Hydraulic Complexity Metrics for Evaluating In-Stream Brook Trout Habitat

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Abstract: A two-dimensional hydraulic model (River2D) was used to investigate the significance of flow complexity on habitat preferences of brook trout (*Salvelinus fontinalis)* in the high-gradient Staunton River in Shenandoah National Park, Virginia. Two 100-m reaches were modeled where detailed brook trout surveys (10–30-m resolution) have been conducted annually since 1997. Spatial hydraulic complexity metrics including area-weighted *circulation* and *kinetic energy gradients* (KEG) were calculated based on modeled velocity distributions. These metrics were compared to fish density in individual habitat complexes (10–30-m subreaches) to evaluate relationships between fish location and average flow complexity. In addition, the fish density was compared to additional habitat variables including percent cascade (CS), pool (PL) and riffle, and in-stream (ISC_N) and riparian cover. There were negative correlations between modeled mean velocity (VEL) and maximum depth (MAXD) and fish density; however, there were no statistically significant correlations between KEGs or area-weighted circulation and fish density. Fish density was negatively correlated to ISC_N and positively correlated to the percent of the channel dominated by protruding boulders (BD) and CS. The structural complexity of cascade habitat and areas with protruding boulders creates complex flow patterns indicating that flow complexity plays an important role in brook trout habitat preferences at the local scale. Linear discriminate analysis was used to further investigate the relationships between habitat variables and fish density. Using backward stepwise variable selection, the final explanatory model contained the BD, ISC_N, MAXD, PL, and VEL variables. These observations indicate that at a coarse spatial scale hydraulic complexity may be an important component in fish habitat preferences; however, other habitat variables cannot be ignored and the hydraulic complexity metrics calculated using 2D modeling results were not explanatory. While spatial hydraulic complexity metrics provide quantifiable measures for evaluating stream restoration project impacts on in-stream habitat quality, the relationships between fish density and hydraulic complexity were not straightforward. This is likely due in part to modeling limitations in this high-gradient complex stream. Further research is needed at a range of spatial scales, stream types, and fish species to fully investigate the use of hydraulic complexity metrics to quantify in-stream habitat.

DOI: 10.1061/(ASCE)HY.1943-7900.0000197

CE Database subject headings: Aquatic habitats; Fish management; Hydraulic models; Two-dimensional models; Mountains; Rivers and streams; Boulders; Virginia.

Author keywords: Aquatic habitats; Hydraulic models; Two-dimensional models; Mountain streams; Boulders.

Introduction

Interest in river and stream restoration has increased dramatically over the past two decades. Conservative estimates place river restoration costs for the continental United States in excess of $14 billion since 1990 with more than $400 million spent on restoration projects in the Chesapeake Bay Watershed alone (Bernhardt et al. 2005; Hassett et al. 2005). The most commonly stated restoration goals include water quality, riparian management, in-stream habitat, fish passage, and bank stabilization (Bernhardt et al. 2005). This research focuses on the interdisciplinary linkage between aquatic ecology and engineering that must occur for successful stream restoration by addressing the lack of consistent methods to evaluate stream restoration projects. Understanding the relationships between structural complexity and hydraulic complexity will result in quantifiable metrics for evaluating stream restoration projects' impacts on in-stream habitat quality. The overall goal of this research was to assess the hydraulic characteristics of in-stream habitat that need to be considered for successful stream habitat restoration. The specific goals of this research were to quantify in-stream hydraulic complexity using metrics to describe flow structure, quantify the relationship between hydraulic complexity and fish habitat preferences, and ultimately, using metrics determined to be biologically relevant, evaluate in-stream habitat structures for their ability to create preferred hydraulic conditions for fish.

In-stream habitat refers to the physical habitat or "living" space of in-stream biota that encompasses the channel's physical structure and the spatial and temporal dynamics of the flow regime (Maddock 1999). The most important reach-scale abiotic factors that affect fish in running water are temperature (directly

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Note. This manuscript was submitted on November 6, 2008; approved on December 29, 2009; published online on November 15, 2010. Discussion period open until May 1, 2011; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Hydraulic Engineering***, Vol. 136, No. 12, December 1, 2010. ©ASCE, ISSN 0733-9429/2010/12-1067–1076/$25.00.

and indirectly through oxygen consumption), rate of flow and fluctuation in discharge, and availability of suitable shelter (substratum) (Hynes 1970); however, mesohabitat characteristics including depth, velocity, substrate, and cover are important to fish for spawning, feeding, and refugia during high flows (Maddock 1999; Rempel et al. 1999; Schwartz and Herricks 2005; Smith et al. 2006).

In many ecological systems, biotic diversity is positively correlated with habitat heterogeneity (Bell et al. 1991; Rosenzweig 1995). Habitat heterogeneity in streams has been shown to be related to macroinvertebrate taxon richness, fish species diversity and density, periphyton, and processing of coarse particulate organic matter (Gorman and Karr 1978; Biggs and Stokseth 1996; Brown 2003; Lepori et al. 2005b). In-stream habitat heterogeneity can refer both to substrate and flow characteristics such as depth or velocity. The spatial heterogeneity (or variability) of flow is associated with the hydraulic complexity within a stream. Aquatic organisms often inhabit and utilize complex flow patterns such as eddies, transverse flows, and velocity gradients (Fausch and White 1981; Hayes and Jowett 1994; Biggs et al. 1997; Rempel et al. 1999), while other complex hydraulic characteristics such as turbulent kinetic energy have been found to predict salmonid density (Smith et al. 2006).

Tritico and Hotchkiss (2005) evaluated turbulence parameters downstream of natural boulders in gravel-bed streams with varying degrees of roughness. Their findings, using isolated boulders, confirm that natural boulders create vertically oriented vortex structures. The kinetic energy in these flow structures can be used by swimming fish (Videler et al. 1999; Enders et al. 2003; Liao et al. 2003). In addition, locally accelerated streamwise velocity around obstructions provides favorable migration corridors for juvenile salmonids as it provides mean velocities that are greater than average reach velocities with low relative turbulence (Tritico and Hotchkiss 2005).

To describe in-stream hydraulic conditions with potential biological importance, metrics were proposed by Crowder and Diplas (2000, 2002, 2006) including vorticity, circulation, and kinetic energy gradients in an effort to quantify the flow variability that many species exploit. *Vorticity* (ξ) is a point metric that represents twice the rate that a fluid element rotates about its vertical axis [for two-dimensional (2D) flow]

$$\xi = \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right) \tag{1}$$

where v = velocity in the x direction and u = velocity in the y direction. Vorticity created by exposed boulders and spur dykes can generate important habitat such as scour holes (Shields et al. 1995) and can be exploited by macroinvertebrates feeding on drifting material (e.g., Way et al. 1995). The modified *circulation* metric (CRC) proposed by Crowder and Diplas (2000) is the average absolute vorticity per unit area and represents a means to quantify area-weighted flow complexity

$$|\xi|_{\mathrm{AVE}} = \frac{\int\int_{A_{\mathrm{tot}}} |\xi| dA}{A_{\mathrm{tot}}} = \mathrm{CRC} \tag{2}$$

where $|\xi|$ = absolute value of the vorticity and A_{tot} = area of the region of interest. Kinetic energy gradients (KEG) quantify the spatial rate at which a flow's kinetic energy is changing around a point (or the average spatial change in kinetic energy between two points) and may be used to describe salmonid feeding locations where fish rests in relatively slow-moving water that is adjacent to faster water that transports food (e.g., Crowder and Diplas 2006). The KEG between two points can be estimated as

$$\left|\frac{\partial}{\partial x}\frac{V^2}{2}\right| \cong \left|\frac{2V_{\mathrm{AVE}}\dfrac{V_2 - V_1}{\Delta x}}{V_1^2}\right| = \mathrm{KEG} \tag{3}$$

where V = velocity magnitude and Δx = distance between two points. Shields and Rigby (2005) used the flow complexity metrics developed by Crowder and Diplas (2000,2002,2006) to discriminate between flow patterns upstream and downstream of an obstruction. However, no studies have been conducted to evaluate whether or not these metrics are biologically relevant at different spatial scales. Specifically, no studies address the following questions: (1) Do fish prefer flow structures identified by flow complexity metrics? (2) Can these metrics be used to predict the location of fish populations? (3) Can they be used to guide or evaluate stream habitat restoration? This study addresses the last two questions at a coarse (>10-m) spatial scale.

Several hydraulic models have been used to simulate in-stream habitat suitability. The physical habitat simulation model (PHABSIM) is a well-established hydro-ecological model that provides a suite of tools for the numerical modeling of hydraulic habitat suitability for fish and invertebrate species based on field measurements of channel slope, water depth, velocity, and substrate (Bovee 1982; Maddock 1999; Booker and Dunbar 2004); however, PHABSIM is one-dimensional (1D) and averages velocity, substrate, and depth values between measured cross sections and cannot account for the range of habitat types or physical conditions adjacent to a location within a stream (Maddock 1999; Waddle 2001). Two- and three-dimensional (3D) hydraulic models have been used to calculate flow characteristics in streams as a measure of habitat suitability (Booker 2003; Crowder and Diplas 2006; Clark et al. 2008; Shen and Diplas 2008). The advantage of 2D and 3D habitat models over the conventional 1D models (e.g., PHABSIM) is the ability to spatially determine depth, velocity, and flow direction, allowing the user to evaluate areas of particular ecological importance, such as refugia from high flows (Shen and Diplas 2008). Similar to PHABSIM, a 2D hydraulic model such as River2D (Steffler and Blackburn 2002) can be combined with habitat suitability indices for target species to predict the weighted usable area (WUA) or relative amount of preferred habitat available to a target species (Ghanem et al. 1996; Steffler and Blackburn 2002). However, WUA ignores local flow complexity and structure and predicts habitat suitability based on single-point flow and depth requirements for a particular species while in reality, the spatial distribution of WUA provides a more realistic view of habitat within the stream. Previous research using River2D found reach-averaged WUA that did not correlate to fish populations and the distribution of usable habitats was a better determining factor (Clark et al. 2008).

Channel alterations, such as straightening and removal of flow obstructions, result in a loss of physical habitat diversity. Traditionally, engineers concerned primarily with flood mitigation eliminated complexity from streams. In reverse, many restoration projects aim to restore some level of complexity to streams. Common in-stream habitat restoration or improvement activities include the addition of boulders and large woody debris (LWD) (Bernhardt et al. 2005). Other stream restoration practices such as weirs (low dams) and deflectors are used for habitat enhancement (Biron et al. 2005; de Jalon and Gortazar 2007). It is difficult to quantify the success of these habitat restoration projects since the success of a restoration project is dependent on the specific goals

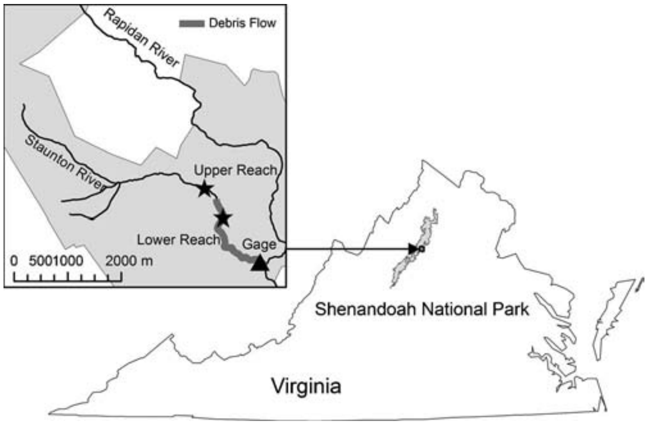

Fig. 1. Staunton River is located in Shenandoah National Park

of the project. There is evidence, however, that goals of increased fish biodiversity and density are not always met by changes to the in-stream physical habitat (Bond and Lake 2003; Lepori et al. 2005a; Thompson 2006). While it is probable that there are other factors inhibiting fish populations, such as water quality (e.g., Bond and Lake 2003), there is a need to better understand the relationship between stream restoration practices and the resulting changes to in-stream habitat. The literature related to the flow characteristics created by in-stream structures is limited (e.g., Biron et al. 2005), although the biological importance of flow characteristics is assumed. Recent studies (Lepori et al. 2005b; de Jalon and Gortazar 2007) indicate the need for more research to define habitat characteristics important to hydraulic modeling and stream restoration.

Methods

Study Site

The Staunton River is a second-order headwater stream originating on the eastern slope of the Blue Ridge Mountains in Shenandoah National Park (SNP), Virginia (Fig. 1). This river flows approximately 6.5 km to its confluence with the Rapidan River and drains approximately 11 km^2 (Hyer et al. 1995). The average channel width is 3.5 m and the average channel gradient is 10%. The channel consists of pools separated by step-pool cascades, small (<2-m) waterfalls, and bedrock slides and has been subject to long-term flow and water-quality monitoring (Department of Environmental Sciences at the University of Virginia, Charlottesville). There are two primary fish species in the Staunton River: brook trout *Salvelinus fontinalis* and blacknose dace *Rhinichthys atratulus*. In June 1995, a debris flow completely eliminated brook trout from the lower 1.9 km of the Staunton River and removed trees from a 30-m band in the riparian area (Roghair et al. 2002). The June 1995 storm and resulting debris flow are described by Karish et al. (1997).

Brook Trout Population Density

This study focused on brook trout (*Salvelinus fontinalis*), a valuable native game fish in Virginia. We evaluated hydraulic complexity in two 100-m reaches on the Staunton River. The Staunton River was chosen as a study site because there are long-term (11 years) and high resolution (sampled every 10–30 m) brook trout data available from previous studies. The brook trout data used in this study were collected as part of a recolonization and postrecolonization brook trout movement study (Roghair et al. 2002; Roghair 2005). Beginning in 1997, brook trout were sampled biannually (May and October) in a continuous 1-km reach of the Staunton River: 575 m in the debris flow affected area and 390 m in the unaffected area of the stream (above the debris flow). The total brook trout abundance data set used in this study ranges from 1997 to 2004 in autumn (mid-October) and from 1997 to 2007 in spring (mid-May to mid-June). To locate fish, the river was subdivided into habitat complexes (10–30-m subreaches comprised of multiple pools and riffles and terminating at potential low flow barriers). Brook trout were captured by making a single pass through each habitat complex with a backpack electrofishing unit (73% fist pass capture efficiency; Roghair 2005). The length (mm), weight (g), and location of capture (habitat complex) were recorded for each fish (Roghair 2005). From this larger data set, brook trout abundance data for two modeled 100-m reaches were used in our study to evaluate hydraulic characteristics of brook trout habitat preferences. The lower reach was within the debris flow affected area, and the upper reach was approximately 600-m upstream. The study reaches were chosen using the following criteria: at least five habitat complexes, no tributaries over the study reach, single channel, and no major waterfalls or wood jams. The average channel gradient within the study reaches is 7%.

Habitat Survey

To characterize habitat within each reach, a field survey was conducted to measure in-stream cover (ISC), riparian cover (RC), LWD, and areal percent of pool (PL), riffle (RF), or cascade (CS) in each habitat complex. Each habitat complex was visually divided into percent pool, riffle, and cascade habitat. Riffles and pools were identified using descriptions similar to those in Gordon et al. (2004). Cascades were steeper areas with larger (boulder) bed material. The areal percent of the stream channel dominated by protruding boulders (BD) was visually estimated. RC was measured within each habitat complex using a convex densitometer. Four densitometer measurements, one each facing upstream, left bank, right bank, and downstream, were averaged. The amount of ISC within each habitat complex was estimated in the field by measuring the horizontal width and length of undercut boulders, banks, or overhanging vegetation. The volume of large wood (>1 m in length and >10 cm diameter) within the channel was quantified. The measured ISC area and large wood volume were normalized by the length of each habitat complex (ISC_N; LWD_N). Reach-wide pebble counts were conducted to characterize bed substrate (Wolman 1954). Substrate samples were collected in each reach on two different days with 100 pebbles collected in a representative riffle and 100 pebbles collected in a representative pool. On the second sampling date, a substrate sample (100 random pebbles) was collected in a transition area (or a segment of stream that was not classified as pool or riffle).

Hydraulic Modeling

A 2D hydraulic model (River2D) was used to calculate the spatial distribution of velocity vectors needed to calculate flow complexity metrics such as those described by Crowder and Diplas (2006) following the procedure outlined by Steffler and Blackburn

(2002). The metrics were compared to spatially and temporally extensive fish data to determine which are relevant to habitat preferences.

Typical input to River2D includes bed topography, initial roughness estimates, discharge at the upper cross section, and water surface elevations at the downstream cross section (Steffler and Blackburn 2002). Bed topography was measured in each 100-m reach by detailed electronic total station surveys ($>2,400$ points per reach; >1 point/0.5 m^2). To accurately represent complex topography, the shape of each boulder was captured by surveying the apex(es) of large boulders and surveying a minimum of four points around the base. Initial bed roughness values were obtained from standard pebble counts. A finite element triangular computational mesh consisting of approximately 100,000 nodes was created for each reach.

The primary calibration factor for River2D is the roughness factor, k_s, and the model was calibrated by minimizing the mean absolute error (MAE) between measured depth and velocity values and model output (Lacey and Millar 2004). Velocity was measured using a 3D acoustic Doppler velocimeter (SonTek FlowTracker Handheld ADV) at three cross sections and a minimum of 25 additional points throughout each reach (right, left, and center every 5–10 m). Velocity measurements with high numbers of spikes, high signal to noise ratio variation, or with boundary condition interference were either repeated in the field or removed prior to calibration. Each velocity, depth, or water surface measurement was surveyed to overlay the measurement with the model results. The Shenandoah Watershed Study (SWAS) maintains a continuous discharge gauge (1993–2006) on the Staunton River approximately 2-km downstream of the lower study reach near the confluence with the Rapidan (Fig. 1). Flows in the study reach were calculated by adjusting the measured discharge by the watershed size. The discharge measurements corresponding to the brook trout sampling dates ranged from base flow (0.02 m^3/s) to 0.3 m^3/s. The model was calibrated at the middle model flow (0.2 m^3/s) within the lower reach. The calibration was then checked at high flow (0.8 m^3/s) in the lower reach and low flow (0.1 m^3/s) in the upper reach.

River2D allows adjustment of flow options including the upwinding coefficient of the Petrov-Galerkin finite-element scheme used to solve the hydrodynamic equations. Because this model was run as steady state, the default value of 0.5 was used. For this study, default values were also used for the groundwater flow options, storativity and minimum depth for groundwater flow. The transmissivity parameter was changed to 0.05 from the default value of 0.1 to reduce the loss of flow to groundwater (Steffler and Blackburn 2002). This value was chosen to minimize the loss of flow to groundwater while not dramatically increasing the model run time. River2D models transverse turbulent shear stresses with a Boussinseq type eddy viscosity with three user definable coefficients (Steffler and Blackburn 2002). The first term, ε_1, is a constant that can be used to stabilize the solution for very shallow flows. The second term, ε_2, is an eddy viscosity bed shear parameter that typically ranges from 0.2 to 1.0. The default value suggested in the River2D manual is 0.5 (Steffler and Blackburn 2002). The third term, ε_3, represents the horizontal shear and can become important in deeper lake flows or flows with high transverse velocity gradients. In general, River2D is insensitive to values of ε_2 (Lacey and Millar 2004). The sensitivity of this River2D model to these terms was evaluated by varying the values of ε and comparing to the calibration flow of 0.2 m^3/s in the lower reach.

Typical output of River2D includes depth, water surface elevation, and velocity in two dimensions (across and downstream) (Fig. 2). The model was run at three different flows to coincide with select brook trout sampling dates, 0.1, 0.2, and 0.3 m^3/s. Base flow sampling dates were excluded from this analysis because of the instability of the model at low flows. Velocity vectors from each run were exported on a 0.10-m grid and used to calculate flow complexity metrics. The mean vorticity and KEG within each habitat complex were calculated, and the vorticity values were used to calculate the modified circulation (area-weighted metric that allows comparison of flow complexity between habitat complexes and reaches).

Statistical Analysis

Statistical analyses were performed on habitat variables and flow complexity variables between and among reaches. The habitat variables included RC (%), ISC_N (m^2/m), LWD_N (m^3/m), D_{50} (mm), RF (%), PL (%), and CS (%). The analyses also included the areal percent protruding boulders estimated during the habitat survey BD (%). The flow variables used in statistical analyses included area-weighted circulation (CRC), maximum depth (MAXD), mean velocity (VEL), and mean KEG.

To compare reach-level differences in fish, habitat, and flow variables, the groups were compared using SigmaPlot [SigmaPlot, Version 10, Systat Software, Inc., San Jose, Calif. (2007)]. Variables that passed the normality and equal variance test were analyzed using a t-test. Variables that failed the normality or equal variance test were compared using a nonparametric Mann-Whitney Rank Sum test (Conover 1999). The results for the 0.2-m^3/s modeled discharge were used to compare the differences in hydraulic complexity between reaches. Differences in brook trout abundance sampled in each habitat complex were analyzed using the nonparametric Kruskal-Wallis one-way ANOVA on ranks (Ott and Longnecker 2001). Similarly, differences in brook trout abundance by sampling date were evaluated.

To examine the importance of the habitat and flow complexity variables on brook trout density, the habitat and hydraulic variables were compared to the brook trout density (fish/area) for each reach individually and for the reaches combined. Spearman's rank nonparametric correlation coefficients were calculated using JMP software [JMP, Version 7, SAS Institute, Inc., Cary, N.C. (1989)] (*JMP Statistics and Graphics Guide* 2007).

Finally, the brook trout data were divided into four groups based on quartiles ranging from low density (A) to high density (D). Stepwise discriminant analysis, a multivariate technique, was used to evaluate the ability to classify the brook trout into density groups based on hydraulic complexity and habitat variables. General trends in the variable means for the predicted classification groups were evaluated. This analysis was conducted using JMP software.

Results

Hydraulic Model Results

The calibration MAEs at 0.2 m^3/s for water surface elevations were 0.05% (0.05 m), 25% (0.06 m) for depth, and 48% (0.12 m/s) for velocity. At the 0.8-m^3/s flow, the MAEs for water surface elevations were 0.06% (0.06 m), 27% for depth (0.07 m), and 45% (0.14 m/s) for velocity values. These values are higher than other River2D calibration values reported in the literature (Lacey and Millar 2004; Hayes et al. 2007); however, these were

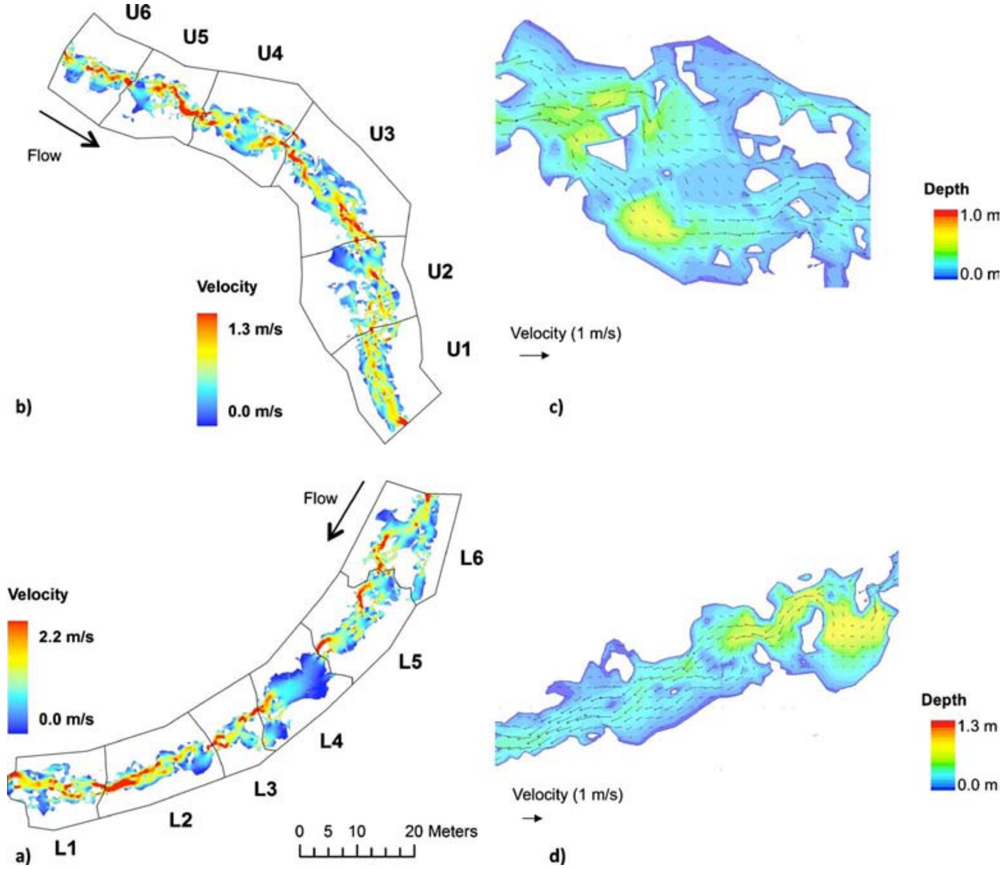

Fig. 2. Modeled velocity in (a) lower; (b) upper reach for the 0.3-m^3/s model run. Modeled velocity vectors and depth for the 0.3-m^3/s run for habitat complex: (c) U4; (d) L2 (see Table 1).

the minimum absolute errors achieved by adjusting the roughness factor, k_s, and the eddy viscosity parameters and are indicative of the issues of modeling complex systems such as the Staunton River. The model results were also checked at low (0.1-m^3/s) flows on the upper reach resulting in MAEs of 0.07% (0.07 m), 30% (0.06 m), and 56% (0.12 m/s) for water surface elevation, depth, and velocity, respectively.

The model was most sensitive to the ε_2 eddy viscosity coefficient; changing this value to 0.2 and 1.0 resulted in a change in velocity values of 0.02 and 0.1%, respectively. In general, increasing this value resulted in faster flows behind obstructions and slower flows midstream compared to the default value, while decreasing ε_2 resulted in slower flows behind obstructions and faster flows in midstream. Using the 0.2-m^3/s flow in the lower reach to calibrate, the final eddy viscosity coefficients values were 1.0, 0.01, and 0.1 for ε_2, ε_1, and ε_3, respectively. The predicted depth and velocity for the 0.3-m^3/s flow are shown in detail in Fig. 2.

Reach Scale Comparison

Over the time period of this study, within the modeled reaches, the abundance of brook trout normalized by the length was significantly different between habitat complexes and sampling dates (Mann-Whitney Rank Sum test; $p<0.001$; Figs. 3 and 4); however, there was no significant difference in brook trout abundance between seasons (spring and fall) or between reaches (lower and upper) (Fig. 5).

Differences between the two reaches were most evident in the habitat survey results. The median value for the upper reach was 87.8% RC, while the median value for the lower reach was 54.9% (Table 1). These values are significantly different ($p=0.002$; Mann-Whitney rank sum test). The mean ISC_N was 0.38 m^2/m in the lower reach and 0.17 m^2/m in the upper reach; these values were also significantly different ($p=0.011$; t-test). The percent of each habitat complex characterized as pool was also significantly different between reaches ($p=0.027$; t-test). The mean in the lower reach was 50.8% covered by pools and 28.3% of the wetted area in the upper reach was characterized as pool. In general, the substrate in the debris flow lower reach was larger than that in the upper reach (Table 2). The LWD_N, RF, CS, and BD habitat variables were not significantly different between reaches. In addition, the hydraulic variables, MAXD, VEL, KEG, and CRC were not significantly different between reaches (Table 3).

The debris flow affected reach (lower) had more pool area, more ISC, and less RC. The debris flow event (June 1995) removed all vegetation from a 30-m band in the riparian area (Roghair et al. 2002); therefore, the vegetation in the lower reach was a maximum of 13 years old at the time of the RC measurements. It is likely that the difference in ISC between reaches was also due to the effects of the 1995 debris flow. The majority of the measured ISC was attributed to the underside of boulders within the channel. In the upper reach, these spaces have been filled in with sediment, while the lower reach is most likely still redistributing boulders from the debris flow. The hydraulic variables were not significantly different between reaches; however, these vari-

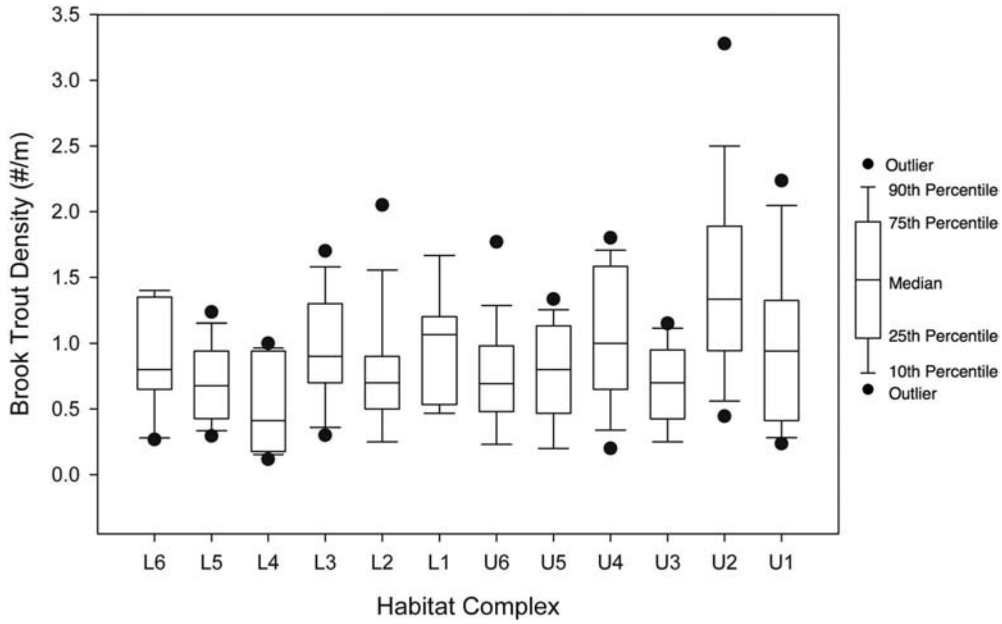

Fig. 3. Brook trout caught per unit length of stream in each habitat complex combining all sampling dates (Fall 1997–2004 and Spring 1997–2007)

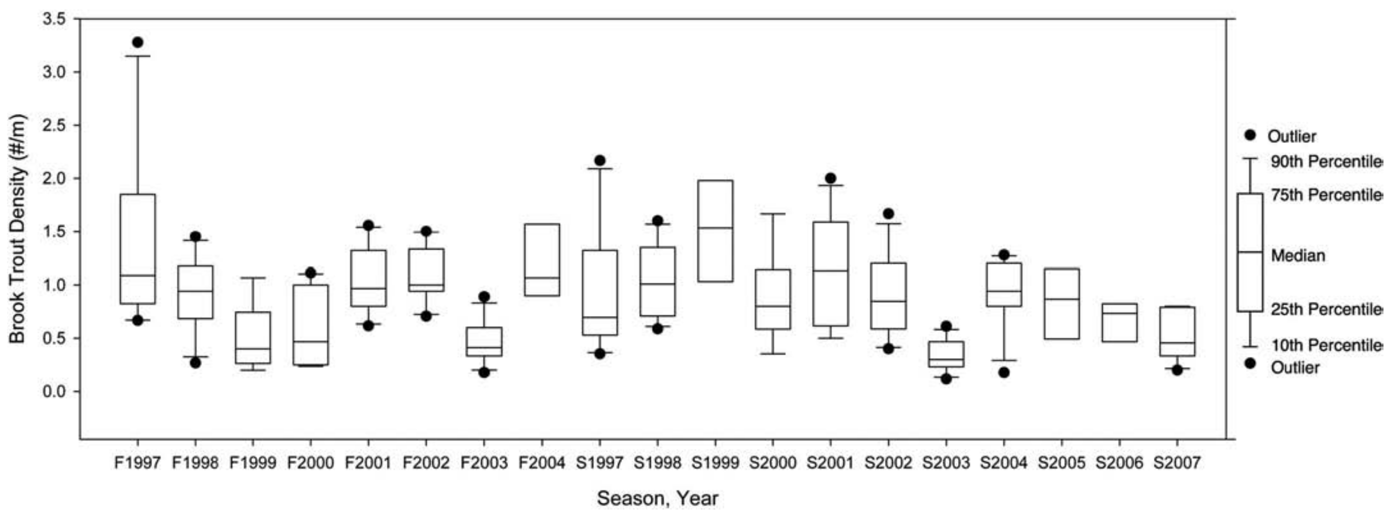

Fig. 4. Brook trout per unit length stream length for each sampling date for all habitat complexes within the study reaches. F signifies sampling dates in fall (October) and S signifies spring sampling dates (late May/early June)

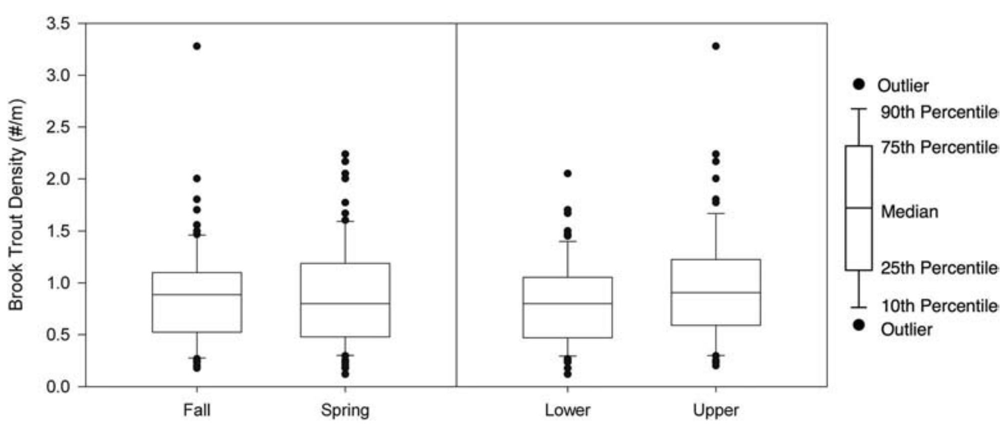

Fig. 5. Brook trout caught per meter stream length: (a) during fall and spring sampling; (b) in upper and lower reaches on the Staunton River

Table 1. Habitat Survey Variables and Mean Brook Trout Counts for Each Habitat Complex on the Lower and Upper Study Reaches of the Staunton River

Habitat complex[a]	Length (m)	RC	In-stream cover (ISC_N) (m^2/m)	LWD_N[b] volume (m^3/m)	Riffle (RF)	Pool (PL)	Cascade (CS)	Boulders (BD)	Number of brook trout/m (mean ± SD)
L1	15	38.5	0.45	0.01	40	40	20	50	0.96 ± 0.41
L2	20	80.3	0.31	0	20	60	20	50	0.75 ± 0.49
L3	10	41.3	0.20	0	10	50	40	50	0.89 ± 0.44
L4	17	49.9	0.44	0	10	80	10	30	0.52 ± 0.34
L5	17	59.8	0.55	0.01	30	50	20	30	0.66 ± 0.33
L6	15	60.8	0.33	0.02	60	25	15	50	0.85 ± 0.38
U1	17	86.8	0.10	0.02	70	20	10	10	1.01 ± 0.59
U2	18	84.8	0.12	0.06	40	40	20	44	1.43 ± 0.69
U3	20	85.3	0.29	0	60	30	10	40	0.68 ± 0.29
U4	15	92	0.33	0.02	35	15	50	55	1.05 ± 0.49
U5	15	88.7	0.09	0.10	40	25	35	65	0.78 ± 0.36
U6	13	90.5	0.11	0	45	40	15	30	0.75 ± 0.39

[a]Habitat complexes were numbered progressing upstream in each reach. *U* refers to the upper (unaffected) reach. *L* refers to the lower (affected) reach.
[b]LWD_N is the volume of LWD measured per unit stream length.

ables were calculated with a 2D model that cannot account for 3D flow structure that could occur due to complex topography such as the underside of boulders.

Local Scale Comparison

Since we found no significant difference between the abundance of brook trout sampled in each reach, the results were combined to examine the habitat variables' influence on brook trout habitat preference (the number of brook trout sampled in each habitat complex) using a nonparametric correlation analysis. To evaluate habitat complexity, the brook trout density was compared to MAXD, VEL, KEG, and CRC within each habitat complex (Table 4). The brook trout density was not significantly correlated ($\alpha = 0.05$) to the KEG or CRC when both reaches were combined but was negatively correlated to both the MAXD and VEL metrics. For the habitat variables, the strongest significant ($\alpha = 0.05$) correlated variable was CS (Spearman's $\rho = 0.35$) followed by ISC_N ($\rho = -0.19$) and BD ($\rho = 0.18$).

CRC metric represents a means of calculating the 2D horizontal flow complexity, while the KEG metric quantifies the average spatial change in kinetic energy between two points. In general, brook trout density tended to increase with increasing flow complexity. This was evidenced by positive correlations with the CS and BD metrics. The reverse was true in the upper reach where brook trout density was negatively correlated to the CRC metric (Fig. 6). Further inspection of Fig. 6 indicates that there may be a threshold in brook trout habitat complexity somewhere between approximately 0.3 and 0.5 s^{-1}. In this study, KEG metrics were calculated for each point from the surrounding points and the

Table 2. Substrate Distribution in the Lower and Upper Reaches of the Staunton River

	Upper			Lower			Combined
	Pool	Riffle	Total	Pool	Riffle	Total	Total
D_{50}[a] (mm)	11	22	13	35	44	33	19
D_{84}[b] (mm)	150	160	150	300	310	300	270

[a]Median particle size.
[b]84th percentile particle size.

Table 3. Modeled Hydraulic Variables (0.2 m^3/s) for Each Habitat Complex on the Lower and Upper Study Reaches of the Staunton River

	Flow 0.1 m^3/s				Flow 0.2 m^3/s				Flow 0.3 m^3/s			
Habitat complex	Maximum depth (MAXD) (m)	Mean velocity (VEL) (m/s)	Mean KEG (m^{-1})	Area-weighted circulation (CRC) (s^{-1})	Maximum depth (MAXD) (m)	Mean velocity (VEL) (m/s)	Mean KEG (m^{-1})	Area-weighted circulation (CRC) (s^{-1})	Maximum depth (MAXD) (m)	Mean velocity (VEL) (m/s)	Mean KEG (m^{-1})	Area-weighted circulation (CRC) (s^{-1})
L1	0.50	0.16	7.9	0.40	0.57	0.23	8.1	0.53	0.61	0.29	7.5	0.61
L2	0.69	0.17	9.0	0.40	0.78	0.24	5.9	0.49	0.85	0.30	6.4	0.50
L3	0.29	0.17	6.3	0.43	0.55	0.25	6.7	0.61	0.62	0.33	5.8	0.81
L4	1.12	0.07	8.3	0.12	1.22	0.11	7.8	0.18	1.27	0.14	6.9	0.26
L5	0.42	0.14	7.0	0.30	0.50	0.21	7.0	0.44	0.56	0.27	8.2	0.64
L6	0.41	0.12	10.9	0.26	0.50	0.19	6.3	0.36	0.55	0.24	6.1	0.46
U1	0.28	0.18	6.6	0.37	0.34	0.25	6.6	0.51	0.39	0.29	7.0	0.64
U2	0.43	0.12	7.3	0.31	0.51	0.19	7.7	0.45	0.55	0.23	6.6	0.51
U3	0.41	0.15	7.4	0.42	0.48	0.23	9.2	0.47	0.52	0.29	6.4	0.55
U4	0.44	0.16	6.3	0.35	0.55	0.22	5.0	0.45	0.59	0.28	6.4	0.53
U5	0.84	0.14	7.9	0.45	0.94	0.24	7.5	0.66	0.98	0.30	7.8	0.69
U6	0.45	0.16	10.5	0.51	0.56	0.23	7.8	0.65	0.62	0.28	9.6	0.62

Table 4. Spearman's Rank Correlation Coefficients (ρ) and *p*-Values Comparing Brook Trout Density to Habitat Variables; *p*-Values Less Than 0.05 Indicate Significant Correlations

Variable	Combined		Lower		Upper	
	ρ	*p*-value	ρ	*p*-value	ρ	*p*-value
CS	0.3486	<0.0001	0.549	<0.0001	0.2287	0.0533
PL	−0.0888	0.3005	−0.3374	0.0056	0.1239	0.2998
BD	0.1772	0.0376	0.4229	0.0004	0.3091	0.0115
ISC_N	−0.1912	0.0247	−0.3368	0.0057	−0.0106	0.9298
RC	0.0351	0.6826	−0.0801	0.5225	0.0145	0.9039
RF	−0.0333	0.6979	0.016	0.8982	−0.2382	0.0439
LWD_N	0.1445	0.0908	0.0378	0.7634	0.2041	0.0855
MAXD	−0.4148	<0.0001	−0.6775	<0.0001	−0.1193	0.3183
KEG	−0.0529	0.5376	−0.0872	0.4862	0.0448	0.7087
CRC	−0.1071	0.2112	0.2143	0.084	−0.4257	0.0002
VEL	−0.2108	0.0131	0.1148	0.3586	−0.528	<0.0001

mean KEG for each habitat complex was not significantly correlated to fish density. Stronger spatial changes in kinetic energy would be found in complex flows such as flows around an obstruction (boulder). Future work should identify and quantify the relative habitat area of specific circulation zones (wakes behind boulders) within each habitat complex and evaluate KEG based on predictions from Crowder and Diplas (2006) for ideal feeding habitat for brook trout (KEG from 4 to 14 m^{-1}). In this study, the average KEG in each habitat complex fell within this range indicating that there was significant flow complexity as represented by KEG in every habitat complex. Fish density was negatively correlated to both average velocity (VEL) and maximum depth (MAXD) in each habitat complex. These relationships indicate that velocity or depth characteristics are inadequate to represent brook trout habitat preferences in the complex flows created by boulders and other flow obstructions in Staunton River.

Discriminant Analysis

The importance of the habitat variables was further analyzed using linear discriminant analysis to classify the brook trout density into categories. Because the percent BD was highly correlated to the CS, the BD variable was included in all discriminant analyses. The discriminant analysis using habitat variables (LWD_N, PL, ISC_N, RC, and BD) misclassified 56% of the fish density samples. Or in reverse, predicted classifications of brook trout density-based habitat variables were only 44% correct indicating that these variables alone were not able to predict brook trout habitat preferences. When the brook trout densities were misclassified based on habitat variables, the mean misclassification was 1.51 categories. General trends between group means for the predicted trout density categories indicated that brook trout density increased as R increased, PL decreased, BD increased, and the large wood volume (LWD_N) increased (Table 5).

Linear discriminant analysis was again performed using the modeled hydraulic variables. When compared to the discriminant analysis for only the habitat variables, there is more separation between the brook trout density categories when the discriminant analysis is conducted using the modeled hydraulic variables; however, the hydraulic variables alone did not adequately categorize the brook trout habitat preferences (misclassified—51%; mean misclassification of 1.48 categories). In general, for the habitat complexes in this study, the brook trout density increased as MAXD and VEL decreased (Table 6) as predicted by the correlation analysis. As there were no correlations between KEG, CRC, and brook trout density, the relationship between brook trout density and the trend in predicted means of these variables is also not straightforward. The mean KEG had a maximum value at medium brook trout densities, while the area-weighted circulation metric had a minimum value at the same density. Although there is not much variation in the predicted means from the discriminant analysis, it is likely that there is a threshold flow complexity preferred by brook trout indicated by the lack of a straight forward correlation.

The best discriminant analysis model combined both the habitat variables and the hydraulic variables. While the brook trout density was misclassified 45% of the time, the majority of the misclassifications were by one fish density category (mean misclassification of 1.35 categories). Using backward stepwise variable selection ($\alpha = 0.1$), the final model contained the BD, ISC_N, PL, MAXD, and VEL variables. While hydraulic complexity metrics are not represented in this model, the nonhydraulic variable (percent BD) represents the structural complexity within the channel and certainly creates flow complexity; however, this flow complexity may be better represented using a 3D hydraulic model.

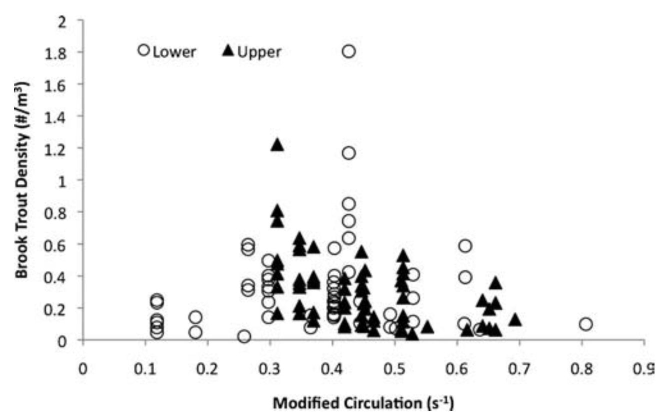

Fig. 6. Brook trout density and area-weighted circulation (CRC) in the lower (debris-flow affected) and upper reaches of the Staunton River

Table 5. Predicted Habitat Variable Means for Fish Density Categories Resulting from Discriminant Analysis

Fish density category	RC	% pool (PL)	% boulder (BD)	In-stream cover (ISC_N)	Large wood (LWD_N)
A (low)	50	80	30	0.4	0
B	71	55	41	0.1	0
C	73	26	40	0.3	0.01
D (high)	77	39	47	0.1	0.04

Conclusions

While our study was limited to one fish species in one stream, results indicate that metrics based on hydraulic engineering principles may be used to evaluate in-stream habitat at coarse spatial scales (10–30 m) but not without evaluating other nonhydraulic habitat parameters. The debris flow that disturbed the lower reach of this study site in 1995 appears to have lasting impacts on the stream structure and habitat. Although there were no significant differences in brook trout density between the reaches, there were differences in habitat variables, as well as which habitat variables were correlated to brook trout density. There was not a strong correlation among reaches between the CRC metric and brook trout density; however, there may be a threshold value for brook trout hydraulic complexity preferences (see Fig. 6), but more data over a larger area and range of flows would be needed to confirm this hypothesis. While velocity characteristics and flow structure play a role in the brook trout habitat preferences at the local scale (10–30 m), the relationships between variables are complex and difficult to predict as with any natural system.

Our results illustrate that hydraulic complexity metrics calculated from 2D hydraulic models can be useful in describing flow structure of in-stream habitat that cannot be modeled by 1D hydraulic models. However, the model did not accurately predict depth or velocity values particularly well because of the complex topography and steep slope of the stream. Therefore, the hydraulic modeling results of this study should not be used as predictive values but as a tool to evaluate trends in hydraulic complexity and brook trout habitat preferences. This study spanned 11 years and included both spring and autumn samplings providing a unique opportunity to evaluate hydraulic complexity metrics integrated over time at a coarse scale; however, to evaluate the applicability of hydraulic complexity metrics for habitat modeling and stream restoration, individual habitat areas such as wakes behind boulders need to be recognized.

Acknowledgments

The writers acknowledge the assistance of the SWAS for the use of flow data for the Staunton River and the field assistance of Bethany Bezak, Barb Utley, Sheila Ranganath, Alan Simpson, Kristine Bronnenkant, Andrea Ludwig, Jonathan Resop, and Craig Roghair (USFS). The writers would especially like to acknowledge the contribution of Julia Pryde and dedicate this work in her memory.

Table 6. Predicted Hydraulic Variable Means for Fish Density Categories Resulting from Discriminant Analysis

Fish density category	Maximum depth (MAXD) (m)	Mean velocity (VEL) (m/s)	Mean KEG (m^{-1})	Circulation (CRC) (s^{-1})
A (low)	0.73	0.21	7.3	0.45
B	0.57	0.16	7.7	0.38
C	0.42	0.16	8.1	0.37
D (high)	0.48	0.15	7.8	0.41

Notation

The following symbols are used in this paper:

A_{tot} = area of region of interest (i.e., habitat complexes);
BD = percent of wetted channel dominated by protruding boulders;
CRC = area-weighted modified circulation metric;
CS = percent characterized as cascade;
ISC_N = in-stream cover area normalized by habitat complex length;
KEG = average spatial change in kinetic energy between two points;
k = unit vector in vertical direction;
k_s = roughness height;
LWD_N = large wood volume normalized by habitat complex length;
MAXD = maximum depth in area of interest;
PL = percent characterized as pool;
RF = percent characterized as riffle;
u, v = velocity in x- and y-directions;
V = velocity magnitude;
VEL = average velocity in area of interest;
Δx = distance between two points;
ε_1 = River2D eddy viscosity constant;
ε_2 = River2D eddy viscosity bed shear parameter;
ε_3 = River2D eddy viscosity horizontal shear parameter; and
ξ = vorticity.

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