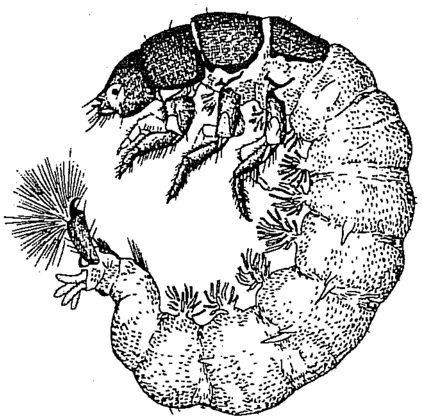
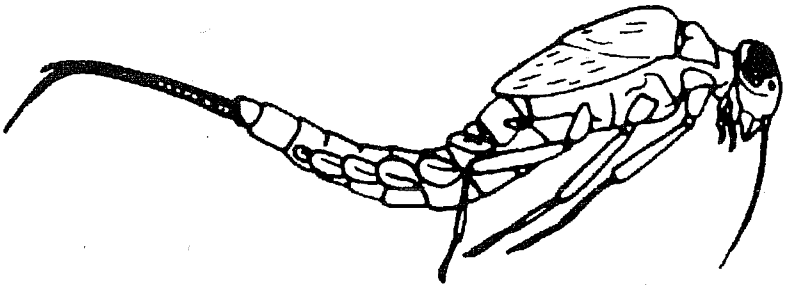
FLOW-HABITAT RELATIONSHIPS FOR MACROINVERTEBRATES IN THE SACRAMENTO RIVER BETWEEN KESWICK DAM AND BATTLE CREEK





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CVPIA INSTREAM FLOW INVESTIGATIONS
SACRAMENTO RIVER BETWEEN KESWICK DAM TO BATTLE CREEK
MACROINVERTEBRATE HABITAT

PREFACE

The following is the final report for the U. S. Fish and Wildlife Service's investigations on macroinvertebrate habitat in the Sacramento River between Keswick Dam and Battle Creek. These investigations are part of the Central Valley Project Improvement Act (CVPIA) Instream Flow Investigations, a 7-year effort which began in February, 1995. Title 34, Section 3406(b)(1)(B) of the CVPIA, P.L. 102-575, requires the Secretary of the Interior to determine instream flow needs for anadromous fish for all Central Valley Project controlled streams and rivers, based on recommendations of the U. S. Fish and Wildlife Service after consultation with the California Department of Fish and Game (CDFG). The purpose of these investigations are to provide scientific information to the U. S. Fish and Wildlife Service Central Valley Project Improvement Act Program to assist in developing such recommendations for Central Valley rivers.

Written comments or questions about this report or these investigations should be submitted to:

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ACKNOWLEDGMENTS

The field work for this study was conducted by Ed Ballard, Mark Gard, Erin Sauls, Jerry Big Eagle, Bob Null, Rich DeHaven, Elizabeth Irwin, Larry Thompson, Dan Buford and Rick Williams. Jerry Big Eagle, Levi Lewis and Kim Turner conducted initial analysis of a third of the samples, separating macroinvertebrates from detritus. The remaining portion of the sample analysis was conducted by Environmental Services and Consulting, LLC. Data analysis and report preparation were performed by Mark Gard. Funding was provided by the Central Valley Project Improvement Act.

ABSTRACT

Flow-habitat relationships for the Sacramento River between Keswick Dam and Battle Creek were derived for three macroinvertebrate community metrics. One of the metrics (biomass of Baetids, Chironomids and Hydropsychids) was selected to represent food supply for juvenile salmonids, while the other two metrics (total biomass and diversity) were selected as measures of ecosystem health. Habitat suitability criteria were developed using data from 75 macroinvertebrate samples stratified by season, mesohabitat type, depth, velocity and substrate. The criteria for depth, velocity and substrate were developed taking into account several potential confounding variables, and using a polynomial regression for depth and velocity, and analysis of variance for substrate (a categorical variable). The criteria showed no effect of substrate on Baetid/Chironomid/Hydropsychid biomass or diversity, but indicated a higher suitability for larger cobbles, versus other substrates, for total biomass. The optimum depths for Baetid/ Chironomid/Hydropsychid biomass, total biomass and diversity were, respectively, 2.7 to 2.8 feet, 2.0 to 2.2 feet and 3.8 to 3.9 feet. The optimum velocities for Baetid/Chironomid/ Hydropsychid biomass, total biomass and diversity were, respectively, 2.4 to 2.6 feet/sec, 2.0 to 2.2 feet/sec, and 2.0 to 2.4 ft/s. The flow with the maximum habitat varied by reach, and ranged from 3,250 cfs to 6,000 cfs for all three macroinvertebrate metrics. We were able to successfully develop criteria for all three macroinvertebrate metrics while taking into account potentially confounding factors, so that the factors did not obscure nor did they cause the relationships that we derived between the macroinvertebrate metrics and depth, velocity and substrate. Suggestions for development of future macroinvertebrate criteria for instream flow studies include: 1) stratifying sampling by depth, velocity and substrate; 2) measuring the amount of organic matter in samples for use as an additional potential confounding factor; and 3) sampling a large area (9 square feet) with a sampler with a rubber foam lining on the bottom of the sampler. This study supported and achieved the objective of producing models predicting the hydraulic and structural characteristics of sites for macroinvertebrates in the Sacramento River between Keswick Reservoir and Battle Creek over a range of streamflows.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

In response to substantial declines in anadromous fish populations, the Central Valley Project Improvement Act provided for enactment of all reasonable efforts to double sustainable natural production of anadromous fish stocks including the four races of Chinook salmon (fall, late-fall, winter, and spring runs), steelhead, white and green sturgeon, American shad and striped bass. For the Sacramento River, the Central Valley Project Improvement Act Anadromous Restoration Plan calls for October through April flows ranging from 3,250 to 5,500 cfs, with the recommended flow varying with the October 1 carryover storage in Shasta Reservoir (U. S. Fish and Wildlife Service 1995). In December 1994, the U. S. Fish and Wildlife Service prepared a study proposal to identify the instream flow requirements for anadromous fish in certain streams within the Central Valley of California, including the Sacramento River. The purpose of this report is to produce models predicting the hydraulic and structural characteristics of sites for macroinvertebrates in the Sacramento River between Keswick Reservoir and Battle Creek over a range of streamflows. Macroinvertebrates were selected as a measure of food abundance for juvenile salmonids, as well as an indicator of ecosystem health. The macroinvertebrate criteria were run on juvenile salmonid rearing site habitat models to predict the relationship between flow and macroinvertebrate biomass and diversity.

Habitat suitability criteria for use in instream flow studies have been developed previously (Gore et al. 2001). Most of the previous macroinvertebrate habitat suitability criteria have been developed for individual taxa (Morin et al. 1986, Jowett et al. 1991, Wills et al.2006). The use of curves for individual taxa in instream flow studies can be problematic - if curves are run for many species with different flow-habitat relationships, it is unclear how to choose which curve to use. Gore et al (2001) present habitat suitability criteria for macroinvertebrate community diversity, noting that the evaluation of macroinvertebrate communities in instream flow studies is warranted because of the critical role of aquatic invertebrates in the processing of nutrients and organic energy in lotic systems and the increased emphasis on multi-species conservation. Gore et al (2001) found that the bottleneck in a North Carolina stream was macroinvertebrate, rather than fish, habitat. Macroinvertebrate instream flow studies are needed for two reasons: 1) community-based criteria, such as with macroinverebrates, are a better measure of ecosystem health than single-species habitat suitability criteria; and 2) if food rather than physical habitat is the limiting factor for juvenile salmonids, it is better to set flows based on macroinvertebrate habitat than juvenile habitat. More macroinvertebrate habitat results in more food for juveniles, which increases juvenile growth rates, and thus higher survival when juveniles reach salt water.

The range of Sacramento River flows to be evaluated for management generally falls within the range of 3,250 cfs (the minimum required Sacramento River flow) to 15,000 cfs (the maximum generating capacity at Keswick Dam). Accordingly, the range of study flows encompasses the range of flows to be evaluated for management. The assumptions of this study are: 1) that invertebrates adjust to flows in 30 days; and 2) that invertebrates may be affected by season (early July and mid-fall), mesohabitat type, picker, depth, velocity and substrate.

METHODS

A 2-dimensional hydraulic and habitat model (RIVER2D) was used for this modeling, instead of the Physical Habitat Simulation (PHABSIM[1]) component of the Instream Flow Incremental Methodology (IFIM). 2-D model inputs include the bed topography and bed roughness, and the water surface elevation at the downstream end of the site. The amount of habitat present in the site is computed using the depths and velocities predicted by the 2-D model, and the substrate and cover present in the site. The 2-D model avoids problems of transect placement, since data is collected uniformly across the entire site. The 2-D model also has the potential to model depths and velocities over a range of flows more accurately than PHABSIM because it takes into account upstream and downstream bed topography and bed roughness, and explicitly uses mechanistic processes (conservation of mass and momentum), rather than Manning's Equation and a velocity adjustment factor (Leclerc et al. 1995). Other advantages of 2-D modeling are that it can explicitly handle complex hydraulics, including transverse flows, across-channel variation in water surface elevations, and flow contractions/expansions (Ghanem et al. 1996, Crowder and Diplas 2000, Pasternack et al. 2004). With appropriate bathymetry data, the model scale is small enough to correspond to the scale of microhabitat use data with depths and velocities produced on a continuous basis, rather than in discrete cells. The 2-D model, with compact cells, should be more accurate than PHABSIM, with long rectangular cells, in capturing longitudinal variation in depth, velocity, substrate and cover. The 2-D model should do a better job of representing patchy microhabitat features, such as gravel patches. The data can be collected with a stratified sampling scheme, with higher intensity sampling in areas with more complex or more quickly varying microhabitat features, and lower intensity sampling in areas with uniformly varying bed topography and uniform substrate. Bed topography and substrate mapping data can be collected at a very low flow, with the only data needed at high flow being water surface elevations at the up- and downstream ends of the site and flow and edge velocities for validation purposes. In addition, alternative habitat suitability criteria, such as measures of habitat diversity, can be used.

Study Site Selection, Transect Placement (study site setup), Hydraulic and Structural Data Collection and Hydraulic Model Construction and Calibration

We have divided the Sacramento River study area into six stream segments (Figure 1), based on hydrology and other factors: Grimes to Colusa (Segment 1); Deer Creek to Red Bluff Diversion Dam (Segment 2); above Lake Red Bluff to Battle Creek (Segment 3); Battle Creek to Cow Creek (Segment 4); Cow Creek to ACID (Segment 5); and ACID to Keswick Dam (Segment 6). This report addresses a total of 17 sites in Segments 4 to 6. Details on study site selection, transect placement (study site setup), hydraulic and structural data collection and hydraulic model construction and calibration are given in U.S. Fish and Wildlife Service (2005).

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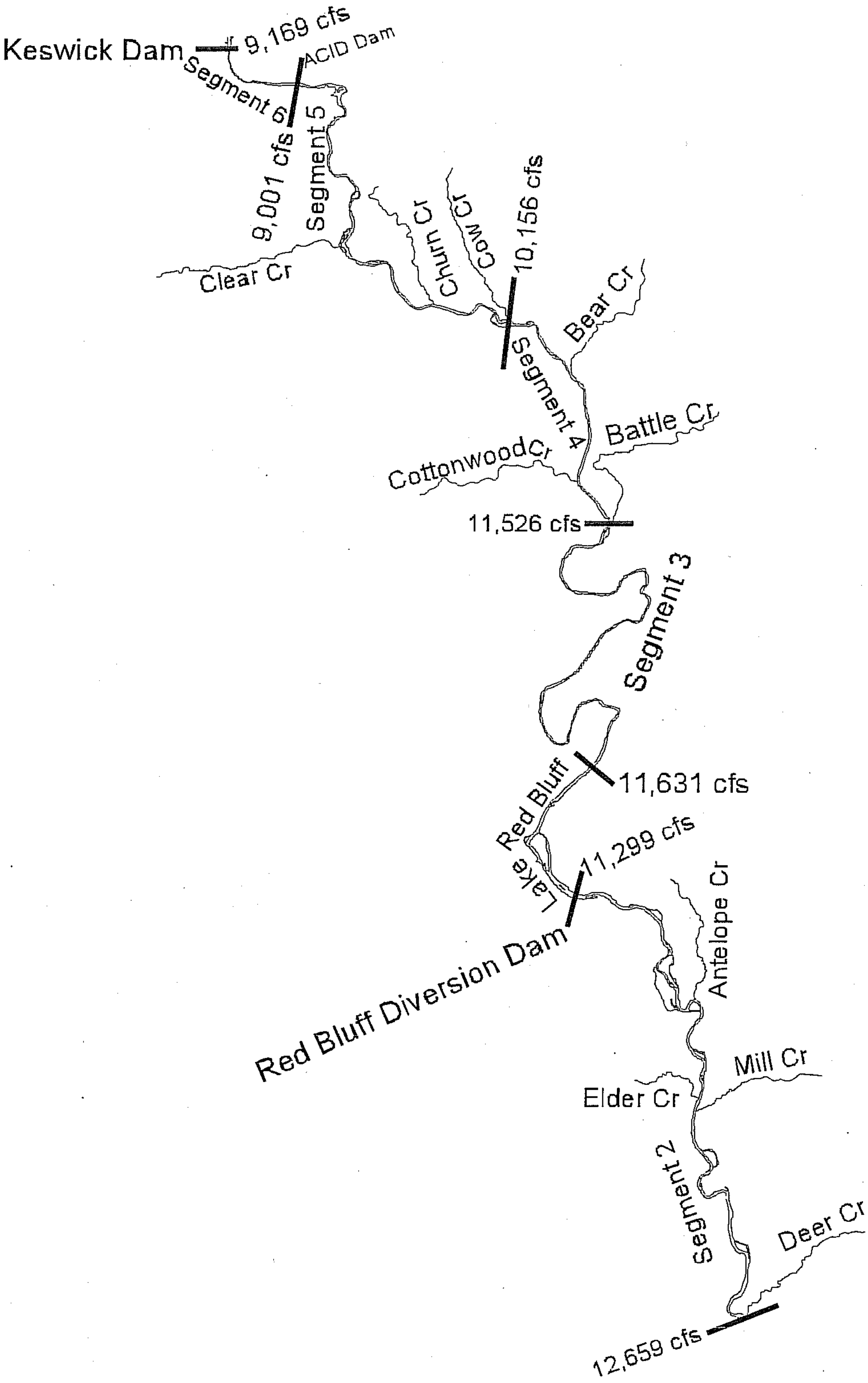
[1] PHABSIM is the collection of one dimensional hydraulic and habitat models which are used to predict the relationship between physical habitat availability and streamflow over a range of river discharges.

Figure 1. Sacramento River stream segments. Flows are the average flows for the period October 1974 to September 1993 at the top of each segment.



Habitat Suitability Criteria Development

Habitat suitability criteria (HSC) are used within both PHABSIM and 2-D habitat modeling to translate hydraulic and structural elements of rivers into indices of habitat quality (Bovee 1986). The collection of macroinvertebrate HSC data began in July 1999 and was completed in January 2001. To eliminate potential effects on the macroinvertebrate population due to changes in flow, our goal was to have at least 30 days of stable discharge from Keswick Dam prior to sample collection. We were unable to sample from August to October 1999, December 1999 to July 2000, and from September to October 2000 due to varying flows.

Our sampling plan included stratifying our sampling by season, mesohabitat type, depth, velocity and substrate. Specifically, for each 2-week sampling period, we attempted to collect one sample in each combination of 1-foot increments of depth (up to 4 feet), 1-foot/sec increments of velocity (up to 4 feet/sec) and five ranges of substrate size, and to collect equal numbers of samples in riffle, run, glide and pool mesohabitat types. We also attempted to have one sampling period every 3 months. However, frequent fluctuations of Keswick Dam releases during most of the year typically only leaves two periods which have relatively constant flows for 30 days: mid-summer, typically starting around early July; and mid-fall, typically starting around early October. Thus the only times suitable for sampling were typically in mid-August and mid-November. However, relatively constant flows from Keswick Dam extended into the winter of 2000-2001, allowing additional sampling to occur in December 2000 and January 2001.

Sampling sites were selected based on the above stratification protocol with a tag placed at the sampling location. Before a sample was collected, the depth and mean column velocity at the sampling site were measured and the substrate size (Table 1) noted.

We constructed a customized macroinvertebrate Surber sampler to use in this effort. The sampler was used to collect macroinvertebrates from a 9-square-foot area. The sampler was 4 feet high, so it could be used to sample areas with depths up to 4 feet. The sampler consisted of a steel-rod frame with fine-mesh seine material on the sides and brackets for a detachable net on the back. The net had a 3 foot x 4 foot opening, a mesh size of 600 μm, and was mounted on a rectangular 3 foot x 4 foot steel frame. The bottom of the sampler had a rubber foam lining to provide a tight seal with the substrate when the sampler was pressed down to the river bottom. The sampler required three individuals - one to hold the sampler in place, and the other two individuals to clean off rocks within the 9-square-foot area, with the current carrying the macroinvertebrates into the net. Rocks were cleaned to a depth of 4-6 inches. Bedrock was cleaned with a 3 inch x 6 inch scrub brush, while rocks were picked up and cleaned underwater by rubbing with neoprene gloves. Sites less than 3 feet deep were sampled by two individuals with snorkel gear, while sites over 3 feet deep were sampled by one individual with scuba gear. After sampling was completed, the net was detached from the sampler, the macroinvertebrates in the net were washed into the cod end of the net and then transferred to jars with 70% alcohol for transport back to the lab for analysis.

Table 1. Substrate codes, descriptors and particle sizes.

Code	Type	Particle Size (inches)
0.1	Sand/Silt	< 0.1
1	Small Gravel	0.1 - 1
1.2	Medium Gravel	1 - 2
1.3	Medium/Large Gravel	1 - 3
2.3	Large Gravel	2 - 3
2.4	Gravel/Cobble	2 - 4
3.4	Small Cobble	3 - 4
3.5	Small Cobble	3 - 5
4.6	Medium Cobble	4 - 6
6.8	Large Cobble	6 - 8
8	Large Cobble	8 - 10
9	Boulder/Bedrock	> 12
10	Large Cobble	10-12

Fish and Wildlife Service staff conducted the initial processing of one third of the samples, separating macroinvertebrates from detritus. The remaining processing of the samples, including sorting, identification and enumeration of taxa and measurement of biomass (ash-free dry weight) of Baetidae, Chironomidae, Hydropsychidae, and all remaining taxa, was conducted by Environmental Services and Consulting, LLC (ESC), under contract to the U.S. Fish and Wildlife Service. We developed three metrics for the macroinvertebrate data to use in deriving HSC: 1) Shannon Diversity Index (Zar 1994); 2) combined ash-free dry weight (AFDW) of Baetidae, Chironomidae and Hydropsychidae[2]; and 3) total AFDW of macroinvertebrates.

The first step in developing the HSC was to determine if there were significant correlations between depth, velocity and substrate size. Kolmogorov-Smirnov one sample tests (SYSTAT 2002) were then used to determine if the Shannon Diversity Index (diversity),

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[2] These three taxa were chosen because they are the dominant taxa present in stomach contents samples of Sacramento River juvenile chinook salmon (Saiki et al. 2001).

Baetid/Chironomid/Hydropsychid (BCH) AFDW and total AFDW were normally distributed or if they could be transformed to be normally distributed via a logarithmic or square root transformation.

Three potentially confounding categorical variables were identified: 1) picker (whether samples had been initially processed by U. S. Fish and Wildlife Service staff or by ESC); 2) mesohabitat type (with four levels: riffle, run, pool or glide); and 3) sampling week (with four levels: July 1999, November 1999, August 2000, and November 2000-January 2001). Kruskal-Wallis One-Way Analysis of Variance (SYSTAT 2002) was used to test if these confounding variables had a significant effect on diversity, BCH AFDW and total AFDW. In cases where there was a significant effect of one or more confounding variables on a HSC metric, a general linear model (SYSTAT 2002) was tested with terms consisting of the confounding variable(s) and D, D^2, D^3 and D^4, where D is depth or velocity or of terms consisting of the confounding variable(s) and substrate code (as a categorical variable). If there was no significant effect of the confounding variable(s) in the general linear model, the confounding variable(s) were dropped from the analysis. In these cases, substrate HSC were developed for each macroinvertebrate metric using one-way analysis of variance (SYSTAT 2002), or t-tests were the substrate categories were merged into two groups.

For cases in which the confounding variable(s) were dropped from the analysis, depth and velocity HSC for each macroinvertebrate metric were derived using a polynomial regression (SYSTAT 2002), with dependent variable diversity, BCH AFDW or total AFDW, and independent variable depth or velocity. The regression fit the data to the following expression:

$$\text{Metric} = I + J * V + K * V^2 + L * V^3 + M * V^4$$

where metric was diversity, BCH AFDW or total AFDW; I, J, K, L, and M are coefficients calculated by the regression; and V is velocity or depth. The regressions were conducted in a sequential fashion, where the first regression tried was a fourth order regression with all terms. If any of the coefficients or the constant were not statistically significant at $p = 0.05$, the term with the highest p value was dropped from the regression equation, and the regression was repeated, until a regression was arrived at for which all terms had $p < 0.05$.

Where the confounding variable(s) were significant in the general model, two different approaches were taken to incorporate these variables into the subsequent development of depth and velocity HSC: 1) an adjusted metric was used in the polynomial regression, calculated as the original metric minus the average metric for each level of the confounding variable plus a constant; and 2) additional terms consisting of design variables for each level of the confounding variable, where the design variable had a value of one for a given level of the confounding variable and a value of zero for all other levels of the confounding variable, were incorporated into the polynomial regression. A value of the constant for the first technique was selected so that there would not be any negative values of the adjusted metric. The results of the regression equations were rescaled so that the highest value was 1.0, and were truncated at the upper end where the value of the regression reached zero.

Habitat Simulation

The final step was to simulate available habitat for each site. An preference curve file, containing the digitized HSC, was created. The final cdg files, the substrate file and the preference curve file were used in RIVER2D to calculate the WUA values for each site over the desired range of flows (3,250 cfs to 5,500 cfs by 250 cfs increments, 5,500 cfs to 8,000 cfs by 500 cfs increments, 8,000 cfs to 15,000 cfs by 1,000 cfs increments, and 15,000 cfs to 31,000 cfs by 2,000 cfs increments). We then multiplied the WUA values for each habitat unit modeled by the ratios in Table 2, and then summed the resulting products to calculate the total WUA for each reach.

Table 2. Ratio of habitat lengths in reach to habitat lengths in modeled sites. The values in this table were calculated by dividing the total length of each habitat type present in a given reach by the length of each habitat type that was modeled in that reach. Entries with an asterisk indicate that the habitat type was not present or used in that reach.

Habitat Type	Reach 6	Reach 5	Reach 4
Flatwater Glide	5.77	32.50	31.43
Flatwater Pool	6.87	1.88	1.00
Flatwater Riffle	*	7.41	5.97
Flatwater Run	*	14.55	4.63
Bar Complex Glide	*	11.54	2.89
Bar Complex Pool	*	3.64	2.42
Bar Complex Riffle	*	35.44	5.91
Bar Complex Run	*	19.56	2.18
Side Channel Pool	*	2.00	*
Side Channel Riffle	*	16.23	*
Side Channel Run	*	4.92	*
Run	15.03	*	*

RESULTS

Habitat Suitability Criteria Development

We collected a total of 75 macroinvertebrate samples (Table 3)[3]. Of these samples, 22 were collected in riffles, 20 in runs, 13 in pools and 20 in glides. Depths of the samples ranged from 0.8 to 4.3 feet, while the velocities of the samples ranged from 0.40 to 4.86 ft/s. Samples were collected for the entire range of substrate types in Table 1, ranging from sand/silt to bedrock.

Table 3. Macroinvertebrate HSC sampling dates, flows and samples.

Sampling Dates	Keswick Release During Sampling (cfs)	Keswick Release for 30 Days Prior to Sampling (cfs)	Number of Samples
July 26-28, 1999	13,133	13,372 ± 5%	10
November 16, 1999	6,300	6,179 ± 3%	6
August 1-4, 2000	15,050	14,868 ± 6%	19
August 7, 2000	14,200	14,868 ± 6%	2
November 28-30, 2000	6,023	5,418 ± 18%	14
December 4-6, 2000	5,697	5,405 ± 6%	12
January 16-18, 2001	4,357	4,390 ± 9%	12

A correlation analysis (Figure 2, SYSTAT 2002), indicated that there were not any significant ($p > 0.1$) correlations between depth, velocity and substrate size. Kolmogorov-Smirnov one sample tests (SYSTAT 2002) indicated that diversity, BCH AFDW and total AFDW were not normally distributed ($p < 0.01$), nor would they be normally distributed with a logarithmic or square root transformation ($p < 0.01$).

There were significant effects of picker on BCH AFDW and diversity, and of sampling week on total AFDW and diversity ($p < 0.05$, Kruskal-Wallis One-Way Analysis of Variance (SYSTAT 2002)). In contrast, there was no significant effect at $p = 0.05$ of picker on total AFDW, of sampling week on BCH AFDW, or of mesohabitat type on any of the three macroinvertebrate metrics.

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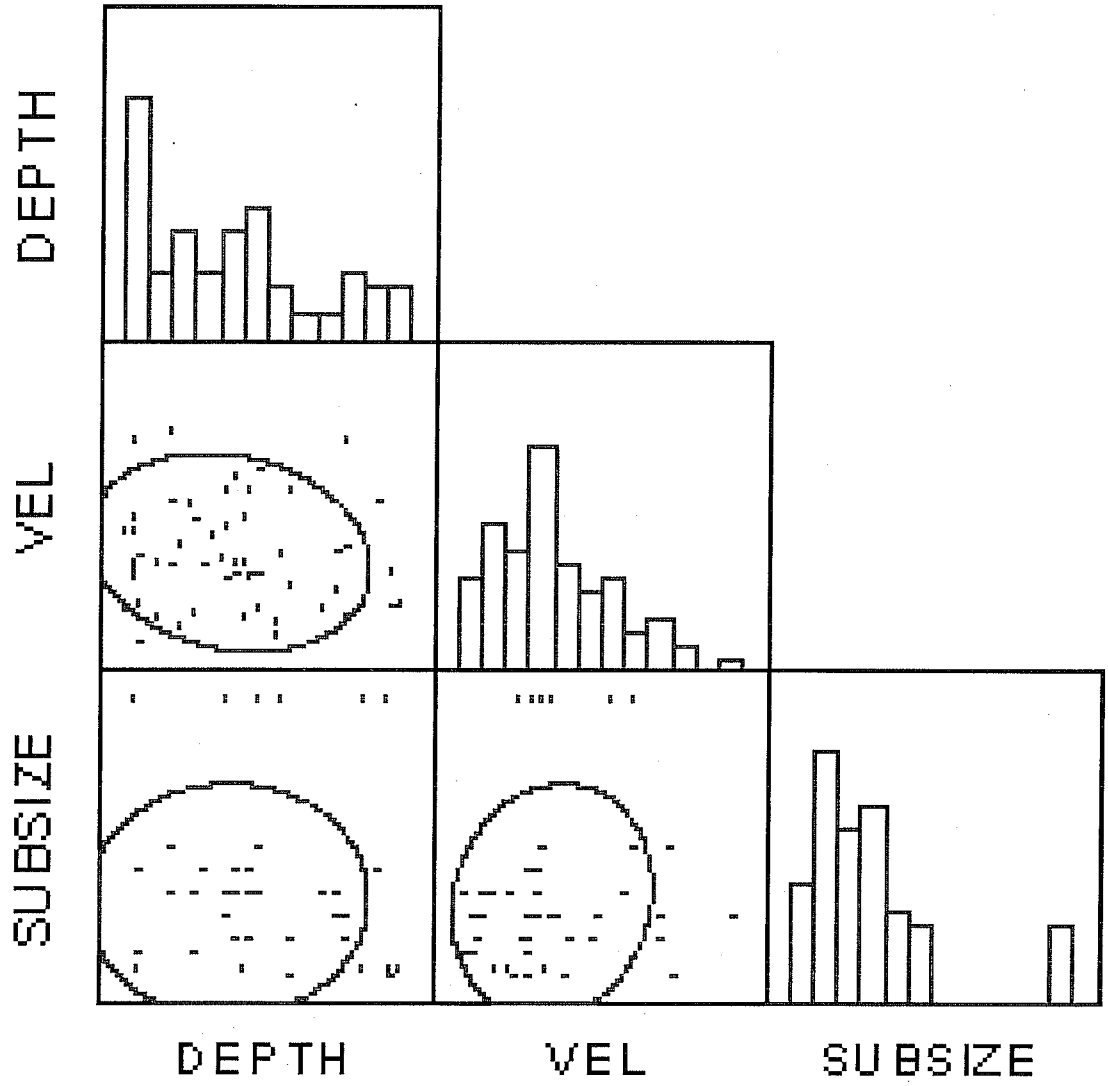
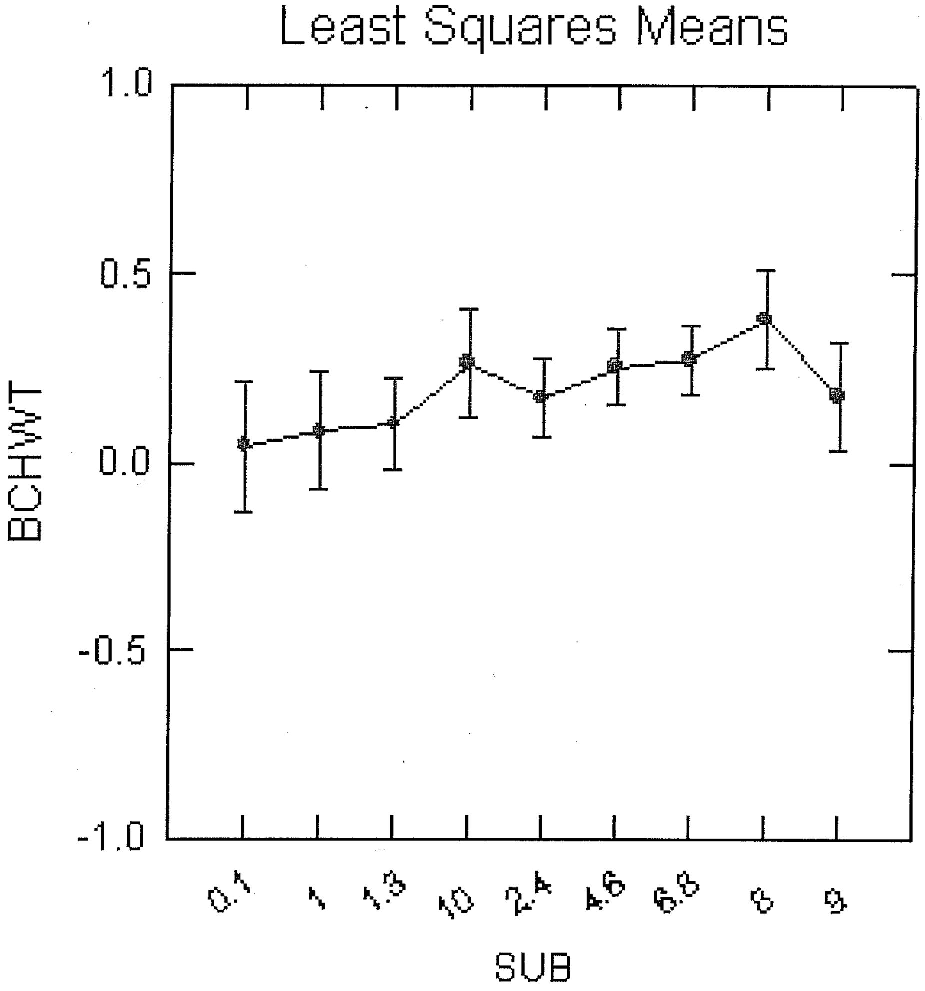
[3] Given the stratification of the sampling by depth, velocity and substrate, we concluded that the 75 samples collected were sufficient to generate habitat suitability criteria.

Figure 2. Correlation analysis of depth, velocity and substrate size (SUBSIZE). Bar charts show frequency distribution of depth, velocity and substrate size. Scatter plots show correlation patterns between depth, velocity and substrate size. There were not any significant ($p > 0.1$) correlations between depth, velocity and substrate size.



For BCH AFDW versus depth, velocity and substrate, there was no significant effect of picker ($p > 0.13$, general linear model (SYSTAT 2002)), and thus picker was dropped from the analysis. The general linear model for substrate did not show a significant effect of substrate ($p = 0.66$, Figure 3).

Figure 3. Mean BCH AFDW (± SE) for each substrate code. There was no significant effect of substrate on mean BCH AFDW (general linear model, p = 0.66). Key: BCHWT = BCH AFDW, SUB = substrate code.



For total AFDW versus depth, velocity and substrate, there was no significant effect of sampling week (p > 0.125, general linear model (SYSTAT 2002)), and thus sampling week was dropped from the analysis. The general linear model for substrate did not show a significant effect of substrate (p = 0.46), nor did a one-way analysis of variance (p = 0.48). There appeared to be a difference in total AFDW between larger substrates (substrate codes 6.8, 8 and 10) and smaller substrates and bedrock (Figure 4). A two-sample t-test showed a significant difference between larger (mean = 2.76 g) and smaller substrates (mean = 0.74 g, p = 0.039), as did a general linear model with sample week and the above two levels of substrate (p = 0.01)[4]. As a result, we assigned a total AFDW suitability of 1.0 for substrate codes 6.8, 8 and 10, and a suitability of 0.27 (0.74/2.76) for all other substrate codes (Figure 5, Appendix A).

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[4] The effect of sampling week was not significant (p = 0.36) in this general linear model.

Figure 4. Mean total AFDW (± SE) for each substrate code. There appears to be a difference in total AFDW between larger substrates (substrate codes 6.8, 8 and 10) and smaller substrates and bedrock. Key: ALLWT = total AFDW, SUB = substrate code.

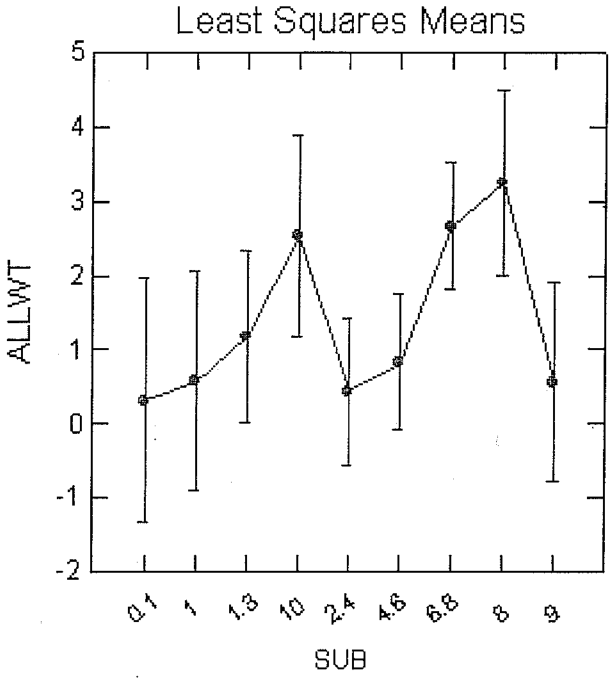
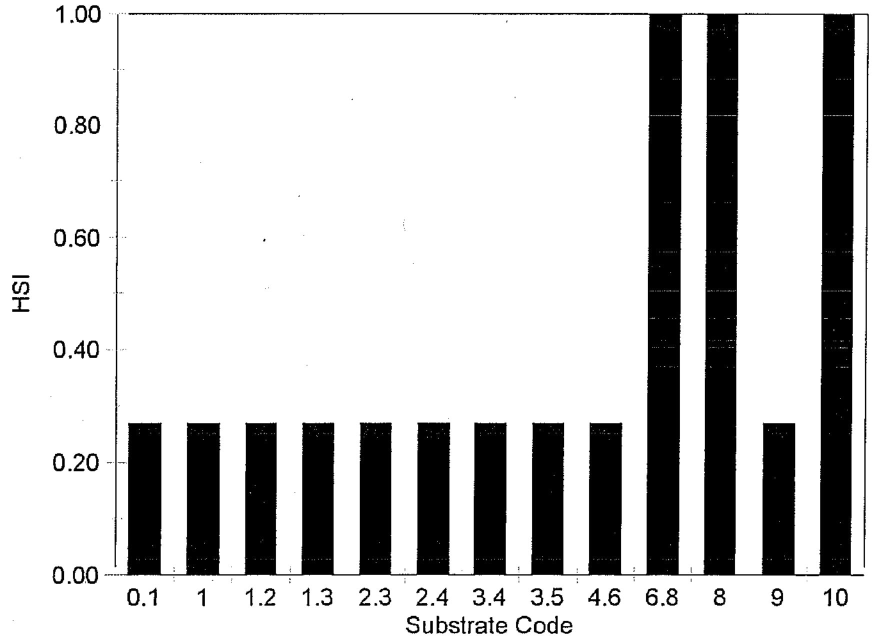
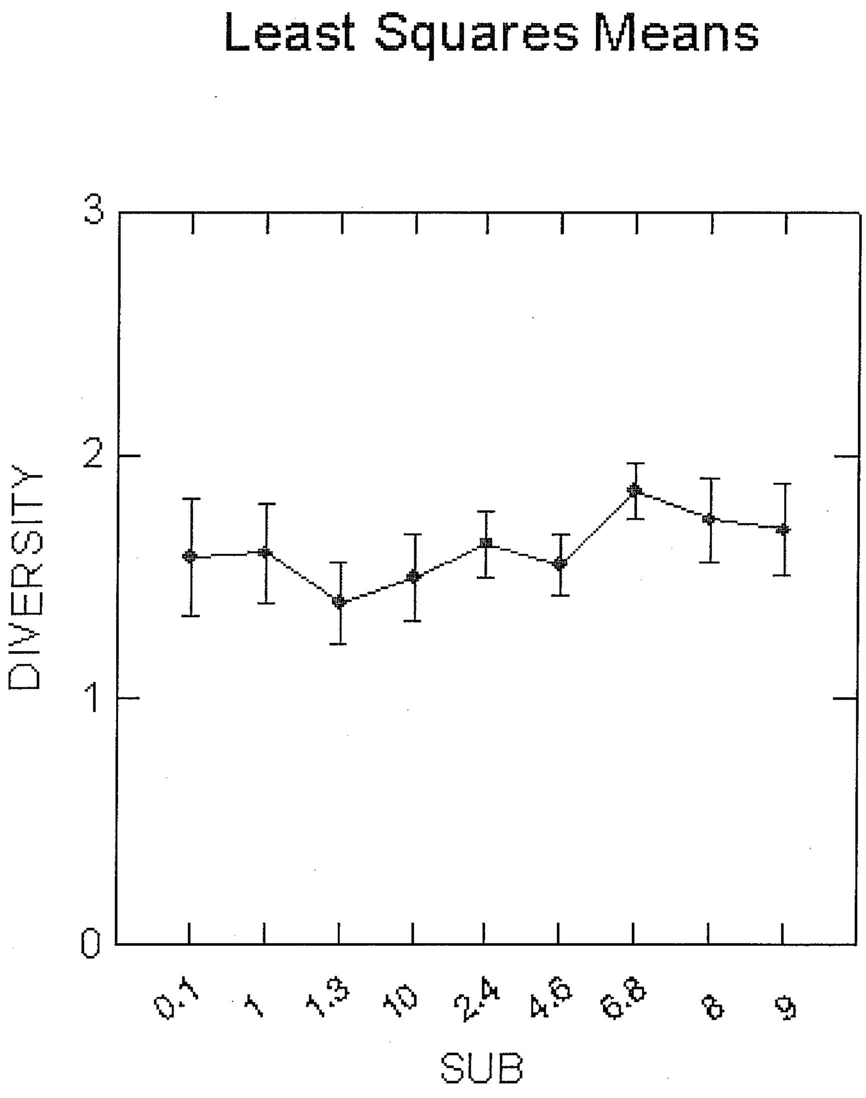


Figure 5. Total Macroinvertebrate Ash Free Dry Weight Substrate HSC



For diversity versus depth, velocity and substrate, there was no significant effect of picker ($p > 0.54$, general linear model (SYSTAT 2002)), and thus picker was dropped from the analysis. However, there was a significant effect of sampling week ($p < 0.0009$) for all three variables. The general linear model for substrate did not show a significant effect of substrate ($p = 0.45$), nor did there appear to be any significant differences in diversity between substrate codes (Figure 6). A Kruskal-Wallis one-way analysis of variance (SYSTAT 2002) also did not show a significant difference in diversity between substrates ($p = 0.42$).

Figure 6. Mean Shannon Weaver diversity index (± SE) for each substrate code. There was no significant effect of substrate on mean Shannon Weaver diversity index (general linear model, $p = 0.45$). Key: DIVERSITY = Mean Shannon Weaver diversity index, SUB = substrate code.



Sampling week was incorporated into the subsequent development of depth HSC for diversity using an adjusted diversity, calculated as the original diversity minus the average diversity for each sampling week plus 2. A value of two was selected so that there would not be any negative values of the adjusted diversity - the average diversity for the highest diversity sampling week was 1.996. There was only a weak effect of depth on adjusted diversity - after following the above procedure, we were left with only the constant ($p < 0.00001$) and D^2 ($p = 0.24$) terms. We then dropped the constant from the regression and added the remaining terms back in to get the final regression equation (Table 4). Sampling week was incorporated into the subsequent development of velocity HSC for diversity by incorporating additional terms consisting of design variables for each level of sampling week, where the design variable had a value of one for the given sampling week and a value of zero for all other sampling weeks. The coefficients for the final regressions for depth and velocity for each macroinvertebrate metric are shown in Table 4.

Table 4. Coefficients for the final regressions for depth and velocity for each macroinvertebrate metric. The p values for all of the non-zero coefficients were less than 0.05, as were the p values for the overall regressions. The only exception to this was the V^2 term for BCH AFDW, with a p value of 0.058. This term was retained even though its p-value was greater than 0.05 because the regression would be biologically unrealistic (continually increasing HSI with velocity) with only the V term. I is the constant and J, K, L and M are the regression coefficients in the equation on page 6. A coefficient or constant value of zero indicates that term or the constant was not used in the logistic regression, because the p-value for that coefficient or for the constant was greater than 0.05.

metric	parameter	I	J	K	L	M	R^2
BCH AFDW	depth	0	0	0.1614	- 0.0393	0	0.24
BCH AFDW	velocity	0	0.2588	- 0.0517	0	0	0.23
total AFDW	depth	0	1.87	- 0.4366	0	0	0.20
total AFDW	velocity	0	1.726	- 0.3914	0	0	0.19
diversity	depth	0	4.3263	- 3.0889	0.8829	- 0.0867	0.97
diversity	velocity	1.5606	0	0.387713	- 0.1819	0.0218	0.37

For total AFDW versus velocity, the regression equation predicted that total AFDW would become negative at values less than the largest sampled velocity, even though there was a non-zero measured total AFDW at this value (4.86 ft/s). In this case, we stopped using the regression at the highest velocity which had a predicted total AFDW greater than zero (4.3 ft/s), then calculated a HSI value for 4.86 ft/s by dividing the total AFDW at 4.86 ft/s (1.21 g) by the highest measured total AFDW (20.27 g), and set the suitability for velocities greater than 4.86 ft/s to zero. For diversity versus velocity, the regression equation predicted that diversity would continually increase for velocities greater than the maximum sampled velocity (4.86 ft/s). As a result, we truncated the regression at 4.86 ft/s, setting the suitability for velocities greater than 4.86 ft/s to zero. The final depth and velocity criteria are shown in Figures 7 through 12 and Appendix A.

Figure 7. BCH AFDW depth HSC. The HSC show that BCH AFDW has a non-zero suitability for depths of 0.2 to 4.0 feet, and an optimum suitability at depths of 2.7 to 2.8 feet.

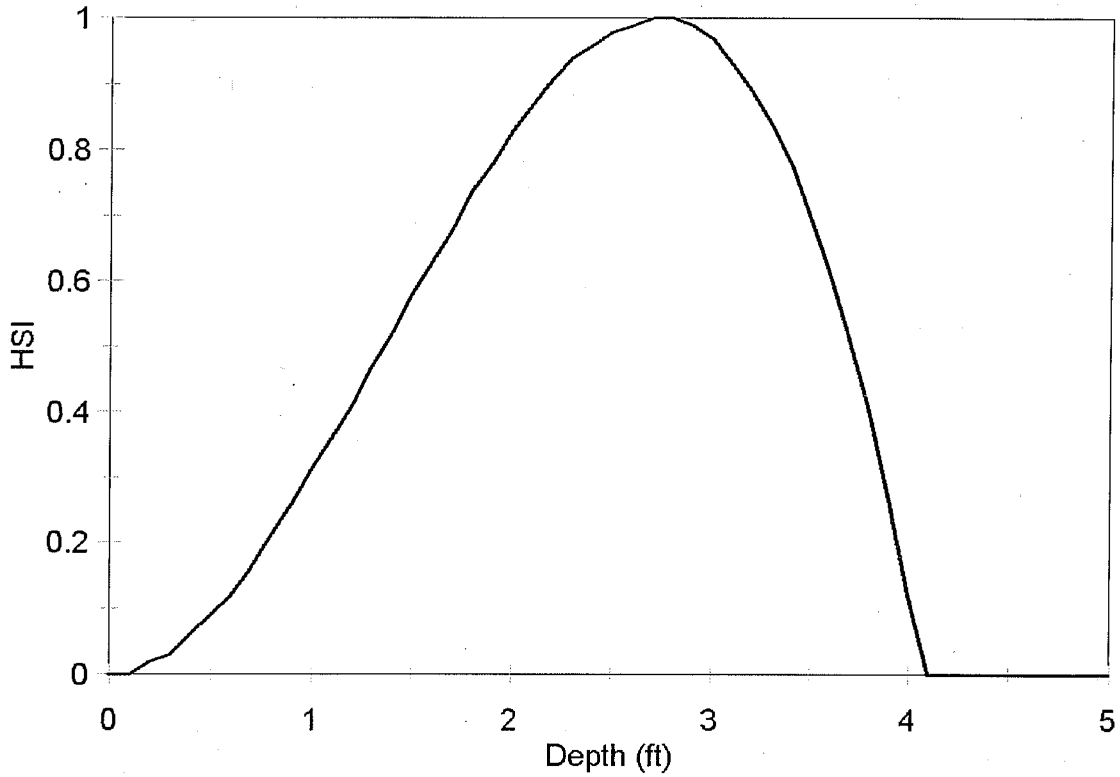


Figure 8. BCH AFDW velocity HSC. The HSC show that BCH AFDW has a non-zero suitability for velocities of 0.01 to 4.99 feet/sec, and an optimum suitability at velocities of 2.4 to 2.6 feet/sec.

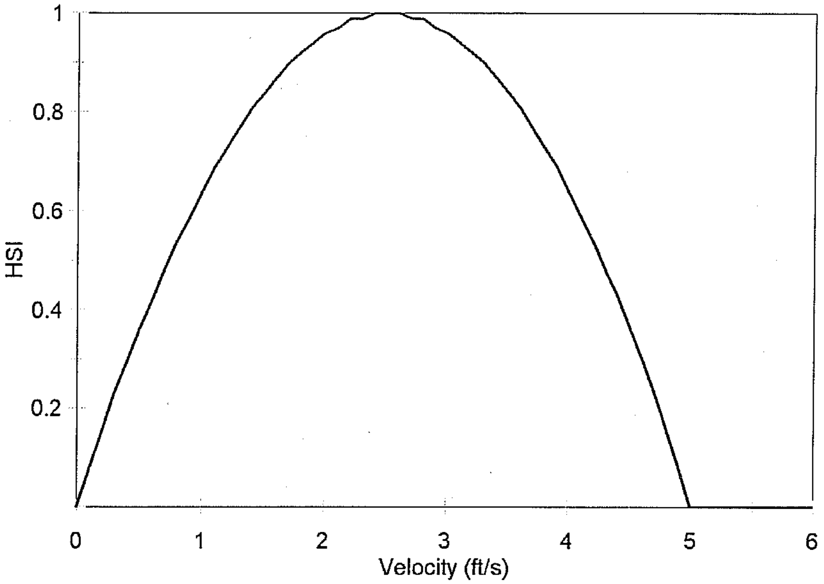


Figure 9. Total macroinvertebrate AFDW depth HSC. The HSC show that total AFDW has a non-zero suitability for depths of 0.1 to 4.2 feet, and an optimum suitability at depths of 2.0 to 2.2 feet.

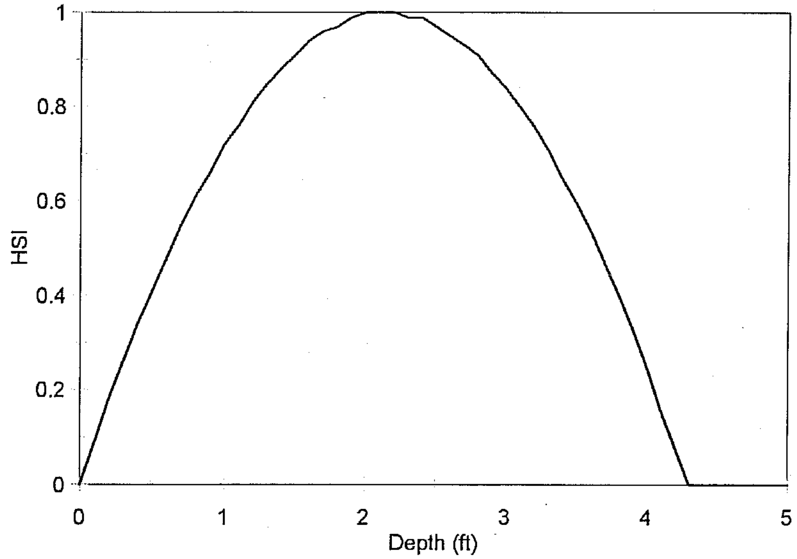


Figure 10. Total macroinvertebrate AFDW velocity HSC. The HSC show that total AFDW has a non-zero suitability for velocities of 0.01 to 4.86 feet/sec, and an optimum suitability at velocities of 2.0 to 2.2 feet/sec.

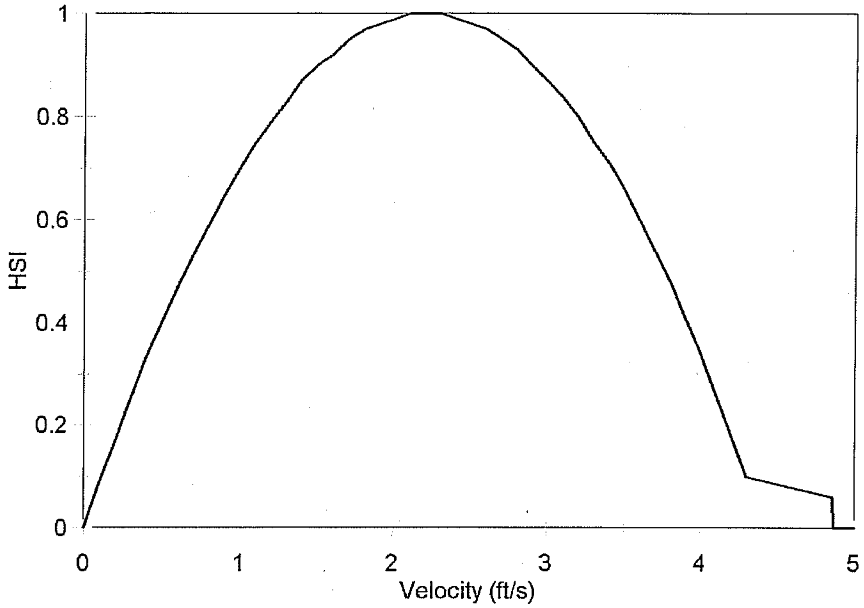


Figure 11. Shannon Diversity Index depth HSC. The HSC show that diversity has a non-zero suitability for depths of 0.1 to 5.1 feet, and an optimum suitability at depths of 3.8 to 3.9 feet.

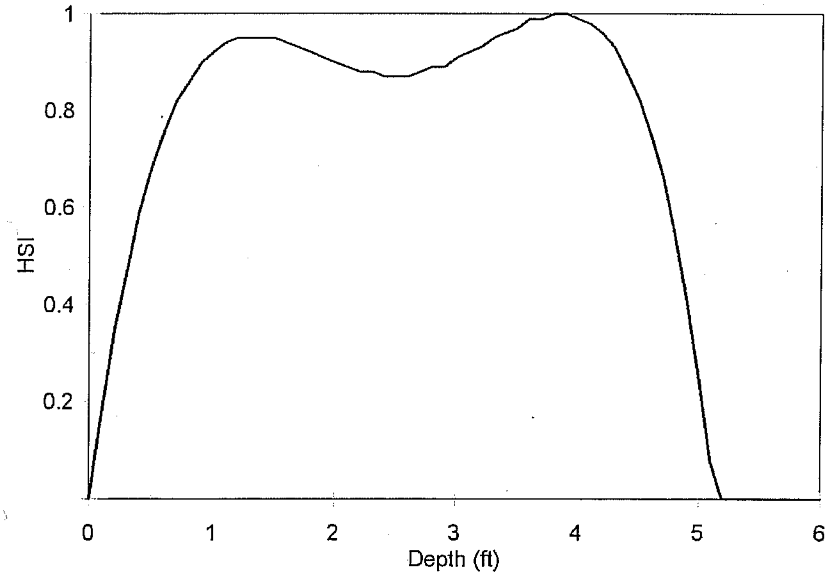
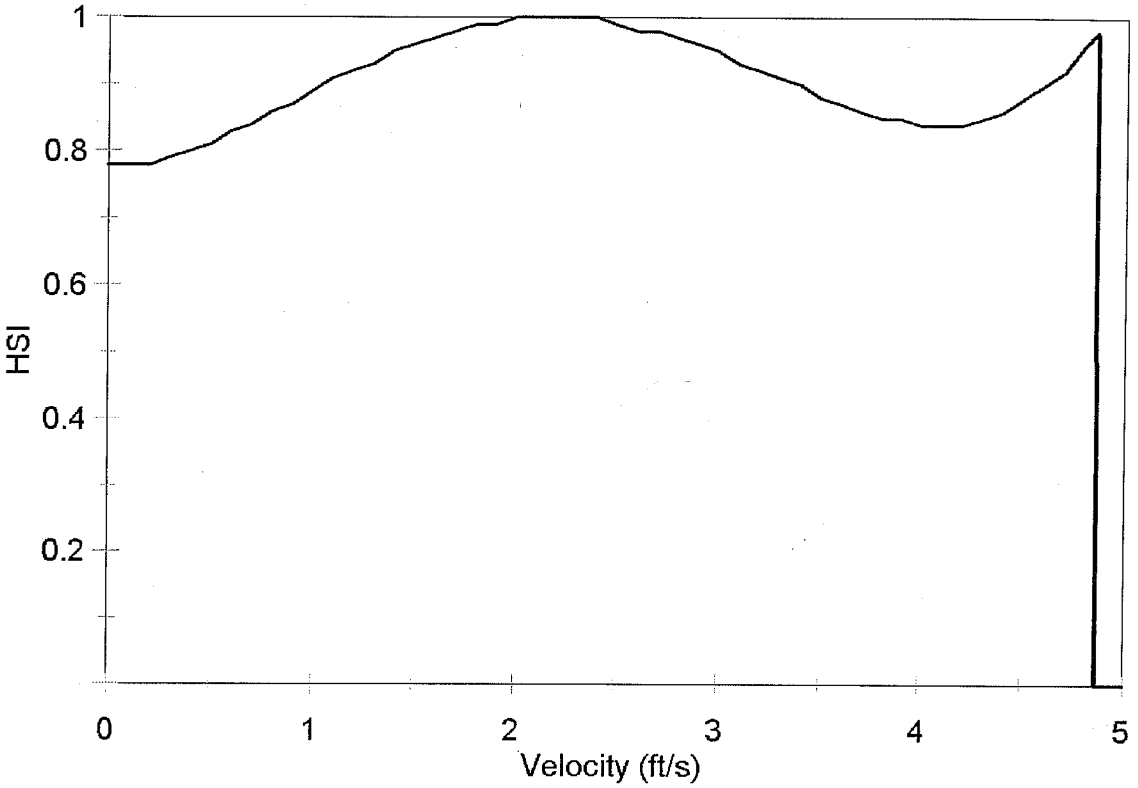


Figure 12. Shannon Diversity Index velocity HSC. The HSC show that diversity has a non-zero suitability for velocities of 0 to 4.86 feet/sec, and an optimum suitability at velocities of 2.0 to 2.4 feet/sec.



Habitat Simulation

The WUA values calculated for each site and criteria set are contained in Appendix B. The flow-habitat relationships for BCH AFDW, total AFDW and diversity are shown in Figures 13 to 15 and Appendix C. These flow-habitat relationships are the final results of the models predicting the hydraulic and structural characteristics of sites for macroinvertebrates in the Sacramento River between Keswick Reservoir and Battle Creek over a range of streamflows.

Figure 13. BCH AFDW flow-habitat relationships. The flow with the maximum BCH AFDW habitat varies with reach, and ranges from 3,250 to 6,000 cfs.

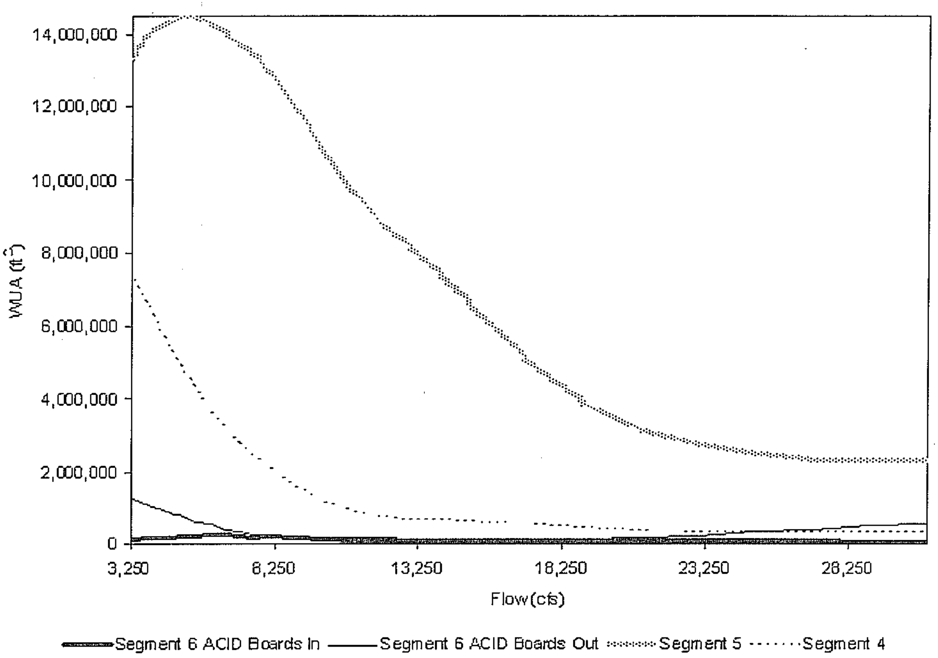


Figure 14. Total macroinvertebrate AFDW flow-habitat relationships. The flow with the maximum total AFDW habitat varies with reach, and ranges from 3,250 to 6,000 cfs.

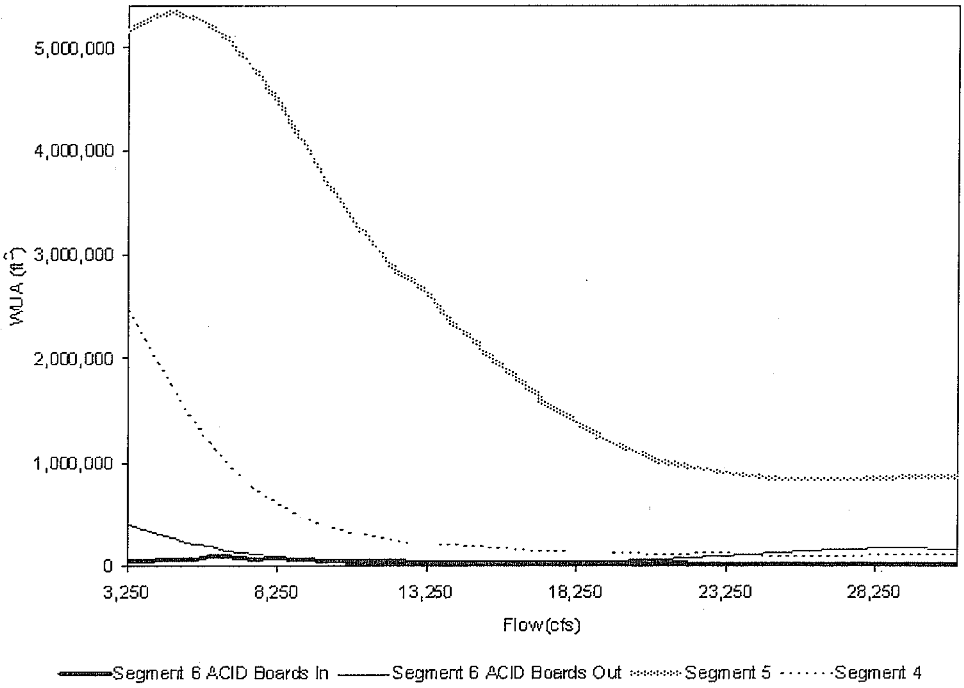
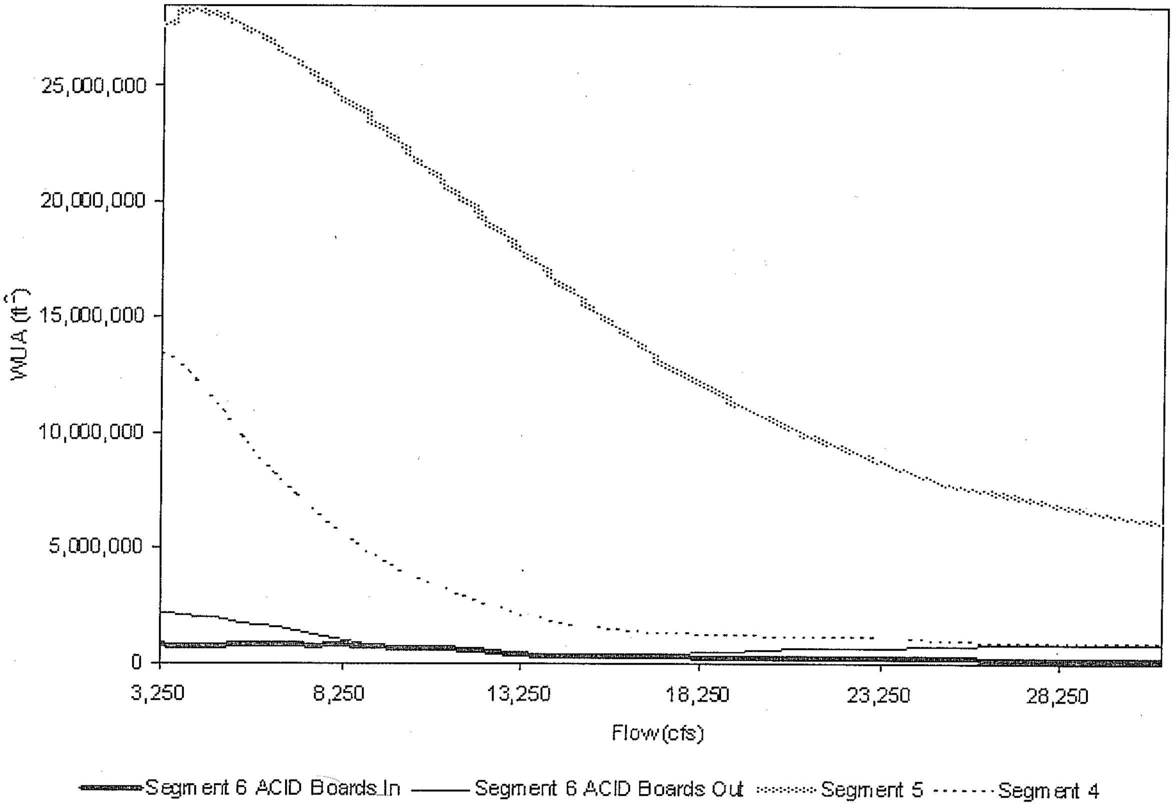


Figure 15. Shannon Diversity Index flow-habitat relationships. The flow with the maximum diversity habitat varies with reach, and ranges from 3,250 to 6,000 cfs.



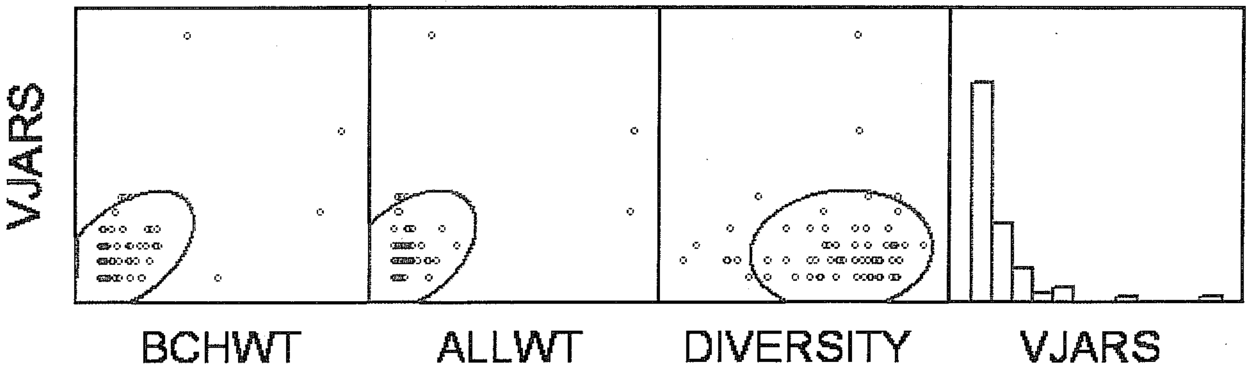
DISCUSSION

Habitat Suitability Criteria Development

Only 10 samples were collected in July 1999 and 6 samples in November 1999 due to equipment problems. The November 1999 sampling was halted after 1 week because Keswick releases started to ramp up, while the August 2000 sampling was halted 1 day into the second week because Keswick releases started to ramp down. By using the variable sampling week (with four levels: July 1999, November 1999, August 2000, and November 2000-January 2001) in our analysis, we were able to take into account responses of the macroinvertebrate community to changes in the amount of organic matter accumulated in the riverbed due to seasonal flood flows as well as changes in macroinvertebrate communities associated with seasonal effects on their life cycles. We can conclude that the above seasonal variations did not affect BCH AFDW since there was no significant effect of sampling week on this metric. Further, after depth, velocity and substrate were taken into account, there were no effects of sampling week on total AFDW. Thus we conclude that any apparent effects of seasonal variations on total AFDW were actually due to variations between sampling periods in the depths, velocities and substrates sampled. By including sampling week in the development of the HSC for diversity, we were able to determine the effects of depth, velocity and substrate that were independent of seasonal variations in macroinvertebrate diversity, and thus find that the HSC that we derived for diversity were not affected by seasonal variations in macroinvertebrate diversity. Put another way, the seasonal variations in macroinvertebrate diversity did not obscure nor did they cause the relationships that we derived between diversity and depth, velocity and substrate.

While we did not measure the amount of organic matter in the samples, the number of jars per sample (ranging for 1 to 16) is a rough surrogate for the amount of organic matter in the samples. Samples with only 1 jar had little organic matter, while the sample with 16 jars (collected in an area with abundant aquatic moss) had lots of organic matter. While there was not a significant correlation between diversity and the number of jars per sample ($p > 0.50$), there were significant correlations between BCH AFDW and total AFDW and the number of jars per sample ($p < 0.001$, Figure 16). When four outliers for BCH AFDW and three outliers for total AFDW are excluded, there was still a significant correlation between the number of jars and BCH AFDW ($p = 0.023$) but there was no longer a significant correlation between the number of jars and total AFDW ($p > 0.10$). While we do not feel that the amount of organic matter in the samples significantly affected the overall results of this study, since the flow-habitat relationships for BCH AFDW and total AFDW were similar, we would recommend that future studies measure the amount of organic matter in the samples to use as an additional potential confounding variable in developing macroinvertebrate HSC.

Figure 16. Correlation analysis of the number of jars versus diversity, BCH AFDW and total AFDW. Bar chart shows frequency distribution of the number of jars (VJARS). Scatter plots show correlation patterns between the number of jars and diversity, BCH AFDW and total AFDW. While there was not a significant correlation between diversity and the number of jars per sample ($p > 0.50$), there were significant correlations between BCH AFDW and total AFDW and the number of jars per sample ($p < 0.001$).



The linear models used in this study addressed the assumptions that invertebrates are affected by season, mesohabitat and picker by separating out the effects of these potentially confounding variables from the effects of depth, velocity and substrate on the macroinvertebrate metrics used in this study. The analysis took into account the duration of flooding/flow 30 days prior to sampling by only collecting samples when the flows were relatively constant for the 30 days prior to sampling (Table 3), ensuring that the depths and velocities present during data collection were similar to those present during macroinvertebrate colonization. We conclude that it is not necessary to take into account the duration of flooding/flow 45 or 60 days prior to sampling, based on Harvey's (1986) findings that macroinvertebrates had completely recolonized areas below suction dredge mining areas within 45 days after the cessation of suction dredge mining; if macroinvertebrates can completely recolonize areas within 45 days, it is reasonable to expect that macroinvertebrate community characteristics would adjust to changes in depth and velocity within 30 days. Based on the above discussion, we conclude that the assumptions used in this study are valid.

There are significant differences between the diversity HSC from Gore et al. (2001) and those developed in this study (Figures 17 to 19). For example, this study found that the maximum suitability for depth was at 3.8 feet, while the Gore et al. (2001) criteria had a suitability for diversity that reached zero at a depth of 1.35 feet. Further, this study found a relatively weak effect of depth, velocity and substrate on diversity. We conclude that the differences between the HSC from this study and those from Gore et al. (2001) were because the HSC in this study were developed from samples taken from a single stream, which the HSC in Gore et al. (2001) were developed from samples taken from multiple streams. The results of this study indicate that biomass may be a better metric of macroinvertebrates than diversity for instream flow studies, although biomass does have some drawbacks, such as favoring larger-bodied species.

Figure 17. Diversity depth HSC from this study and from Gore et al. (2001). The HSC from this study had an optimum suitability at depths of 3.8 to 3.9 feet, while the HSC from Gore et al. (2001) had zero suitability for depths greater than 1.35 feet.

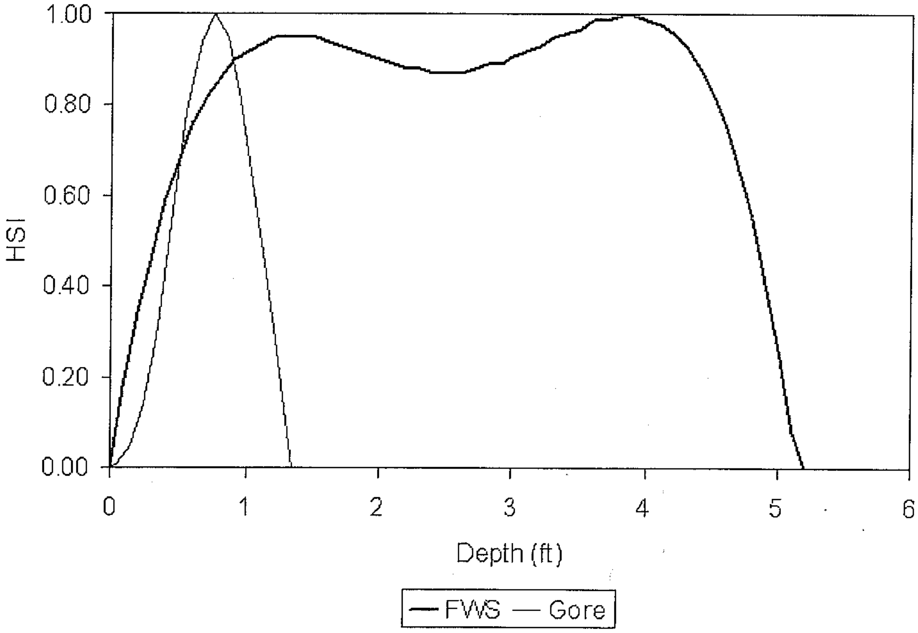


Figure 18. Diversity velocity HSC from this study and from Gore et al. (2001). The HSC from this study had an optimum suitability at velocities of 2.0 to 2.4 feet/sec, while the HSC from Gore et al. (2001) had an optimum suitability at velocities of 0.95 to 1.05 ft/s.

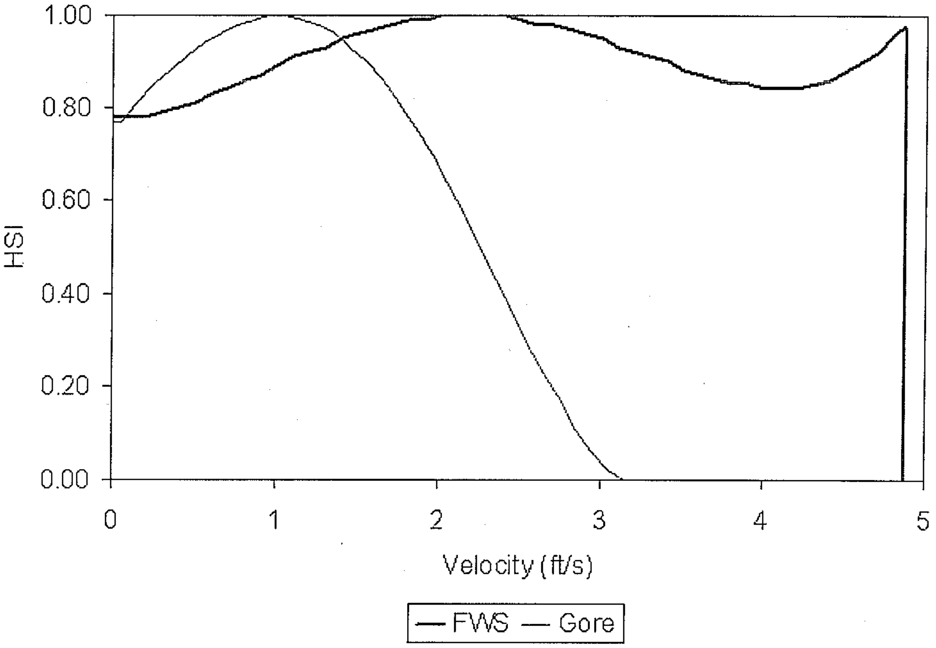
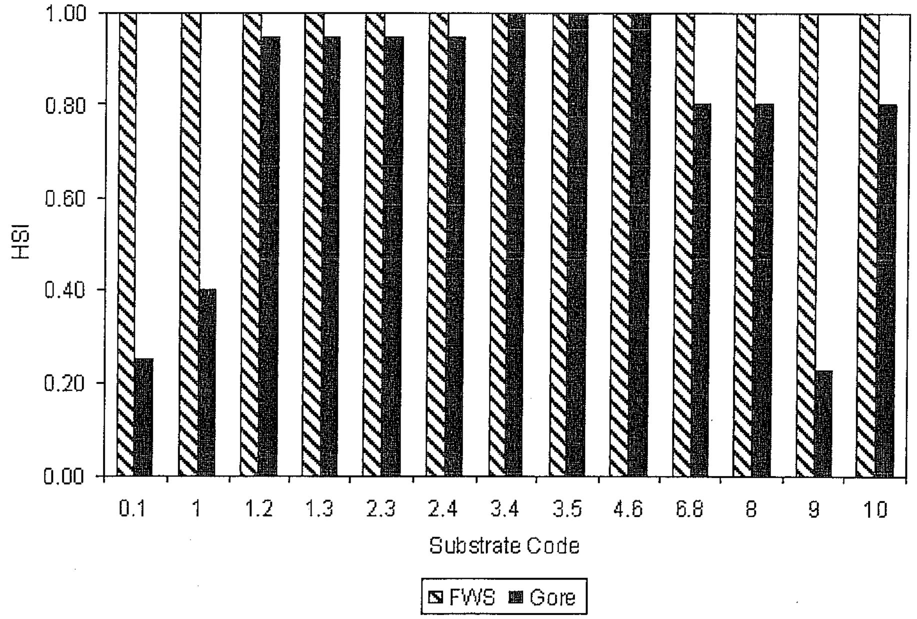


Figure 19. Diversity substrate HSC from this study and from Gore et al. (2001). The HSC from this study had no effect of substrate on suitability, while the HSC from Gore et al. (2001) had diversity suitabilities ranging from 0.225 for boulders and bedrock to 1.0 for small cobble.



The lack of significant correlations between depth, velocity and substrate size was expected, given the stratified sampling design. To the extent practicable, we used nonparametric tests for analyses, given that diversity, BCH AFDW and total AFDW were not normally distributed nor could they be transformed to be normally distributed via a logarithmic or square root transformation. Since the general linear models for BCH AFDW and diversity did not show a significant effect of substrate, we concluded that there was no significant effect of substrate for these two metrics, and set the HSI value of these two metrics to 1.0 for all substrate codes (Appendix A).

This study shows the importance of stratifying sampling of macroinvertebrate samples by depth, velocity and substrate. Without stratified sampling, there would a tendency to get low suitabilities for large depths if all of the samples with large depths were collected in areas with low velocities, which would bias the depth criteria towards shallow depths. This study also demonstrates the need for a larger sampler when sampling large substrate sizes. With the usual 1 ft^2 sampler, only one large cobble would be sampled, which would be too small of a sample. Having a rubber foam lining on the bottom of the sampler is critically important, particularly for larger-sized substrates. Many of the invertebrates would be lost passing under the frame of a typical Surber sampler.

Habitat Simulation

The model developed in this study is predictive for flows ranging from 3,250 cfs to 31,000 cfs. The results of this study can be used to evaluate 360 different hydrograph management scenarios (each of the 30 simulation flows in each of 12 months). For example, increasing flows from 3,250 cfs to 5,500 cfs during April and May would result in an increase of 8.8% of habitat during these months in Segment 5 for biomass of macroinvertebrates used as forage by salmonid fry, parr, and smolts. We do not feel that there are any significant limitations of the model.

This study supported and achieved the objective of producing models predicting the hydraulic and structural characteristics of sites for macroinvertebrates in the Sacramento River between Keswick Reservoir and Battle Creek over a range of streamflows. The results of this study are intended to support or revise the flow recommendations in the introduction. The results of this study, showing flows with the maximum value of macroinvertebrate habitat ranging from 3,250 to 6,000 cfs, are consistent with the flow recommendations in the introduction.

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APPENDIX A
HABITAT SUITABILITY CRITERIA

Baetid/Chironomid/Hydropsychid Ash Free Dry Weight

Water Velocity (ft/s)	SI Value	Water Depth (ft)	SI Value	Substrate Code	SI Value
0.0	0.00	0.0	0.00	0	0.00
0.1	0.08	0.1	0.00	0.1	1.00
0.2	0.15	0.2	0.02	1	1.00
0.3	0.23	0.3	0.03	1.2	1.00
0.4	0.29	0.4	0.06	1.3	1.00
0.5	0.36	0.5	0.09	2.3	1.00
0.6	0.42	0.6	0.12	2.4	1.00
0.7	0.48	0.7	0.16	3.4	1.00
0.8	0.54	0.8	0.21	3.5	1.00
0.9	0.59	0.9	0.26	4.6	1.00
1.0	0.64	1.0	0.31	6.8	1.00
1.1	0.69	1.1	0.36	8	1.00
1.2	0.73	1.2	0.41	9	1.00
1.3	0.77	1.3	0.47	10	1.00
1.4	0.81	1.4	0.52	11	0.00
1.5	0.84	1.5	0.58	100	0.00
1.6	0.87	1.6	0.63		
1.7	0.90	1.7	0.68		
2.0	0.96	1.8	0.74		
2.1	0.97	1.9	0.78		
2.2	0.99	2.0	0.83		
2.3	0.99	2.1	0.87		
2.4	1.00	2.2	0.91		
2.6	1.00	2.3	0.94		
2.7	0.99	2.4	0.96		
2.8	0.99	2.5	0.98		
2.9	0.97	2.6	0.99		
3.0	0.96	2.7	1.00		
3.1	0.94	2.8	1.00		
3.3	0.90	2.9	0.99		
3.7	0.77	3.0	0.97		
3.8	0.73	3.1	0.93		
3.9	0.69	3.2	0.89		
4.0	0.64	3.3	0.84		
4.1	0.59	3.4	0.78		
4.2	0.54	3.5	0.70		
4.3	0.48	3.6	0.61		
4.4	0.43	3.7	0.51		
4.5	0.36	3.8	0.40		
4.6	0.30	3.9	0.27		
4.7	0.23	4.0	0.12		
4.8	0.16	4.1	0.00		
5.0	0.00	100.0	0.00		
100.0	0.00				

Total Ash Free Dry Weight

Water Velocity (ft/s)	SI Value	Water Depth (ft)	SI Value	Substrate Code	SI Value
0.0	0.00	0.0	0.00	0	0.00
0.1	0.09	0.1	0.09	0.1	0.27
0.2	0.17	0.2	0.18	1	0.27
0.3	0.25	0.3	0.26	1.2	0.27
0.4	0.33	0.4	0.34	1.3	0.27
0.5	0.40	0.5	0.41	2.3	0.27
0.6	0.47	0.6	0.48	2.4	0.27
0.7	0.53	0.7	0.55	3.4	0.27
0.8	0.59	0.8	0.61	3.5	0.27
0.9	0.65	0.9	0.66	4.6	0.27
1.0	0.70	1.0	0.72	6.8	1.00
1.1	0.75	1.1	0.76	8	1.00
1.2	0.79	1.2	0.81	9	0.27
1.3	0.83	1.3	0.85	10	1.00
1.4	0.87	1.4	0.88	11	0.00
1.5	0.90	1.5	0.91	100	0.00
1.6	0.92	1.6	0.94		
1.7	0.95	1.7	0.96		
1.8	0.97	1.8	0.97		
2.1	1.00	1.9	0.99		
2.3	1.00	2.0	1.00		
2.6	0.97	2.2	1.00		
2.8	0.93	2.3	0.99		
3.1	0.84	2.4	0.99		
3.2	0.80	2.8	0.91		
3.3	0.75	2.9	0.87		
3.4	0.71	3.0	0.84		
3.5	0.66	3.2	0.76		
3.6	0.60	3.3	0.71		
3.7	0.54	3.4	0.65		
3.8	0.48	3.5	0.60		
3.9	0.41	3.6	0.54		
4.0	0.34	3.7	0.47		
4.1	0.26	3.8	0.40		
4.2	0.18	3.9	0.33		
4.3	0.10	4.0	0.25		
4.86	0.06	4.1	0.16		
4.87	0.00	4.3	0.00		
100.0	0.00	100.0	0.00		

Shannon Diversity Index

Water Velocity (ft/s)	SI Value	Water Depth (ft)	SI Value	Substrate Code	SI Value
0.0	0.78	0.0	0.00	0	0.00
0.2	0.78	0.1	0.18	0.1	1.00
0.5	0.81	0.2	0.34	1	1.00
0.6	0.83	0.3	0.47	1.2	1.00
0.7	0.84	0.4	0.59	1.3	1.00
0.8	0.86	0.5	0.68	2.3	1.00
0.9	0.87	0.6	0.76	2.4	1.00
1.0	0.89	0.7	0.82	3.4	1.00
1.1	0.91	0.8	0.86	3.5	1.00
1.3	0.93	0.9	0.90	4.6	1.00
1.4	0.95	1.0	0.92	6.8	1.00
1.8	0.99	1.2	0.95	8	1.00
1.9	0.99	1.5	0.95	9	1.00
2.0	1.00	1.6	0.94	10	1.00
2.4	1.00	2.2	0.88	11	0.00
2.5	0.99	2.3	0.88	100	0.00
2.6	0.98	2.4	0.87		
2.7	0.98	2.6	0.87		
3.0	0.95	2.7	0.88		
3.1	0.93	2.8	0.89		
3.4	0.90	2.9	0.89		
3.5	0.88	3.0	0.91		
3.8	0.85	3.2	0.93		
3.9	0.85	3.3	0.95		
4.0	0.84	3.5	0.97		
4.2	0.84	3.6	0.99		
4.4	0.86	3.7	0.99		
4.7	0.92	3.8	1.00		
4.8	0.96	3.9	1.00		
4.86	0.98	4.1	0.98		
4.87	0.00	4.2	0.96		
100.0	0.00	4.3	0.93		
		4.4	0.88		
		4.5	0.82		
		4.6	0.75		
		4.7	0.66		
		4.8	0.55		
		4.9	0.41		
		5.0	0.26		
		5.1	0.08		
		5.2	0.00		
		100.0	0.00		

APPENDIX B
SITE HABITAT MODELING RESULTS

Salt Creek Study Site WUA (ft^2)

	ACID Boards In			ACID Boards Out		
Flow (cfs)	BCH AFDW	Total AFDW	Diversity	BCH AFDW	Total AFDW	Diversity
3,250	833	318	8,355	356	121	7,850
3,500	978	370	8,726	834	316	8,181
3,750	1,141	435	9,123	986	377	8,519
4,000	1,322	501	9,541	1,152	438	8,876
4,250	1,465	553	9,891	1,307	498	9,218
4,500	1,635	609	10,307	1,461	553	9,574
4,750	1,810	670	10,936	1,622	614	9,903
5,000	1,958	723	11,786	1,788	670	10,259
5,250	2,079	805	12,648	1,962	725	10,739
5,500	2,206	889	13,379	2,128	785	11,464
6,000	5,054	2,424	14,327	4,914	2,060	14,198
6,500	4,843	2,035	14,187	2,685	1,187	14,090
7,000	3,182	1,270	13,745	2,856	1,278	14,607
7,500	1,841	586	11,356	3,073	1,372	14,854
8,000	3,930	1,771	14,445	3,340	1,478	14,897
9,000	3,990	1,675	14,090	4,007	1,730	14,564
10,000	3,898	1,561	14,015	4,271	1,796	14,208
11,000	3,449	1,325	13,745	4,290	1,742	14,133
12,000	2,897	1,040	13,336	3,992	1,565	14,025
13,000	2,394	734	11,108	3,414	1,298	13,670
14,000	2,611	829	11,248	2,975	1,021	13,326
15,000	2,847	859	10,241	2,840	901	12,572
17,000	3,031	912	10,290	2,626	845	10,457
19,000	3,287	981	10,330	2,712	822	10,219
21,000	3,549	1,052	10,439	2,867	891	10,249
23,000	2,929	836	10,979	3,500	1,038	10,354
25,000	2,951	826	10,807	3,686	1,061	10,555
27,000	3,153	868	7,759	2,559	730	9,695
29,000	2,544	750	8,639	2,777	763	10,233
31,000	3,025	845	7,703	2,494	691	9,340

Upper Lake Redding Study Site WUA (ft^2)

	ACID Boards In			ACID Boards Out		
Flow (cfs)	BCH AFDW	Total AFDW	Diversity	BCH AFDW	Total AFDW	Diversity
3,250	2,734	900	26,458	160,995	45,025	257,213
3,500	2,781	894	21,388	150,802	41,732	253,844
3,750	2,838	896	18,191	140,124	38,330	249,571
4,000	2,913	910	15,941	129,737	35,230	244,157
4,250	3,016	936	14,370	118,467	32,033	237,203
4,500	3,110	961	13,326	106,810	28,718	229,324
4,750	3,171	981	12,594	94,991	25,532	220,993
5,000	3,225	1,000	12,045	86,563	23,304	214,104
5,250	3,288	1,019	11,636	73,323	19,956	202,361
5,500	3,338	1,026	11,388	62,635	17,158	190,994
6,000	3,458	1,066	11,184	45,714	12,669	169,014
6,500	3,536	1,085	11,151	32,195	8,872	146,227
7,000	3,442	1,046	10,990	22,303	6,506	124,226
7,500	3,302	1,010	10,746	14,725	4,695	102,827
8,000	3,116	941	10,444	10,775	3,367	83,280
9,000	3,002	925	9,877	7,118	2,213	52,291
10,000	3,137	976	9,695	5,940	1,840	32,205
11,000	3,132	972	9,642	5,673	1,664	19,935
12,000	3,117	961	9,619	5,590	1,612	14,843
13,000	3,016	913	9,427	5,483	1,577	12,755
14,000	3,136	966	9,079	5,429	1,560	11,873
15,000	3,527	1,135	9,085	5,370	1,535	11,668
17,000	3,581	1,041	8,894	4,729	1,320	11,108
19,000	2,699	750	8,092	4,330	1,215	10,307
21,000	1,347	407	7,480	4,336	1,225	9,972
23,000	931	278	5,880	4,229	1,200	9,711
25,000	896	272	5,392	4,153	1,186	9,722
27,000	601	187	4,705	4,078	1,136	9,623
29,000	525	167	3,520	3,913	1,061	9,183
31,000	897	262	2,888	3,697	1,042	8,431

Lower Lake Redding Study Site WUA (ft^2)

	ACID Boards In			ACID Boards Out		
Flow (cfs)	BCH AFDW	Total AFDW	Diversity	BCH AFDW	Total AFDW	Diversity
3,250	16,296	5,814	79,265	45,219	19,601	90,879
3,500	17,653	6,213	79,814	44,649	19,160	88,823
3,750	18,794	6,511	80,298	43,669	18,503	86,380
4,000	19,881	6,805	80,707	42,657	17,836	84,443
4,250	20,839	7,061	81,063	41,279	17,082	82,720
4,500	21,635	7,295	81,429	40,031	16,426	81,386
4,750	22,249	7,499	81,795	38,341	15,651	80,094
5,000	22,776	7,663	82,182	36,931	15,005	79,147
5,250	23,142	7,765	82,613	35,349	14,327	78,232
5,500	23,304	7,825	82,968	33,755	13,681	77,306
6,000	22,873	7,804	83,528	29,848	12,228	74,260
6,500	22,292	7,552	83,635	25,693	10,861	69,309
7,000	21,076	7,214	83,065	21,603	9,606	65,380
7,500	19,838	6,725	81,622	18,126	8,487	61,731
8,000	18,449	6,184	79,448	15,478	7,468	58,319
9,000	14,973	4,990	71,666	13,089	5,946	50,343
10,000	10,136	3,575	60,482	12,131	5,086	41,699
11,000	6,242	2,246	50,493	11,593	4,651	33,885
12,000	4,991	1,618	40,321	11,044	4,210	27,426
13,000	4,416	1,438	29,676	10,796	4,040	24,994
14,000	4,101	1,368	22,055	10,380	3,897	25,769
15,000	3,936	1,327	19,504	9,958	3,739	26,824
17,000	3,918	1,238	17,071	9,980	3,943	34,757
19,000	3,514	1,063	14,768	11,765	4,929	45,908
21,000	2,612	767	14,111	14,660	6,542	56,941
23,000	1,806	519	12,486	20,354	9,846	70,428
25,000	1,035	332	10,427	33,745	15,608	82,860
27,000	644	200	8,412	49,449	20,279	89,459
29,000	427	129	5,876	62,656	22,378	91,697
31,000	304	95	4,435	68,415	21,603	92,946

Posse Grounds Study Site and Study Site 130 WUA (ft^2)

	Posse Grounds Study Site			Study Site 130		
Flow (cfs)	BCH AFDW	Total AFDW	Diversity	BCH AFDW	Total AFDW	Diversity
3,250	22,313	22,518	58,265	2,941	2,635	20,387
3,500	23,239	23,013	51,699	3,282	3,002	20,677
3,750	24,294	24,046	66,348	3,689	3,405	20,936
4,000	25,650	25,177	69,427	4,155	3,809	21,076
4,250	26,415	25,037	72,204	4,649	4,283	21,108
4,500	27,190	25,618	73,140	5,230	4,776	21,065
4,750	28,287	25,909	76,090	5,673	5,148	21,022
5,000	30,128	26,953	78,092	6,155	5,465	20,979
5,250	31,829	27,469	79,642	6,690	5,826	21,000
5,500	32,798	27,448	80,395	7,240	6,150	21,043
6,000	34,530	26,791	81,633	8,177	6,704	21,226
6,500	35,897	25,779	83,366	8,968	7,114	21,495
7,000	38,126	25,101	83,635	9,587	7,300	21,668
7,500	40,634	24,283	82,925	9,999	7,328	21,861
8,000	42,194	22,486	82,656	10,281	7,200	22,174
9,000	44,412	18,320	80,298	10,343	6,618	22,593
10,000	42,959	13,950	80,794	9,682	5,708	22,690
11,000	40,052	10,850	75,939	8,806	4,736	22,453
12,000	34,574	8,419	68,738	7,995	3,897	22,195
13,000	28,384	6,139	62,172	7,331	3,271	21,786
14,000	22,959	4,620	55,606	6,759	2,862	20,764
15,000	18,180	3,654	50,913	6,072	2,525	18,815
17,000	10,376	2,274	36,877	5,882	2,624	17,556
19,000	6,112	1,351	22,001	6,117	2,760	17,750
21,000	4,522	1,012	12,755	6,007	2,696	17,481
23,000	3,435	760	10,256	4,558	2,328	16,436
25,000	1,787	448	8,070	4,346	2,172	15,360
27,000	1,245	315	6,671	4,554	2,154	14,101
29,000	1,198	364	5,705	3,604	1,876	12,443
31,000	1,308	440	5,401	3,452	1,774	11,894

Study Sites 112 and 96 WUA (ft^2)

	Study Site 112			Study Site 96		
Flow (cfs)	BCH AFDW	Total AFDW	Diversity	BCH AFDW	Total AFDW	Diversity
3,250	80,837	25,564	159,155	1,671	1,763	17,986
3,500	80,309	24,671	158,121	4,600	4,610	22,679
3,750	80,309	23,939	157,282	7,585	7,104	26,404
4,000	80,643	23,519	156,431	10,173	9,035	29,267
4,250	79,588	22,723	155,398	12,637	10,708	31,484
4,500	77,694	21,743	151,566	14,865	12,066	33,142
4,750	75,638	20,796	148,961	16,975	13,207	34,563
5,000	73,248	19,784	146,701	18,858	14,176	35,618
5,250	70,751	18,826	143,278	20,484	14,929	36,371
5,500	67,920	17,922	140,329	22,109	15,651	36,952
6,000	59,998	16,092	133,235	24,574	16,393	37,512
6,500	52,420	14,736	128,553	26,296	16,512	37,674
7,000	48,846	13,014	128,607	27,276	16,286	37,598
7,500	44,444	12,239	121,772	27,674	15,887	37,447
8,000	39,988	11,550	114,926	27,588	15,371	37,329
9,000	31,248	10,516	100,847	26,296	14,036	37,221
10,000	24,057	9,564	86,003	23,261	12,357	36,985
11,000	19,536	9,232	75,433	19,203	10,713	36,274
12,000	16,415	9,342	66,079	15,317	9,262	33,282
13,000	15,694	9,921	58,319	12,131	7,587	29,009
14,000	13,821	9,225	51,204	9,826	6,054	26,092
15,000	12,734	8,173	45,789	7,812	4,635	23,293
17,000	12,023	6,487	35,865	4,962	2,706	17,362
19,000	11,733	5,185	31,829	3,461	1,875	13,304
21,000	12,077	4,346	33,497	2,904	1,678	10,528
23,000	11,496	4,083	36,403	2,679	1,621	8,452
25,000	11,679	4,217	38,481	2,823	1,495	6,838
27,000	13,283	4,782	38,997	2,539	1,264	5,909
29,000	17,416	6,048	39,041	2,223	1,162	5,598
31,000	20,624	6,351	38,319	1,946	1,153	5,385

Study Sites 81 and 80 WUA (ft^2)

	Study Site 81			Study Site 80		
Flow (cfs)	BCH AFDW	Total AFDW	Diversity	BCH AFDW	Total AFDW	Diversity
3,250	99,986	54,842	227,268	0	0	0
3,500	98,479	54,476	222,166	0	0	0
3,750	96,875	54,142	217,592	203	102	48,405
4,000	95,637	54,099	213,598	490	228	50,730
4,250	93,603	54,756	209,433	3,453	1,602	52,635
4,500	91,590	56,037	204,987	1,879	815	53,981
4,750	89,857	56,510	199,907	2,292	959	55,531
5,000	88,425	56,467	195,181	3,495	1,429	56,672
5,250	86,649	56,015	191,597	4,588	1,834	57,673
5,500	84,830	55,412	188,734	5,654	2,213	58,480
6,000	81,267	54,250	183,179	8,352	3,095	60,170
6,500	75,358	51,387	176,183	11,647	3,638	61,698
7,000	70,514	48,448	169,509	14,650	5,129	63,485
7,500	65,326	45,380	161,975	17,728	6,077	65,068
8,000	60,493	42,539	154,601	20,807	6,966	66,542
9,000	51,559	37,178	140,350	24,886	8,090	69,793
10,000	44,326	32,249	127,014	26,447	8,591	72,419
11,000	39,729	28,287	116,411	28,008	9,135	74,142
12,000	36,597	25,467	107,520	27,168	8,867	73,356
13,000	35,359	24,886	100,276	25,715	8,251	69,782
14,000	33,185	23,401	94,205	23,777	7,500	63,927
15,000	31,043	21,657	89,071	22,217	6,681	56,715
17,000	27,319	17,997	79,351	19,450	5,621	47,479
19,000	24,488	15,478	72,667	16,867	4,575	40,623
21,000	22,174	14,004	66,069	14,488	3,777	35,209
23,000	20,914	13,057	61,645	12,131	3,204	32,335
25,000	20,871	12,109	58,093	10,494	2,846	28,869
27,000	20,139	11,270	54,541	9,473	2,718	25,683
29,000	20,322	11,302	52,226	8,755	2,692	24,542
31,000	19,644	10,233	49,309	7,857	2,619	22,862

Study Sites 61/63 and 52 WUA (ft^2)

	Study Site 61/63			Study Site 52		
Flow (cfs)	BCH AFDW	Total AFDW	Diversity	BCH AFDW	Total AFDW	Diversity
3,250	273,812	103,145	507,419	2,415	954	21,614
3,500	287,260	106,358	523,877	2,745	1,048	21,431
3,750	298,523	109,436	539,991	2,659	999	21,065
4,000	308,154	112,327	552,197	2,517	955	20,656
4,250	315,895	114,867	563,338	2,404	924	20,042
4,500	322,292	117,108	572,196	2,344	903	19,353
4,750	328,255	119,509	579,484	2,082	783	18,417
5,000	333,798	121,708	584,403	2,045	764	17,567
5,250	338,976	123,732	586,835	2,014	774	16,824
5,500	343,540	125,394	587,804	2,057	791	16,243
6,000	349,610	127,154	590,495	2,116	812	15,188
6,500	350,665	126,723	587,653	2,127	809	14,230
7,000	347,576	124,581	585,210	2,014	777	13,509
7,500	341,914	121,033	582,939	2,157	817	12,992
8,000	333,023	115,987	576,502	2,221	844	12,615
9,000	308,772	104,585	563,198	2,118	758	12,023
10,000	280,991	92,670	542,208	1,745	648	11,528
11,000	255,986	81,837	515,471	1,789	687	11,388
12,000	239,033	72,720	481,392	1,562	640	11,119
13,000	222,898	65,015	454,203	1,526	648	10,807
14,000	204,998	57,741	424,236	1,898	745	10,775
15,000	185,225	50,441	395,518	1,879	780	10,979
17,000	141,448	36,479	332,270	2,816	1,076	11,603
19,000	99,283	25,386	286,523	2,886	1,048	11,356
21,000	69,290	18,299	244,372	2,955	1,043	11,194
23,000	52,754	14,177	211,381	3,271	1,029	11,054
25,000	43,866	11,730	178,551	2,709	776	9,739
27,000	35,664	9,416	147,906	2,639	733	9,609
29,000	31,555	8,732	115,001	2,044	603	9,703
31,000	29,132	8,393	96,175	1,745	523	9,634

Above Hawes Hole Study Site and Study Site 28 WUA (ft^2)

	Above Hawes Hole Study Site			Study Site 28		
Flow (cfs)	BCH AFDW	Total AFDW	Diversity	BCH AFDW	Total AFDW	Diversity
3,250	172,965	61,376	446,238	3,532	1,113	15,920
3,500	173,492	60,870	437,777	3,323	1,085	15,565
3,750	172,986	59,987	427,842	3,327	1,034	15,209
4,000	171,641	58,964	417,746	3,423	1,006	14,865
4,250	170,112	57,877	408,478	3,484	1,017	14,564
4,500	169,025	56,618	399,953	3,522	1,018	14,348
4,750	168,605	55,369	392,268	3,541	1,016	14,176
5,000	168,885	54,271	384,604	3,525	1,017	13,907
5,250	169,402	53,303	377,715	3,466	1,016	13,562
5,500	169,509	52,388	370,654	3,413	1,034	13,358
6,000	167,421	50,569	356,349	3,571	1,110	13,745
6,500	163,062	48,696	340,849	3,712	1,108	14,058
7,000	159,348	47,113	322,302	3,746	1,119	14,208
7,500	155,333	45,757	306,458	3,697	1,110	14,144
8,000	150,802	44,250	296,577	3,542	1,057	13,778
9,000	139,973	39,597	284,338	3,539	1,012	13,336
10,000	125,119	35,168	270,216	4,364	1,339	13,014
11,000	112,805	31,525	255,976	4,663	1,492	12,895
12,000	103,150	28,784	241,251	5,158	1,556	14,154
13,000	95,217	26,460	230,239	5,293	1,620	15,543
14,000	86,025	23,628	215,127	5,426	1,860	16,738
15,000	79,448	22,256	200,832	5,173	1,875	17,050
17,000	65,681	19,518	179,283	4,540	1,713	16,275
19,000	58,555	18,411	161,372	4,835	1,565	14,757
21,000	56,047	17,159	142,492	4,958	1,367	13,057
23,000	55,133	16,034	127,197	4,907	1,279	12,583
25,000	49,847	14,936	114,549	3,559	971	12,594
27,000	45,090	15,164	114,345	2,171	753	12,099
29,000	41,775	14,692	114,571	1,882	790	11,603
31,000	39,331	14,638	113,085	1,777	880	9,591

Powerline Riffle Study Site and Study Site 15/17 WUA (ft^2)

	Powerline Riffle Study Site			Study Site 15/17		
Flow (cfs)	BCH AFDW	Total AFDW	Diversity	BCH AFDW	Total AFDW	Diversity
3,250	188,357	60,633	335,973	201,177	97,370	403,204
3,500	177,001	57,253	331,387	200,294	94,701	398,080
3,750	165,355	53,787	324,358	198,335	91,568	392,343
4,000	154,440	50,418	314,929	195,429	87,995	388,436
4,250	143,418	47,092	302,906	191,242	84,103	380,589
4,500	133,515	43,949	289,591	186,183	80,091	373,399
4,750	124,215	40,817	274,941	180,478	75,639	365,918
5,000	116,196	37,846	259,926	174,299	71,045	362,290
5,250	108,209	35,079	245,029	167,507	67,483	356,004
5,500	100,276	32,528	230,045	160,296	62,349	350,353
6,000	85,174	27,674	202,404	145,097	54,366	342,216
6,500	72,010	23,218	177,507	131,653	47,908	328,330
7,000	60,999	19,332	155,538	120,954	42,872	313,218
7,500	51,720	15,877	137,013	111,621	38,290	294,995
8,000	43,691	13,024	122,525	102,533	34,981	275,372
9,000	28,503	8,262	96,218	88,619	31,637	231,714
10,000	17,136	4,800	74,830	80,862	29,721	202,479
11,000	9,055	2,549	58,663	75,773	28,372	186,333
12,000	4,380	1,232	43,970	68,063	25,510	171,370
13,000	2,301	729	30,828	60,777	22,252	156,847
14,000	2,120	624	20,893	54,116	19,524	142,606
15,000	1,982	512	14,305	50,333	17,278	132,204
17,000	1,636	424	8,288	40,049	13,731	111,717
19,000	1,604	485	7,610	32,131	11,468	98,454
21,000	2,452	769	7,484	26,031	9,331	89,902
23,000	2,873	1,211	10,818	19,626	8,243	85,774
25,000	3,013	746	7,897	20,390	8,289	80,309
27,000	3,514	885	8,581	21,418	8,996	77,876
29,000	3,542	927	9,794	23,917	10,050	73,666
31,000	3,684	988	10,764	25,888	10,150	68,796

Study Site 9 and Price Riffle Study Site WUA (ft^2)

	Study Site 9			Price Riffle Study Site		
Flow (cfs)	BCH AFDW	Total AFDW	Diversity	BCH AFDW	Total AFDW	Diversity
3,250	20,581	8,773	82,322	161,006	50,149	254,964
3,500	19,849	8,906	75,369	157,109	47,792	254,017
3,750	18,568	8,557	69,965	152,406	45,413	257,407
4,000	17,201	8,200	65,853	146,744	42,948	258,860
4,250	16,350	7,813	62,646	140,253	40,182	256,804
4,500	15,823	7,513	60,342	134,042	37,738	257,321
4,750	15,274	7,337	58,383	128,198	35,435	256,374
5,000	14,488	7,040	56,553	122,396	33,013	256,008
5,250	13,702	6,718	54,820	117,412	31,194	254,512
5,500	12,884	6,440	53,109	112,676	29,590	252,725
6,000	10,420	5,185	48,889	103,947	27,235	248,409
6,500	10,485	5,202	48,405	98,403	25,876	244,437
7,000	9,651	4,959	46,629	95,110	24,951	237,645
7,500	8,743	4,637	44,670	90,061	23,699	222,306
8,000	8,287	4,222	42,345	87,295	22,882	206,182
9,000	8,537	3,991	38,987	80,255	21,577	179,326
10,000	8,692	4,012	36,565	77,575	21,389	165,947
11,000	8,689	3,779	35,618	75,971	20,776	153,396
12,000	7,910	3,303	33,992	74,787	19,875	140,339
13,000	6,812	2,682	31,893	74,109	18,790	131,341
14,000	5,597	2,003	28,923	74,357	17,896	122,417
15,000	4,461	1,555	26,888	72,548	16,786	116,508
17,000	3,494	1,208	24,100	59,793	12,852	107,940
19,000	4,908	1,659	22,776	40,635	8,847	97,661
21,000	5,851	1,826	22,163	26,190	5,955	85,368
23,000	5,395	1,755	23,422	20,050	4,506	70,953
25,000	5,117	1,832	25,855	15,630	3,636	55,585
27,000	6,276	2,379	27,889	12,385	2,718	41,779
29,000	8,496	3,077	28,686	10,158	2,361	32,625
31,000	12,411	4,332	32,668	8,587	2,127	27,355

APPENDIX C
SEGMENT HABITAT MODELING RESULTS

Baetid/Chironomid/Hydropsychid Ash Free Dry Weight WUA (ft^2)

Flow (cfs)	Segment 6 Boards In	Segment 6 Boards Out	Segment 5	Segment 4
3,250	140,272	1,245,457	13,319,917	7,500,753
3,500	152,047	1,189,874	13,642,372	7,118,663
3,750	162,659	1,123,783	13,906,018	6,718,450
4,000	173,275	1,059,358	14,135,774	6,332,682
4,250	182,605	987,162	14,264,112	5,935,117
4,500	191,174	913,599	14,328,297	5,569,426
4,750	198,381	836,186	14,391,106	5,220,991
5,000	204,532	780,334	14,453,776	4,911,891
5,250	209,225	695,652	14,488,262	4,604,066
5,500	212,529	625,494	14,490,460	4,296,541
6,000	253,074	542,834	14,315,364	3,701,949
6,500	246,357	402,736	13,989,229	3,195,852
7,000	212,497	320,099	13,742,511	2,783,796
7,500	183,026	255,734	13,381,979	2,422,429
8,000	203,813	218,748	12,901,676	2,115,995
9,000	180,173	191,252	11,843,655	1,548,746
10,000	146,331	181,829	10,627,765	1,165,461
11,000	112,803	176,882	9,602,793	902,222
12,000	95,823	168,150	8,776,383	737,155
13,000	83,735	157,147	8,134,231	657,405
14,000	85,526	147,373	7,385,173	635,287
15,000	90,199	142,094	6,648,108	616,728
17,000	93,151	135,343	5,135,411	526,806
19,000	89,132	146,599	3,883,686	416,302
21,000	79,061	168,854	3,171,658	348,779
23,000	61,805	216,873	2,783,418	305,270
25,000	56,645	311,213	2,510,764	284,150
27,000	55,275	401,745	2,336,462	284,303
29,000	44,197	494,813	2,322,514	284,764
31,000	52,722	528,881	2,354,354	292,817

Total Ash Free Dry Weight WUA (ft^2)

Flow (cfs)	Segment 6 Boards In	Segment 6 Boards Out	Segment 5	Segment 4
3,250	49,910	396,412	5,148,138	2,473,285
3,500	53,415	377,309	5,198,325	2,347,409
3,750	56,441	354,068	5,242,180	2,215,012
4,000	59,527	332,509	5,288,030	2,083,773
4,250	62,235	309,783	5,312,254	1,951,783
4,500	64,824	286,958	5,326,924	1,826,578
4,750	67,247	264,146	5,329,768	1,701,035
5,000	69,292	247,687	5,326,839	1,580,497
5,250	71,336	224,543	5,312,507	1,469,491
5,500	73,050	204,840	5,289,249	1,365,644
6,000	96,202	188,115	5,206,193	1,171,234
6,500	88,743	143,679	5,078,044	1,002,289
7,000	74,694	122,757	4,915,165	860,411
7,500	60,836	106,045	4,752,777	731,727
8,000	74,531	92,959	4,548,310	629,332
9,000	64,796	79,626	4,095,249	470,276
10,000	53,654	72,564	3,626,409	363,853
11,000	40,961	67,738	3,228,889	291,077
12,000	32,292	61,755	2,907,415	239,099
13,000	26,183	56,369	2,666,466	208,093
14,000	27,431	51,128	2,380,728	189,638
15,000	28,578	48,094	2,107,289	172,721
17,000	28,216	47,407	1,608,424	140,135
19,000	26,376	53,239	1,245,113	115,229
21,000	23,428	65,416	1,023,780	100,639
23,000	17,738	90,170	908,778	104,086
25,000	16,259	130,033	848,332	84,896
27,000	15,496	156,854	829,498	86,979
29,000	13,127	171,348	856,458	90,835
31,000	14,861	164,827	853,175	92,856

Shannon Diversity Index WUA (ft^2)

Flow (cfs)	Segment 6 Boards In	Segment 6 Boards Out	Segment 5	Segment 4
3,250	822,910	2,227,267	27,617,613	13,455,370
3,500	802,996	2,198,659	27,791,476	13,264,048
3,750	793,838	2,162,282	28,182,965	13,022,775
4,000	789,938	2,123,085	28,294,227	12,706,776
4,250	788,564	2,076,255	28,357,323	12,277,125
4,500	791,312	2,026,953	28,244,835	11,825,440
4,750	799,049	1,974,917	28,158,714	11,327,328
5,000	811,323	1,933,995	28,042,231	10,836,032
5,250	824,862	1,867,130	27,859,458	10,334,015
5,500	836,875	1,806,038	27,662,406	9,832,212
6,000	853,776	1,699,313	27,195,091	8,906,032
6,500	852,226	1,532,127	26,613,187	8,059,358
7,000	840,741	1,385,886	26,102,922	7,285,034
7,500	793,506	1,241,003	25,414,525	6,559,866
8,000	823,258	1,105,361	24,773,595	5,943,303
9,000	761,176	866,646	23,585,379	4,799,744
10,000	682,155	685,970	22,251,555	3,934,640
11,000	609,177	560,308	20,935,841	3,305,334
12,000	533,006	484,926	19,476,545	2,725,885
13,000	425,271	450,818	18,247,996	2,225,735
14,000	373,007	445,871	16,888,823	1,831,419
15,000	340,369	440,613	15,666,637	1,575,341
17,000	323,299	460,096	13,265,187	1,282,381
19,000	303,443	528,513	11,508,367	1,182,472
21,000	297,030	602,830	10,035,832	1,102,407
23,000	284,750	695,560	8,914,546	1,136,089
25,000	265,193	784,064	7,902,803	949,278
27,000	201,568	815,900	7,293,186	881,437
29,000	190,536	836,830	6,664,849	843,183
31,000	162,912	827,644	6,192,428	823,242