the number of occupied cells that PHABSIM predicted having a CSI of 0 as a result of the cause given for that column. The percent of occupied cells with a CSI of 0 is the total number of occupied cells with a CSI of 0 (incuding all of the causes in the last five columns) divided by the total number of occupied cells (as given in Table 4).

River	Race	% Occupied cells with CSI of 0	Substrate too large or small	Dry	Too shallow	Too slow	Too fast
Merced	Fall	4%	1	0	0	0	0
American	Fall	36%	24	7	1	0	5
Sacramento	Fall	28%	16	4	0	0	0
Sacramento	Late-Fall	18%	3	1	0	0	0
Sacramento	Winter	22%	11	0	0	0	0

River2D models habitat predictions can be attributed to errors in the GPS measurements of redd locations, rather than errors in the habitat predictions of the models. The location of redds indicated by the GPS measurement can be as much as 5 m from the actual redd location (Gard and Ballard, 2003). In several cases, the redd location indicated by the GPS measurement was up onto the riverbank above water's edge.

The ability of PHABSIM in this case to relatively accurately predict the CSI of redd locations can be attributed to the number and spacing of transects, such that conditions at the transect tended to be representative of the depths, velocities and substrates present throughout the cells, and because flow at the sites chosen is largely one-dimensional, with only limited two-dimensional effects, such as transverse flows and across-channel variation in water surface elevations. There is a balance in the predictive accuracy of PHABSIM and River2D between the shapes of cells and the velocity information provided to each model. River2D will tend to be more accurate than PHABSIM because of the smaller triangular elements used by River2D, compared to the large rectagular cells used by PHABSIM. At least at flows close to those at which velocity data were collected and at locations close to the transect, PHABSIM will typically do a good job in predicting velocities, since it calculates the Manning's n value for each cell from the measured depth and velocity, and then calculates the simulated velocity from the Manning's n value. In contrast, River2D does not use any measured velocity data to predict velocities. While the only way to improve the performance of the PHABSIM habitat predictions would have been to increase the number of transects, and thus decrease the longitudinal length of the cells, there are several techniques that could have been used to improve the performance of the River2D habitat predictions with the existing dataset. It appears based on our substrate data that substrate varies more laterally than longitudinally. To test whether this supposition could be used to improve the performance of River2D, a test channel index file was created for the American River site in Figures 6 and 8 in which longitudinal breaklines were added to force River2D to predict substrate at a given location based on the nearest longitudinal point where substrate data was collected. This decreased the number of redds with predicted substrate suitability of zero

Table 9 Characteristics of occupied locations predicted by River2D. The numbers in the last five columns are the number of occupied locations that River2D predicted having a CSI of 0 as a result of the cause given for that column. The percent of occupied locations with a CSI of 0 is the total number of occupied locations with a CSI of 0 (incuding all of the causes in the last five columns) divided by the total number of occupied locations (as given in Table 5).

River	Race	% Occupied cells with CSI of 0	Substrate too large or small	Dry	Too shallow	Too slow	Too fast
Merced	Fall	0%	0	0	0	0	0
American	Fall	33%	52	5	0	1	3
Sacramento	Fall	22%	13	1	1	0	1
Sacramento	Late-fall	37%	6	0	0	0	0
Sacramento	Winter	34%	13	0	4	3	0

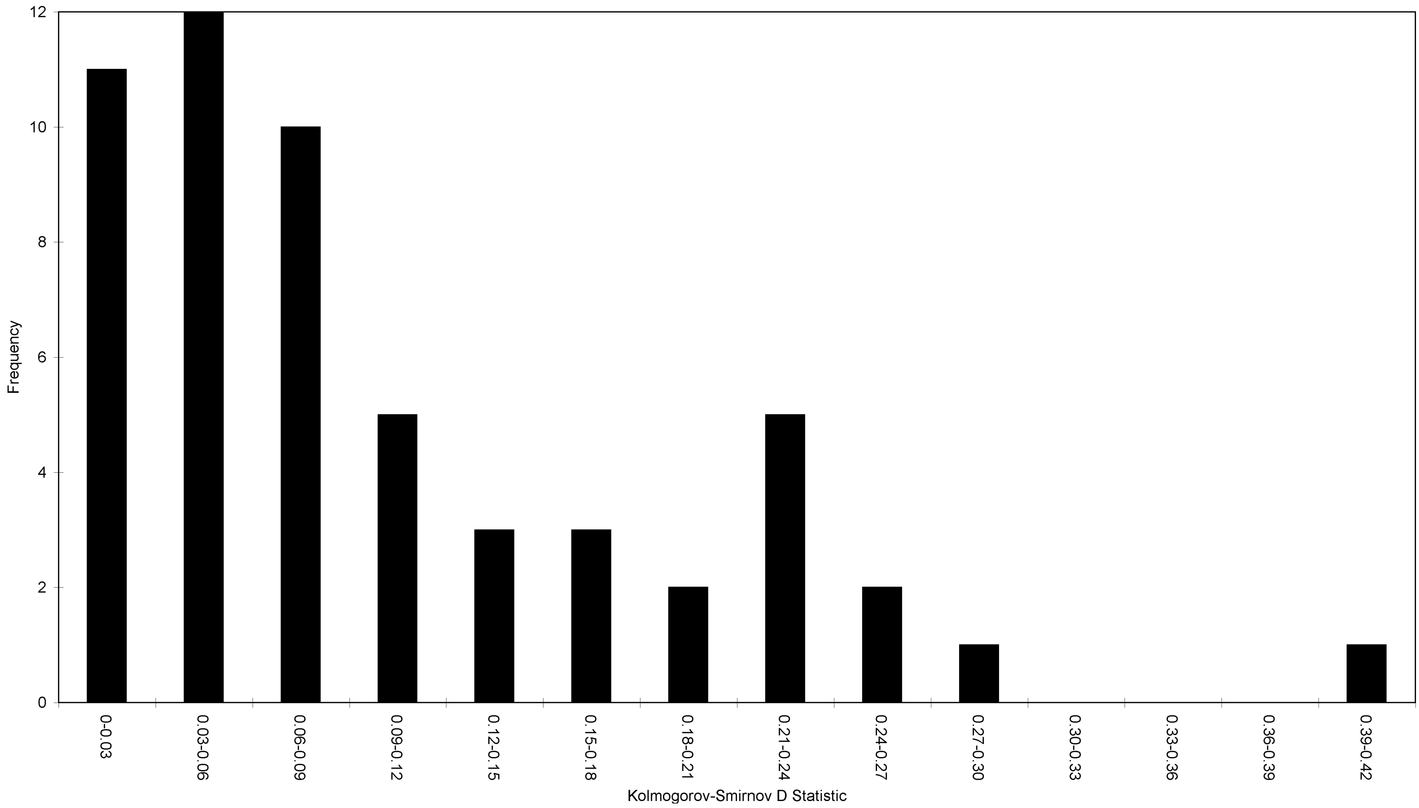
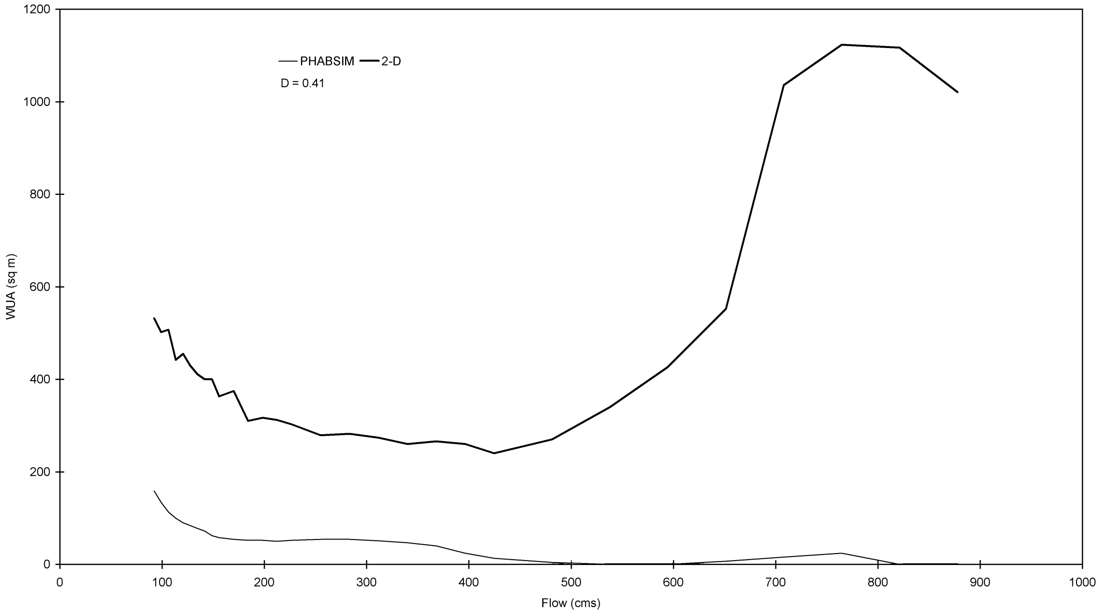


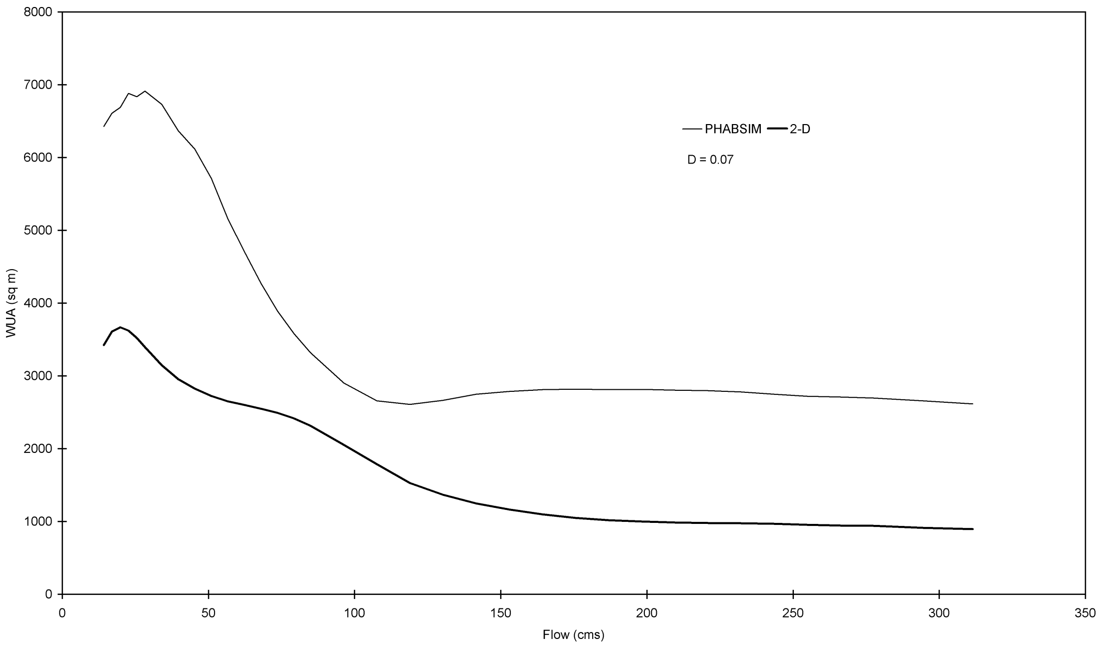
Figure 9 Results of Kolmogorov-Smirnov tests of PHABSIM versus River2D flow-habitat relationships. One of 55 tests was significant at $p = 0.05$.

from 22 with the original channel index file (Figure 11A) to 13 with the test channel index file (Figure 11B). The distribution of flow across the inflow boundary can have a substantial effect on the velocities predicted by River2D, at least in the upper portions of the sites. Accordingly, the performance of River2D could be improved by having a bed topography at the inflow boundary that is proportional to the measured distribution of velocities at the top of the site, so that the thalweg at the inflow boundary would be directly upstream of the highest velocity at the top of the site. The performance of the River2D model could also have been improved by collecting two additional types of data: the bed topography in one channel-width upstream of the top of the site, and mapping polygons of the substrate distribution. The velocity simulation within the site would have been improved by incorporating the actual bed topography upstream of the site into the computational mesh, instead of using an artificial upstream extension, as was done in this study. Since the substrate at a given point is assigned based on the closest point where substrate data was collected, River2D assumes that the substrate changes half-way in between two sets of cross-sectional points. Mapping substrate polygons would more accurately define where changes in substrate occur, and thus improve the performance of River2D with respect to substrate distribution.

The purpose of this study was to compare the habitat predictions of PHABSIM and River2D, rather than to validate either the HSC curves or the hydraulic modeling of PHABSIM and River2D. The performance of PHABSIM and River2D in predicting the CSI of occupied locations should be viewed as a combination of errors due to the predictive accuracy of the HSC curves used and the accuracy of PHABSIM and River2D to predict the depth, velocity and substrate spatial distribution within the sites. The combined errors were tested against fish data (redd



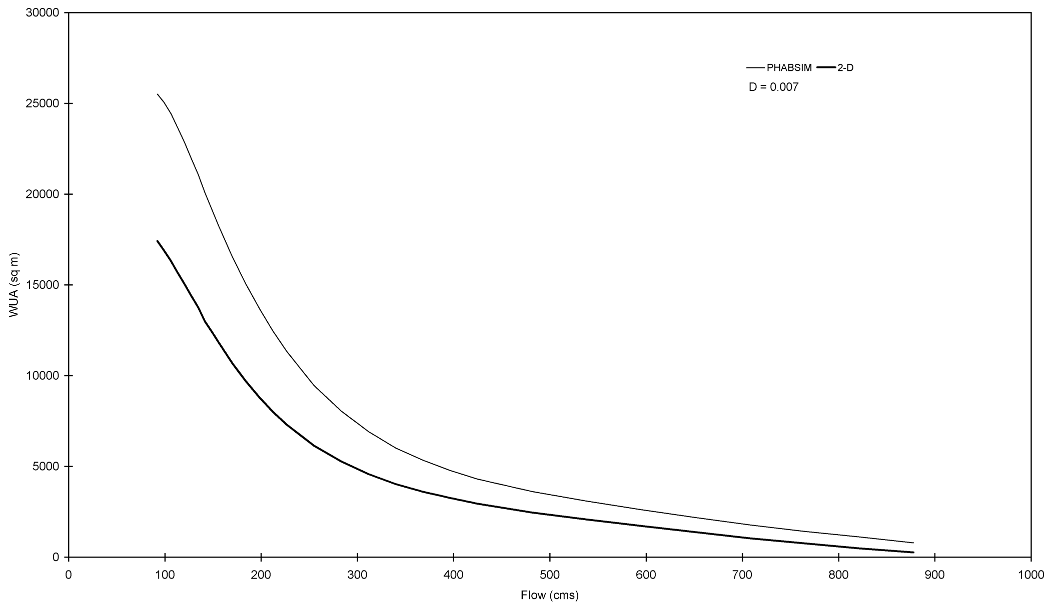
(a)



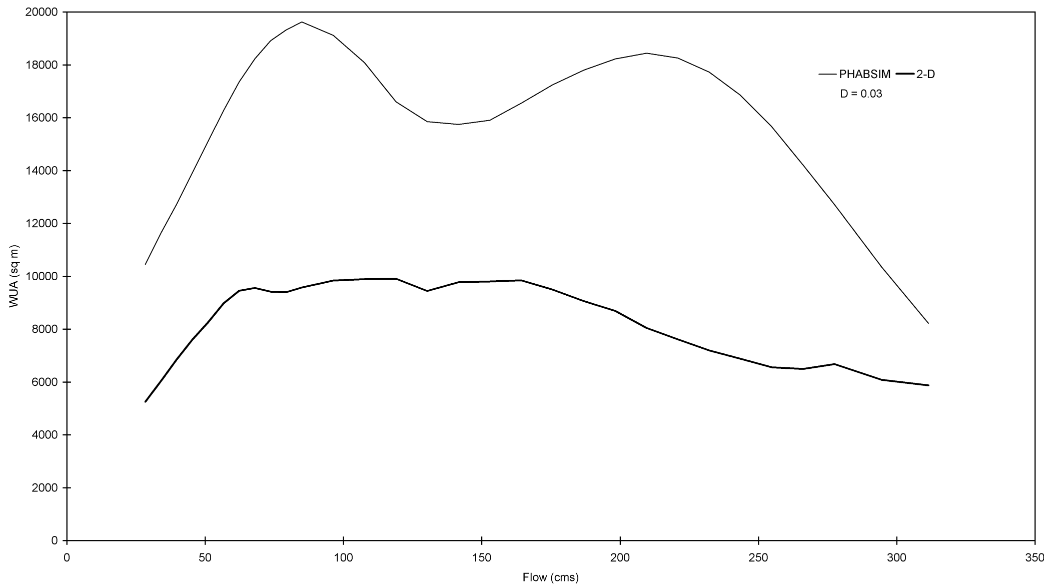
(b)

Figure 10 Sample PHABSIM and River2D flow-habitat relationships. A. Lower Lake Redding (Sacramento River) site, ACID boards out, steelhead spawning. Flow-habitat relationship with highest Kolmorogorov-Smirnov D statistic, $p < 0.05$. B. El Manto (American River) site, fall-run chinook salmon spawning. Flow-habitat relationship with median Kolmorogorov-Smirnov D statistic, $p > 0.05$. C. Upper Lake Redding (Sacramento River) site, ACID boards out, late-fall-run chinook salmon spawning. Flow-habitat relationship with lowest Kolmorogorov-Smirnov D statistic, $p > 0.05$. D. Sailor Bar (American River) site, fall-run Chinook salmon spawning.

locations) across systems and flow levels. Since the same HSC were used for PHABSIM and River2D, differences between the two models in predicting the CSI of occupied locations is entirely due to the ability of the two models to predict depths, velocities and substrates, which are translated into CSI by the HSC. Within the usual use of calibration, the only data used to calibrate the two models were water surface elevations. The data used to develop the HSC (Table 3) could also be viewed as calibration data. Since the redd location data used to compare the habitat predictions of PHABSIM and River2D for the Sacramento and Merced Rivers were a subset of the data used to develop the HSC for these rivers, these data can not properly be considered validation data. In contrast, the redd location data for the American River were not used to develop the American River HSC, and thus the results of the comparisons of the CSI predictions of PHABSIM and River2D can be viewed as a validation of the combination of the American River HSC and the hydraulic modeling of PHABSIM and River2D. The results for each model help to validate the hydraulic modeling of the other, while the combined results of the two models help to validate the HSC.



(c)

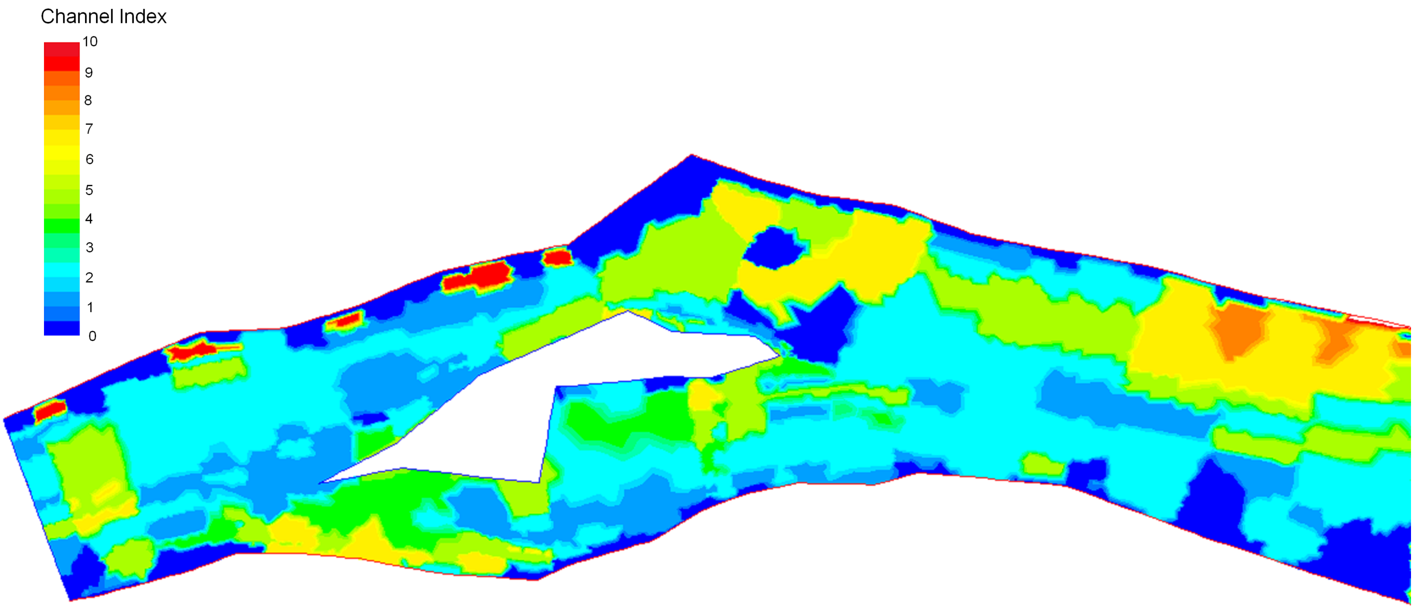


(d)

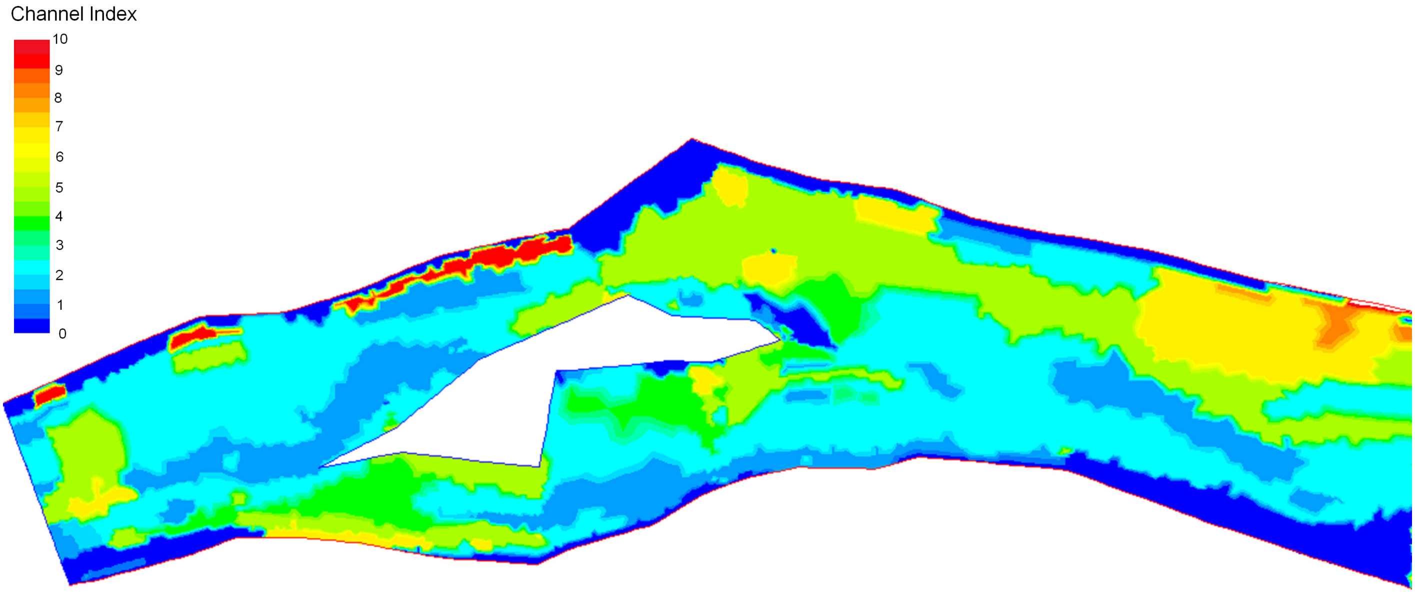
Figure 10 (*Continued*)

There were several limitations of the tests used in this study. The low number of occupied late-fall spawning locations (22 and 16 for, respectively PHABSIM and River2D) resulted in a low power of the Mann-Whitney U test for this race. In this regard, Thomas and Bovee (1993) found in the analagous transferability test that the power of the test was significantly reduced if the number of occupied locations was less than 45. Guay *et al.* (2000) found a significant positive relationship between fish densities and habitat quality indices, similar to our results that the CSI predicted by River2D of occupied locations was greater than for unoccupied locations for the remaining tests. The main limitation of the comparison of the PHABSIM and River2D flow-habitat relationships was that we were not able to compare the flow-habitat relationships of PHABSIM and River2D for areas which could not be modeled with PHABSIM. Similar to the results of this study, Waddle *et al.*, (2000) found mixed results in PHABSIM and River2D's abilities to predict velocities.

This study had mixed results on whether River2D is better than PHABSIM at predicting spawning habitat, and found little difference between PHABSIM and River2D in flow-habitat relationships. However, with the refinements suggested above, River2D has the potential to significantly outperform PHABSIM at predicting spawning habitat. Probably the main advantage of River2D is its ability to model conditions, such as transverse flow, across-channel variations in water surface elevation, and flow contractions/expansions, which cannot be modeled with PHABSIM. If flow-habitat relationships for areas that cannot be modeled with PHABSIM are significantly different from areas,



(a)



(b)

Figure 11 Distribution of substrate predicted by River2D for the American River site in Figures 6 and 8. A. Distribution of substrate using the original channel index file. B. Distribution of substrate using the test channel index file where substrate was determined based on the closest longitudinal substrate datapoint.

such as those used in this study, which can be modeled with PHABSIM, the choice of model would have an effect on instream flow prescriptions.

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