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MODELLING WHITEWATER PARK HYDRAULICS AND FISH HABITAT IN COLORADO

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ABSTRACT

Whitewater parks (WWPs) are increasingly popular recreational amenities, but the effects of WWPs on fish habitat and passage are poorly understood. This study investigated the use of a two-dimensional (2-D) model as compared with a three-dimensional (3-D) hydrodynamic model (FLOW-3D®) for assessing effects of WWPs on fish habitat. The primary aims of this study were to (1) examine the utility of 3-D modelling versus 2-D modelling in a hydraulically complex WWP and (2) compare modelled habitat quality for resident fishes with actual fish abundance and biomass generated from field sampling surveys. Two reaches of a wadeable river in Colorado were modelled: a natural reach and a reach containing a WWP. A 2-D habitat suitability analysis for juvenile and adult brown trout, juvenile and adult rainbow trout, longnose dace and longnose sucker predicted the same or higher habitat quality in the WWPs than the natural pools for all four species and for all modelled flow rates; however, results from fish sampling found significantly higher fish biomass for all four species in natural pools compared with WWP pools. All hydraulic metrics (depth, depth-averaged velocity, turbulent kinetic energy, 2-D and 3-D vorticity) had higher magnitudes in WWP pools than in natural pools. In the WWP pools, 3-D model results described the spatial distribution of flow characteristics or the magnitude of variables better than 2-D results. This supports the use of 3-D modelling for complex flows found in WWPs, but improved understanding of linkages between fish habitat quality and 3-D hydraulic descriptors is needed. Copyright © 2015 John Wiley & Sons, Ltd.

KEY WORDS: whitewater park; kayak; FLOW-3D; hydraulic modelling; flow complexity; fish habitat; habitat modelling; vorticity

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INTRODUCTION

Hydraulic condition in lotic systems is one of the many factors influencing stream ecosystem health and function (Lamouroux *et al*., 1995). Flow patterns and characteristics influence fish habitat in many ways, by creating cover, influencing oxygen availability, influencing quality and quantity of available food sources, regulating water temperature and shaping channel morphology (Poff *et al*., 1997). River engineering projects, such as dam construction, dredging, channelization or addition of instream habitat structures clearly create changes in these hydraulic conditions (Roni and Beechie, 2013). It is not always clear how such structural changes may positively or negatively influence habitat quality for fish and other aquatic organisms; however, fragmentation tends to have a negative impact on instream biota (Dudgeon *et al*., 2005).

For the last three decades, researchers have studied the effects of hydraulic conditions on fish habitat quality using the Physical Habitat Simulation model and other hydrodynamic modelling tools (Bovee, 1982; Booker *et al*., 2004), which rely on depth and depth-averaged velocity to predict fish habitat quality. The importance of other hydraulic variables, such as turbulence, vorticity, circulation, velocity gradients and kinetic energy gradients, has only recently been examined (Cotel and Webb, 2012; Lacey *et al*., 2012). Turbulence is a measurement of rapid velocity fluctuations. It can increase the energy expenditure of swimming and resting fish, cause bodily injuries at very high levels and can trigger or discourage migration, depending on the magnitude and context (Smith, 1975; Silva *et al*., 2012). Vorticity and circulation describe flow complexity, but it is unknown how specific organisms react to different amounts of flow complexity (Crowder and Diplas, 2002). Velocity gradients and kinetic energy gradients describe spatially varying flow that influences where a fish chooses to travel, feed, rest or conversely create conditions that fish choose to avoid; but again, the exact effects of different gradient scales on specific fish species is unknown (Crowder and Diplas, 2000).

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Much more research is necessary before clear correlations can be made between these variables and habitat quality (Kozarek *et al*., 2010).

Whitewater parks (WWPs) are built as a recreational amenity in many rivers, and as with the construction of other types of channel-spanning structures, they significantly alter hydraulic conditions. Specifically, they create an abrupt lateral flow constriction (chute), a high-velocity vertical drop and a downstream pool with substantial horizontal and vertical recirculation. It is widely assumed that the installation of WWPs has a positive effect on fish habitat quality because it increases pool area, which is a key component of healthy salmonid habitat and is often a primary goal of habitat-improvement projects in the USA (Larscheid and Hubert, 1992; Roni *et al*., 2008). Also, deeper pools are beneficial to fish because they provide cover and essential habitat during very low flows (Binns, 1994; Harig *et al*., 2000). In our experience, designers of WWPs generally assume they are adding features similar to engineered habitat-enhancement structures, such as cross vanes and j-hooks, and that WWPs should confer similar positive effects on fish habitat (e.g. McGrath, 2003); however, this assumption has yet to be demonstrated and tested rigorously.

Numerical modelling can be used to describe the hydraulic conditions found in WWPs. When building a model, it is important to identify the flow features of interest in each specific project and choose a one-dimensional (1-D), two-dimensional (2-D) or three-dimensional (3-D) numerical modelling method that accurately describes those features (Crowder and Diplas, 2000). 1-D and 2-D numerical modelling has been successfully applied to many natural river systems (Ghanem *et al*., 1996; Booker and Dunbar, 2004; Lacey and Millar, 2004), but understanding 3-D hydraulics is important in systems such as WWPs, which have a substantial vertical flow component (Lane *et al*., 1999) and complex horizontal and vertical velocity gradients (Booker *et al*., 2004).

There is a paucity of research specifically addressing the effects of WWPs on fish habitat or the use of 3-D modelling to simulate modifications of fish habitat. Habitat modelling, although common in natural and restored river reaches (Booker and Dunbar, 2004; Lacey and Millar, 2004), has not occurred in any published WWP studies. The primary limitation to research on this topic is that ecological functions important for assessing habitat have not been correlated to 3-D hydrodynamics (Pasternack *et al*., 2008). 2-D models of habitat quality can be powerful and important tools for managers, but they have many well-documented limitations, including simplified hydraulic inputs (Crowder and Diplas, 2000) and exclusion of other factors that may influence habitat quality and fish location preferences (Shuler and Nehring, 1993; Booker *et al*., 2004).

There is also little research that surveys on-the-ground biological or ecological conditions to evaluate the actual impacts of WWPs. This lack of information creates a problem for state wildlife agency personnel, who are asked to comment on the 404 permits required for WWP construction. They must provide their expert opinion without having many rigorous studies to inform that opinion.

This study addresses some of the gaps and limitations present when modelling the hydraulics and habitat conditions found within WWPs, using 3-D modelling to characterize and predict the complex 3-D nature of fish and aquatic habitat. The specific objectives are as follows: (1) describe and compare fish habitat quality in WWPs and natural reaches using a traditional method based on 2-D hydraulic modelling and habitat suitability criteria; (2) use 3-D modelling to describe and compare ecologically relevant hydraulic descriptors in WWPs versus natural reaches; (3) compare 2-D and 3-D hydraulic and habitat modelling results and examine whether 3-D modelling is justified for assessing habitat quality in WWPs; and (4) compare predicted fish habitat quality to actual estimates of abundance and biomass generated from fish sampling surveys.

METHODS

Site description

North St. Vrain Creek (Lyons, Colorado) drains an area of 322 km^2 of mostly forested land cover with some suburban development at the lower elevations. The natural snowmelt hydrology is highly regulated by upstream dams and diversions, and in a typical year, the flow varies between 0.1 and 11 cms. Within the study site, the channel is low gradient (1%) and has a cobble-dominated/boulder-dominated bed.

The study design included three WWP chute/pool structures located in the town of Lyons (‘WWP reaches’) and three natural riffle/pool reaches located approximately 1 km upstream of the WWP (‘natural reaches,’ which are not truly natural but have experienced much less channel manipulation than the WWP reaches) (Figure 1). This site was chosen for this study because of the following: (1) the stream was small enough to perform wading surveys under low-flow conditions, (2) the WWP structures in Lyons are representative of many other locations across Colorado (of 21 existing WWPs in Colorado, 66% of the locations are constructed using a similar grouted chute/drop approach), and (3) the study site is part of a larger study that includes investigating fish movements using passive integrated transponder tag technology. The WWP reaches were labelled WWP1, WWP2 and WWP3 (downstream to upstream), respectively, and the natural reaches were labelled NR1, NR2 and NR3 (downstream to upstream), respectively.

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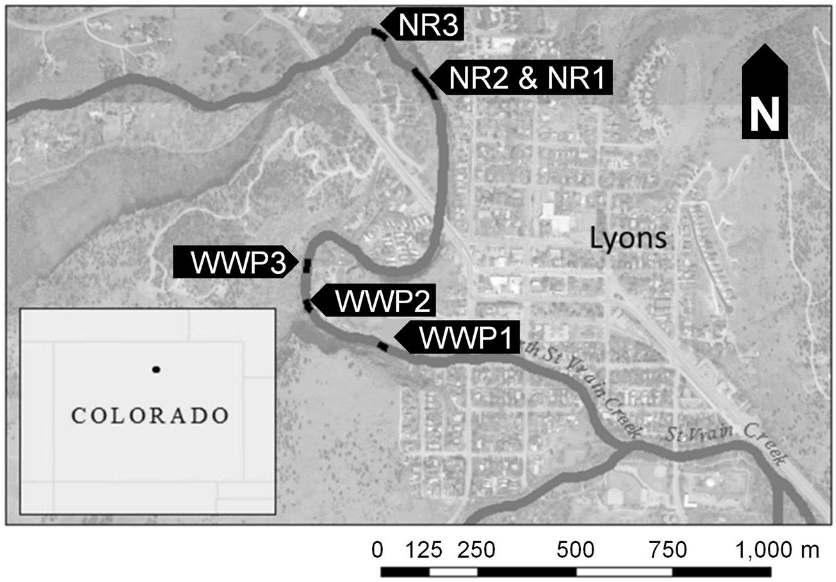

Figure 1. Map of study site

Bathymetric and hydrologic surveys

Bathymetry data were collected in the form of XYZ coordinates using a ground-based light detection and ranging system, a Leica Total Station (Leica Geosystems, Norcross, GA, USA) and a Topcon® HiPer XT™ (Topcon Corporation, Tokyo, Japan) global positioning system (GPS) base and rover system. The total station and GPS system were used to survey underwater cross sections, and breaklines and extra points were surveyed to increase resolution. Measured hydrologic data included water surface elevation, wetted perimeter location and velocity profiles. Velocity profiles were measured using an acoustic Doppler velocimeter and a Marsh McBirney flow metre.

Numerical hydraulic modelling

The 3-D computational fluid dynamics (CFD) software FLOW-3D® v10.0 (Flow Science Inc., Santa Fe, New Mexico, USA; hereafter referred to as FLOW-3D) was used to model each of the study reaches. FLOW-3D was chosen for this study over other 3-D CFD software packages because of its efficacy in accurately representing free-surface systems such as natural river channels. FLOW-3D uses Cartesian coordinates to create a hexahedral grid, also called a mesh, in the computational domain. Model input includes channel bathymetry, discharge at the upstream boundary, water surface elevation at the downstream boundary and a roughness approximation for the bed surface. Sensitivity analyses were performed to determine appropriate mesh size, roughness parameters and turbulence model. The final models had mesh sizes ranging from 3.81 to 15.24 cm, used a porous layer for roughness approximation (Carney *et al*., 2006) and used the default renormalization group turbulence closure with dynamically computed turbulent mixing length. Five different flow rates were simulated, two for validation of the models (low and medium) and three for habitat suitability calculations and hydraulic characterization (low, medium and high). All post-processing of hydraulic results (except habitat suitability calculations) were performed using EnSight® Standard v10.0.2 (CEI Inc., Apex, NC, USA; hereafter referred to as EnSight).

Model validation

In order to validate the 3-D modelling results, modelled variables were compared with measured conditions using velocity profiles, water surface elevation, wetted perimeter and observed locations of hydraulic features such as eddies and jumps. In every WWP reach, the flow profiles over the drop structure (the primary area of concern) validated well, with a maximum distance of 3 cm between the measured and modelled water surface profiles. Using a survey rod to measure water surface elevation adds a potential error of at least ±2 cm, so these results are well within the range of acceptable error. In downstream pools associated with each WWP structure, modelled water surface elevations differed by less than 1 cm from the measured elevations. The modelled velocity profiles in the three WWP validation simulations had error rates of less than 16%, which is within an acceptable error range based on the previous studies (Kozarek *et al*., 2010).

In the natural reaches, the error in water surface elevations was less than 5 cm, and it was determined that this amount of error was acceptable. Velocity profiles were not

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measured in the natural reaches, although the modelled velocities were deemed reasonable based on knowledge of the site.

Hydraulic output

FLOW-3D output used in this study included depth, depth-averaged velocity, point velocity and turbulent kinetic energy (TKE). Depth and depth-averaged velocity are often used for habitat modelling because their relationship with habitat quality is better understood than that of other hydraulic variables. Point velocities are often used to describe the actual conditions experienced by fish. TKE is a measurement of rapid velocity fluctuations, and it affects fish in both negative and positive ways (Silva *et al.*, 2012). 2-D vorticity (rotation of a particle around its vertical axis) and 3-D vorticity (rotation of a particle around all its axes), as defined in Crowder and Diplas (2002), are important descriptors of flow complexity, a key component in habitat quality. In this analysis, vorticity values were calculated using the calculator tool in EnSight.

2-D habitat modelling

The habitat suitability equations used in this analysis were based on data collected by Colorado Parks and Wildlife in the Cache la Poudre River, an adjacent watershed similar to the St. Vrain (Miller and Swaim, 2011). Input for these equations were generated through vertical averaging of 3-D model results, as 3-D habitat suitability index (HSI) data are not currently available. The species and life stages analysed in this study were juvenile and adult rainbow trout (*Oncorhynchus mykiss*), juvenile and adult brown trout (*Salmo trutta*), longnose dace (*Rhinichthys cataractae*) and longnose sucker (*Catostomus catostomus*). Adult trout were classified as having lengths greater than or equal to 150-mm total length (TL). Juvenile trout were classified as having lengths less than 150-mm TL. The hydraulic input for each species-specific habitat suitability equation included depth and depth-averaged velocity, and the output was an HSI value ranging between 0 (no habitat value) and 1 (optimal habitat). Each equation had upper limits for depth and velocity inputs. Any computational cell with a depth or velocity exceeding these limits was assigned an HSI value of 0. Any computation cell with an HSI value greater than 1, but with depth and velocity parameters within the predefined limits, was assigned a value of 1. HSI calculations were performed on the hydraulic output data from FLOW-3D using R statistical computing software (R Development Core Team, 2012). Contour plots showing habitat quality were developed for each reach. Any areas with an HSI value greater than 0 were deemed to have 'some' habitat, while areas with an HSI value greater than 0.5 were classified as 'good' habitat, following Miller (2013, pers. comm.). To compare habitat quality in WWP reaches and natural reaches, a Student's *t*-test and Wilcoxon signed-rank test were used. For this analysis, a result was considered significant only when *both* tests yielded $p \leq 0.05$.

Fish sampling

Colorado Parks and Wildlife conducted fish sampling of pools associated with WWP structures and adjacent natural pools. Electrofishing surveys were conducted within the same six pools that were evaluated in this current study using a shore-based electrofishing unit with four electrodes and a crew of 10 to 12 people. Fish surveys were conducted during low-flow periods in the fall (November/October) and spring (April/May) to correspond with the timing of brown and rainbow trout spawning. Spring and fall surveys occurred well before and after the summer period of heavy recreational use in the study site. Block nets were installed on upstream and downstream boundaries of each pool site to maintain our assumption of closure. Three passes were conducted through each pool site, and all individuals were identified to species, weighed (g) and measured (TL) to the nearest millimetre. Fish sampling results were used to generate estimates of fish abundance (number of fish/hectare) and biomass (kg ha^{-1}). Three-pass depletion estimation methods were used to generate fish abundance estimates (Seber and Whale, 1970), which were used to estimate fish density and fish biomass (Hayes *et al.*, 2007).

RESULTS

2-D and 3-D hydraulic variables

The modelled hydraulic conditions of the WWP pools were substantially different than the conditions found in natural pools based on results generated utilizing 2-D and 3-D modelling. The 2-D hydraulic results yielded a substantially different picture of flow conditions compared with a 3-D interpretation. In all contour plots, flow is from left to right, in the positive x-direction.

Depth. Model results showed that the maximum depth in the WWP pools (averaged for all WWP pools) was higher than the maximum depth in the natural pools (averaged for all natural pools) for all flow rates (Table I).

Velocity. The estimated maximum depth-averaged velocity was 46% to 188% greater in the WWP pools than in the natural pools for all flow rates (Table I), and the vertical velocity distribution was substantially different between the two types of pools. To visually depict differences in velocity, two representative pools were chosen, one WWP pool (WWP2) and one natural pool (NR3) (Figure 2). WWP2 was chosen because it had the most rapid and

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Table I. Maximum flow depth, depth-averaged velocity, TKE, 3-D vorticity and 2-D vorticity in WWP pools and natural pools for all flow rates

Metric	Flow rate	WWP pools	Natural pools
Maximum flow depth in all pools (m)	Low	1.5	0.6
	Medium	1.8	0.9
	High	2.1	1.1
Maximum depth-averaged velocity in all pools ($m\,s^{-1}$)	Low	2.3	0.8
	Medium	3.6	2.1
	High	3.8	2.6
Maximum TKE ($m^2\,s^{-2}$) in all pools (s^{-1})	Low	0.19	0.03
	Medium	0.40	0.17
	High	0.51	0.21
Maximum 3-D vorticity in all pools (s^{-1})	Low	9.3	4.5
	Medium	17.7	10.8
	High	17.7	8.3
Maximum 2-D vorticity in all pools (s^{-1})	Low	5.7	2.0
	Medium	12.0	4.5
	High	10.3	5.5

WWP, whitewater parks.

complex flow in any of the three WWP pools, while NR3 was chosen because it was the deepest of the three natural pools and provided the best comparison with the deeper WWP pools.

Cross sections were sampled in these two representative pools to better understand the 3-D velocity distribution. A cross section sampled at the top end of the pool in NR3 showed a typical open-channel velocity profile, with lower velocities near the channel bed and higher velocities near the surface (considering only the downstream velocity component) (Figure 3(b)). Conversely, a cross section sampled just below the drop structure in WWP2 included a submerged jet and produced a velocity profile that was much higher near the bed than at the surface (Figure 3(a)).

Turbulent kinetic energy. Estimated maximum TKE values for each flow rate were averaged for all the WWP pools and all the natural pools. TKE was 135% to 533% higher in the WWP pools than in the natural pools and increased with flow rate (Table I). In the natural pool, areas with high turbulence were concentrated in the upper half of the water column in the thalweg. In contrast, areas of high turbulence in the WWP pools were not confined to the thalweg alone and extended laterally across the pools (Figure 4).

Vorticity. The maximum 3-D and 2-D vorticity values for each flow rate were averaged for all the WWP pools and all the natural pools (Table I). Both vorticity metrics were consistently higher in the WWP pools than in the natural pools. Neither metric had a consistent relationship with flow rate. There was a larger spatial distribution of higher vorticity magnitudes in the WWP pool (distributed throughout the water column) than in the natural pool (concentrated near the bed) (Figure 5).

There were clear differences between 2-D and 3-D vorticity. Just below the water surface, there was a large eddy that exhibited high 3-D vorticity but was barely observed in the 2-D vorticity calculations, indicating that there was substantial tumbling motion in that area. 2-D modelling also omitted a large area of vorticity downstream of the high-velocity jet, which was resolved by 3-D representation (Figure 5). From field surveys, it was clear that this downstream area contained flow complexity in the form of churning and boils, and that information is lost in the 2-D interpretation.

3-D flow patterns and 2-D habitat modelling

Flow patterns in the WWP reaches included large lateral and vertical eddies just below the drop structure. In the natural reaches, flow was primarily in the downstream direction, with very little recirculation.

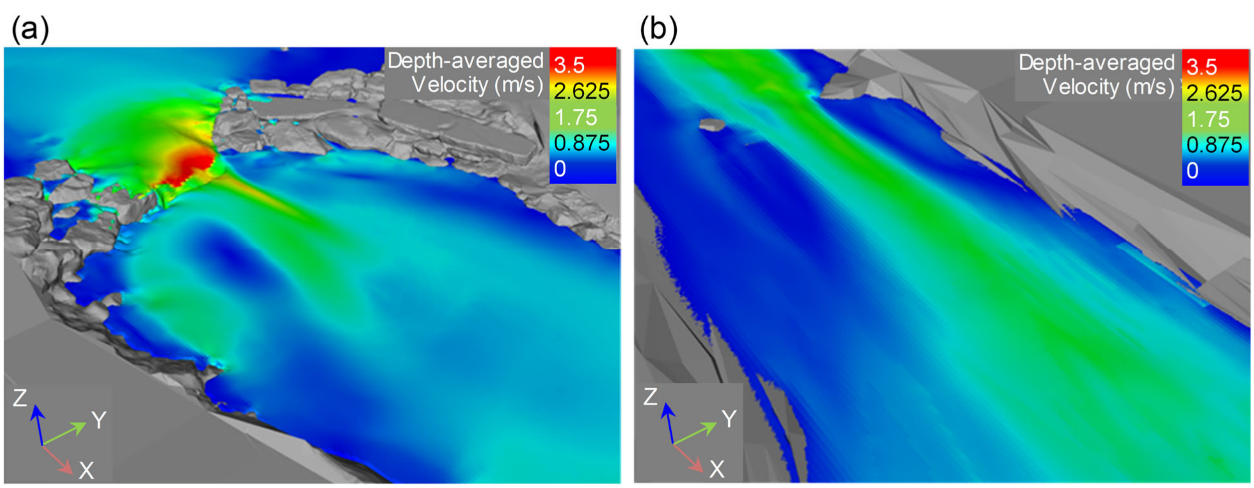

Figure 2. Depth-averaged velocity ($m\,s^{-1}$) in pools: (a) WWP2 and (b) NR3 at 4.25 cms. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

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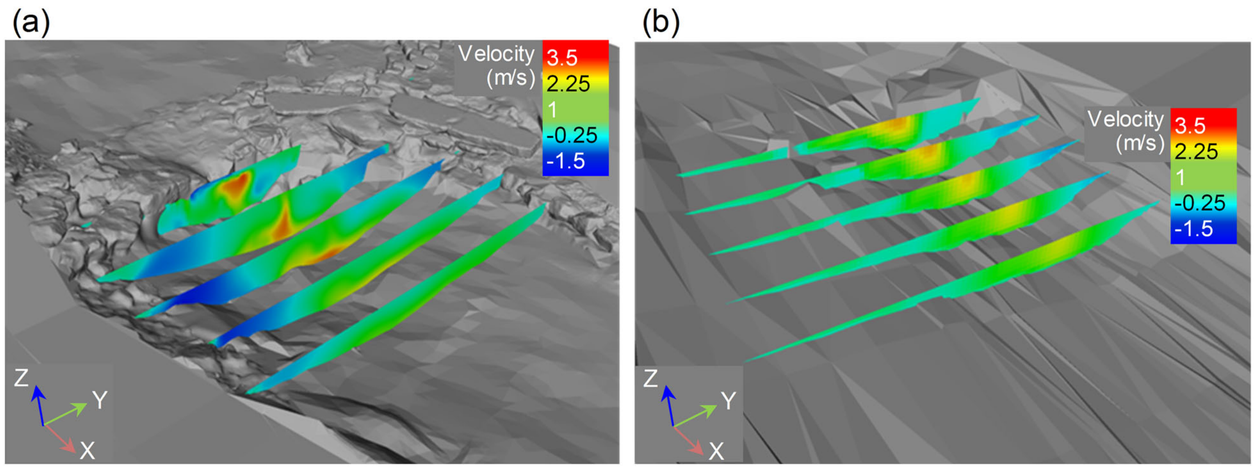

Figure 3. Cross sections showing the downstream velocity component (m s^{-1}) in pools: (a) WWP2 and (b) NR3 at 4.25 cms. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

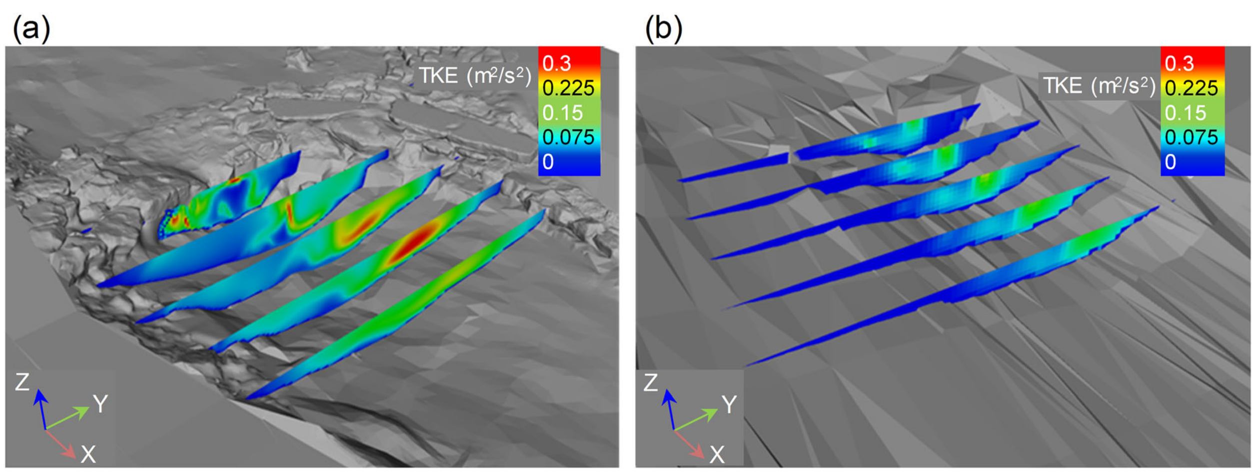

Figure 4. Cross sections showing TKE ($m^2 s^{-2}$) in pools: (a) WWP2 and (b) NR3 at 4.25 cms. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

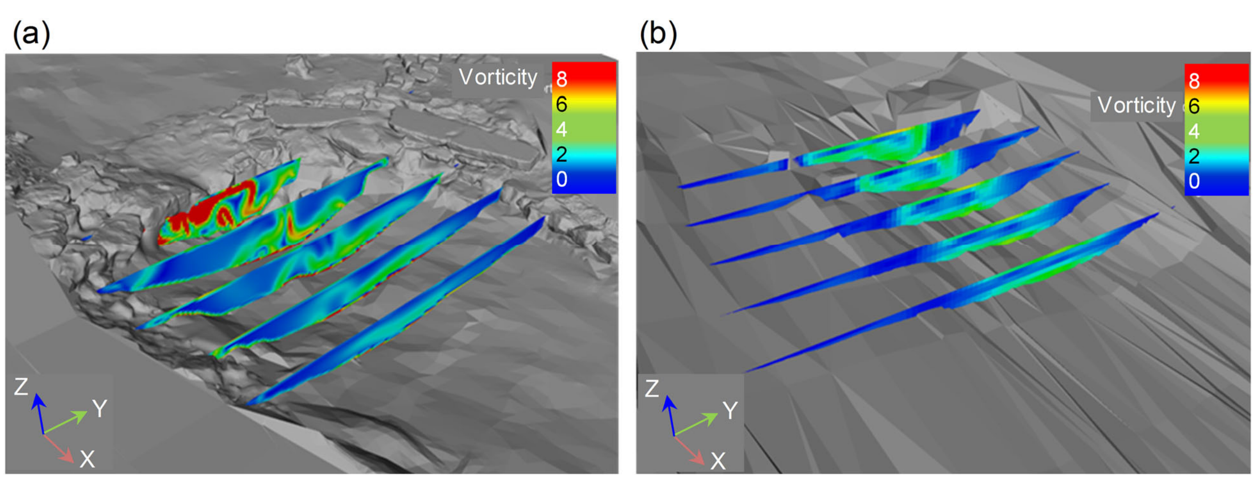

Figure 5. Cross sections showing 3-D vorticity (s^{-1}) in pools: (a) WWP2 and (b) NR3 at 4.25 cms. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

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The 2-D habitat analysis resulted in few significant differences between the predicted habitat for WWP pools and natural pools. WWP pools were predicted to have the same or higher amount of 'good' habitat for all species at all flow rates tested as compared with natural pools. (Table II).

Juvenile brown trout. Modelled 'good' juvenile brown trout habitat was concentrated around the margins of the WWP pools and decreased as the flow rate increased. At low flow in the natural pools, good habitat was concentrated in the thalweg, but moved to the margins of the channel as flow increased. When the average percentage of good habitat ($HSI > 0.5$) was compared between WWP pools and natural pools, there were no significant differences (Table II).

Adult brown trout. There was a paucity of adult brown trout habitat in WWP pools at any flow rate. The small areas of good habitat were concentrated at the margins of eddies and jets (Figure 6(a)) and increased slightly with flow rate. In the natural pools, good habitat was minimal and remained constant with increasing flow rate. At low flow rates, there were no significant differences between the modelled percentage of good adult brown trout habitat in the WWP pools and natural pools (Table II). At medium flow rate (4.25 cms), the WWP pools contained significantly higher good habitat (8.8%) than the natural pools (0.9%) (t-test $p = 0.001$; Wilcoxon $p = 0.049$). At high flow rate (8.5 cms), the WWP pools contained larger amounts of good habitat (6.2%) than the natural pools (0.9%) (t-test $p = 0.12$; Wilcoxon $p = 0.057$) (Figure 7(a)).

Juvenile rainbow trout. The 2-D habitat analysis showed that 'good' juvenile rainbow trout habitat was high in the WWP pools and found everywhere except for the deepest parts of the pools. The amount of good habitat decreased as the flow rate increased, but remained above 13% of area. At low flow in the natural reaches, good juvenile rainbow trout habitat was concentrated in the thalweg, but moved to the margins of flow as flow rate increased. There were no significant differences between percentage of good habitat in WWP pools and natural pools for all flows tested (Table II).

Adult rainbow trout. In the WWP pools, 'good' adult rainbow trout habitat was concentrated in areas of higher depth, but as flow rate increased, good habitat moved to the margins of jets and eddies, similar to adult brown trout habitat (Figure 6(b)). In the natural pools, there was minimal good habitat available, and habitat suitability remained low with increasing flows. At low flows, the percentage of good habitat was not significantly different between WWP pools and natural pools. For medium flow, the percentage of good habitat was significantly higher in the WWP pools (17.6%) compared with natural pools (0.7%) (t-test $p = 0.00002$; Wilcoxon $p = 0.043$). The same was true for high flow where WWP pools had an average of 16.7% good habitat and natural pools had an average of 0.7% good habitat (t-test $p = 0.008$; Wilcoxon $p = 0.049$) (Table II, Figure 7(b)).

Longnose dace. Predicted good longnose dace habitat was abundant in the WWP pools and occurred everywhere except for in the deepest part of the pools. In natural pools, habitat was concentrated in the thalweg for low flow, and then moved to the margins as flow rate increased. At low flows, the predicted percentage of good habitat was actually higher in the natural pools than in the WWP pools (t-test $p = 0.002$; Wilcoxon $p = 0.057$) (Table II). At medium and high flows, there was a higher percentage of good habitat in the WWP pools than in the natural pools (t-test $p = 0.04$; Wilcoxon $p = 0.057$).

Longnose sucker. Predicted longnose sucker habitat occurred throughout the WWP pools and natural pools, except in the deepest pools at the highest flows. There were no significant differences in longnose sucker habitat between WWP pools and natural pools (Table II).

Fish sampling

Fish sampling estimates for adult brown trout and adult rainbow trout from the fall of 2010 (Figure 8) found over two times higher adult brown trout biomass in natural pools (221.5 kg ha^{-1}) compared with WWP pools (90.7 kg ha^{-1}). Adult rainbow trout biomass in natural pools was 27.5 kg ha^{-1} compared with 0 kg ha^{-1} for adjacent WWP pools (no adult rainbow trout were sampled in any WWP pools). Adult brown

Table II. Percentage of pool area with good habitat ($HSI > 0.5$) for each species life stage and flow rate

Flow (cms)	Juvenile brown		Adult brown		Juvenile rainbow		Adult rainbow		Dace		Sucker	
	WWP	Natural	WWP	Natural	WWP	Natural	WWP	Natural	WWP	Natural	WWP	Natural
0.42	14.1	16.3	0.3	0.2	37.5	19.6	3.6	0.8	5.2	25.5	21.8	36.5
4.25	9.6	8.6	**8.8**	**0.9**	18.7	15.3	**17.6**	**0.7**	40.7	15.3	42.0	42.8
8.5	7.7	8.6	6.2	0.9	13.0	11.5	**16.7**	**0.7**	21.6	14.0	20.3	28.0

Note: Values in bold indicate significant differences between WWP pools and natural pools ($p < 0.05$ for Wilcoxon and t-test). WWP, whitewater parks.

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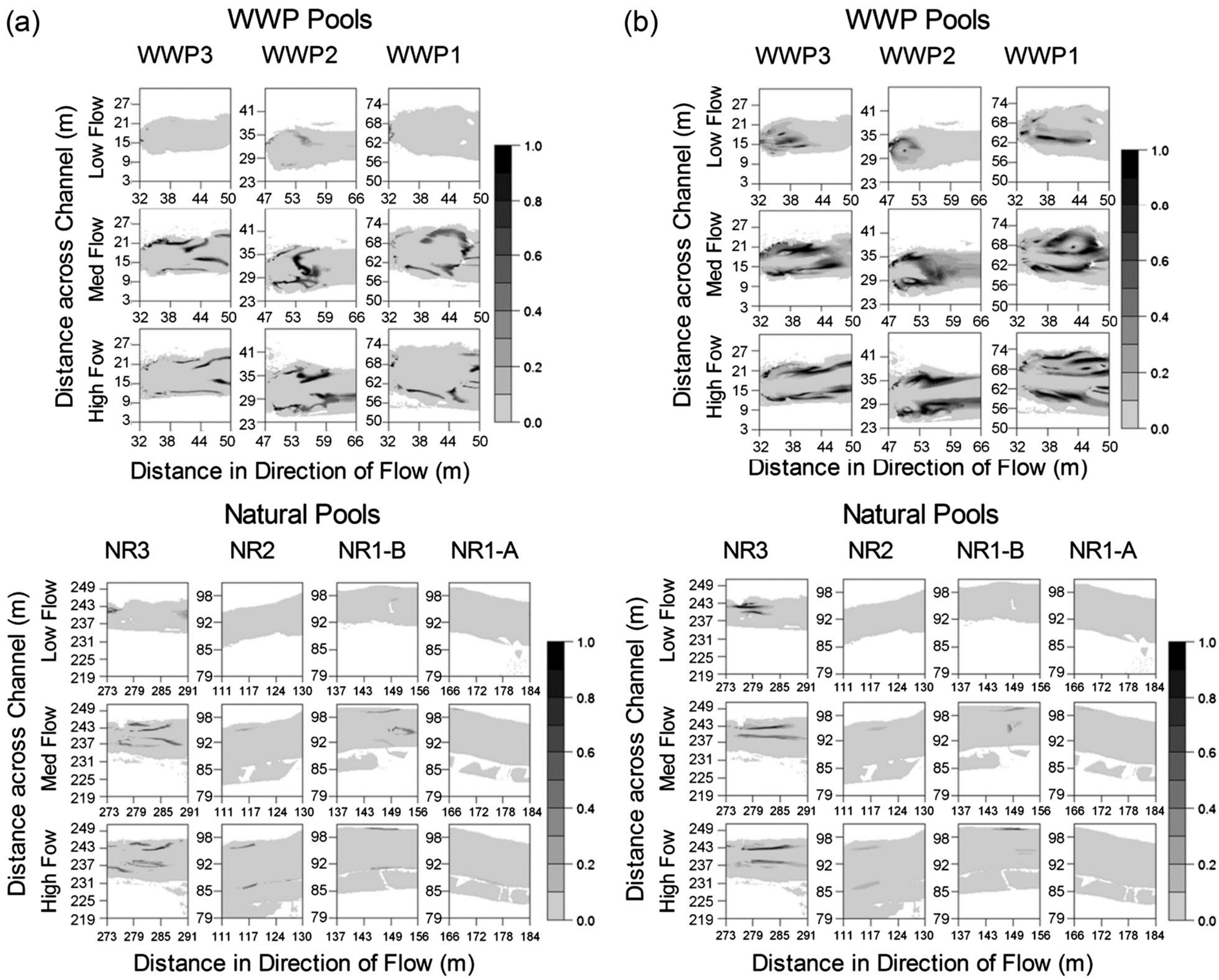

Figure 6. Habitat suitability results for (a) adult brown trout and (b) adult rainbow trout in WWP pools and natural pools

trout densities in natural pools were four times higher in natural pools (3128 fish ha^{-1}) than WWP pools (835 fish ha^{-1}). Adult rainbow trout densities were higher in natural pools (232 fish ha^{-1}) than WWP pools (0 fish ha^{-1} with no adult rainbow trout detected). Native fish biomass was nearly four times greater in natural pools (18.6 kg ha^{-1}) than WWP pools (5.3 kg ha^{-1}). However, there was no significant difference in native fish densities between natural pools (274 fish ha^{-1}) and WWP pools (99 fish ha^{-1}) (Figure 9).

DISCUSSION

Hydraulic variables

Substantial differences were found between the hydraulic characteristics in WWP pools and natural pools. Depth, depth-averaged velocity, TKE and 2-D and 3-D vorticity all had higher magnitudes in the WWP pools than in the natural pools. Pairing these results with the Colorado Parks and Wildlife fish sampling results, which showed higher abundance and biomass in the natural pools than the WWP pools, suggests that correlations could exist between these hydraulic variables, and abundance and biomass. Correlations are especially important to consider for variables that have not quantitatively been linked to habitat quality thus far, specifically TKE, 2-D vorticity and 3-D vorticity. All three of these metrics are substantially higher in the WWP pools than in the natural pools and may explain why abundance and biomass were higher in the natural pools and provide a starting point for examining the effects of these flow characteristics on habitat quality in the future.

Velocity and vorticity both showed stark differences between 2-D and 3-D methods, and TKE provided information that was unavailable with 2-D methods. In a channel with little complexity, depth-averaged velocity is a useful metric because the logarithmic velocity profile is highly

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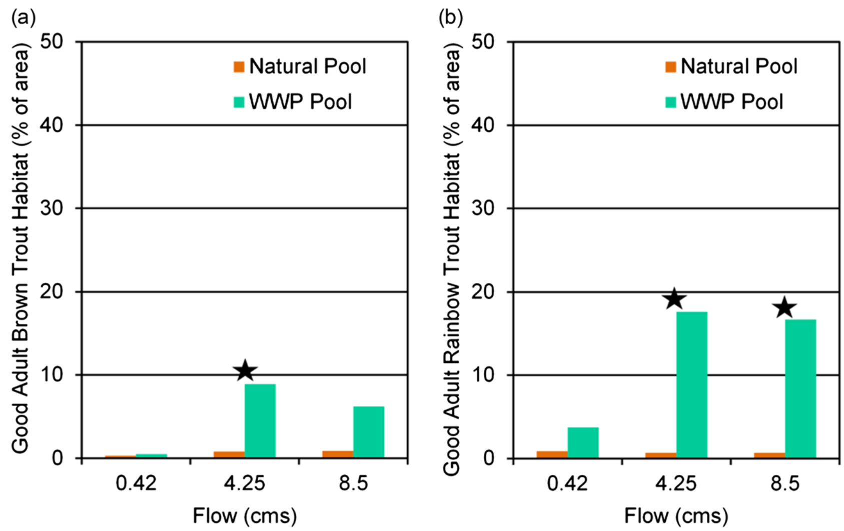

Figure 7. Model predictions of average good (a) adult brown trout and (b) adult rainbow trout habitats as a percentage of wetted area for low, medium and high flow rates. Stars indicate significant differences in amount of habitat between WWP pools and natural pools. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

predictable. WWP pools did not exhibit a logarithmic velocity profile typical of natural pools found in lower gradient pool-riffle systems (Figure 3). Exclusive use of depth-averaged data could lead to erroneous assumptions that flow conditions are functionally the same and reveal nothing about the actual velocity distribution.

It is important to consider what conditions fish in this stream are adapted to, which in the case of velocity likely includes slower near-bed flows. A fish could be accustomed to sheltering itself in the bottoms of pools that provide ample cover and adequately low velocities but will avoid the high-velocity conditions at the bottom of a deep WWP pool. In a natural step-pool system, which could be found in stream types with a higher gradient than the St. Vrain, fish might be more accustomed to higher near-bed velocities and complex flow patterns found in WWPs. Similar flow patterns might be found in step pools created by lateral constrictions, including plunging flow, hydraulic jumps and recirculating eddies (Thompson *et al*., 1998). However, large lateral constrictions are not found naturally occurring in this section of St. Vrain Creek, and there is a reason to believe fish would not be adapted to this kind of flow complexity.

The spatial distribution of high vorticity varied greatly between WWP pools and natural pools. In natural pools, vorticity was concentrated near the thalweg, while in WWP pools, the areas of maximum vorticity were much larger and were spread laterally and vertically throughout most of the pool. Vorticity is correlated with flow complexity, but specific relationships with fish preference are not known. It is plausible that low levels of vorticity are tolerable to many fish, whereas high levels may become unsuitable. The actual role vorticity plays in determining optimal aquatic habitat is an open question, but if further research shows that high vorticity is detrimental or beneficial to certain fish, then vorticity must be characterized accurately. The results from this study show that resolving these characteristics in 3-D will be essential for prediction, supporting the results of a previous study that determined rotation in the vertical plane to be the best distinguishing factor between sampled modified and natural river reaches (Shields and Rigby, 2005).

Similar to vorticity, the distribution of high TKE in WWP pools is very different from that in natural pools. Within WWP pools, high TKE values follow the location of the high-speed jet of water in the middle of the water column and extend laterally. If it is assumed that fish in this stream are adapted to the more natural conditions, it would mean that they expect a jet of higher turbulence in the upper half of the water column along the thalweg, not in a large region of submerged, near-bed, high-magnitude TKE. Turbulence can be beneficial or detrimental to fish, depending on the situation. Silva *et al*. (2012) found that fish in laboratory flumes tended to avoid turbulent areas, presumably in an effort to conserve energy and maximize stability. Small amounts of turbulence can attract fish and trigger migration as well as propel fish under the right conditions, but too much turbulence could cause fish avoidance and prevent migration (Silva *et al*., 2012). Lacey *et al*. (2012) suggest that TKE not only influences fish directly through affecting swimming ability but also could affect them indirectly through limiting food availability. This indirect effect could occur because food availability is influenced by local

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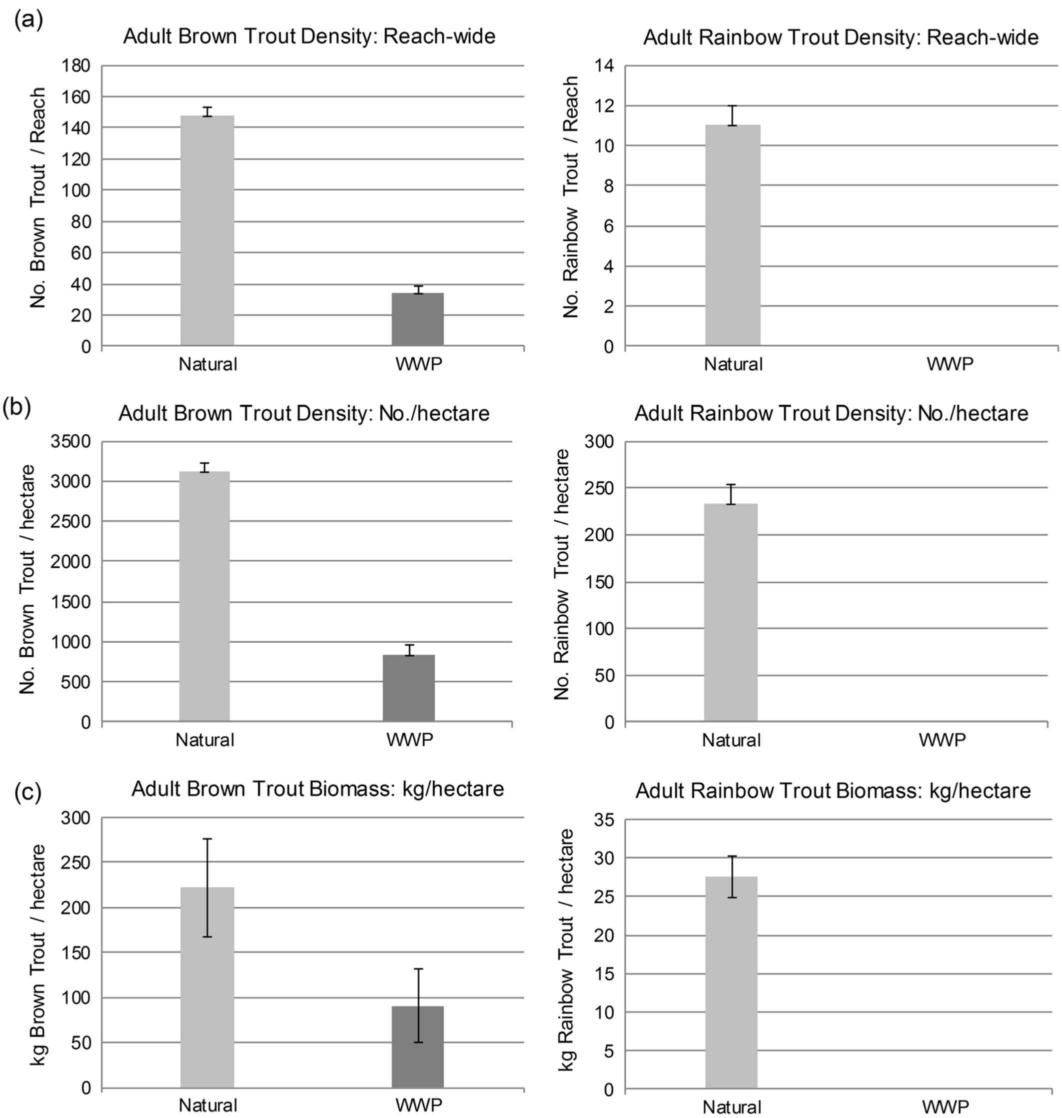

Figure 8. Sampling estimates for adult brown trout and adult rainbow trout (for fish greater than or equal to 150 mm in length): (a) reach-wide density, (b) fish abundance and (c) fish biomass in WWP pools and natural pools in 2010. Error bars represent 95% confidence intervals

water velocity, which is often correlated with TKE. Because certain amounts of turbulence and flow complexity are beneficial, it is probable that thresholds exist for turbulence effects, and those thresholds could vary for different species, size classes and hydraulic environments (Lacey *et al.*, 2012).

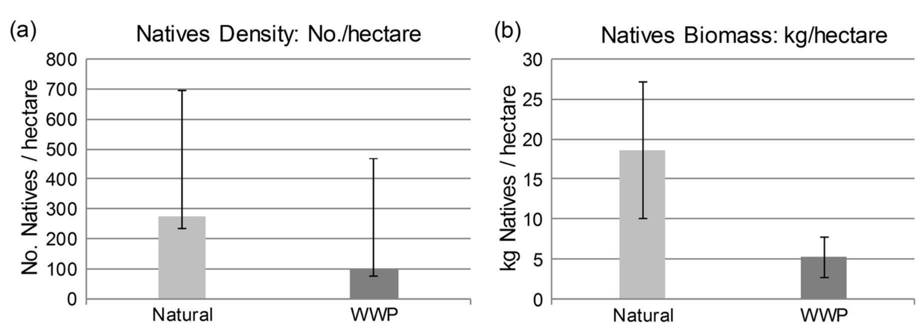

Figure 9. Sampling estimates for native fish: (a) fish abundance and (b) fish biomass in WWP pools and natural pools in 2010. Error bars represent 95% confidence intervals

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2-D habitat models

2-D HSI results predicted WWP pools were predicted to have substantially more ‘good’ fish habitat than natural pools for native fish, adult brown trout and adult rainbow trout over the range of flows tested (low = 0.42 cms, medium = 4.25 cms and high = 8.5 cms) (Figure 7(a) and (b)). However, the fish sampling results, which showed higher biomass and density of adult brown and rainbow trout in natural pools compared with WWP pools, run counter to the 2-D habitat analysis. The sampling result also contrasts with several previous studies suggesting that deeper pools should provide more and higher quality habitat for adult salmonids (e.g. Binns, 1994; Harig *et al*., 2000).

The dichotomy between the 2-D HSI predictions and the fish sampling results could have many plausible explanations. As explained earlier, HSI calculations are a gross simplification of a complex system; fish are living in a 3-D world, while the habitat suitability criteria are based on a 2-D simplification. The large differences between the 2-D and 3-D conditions pertaining to velocity, vorticity and TKE are likely part of the explanation for the contrast between the 2-D HSI results and the actual measurements of fish biomass and abundance. Fish biomass surveys are a snapshot in time but reflect the accumulated effects of antecedent flow conditions and biotic influences, whereas the 2-D HSI analysis reflects only hydraulic conditions at one model time step. In general, fish habitat is not just a function of hydraulic conditions but is also influenced by other factors including barriers to movement, substrate, bank complexity and overhead cover, as well as biological factors such as food availability, competition and predation. The presence of kayakers or other recreational users in the WWP pools might also have an effect on the ways fish use pool habitat; however, they were never observed during our fall or spring sampling over 3 years. Overall, 2-D hydraulic modelling can be a useful way to describe habitat conditions, but until researchers can ascertain the extent to which the simple hydraulic metrics used in the HSI models accurately correlate to habitat quality in regions of very complex 3-D flow, 2-D hydraulic modelling should not be used as the sole tool in habitat quality assessment.

Future implications

Overall, it is clear that by ignoring the third dimension of flow in a 2-D hydrodynamic simulation, key information about hydraulic habitat quality is being lost. 3-D modelling has the potential to be a very important tool for the future of WWP design. As we improve our understanding of how 3-D hydraulic variables influence fish habitat suitability, design modifications can be tested to minimize negative effects on aquatic organisms. Nevertheless, 2-D modelling still has important utility given its lower costs in terms of software, computational power, required expertise and time required for data collection and modelling. Thus, the efficacy of 2-D versus 3-D modelling must be assessed on a case-by-case basis.

We suggest replication of the CFD modelling and fish biomass studies in other WWPs in order to understand general trends, preferably with the inclusion of pre-construction baseline data, such as a before/after/control/impact design.

CONCLUSIONS

In this study, the effects of WWPs on aquatic habitat were examined using a 2-D and 3-D hydrodynamic model. Two sections of a wadeable stream in Colorado were modelled for comparison: one natural section and one section containing a WWP with engineered drop structures. All hydraulic metrics (depth, depth-averaged velocity, TKE, 2-D vorticity and 3-D vorticity) had higher magnitudes in the WWP pools than in the natural pools. A 2-D habitat suitability analysis for juvenile and adult brown trout, juvenile and adult rainbow trout, longnose dace and longnose sucker predicted the same or higher habitat quality in the WWPs than in the natural reaches for all species and all flow rates. Conversely, instream surveys showed significantly higher fish abundance (for adult brown trout and rainbow trout) and biomass for all species in the natural pools compared with WWP pools when surveyed under the ‘low’ flow condition. In the WWP pools, 2-D model results did not meaningfully describe the magnitudes and spatial distributions of ecologically relevant flow characteristics as well as 3-D results. This study generally supports the use of 3-D modelling for complex flow found in WWPs and suggests that projects should be evaluated case-by-case to determine if the simplified 2-D rendering of flow characteristics adequately resolves key hydraulic characteristics. For 3-D modelling to be widely useful, improved understanding of linkages between 3-D fish habitat quality and hydraulic descriptors such as TKE, vorticity and velocity is needed.

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