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VARIABILITY IN FLOW–HABITAT RELATIONSHIPS AS A FUNCTION OF TRANSECT NUMBER FOR PHABSIM MODELLING†

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ABSTRACT

A bootstrap analysis was used to assess the variability in flow–habitat relationships for juvenile and adult rainbow trout (*Oncorhynchus mykiss*) in the Cache La Poudre River as a function of the number of Physical Habitat Simulation System (PHABSIM) transects. The bootstrap analysis was conducted by selecting without replacement different numbers of transects, ranging from six to 40, from a pool of 107 transects. The variability in flow–habitat relationships, as quantified by the 95% confidence interval for the flow with the peak habitat, decreased with increasing numbers of transects, and was greater for juveniles than for adults. The 95% confidence limits ranged from 9% for adult trout with 40 transects to 73% for juvenile trout with six transects. The results of this study can be used in negotiations for the number of transects selected during scoping of instream flow studies, as well as in assessing the relative confidence that should be placed in flow–habitat relationships for different species and life stages. Published in 2005 by John Wiley & Sons, Ltd.

KEY WORDS: Instream Flow Incremental Methodology (IFIM); rainbow trout; Physical Habitat Simulation System (PHABSIM); bootstrap analysis; hydropower relicensing

INTRODUCTION

The Physical Habitat Simulation System (PHABSIM) component of the Instream Flow Incremental Methodology (IFIM) is still the most commonly used technique for predicting potential habitat for aquatic species with changes in stream flow (Annear *et al*., 2002). By applying species- and life-stage-specific habitat suitability criteria for depth, velocity, substrate and cover, PHABSIM predicts depth and velocity across a channel and combines these with substrate or cover into a habitat index known as weighted useable area (WUA) (Bovee, 1982; Milhous *et al*., 1989). The WUA output is generally simulated for river reaches over a range of stream flows.

The number of transects to be used for PHABSIM studies in hydropower relicensing is frequently a point of contention between resource agencies and hydropower operators, because there are no clear guidelines in the IFIM literature describing how many transects are necessary to produce reliable flow–habitat relationships (Payne *et al*., 2003). Payne *et al*. (2003) found that, for 616 instream flow studies, the median number of transects per reach was eight, with a maximum of 71 transects in a large high-gradient stream. Williams (1996) concluded that more than 15 transects were needed to develop a meaningful flow–habitat relationship for juvenile chinook salmon (*Oncorhynchus tschawytscha*), while Payne *et al*. (2003) concluded that six to ten transects were needed for simple reaches and 18–20 transects for reaches with more complex habitat. The purpose of this study was to investigate how the variability in flow–habitat relationships changes with the number of transects used to develop the relationships using PHABSIM.

METHODS

The US Geological Survey Fort Collins Science Center (USGS) provided me with PHABSIM data files for a total of 107 transects of six habitat types (Table I) from a 9 km section of the Cache la Poudre River, located

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Table I. Number of transects and percentage of total habitat for each habitat type. Definitions of the habitat types are given in Thomas and Bovee (1993)

Habitat type	Number of transects	Percentage of total habitat
Pocket water	20	18.7
High-gradient riffle	22	10.3
Low-gradient riffle	11	20.6
Deep pool	26	24.3
Shallow pool with boulders	17	15.9
Shallow pool without boulders	11	10.3

approximately 75 km west of Fort Collins, Colorado (Thomas and Bovee, 1993). The PHABSIM files included average water column velocities, water surface elevations, riverbed elevations, cell cover categories, and site discharges. Water surface elevations were measured at three to five calibration flows for each transect, ranging from 0.93 to 11.16–19.94 m^3/s. Velocity sets were typically collected at the highest flow. The USGS also provided habitat suitability criteria (HSC) (Figure 1) for active juvenile (7–17 cm total length) and adult (greater than 17 cm total length) rainbow trout (*Oncorhynchus mykiss*). The HSC were developed from microhabitat use data collected on the Cheesman–Decker reach of the South Platte River (Thomas and Bovee, 1993). Thomas and Bovee (1993) found that these HSC were transferable to the above section of the Cache la Poudre River.

I calibrated the hydraulic data in the PHABSIM files following procedures in Milhous *et al.* (1989). The calibrated files were used to simulate hydraulic conditions at each transect for 30 flows ranging from 0.42 m^3/s (40% of the lowest calibration flow) to 24.07 m^3/s (2.5 times the highest calibration flow for all of the transects). The HSC in Figure 1 were then used to calculate WUA for each transect at each of the 30 simulation flows. The percentages of total habitat in Table I were used to weight each transect, with the results summed for all transects, to generate the overall flow–habitat relationships for juvenile and adult rainbow trout.

A bootstrap analysis (Efron and Tibshirani, 1993) was used to construct flow–habitat curves using 6, 11, 20, 31 and 40 transects. For each number of transects, the transects used to represent each habitat type in Table II were randomly selected without replacement. For the analyses with more than six transects, the number of transects per habitat type was selected to equalize the percentage of stream represented by each transect, with transects selected proportional to habitat types present. The transects of each habitat type were weighted by the percentages of total habitat in Table I, and then summed. This process was repeated for 200 replicates for each of the five transect sample sizes. The number of replicates should be large enough to ensure that the results are stable. The above analysis was conducted using the WUA for both adult and juvenile rainbow trout. Because the flow at which the WUA had its maximum value (hereafter called the peak flow) is the most commonly examined characteristic of flow–habitat relationships, it was selected as an index of the shape of the flow–habitat curves. The minimum, mean and maximum peak flows from the 200 replicates were calculated, as well as the 95% confidence limits (computed as 1.96 times the standard deviation) around the mean peak flow.

RESULTS

The peak flows for the flow–habitat curves constructed using all 107 transects were 9.20 and 4.25 m^3/s for, respectively, adult and juvenile rainbow trout (Figure 2). Variability in flow–habitat relationships decreased with increasing numbers of transects (Table III, Figures 3 and 4) for both adult and juvenile rainbow trout. The rate of change of variability decreased with increasing numbers of transects, and the mean peak flow did not demonstrate much change with the number of transects (Table III). The flow–habitat relationships for juvenile rainbow trout showed more variability than the flow–habitat relationships for adult rainbow trout.

DISCUSSION

The primary difference between the methods used in this study and in Williams (1996) was selecting transects without replacement in this study. Selecting transects with replacement, as was done by Williams (1996),

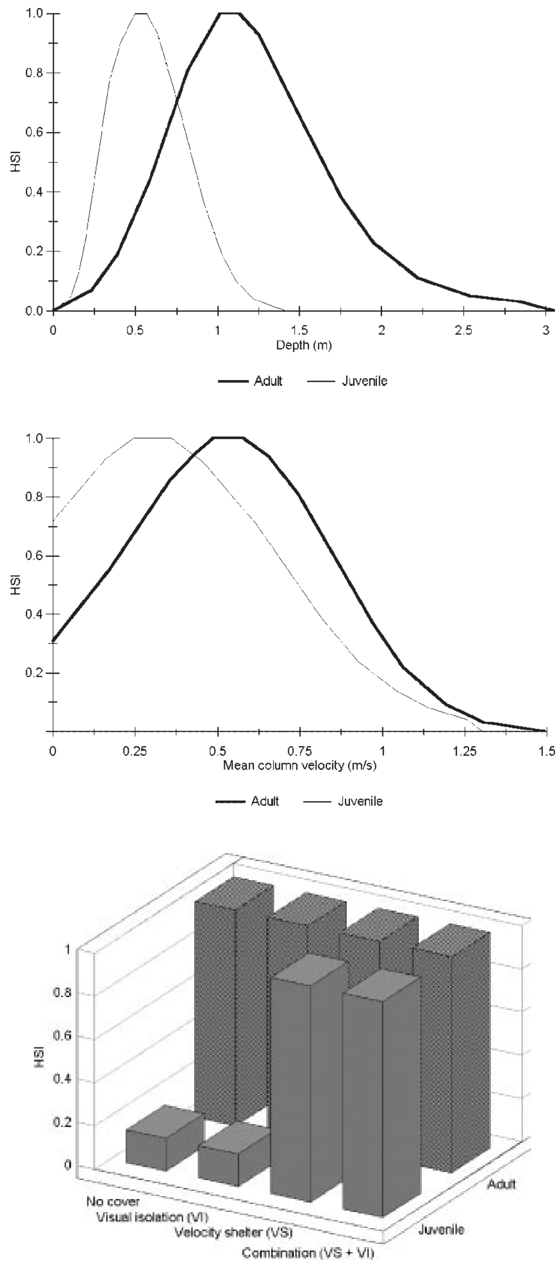

Figure 1. Habitat suitability criteria used in this study

overestimates the variability that would be expected in a real PHABSIM study, since in a real PHABSIM study, the same transect would not be selected more than once. Selecting transects without replacement more realistically captures the variability that would be associated with transect selection in a real PHABSIM study. However, selecting transects without replacement would artificially decrease the estimates of variability as the number of transects selected approaches the total number of transects, since more and more of the same transects would be included in the replicates. At the limit, if all of the transects were selected, there would be no variability, since in every replicate all of the transects would be used. I avoided this problem in this study by restricting the number of transects to less than half ($N_{\max} = 40$) of the total number of transects. The above illustrates that a bootstrap analysis cannot be

Table II. Number of transects of each habitat type used in the bootstrap analysis

Habitat type	Number of transects				
	6	11	20	31	40
Pocket water	1	2	4	6	8
High-gradient riffle	1	2	4	6	8
Low-gradient riffle	1	1	2	3	4
Deep pool	1	3	5	8	10
Shallow pool with boulders	1	2	3	5	6
Shallow pool without boulders	1	1	2	3	4

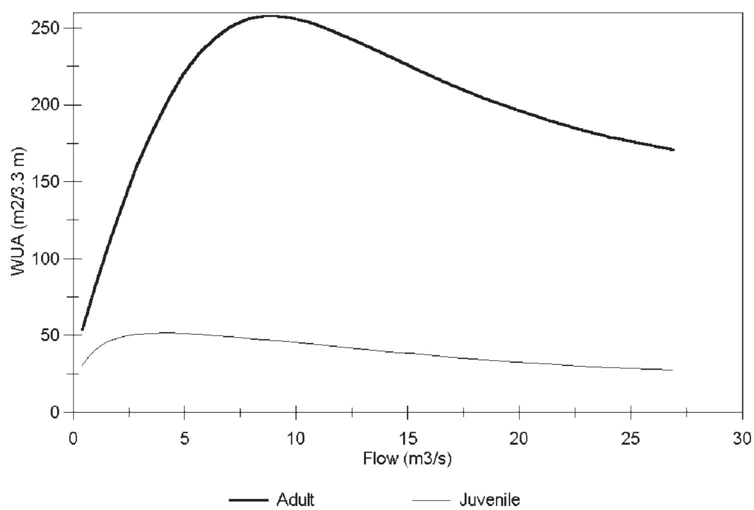

Figure 2. Flow–habitat relationships for juvenile and adult rainbow trout computed using all 107 transects

Table III. Results of bootstrap analysis, showing the minimum, mean and maximum flows associated with the highest WUA value from each set of bootstrap replicates, and 95% confidence limits on the mean, expressed as a percentage of the mean

Life stage	Number of transects	Flow (m^3/s)			95% Confidence limit (%)
		Minimum	Mean	Maximum	
Adult	6	7.08	8.89	14.16	± 26
Adult	11	7.08	8.95	11.33	± 17
Adult	20	7.79	9.03	10.62	± 13
Adult	31	7.79	8.92	9.91	± 10
Adult	40	7.79	8.86	9.91	± 9
Juvenile	6	1.98	4.42	12.74	± 73
Juvenile	11	1.98	4.30	11.33	± 60
Juvenile	20	2.41	4.36	9.91	± 40
Juvenile	31	2.41	4.16	6.37	± 28
Juvenile	40	2.83	4.13	4.96	± 25

used in most instream flow studies, since a large number of total transects would be needed to conduct the analysis. The main differences between this study and Payne *et al*. (2003) are the use of field-collected HSC in this study, compared to generic HSC in Payne *et al*. (2003), and the use of a more statistically rigorous analysis in this study, compared to visual comparison of repeat sampling by sample size in Payne *et al*. (2003). The large number of transects available for this study also helped to prevent convergence of habitat–flow relationships associated with

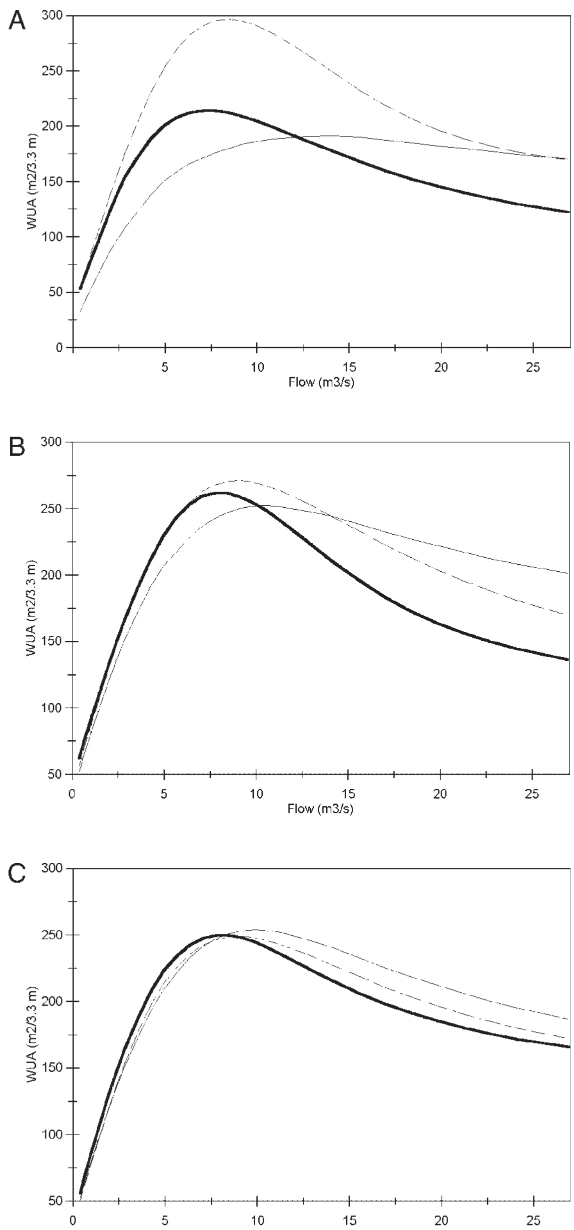

Figure 3. Representative bootstrap replicates of adult rainbow trout flow–habitat relationships. The replicates shown are examples of replicates with the minimum (heavy line), mean (dashed line) and maximum (thin line) flow at the highest weighted useable area value. Number of transects used: (A) 6; (B) 20; (C) 40

larger subsamples becoming a greater proportion of the flow–habitat relationship derived from all of the transects, as noted by Payne *et al*. (2003).

The results of this study can be used as a guide in selecting the number of transects to use in instream flow studies. For example, I would recommend using 31 transects if the goal was to be within 10% of the true population mean of flow–habitat relationships for adult trout, while I would recommend using 40 transects if the goal was to be within 25% of the true population mean of flow–habitat relationships for juvenile trout. The choice of the number of transects should not be viewed as an absolute requirement, but as a tradeoff between the cost of the study and

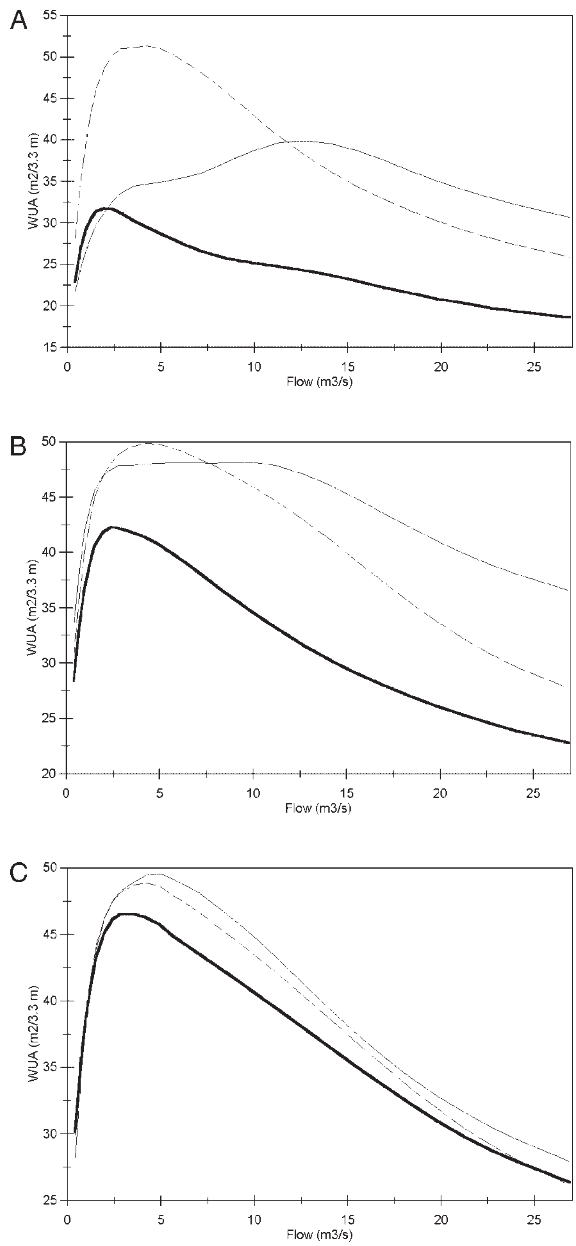

Figure 4. Representative bootstrap replicates of juvenile rainbow trout flow–habitat relationships. The replicates shown are examples of replicates with the minimum (heavy line), mean (dashed line) and maximum (thin line) flow at the highest weighted useable area value. Number of transects used: (A) 6; (B) 20; (C) 40

the reliability of the results. In situations in which more reliable results are needed, such as with an endangered species, it would be appropriate to have more transects to ensure more reliable results. In contrast, in a stream with only planted trout, for example, it might be appropriate to be satisfied with less reliable results. The tradeoff between cost and reliability could be factored into the negotiations between hydropower operators and resource agencies during study scoping. For example, for a stream which has limited hydropower generation potential, there might be a tradeoff of only having six transects, but implementing a flow regime based on 100% of the peak flow for the adult flow–habitat relationship.

An important result of this study is the finding that there is more variability in flow–habitat relationships for species or life stages, such as rainbow trout juvenile or fry, which have more restrictive habitat requirements. Since fry and juveniles are typically restricted to low velocities due to bioenergetic constraints, fry and juvenile habitat tends to be limited to only a few cells per transect, located on the stream margins. This effectively reduces the sample size used in the flow–habitat relationships, since the sample size is more related to the total number of cells, rather than the number of transects. Less confidence should be given to fry and juvenile flow–habitat relationships due to the greater variability in flow–habitat relationships due to smaller sample sizes, versus adult flow–habitat relationships. This also suggests that more transects would be required if fry or juvenile habitat is judged to be the limiting life stage, rather than adult habitat. Alternatively, this could be viewed as another opportunity for negotiations in the study planning process: if agreement is reached that adult habitat is the limiting life stage, then resource agencies may agree that less transects are required.

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