HABITAT MODELS FOR THE FOOTHILL YELLOW-LEGGED FROG (*RANA BOYLII*) IN THE SIERRA NEVADA OF CALIFORNIA

Regional Habitat Suitability Criteria, and Instream Modeling Methods

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ABSTRACT

In many current hydropower project relicensing studies, instream flow assessment methods are used to evaluate flow effects and proposed flow prescriptions on fish. These techniques may be applicable to other sensitive aquatic species, such as the riverine-breeding Foothill Yellow-legged frog (*Rana boylii*). Two major components of flow modeling were evaluated as part of this study. First, regional habitat suitability criteria (HSC) were developed using standard univariate and multivariate techniques and the predictive performance and transferability of different HSC methods were evaluated. Based on this evaluation, we recommend that separate creek and river HSC for the Sierra Nevada *R. boylii* be based on a percentile method. Second, three of the most commonly used instream flow assessment techniques: (1) one-dimensional habitat modeling, (2) two-dimensional hydrodynamic modeling, and (3) expert habitat mapping (judgment-based mapping by species experts), were evaluated. Several flow/ habitat relationships were compared among the three modeling methods: total suitable habitat, effective habitat during flow recession, and gradients of suitability during a pulsed flow. Level of effort, scale of resolution, capacity for extrapolation, and specificity of modeling analyses were also qualitatively assessed. A comparison table is provided to aid resource managers in selecting the most appropriate habitat assessment method for *R. boylii*, given the specific conditions of a hydropower relicensing project. Finally, a website was constructed to provide an updated and publicly accessible synopsis of the status of knowledge on *R. boylii*, with particular focus on the effects of river regulation on this species. The website provides access to relevant data and literature, tabular summaries of ecology and risks, and a species locality map derived from multiple data sources. Collectively, the elements of the website offer a comprehensive update on the species and may help identify reference populations for monitoring and research.

Keywords: habitat suitability criteria, habitat suitability indices, One-dimensional (1D) instream flow model, two-dimensional (2D) hydrodynamic model, expert habitat mapping, river regulation, website

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EXECUTIVE SUMMARY

Resource managers use a variety of tools in hydropower relicensing to determine impacts from flow prescriptions on sensitive aquatic species. For the Foothill yellow-legged frog (*Rana boylii)*, instream flow modeling is one tool that can be used to assess habitat suitability for egg mass and tadpole life stages. Several instream flow modeling methods are commonly used (e.g., one-dimensional habitat modeling, two-dimensional hydrodynamic models, and expert habitat mapping) and all modeling techniques require that habitat suitability be defined for each target species and lifestage. The models and criteria typically focus on three key characteristics of instream aquatic habitats – water depth, water velocity, and substrate – but may include habitat conditions. This study compares commonly used methods of defining habitat suitability criteria and applying those to instream flow models for *R. boylii* in the Sierra Nevada of California. In addition, this project provides a compilation of recent literature and reports on basic ecology of *R. boylii* and effects of river regulation. This compilation is presented on a new website, hosted by the USDA Forest, Pacific Southwest Research Station and includes maps, a bibliography with abstracts, and tabular and narrative summaries:
(http://www.fs.fed.us/psw/topics/wildlife/herp/rana_boylii/).

Regional Habitat Suitability Criteria

In order to use instream flow models to assess habitat suitability, species and lifestage-specific habitat suitability criteria are needed. There are several accepted approaches to developing habitat suitability criteria, but these have never been compared and evaluated for *R. boylii*. A series of habitat suitability criteria (HSC) were recently developed for two independent hydropower relicensing studies using data collected from local rivers; however, their transferability to other watersheds where impact assessments may be made is unknown. This study provides an assessment of microhabitat conditions at *R. boylii* oviposition and tadpole rearing locations across eight study sites in the northern Sierra Nevada, California. Regional HSC were developed using three standard univariate and multivariate techniques. The predictive performance and transferability of the HSC models were compared by applying the models to a validation dataset gathered from other rivers in the Sierra Nevada region. Conditions under which predictive performance was poor were evaluated to discern the predictive restrictions for each model. Univariate percentile-based habitat suitability indices (HSI) that assess categorical levels of suitability (unsuitable, low, moderate or high) classified the most egg mass and tadpole locations as highly suitable at all validation sites. However, to determine finer degrees of habitat suitability, univariate interval-based or multivariate logistic regression HSI are required. The logistic regression HSI classified the least number of egg mass locations as unsuitable, but also classified the largest total area of river as suitable, suggesting this model may misclassify unsuitable areas of the river as suitable. Both univariate models performed well on rivers that have a similar geomorphology to the eight rivers used to create the HSI, and thus can be transferred to other large, Sierran rivers with coarse substrates to predict suitability for *R. boylii* egg masses and tadpoles. Small rivers and creeks with shallow depths and finer substrates dominated by gravel, sand and small cobbles require locally-derived HSI. The univariate percentile-based HSI is recommended as a regional habitat suitability criteria when the goal is to assess categorical levels of suitability. The univariate interval-based HSI would be appropriate if further information on population outcomes (e.g., population trajectory, survival rates) could be quantitatively linked to fine scale gradients of suitability in hydraulic conditions. The univariate HSI are easily applied in two-dimensional hydrodynamic models, which can provide detailed assessments of oviposition and tadpole rearing conditions under various flow regimes. This information will allow managers to make flow recommendations beneficial to *R. boylii* during the hydropower relicensing process.

Comparison of Instream Flow Modeling Methods

In many current hydropower project relicensing studies, a variety of instream flow assessment methods are used to evaluate flow effects and proposed flow prescriptions on fish. These techniques may be applicable to other sensitive aquatic species, such as the riverine-breeding Foothill Yellow-legged frog (*Rana boylii*). This study sought to evaluate three of the most commonly used instream flow assessment techniques: (1) one-dimensional (1D) habitat modeling, such as the Physical Habitat Simulation (PHABSIM) System, (2) habitat modeling using a two-dimensional (2D) hydrodynamic model (River2D), and (3) expert habitat mapping (EHM) (specifically, judgement-based mapping by species experts). The primary objective was to provide comparative information so that resource managers can choose the most appropriate habitat assessment method for *R. boylii* given the circumstances specific to a particular hydropower relicensing project. Using a case study approach, each method was completed independently at a single study site, and two of the methods were completed at a second study site. Predicted habitat suitability from each of the methods was compared to observed habitat utilizations to determine advantages, disadvantages, and the range of accuracy of each method. A comparative summary of each method was created to facilitate management decisions, including: the costs and benefits of each method, the level of effort, the scale of resolution, the capacity for extrapolation, and the types of questions that can be addressed. In general, the study results indicated that while more time-consuming, 2D modeling provided higher resolution data that could be used to answer a wider variety of questions pertinent to the assessment of managed flow regimes for *R. boylii*. None of the three methods were able to address issues at the larger river segment scale, as each evaluated conditions at the local reach scale under the assumption that the modeled reach was representative of the river as a whole. Although habitat factors other than flow conditions are important for maintaining successful *R. boylii* populations, the potentially negative impacts from adverse flow conditions warrant the use of these instream flow assessment methods in managed rivers.

Development of a *Rana boylii* Website

The purpose of this website is to provide an updated and publicly accessible synopsis of the status of knowledge on Foothill Yellow-Legged Frog (*Rana boylii*), with particular focus on the effects of river regulation on the species. The website provides access to relevant data and literature that will help facilitate more effective conservation management approaches during river regulation processes, as well as guide future research and monitoring efforts. Information is organized by conservation risk and geographic region in order to allow quick access to relevant data, and where possible, complete abstracts of all literature cited are provided. Changes to flow regimes and downstream habitat alteration resulting from hydroelectric power generation and other water management projects have the greatest impact on *R. boylii* because of the species dependence on riverine environments. Effects of regulation on *R. boylii* are detailed by season (e.g., spring, summer, fall, winter) and lifestage. Additional background on other conservation risks is also provided, as well as lifestage-specific detail on relevant ecology and life-history. A map utilizing over 6,000 records from museum collections, research projects, technical reports, and government databases provides a comprehensive update on the species status. All records are provided in a Google Earth download (".kmz" file), which allows individual users to locate records and determine the year the observation was made, the source of the record, a unique record identifier (e.g., to look up a specific museum record), and whether breeding was recorded (presence of egg masses or larvae). This map will be a useful tool to help identify reference locations for future monitoring and research.

Foothill Yellow-legged Frog (*Rana boylii*),
Adult Female, NF of MF American River, Spring 2009
Photo Credit: A. Lind

CHAPTER 1:
Development of Regional Foothill Yellow-Legged Frog (*Rana boylii*) Habitat Suitability Criteria for Oviposition and Tadpole Rearing in the Northern Sierra Nevada, California

1.1 Introduction

The foothill yellow-legged frog (*Rana boylii*), a California State Species of Special Concern, is one of several focal species evaluated when the Federal Energy Regulatory Commission (FERC) relicenses hydroelectric dams. *R. boylii* reproduction is exclusively associated with stream environments, rendering its persistence particularly vulnerable to alterations in the natural flow regime. Adults breed and deposit egg masses in the spring as flows begin to recede, and tadpoles grow and develop during stable low flows in the summer. Metamorphosis occurs in early fall with froglets remaining in the margins of the river or nearby riparian areas, springs, or small tributary streams through the following spring. Over the last half century, *R. boylii* has declined dramatically, most notably in streams below dams (Lind, 2005). Altered stream flow regimes, changes in sediment supply and instream habitat, and establishment of non-native species are some of the primary factors contributing to this decline (Lind, 2005; Yarnell, 2000; Kupferberg, 1996).

One method to assess impacts from various flow prescriptions is instream flow modeling for *R. boylii* egg mass and tadpole life stages, similar to instream flow analyses often used for fish (Ahmadi-Nedushan et al., 2006; Huckstorf et al., 2008). Previous studies have shown that *R . boylii* are not adapted to withstand flow disturbance if it occurs out of sync with the natural flow regime. Flow fluctuations can have negative effects on the survival of egg masses via scour or stranding (Kupferberg et al., 2009a; Kupferberg et al. *In Press* [2011]), and even minor velocity increases during summer can have drastic effects on population size as tadpoles are displaced (Kupferberg et al. 2009b). Due to this sensitivity to flow conditions, suitability of egg mass and tadpole habitats under different flows varies from site to site depending on channel shape and bank slope (Yarnell et al. 2010). Instream flow modeling can precisely quantify local changes in depth and velocity conditions at oviposition and tadpole rearing locations, and thus provides a valuable tool for assessing impacts to habitat suitability under a range of flow proposals (Yarnell et al. 2010).

In a recent hydropower project relicensing, a series of habitat suitability criteria (HSC) focusing on hydraulic conditions (depth, velocity and substrate) were developed for *R. boylii* egg mass and tadpole lifestages for the DeSabla-Centerville hydropower relicensing project (Lind and Yarnell, 2008). Consistent with standard methods (e.g., Bovee 1986), these criteria were based on the frequency of use observed primarily in the project streams, under the assumption that higher use correlates with higher habitat suitability. Data on habitat availability were not available, so an assessment of whether the criteria should be adjusted for the prevalence of hydraulic conditions in the river (Heggins, 1991) could not be made. While these HSC were found to be applicable to the DeSabla project streams, their transferability to other river systems was unknown. Previous studies have shown site-specific habitat suitability curves are usually not applicable in other watersheds (Maki-Petays et al. 2002; Guay et al. 2003; Nykanen and Huusko, 2004). As a result, in a subsequent hydropower relicensing study (Placer County Water Agency [PCWA], Middle Fork American River Project), a new set of habitat suitability criteria were developed for *R. boylii* that combined data from streams within the project and data from the DeSabla project. Although the PCWA HSC were similar to the DeSabla HSC, their transferability to other watersheds was still unknown.

The objectives of this study were to: (1) determine the most appropriate method for developing HSC for *R. boylii*; (2) assess whether HSC for this species are transferable to other rivers within the northern Sierra Nevada, CA, and if possible; (3) to develop region-wide HSC for *R. boylii* from sample sites in the northern Sierra Nevada, CA that may be applicable to other rivers within this geographic range. To meet these objectives, a variety of standard univariate and multivariate techniques were used to develop HSC for *R. boylii* egg mass and tadpole lifestages. For the univariate techniques, the degree to which HSC should be adjusted for the availability of hydraulic conditions was assessed. The performance and transferability of the resulting three types of HSC were assessed using a validation dataset gathered from other rivers in the region. Lastly, the applicability of these habitat models to assessment of instream flows was evaluated using a two-dimensional (2D) hydrodynamic model in conjunction with known information on egg mass and tadpole locations.

1.2 Methods

1.2.1 Study Sites

Study sites were located on eight rivers ranging across the northern Sierra Nevada Mountains, California (Figure 1.1). Selected to represent typical geographic and hydrologic conditions in the northern Sierras, half of the rivers were regulated, primarily as diversion reaches, and half were unimpaired (Table 1.1). All eight sites had trout species present, and several of the sites also had non-native small mouth bass or crayfish. Mining activities (panning and dredging) take place in many northern Sierra Nevada rivers and occurred at six of the sites with varying degrees of severity. Two of the study sites were located in drainages greater than 2000 km^2 (North Fork (NF) and Middle Fork (MF) Feather), while two study sites were in drainages less than 300 km^2 (Middle Fork (MF) Yuba and North Fork Middle Fork (NFMF) American) (Table 1.2). The elevation of the study sites ranged from 350 m at the North Fork (NF) American to 930 m at the South Fork (SF) American, with half of the sites located between 400-500 m. The gradient of each study site ranged from 0.044 at the SF American to 0.008 at the NF Feather. Study sites ranged from 500 m to 1 km in length and were located at known breeding locations where high numbers of individuals had been documented in previous studies for at least two or more years.

Figure 1.1: Study Site Locations

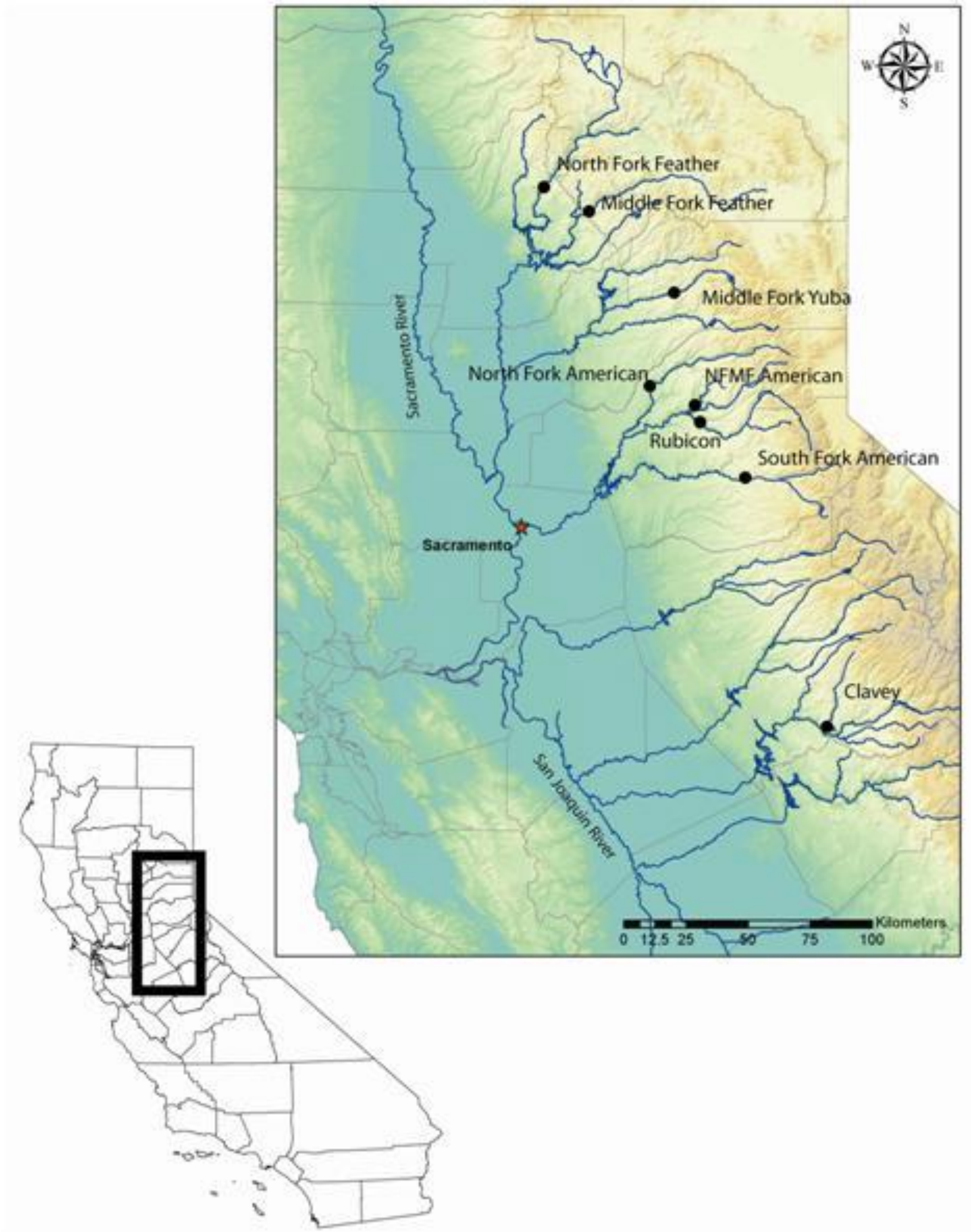


Table 1.1: Qualitative characteristics of each study site

Site	Flow Regime	Human Activity	Aquatic Species Interactions	Algae Observations	Riparian vegetation
Middle Fork Feather	Natural	Light use (boating, fishing) Light mining (panning bars)	Abundant crayfish Trout, Small-mouth Bass	Low algae cover in main channel and side-channel pools	Low density (willow/alder at high water, few sedges at low water)
North Fork Middle Fork American	Natural	Heavy use (recreational) Heavy mining (suction dredge)	Trout	High algae cover in main channel, abundant in side-channel pools	Low density (willow/alder at high water)
North Fork American	Natural	Heavy use (recreational, boating, fishing) Heavy mining (panning bars)	Trout and Small mouth Bass	Low algae cover in main channel; abundant in side-channel pools	Successional riparian vegetation (sedges at low water, willows at high water, alders in floodplain)
Clavey	Natural	Low use (recreational, fishing) No mining	Trout	Moderate algae cover in main channel, abundant in side channel pools, in late summer thick green algae very abundant	Low density (willow/alder at high water, few sedges at low water)
North Fork Feather	Regulated	Moderate use (recreational, fishing) No mining	Abundant crayfish Trout and Small mouth Bass	Thick brown algae that creates a mat-like coating on rocks	Heavy vegetation encroachment (Alder, Willow, Blackberry)
Rubicon	Regulated	Light use (fishing) No mining	Trout	High algae cover in main channel, abundant in side-channel pools	Moderate density (willow/alder at high water)
Middle Fork **Yuba**	Regulated	Light use Heavy mining upstream (dredge)	Trout	Moderate algae cover in main channel, abundant in side-channel pools	Moderate density (willow/alder at high water, willows at low water)
South Fork American	Regulated	Heavy use (recreational, boating, fishing) Light mining	Crayfish present Trout	Moderate algae cover in main channel, abundant in side-channel pools	Moderate density (willow/alder at high water, willows and sedges at low water)

Table 1.2: Quantitative characteristics of each study site

Site	Elevation[1] (m)	Drainage area (m)	Stream gradient (m/m)	Reach Type	Site length (m)	Data collected[2]
Middle Fork Feather	500	2417	0.0106	Riffle – Pool	500	VES, Habitat Use and Availability
North Fork Middle Fork American	400	229	0.0444	Riffle – Run	500	VES, Habitat Use and Availability
North Fork American	350	601	0.0077	Riffle – Pool	500	VES, Habitat Use and Availability
Clavey	375	408	0.0389	Cascade - Pool	1,000	VES and Habitat Use
North Fork Feather	405	5078	0.0081	Riffle – Run	500	VES, Habitat Use and Availability
Rubicon	425	807	0.0173	Riffle – Pool	500	VES, Habitat Useand Availability
Middle Fork Yuba	920	246	0.0209	Riffle – Pool	500	VES, Habitat Use and Availability
South Fork American	930	646	0.0142	Cascade - Pool	1,000	VES and Habitat Use

[1] Elevation at center of study site
[2] VES: visual encounter survey

1.2.2 Field Sampling

1.2.2.1 Egg mass and tadpole microhabitat use

Data on hydraulic habitat conditions at egg mass locations were collected during visual encounter surveys in May and June, 2009. Visual encounter surveys (VES) involved two surveyors walking along each side of the river channel and visually scanning the shallow water habitat for egg masses (Heyer et al., 1994). Surveyors walked upstream to minimize substrate disturbance and maximize egg mass detections as the majority of egg masses are laid on the downstream side of substrate. Since many egg masses are tucked up underneath boulders out of view, the visual search effort was supplemented by feeling around and underneath large boulders, cobbles, and overhanging bedrock shelves. Masks and snorkels were also used to further explore deep, concealed locations. Surveyors were limited to wading in depths less than 1.2 m due to the physical constraints and safety concerns of working in rivers at high flows. Surveys were completed once per week at each of the eight study sites until no new egg masses were found on subsequent surveys.

At each egg mass several microhabitat hydraulic variables were collected. Total depth of water column was measured with a wading rod, and mid-column velocity was measured using a Marsh McBirney Flow Meter (Hach Company, Loveland, CO). Mid-column velocity was converted into absolute velocity to reflect the actual movement of water over the egg mass, rather than directional movement of water. Egg mass attachment substrate was recorded as a categorical variable based on grain size diameter of the median axis: silt/ fines, sand (<2 mm), gravel (2-64 mm), small cobble (64-128 mm), large cobble (128-256 mm), small boulder (256- 512 mm), large boulder (>512 mm) and bedrock (Harrelson et al., 1994). GPS coordinates were recorded for each egg mass location so that these locations could later be mapped using a Geographic Information System (Arcview 9.0, ESRI, Redlands, CA).

Tadpole surveys began one month after the last egg mass was found at each site and were conducted once per month from July through September, 2009. Surveyors waded along the margins of both sides of the channel while visually scanning for tadpoles. To enhance the search effort surveyors also turned over small cobbles and gravel to search the interstitial spaces, and felt under boulders to chase tadpoles out from underneath them. To detect tadpoles in deepwater, snorkel surveys were completed with observers visually scanning the river bed, manually turning over cobbles and diving down to the bottom of the river in up to two meters of water. At each tadpole location the same hydraulic data were collected as described for the egg mass microhabitat conditions, including a GPS location for spatial analysis of tadpole distributions. If visual confirmation of tadpole developmental structures were feasible, then lifestage categories were assigned as: Stage 1 (no rear limbs present or only small limb buds), Stage 2 (rear legs present), Stage 3 (rear legs with toes and front limb buds present) or Stage 4 (front limbs developed, tail still visible).

1.2.2.2 Habitat availability

To quantify the available habitat for *R. boylii* oviposition and tadpole rearing, habitat availability assessments were conducted at six of the eight study sites during each visual encounter survey. At the two study sites where availability data was not collected (Clavey and SF American), a longer reach of river was surveyed for egg masses and tadpoles (Table 1.2). Within each of the six study sites, a series of systematic transects was established to collect cross sectional data. Transects were distributed across all mesohabitat types in order to capture the full range of depths, velocities and substrate present. To determine the location of the initial transect, as well as the spacing between subsequent transects, surveys were conducted prior to the breeding season to map mesohabitat types at each site. Mesohabitat unit types were based on Hawkins et al. (1993). A tape measure or laser range finder was used to measure the length of each mesohabitat unit type. The length of the shortest mesohabitat type was used to determine the minimum distance between transects in order to ensure that each mesohabitat type was included in the survey. A random number between one and the length between transects was selected to establish the placement of the first transect. Transects were then permanently marked with flagging and stakes for use in all subsequent surveys.

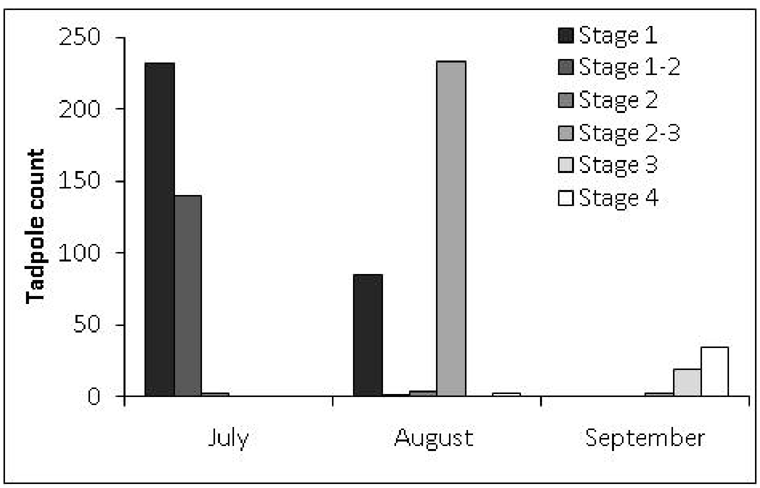
During each survey, a tape measure was strung across the river at each transect perpendicular to streamflow. To reduce potential point selection bias, the first measurement point on each transect was a randomly selected location between 0-150 cm (0-200 cm at the NF Feather site, due to the large channel size) from the wetted edge of the cross section. Subsequent measurement points were spaced at 1.5 m increments along each transect (2.0 m spacing at NF Feather site). At each survey point, total depth, mid-column velocity and dominant substrate type were collected using the same methods as described for the data collection at egg masses. If measurement points were located on a boulder or dry area above the water surface larger than 0.5 m^2, they were recorded as “dry” (zero depth, zero velocity). If the dry feature was smaller than 0.5 m^2, the measurement was taken on the downstream side of the feature. If the water depth or velocity was such that it was unsafe to wade (depth > 1.10 m or velocity >1 m/ s during high flows in the spring), a range finder was used to determine the total wetted width of each cross section to account for any unsurveyable points.

1.2.3 Habitat Suitability Criteria Development

We assessed three types of HSC commonly used for predicting suitable instream habitat: (1) a composite habitat suitability index (HSI) created from combining interval-based univariate suitability indices (SI) (Guay et al., 2003; Vismara et al., 2001; Guay et al., 2000), (2) a composite HSI created from combining percentile-based univariate SI (Lind and Yarnell, 2008), and (3) a multivariate habitat suitability index using a logistic regression approach (Guay et al., 2000;

Rashleigh et al., 2005; Dixon and Vokoun, 2008). For each technique, three hydraulic variables, total depth, mid-column velocity and dominant substrate (attachment substrate for egg masses and dominant microhabitat substrate for tadpoles) were used to define suitable microhabitats. To develop region-wide HSC for oviposition site selection, the use data were pooled across all eight study sites and across all egg mass surveys. The availability data from the spring survey in which the largest numbers of new egg masses were found was selected for analysis, as representative of the river conditions during the peak of breeding season. To develop region-wide HSC for tadpole rearing throughout the summer, use data were pooled across all eight study sites and two developmental stage groups were defined. The majority of tadpoles found during the first survey were stage one and in transition from stage one to stage two (Figure 1.2). In the second and third surveys, tadpoles were primarily of later stages (2-3 to 4). Thus, the tadpole data was split into early and late stage groups according to the month of the survey. Tadpoles from the July surveys were categorized as 'early' and those from the August and September surveys were combined and categorized as 'late'. Designating tadpole stages by survey month also had the advantage of more directly applying to regulated flow management schedules, which are typically proposed on a monthly basis. The tadpole availability data was also categorized as either 'early-stage' or 'late-stage' according to the month of survey, and data from the six availability sites were pooled.

Figure 1.2: The number of tadpoles in different developmental stages counted during each survey at all eight study sites. Stage one tadpoles (no limb buds present) were considered early-stage tadpoles and were most abundant during July. Tadpoles in stages two (rear limbs present) through four (all limbs formed) were considered late-stage tadpoles and were most abundant in August and September



1.2.3.1 Univariate Habitat Suitability Indices

Previous studies have suggested that Habitat Suitability Indices (HSI) derived from use only data may not accurately represent selection, if the habitat available provides only a limited range of conditions (Heggins, 1991). These studies concluded that less abundant but highly used habitats may indicate a stronger preference, while moderate to high use in highly abundant habitats may simply reflect their greater availability (Moyle and Baltz, 1985). Suitability Indices (SI), therefore, are commonly adjusted to represent a proportion of use relative to the proportion available for each environmental parameter by dividing the percentage of use ($\%U_{c,i}$) by the percentage of available habitat ($\%A_{c,i}$) for each numeric interval (Guay et al., 2000, Vismara et al., 2001). Availability of microhabitats used for oviposition and tadpole rearing were assessed by graphically comparing the proportion of use to the proportion available for each hydraulic variable.

To create interval-based univariate SI's, each continuous variable was converted to a series of intervals: 0.10 m increments for total depth (ranging from 0.00 to 1.10 m), and 0.05 m/ s increments for mid column velocity (ranging from 0.00 to 1.90 m/ s). Attachment substrate for egg masses and dominant substrate at tadpoles was treated as an ordinal variable (range of 1-8) based on increasing diameter size. To create a substrate SI that could be evaluated and compared with other data sources, the substrate data was reclassified to coincide with those of the other data (range of 1-6). Specifically, small and large cobble was reclassified as cobble, and small and large boulder was reclassified as boulder. The frequency of use for each interval of the three hydraulic variables was calculated and normalized from 0-1 by the highest frequency to the nearest hundredth. The resulting SI is a curve representing the relationship between suitability (ranging from 0 to 1) and the range of each hydraulic variable.

Often SI curves are smoothed using polynomial regression models of two or more orders of magnitude (Vismara et al., 2001). Smoothed curves yield predictive regression equations that can be used to assign HSI values to actual point values for total depth, mid-column velocity and substrate type. Polynomial regressions of the 2^{nd} to 4^{th} order were fit to the data in attempts to produce a smoothed SI curve. However, resulting curves produced low R^2 values, and based on visual inspection did not accurately describe the observed relationship between suitability and hydraulic condition. As a result, the interval-based SI curves were not smoothed and thus simply represent SI values for each interval of data.

To create suitability indices based upon percentiles of use, specific ranges of observed mid-column velocities, total depths, and attachment substrates were assigned a single SI value. Three categories of suitability: high, low, and unsuitable, were chosen to represent the observed use data. Hydraulic conditions of 'high suitability' represented the numerical range of 90% of observed use values and were assigned a suitability of 1.0. Conditions of 'low suitability' encompassed the remaining 10% of observations were assigned a suitability of 0.1. All values outside of these ranges of use were assigned an SI of 0.0.

Each univariate SI must be combined to create a composite HSI that can be applied to any instream habitat location. Various methods are used to combine SIs, each with different underlying assumptions that yield varying results (Ahmadi-Nedushan et al., 2006). The multiplicative method assumes that habitat selection for one variable is independent of the other variables, so if any of the hydraulic conditions are unsuitable, the composite index will be zero. The limited method assumes that habitat suitability is limited by the hydraulic variable with the lowest suitability value, and as with the multiplicative method, if any variable has a zero value the composite suitability is zero. Calculating the geometric mean of the each SI assumes that high suitability for one variable can compensate for low suitability of another variable by finding the central tendency of all SI values. However, zero suitability for any variable also results in a composite HSI value of zero. The arithmetic mean also assumes high suitability of one variable compensates for other poor conditions, but unlike the geometric mean, any zero suitability will be averaged out. Lastly, the weighted multiplicative method assumes habitat selection for one variable is independent of another, but not with equal importance. The weighted mean method allows expert judgment to be used to designate those variables that are most important to the species during habitat selection by increasing the weight of certain variables in the model. For this study, on the basis of field observations and a literature review, it was assumed that velocity was twice as important as depth and substrate for *R. boylii* oviposition and tadpole rearing, and assigned weights accordingly.

- **Multiplicative**

$$HSI = SI_D \times SI_V \times SI_S$$

- **Limited**

$$HSI = min\ (SI_D, SI_V, SI_S)$$

- **Geometric mean**

$$HSI = \sqrt[3]{(SI_D \times SI_V \times SI_S)}$$

- **Arithmetic mean**

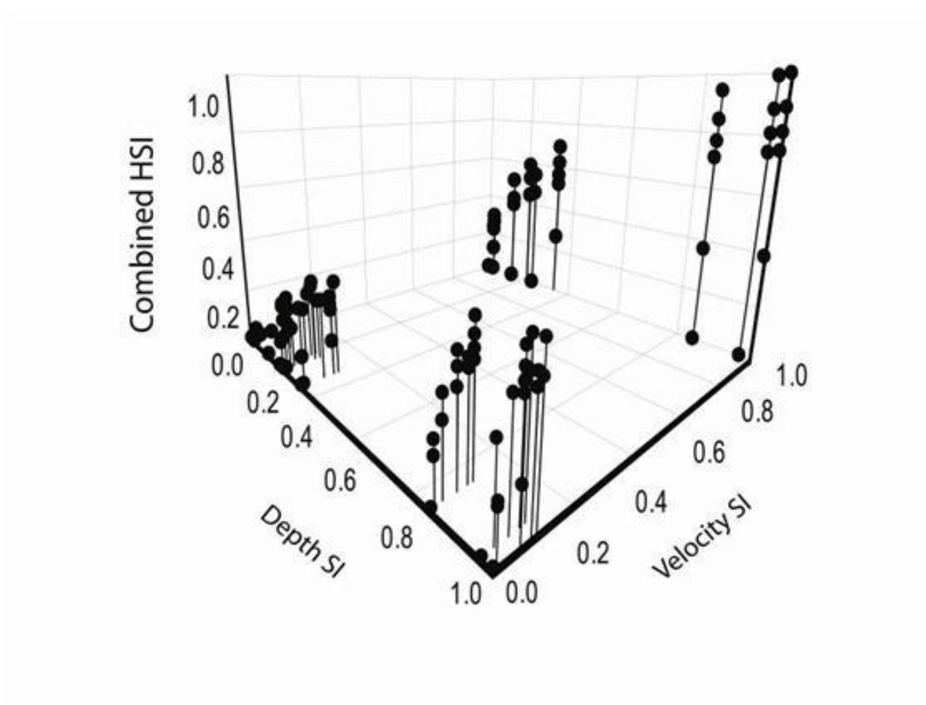
$$HSI = \frac{SI_D + SI_V + SI_S}{3}$$

- **Weighted multiplicative**

$$HSI = SI_D^{0.25} \times SI_V^{0.50} \times SI_S^{0.25}$$

To evaluate which combination technique was most appropriate for *R. boylii*, composite HSI were created using all five methods and graphically examined the relationships between water depth, water velocity, and HSI for the interval-based egg mass data. A comparison of the HSI values produced by each combination method showed the geometric mean produced highest values for locations with egg masses and assigned a zero if any of the three variables were unsuitable. This method also allowed for high SI values representing good conditions for one variable to compensate for a low SI value from poor conditions in another variable (Figure 1.3). The other methods did not properly assign HSI values (Appendices 1.6.A, 1.6.B) due to either a lack of compensation (limited and multiplicative) or over-compensation (arithmetic mean and weighted multiplicative).

Figure 1.3: Distribution of HSI values using the geometric mean combination method. High suitability of one hydraulic parameter compensates for low suitability of another hydraulic parameter, yet an unsuitable parameter (SI = 0) results in a zero combined suitability



1.2.3.2 Multivariate Habitat Suitability Criteria

Habitat selection is most likely a multivariate process rather than a combination of independent factors and a wide variety of techniques are being used (Ahmadi-Nedushan et al., 2006). The use of logistic regression to develop a multivariate model has become increasingly prevalent in habitat selection studies for a variety of species, particularly in instream flow studies (Thomas and Taylor, 2006). Recent research has shown that these models incorporated into a two-dimensional hydrodynamic model more accurately predicted fish locations when compared to traditional univariate HSI (Guay et al., 2000; Guay et al., 2001). For comparison to the univariate HSI developed in this study, a logistic regression approach was used to develop a multivariate model that could predict habitat suitability for oviposition and tadpole rearing.

Logistic regression models describe a probability function for a binary dependent variable (use versus non-use) in response to a set of continuous and categorical predictor variables (hydraulic conditions). In many habitat selection studies, use is compared to a sample of available or non-use points and does not represent the true probability of use (Thomas and Taylor, 2006; Johnson et al., 2006). Rather, the method yields an index of use based upon the dataset only. Only when a random sample of points are selected and categorized as use or non-use, and the true probability of use in the population is known, than the logistic regression will yield the actual probability of use (Keating and Cherry, 2004). Based upon field observations in this study, the actual probability of use for any given egg mass and tadpole location is extremely small compared to the amount of non-used locations available in a river environment. Thus, availability points in this dataset were regarded as non-use points. A case-control type logistic regression (Thomas and Taylor, 2006) was used to compare use points to an equal number of non-use points randomly sampled from the availability data.

The logistic regression equation was used to predict an index of use based upon the predictor variables total depth, mid-column velocity and substrate type. Due to the extreme right skew and high frequency of zero values in the velocity data, 0.005 was added to all values and this variable was square root transformed. The relationship between use and water depth was unimodal – i.e., use was low at both very shallow and very deep depths. To represent this relationship, the original depth variable and another variable that was the square of depth were both included. Substrate was treated as an ordinal variable based on increasing grain size (1-6), and a squared term was also included to reflect the unimodal relationship between use and substrate size. Data from the six sites in which both use and availability data were collected were combined and used in the logistic analysis. The South Fork American and Clavey study site data were not included in this analysis, since only use data were collected at these sites. The logistic regression was performed in NCSS statistical software and significance of parameters was assessed using α=0.05.

1.2.3.3 Model Evaluation and Transferability

To evaluate the performance and transferability of the univariate and multivariate habitat models, a validation dataset was compiled from microhabitat use data collected on egg masses (Table 1.3) and tadpoles (Table 1.4) in previous years and other rivers. This data was obtained from hydropower relicensing studies (Pacific Gas and Electric Company [PG&E], Desabla-Centerville Project) and other unpublished data (Yarnell, 2005). The new habitat models were applied to the values of total depth, mid-column velocity and substrate type for each egg mass and tadpole location in the validation dataset to produce an associated HSI value ranging from 0-1, and histograms were used show the distribution of HSI values that resulted. To assess the transferability of each model to other years and sites, the distribution of the assigned HSI values were compared across sites for each model type. To simplify interpretation, three broad HSI categories were defined: high suitability with HSI values >0.66; moderate suitability with HSI values ranging from 0.33-0.66; low suitability for HSI values from 0.01-0.33, and unsuitable for HSI values <0.01.

Table 1.3: Number of validation data points used to evaluate the performance of the habitat suitability criteria models for oviposition, early-, and late-stage tadpole site selection. Streams listed above the double line are from the same rivers as the current study but data were collected in different years; sites below the double line are from different rivers

Stream	Year	Source[1]	Egg Masses	Early-Stage Tadpoles	Late-Stage Tadpoles
Rubicon River	2007, 2008	PCWA	80	*n/a*	66
Middle Yuba River	2008	PG&E	51	79	61
West Branch Feather River	2006	PG&E	31	37	13
Pit River	2002, 2003, 2004	PG&E	108	*n/a*	*n/a*
South Yuba River	2008, 2009	PG&E	69	29	*n/a*
Butte Creek	2006	PG&E	33	125	34
Shady Creek	2003	S. Yarnell	21	30	91
Steep Hollow Creek	2008	PG&E	*n/a*	*n/a*	23
TOTALS			**393**	**300**	**288**

[1] PCWA – Placer County Water Agency, Auburn, CA; PG &E – Pacific Gas and Electric Company, San Francisco, CA; S. Yarnell – Sarah M. Yarnell, unpublished data.

1.2.3.4 Application within a 2D hydrodynamic model

A two-dimensional (2D) hydrodynamic model (River2D) was used to predict depths, mid-column velocities and dominant substrate types for egg masses and tadpoles at one "case-study" site (the Rubicon River). River2D is a depth-averaged finite element model freely available and used by the California Department of Fish and Game, U.S. Fish and Wildlife Service and others in fish habitat evaluation studies (Steffler and Blackburn, 2002; Tiffan *et al*., 2002; Hanrahan *et al*., 2004; Gard, 2005). The 2D model for the Rubicon study site was developed within the instream flow study for the PCWA Middle Fork American hydropower relicensing project (FERC #2079) for use in evaluating potential project effects on instream flow conditions. Details on the calibration of the model, including information on the input topography, mesh density and model error, can be found online (PCWA, 2010). The calibrated model was provided for use in this study by PCWA.

Each of the three types of HSC (interval, percentile, logistic regression) were input into the 2D model and habitat suitability ranging from 0-1 was mapped across the modeled river reach. Point locations for egg masses and tadpoles (late-stage only) surveyed at the modeled reach in 2008 were then overlaid onto the habitat suitability maps. The number of egg mass and tadpole locations that fell within one of four HSI categories were counted and plotted for comparison. HSI categories were defined as stated above (high, moderate, low, unsuitable). Habitat suitability was evaluated at the modeled flows that were observed when the egg mass and tadpole data were collected, 55 cfs and 36 cfs, respectively.

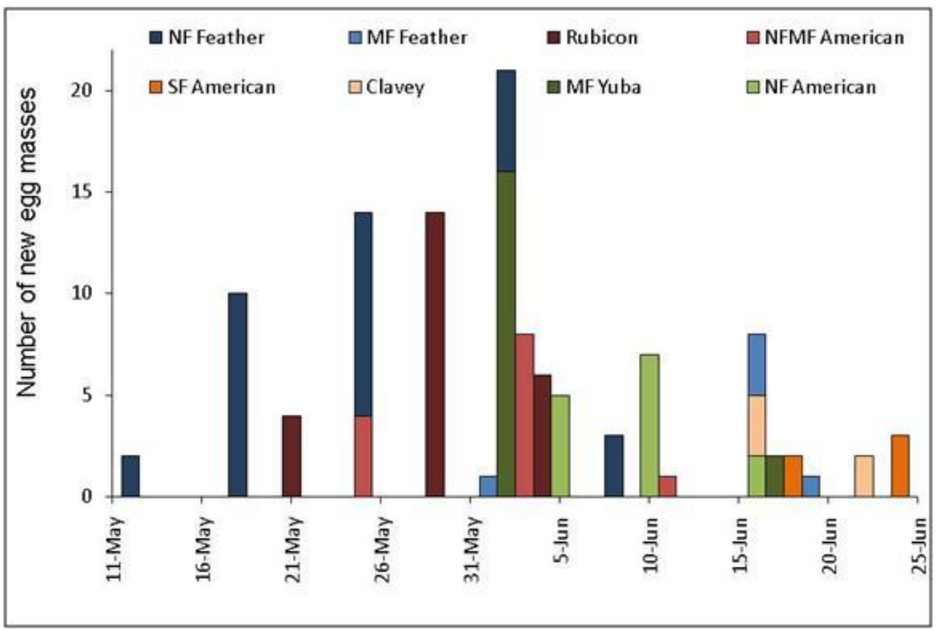
1.3 Results

1.3.1 Survey Effort and Habitat Use by Lifestage

1.3.1.1 Egg Masses

A total of 147 egg masses were found at all eight study sites between May 12, 2009 and June 19, 2009 (Figure 1.4), with approximately one third (50 of 147) of the egg masses occurring at the NF Feather site. The timing of egg mass deposition and the duration of the breeding season varied widely between sites. The start of the breeding season ranged from May 12 (NF Feather) to June 24 (SF American), and the duration ranged from 3.5 weeks at the NF Feather to only six days at the SF American. The remaining study sites varied in duration and timing within these extremes (Figure 1.4). Three availability datasets were collected at each of five availability census study sites, and five availability datasets were collected at the NF Feather due to the extended duration of breeding (Figure 1.4). The habitat availability dataset corresponding to the peak of the breeding season on each river was selected for further analysis (e.g. May 29 for Rubicon and June 10 for NF American; Figure 1.4).

Figure 1.4: Bar graph of the number of new egg masses found for each visual encounter survey. The survey date on which the greatest number of new egg masses were found was considered the peak of breeding for that site (e.g. June 2 for NF Feather)



At all eight river sites, *R. boylii* oviposition sites had moderate depths, low velocities and course attachment substrate types (Figure 1.5, Tables 1.4-1.6). The deepest egg mass observed at any study site was at 0.87 m total depth, and the highest mid-column velocity observed at any egg mass location was 0.13 m/ s. Because significant portions of the center of the river channel were unsurveyable during spring flows, the habitat availability data reflect depths up to 1.1 m and velocities below 1.9 m/ s. However, greater depths and velocities existed in the river during the breeding season. Thus, the availability data underestimated the actual amount of deeper water and faster velocities that were available to frogs during the breeding season. A comparison of use and available hydraulic conditions shows frogs selected a subset of available microhabitat conditions for oviposition, suggesting selection was not limited by conditions available in the river (Figure 1.6).

Figure 1.5: Histograms of the frequency of oviposition habitat use and availability for (A) total depth, (B) mid-column velocity, and (C) attachment substrate type

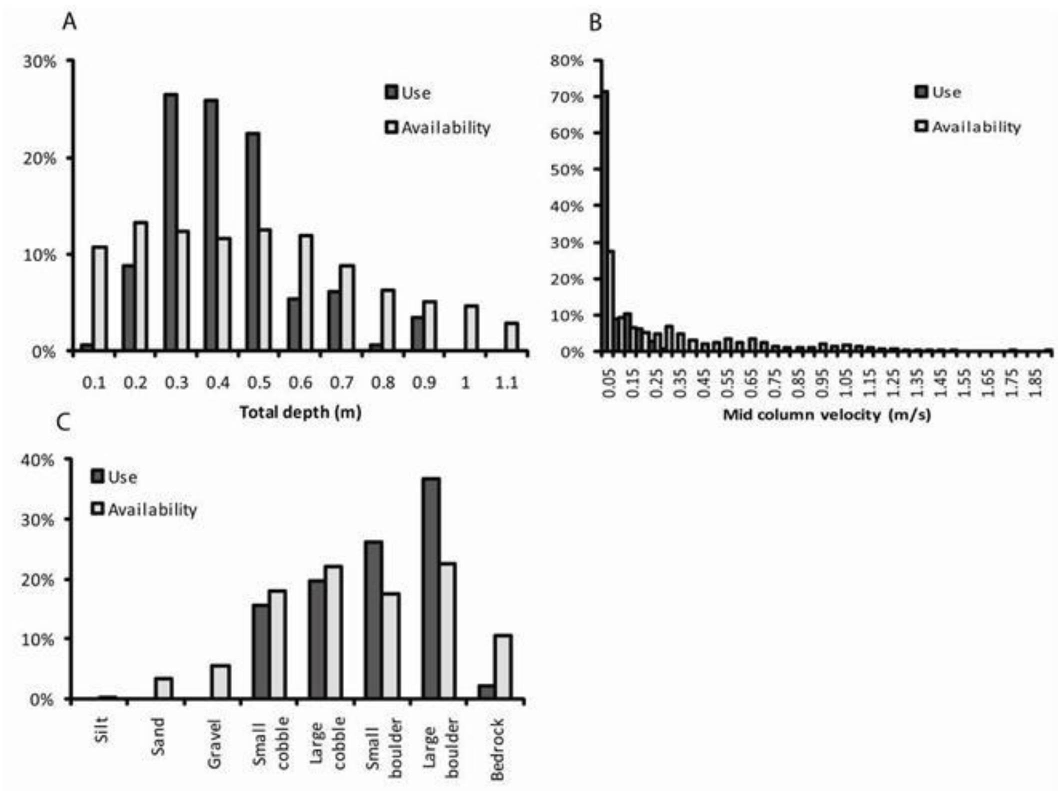


Table 1.4: Descriptive statistics for oviposition habitat use and availability for total depth at each study site and all sites combined

	Use				Available				
Site	**Count**	**Mean+SD**	**Min**	**Max**	**Count**	**Mean+SD**	**Min**	**Max**	**% Reach not surveyed**
Middle Fork Feather	10	0.53 + 0.17	0.18	0.82	122	0.44 + 0.30	0.01	1.07	47%
North Fork Middle Fork American	13	0.32 + 0.12	0.12	0.48	111	0.48 + 0.27	0.01	1.09	6%
North Fork American	14	0.29 + 0.13	0.10	0.62	158	0.44 + 0.25	0.01	1.08	23%
North Fork Feather	50	0.33 + 0.85	0.14	0.52	103	0.50 + 0.29	0.01	1.06	1%
Rubicon	24	0.35 + 0.14	0.12	0.60	145	0.43 + 0.27	0.01	1.08	21%
Middle Fork Yuba	24	0.52 + 0.19	0.18	0.87	145	0.43 + 0.26	0.01	1.07	19%
Clavey	7	0.48 + 0.15	0.24	0.44					
South Fork American	5	0.40 + 0.07	0.28	0.46					
All Rivers	**147**	**0.39 + 0.16**	**0.10**	**0.87**	**784**	**0.45 + 0.27**	**0.01**	**1.09**	

Table 1.5: Descriptive statistics for oviposition habitat use and availability for mid-column velocity at each study site and all sites combined

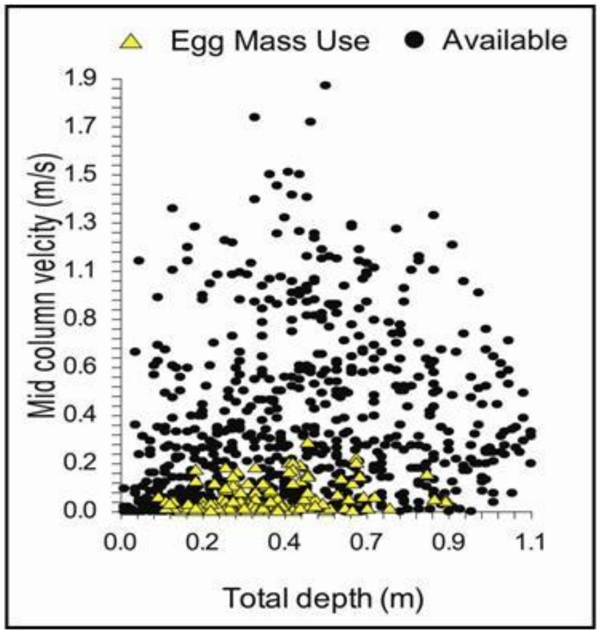
	Use				Available				
Site	**Count**	**Mean+SD**	**Min**	**Max**	**Count**	**Mean+SD**	**Min**	**Max**	**% Reach not surveyed**
Middle Fork Feather	10	0.15 + 0.10	0.01	0.30	121	0.23 + 0.29	0.00	1.48	47%
North Fork Middle Fork American	13	0.02 + 0.02	0.00	0.08	111	0.30 + 0.35	0.00	1.87	6%
North Fork American	14	0.03 + 0.03	0.00	0.09	158	0.53 + 0.44	0.00	1.71	23%
North Fork Feather	50	0.06 + 0.08	0.00	0.40	103	0.20 + 0.22	0.00	1.23	1%
Rubicon	24	0.05 + 0.05	0.00	0.21	145	0.37 + 0.35	0.00	1.73	21%
Middle Fork Yuba	24	0.03 + 0.03	0.00	0.12	144	0.29 + 0.31	0.00	1.22	19%
Clavey	7	0.7 + 0.06	0	0.18	NA	NA	NA	NA	
South Fork American	5	0.10 + 0.06	0.04	0.17	NA	NA	NA	NA	
All Rivers	**147**	**0.05 + 0.06**	**0.00**	**0.30**	**782**	**0.34 + 0.36**	**0.00**	**1.87**	

Table 1.6: Descriptive statistics for oviposition habitat use and availability for attachment substrate type at each study site and all sites combined

	Use				Available				
Site	**Count**	**Mode[1]**	**Min[1]**	**Max[1]**	**Count**	**Mode[1]**	**Min[1]**	**Max[1]**	**% Reach not surveyed**
Middle Fork Feather	9	SC	SC	LB	122	LB	SND	BED	47%
North Fork Middle Fork American	9	LB	LC	BED	111	LB	SND	BED	6%
North Fork American	14	SB	SC	BED	158	LC	SND	BED	23%
North Fork Feather	50	SB	SC	LB	103	SB and LB	SND	BED	1%
Rubicon	24	LB	SC	LB	145	LC	SLT	BED	21%
Middle Fork Yuba	24	SC	SC	LB	145	SC	SND	BED	19%
Clavey	7	LB	LB	LB	NA	NA	NA	NA	
South Fork American	5	SC	SC	LB	NA	NA	NA	NA	
All Rivers	**142**	**LB**	**SC**	**BED**	**784**	**LB**	**SLT**	**BED**	

[1]SLT=silt, SND=sand, SC=small cobble, LC=large cobble, SB=small boulder, LB=large boulder, BED=bedrock

Figure 1.6: Hydraulic conditions at measured oviposition use and availability points across all eight study sites. Oviposition locations were found in lower velocity and depth microhabitats than those available in the surveyable areas of each study site


Egg Mass Use
Available
Mid column velcity (m/s)
1.9
1.7
1.5
1.3
1.1
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.7
0.9
1.1
Total depth (m)

1.3.1.2 Tadpoles

Three visual encounter surveys at each of the eight study sites, and associated habitat availability surveys at six of the sites, were completed during the tadpole rearing season from July through September. Microhabitat data were collected on 694 early-stage and 638 late-stage tadpoles. Early-stage tadpole rearing sites had an average total depth of 0.26 m, whereas late-stage tadpoles were found in shallower depths (average of 0.18 m, Table 1.7). All tadpole stages used microhabitats with low velocities, although the average mid-column velocity was lower for late-stage tadpoles (0.03 m/ s) compared to early-stage tadpoles (average of 0.05 m/ s, Table 1. 8). The most frequently used dominant substrate was cobble for both early- and late-stage tadpoles (Figure 1.7, Table 1.9). Similar to egg mass habitat selection, early- and late-stage tadpole habitat selection did not appear to be limited by the wide range of conditions available in the river. Both early- and late-stage tadpoles were found in microhabitats that had velocities and depths that clustered in the lowest range of what was available in the river (Figure 1.8).

Figure 1.7: Histograms of the frequency of early- and late-stage tadpole habitat use and availability for (A) total depth, (B) mid-column velocity, and (C) attachment substrate type

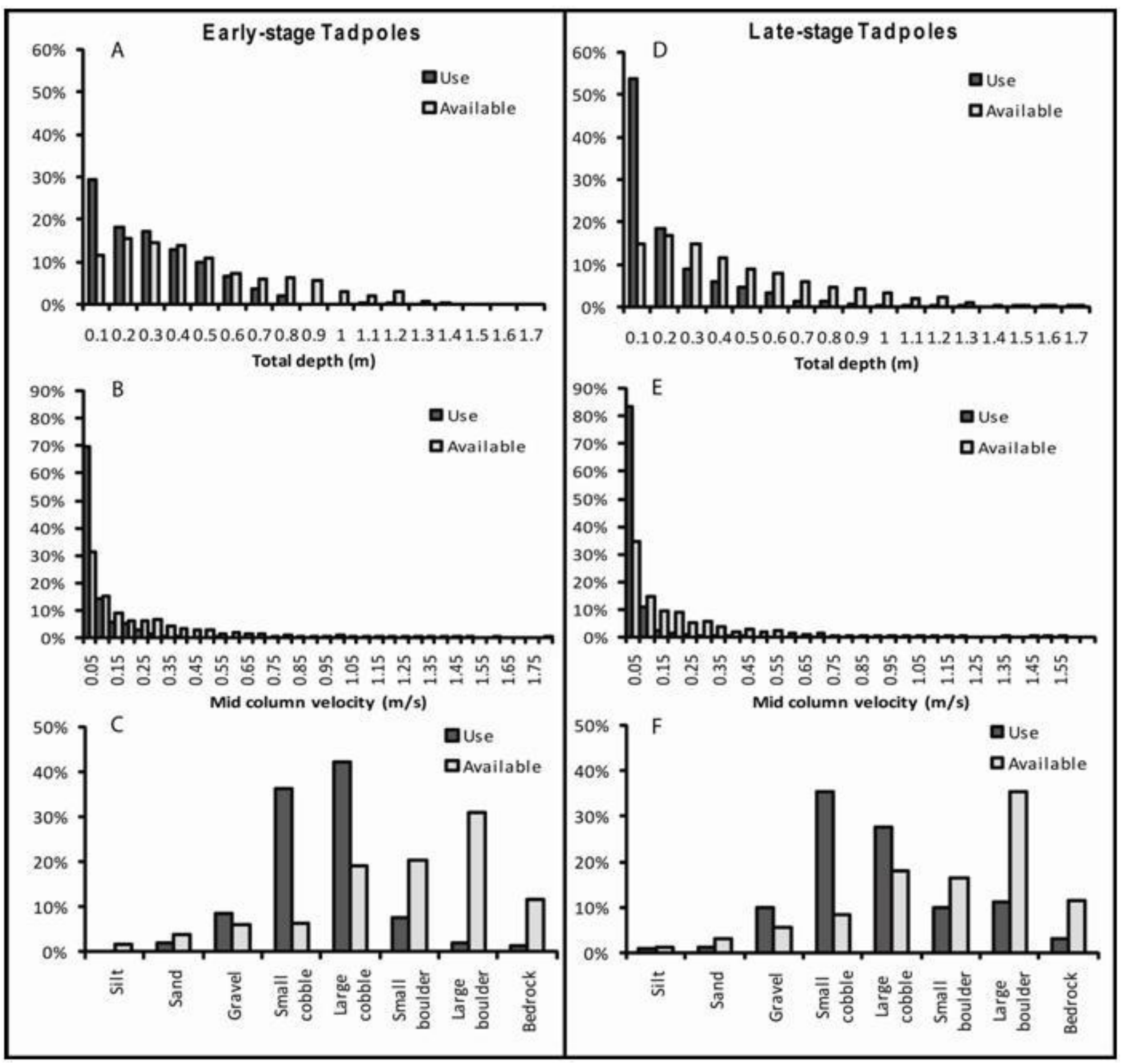


Table 1.7: Descriptive statistics for tadpole microhabitat use and availability for total depth at each study site and all sites combined

	Use				Available				
Site	**Count**	**Mean±SD**	**Min**	**Max**	**Count**	**Mean±SD**	**Min**	**Max**	**% Reach not surveyed**
Middle Fork Feather									
Early-stage	5	0.14 ± 0.03	0.09	0.18	175	0.57 ± 0.33	0.02	2.00	34%
Late-stage	3	0.26 ± 0.13	0.12	0.37	333	0.54 ± 0.32	0.01	1.40	20%
North Fork Middle Fork American									
Early-stage	109	0.28 ± 0.19	0.01	1.02	132	0.44 ± 0.33	0.02	1.27	2%
Late-stage	74	0.25 ± 0.19	0.01	0.77	228	0.40 ± 0.33	0.01	1.50	1%
North Fork American									
Early-stage	101	0.11 ± 0.10	0.01	0.68	152	0.39 ± 0.26	0.01	1.28	7%
Late-stage	122	0.06 ± 0.06	0.01	0.28	303	0.30 ± 0.24	0.01	1.42	5%
North Fork Feather									
Early-stage	0				102	0.56 ± 0.31	0.02	1.30	0%
Late-stage	4	0.16 ± 0.05	0.10	0.22	191	0.56 ± 0.31	0.02	1.35	0%
Rubicon									
Early-stage	142	0.20 ± 0.17	0.02	0.65	144	0.31 ± 0.26	0.01	1.16	16%
Late-stage	186	0.16 ± 0.25	0.01	1.65	286	0.38 ± 0.35	0.01	1.70	15%
Middle Fork Yuba									
Early-stage	168	0.32 ± 0.16	0.06	0.79	137	0.37 ± 0.26	0.01	1.22	7%
Late-stage	186	0.24 ± 0.23	0.01	1.5	253	0.36 ± 0.30	0.01	1.35	4%
Clavey									
Early-stage	103	0.33 ± 0.27	0.02	1.4					
Late-stage	46	0.26 ± 0.21	0.04	0.78					
South Fork American									
Early-stage	66	0.37 ± 0.16	0.08	0.73					
Late-stage	17	0.16 ± 0.11	0.02	0.39					
All Rivers									
Early-stage	694	0.26 ± 0.20	0.01	1.40	842	0.44 ± 0.31	0.01	2.00	
Late-stage	638	0.18 ± 0.22	0.01	1.65	1594	0.42 ± 0.32	0.01	1.70	

Table 1.8: Descriptive statistics for tadpole microhabitat use and availability for mid-column velocity at each study site and all sites combined

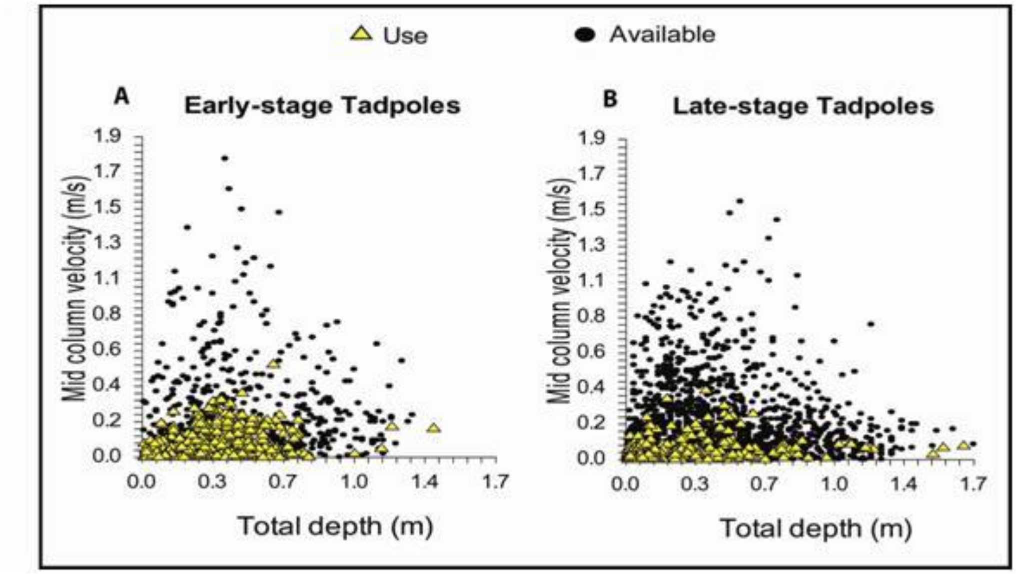
	Use				Available				
Site	**Count**	**Mean±SD**	**Min**	**Max**	**Count**	**Mean±SD**	**Min**	**Max**	**% Reach not surveyed**
Middle Fork Feather									
Early-stage	5	0.00 ± 0.00	0.00	0.00	175	0.29 ± 0.34	0.00	1.59	34%
Late-stage	3	0.10 ± 0.05	0.05	0.15	333	0.22 ± 0.25	0.00	1.42	20%
North Fork Middle Fork American									
Early-stage	109	0.05 ± 0.06	0.00	0.23	132	0.19 ± 0.26	0.00	1.33	2%
Late-stage	74	0.03 ± 0.04	0.00	0.27	228	0.16 ± 0.23	0.0	1.46	1%
North Fork American									
Early-stage	101	0.02 ± 0.03	0.00	0.20	152	0.22 ± 0.21	0.00	1.00	7%
Late-stage	122	0.02 ± 0.03	0.00	0.20	302	0.21 ± 0.22	0.00	1.17	5%
North Fork Feather									
Early-stage	0				102	0.24 ± 0.23	0.00	1.13	0%
Late-stage	4	0.02 ± 0.03	0.00	0.06	191	0.22 ± 0.26	0.00	1.53	0%
Rubicon									
Early-stage	142	0.06 ± 0.07	0.00	0.29	144	0.21 ± 0.25	0.00	1.36	16%
Late-stage	186	0.03 ± 0.04	0.00	0.21	286	0.18 ± 0.21	0.00	1.12	15%
Middle Fork Yuba									
Early-stage	168	0.04 ± 0.05	0.00	0.33	137	0.17 ± 0.25	0.00	1.77	7%
Late-stage	186	0.03 ± 0.06	0.00	0.36	253	0.13 ± 0.17	0.00	0.83	4%
Clavey									
Early-stage	103	0.04 ± 0.08	0.00	0.55					
Late-stage	46	0.03 ± 0.05	0.00	0.26					
South Fork American									
Early-stage	66	0.12 ± 0.10	0.00	0.38					
Late-stage	17	0.05 ± 0.10	0.00	0.41					
All Rivers									
Early-stage	694	0.05 ± 0.07	0.00	0.55	842	0.22 ± 0.27	0.00	1.77	
Late-stage	638	0.03 ± 0.04	0.00	0.41	1593	0.19 ± 0.23	0.00	1.53	

Table 1.9: Descriptive statistics for tadpole microhabitat use and availability for dominant substrate type at each study site and all sites combined

	Use				Available				
Site	**Count**	**Mode[1]**	**Min[1]**	**Max[1]**	**Count**	**Mode[1]**	**Min[1]**	**Max[1]**	**% Reach not surveyed**
Middle Fork Feather									
Early-stage	5	LC	SC	SB	175	LB	SND	BED	34%
Late-stage	3	SC	SC	SC	332	LB	SND	BED	20%
North Fork Middle Fork American									
Early-stage	109	LC	GRV	LB	132	LB	SND	BED	2%
Late-stage	74	LB	SND	BED	228	LB	SND	BED	1%
North Fork American									
Early-stage	101	SC	SND	BED	152	SB	SND	BED	7%
Late-stage	122	SC	GRV	BED	303	SB	SND	BED	5%
North Fork Feather									
Early-stage	0	NA	NA	NA	102	SB	SLT	BED	0%
Late-stage	4	SLT	SLT	SLT	191	LB	SLT	BED	0%
Rubicon									
Early-stage	142	LC	SND	LB	144	LC	SLT	BED	16%
Late-stage	186	SC/LC	GRV	BED	286	LC	SND	BED	15%
Middle Fork Yuba									
Early-stage	168	SC	SND	LB	137	LB	SND	BED	7%
Late-stage	186	SC	SND	BED	252	LB	SND	BED	4%
Clavey									
Early-stage	103	SC	SND	BED					
Late-stage	45	SC	GRV	BED					
South Fork American									
Early-stage	66	SC	SND	SB					
Late-stage	17	LC	SLT	LB					
All Rivers									
Early-stage	694	SB	SND	BED	842	LB	SLT	BED	
Late-stage	637	LC	SLT	BED	1592	LB	SLT	BED	

[1]SLT=silt, SND=sand, SC=small cobble, LC=large cobble, SB=small boulder, LB=large boulder, BED=bedrock

Figure 1.8: Hydaulic conditions at (A) early-stage and (B) late-stage tadpole use and availability points across all eight study sites. Tadpoles were found in lower velocity and depth microhabitats than those available in the surveyable areas of each study site

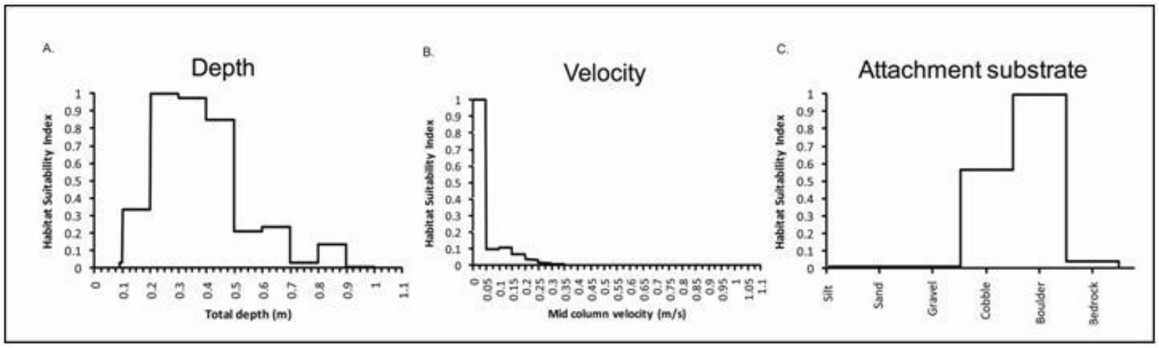


1.3.2 Habitat Suitability Criteria

1.3.2.1 Interval Habitat Suitability Indices

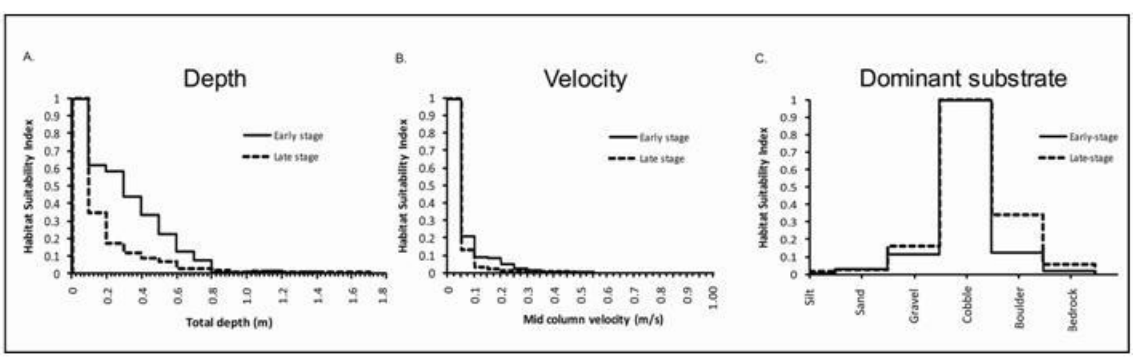
The interval-based suitability index for oviposition selection was normally distributed for total depth and substrate type, but highly right-skewed for mid-column velocity (Figure 1.9). The suitability index for depth was low for shallow depths ($\leq$0.20 m), then increased to optimum for depths between 0.21 and 0.3 m. Use, and thus suitability, remained high for depths between 0.3 and 0.50 m, then decreased until 0.90 m. Depths greater than 0.90 m were not used, and thus had a suitability of zero. Oviposition habitat use was most frequent in extremely low mid-column velocities ($\leq$0.05 m/ s), thus the optimum suitability occurred at mid-column velocities ranging from 0.0 to 0.05 m/ s (Figure 1.9b). Use dramatically declined with increasing mid-column velocity, such that velocities from 0.051 and 0.29 m/ s had low suitability, and velocities greater than 0.30 m/ s were unsuitable due to lack of use. Fine substrates with no use (silt, sand and gravel) had suitability index values of zero. Oviposition suitability increased with increasing attachment substrate size to an optimum value of 1.0 for boulders.

Figure 1.9: Interval-based univariate egg mass suitability indices for each hydraulic variable: (A) total depth, (B) mid-column velocity and (C) attachment substrate type. SIs calculated from the frequency distribution of use data pooled across all study sites



The suitability indices for both early- and late-stage tadpole rearing microhabitats were skewed for total depth and mid-column velocity and normally distributed for substrate size (Figure 1.10). For both tadpole stages, the suitability index for depth was zero at very shallow depths (<0.01 m) and increased to optimum between 0.01 and 0.10 m. Suitability values decreased for both stages as depth increased to 0.8 m, but the decline was greater for the late-stage tadpoles. At depths greater than 0.8 m, suitability values varied from very low to zero for both stages due to the methodology. Each 0.1 m increment of depth was individually assigned an SI value based on use in that bin. As a result, depths from 0.8-1.0 m and 1.2-1.3 m have a suitability of zero, while depths from 1.0-1.2 m and 1.3-1.4 m have a suitability of 0.01 for early-stage tadpoles. The suitability index remained zero for depths greater than 1.4 m for early-stage and 1.7 m for late-stage tadpoles. Velocity suitability values were similar for both stages, with the highest values occurring between 0.00 and 0.05 m/ s and dramatically declining as velocity increased. Velocities greater than 0.35 m/ s were not used by either stage, and thus had a suitability value of zero. Cobble and boulder substrates had the highest suitability value for both early- and late-stage tadpoles, while sand, gravel and bedrock had low suitability values for both stages. Silt had a very low suitability value for late-stage tadpoles, but was classified as unsuitable for early-stage tadpoles.

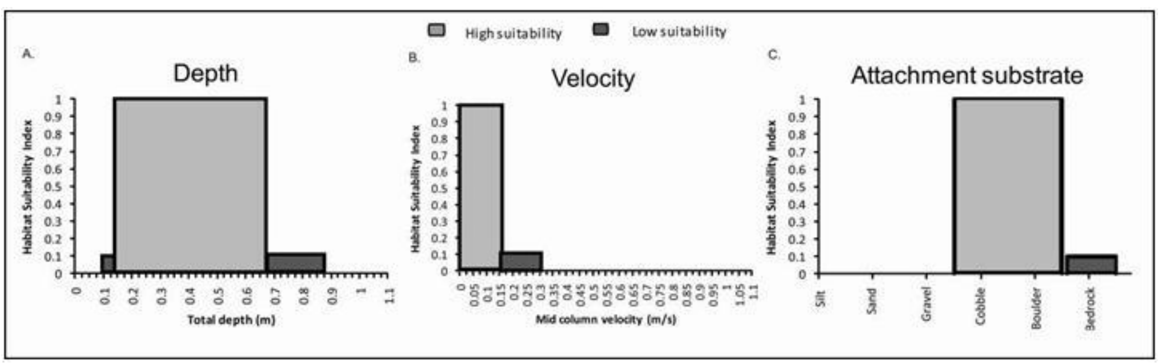
Figure 1.10: Interval-based univariate suitability indices for early- and late-stage tadpole rearing sites for each hydraulic variable: (A) total depth, (B) mid-column velocity and (C) attachment substrate type. SIs calculated from the frequency distribution of use data pooled across all study sites



1.3.2.2 Percentile Habitat Suitability Indices

Percentile-based suitability indices reflect the extremes of use, and thus have only three suitability index values: 1.0 for high suitability, 0.1 for low suitability and 0.0 for unsuitable (Table 1.11). Reflecting the unimodal distribution of depth use observations, the central 90% of the observations defined the high suitability category, while the remaining 10% of observations at the tails of the curve defined the low suitability category. The central ninety percent of egg mass locations occurred in depths ranging from 0.14 to 0.67 m, and thus were assigned a suitability value of 1.0 (Figure 1.11). The lower and upper 5% of use occurred between depths of 0.01 m and 0.13 m, and 0.68 m and 0.87m, respectively, and were assigned a suitability index of 0.1. Unlike the interval HSI, all values up to the maximum observed use value are assigned a positive SI value (>0.0), regardless of whether use was observed at the intermediate values. All remaining depths beyond the minimum and maximum observed values were given a suitability value of zero. The high suitability category for egg mass mid-column velocity ranged from 0.00 m/ s to 0.15 m/ s (Figure 1.11). The remaining 10% of velocity use occurred within 0.16 m/ s to 0.30 m/ s and was classified as low suitability. Mid-column velocities greater than 0.31 m/ s were not observed at egg mass locations in this study, and thus were assigned a suitability index of zero. The smallest grain sizes (silt, sand and gravel) were not used and thus were classified as unsuitable (Figure 1.11). Cobble and boulder encompassed 94% of the use observations and thus were classified as high suitability, while only 6% of egg masses were attached to bedrock and were assigned a low suitability.

Figure 1.11: Percentile-based univariate egg mass suitability indices for each hydraulic variable: (A) total depth, (B) mid-column velocity and (C) attachment substrate type. SIs calculated from the frequency distribution of use data pooled across all study sites



Reflecting the shape of the distribution of tadpole use observations, the high suitability category for depth encompassed 90% of use values starting at the shallow end of the range, rather than the central 90% as was done for egg masses. The remaining 10% of use observations defined the low suitability category. Ninety percent of early-stage tadpoles occurred in depths ranging from 0.01 m to 0.54 m, and the remaining 10% were in depths from 0.55 m to 1.4 m (Figure 1.12; Table 1.10). Late-stage tadpoles had similar high (0.01 m to 0.51 m) and low suitability (0.52 m to 1.66 m) depth ranges (Figure 1.13). Tadpoles were not observed in depths less than 0.01 m, or depths greater than 1.4 m for early-stages and 1.6 m for late stages . High suitability mid-column velocities ranged from 0.00 m/ s to 0.16 m/ s, for early-stage tadpoles, and low suitability values ranged from 0.17 m/ s to 0.55 m/ s. Late-stage tadpoles used simliar but slightly lower ranges of mid-column velcoties. Velocities greater than 0.56 m/ s for early and 0.42 m/ s for late-stage tadpoles were not used and classified as unsuitable. Early-stage tadpoles used all substrate types, except silt, with cobble and boulder classified as highly suitable. Late-stage tadpoles used all substrate types, with gravel, cobble, and boulder assigned a high suitability, and silt, sand, and bedrock classified as low suitability.

Figure 1.12: Percentile-based univariate early-stage tadpole suitability indices for each hydraulic variable: (A) total depth, (B) mid-column velocity and (C) attachment substrate type. SIs calculated from the frequency distribution of use data pooled across all study sites

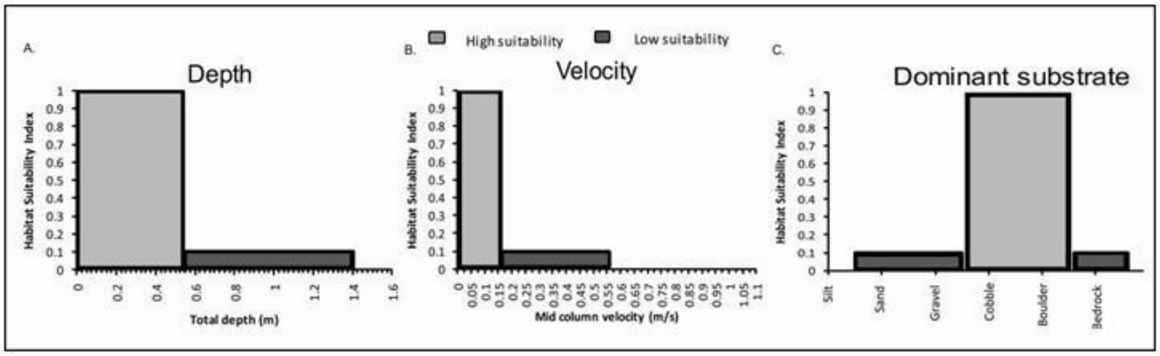


Figure 1.13: Percentile-based univariate late-stage tadpole suitability indices for each hydraulic variable: (A) total depth, (B) mid-column velocity and (C) attachment substrate type. SIs calculated from the frequency distribution of use data pooled across all study sites

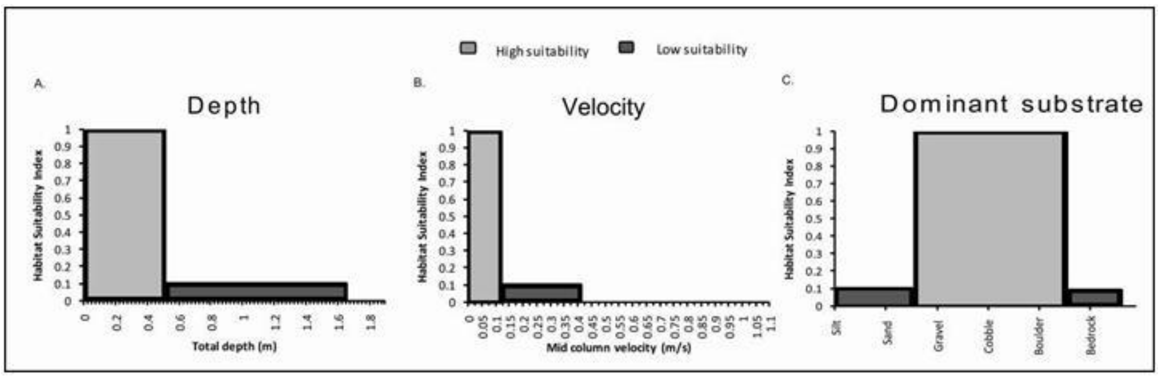


Table 1.10: R. boylii egg mass and tadpole rearing habitat suitability criteria based upon percentile of use. n = valid sample size for depth/velocity/substrate if they differed among variables. 0 = not suitable, 0.1 = marginally suitable, 1 = highly suitable. Categories are delineated to the nearest tenth meter for mid-column velocity and total depth, reflecting the level of accuracy for this study

	Total Depth (m) Suitability				Mid-column Water Velocity (m/sec) Suitability				Substrate Suitability			
Lifestage	**n**	**0**	**0.1**	**1**	**n**	**0**	**0.1**	**1**	**n**	**0**	**0.1**	**1**
Egg mass	147	<0.10, >0.87	0.10-0.13, 0.68-0.87	0.14 -0.67	147	≥0.31	0.16-0.30	0.00-0.15	142	Silt/clay, sand and gravel	Bedrock	Cobble and boulder
Early- stage tadpole	694	<0.01, >1.40	0.55-1.40	0.01- 0.54	694	≥0.56	0.17-0.55	0.00-0.16	694	Silt	Sand, gravel, bedrock	Cobble and boulder
Late-stage tadpole	638	<0.01, >1.65	0.52-1.65	0.01- 0.51	694	≥0.42	0.13-0.41	0.00-0.12	637		Silt, sand, bedrock	Gravel, cobble, boulder

1.3.2.3 Multivariate Logistic Habitat Suitability Index

Three different multivariate logistic predictive models were developed; one for each *R. boylii* life stage (Table 1.11). In each model the hydraulic parameters were significant (P<0.001), but parameter coefficients differed among life stages. For oviposition sites and early-stage tadpole locations, there was a positive coefficient associated with depth and a negative coefficient with the depth^2 variable that is used to describe the unimodal relationship between use and water depth. The late-stage tadpoles had greater use in shallower habitats indicated by the negative coefficient associated with depth and positive coefficient with the depth^2 term. All lifestages had negative mid-column velocity coefficients that decreased in value across progressive lifestages from egg mass to late-stage tadpoles. A unimodal relationship between use and substrate size occurred for all lifestages with positive substrate and negative substrate^2 coefficients. The value of both substrate coefficients decreased progressively across lifestages from egg masses to late-stage tadpoles, as use of finer substrates increased through time. The coefficients were used to predict habitat suitability using the logistic regression equation:

$$\text{Habitat Suitability Index} = \frac{\exp(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5)}{1 + \exp(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5)}$$

Table 1.11: Coefficients for logistic regression models. Significance (P) of parameters was assessed using α=0.05

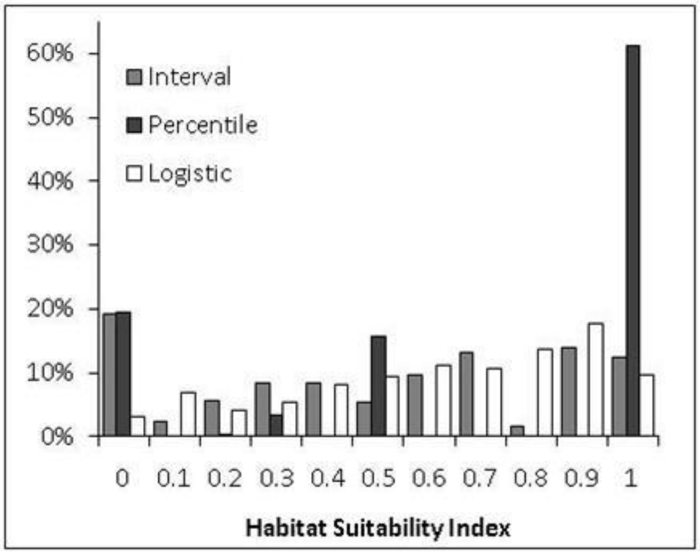
Model	Intercept	Depth		Depth -squared		Square root of Velocity+0.005		Substrate Type		Substrate type - squared	
		B_1	*P*	B_2	*P*	B_3	*P*	B_4	*P*	B_5	*P*
Egg masses	-31.019	16.209	0.00	-15.930	0.00	-8.001	0.00	13.490	0.00	-1.472	0.00
Early-stage tadpoles	-13.022	3.149	0.01	-5.427	0.00	-10.554	0.00	7.958	0.00	-1.074	0.00
Late-stage tadpoles	-3.324	-4.533	0.00	2.214	0.00	-12.967	0.00	3.510	0.00	-0.511	0.00

1.3.3 Model Evaluation and Transferability

1.3.3.1 Egg masses

To evaluate the predictability and transferability of the habitat suitability criteria, the models were used to assign HSI values to 393 egg mass locations from seven validation datasets. These seven datasets included five new rivers and two rivers from the current study (Middle Yuba and Rubicon) but with data from different survey years (Table 1.3). The three HSC models classified these validation egg mass locations differently both across and among datasets. The percentile HSI classified the majority of all egg masses combined with an HSI value of 1.0 (61%), whereas the interval and logistic regression HSI classified all egg masses across gradients of suitability (Figure 1.14). The interval and percentile HSI classified 19.0% and 19.5% of all egg masses as unsuitable (0.00), respectively, while the logistic regression HSI classified only 3% of all egg masses as unsuitable.

Figure 1.14: Distribution of habitat suitability index outcomes assigned to egg mass locations from the validation datasets using the interval, percentile, and logistic HSI models



To assess transferability, the HSC models were compared among the seven datasets (Tables 12-14). The interval and percentile HSI classified the largest number of egg masses as unsuitable on Butte Creek and Shady Creek, the two smallest streams of the validation datasets (Tables 12 and 13). Oviposition sites at Shady Creek and Butte Creek occurred in shallower depths and on finer substrates than the interval and percentile HSI models classified as suitable. At Butte Creek, 18 % of egg masses were attached to substrates smaller than cobble, and 40% were in depths less than 0.10 m. Similarly, 95% of egg masses at Shady Creek were in shallow depths (<0.10 m) and consequently assigned an HSI of zero. In contrast, the logistic regression model did not classify many egg masses as unsuitable at the two creeks (Table 1.14). However, due to the inverse linear relationship between HSI and depth, and the positive linear relationship between HSI and substrate size, the regression model predicts HSI values for depths and substrates in which there is no use. At Shady Creek, only one egg mass received an HSI value of zero due to gravel substrate and extremely shallow depth. Similarly, at Butte Creek, egg masses in shallow depths received low (<0.33) and moderate (0.33-0.66) suitability values, and only one egg mass found on silt was classified as unsuitable.

Each of the three HSC models performed similarly within the remaining five large river datasets. Each of the models classified a portion of egg masses at the South Yuba as unsuitable due to deep water (>0.90 m). The interval and percentile HSI models classified 14 (20%) egg masses as unsuitable due to their locations in depths greater than 0.90 m. Similarly, the logistic regression classified 13 (19%) egg masses at the South Yuba as unsuitable. However, due to the multivariate nature of the logistic model an egg mass at a deep depth (0.99 m) attached to a boulder substrate received a low suitability value, while an egg mass in 0.95 m of water attached to bedrock was assigned an HSI of zero. All three of the HSC models classified the most egg masses as highly suitable for the remaining four datasets (WB Feather, Rubicon, Pit and M Yuba). Two of these datasets are from the same rivers where the current study data were collected (Rubicon and M Yuba). Each of these four rivers are characterized as large, high gradient, boulder and bedrock dominated rivers, suggesting the current HSC models will perform well on these types of rivers.

Table 1.12: Classification of egg masses from the validation datasets using the Interval HSI model. For example, 45 of 80 egg masses (56%) in the Rubicon dataset were classified as occurring in high suitability habitat, with an HSI value of >0.66. River sites with gray shading are from the same rivers as the current study but data were collected in different years; sites with no shading are from different rivers

River	N	High (>0.66)		Moderate (0.33-0.66)		Low (<0.33)		Unsuitable (0.00)	
		Count	*Percent*	*Count*	*Percent*	*Count*	*Percent*	*Count*	*Percent*
Rubicon	80	45	56	23	29	11	14	1	1
M Yuba	51	24	47	11	22	8	16	8	16
WB Feather	31	12	39	6	19	11	35	2	6
Pit	108	60	56	23	21	18	17	7	6
S Yuba	69	11	16	13	19	27	39	18	26
Butte Creek	33	4	12	5	15	5	15	19	58
Shady Creek	21	0	0	1	5	0	0	20	95
All Rivers	**393**	**156**	**40**	**82**	**21**	**80**	**20**	**75**	**19**

Table 1.13: Classifications of egg masses from the validation dataset using the Percentile HSI model. For example, 71 of 80 egg masses (89%) in the Rubicon dataset were classified as occurring in high suitability habitat, with an HSI value of >0.66. River sites with gray shading are from the same rivers as the current study but data were collected in different years; sites with no shading are from different rivers

River	N	High (>0.66)		Moderate (0.33-0.66)		Low (<0.33)		Unsuitable (0.00)	
		Count	*Percent*	*Count*	*Percent*	*Count*	*Percent*	*Count*	*Percent*
Rubicon	80	71	89	8	10	0	0	1	1
M Yuba	51	39	77	4	8	0	0	8	16
WB Feather	31	18	58	10	32	0	0	3	10
Pit	108	81	75	20	19	0	0	7	7
S Yuba	69	21	30	16	23	14	20	18	26
Butte Creek	33	10	30	4	12	0	0	19	58
Shady Creek	21	1	5	0	0	0	0	20	95
All Rivers	**393**	**241**	**61**	**62**	**16**	**14**	**4**	**76**	**19**

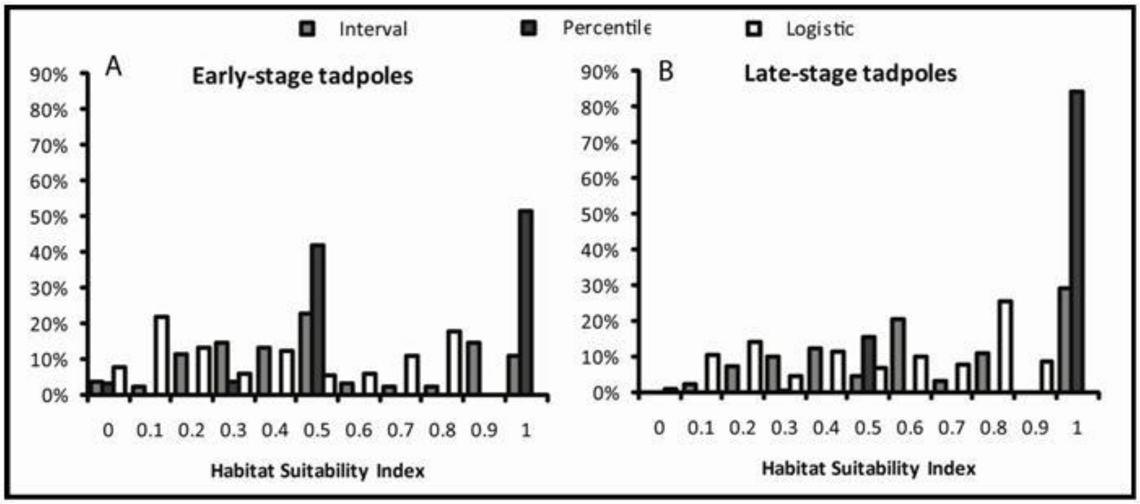
Table 1.14: Classifications of egg masses from the validation dataset using the logistic regression HSI model. For example, 53 of 80 egg masses (66%) in the Rubicon dataset were classified as occurring in high suitability habitat, with an HSI value of >0.66. River sites with gray shading are from the same rivers as the current study but data were collected in different years; sites without shading are from different rivers

River	N	High (>0.66)		Moderate (0.33-0.66)		Low (<0.33)		Unsuitable (0.00)	
		Count	*Percent*	*Count*	*Percent*	*Count*	*Percent*	*Count*	*Percent*
Rubicon	80	53	66	23	29	4	5	0	0
M Yuba	51	31	61	15	29	5	10	0	0
WB Feather	31	14	45	13	42	4	13	0	0
Pit	108	52	48	40	37	15	14	1	1
S Yuba	69	22	32	12	17	22	32	13	19
Butte Creek	33	8	24	17	52	7	21	1	3
Shady Creek	21	1	5	8	38	11	52	1	5
All Rivers	**393**	**181**	**46**	**128**	**33**	**68**	**17**	**16**	**4**

1.3.3.2 Tadpoles

Habitat suitability index values for 300 early- and 288 late-stage tadpoles from the seven validation datasets (Table 1.3) were compared to evaluate the predictive and transferability capabilities of the three HSC models. As with the egg mass models, each HSC model classified tadpole rearing locations differently across and among datasets. The percentile HSI classified the majority (52%) of all early-stage tadpole locations with an HSI value of 1.0, whereas the interval and logistic regression HSI classified 11% and 0% of all tadpoles, respectively, with an HSI value of 1.0, (Figure 1.15a). Late-stage tadpoles were classified similarly, but all three HSI had a larger percent classified in high suitability categories (Figure 1.15b). The interval and percentile HSI performed well for all tadpole stages, with only 4% and 3%, respectively, of early-stage tadpoles, and 0% of late-stage tadpoles classified with an HSI value of zero. The logistic regression HSI classified 13% of early-stage and 4% of late-stage tadpoles as occurring in unsuitable habitat.

Figure 1.15: Distribution of habitat suitability index values assigned to (A) early-stage and (B) late-stage tadpole microhabitat locations from the validation datasets using the interval, percentile, and logistic habitat suitability index models



Each of the tadpole HSC models classified a large percentage of tadpole locations as suitable, with a few exceptions. The interval HSI (Tables 15 and 16) and percentile HSI (Tables 17 and 18) transferred well to other rivers for both tadpole stages, classifying low numbers of early-stage tadpole locations and none of the late-stage tadpole locations as unsuitable. In the Butte Creek dataset, the interval and percentile HSI classified 6% of early-stage tadpoles as unsuitable due to observations of tadpoles on silt substrate and in deep depths (>1.4 m). In the S Yuba dataset, two tadpole locations (17%) were in depths >0.90 m, and thus were classified as unsuitable with the interval HSI, while only one of these was classified as unsuitable with the percentile HSI. These small differences in HSI classification are due to methodological differences. The percentile HSI includes all values up to the highest use value even when some intermediate values do not have use, whereas the interval HSI only assigns a positive SI value (>0.0) to those bins with use. The logistic regression model classified low numbers of tadpole observations as unsuitable on most rivers, with the exception of Butte Creek and the S Yuba (Tables 19 and 20). Twenty percent of early- and 3% of late-stage tadpoles on Butte Creek were classified as unsuitable due to the combined association of high depth or velocity with silt or bedrock, while 31% of early-stage tadpoles on the S Yuba were classified as unsuitable due to high depths. Overall, distinctions in performance and transferability between large rivers and small creeks for the tadpole HSC models were less evident than for the egg mass models.

Table 1.15: Classifications of early-stage tadpoles from the validation dataset using the interval HSI model. River sites with gray shading are from the same rivers as the current study but data were collected in different years; sites without shading are from different rivers

River	N	High (>0.66)		Moderate (0.33-0.66)		Low (<0.33)		Unsuitable (0.00)	
		Count	*Percent*	*Count*	*Percent*	*Count*	*Percent*	*Count*	*Percent*
Rubicon	0								
M Yuba	79	28	35	40	51	11	14	0	0
WB Feather	37	13	35	16	43	6	16	2	5
Chicago Park	0								
S Yuba	29	5	17	7	24	15	41	2	17
Butte Creek	125	28	22	41	33	49	39	7	6
Shady Creek	30	12	40	13	43	5	17	0	0
All Rivers	**300**	**86**	**29**	**117**	**39**	**86**	**29**	**11**	**4**

Table 1.16: Classifications of late-stage tadpoles from the validation dataset using the interval HSI model. River sites with gray shading are from the same rivers as the current study but data were collected in different years; sites without shading are from different rivers

River	N	High (>0.66)		Moderate (0.33-0.66)		Low (<0.33)		Unsuitable (0.00)	
		Count	*Percent*	*Count*	*Percent*	*Count*	*Percent*	*Count*	*Percent*
Rubicon	66	56	85	7	11	3	5	0	0
M Yuba	61	21	34	33	54	7	11	0	0
WB Feather	13	8	62	2	15	3	23	0	0
Chicago Park	23	5	22	12	52	6	26	0	0
S Yuba	0								
Butte Creek	34	10	29	10	29	14	41	0	0
Shady Creek	91	24	26	37	41	30	33	0	0
All Rivers	**288**	**124**	**43**	**101**	**35**	**63**	**22**	**0**	**0**

Table 1.17: Classifications of early-stage tadpoles from the validation dataset using the percentile HSI model. River sites with gray shading are from the same rivers as the current study but data were collected in different years; sites without shading are from different rivers

River	N	High (>0.66)		Moderate (0.33-0.66)		Low (<0.33)		Unsuitable (0.00)	
		Count	*Percent*	*Count*	*Percent*	*Count*	*Percent*	*Count*	*Percent*
Rubicon	0								
M Yuba	79	56	71	23	29	0	0	0	0
WB Feather	37	18	49	16	43	2	5	1	1
Chicago Park	0								
S Yuba	29	12		12		4		1	
Butte Creek	125	48	38	65	52	5	4	7	6
Shady Creek	30	21	70	9	30	0	0	0	0
All Rivers	**300**	**155**	**52**	**125**	**42**	**11**	**4**	**9**	**3**

Table 1.18: Classifications of late-stage tadpoles from the validation dataset using the percentile HSI model. River sites with gray shading are from the same rivers as the current study but data were collected in different years; sites without shading are from different rivers

River	N	High (>0.66)		Moderate (0.33-0.66)		Low (<0.33)		Unsuitable (0.00)	
		Count	*Percent*	*Count*	*Percent*	*Count*	*Percent*	*Count*	*Percent*
Rubicon	66	63	95	3	5	0	0	0	0
M Yuba	61	59	97	2	3	0	0	0	0
WB Feather	13	9	69	4	31	0	0	0	0
Chicago Park	23	20	87	3	13	0	0	0	0
S Yuba	0								
Butte Creek	34	18	53	15	44	1	3	0	0
Shady Creek	91	74	81	17	19	0	0	0	0
All Rivers	**288**	**243**	**84**	**44**	**15**	**1**	**1**	**0**	**0**

Table 1.19: Classifications of early-stage tadpoles from the validation dataset using the logistic regression HSI model. River sites with gray shading are from the same rivers as the current study but data were collected in different years; sites without shading are from different rivers

River	N	High (>0.66)		Moderate (0.33-0.66)		Low (<0.33)		Unsuitable (0.00)	
		Count	*Percent*	*Count*	*Percent*	*Count*	*Percent*	*Count*	*Percent*
Rubicon	0								
M Yuba	79	26	33	28	35	25	32	0	0
WB Feather	37	9	24	14	38	11	30	3	8
Chicago Park	0								
S Yuba	29	3	10	8	28	9	31	9	31
Butte Creek	125	24	19	28	22	48	38	25	20
Shady Creek	30	6	20	6	20	17	57	1	3
All Rivers	**300**	**68**	**23**	**84**	**28**	**110**	**37**	**38**	**13**

Table 1.20: Classifications of late-stage tadpoles from the validation dataset using the logistic regression HSI model. River sites with gray shading are from the same rivers as the current study but data were collected in different years; sites without shading are from different rivers

River	N	High (>0.66)		Moderate (0.33-0.66)		Low (<0.33)		Unsuitable (0.00)	
		Count	*Percent*	*Count*	*Percent*	*Count*	*Percent*	*Count*	*Percent*
Rubicon	66	42	64	21	32	3	5	0	0
M Yuba	61	15	25	35	57	11	18	0	0
WB Feather	13	8	62	1	8	4	31	0	0
Chicago Park	23	8	35	9	39	6	26	0	0
S Yuba	0								
Butte Creek	34	13	38	9	27	11	32	1	3
Shady Creek	91	17	19	11	12	53	58	10	11
All Rivers	**288**	**103**	**36**	**86**	**30**	**88**	**30**	**11**	**4**

1.3.3.3 Application within a 2D hydrodynamic model

To determine the performance of the three HSC models across a river reach, the HSI were input into a 2D model of the Rubicon study site. The spatial distribution of different suitability categories were compared with observed egg mass and late-stage tadpole locations. At a typical late spring flow when egg masses were observed (55 cfs), the HSC models classified modeled depths, mid-column velocities and dominant substrate types at egg mass locations in a similar fashion to the classifications within the validation datasets (Figures 1.16 and 1.17). The percentile HSI classified the majority (56%) of egg mass locations as highly suitable (>0.66), while the interval and logistic regression HSI classified 13% and 19% of locations as highly suitable, respectively. The interval and logistic HSI classified the highest number of egg mass locations as moderate and low suitability. The logistic HSI classified the least number of egg mass locations as unsuitable (19%), while the interval and percentile HSI each classified 31% of observed egg masses as occurring in unsuitable habitat.

Figure 1.16: Modeled oviposition habitat suitability at Rubicon study site using (A) interval HSI, (B) percentile HSI, and (C) logistic regression HSI. Dots represent surveyed locations of egg masses in spring, 2008; color bands represent habitat suitability values ranging from 0-1

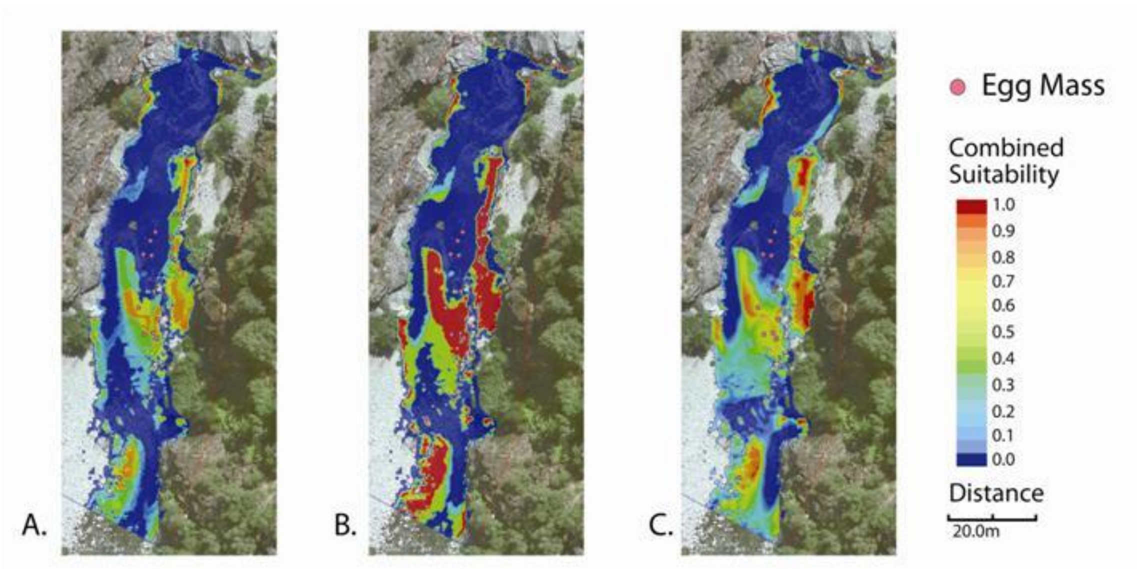
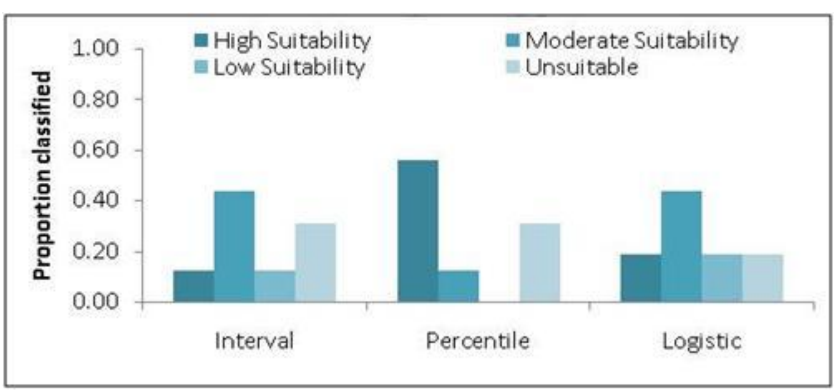
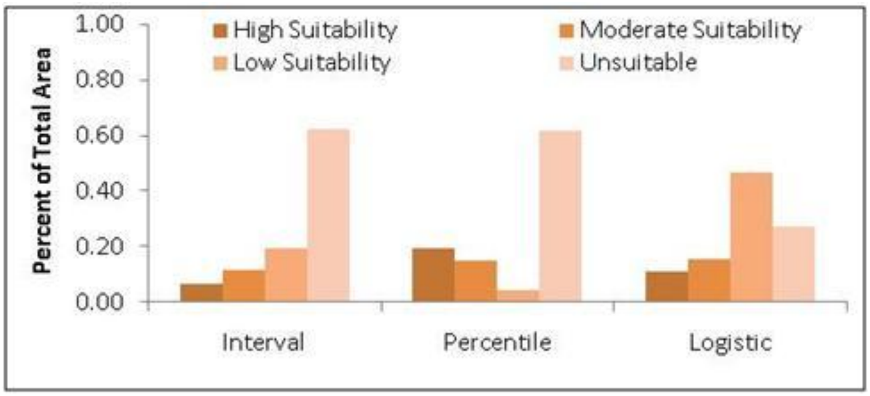


Figure 1.17: Percent of egg mass locations classified as occurring in high (>0.66), moderate (0.33-0.66), low (<0.33), or unsuitable (0.0) habitat within the 2D modeling reach using each of the three HSC models



To assess how the egg mass HSC models classified unoccupied areas of the river, the total reach area that each HSI classified as high, moderate, low and unsuitable was determined (Figure 1.18). The interval and percentile HSI classified twice the area of river as unsuitable for oviposition than the logistic regression HSI (62% versus 27%), primarily due to differences in how the models incorporated substrate suitability. The interval and percentile HSI assigned an SI of zero to gravel-dominated substrate, while the logistic HSI was a low but suitable value if the other hydraulic variables were suitable. Similarly, the logistic HSI was more lenient with mid-column velocity, classifying areas in the river with high mid-column velocities (>0.30 m/ s) as low suitability, rather than unsuitable. As a result, the logistic HSI classified the majority of the river as low suitability habitat. The interval HSI classified the least area of river as highly suitable (7%), while the percentile HSI classified the greatest portion as highly suitable (19%), reflecting differences in how each method assigns HSI values to generally suitable habitats.

Figure 1.18: Percent of total modeled reach area classified as high (>0.66), moderate (0.33-0.66), low (<0.33), or unsuitable (0.0) oviposition habitat within the 2D modeling reach using each of the three oviposition HSC models



At a typical late summer flow when tadpoles were observed (36 cfs), the late-stage tadpole HSC models performed well in the 2D model, classifying all modeled depths, mid-column velocities and dominant substrate types at tadpoles locations as suitable (Figures 1.19 and 1.20). The percentile HSI classified 95% of tadpole locations as highly suitable (>0.66), while the interval HSI classified 66% of locations as highly suitable. The remaining tadpole locations were classified as moderate suitability by the percentile HSI, or moderate (31%) and low (3%) suitability by the interval HSI. While the logistic HSI did not classify any tadpole locations as unsuitable, only 3% were designated as highly suitable, and 76% were assigned a moderate suitability. The remaining 21% of tadpole locations were classified as low suitability, a greater proportion than either of the other HSC models.

Figure 1.19: Modeled late-stage tadpole habitat suitability at Rubicon study site using (A) interval HSI, (B) percentile HSI, and (C) logistic regression HSI. Dots represent surveyed locations of tadpoles in August, 2008; color bands represent habitat suitability values ranging from 0-1

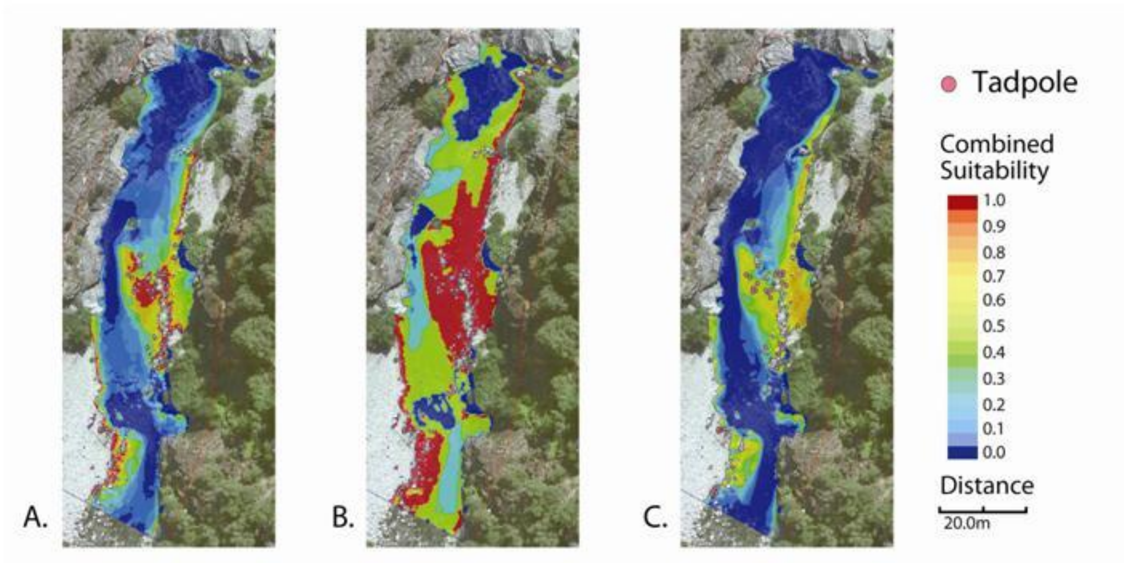
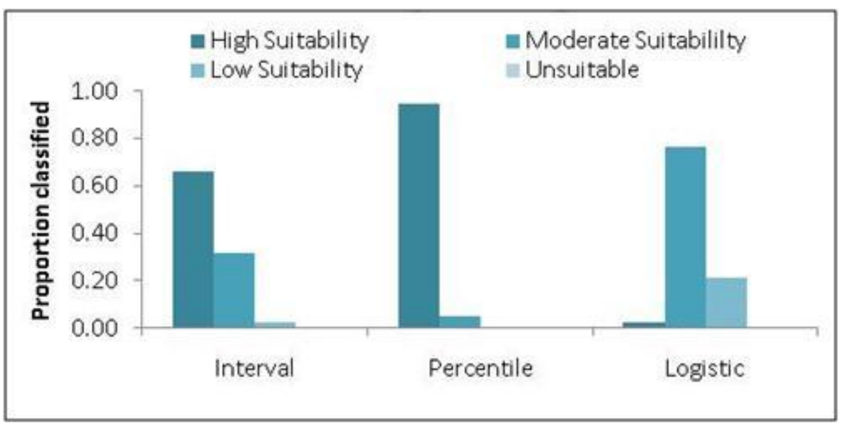
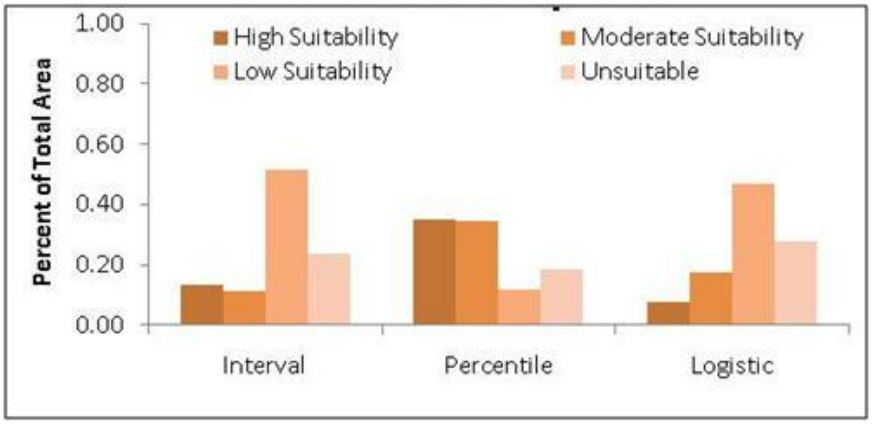


Figure 1.20: Percent of late-stage tadpole locations classified as occurring in high (>0.66), moderate (0.33-0.66), low (<0.33), or unsuitable (0.0) habitat within the 2D modeling reach using each of the three HSC models



Reflective of the lower modeled flow (36 cfs) at which the tadpoles were observed (versus 55 cfs for egg masses), the majority of river habitat was classified as suitable by each of the late-stage HSC models (Figures 1.19 and 1.21). Each HSI model classified a similar proportion (18% - 28%) of the area of river as unsuitable for tadpole rearing; however, the distribution of HSI values in suitable habitat varied widely between methods. Similar to the egg mass HSC, the logistic HSI classified the majority of river habitat as a low suitability for tadpole rearing, while the percentile HSI classified the majority as highly or moderately suitable. The logistic HSI classified the least area of river as highly suitable (8%), while the percentile HSI classified the greatest portion as highly suitable (35%). The interval HSI performed similarly to the logistic HSI, classifying 51% of the total area as low suitability for late-stage tadpoles and only 13% as highly suitable. As with the egg mass evaluation, the differences in distribution of HSI values within suitable habitat reflects the different methods inherent to each HSC model.

Figure 1.21: Percent of total modeled reach area classified as high (>0.66), moderate (0.33-0.66), low (<0.33), or unsuitable (0.0) tadpole rearing habitat within the 2D modeling reach using each of the three late-stage tadpole HSC models



1.3.4 Overall Evaluation of Habitat Suitability Criteria Models

Each of the three HSC methods generally performed well on the larger rivers where geomorphology and substrate conditions were similar to the rivers from which the models were developed (Table 1.21). In the smaller creeks, egg masses were located in shallower depths and attached to finer substrates, such as gravel, than those in the larger rivers. As a result, the univariate HSI, which has distinct bounds in suitability based on observed use in the larger rivers, had poor predictive accuracy for egg masses in the creeks. Conversely, the logistic regression HSI had softer bounds on suitability assigning very low values to high velocities and fine substrates. As a result, the logistic HSI had high predictive accuracy for egg mass presence (i.e. few egg masses were classified into unsuitable locations), but low predictive accuracy for egg mass suitability (i.e. many egg mass locations were assigned low suitability values). Similarly, the soft bounds on velocity and substrate in the logistic HSI resulted in low rather than zero suitability values throughout much of the river reach, even in high velocity riffles where previous studies suggest egg masses do not occur (Kupferberg et al., 2009a; Yarnell, 2005).

Table 1.21: Author's summary of performance of each habitat suitability criteria model. Transferability assesses how well the method works across rivers. Interpretability relates to the application of a model and whether the outcome and suitability values are clear and understandable. The resolution/gradient provided an assessment of how detailed the suitability criteria are and whether the criteria can depict gradients of the suitabilities or simple classes only. Predictive accuracy presence provides an assessment of how well the method classifies the suitability of known egg mass or tadpole locations as occurring in any suitable habitat. Predictive accuracy suitability assesses how well the method classifies known egg mass or tadpole locations into moderate or high suitability categories. Predictive accuracy reach-scale suitability is based on the application of each model in a 2D modeling framework. It refers to how well a method classifies habitat suitability across an entire river reach (e.g., is the whole river classified as suitable?)

Lifestage	Model	Transferability (LR – large rivers, CK – creeks)	Interpretability	High Resolution/ Gradient	Predictive Accuracy		
					Presence	Suitability	Reach-Scale Suitability
Egg masses	Interval	LR - Good CK - Poor	Poor	Yes	LR - Good CK - Poor	LR - Good CK - Poor	Good
	Percentile	LR - Good CK - Poor	Good	No	LR - Good CK - Poor	Good	Good
	Logistic	Good	Poor	Yes	Good	LR - Good CK - Poor	Poor
Tadpoles early-stage	Interval	Good	Poor	Yes	Good	Poor	N/A
	Percentile	Good	Good	No	Good	Good	N/A
	Logistic	Poor	Poor	Yes	Poor	Poor	N/A
Tadpoles late-stage	Interval	LR - Good CK - Poor	Poor	Yes	Good	Good	Good
	Percentile	Good	Good	No	Good	Good	Poor
	Logistic	LR - Good CK - Poor	Poor	Yes	Good	Poor	Good

The percentile HSI had the highest predictive accuracy for egg mass suitability due to the method of combining suitability values into three categories. Any location with two of three highly suitable hydraulic variables, regardless of the variable type, received a high HSI value. The more continuous nature of the interval HSI and logistic HSI allowed for a finer degree of resolution in the habitat suitability values, ranging fully from 0-1. However data is currently lacking to associate degrees of suitability with population outcomes (e.g., population trajectory, stability, lifestage-specific survival rates), and thus interpretability is limited. The categories inherent in the percentile HSI provide transparency in the resulting HSI value, because only five numeric values can occur. These numeric values indicate how many hydraulic variables were suitable and to what degree, allowing for a high degree of interpretability (Table 1.21).

The differences in performance observed between the HSC models for tadpoles were similar in some respects, such as interpretability and resolution, to those for the egg masses (Table 1.21). However, the tadpole models performed more similarly across streams of varying size, and had a high degree of predictive accuracy for tadpole presence (i.e. few tadpole locations were classified as unsuitable). Predictive accuracy was highest (i.e. majority of actual tadpole locations classified as high suitability) for the Percentile HSI, and lowest for the logistic HSI due primarily to low suitability associated with deep depths. The depth-squared term in the logistic regression model creates a more distinct bound in suitability at higher depths, similar to that observed in the interval HSI, thus assigning low suitability to locations at higher depths even when velocity and substrate might be highly suitable. The percentile HSI brackets low use at the deep depths, and when combined with highly suitable velocity or substrate, assigns a moderate HSI value. The inclusiveness of the percentile HSI, while resulting in a higher predictive accuracy for suitability at tadpole locations, also results in a large percentage of the river reach classified as moderate to highly suitable. Locations with moderate depths and velocities (up to 0.40 m/s) were classified as moderately suitable with the Percentile HSI, but as low suitability with the interval HSI and logistic HSI.

1.4 Conclusions and Recommendations

1.4.1 Conclusions

Many of the differences observed between the three HSC models are due to fundamental differences in methodology. The logistic HSI relies intrinsically on the range of both the habitat use and availability data input into the model. And the distribution of the resulting HSI values is highly dependent on the mathematical model chosen. For example, in order to accurately depict the unimodal relationship between depth and use, a depth and depth-squared term were incorporated into the model. This resulted in a soft bound at shallow depths—shallow depths were assigned low suitability values rather than classified as unsuitable—but a hard bound at high depths, where values beyond those observed were classified as unsuitable. Similarly, taking the square-root of the velocity term helped to normalize the velocity distribution, but the lack of a hard bound at higher velocities allowed for low suitability values to be assigned to velocities greater than 0.3 m/s. This value may be a critical value associated with scour of egg masses and tadpoles such that higher velocities should be considered unsuitable (Kupferberg et al., 2009a). As a result, the majority of logistic HSI values assigned to egg mass and tadpole locations were in the low and moderate suitability categories, while the majority of the modeled river reach, including areas known to be unsuitable, was classified as low suitability.

The univariate HSI are also defined by the range of use data input into the model, but mathematical adjustments for the range of available habitat or for the observed relationships between use and individual hydraulic variables are completed independently. This has the advantage of allowing for biological knowledge to factor in where needed, such as to allow for one hydraulic variable to compensate for another or to adjust an SI based on the percent of available habitat known to be key to a species. However, it has the disadvantage of assuming hydraulic variables are independent and generally linearly-related in combined habitat suitability indices, which may not the case (Guay et al., 2000). As a result, both the percentile HSI and interval HSI assigned moderate to high suitability values to instream locations similar to those used in the models, but classified any locations on the edges of observed use (e.g., depth of 1.7 m) as unsuitable.

As the number of use points included in the univariate models increases, the tails of the use distributions for each hydraulic variable may extend, such that these edge locations would no longer be categorized as unsuitable. However, how each of the univariate HSI responds mathematically to an increasing number of use points differs. Due to the inclusive nature of the percentile HSI, additional values will expand the hard bounds of suitability for each variable, but the range of values falling within 90% may also increase, resulting in more values classified as highly suitable. A moderate to high depth value falling near the boundary between the 89^{th}

and 90th percentile (e.g. 0.6 m) might be classified as low suitability initially, but with additional use points that expand the bounds, could be classified subsequently as high suitability. Conversely, the interval-based suitability indices will become more 'smoothed' with additional data as each interval of a hydraulic variable is populated with a value proportional to the actual use. The large number of tadpole observations used to create the univariate HSI resulted in a more smoothed distribution in the interval HSI where intervals in the tail of the depth distribution show gradually declining use (Figure 1.10), unlike the intervals in the tail of the egg mass depth distribution which show alternating low and high proportions of use, a phenomenon likely due to the lower sample size (Figure 1.9).

The primary assumption of these HSC models is that a greater frequency of use is equivalent to higher suitability. Habitat models based on individual selection may not accurately represent population level requirements since they merely reflect frequency of use (Van Horn, 1983; Huckstorf et al., 2008). The models developed in this study do not directly incorporate reproductive success factors such as egg mass and tadpole survivorship, which are dependent on both hydraulic conditions (e.g., discharge, water velocity, water depth) (Kupferberg et al., 2009a) and non-hydraulic factors such as water temperature, riparian conditions and valley morphology (Lind, 2005; Lind and Yarnell, 2008). Nevertheless, recent experimental work on tadpole tolerance to variation in water velocity demonstrates similar thresholds between velocities that cause scouring (and likely mortality) of tadpoles and the water velocities defined as unsuitable in the current HSC study (Kupferberg et al., 2009a; Kupferberg et al., *In Press* [2011]). *R. boylii* egg masses and hatchling tadpoles require a sheltered environment to survive water flow fluctuations during the spring runoff period (Kupferberg, 1996, Lind et al., 1996). This is consistent with the large, relatively immoveable substrates (cobble and boulder) that were identified as highly suitable in the current study. Initial efforts linking flow conditions to population outcomes (e.g., population growth rate, extinction probability) have derived predictions about long-term population stability for *R. boylii* under various flow scenarios (Kupferberg et al., 2009b). However, more detailed research on the relationships between local habitat conditions and suitability resulting from flow conditions and population outcomes at multiple spatial and temporal scales is still needed. Ultimately, to conserve and restore aquatic species, instream habitat models will need to better integrate habitat use with population status and recovery outcomes (Rosenfield and Hatfield, 2006).

1.4.2 Recommendations

While the multivariate logistic regression HSI has appealing characteristics, such as incorporating habitat use and availability data and allowing for complex variable interactions, it did not perform well in predicting egg mass or tadpole habitat suitability. Furthermore, the mathematical model used in the logistic HSI resulted in calculations of suitability that were inconsistent with the known hydraulic preferences of *R. boylii*. Therefore, using a logistic regression-based approach to develop HSC for other studies is not recommended. The univariate models, though based on assumptions of hydraulic variable independence, performed well for predicting both oviposition and tadpole rearing habitat. In large rivers, where geomorphology and substrate conditions are similar to those observed in this study, the univariate HSI models shown here will likely perform well. For smaller rivers and creeks with limited depth availability or finer substrates, locally-derived or river-specific HSI should be developed independently.

Until additional habitat use and population outcome data can be collected and related to the interval HSI developed in this study, use of the percentile HSI is recommended for instream flow studies. In rivers with similar geomorphic characteristics and ranges of habitat use to those assessed in this study, instream evaluations can be made using the percentile HSI presented. Rivers and streams with differing habitat conditions and/ or ranges of habitat use may require locally-derived curves to be developed.

As new habitat use data is gathered, continued additions to the percentile HSI developed in this study should be carefully evaluated. Adding a greater number of use points may potentially shift definitions of high and low suitability beyond what is observed for any given river. Rather, large datasets encompassing multiple rivers and years may best be described using the interval HSI methodology where a large number of use points can be more accurately represented at finer resolution. In addition, as new data is gathered regarding links between habitat suitability and survival, the interval HSI methodology will better allow for assessments of shifts in habitat suitability as flows change. Ultimately, should these data become available, the interval HSI methodology may provide a model that will be most transferable across a wide range of Sierran rivers.

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1.6 Appendices

Figure 1.6.A: Distribution of combined HSI values relative to HIS for individual water depth and water velocity values using alternative combination methods defined in section 1.2.3.1.

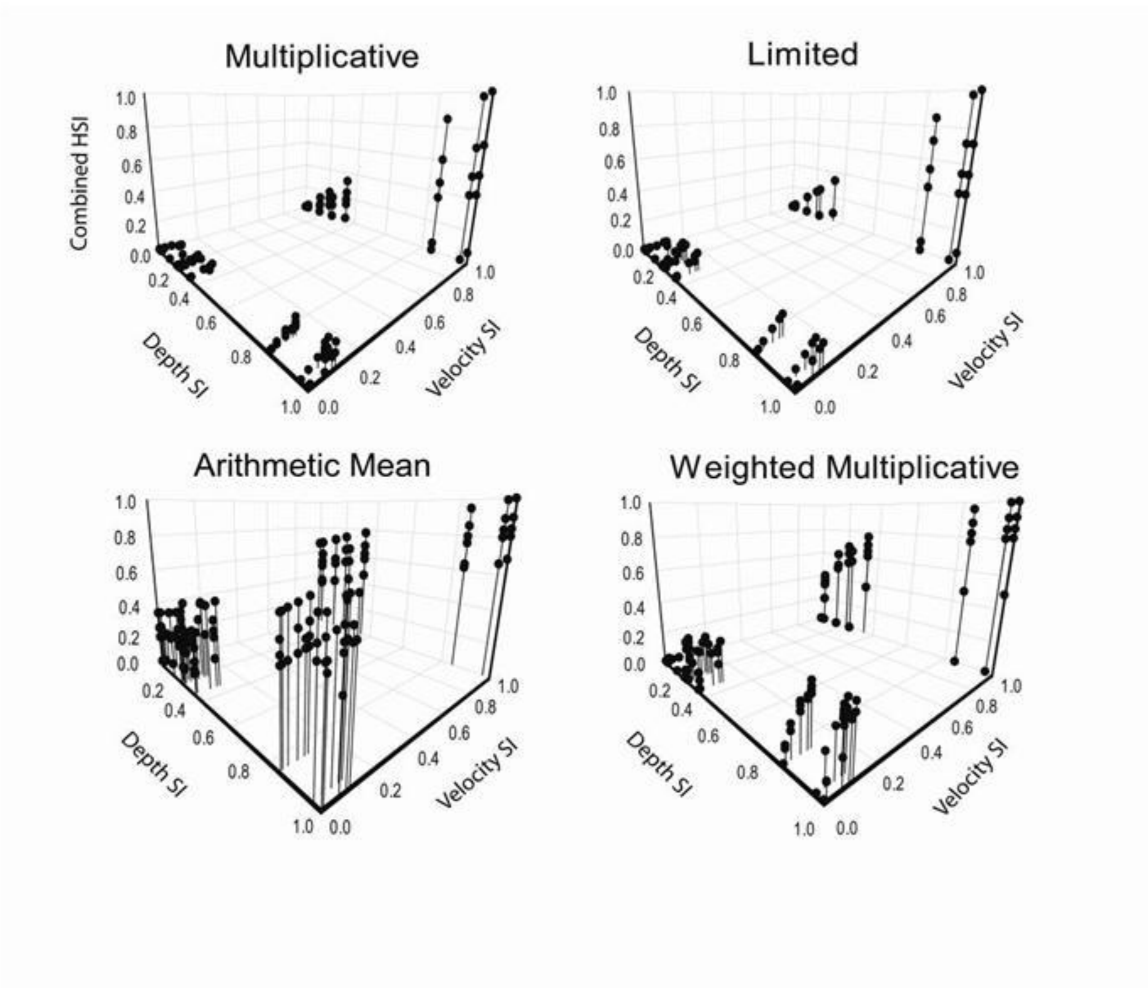


Table 1.6.B: Examples of interval-based habitat suitability index outcomes for selected egg mass and availability locations using the five different combination techniques.

River Points	Actual measurements			HSI values assigned			HSI combination techniques				
	Mid column velocity (m/s)	Total depth (m)	Substrate type	Mid column velocity (m/s)	Total depth (m)	Substrate type	multiplicative	limited	Geometric mean	Arithmetic mean	Weighted multiplicative
Egg	0.09	0.3	5	0.09	1.00	0.54	0.05	0.09	0.36	0.54	0.26
Egg	0.17	0.45	4	0.06	0.85	0.42	0.02	0.06	0.28	0.44	0.19
Egg	0.04	0.3	6	1.00	1.00	0.71	0.71	0.71	0.89	0.90	0.92
Egg	0.01	0.39	6	1.00	0.97	0.71	0.69	0.71	0.89	0.90	0.91
Egg	0.03	0.18	4	1.00	0.33	0.42	0.14	0.33	0.52	0.59	0.61
Egg	0.03	0.36	6	1.00	0.97	0.71	0.69	0.71	0.89	0.90	0.91
Egg	0.04	0.14	6	1.00	0.33	0.71	0.24	0.33	0.62	0.68	0.70
Egg	0.03	0.24	7	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Egg	0.03	0.25	8	1.00	1.00	0.06	0.06	0.06	0.39	0.69	0.49
Egg	0.05	0.49	7	1.00	0.85	1.00	0.85	0.85	0.95	0.95	0.96
Available-poor	1.49	0.45	6	0.00	0.85	0.71	0.00	0.00	0.00	0.52	0.00
Available-poor	1.73	0.36	5	0.00	0.97	0.54	0.00	0.00	0.00	0.50	0.00
Available-poor	0.03	0.41	1	1.00	0.85	0.00	0.00	0.00	0.00	0.62	0.00
Available-poor	0.00	0.01	8	1.00	0.03	0.06	0.00	0.03	0.11	0.36	0.20
Available-poor	0.00	0.02	3	1.00	0.03	0.00	0.00	0.00	0.00	0.34	0.00
Available-good	0.02	0.18	5	1.00	0.33	0.54	0.18	0.33	0.56	0.62	0.65
Available-good	0.02	0.2	7	1.00	0.33	1.00	0.33	0.33	0.69	0.78	0.76
Available-good	0.01	0.3	5	1.00	1.00	0.54	0.54	0.54	0.81	0.85	0.86
Available-good	0.02	0.37	5	1.00	0.97	0.54	0.52	0.54	0.81	0.84	0.85
Available-good	0.01	0.57	4	1.00	0.21	0.42	0.09	0.21	0.44	0.54	0.54

Chapter 2:
Instream Flow Modeling Applications for the Foothill Yellow-legged Frog (*Rana boylii*)

2.1 Introduction

The Foothill Yellow-legged Frog (*Rana boylii*), characteristic for its habitation of riverine environments, has been in decline for the past several decades and is listed as a California State Species of Special Concern (Jennings and Hayes, 1994). Many potential causes have been identified, but of particular note is their marked absence from historic localities in close proximity to large dams (Lind, 2005). Recent studies have demonstrated the negative impacts of altered flow regimes on individuals and their habitat (Kupferberg et al., 2009a; Yarnell et al., 2010), and as a result, resource managers have been faced with the challenging task of prescribing flow regimes below dams that limit effects on *R. boylii*.

In many current hydropower project relicensing studies, a variety of instream flow assessment methods are used to evaluate flow effects and proposed flow prescriptions on fish and other aquatic species. These methods have varying costs and benefits, ranging from relatively inexpensive but non-predictive expert habitat mapping to costly but highly accurate and predictive habitat modeling using three-dimensional hydraulic simulation. Depending on the information required and the nature of the study sites, a combination of methods is often used. While the applicability of these methods for fish-related issues is established, the circumstances in which they might be applicable for evaluating flow effects on *R. boylii* are less certain.

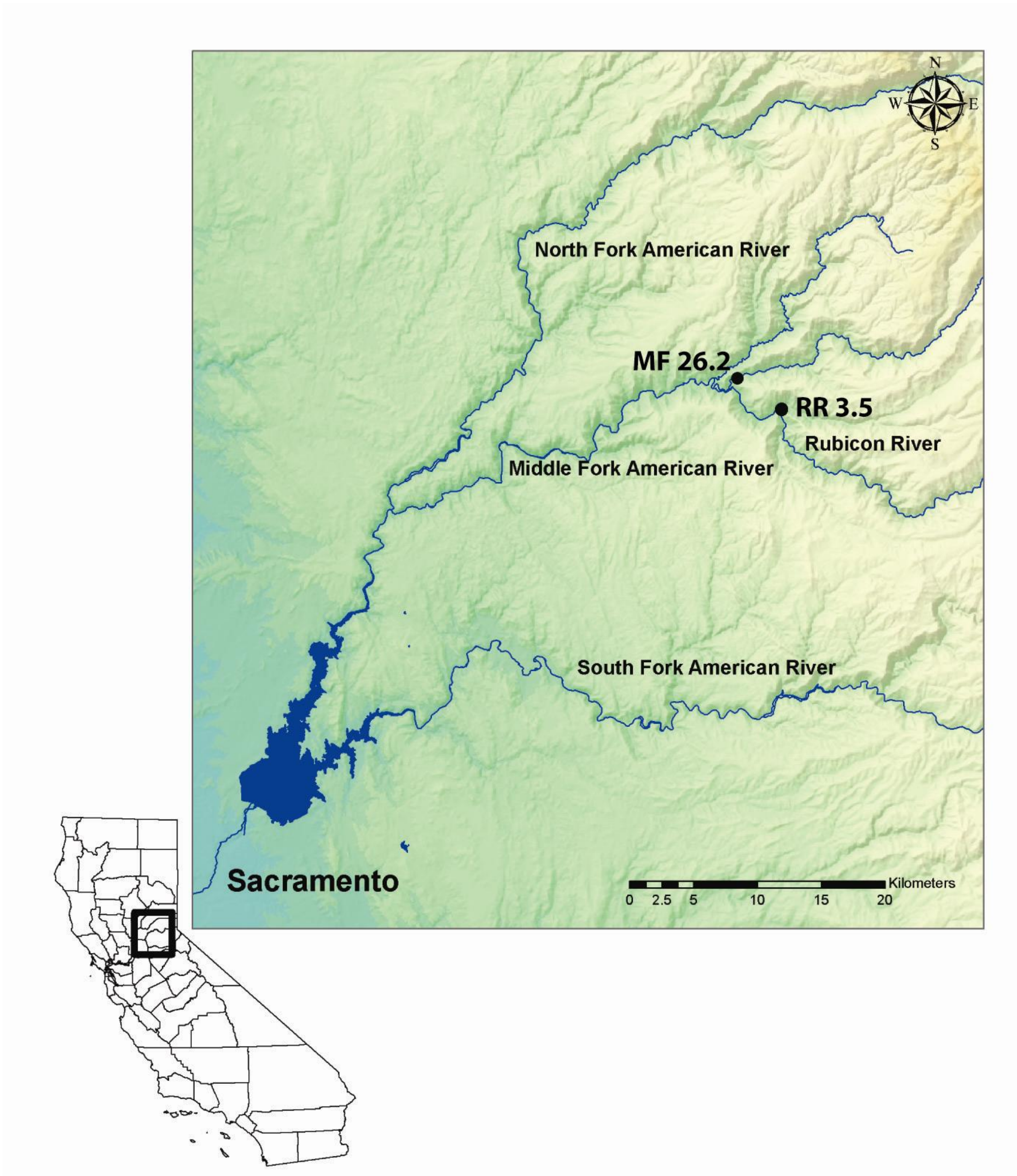
This study sought to evaluate potential instream flow assessment methods that could quantify and simulate flow-related hydropower project effects on *R. boylii*. The study focused on the three most commonly used instream flow assessment techniques: (1) one-dimensional (1D) habitat modeling, such as the Physical Habitat Simulation (PHABSIM) System, (2) habitat modeling using a two-dimensional (2D) hydrodynamic model (River2D), and (3) expert habitat mapping (EHM) (specifically, judgment-based mapping by species experts). The primary objective of the study was to provide comparative information so that resource managers can choose the most appropriate habitat assessment method for *R. boylii* given the circumstances specific to a particular hydropower relicensing project. Specific objectives included comparing observed habitat utilizations at two case study sites to predicted habitat suitability from each of the methods to determine advantages, disadvantages and the range of accuracy of each method, and creating a comparative summary table of each method that includes information on costs and benefits, level of effort, scale of resolution, capacity for extrapolation and applicable management issues.

2.2 Methods

2.2.1 Study Sites

Two study sites in the Middle American River watershed were chosen to compare the applicability of instream flow assessment methods for *R. boylii*: river mile 3.5 on the Rubicon River (RR 3.5) and river mile 26.2 on the Middle Fork American River (MF 26.2) (Figure 2.1). Each of these sites was assessed by Placer County Water Agency (PCWA) during the instream flow study for the Middle Fork project relicensing (FERC #2079) in 2008 and was modeled using standard 2D hydrodynamic modeling methods (PCWA, 2010). RR 3.5 and the associated 2D model are the same study site location and hydrodynamic model used in the evaluation of *R. boylii* habitat suitability criteria presented in Chapter 1. Additionally, at MF 26.2, PCWA conducted 1D modeling following the traditional PHABSIM approach, such that several of the 1D cross-sections spatially overlapped with the 2D modeling area and could be used as calibration cross-sections for the 2D model. The 1D and 2D models, and associated field and hydraulic data were provided by PCWA for use within this study. Each site was then expert-habitat mapped in fall 2009 and spring 2010 by the study authors to allow for an evaluation of each instream flow assessment method at a common locality. We also tracked and summarized the effort (in person-hours) required to complete both field and office components for each method.

Figure 2.1: Study site map



The two study sites are typical of mid-elevation Sierran streams consisting of riffle-pool-run morphologies influenced by bedrock outcrops and confined valley walls (Table 2.1). Substrates are coarse with median sizes ranging from cobble to gravel, and channel slopes are generally high averaging 2-4%. Riparian vegetation is limited to discontinuous floodplain deposits where the valley morphology widens. The hydrology of both study sites is influenced by project operations at upstream reservoirs, such that flows are diverted throughout the year, yet still reach natural peak magnitudes in winter due to 'spill' from the upstream reservoirs. RR 3.5 is located further downstream from regulation than MF 26.2 and receives a greater volume of unimpaired accretion flows. Both study sites support breeding populations of *R. boylii*; however, RR 3.5 has a much higher abundance of all lifestages (PCWA, 2008).

Table 2.1: Qualitative and quantitative study site characteristics

	MF 26.2	RR 3.5
Elevation (m)	360	425
Drainage area (km^2)	287	807
Gradient	0.015	0.017
Site length (m) (2D model / EHM)	130 / 300	186 / 200
Mean Annual Discharge (cms)	3.48	9.12
Dominant Substrate	Medium Cobble (150-230mm)	Small to Medium Cobble (80 - 230 mm)
Reach morphology	run-pool-riffle	riffle-run-pool
Riparian Vegetation	High density (willows on bars, alders at high water)	Moderate density (willow/alder at high water)
Models Compared	EHM, 1D-model, 2D-model	EHM, 2D-model

2.2.2 Two-dimensional (2D) Hydrodynamic Modeling

A 2D hydrodynamic model (River2D) was used to predict depths and mid-column velocities for *R. boylii* egg masses across a wide range of flows at both study sites. River2D is a physically-based depth-averaged finite element model freely available and used by the California Department of Fish and Game, U.S. Fish and Wildlife Service and others in fish habitat evaluation studies (Steffler and Blackburn, 2002; Tiffan *et al*., 2002; Hanrahan *et al*., 2004; Gard, 2006). Using the principals of conservation of mass and momentum, surveyed channel topography, and measured water surface elevations at a series of calibration flows, River2D simulates depth and mid-column velocity at each modeling node across a range of modeled flows. When combined with species preference curves or habitat suitability criteria, River2D provides a measure of the quantity and quality of instream habitat for a particular species or lifestage at any modeled flow.

The River2D models for each study site were developed by PCWA for the Middle Fork Project relicensing following standard procedures (Steffler and Blackburn, 2002) and provided for use in this study. A total of 16 flows were modeled at each site, based on calibration data collected at a low, moderate and high discharge. Details on the calibration of the models, including information on the input topography, mesh density, hydraulic calibration and model error, can be found online (PCWA, 2010).

Suitable oviposition habitat was determined by using the regional percentile-based habitat suitability indices (HSI) for egg masses developed in Chapter 1. The individual HSI were combined in River2D using the geometric mean method to create a combined habitat suitability value (CSI) for each node (modeled point) at each modeled discharge. A primary output of River2D is the total weighted usable area (WUA), an index of habitat area weighted by suitability, for each modeled discharge; however, in order to compare results with the expert habitat mapping method which does not produce a WUA, the total suitable area was calculated at each discharge, where suitable area was defined as the area associated with any node with a combined suitability value greater than zero.

The availability of suitable habitat at a given flow is an important consideration for successful *R. boylii* reproduction; however, recent studies indicate that the *change* in hydraulic conditions as discharge changes over time can greatly impact population dynamics (Kupferberg et al., 2009a; Yarnell et al., 2010, Kupferberg et al., 2010). Therefore, additional data analyses were completed at MF 26.2 regarding the suitability of hydraulic conditions as discharge changed, and the degree to which each instream flow assessment method was able to address these analyses was evaluated.

To determine which channel areas remained suitable as flows fluctuated, an assessment of 'effective habitat' was completed across the range of modeled flows. Conceptually, effective habitat is any habitat location (e.g. a modeled node in the 2D model) that is suitable at one discharge and remains suitable at one or more subsequent discharges. The degree to which effective habitat is evaluated can vary, ranging from a simple assessment of stranding potential, where suitable locations at a high discharge are tracked through time as flows decrease, to a more complicated assessment, where the degree of suitability (high, moderate, low) is tracked as flows increase and decrease. For this study, two analyses were done: a calculation of the amount of effective habitat at each modeled discharge as flows decreased from a maximum to a minimum, and the degree to which suitable habitat became unsuitable during a pulsed flow event.

To facilitate analyzing the large point dataset associated with the MF 26.2 2D modeled site, a computing routine was developed by PCWA to calculate the effective habitat as flows decreased from the maximum modeled discharge through each subsequent discharge to the minimum modeled discharge. The effective habitat at each discharge was calculated as the total weighted usable area of nodes that were suitable (where 'suitable' was defined as a combined suitability > zero) at *both* the current discharge and the previous discharge. Any new nodes which became suitable at the current discharge were not included in the total habitat area calculation. This calculation was then repeated at the subsequent lower discharge, where only those nodes that were suitable at the previous discharge and remained suitable at the subsequent discharge were counted. The amount of effective habitat will generally decrease as discharge decreases and nodes become dry and unsuitable, however the rate and pattern of decreasing habitat between discharges will vary depending on channel morphology.

The pulse flow analysis was completed by modeling the change in suitability as flows increased from a low to high springtime flow, simulating a rain-induced or managed flood event. The number of suitable nodes and their associated suitability (defined as high, moderate or low) were determined at the low flow, and then tracked at the high flow to determine their fate. The degree to which each category of suitability changed was determined and assessed.

2.2.3 One-dimensional (1D) Habitat Modeling

The most common and long-standing instream flow assessment method in the United States (EPRI, 2000), 1D habitat modeling, such as the Physical Habitat Simulation (PHABSIM) System (Bovee et al., 1998), is similar in premise to the 2D model-based flow assessment method. 1D hydraulic models are combined with species preference curves or habitat suitability criteria to provide a measure of the quantity and quality of instream habitat for a particular species or lifestage at any modeled flow. However, while the 2D model is physically-based, 1D models are empirically-derived from cross-section data, resulting in differing scales of spatial resolution, sources of error, and potentially, estimates of habitat suitability between the two methods.

As part of the instream flow technical study for the Middle Fork American relicensing, PCWA conducted 1D modeling at MF 26.2 to assess the relationship between discharge and instream habitat for fish (PCWA, 2010). A total of 23 cross-sections were placed within and upstream of MF 26.2 to represent the range of mesohabitats present within the larger river reach. Standard PHABSIM 1D hydraulic modeling procedures were used for modeling depths and velocities at the 1D cross-sections over a range of flows (Milhous et al., 1989; Waddle, 2001; TRPA, 2009). As with the 2D model, a total of 16 flows were modeled at each cross-section, based on calibration data collected at a low, moderate and high discharge. Details on the calibration of the models, including information on the hydraulic calibration and model error, can be found online (PCWA, 2010).

Of the 23 1D cross-sections at MF 26.2, six overlapped with the 2D modeled area and could be used for direct comparison. PCWA provided the 1D hydraulic simulation data in the form of a series of calibrated models, which were then used in conjunction with the regional percentile-based HSI for egg masses (see Chapter 1) to determine oviposition habitat suitability throughout the study site. As with the 2D modeling, the HSI were combined using the geometric mean method resulting in a combined suitability value for each cross-section cell at each modeled discharge. The primary output of PHABSIM is a WUA for each modeled flow where the weighting reflects the proportion of mesohabitats (represented by cross-sections) present in the river reach. However, in order to compare across methodologies, the total suitable area was calculated for each modeled discharge, where suitable was defined as the area associated with any cross-sectional cell with a combined suitability value greater than zero. To determine the area associated with each cross-sectional cell, the weighting factors for each cross-section were scaled to reflect the actual longitudinal river distance between cross-sections. As a result, the area modeled in the 1D model was similar in river length to the area modeled in the 2D models and mapped by the EHM method.

In order to evaluate the suitability of hydraulic conditions as discharge changed, effective habitat was assessed in a similar manner to the 2D modeling, where 1D cross-section cells were akin to 2D nodes. The effective habitat was calculated as flows decreased from the maximum modeled flow through each subsequent lower flow to the minimum modeled flow using a simple spreadsheet as the number of 1D modeled cells was much smaller than the number of 2D modeled nodes. However, because the calculations were done 'by hand' in the spreadsheet, only 10 of the 16 modeled flows were used to calculated effective habitat, where the 10 flows represented the full range of modeled flows. Additionally, the degree to which habitat suitability changed during a pulse flow was evaluated by modeling the change in suitability as flows increased from a low to high springtime flow. The number of suitable cells and their associated suitability (defined as high, moderate or low) were determined at the low flow, and then tracked at the high flow to determine their fate.

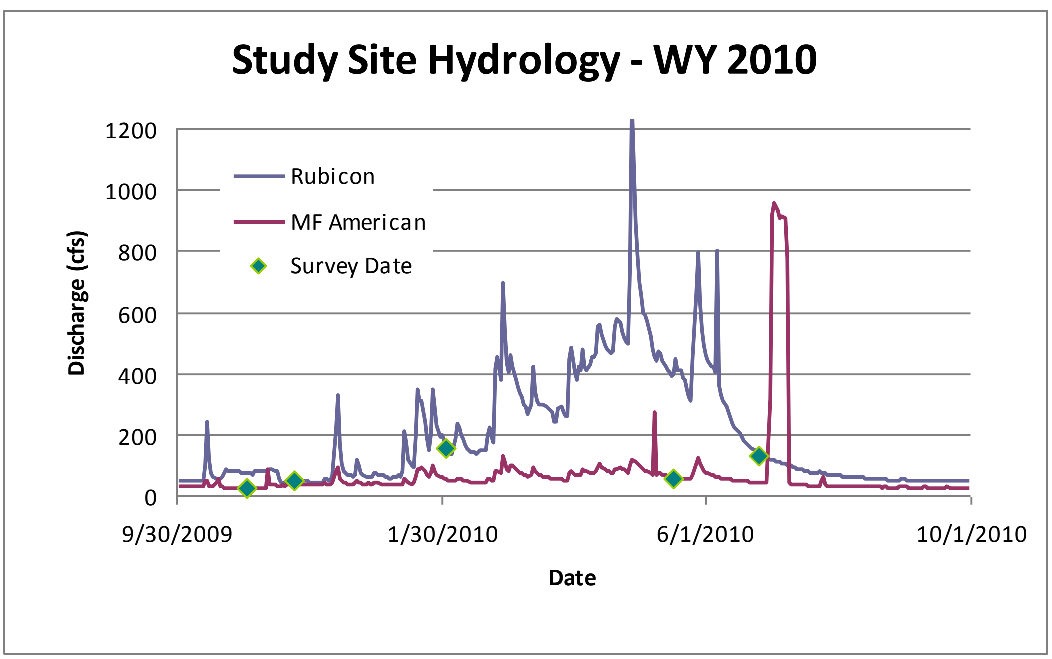
2.2.4 Expert Habitat Mapping

A qualitative instream flow assessment method, expert habitat mapping (EHM) (also referred to as judgment-based mapping, demonstration flow assessments or qualitative observation) uses direct observation of river conditions at several flows to determine the extent of suitable instream habitat for a species of interest or group of aquatic species (Railsback and Kadvany, 2008). At each observed flow, areas of suitable habitat are delineated in the field by a team of species experts, then, following post-processing of the field data, a relationship between flow and habitat area is determined. In comparison to quantitative habitat modeling, EHM does not provide the ability to simulate instream habitat for un-observed flows; however, it does offer the advantage of evaluation of complex river habitats, direct observation of flows of interest, and the ability to directly incorporate professional judgment and conceptual models that extend beyond simple hydraulic habitat selection (EPRI, 2000; Railsback and Kadvany, 2008).

Both study sites were expert-habitat mapped in fall 2009 and spring 2010 following the methods described by McBain and Trush (2008) and Gard (2009). Researchers with expertise in *R. boylii* habitat and ecology walked each study reach assessing locations of suitable oviposition habitat at an observed flow and delineating those habitat 'patches' or 'polygons' on a basemap of the study site. Suitable habitat was defined simply as an area of the channel that the experts considered to be suitable for breeding based on their experience and professional opinion. A tape measure and range finder were used during the survey to measure the size of each habitat polygon and ensure that the polygons were mapped accurately. The basemap for RR 3.5 was an aerial image obtained during a low-elevation LIDAR survey flight in 2008 and provided by PCWA. At MF 26.2, the narrow canyon and dense tree canopy obscured much of the channel view in the aerial image obtained during the same flight, so a sketched basemap hand-drawn to scale using a measuring tape or range-finder and compass in the field was used instead. This mapping procedure was repeated at a series of flows to determine the relationship between oviposition habitat availability and discharge. A 'clean' basemap was used for each survey so that prior survey results would not influence the selection of suitable habitat. Following each field survey, the habitat maps were scanned, adjusted for scale as needed, and imported into Adobe Illustrator for analysis and visualization. The total suitable area at each flow was measured, and compared with the suitable areas determined from the hydraulic modeling methods. Because EHM does not produce detailed quantitative results of hydraulic conditions, the effective habitat and pulse flow analyses could not be completed for this method.

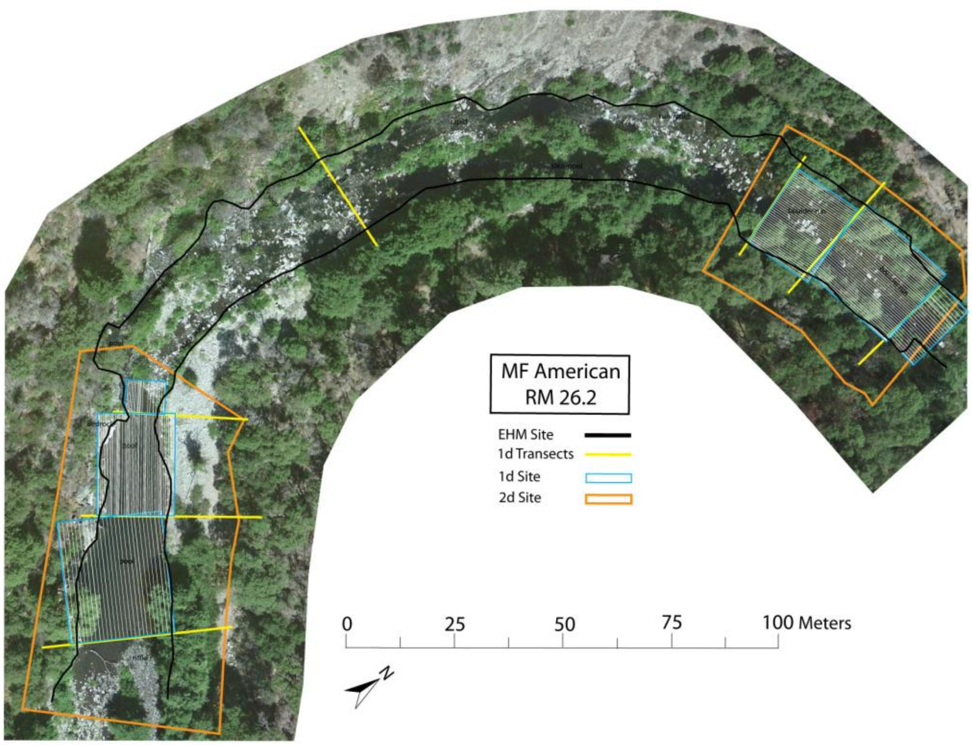
To compare the EHM method with the habitat modeling methods, the goal was to map *R. boylii* oviposition habitat in the field at a minimum of three discharges at each site ranging from low flow in fall, through peak flows in early spring to decreasing flows in late spring. Due to the unpredictability of early spring flows and accessibility issues at high water however, a total of three low to moderate magnitude discharges (49 cfs, 130 cfs and 150 cfs) were mapped at RR 3.5, and only two low and moderate discharges (24 cfs and 55 cfs) were mapped at MF 26.2 (Figure 2.2). Because MF 26.2 had less accretion flow than RR 3.5, flows remained low during most of the spring season making it difficult to 'catch' higher flows for mapping purposes. However, the low flows at each site were representative of typical tadpole rearing habitat in summer, and the moderate discharges were representative of typical spring flows during the breeding season for each site. In particular, *R. boylii* egg masses and early-stage tadpoles were noted and mapped during the June 28, 2010 survey at RR 3.5, and a calling male was observed near a known breeding location at MF 26.2 during the May 17, 2010 survey.

Figure 2.2: Water Year 2010 hydrographs of each study site with EHM survey dates indicated by green diamonds



Due to the differing basemaps between the two study sites (aerial versus hand-drawn), the extent of stream reach that was expert-habitat mapped at each site varied. At RR 3.5, mapping was completed only in the areas where 2D modeling was completed for direct comparison purposes. However, at MF 26.2, the entire study reach from the downstream end of the downstream 2D sub-site to the upstream end of the upstream 2D sub-site was mapped with the intention of comparing the EHM results with the results from the 1D model, which also spanned the entire reach (Figure 2.3). However, after the first field survey, it was apparent that the limited number of 1D cross-sections between the 2D sub-sites did not provide a good representation of the complex channel habitat, so comparisons between the three methods at MF 26.2 were limited to the extent of the 2D modeled sub-sites.

Figure 2.3: Map of MF 26.2 showing extent of EHM, locations of 1D cross-sections and extent of 2D modeled areas



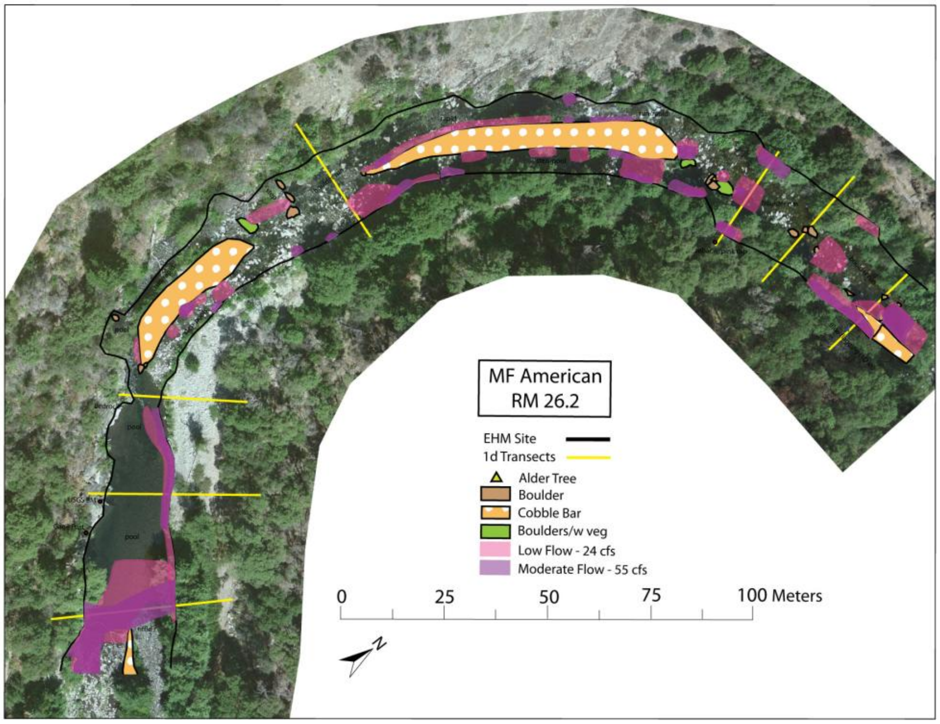
2.3 Results

2.3.1 Habitat Suitability

2.3.1.1 Expert Habitat Mapping

At MF 26.2, the lateral extent of the two observed flows varied only slightly, remaining within the main channels, with the primary observed differences between flows attributed to changes in depth and velocity (Figure 2.4). The large suitable areas in the pool tailout in the downstream end of reach and in the run in the upstream end of reach remained largely intact between the two discharges; however, many of the smaller habitat patches tucked in behind boulders or in small side eddies blinked in and out of suitability, particularly those in the split channel locations. These changes in suitability were due to distinct observed changes in depth and velocity conditions as these pocket habitats became too fast at the higher discharge or too shallow at the lower discharge.

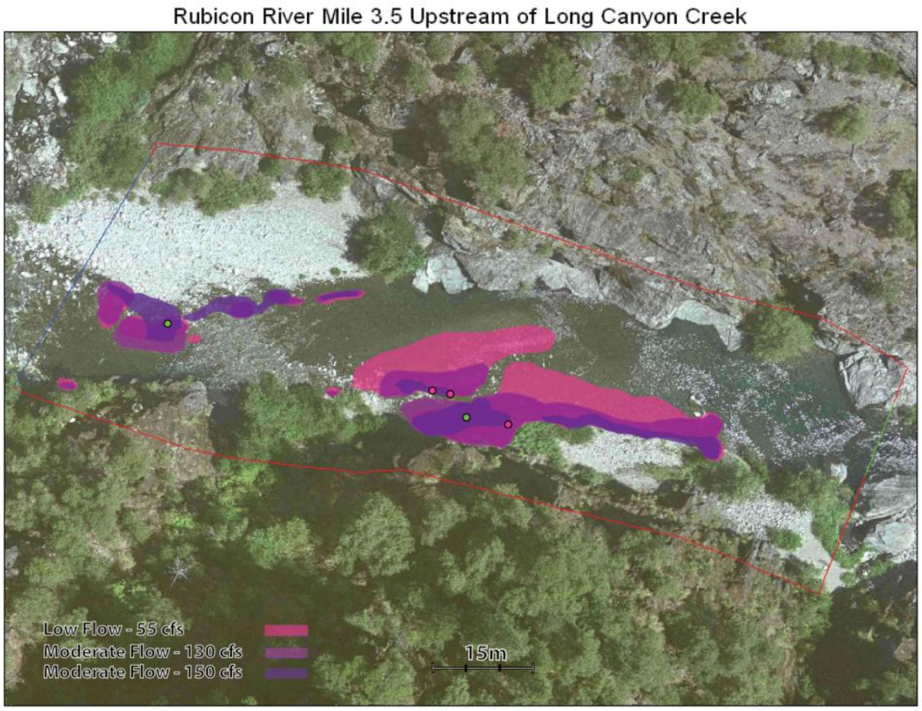
Figure 2.4: EHM results for each of the flows assessed at the MF 26.2 site. Colors indicate mapped suitable habitat at the observed discharges



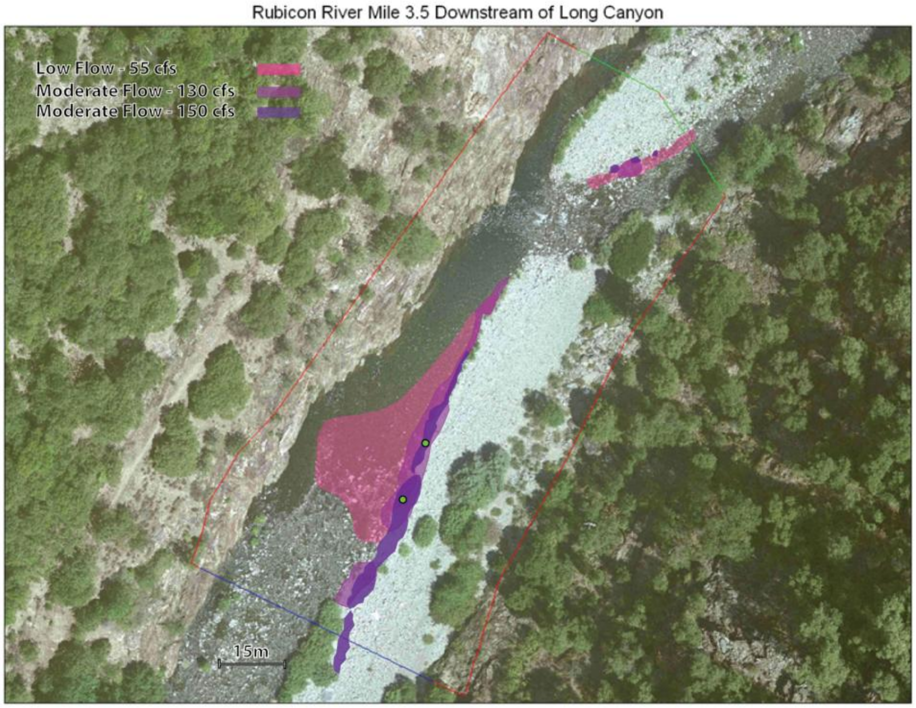
At RR 3.5, the lateral extent of the flows did change between the lowest and highest observed discharges as the water flooded onto the gradually sloping cobble bars in each of the upper and lower sub-sites (Figure 2.5). As a result, the suitable habitat patches remained primarily in the same location, but shifted laterally expanding or contracting depending on the flow change. Egg masses and newly hatched tadpoles were observed in the larger patches, where portions of suitable habitat remained throughout the range of observed flows. Although only two to three discharges were mapped at each study site, the EHM results do provide a rough sense of how connected the suitable habitat areas remained between low to moderate flow changes.

Figure 2.5: EHM results for each of the flows assessed at (a) RR 3.5 upstream sub-site and (b) RR 3.5 downstream sub-site. Dots indicate observed egg mass (pink) and tadpole (green) locations; Colors indicate mapped suitable habitat at the observed discharges

(a)



(b)



2.3.1.2 Total Suitable Habitat

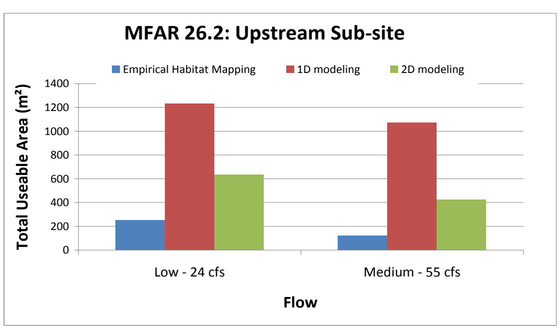
The total suitable breeding area at each mapped discharge as determined by each instream flow assessment method varied widely (Table 2.2). At each of the sites, the total suitable area calculated by the 2D models was 2-3 times the area determined by EHM. At MF 26.2, the area calculated by the 1D model was approximately twice the area calculated by the 2D models, resulting in up to an order of magnitude difference between the 1D modeling results and the EHM results (Figure 2.6). However the relationship between habitat and discharge remained similar between each method, with a decrease in total habitat area as discharge increased. At RR 3.5, not only were the magnitudes of total habitat area different between the methods, but the relationship between habitat area and discharge differed as well. The 2D models showed a gradual decrease in habitat as flows increased, while the EHM results showed a decrease then increase in habitat area (Figure 2.7).

Table 2.2: Summary of suitable breeding area at each study site as determined by each instream flow assessment method

Study Site	Discharge	Usable Area EHM (m^2)	Usable Area 2D (m^2)	Usable Area 1D (m^2)
MF 26.2 downstream	Low - 24 cfs	350	625	1052
	Mod - 55 cfs	234	560	839
MF 26.2 upstream	Low - 24 cfs	249	633	1229
	Mod - 55 cfs	118	424	1072
RR 3.5 (US & DS combined)	Low - 49 cfs	1440	1966	Na
	Mod - 130 cfs	394	1358	Na
	Mod - 150 cfs	687	1264	Na

Figure 2.6: Oviposition habitat suitability at each observed flow as determined by the three instream flow assessment methods at (a) MF 26.2 upstream sub-site and (b) MF 26.2 downstream sub-site

(a)



(b)

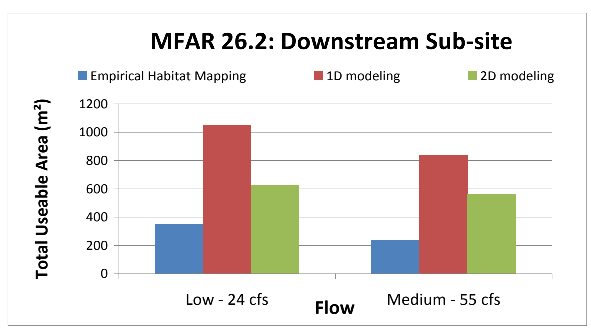
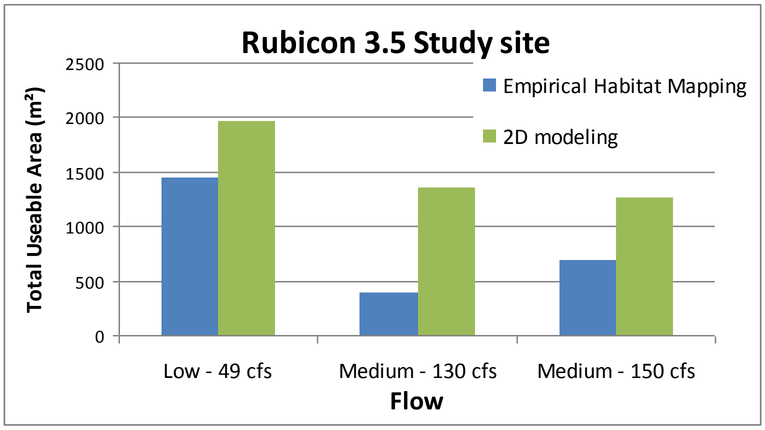


Figure 2.7: Oviposition habitat suitability at each observed flow as determined by EHM and 2D models at both the RR3.5 upstream and downstream sub-sites combined

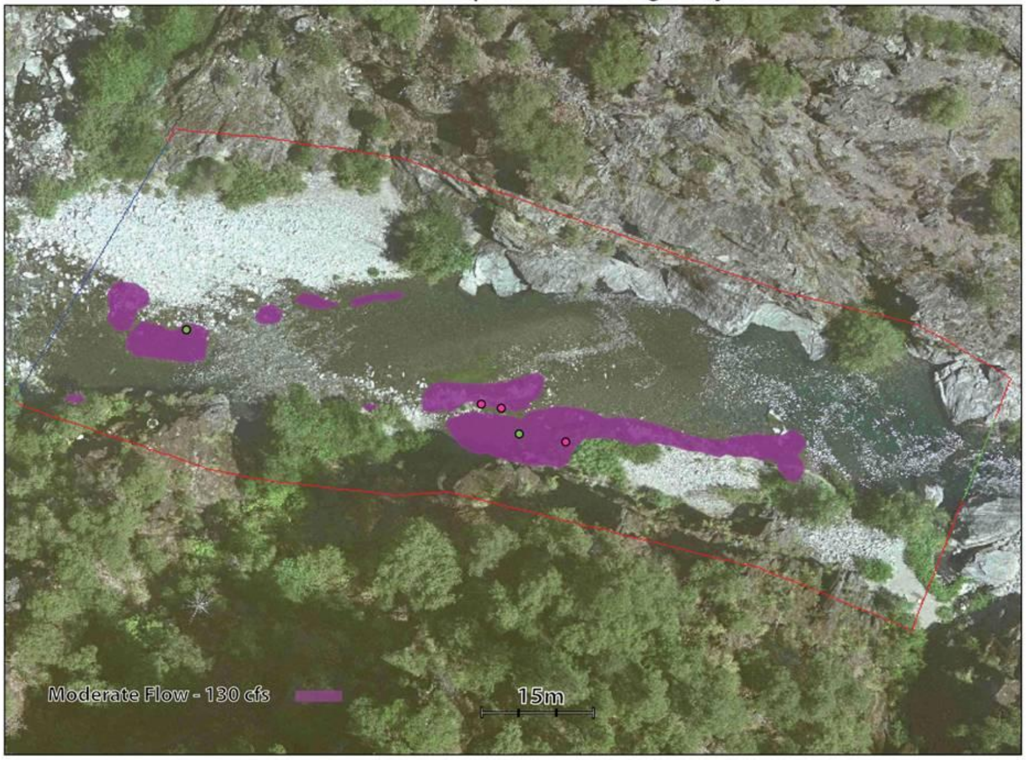


The differences in suitable habitat area resulting from each instream flow assessment method can be seen when comparing habitat suitability at a given flow. At RR 3.5, the general locations of suitable habitat were comparable between the two methods, but the EHM results primarily overlay the highly suitable areas in the 2D models, while areas calculated as moderate to low suitability in the 2D models extend beyond the EHM results (Figure 2.8). Similarly, at MF 26.2, the general locations of suitable habitat are similar, but the EHM and 2D modeling results primarily overlap in areas designated as highly suitable (Figure 2.9). Low and moderate suitability areas in the 2D models are not included in the EHM results. Habitat suitability from the 1D model at MF 26.2 mimics the EHM and 2D modeling results to some degree in that the same large areas of suitable habitat are delineated; however, the coarse resolution of the 1D model generates large estimates of suitable habitat area that extend well beyond the bounds of either of the other methods. For example, the lower half of the pool at the downstream end of the reach is suitable in the 1D model, but only the lower quarter of the pool is suitable in the 2D model and only the lower edge of the pool is suitable in the EHM results (Figure 2.9b).

Figure 2.8 (on following two pages): Oviposition habitat suitability at the June moderate flow (130 cfs) as determined by the EHM and 2D modeling instream flow assessment methods at (a) RR 3.5 upstream sub-site and (b) RR 3.5 downstream sub-site

Figure 2.8 (a)

Rubicon River Mile 3.5 Upstream of Long Canyon Creek



Rubicon River Mile 3.5 Upstream of Long Canyon Creek

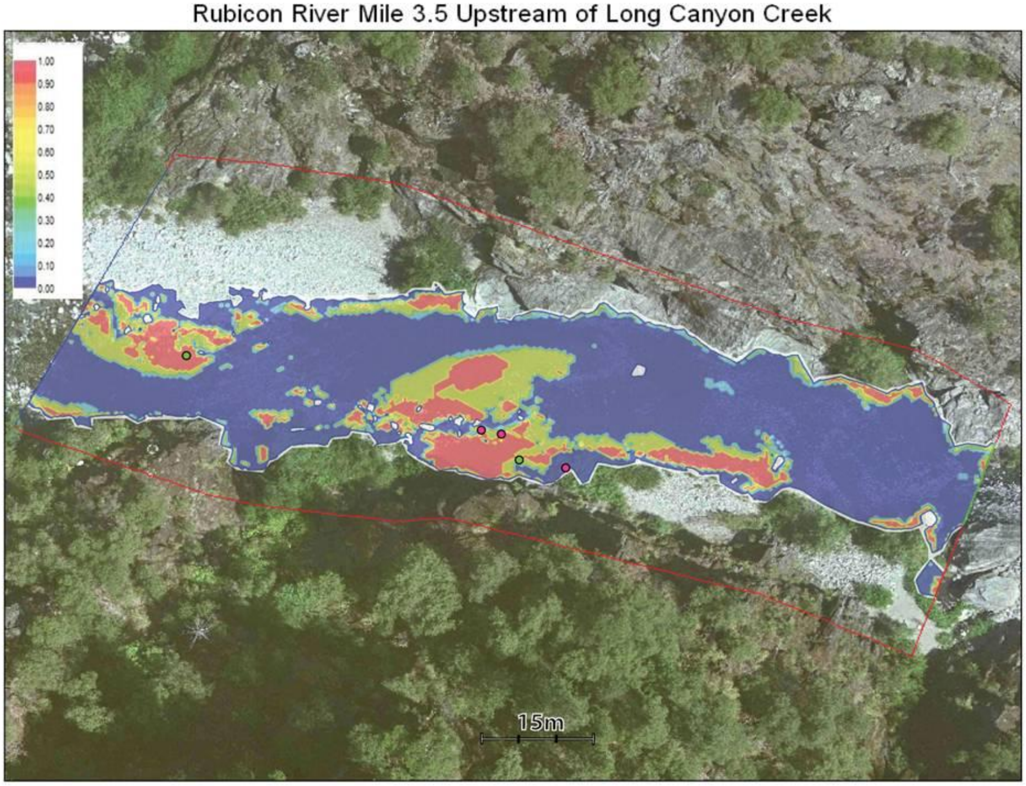
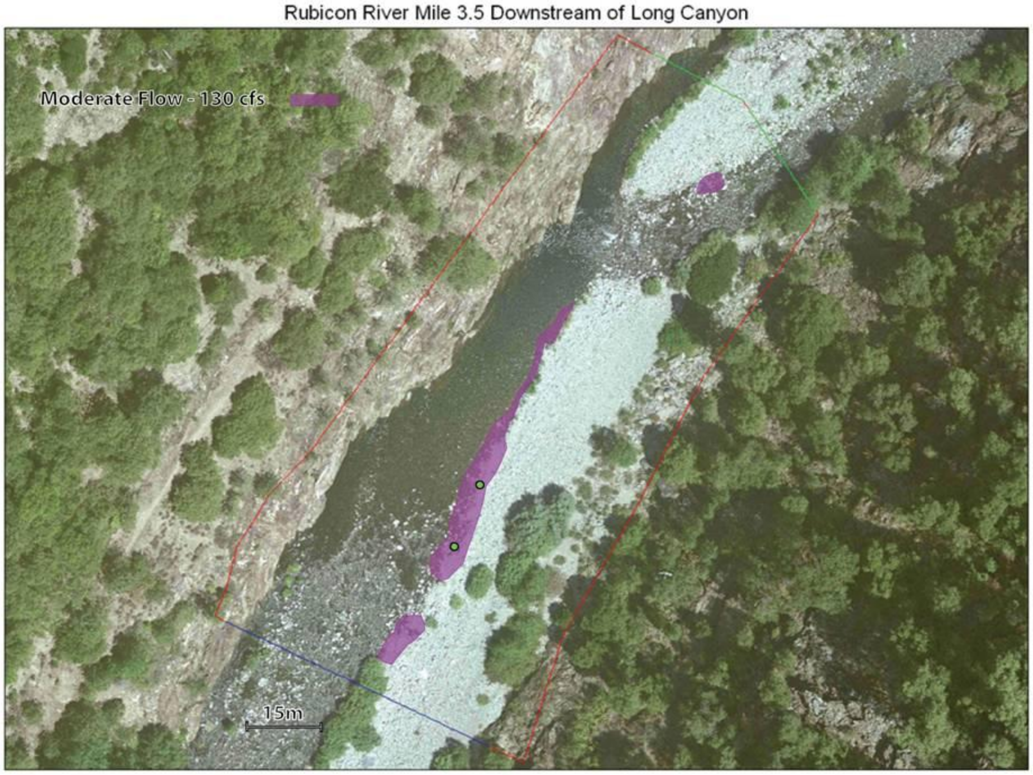


Figure 2.8 (b)


Rubicon River Mile 3.5 Downstream of Long Canyon
Moderate Flow - 130 cfs
15m

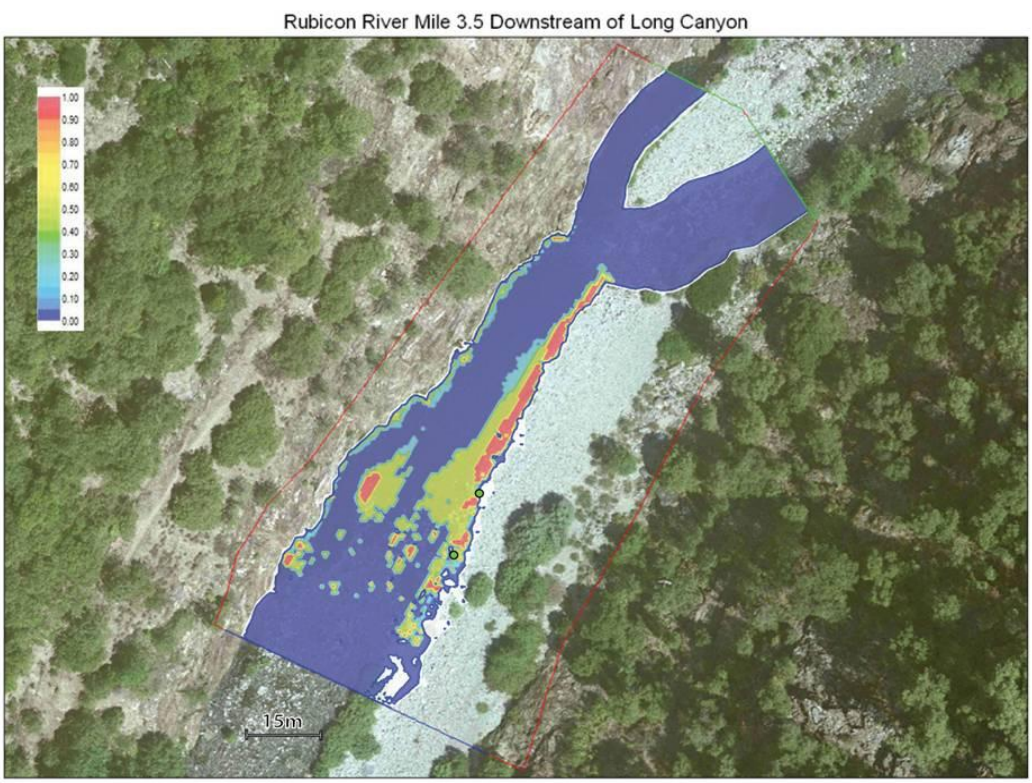

Rubicon River Mile 3.5 Downstream of Long Canyon
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
15m

Figure 2.9: Oviposition habitat suitability at the May moderate flow (55 cfs) as determined by the three instream flow assessment methods at (a) MF 26.2 upstream sub-site and (b) MF 26.2 downstream sub-site

(a)

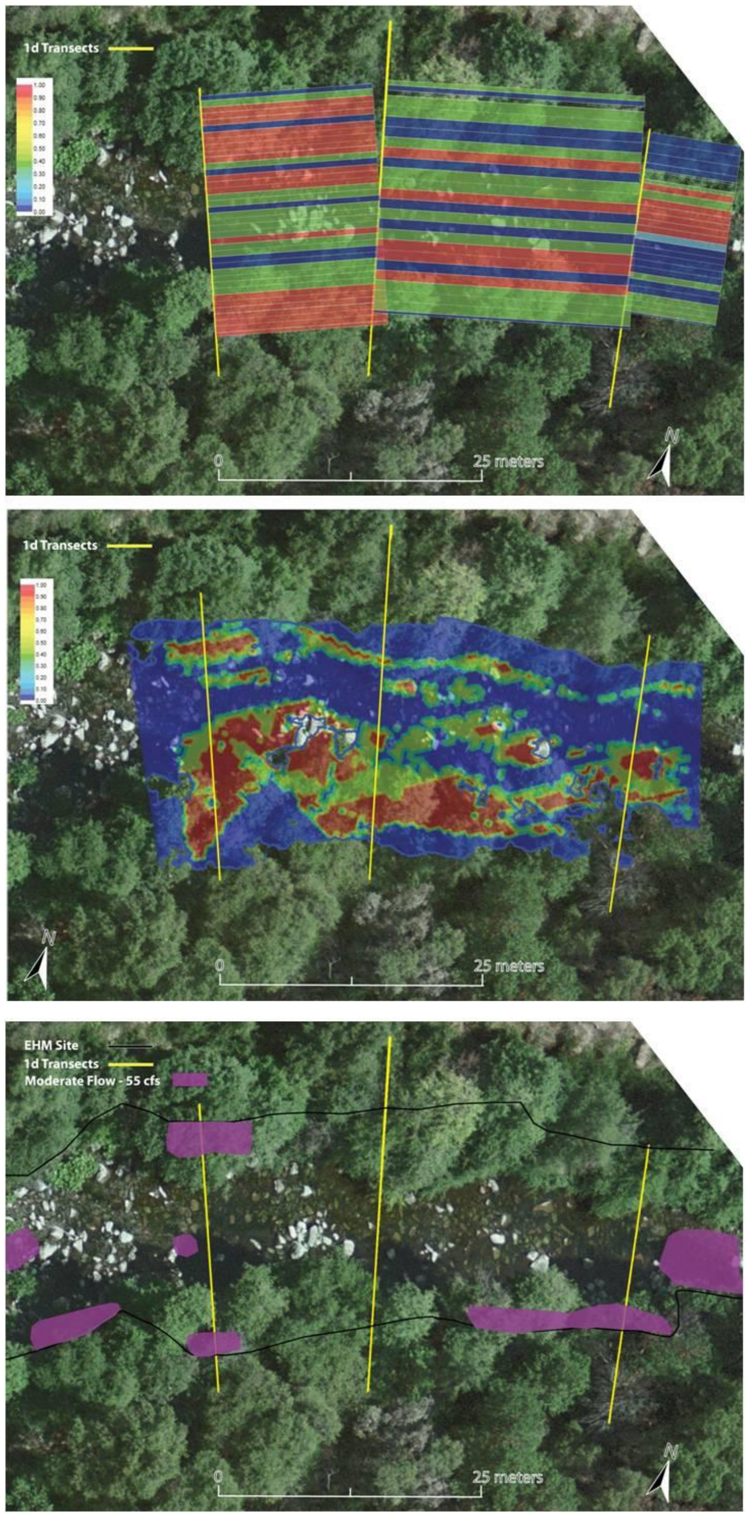
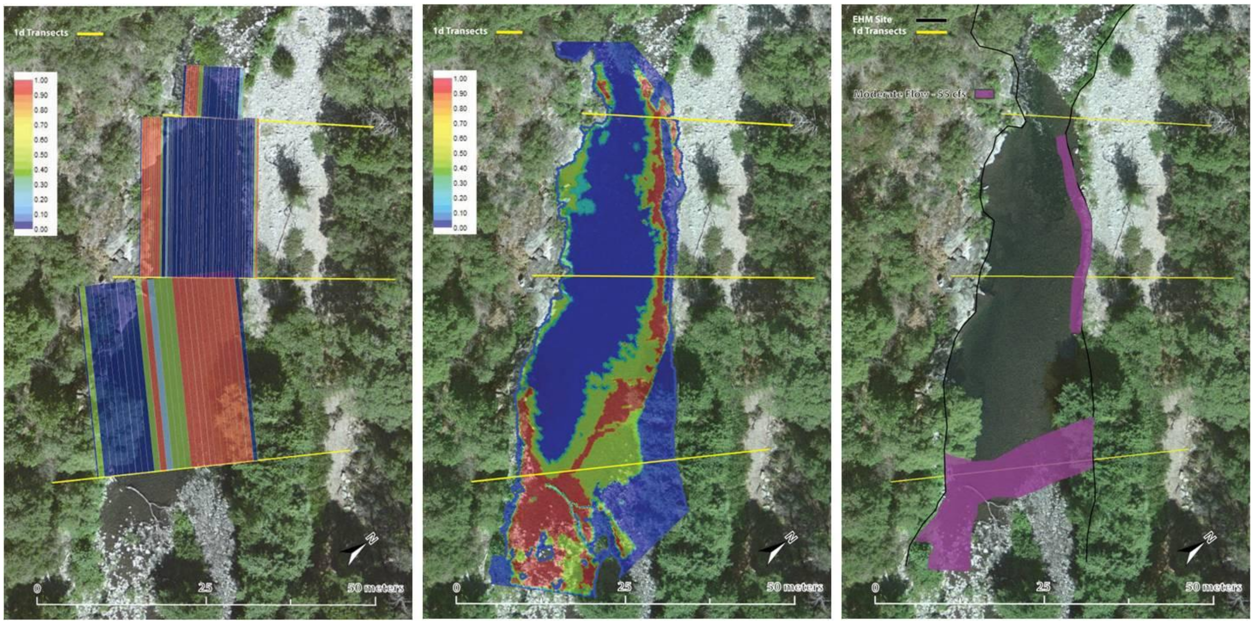


Figure 2.9 (b)



2.3.1.3 Evaluation of Effort

The effort to complete each flow assessment method at the MF 26.2 study site varied from a total of nine days for EHM to eleven days for the 1D model to twenty-five days for the 2D model. The expert habitat mapping took a total of three field days at each study site, with two days required at MF 26.2 to create the scaled hand-drawn basemap at low flow. An additional ten days were spent in the office to scan the field maps, create the visualization layers in Adobe Illustrator and determine the suitable area at each discharge. The 2D modeling effort included five days to survey the channel topography, one field day for each of three flow calibrations, five days for model calibration in the office, and five days for model simulations in the office (personal communication, J. Hammond). The 1D modeling effort had the least time invested with five fields days for three flow calibrations, five office days for model calibration and one office day for model simulation. Because this particular study site was part of a larger hydropower project relicensing, additional days were required to discuss calibration results with project stakeholders, but this additional effort was generally consistent across methods.

2.3.2 Change in Habitat Suitability – Effective Habitat

Effective habitat, those areas that remain suitable as discharge changes, generally decreased as flows decreased and previously suitable locations became too shallow; however, the extent of the effective habitat varied widely between the two hydraulic modeling methods. The 1D model produced larger weighted usable areas at each initial discharge due to the coarser resolution of the modeled cells (some cells covered tens of square-meters), and the amount of effective habitat remained higher in the 1D model than the 2D models (Tables 2.3-2.6). The rate of decrease in effective habitat was also much lower in the 1D model, and at some flows, the amount of effective habitat actually increased slightly as cells with initially low suitabilities became more suitable as discharge decreased (Figures 2.10-2.11). Using a weighted usable area approach to determine the area of effective habitat resulted in a higher sensitivity to changes in suitability, which was further emphasized in the 1D model where individual cells were very large. In the 2D models, nodes were typically associated with areas less than 0.1 m^2, so changes in suitability were not averaged across large channel areas, but varied spatially reflecting local channel conditions.

Table 2.3: Effective habitat area (measured in meters-squared) at the MF 26.2 downstream sub-site at each 1D modeled flow beginning with the maximum modeled discharge through each subsequent lower discharge to the minimum modeled discharge

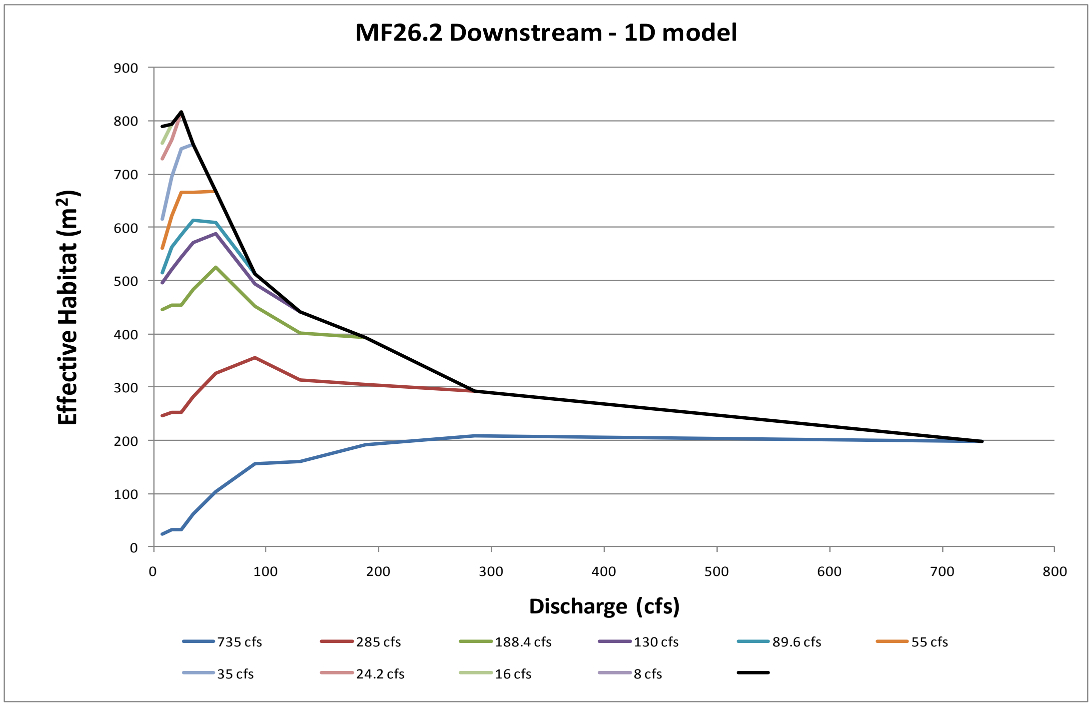
Starting Discharge (cfs)	Ending Discharge (cfs)									
	735	**285**	**188.4**	**130**	**89.6**	**55**	**35**	**24.2**	**16.6**	**8**
735	199	208	192	160	156	104	61	32	32	25
285		293	306	313	355	325	282	253	253	246
188.4			393	401	452	525	483	454	453	446
130				441	493	589	571	544	522	495
89.6					514	610	614	586	564	516
55						669	666	666	622	561
35							757	748	696	617
24.2								817	765	729
16.6									794	758
8										789

Table 2.4: Effective habitat area (measured in meters-squared) at the MF 26.2 downstream sub-site at each 2D modeled flow beginning with the maximum modeled discharge through each subsequent lower discharge to the minimum modeled discharge

Starting Discharge (cfs)	Ending Discharge (cfs)															
	935	**735**	**535**	**385**	**285**	**188.4**	**130**	**89.6**	**65**	**55**	**45**	**35**	**24.2**	**16.6**	**8**	**5**
935	34	21	14	8	5	3	2	1	1	1	0	0	0	0	0	0
735		36	25	16	12	8	5	3	2	2	2	1	1	1	0	0
535			45	33	26	20	16	13	11	10	7	6	5	4	1	1
385				55	47	39	35	31	27	26	22	19	17	12	6	5
285					69	61	55	50	46	43	38	35	31	25	15	13
188.4						126	118	111	105	101	94	87	81	70	52	47
130							211	202	194	189	179	169	159	140	113	104
89.6								285	276	269	256	243	230	204	167	156
65									355	347	332	317	301	271	229	215
55										386	370	355	337	304	259	242
45											429	413	393	355	302	284
35												450	429	390	333	313
24.2													455	414	357	336
16.6														452	388	365
8															446	419
5																446

Figure 2.10: Graphic depiction of effective habitat area (measured in meters-squared) at the MF 26.2 downstream sub-site at each (a) 1D modeled flow and (b) 2D modeled flow beginning with the maximum modeled discharge through each subsequent lower discharge to the minimum modeled discharge

(a)



(b)

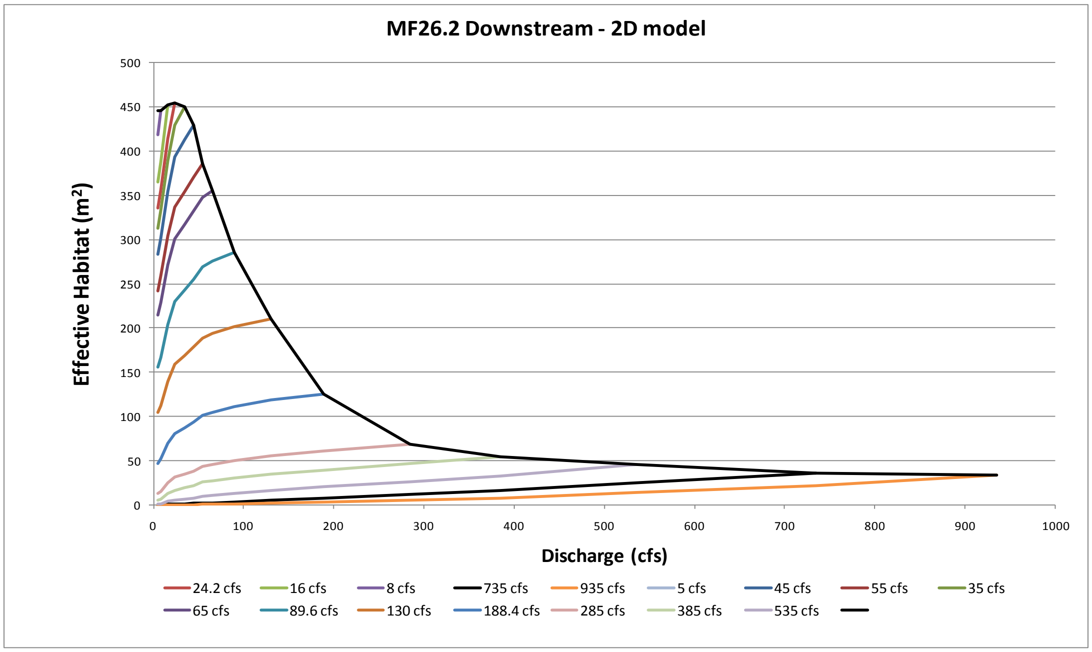


Table 2.5: Effective habitat area (measured in meters-squared) at the MF 26.2 upstream sub-site at each 1D modeled flow beginning with the maximum modeled discharge through each subsequent lower discharge to the minimum modeled discharge

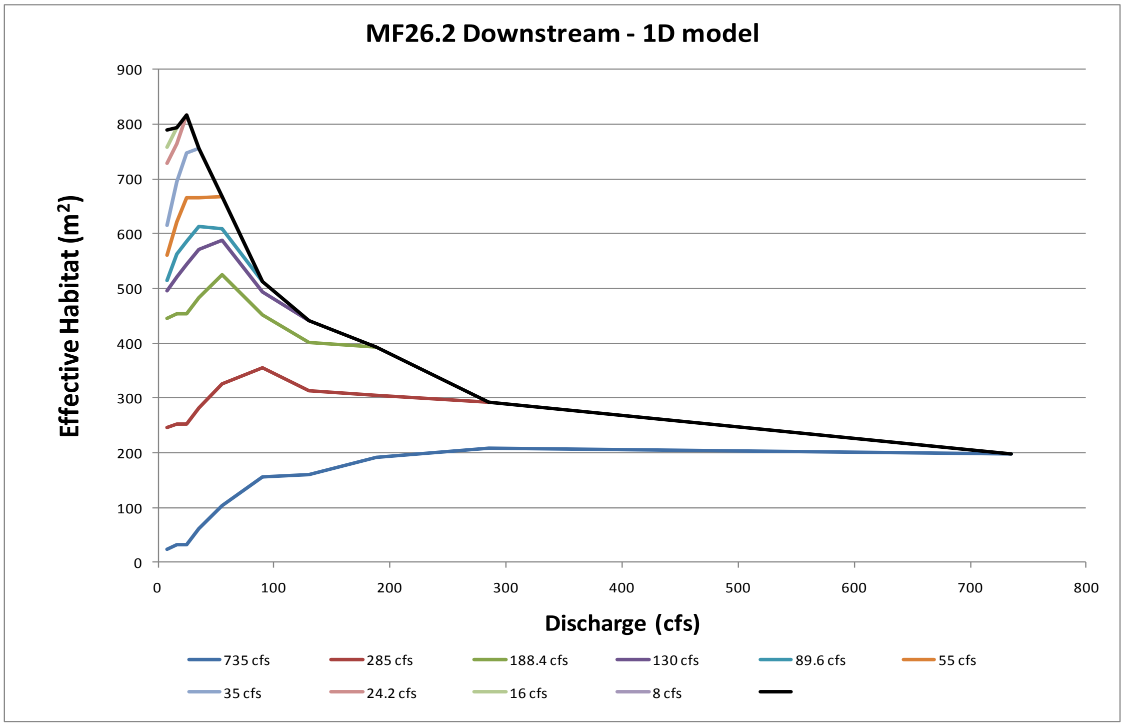
Starting Discharge (cfs)	Ending Discharge (cfs)									
	735	**285**	**188.4**	**130**	**89.6**	**55**	**35**	**24.2**	**16.6**	**8**
735	266	194	175	144	99	55	19	19	9	0
285		370	427	425	391	338	302	283	224	137
188.4			506	508	495	514	478	459	400	313
130				550	536	562	563	544	474	378
89.6					609	637	660	680	629	500
55						772	786	820	854	679
35							884	921	980	844
24.2								941	1000	888
16.6									1000	888
8										888

Table 2.6: Effective habitat area (measured in meters-squared) at the MF 26.2 upstream sub-site at each 2D modeled flow beginning with the maximum modeled discharge through each subsequent lower discharge to the minimum modeled discharge

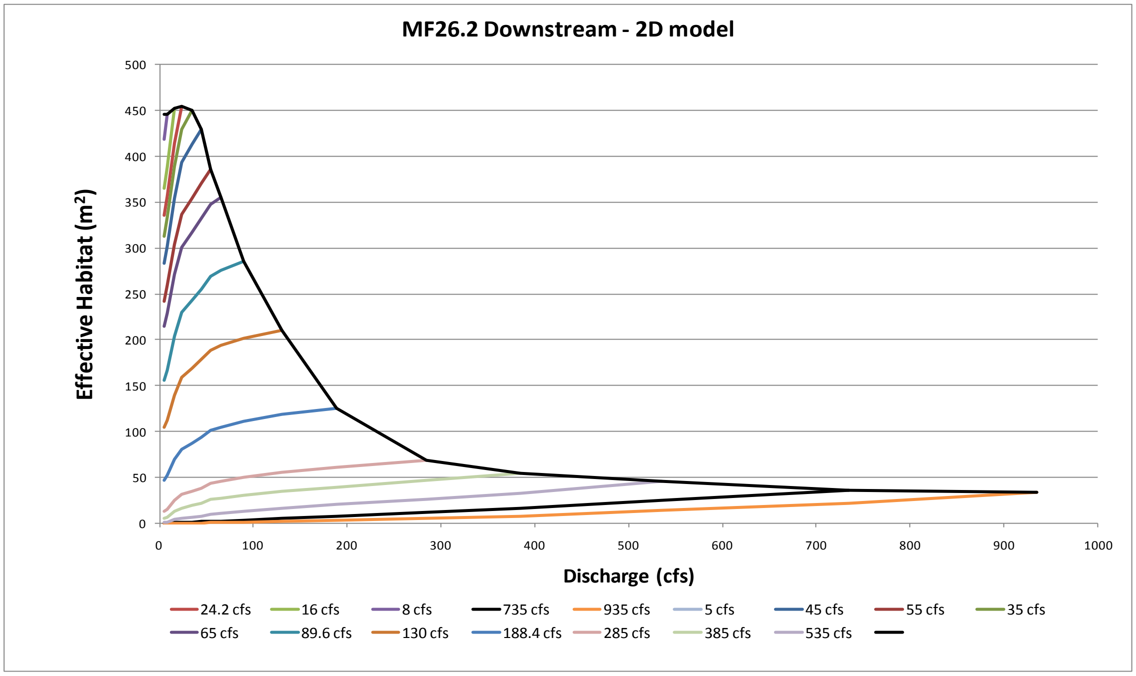
Starting Discharge (cfs)	Ending Discharge (cfs)															
	935	**735**	**535**	**385**	**285**	**188.4**	**130**	**89.6**	**65**	**55**	**45**	**35**	**24.2**	**16.6**	**8**	**5**
935	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
735		4	4	3	3	2	2	2	1	1	1	1	1	0	0	0
535			13	12	12	11	10	9	7	6	5	4	3	2	2	1
385				43	42	40	37	34	26	23	20	17	17	13	8	5
285					85	81	75	71	53	48	43	38	37	29	19	11
188.4						155	144	130	106	98	90	81	79	62	39	23
130							199	172	142	133	123	112	109	87	57	38
89.6								258	186	175	163	150	146	119	83	61
65									289	275	259	240	227	187	132	97
55										311	293	273	258	212	153	115
45											340	318	297	249	184	141
35												370	341	287	216	170
24.2													473	366	287	234
16.6														415	321	260
8															391	322
5																350

Figure 2.11: Graphic depiction of effective habitat area (measured in meters-squared) at the MF 26.2 upstream sub-site at each (a) 1D modeled flow and (b) 2D modeled flow beginning with the maximum modeled discharge through each subsequent lower discharge to the minimum modeled discharge

(a)



(b)



2.3.3 Pulse Flow Analysis

To evaluate how each hydraulic model calculated the impact of an increase in flow on suitable oviposition habitat at MF 26.2, suitable cells (1D) or nodes (2D) were tracked from 55 cfs to 130 cfs to determine the fate of their suitability. Suitable habitat at 55cfs was defined at each modeled cell or node as highly suitable (CSI > 0.66), moderately suitable (CSI = 0.33 – 0.66) or of low suitability (CSI < 0.33). Suitable cells or nodes were then tracked as flows increased to 130cfs, a high spring flow, and changes in suitability were assessed. The initial distribution of suitability at 55 cfs was similar between the two modeling methods with 2%, 50% and 48% of suitable cells classified as low, moderate and high suitability, respectively, at the upstream sub-site in the 1D model, and 2%, 47% and 51% of suitable nodes classified as low, moderate, and high suitability, respectively, in the 2D model. At the downstream sub-site the initial distribution of suitability in the 2D model was similar to the upstream sub-site (4%, 49% and 47% classified as low, moderate and high suitability, respectively), but the coarse resolution of the 1D model, with only 42 modeled cells, resulted in a higher percentage of high suitability habitat (64%) and low suitability habitat (10%), and only 26% of cells classified as moderately suitable.

When flows were increased to 130 cfs at each sub-site, the majority of low and moderately suitable habitat became unsuitable, while over 80% of the highly suitable habitat remained highly or moderately suitable at both sub-sites and in both models (Figures 2.12-2.13). Although the coarse resolution of the 1D model affected the percentage values associated with each suitability category (e.g. 100% of low suitability cells remained of low suitability in the upstream 1D model, but only 1 cell of 42 total was of low suitability), the pattern of change in suitability was similar to the changes calculated in the 2D model.

Figure 2.12: Fate of suitable habitat at the MF 26.2 *downstream* sub-site when flows were increased from 55 cfs to 130 cfs as calculated by (a) 1D modeling and (b) 2D modeling. Suitability was categorized as highly suitable (CSI > 0.66), moderately suitable (CSI = 0.33 – 0.66), of low suitability (CSI < 0.33) or unsuitable (CSI = 0)

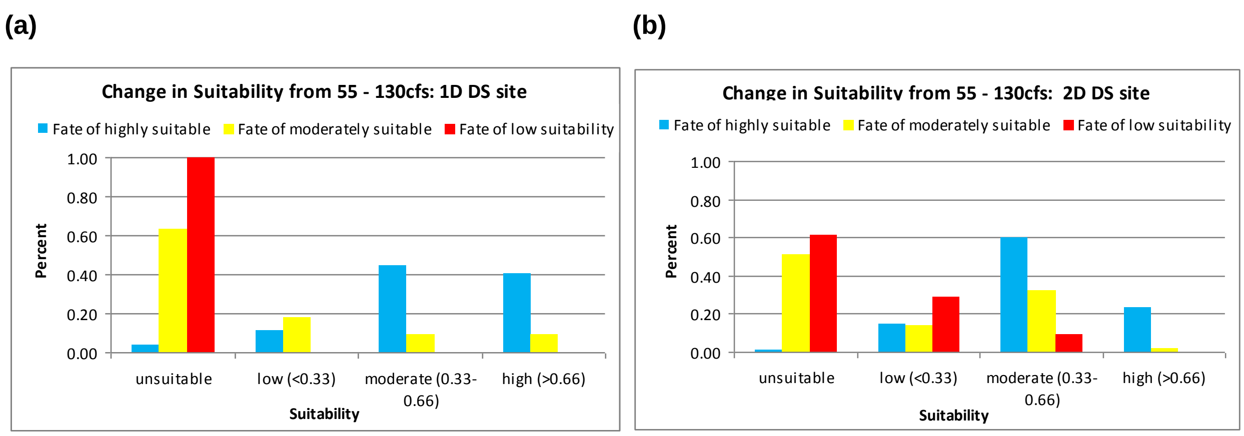
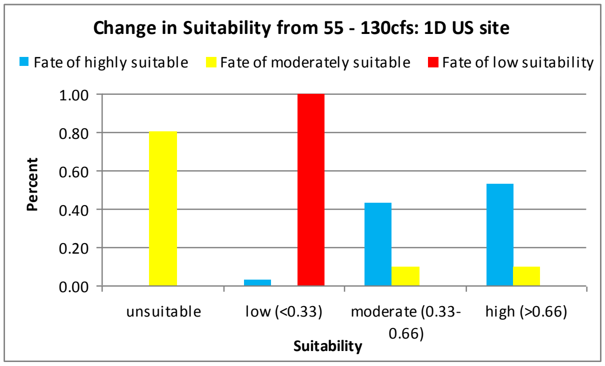
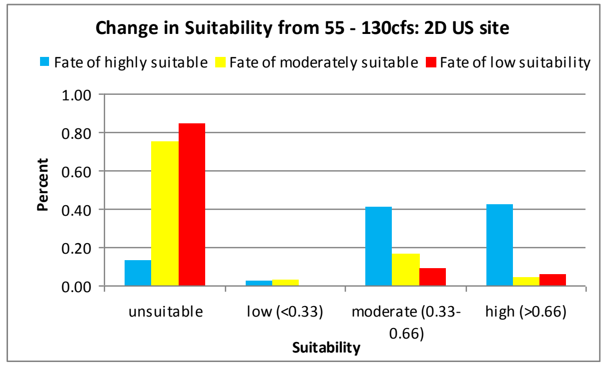


Figure 2.13: Fate of suitable habitat at the MF 26.2 *upstream* sub-site when flows were increased from 55 cfs to 130 cfs as calculated by (a) 1D modeling and (b) 2D modeling. Suitability was categorized as highly suitable (CSI > 0.66), moderately suitable (CSI = 0.33 – 0.66), of low suitability (CSI < 0.33) or unsuitable (CSI = 0)

(a)



(b)



2.4 Conclusions and Recommendations

2.4.1 Summary of Study Results

The habitat suitability results from each of the three instream flow assessment methods differed greatly at both study sites. Not only were the magnitudes of total suitable habitat area different between the methods, but at RR 3.5, the relationship between habitat area and discharge differed as well. These inconsistencies in results can largely be attributed to the assumptions associated with each method. The EHM results showed consistently lower amounts of suitable area than either of the modeling methods largely due to bias towards identification of highly suitable habitat areas. This was evidenced by the observed overlap in the EHM results and the highly suitable areas delineated by modeling (Figures 2.8-2.9). Those areas modeled as low to moderate suitability were generally not included in the EHM results. The difference in magnitude between the 1D and 2D modeling results were primarily due to the large 1D cell sizes, such that the area of suitable habitat was overestimated (Figure 2.9). Additionally, local variations in modeled velocities contributed to differences in suitability at measured cross-sections such that the 1D modeling results predicted higher local suitability at measured cross-sections (Figure 2.9b). These and other general differences between the three flow assessment methods are discussed in further detail below.

Due to modeling constraints, WUA was assessed rather than total suitable area in the effective habitat analysis. The effective habitat results were consistent with the general suitability results in that the 1D model predicted approximately twice the WUA than the 2D model. However, the relationship between habitat and discharge varied between the methods, with the 1D results showing a unimodal relationship at moderate and low discharges, while the 2D results consistently showed decreasing effective habitat as discharge decreased (Figures 2.10-2.11). Because the 1D cells were so large in area, shallow edge water habitats that were barely suitable at low discharge dominated the cell, and then became more suitable as depth initially increased. In the 2D model, these shallow edge water habitats were smaller in size and adjacent to larger areas of suitable habitat. As a result, while the small shallow edges became more suitable as depth increased, their total area was small relative to the rest of the suitable area. While it's uncertain whether similar relationships would result in an effective habitat analysis based on total suitable area rather than WUA, it's likely it would be similar due to the defined nature of effective habitat to remain stable or decrease, and thus implications for management would be similar.

In most instream flow assessments, WUA is the primary desired result used for flow management decisions. We currently lack data to relate different levels of habitat suitability to population outcomes for *R. boylii*. Thus, total suitable area was evaluated in this study under the premise that any suitable area might be used by *R. boylii*. However, results from the pulse flow analysis showed that at both study sites only those areas of high suitability remained moderately or highly suitable as discharge increased (Figures 2.12-2.13). Most low and moderately suitable areas became unsuitable, suggesting high suitability areas, where all of the three hydraulic variables are highly suitable, were most hydraulically stable. Hydraulic stability can increase the likelihood egg masses and tadpoles will reach maturity, and thus is a key component in successful reproduction (Kupferberg, 1996; Kupferberg et al., 2009a). Therefore, while total suitable area at any given flow is an important consideration for *R. boylii*, analyses of change in discharge may be equally informative whether they incorporate total usable area or WUA.

2.4.2 Discussion of Instream Flow Assessment Methods

There is extensive literature regarding the differences, assumptions and errors inherent to habitat modeling methods, particularly 1D models such as PHABSIM and 2D models such as River2D (Williams, 1996; EPRI, 2000; Kondolf et al., 2000; Gard, 2009). The most commonly cited critiques of each method for fish studies are equally applicable to studies of *R. boylii* habitat. Namely that 1) the hydraulic model does not accurately represent the spatial variability within a stream reach, 2) the hydraulic model does not accurately simulate how hydraulic conditions vary with flow, 3) there is a lack of appropriate spatial resolution between the hydraulic model and the habitat models (HSC), 4) hydraulically-based HSC do not adequately represent the full range of instream habitat requirements for a species, and 5) changes in WUA do not have useful biological meaning and therefore are not of sufficient importance to aquatic populations to be useful for instream flow decisions. These criticisms are discussed in the context of this study below.

The most common critique of habitat modeling, and 1D modeling in particular, centers on the coarse spatial resolution of the hydraulic model. When a limited number of cross-sections are chosen to represent an entire river reach, the placement of those cross-sections becomes a determining factor in the modeling results (Williams, 2010). Particularly in complex channel habitats that have a high degree of spatial variability, extrapolation between cross-sections can grossly over- or under-estimate the actual amount of suitable habitat. As shown in this study, the amount of suitable habitat calculated by the 1D model was twice that of the 2D model due to the long length of cross-section cells, and the 1D modeled suitable habitat extended well beyond those areas observed to be suitable (Figure 2.9). The simplest solution to this problem is to increase the number of cross-sections so that longitudinal variations are accounted for. However, as the number of cross-sections increases, the time and cost of the modeling effort increases, to a point where it is simply more efficient to use a 2D model. For *R. boylii*, the diversity of available hydraulic conditions that accompanies highly diverse topographic conditions can be beneficial to successful reproduction, and it’s common for higher densities of individuals to be located in channels of high complexity (Yarnell, 2005). By definition, a 2D model directly addresses this concern by accounting for spatial variation both laterally and longitudinally, and thus can more accurately represent these highly important complex habitat areas than traditional 1D models. In areas where the channel habitat is simple and varies little in the longitudinal direction, such as a straight gravel-bedded run, a 1D model can perform similarly to a 2D model without the added time and cost (EPRI, 2000; Gard, 2009); however, whether these areas are of relevance to *R. boylii* will depend on the stream system and professional opinion.

Whether channel habitats are complex or simple, natural hydraulic conditions vary over time, and particularly as flows fluctuate, resulting in error in hydraulic modeling results. While the empirical nature of a 1D model, based on measured velocities and depths at cross-sections, creates confidence in the hydraulic conditions at the measured flows, flow simulations can be highly subject to error particularly in complex channels where the velocity distribution changes as flows change. Furthermore, while the measured conditions create confidence in the determined habitat suitability at the cross-section, the lack of measured data between cross-sections and the resulting coarse extrapolation produces a high degree of velocity prediction error in channel locations with spatially variable channel conditions. This can present a significant problem in evaluating *R. boylii* breeding and rearing habitat, which commonly is located in complex channel areas where sub-meter scale velocity shelters are important refugia from fluctuating flows (Yarnell, 2005). 2D models are better able than 1D models to represent velocity conditions at various flows due in part to the physical-basis of the model (velocity is calculated not estimated from a regression) and in part to the greater resolution of the modeled area; however, the depth-averaged results from a 2D model still cannot account for the small-scale vertical velocity variations that occur in streams and can provide flow refugia for egg masses and tadpoles. Generally, the immediately surrounding habitat conditions will be reflective of the low velocity conditions preferred for breeding and rearing, and as long as the resolution of the 2D model is sufficient to minimize mid-column velocity error, 2D model predictions will reflect general habitat preferences (Yarnell et al., 2010).

Issues with spatial resolution extend to the scale of the habitat models as well as the hydraulic models. For fish, HSC are commonly derived from point-based observations of fish during snorkel surveys, while hydraulic models can represent habitat areas of one meter-square to several tens of meters-squared in 1D models. Criticisms of whether the hydraulic conditions observed at a fish in a sub-meter habitat area are adequately represented by an average depth and velocity from a ten meter cross-section cell are valid. The same issue is of concern for *R. boylii*, particularly as the relatively little research completed on *R. boylii* HSC has focused on the point hydraulic conditions at an egg mass or tadpole, each of which are less than 10cm in size (Lind and Yarnell, 2008; Chapter 1 of this report). Predictions of habitat suitability under such a discrepancy in scale can lead to large differences is predicted habitat area, as observed with the 1D modeling results in this study (Table 2.2). Cross-section cells located along the edges of the runs in MF 26.2 were often designated as unsuitable due to higher average velocities in the larger cells, while small pockets of suitable habitat were observed at the finer scale of the 2D model (Figure 2.9). The spatial resolution of the 2D model at 0.1-0.5 m^2 more accurately matches the scale of resolution in which the HSC were developed (see Chapter 1).

Criticisms of habitat models often extend to their primary assumption that modeling habitat based on hydraulic conditions alone, specifically depth, velocity and substrate, will adequately reflect the habitat needs of a particular species. This criticism is not only valid for many species of fish (Parasiewicz and Dunbar, 2001; Landcaster and Downes, 2010), but is valid for *R. boylii* as well. Many studies on the life history requirements of *R. boylii* have shown the importance of multiple habitat factors at multiple spatial scales for successful populations (Van Wagoner, 1996; Kupferberg, 1996; Lind, 2005; Yarnell, 2005; Peek, 2010 among others); however, the potentially negative impacts from adverse flow conditions have been shown to be so critical to individual survival that an evaluation of instream flow conditions is an important component of protection and conservation for *R. boylii* (Lind and Yarnell, 2007; Kupferberg et al., 2009a). Hydraulic habitat modeling should simply be considered one aspect of a wider assessment of habitat needs.

The concept of WUA has been debated in the scientific literature as to its relevance for instream flow determinations (Orth, 1987; Zorn and Seelbach, 1995). In the simplest sense, it does provide a measure of the total amount of suitable habitat within a reach, which can be important for species that have been shown to be habitat-limited (Gard, 1998; Gutreuter, 2004). However, for many aquatic species, *R. boylii* included, instream habitat is not limited as there is an abundance of habitat available beyond what they typically use (see results and conclusions and recommendations in Chapter 1). In this instance, the importance of WUA, or total suitable area as calculated in this study, is diminished in favor of other analyses more relevant to the known adverse effects of a certain flow regime. For *R. boylii*, changes in flow conditions during the breeding and rearing season can result in scour, stranding or displacement, each of which has a negative effect on population dynamics (Kupferberg et al., 2009a; Kupferberg et al., 2009b). As a result, other examples of flow impact analyses that can be completed with habitat modeling were included in this study, such as an effective habitat analysis and a pulse flow analysis. In most management applications, particularly for flow recommendations in relicensing, these types of analyses will provide more relevant information for *R. boylii* conservation than a simple WUA calculation.

The primary advantage of the qualitative EHM method is that these five common criticisms of habitat modeling are simply not applicable. EHM can assess complex habitats where modeling might be inaccurate, it can assess longer stream reaches than typical modeling, it can incorporate conceptual models or additional habitat components beyond simple hydraulic habitat conditions, and it can include consideration of specific aquatic resources as well as multiple aquatic species and their lifestages (EPRI, 2000; Railsback & Kadvany, 2008). While these aspects offer a significant advantage over traditional 1D modeling techniques, many of these advantages also apply to 2D models (Gard, 2009). As technology, computer processing and field survey techniques improve over time, the ability to develop a large-scale (kilometers of stream length) highly accurate 2D model that can incorporate multiple species preferences also increases (e.g. PCWA, 2010). To overcome the lack of predictive ability and limit the assumptions of habitat response between observed flows inherent to EHM, a large number of flows must be observed and mapped to adequately represent the variability in flow conditions. The time and cost of such an intensive field effort and the water cost of the various demonstration flows can significantly reduce the affordability of EHM in comparison to 2D models. Additionally, for *R. boylii* studies specifically, the limited data provided by EHM and the inability to evaluate to what degree hydraulic conditions change as flows fluctuate is a significant disadvantage. While there are undoubtedly situations where flow assessment needs for *R. boylii* can be met by EHM, instream flow assessments of *R. boylii* habitat in typical hydropower relicensing situations with complex considerations are best met by a 2D model-based approach.

2.4.3 Recommendations

In general, the study results indicated that while more time-consuming, 2D modeling provided higher resolution data that could be used to answer a wider variety of questions pertinent to the assessment of managed flow regimes for *R. boylii* (Table 2.7). None of the three methods were able to address issues at the larger river segment scale, as each evaluated conditions at the local reach scale under the assumption that the modeled reach was representative of the river as a whole. Although habitat factors other than flow conditions are important for maintaining successful *R. boylii* populations (Lind and Yarnell, 2008), the potentially negative impacts from adverse flow conditions warrant the use of these instream flow assessment methods in managed rivers.

Table 2.7: Comparison of instream flow assessment methods for evaluation of *R. boylii* habitat. *Accuracy* represents how well the method reproduced observed field conditions. *Subjectivity* is the degree of user bias. *Prediction Capability* is the ability to predict beyond observed flows. *Scale of Resolution* represents how fine the method delineated habitat spatially. *Field/Office Time* is the number of person-hours. *Extent of Data Provided* represents the variety of data provided from which to address questions of interest

	Expert Habitat Mapping	1D habitat modeling	2D habitat modeling
Accuracy	Moderate	Low	High
Subjectivity	High	Moderate	Low
Prediction Capability	Low	Moderate	High
Scale of Resolution	Moderate	Moderate	High
Field Time	Moderate – High[1]	Moderate	Moderate
Office Time	Low – Moderate[1]	Moderate	High
Extent of Data provided	Low	Moderate	High
Questions Addressed	Usable Area; Connectivity	Usable Area; Stage changes	Usable Area; Connectivity; Stage changes; Velocity changes
Pros	• Modeling expertise not required • Option to include non-flow related habitat aspects or conceptual models • Ability to evaluate complex habitat and longer reaches	• Often completed for fish studies • Can identify trends in habitat suitability	• Extensive results provided • Highly objective • Fine spatial resolution increases accuracy and precision • Scales of resolution between hydraulic and habitat models match
Cons	• Species expertise required • Minimal predictive capability • Highly subjective • Limited results provided	• Field expertise for picking transects and modeling expertise required • Coarse spatial resolution limits accuracy and precision • Scale of resolution in hydraulic model does not match scale of resolution for HSC	• Modeling expertise required • Data intensive • Expensive

[1]Depends on number of flows observed

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