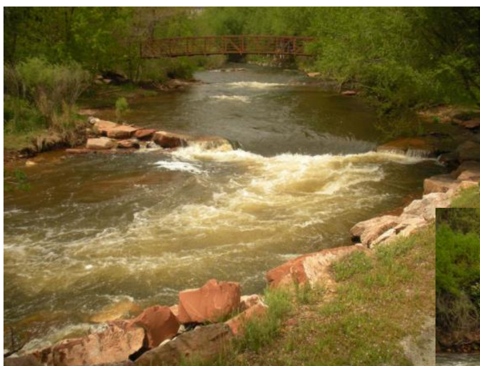
INVESTIGATION OF THE EFFECTS OF WHITEWATER PARKS ON AQUATIC RESOURCES IN COLORADO

Prepared for the

Colorado Water Conservation Board



Prepared by

Brian P. Bledsoe, E. Kolden, B. Fox, and T. Stephens

September 2013

Colorado State University
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EXECUTIVE SUMMARY

Whitewater parks (WWPs) have become a popular recreational amenity in cities across the United States with Colorado being the epicenter of WWP design and construction. Whitewater parks consist of one or more in-stream structures that create a hydraulic wave for recreational purposes. A wave is typically created by constricting flow into a steep chute, creating a hydraulic jump as it flows into a large downstream pool. There is a paucity of research that surveys on-the-ground biological or ecological conditions to evaluate the actual impacts of WWPs. Consequently, the effects of WWPs on aquatic habitat and fish passage are poorly understood. This lack of information creates a problem for state wildlife agency personnel, who are asked to comment on the Section 404 permits required for WWP construction. They must provide their expert opinion without having any concrete studies to inform that opinion. This report provides a brief summary of research examining the complex hydraulic conditions present in WWPs and the effects of WWPs on aquatic habitat and fish passage. The two major sections of this report provide condensed versions of two complementary theses focused on the effects of WWPs on aquatic resources in Colorado.

The objectives of the study conducted by Kolden (2013) were to:

- describe and compare fish habitat quality in WWPs and natural reaches using a traditional method based on two-dimensional (2-D) hydraulic modeling and habitat suitability criteria;
- compare predicted fish habitat quality to results from field surveys that provide preliminary estimates of fish biomass;
- use three-dimensional (3-D) modeling to describe and compare ecologically-relevant hydraulic descriptors in WWPs vs. natural reaches; and
- compare 2-D and 3-D hydraulic and habitat modeling results and examine whether 3-D modeling is justified for assessing habitat quality in WWPs.

Two sections of the North St. Vrain River in Lyons, Colorado, were modeled: one natural section, and one section containing a WWP with three engineered drop structures. The 3-D computation fluid dynamics (CFD) software FLOW-3D® v10.0 (hereafter referred to as FLOW-3D) was used to model each of the reaches.

A 2-D habitat suitability analysis for juvenile and adult brown trout (*Salmo trutta*), rainbow trout (*Oncorhynchus mykiss*), longnose dace (*Rhinichthys cataractae*), and longnose sucker (*Catostomus catostomus*) predicted substantially higher habitat quality in the WWPs than in the natural reaches for adult brown and rainbow trout at some flow rates, while in-stream surveys showed higher fish biomass per volume in the natural pools. All hydraulic metrics (depth, depth-averaged velocity, turbulent kinetic energy (TKE), 2-D vorticity, and 3-D vorticity) had higher magnitudes in the WWP pools than in the natural pools. In the WWP pools, 2-D model results did not resolve the spatial distribution of flow characteristics or the magnitude of variables as well as 3-D results. This study supports the use of 3-D modeling for complex flow

found in WWPs, but other projects should be evaluated case-by-case to determine if the simplified 2-D rendering of flow characteristics is acceptable. For 3-D modeling to be widely useful, improved understanding of linkages between 3-D aquatic habitat quality and hydraulic descriptors such as TKE, vorticity, and velocity is needed.

Fox (2013) completed a field evaluation of the effects of WWPs on upstream fish passage by concurrently monitoring fish movement and hydraulic conditions at three WWP structures and three adjacent natural control (CR) pools. Fish movement was evaluated using a network of Passive Integrated Transponder (PIT) antennas installed at the study sites for a period of 14 months. 1,639 individual fishes including brown trout, rainbow trout, longnose sucker, and longnose dace were tagged and released within the WWP and CR study sites. Detailed hydraulic conditions occurring during the study period were evaluated by developing a fully 3-D hydraulic model using FLOW-3D.

Results indicate that WWP structures can incorporate a broad range of design types that affect small-scale hydraulics and potentially create unique hydraulic conditions that affect fish passage differently. Successful upstream movement of salmonids from 115 to 416 mm total length was observed at all of the WWP locations over the range of flows occurring during the study period, thus demonstrating that the WWPs in this study are not complete barriers to movement of salmonids in these size ranges. However, results indicate that WWPs can suppress movement by size class, and the magnitude of this suppression appears to vary among different WWP structures and CR sites. The differences in passage efficiency from release location range from 29 to 44% in WWP sites and 37 to 63% for control sites. Further, this difference in movement may be related to the variation of hydraulic conditions among the WWP structures, but does not appear to have a strong relationship with burst swimming abilities of salmonids. It is probable that the reduced movement may be attributed to other hydraulic and biologic variables such as turbulence, fish behavior, and motivation. Because of the small numbers of native species monitored in this study, no direct conclusions can be drawn on how this WWP affected their upstream movement ability. This study provided a starting point for understanding how WWPs affect fish movement. Future studies should focus on broadening structure type and species evaluated for passage, and perform more-detailed assessment of how hydraulic conditions other than velocity are affecting upstream movement behavior and motivation.

DESIGN CASE STUDY

The construction of a planned WWP on the Cache La Poudre River in Fort Collins, Colorado, would be an ideal site for a design case study. This project would allow for pre- and post-construction monitoring and data collection; however, there have been significant delays and uncertainty in the initialization of this project. Therefore, the WWP located on the North St. Vrain River in Lyons, Colorado, was utilized for a design case study due to the wealth of data obtained in the aforementioned studies (Fox, 2013; Kolden, 2013). Results from this case study can be used to support management decisions for both existing and future WWPs.

Colorado Parks & Wildlife (CPW) has an ongoing study to quantify biomass of introduced and native fishes in the North St. Vrain. They are surveying fish biomass in the same reaches and pools described in this study. Beginning in Fall 2010, electroshocking surveys occurred each fall (in October or November) and spring (in April). Fall surveys were conducted during low flow and timed to coincide with brown trout spawning, while spring surveys corresponded with rainbow trout spawning. Spring and fall surveys occurred well before and after the summer period of heavy recreational use in the river.

When normalized by pool surface area, adult brown trout biomass was not significantly different in natural pools and WWP pools for either year. However, when biomass was normalized by pool volume, biomass averages were significantly higher in the natural pools than the WWP pools for both years. The per volume analysis accounts for the fact that the WWP pools are much deeper than the natural pools and, therefore, provide much more physical space for fish to inhabit. Continuation and further analysis of the biomass surveys, including detailed methods, will be completed by CPW researchers and will be presented in a forthcoming publication.

Additionally, while the suppression of fish movement may exist, the observations of successful movements indicate that WWPs producing hydraulic conditions within the range of those in this study have the potential to meet both recreational and fish passage goals for salmonids. However, the amount of suppressed movement that is acceptable for a given site is a question that must first be answered through criteria defined by natural resource managers, site-specific constraints and requirements of the target species. In addition, assessing the level of habitat impairment and fragmentation already existing from the presence of diversions, culverts, or other potential passage barriers may help assess the risk of adding a WWP with unknown passage effects. Selection of a site that already has degraded habitat conditions such as existing dams and urban environments where ecological improvement potential is limited may be ideal locations for WWPs. However, without a clear understanding of what is an unacceptable level of impaired passage, it is difficult to objectively weigh the magnitude of any negative effect against the positive benefits of WWPs, and difficulties in decision-making will persist.

DESIGN RECOMMENDATIONS

Knowledge gained from these studies can be applied to future designs to maximize the probability of successful upstream movement of trout. The results suggest that WWPs with laterally-constricted grouted chutes that are installed in streams of similar size and hydrologic characteristics do not serve as complete velocity barriers to upstream migrating salmonids. Structures that maintain short high-velocity zones should be passable for species with similar swimming abilities, behavior, and motivation. In addition, lower velocity routes around high-velocity zones and roughness elements on the lateral margins of the channel would improve passage success by reducing the length and magnitude of a potential velocity challenge.

The unique hydraulic conditions observed at each WWP structure affect passage success differently. Large eddies with lower velocities adjacent to the main velocity jet in the pool were observed in the WWP structure with the highest passage success. Large eddies with low velocities can provide zones for fish to rest and may reduce the length of the high-velocity zone that fish are required to traverse. A lateral expansion near the chute outlet into the pool produced the large eddies adjacent to the main velocity jet. Decreased passage success was observed at a structure where the maximum constriction of the chute was near the outlet into the pool preventing the formation of the large, low-velocity eddies. Roughness elements along the channel margins reduce the local velocity providing high-velocity refugia and passage routes with reduced velocities. Additionally, providing interstitial spaces within the chute may provide zones of lower velocity and potential passage routes for smaller fishes with reduced swimming abilities. The passage success of smaller fishes was more pronounced in the WWP structure that contained interstitial wetted spaces within the center of the chute.

Considering that the formation of a hydraulic jump requires supercritical specific energy ($Fr > 1$) within WWP features, zones of high velocity must occur at some point within a structure. In order to achieve supercritical specific energy on rivers larger than the one examined in these studies, it is possible that higher velocities that exceed salmonid burst swimming abilities within the chute might be required to generate a wave that achieves recreational objectives. As such, any attempt to transfer results of this research to larger rivers must account for scale-dependent differences in the velocities required to generate the type of hydraulic waves preferred by boaters relative to the trout swimming abilities documented in this and other studies. Further, streams with smaller mean discharges will require greater levels of lateral width constriction and vertical drop for the hydraulic wave to meet recreational goals. In such cases, a bypass channel or alternative route around the chute may be required to provide lower velocity passage routes, while meeting recreational needs.

To fully evaluate the variations in design elements and discharge for future WWPs, a site-specific analysis would likely be required to determine if additional zones of lower velocity would exist to allow potential upstream passage routes. It is likely that a site-specific analysis would also be required in order to determine if an existing WWP needed to be modified to provide zones of lower velocity. However, without greater understanding of the specific mechanism causing the suppression of movement, developing detailed design guidelines will remain difficult.

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Symbols:

EVENT	=	CJS variable: tag release events
Fr	=	Froude number
g	=	gravitational acceleration $\left(\frac{\mathrm{L}}{\mathrm{T}^2}\right)$
INT	=	CJS variable: intercept
LCI	=	statistical term: lower confidence interval
LENGTH	=	CJS variable: body length of the fish at time of tagging
LOCATION	=	CJS variable: six specific structure/pool crossing within WWP and CR reaches
MRT	=	CJS variable: three mark-release types
n	=	number of fishes
p	=	probability of encounter
q	=	unit discharge $\left(\frac{\mathrm{L}^2}{\mathrm{T}}\right)$
SE	=	statistical term: standard error
SPECIES	=	CJS variable: trout/non-trout
UCI	=	statistical term: upper confidence interval
v	=	velocity $\left(\frac{\mathrm{L}}{\mathrm{T}}\right)$
y	=	flow depth (L)
β_1, β_2, β_3, β_4, β_5, β_6, β_8, β_9, β_{INT}	=	CJS regression parameters
ϕ	=	upstream movement rate = probability of a successful upstream movement at defined location (WWP or CR site), on condition that the individual is alive and available to move upstream
Ψ	=	apparent successful upstream movement

Units of Measure:

BL/s	body length(s) per second
cfs, ft^3/s	cubic feet per second
cm	centimeter(s)
cms	cubic meter(s) per second
ft	foot or feet
ft/s	feet per second
km	kilometer(s)
km^2	square kilometer(s)
L	length dimension
m	meter(s)
m/s	meter(s) per second
m^2/s^2	square meter(s) per second squared
mi	mile(s)
mm	millimeter(s)
%	percent
s^{-1}	inverse second(s)
T	time dimension

Abbreviations:

1-D	one-dimensional
2-D	two-dimensional
3-D	three-dimensional
ADV	Acoustic Doppler Velocimeter
AIC	Akaike Information Criterion
AICc	corrected Akaike Information Criterion
CFD	computational fluid dynamics
CJS	Cormack Jolly-Seber
CPW	Colorado Parks & Wildlife

CR	control (sites)
DISP	displacement
GPS	Global Positioning System
HDX	half-duplex
HOF	Hofer x Harrison strain
HSI	Habitat Suitability Indices
LGS	longnose sucker
LIDaR	LIght Detection and Ranging
LND	longnose dace
LOC	brown trout
MRT	mark-release types
PHABSIM	Physical HABitat SIMulation
PIT	passive integrated transponder
RBT	rainbow trout
®	registered
RFID	Radio Frequency Identification
RICDs	recreational in-channel diversions
RNG	renormalization group
TKE	turbulent kinetic energy
™	trademark
U.S.	United States
USACE	U.S. Army Corps of Engineers
USGS	U.S. States Geological Survey
WWPs	whitewater parks
x, y, z	coordinates
X, Y, Z	coordinates

SECTION 1

MODELING IN A THREE-DIMENSIONAL WORLD: WHITEWATER PARK HYDRAULICS AND THEIR IMPACT ON AQUATIC HABITAT IN COLORADO

1.1 INTRODUCTION

Hydraulic conditions in lotic systems are one of many important factors influencing stream ecosystem health and function (Lamouroux *et al.*, 1995). Flow patterns and characteristics influence habitat in many ways, by creating cover, influencing oxygen availability, regulating water temperature, and shaping channel morphology. River engineering projects, such as dam construction, dredging, channelization, or addition of in-stream 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 affect habitat quality for aquatic organisms.

For the last three decades, researchers have studied the effects of hydraulic conditions on habitat quality using the Physical HABitat SIMulation (PHABSIM) model and other hydrodynamic modeling processes (Booker *et al.*, 2004; Bovee, 1982), which rely on depth and depth-averaged velocity to predict habitat quality. The importance of other hydraulic variables, such as turbulence, vorticity, circulation, velocity gradients, and kinetic energy gradients, has only recently been examined. Turbulence is a measurement of rapid velocity fluctuations and can increase fish swimming cost, but can also trigger important migratory movements, among other effects (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, or rest; but again, the exact effects of different gradient scales on specific fish species is unknown (Crowder and Diplas, 2000). 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 hydraulic structures, they result in significant changes to hydraulic conditions. Specifically, they create an abrupt lateral flow constriction, 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 aquatic 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 United States (U.S.) (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). 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 aquatic habitat (McGrath, 2003); however, this assumption has yet to be demonstrated and tested rigorously.

Numerical modeling can be used to describe the altered 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 modeling method that accurately describes those features (Crowder and Diplas, 2000). 1-D and 2-D numerical modeling has been successfully applied to many natural river systems (Booker and Dunbar, 2004; Ghanem *et al.*, 1996; 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 aquatic habitat or the use of 3-D modeling to simulate modifications of fish habitat. Habitat modeling, though 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 a powerful and important tool for managers, but have many well-documented limitations, including simplified hydraulic input (Crowder and Diplas, 2000) and exclusion of other factors that influence habitat quality and fish location preference (Booker *et al.*, 2004; Shuler and Nehring, 1993).

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 Section 404 permits required for WWP construction. They must provide their expert opinion without having any concrete studies to inform that opinion.

This research addresses some of the gaps and limitations present when modeling the hydraulics and habitat of WWPs, using a 3-D modeling environment to better characterize and predict the complex 3-D nature of aquatic habitat. Specifically, the research objectives are as follows:

- describe and compare fish habitat quality in WWPs and natural reaches using a traditional method based on 2-D hydraulic modeling and habitat suitability criteria;
- compare predicted fish habitat quality to results from field surveys that provide preliminary estimates of fish biomass;
- use 3-D modeling to describe and compare ecologically-relevant hydraulic descriptors in WWPs vs. natural reaches;

- compare 2-D and 3-D hydraulic and habitat modeling results and examine whether 3-D modeling is justified for assessing habitat quality in WWPs; and
- present future applications and research directions for 3-D hydraulic modeling and habitat quality assessment in complex river settings such as WWPs.

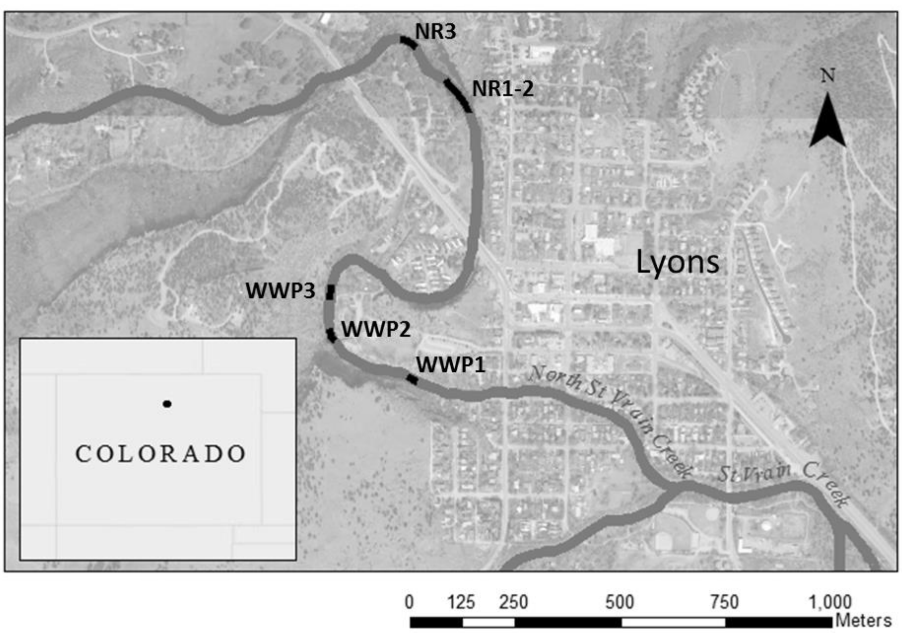
The topic of fish passage in WWPs is addressed in Section 2 of this report (Fox, 2013).

1.2 METHODS

1.2.1 Site Description

The North St. Vrain River (Lyons, Colorado) was chosen for this study. The North St. Vrain drains an area of 322 km^2, which is mostly forested 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 boulder cobble bed.

The study design included three WWP structures located in the town of Lyons ('WWP reaches') and three natural 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 1.1). The WWP reaches were labeled WWP1, WWP2, and WWP3 (downstream to upstream), and the natural reaches were labeled NR1, NR2, and NR3 (downstream to upstream).



Note: Reach NR1-2 includes NR1-A, NR1-B, and NR2

Figure 1.1. Map of study site (Kolden, 2013).

1.2.2 Bathymetric and Hydrologic Surveys

Bathymetry data were collected in the form of XYZ coordinates using a ground-based LIght Detection and Ranging (LIDaR) system, a Leica Total Station, and a Topcon® HiPer XT™ 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 (ADV) and a Marsh McBirney flow meter.

1.2.3 Numerical Hydraulic Modeling

The 3-D computation fluid dynamics (CFD) software FLOW-3D® v10.0 (hereafter referred to as FLOW-3D) was used to model each of the 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 (RNG) 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) was performed using EnSight® Standard v10.0.2 (hereafter referred to as EnSight).

1.2.4 Model Validation

In order to validate the 3-D modeling results, modeled variables were compared to 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 modeled 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 the downstream pools within each WWP reach, modeled water-surface elevations differed by less than 1 cm from the measured elevations. The modeled velocity profiles in the three WWP validation simulations had error of less than 16%, which is within acceptable error rates based on 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 measured in the natural reaches, though the modeled velocities were deemed reasonable based on knowledge of the site.

1.2.5 Hydraulic Output

FLOW-3D output used in this study included depth, depth-averaged velocity, point velocity, and turbulent kinetic energy (TKE). 2-D vorticity and 3-D vorticity were calculated using the calculator tool in EnSight, and the equations used can be found in Crowder and Diplas (2002).

1.2.6 2-D Habitat Modeling

The habitat suitability equations used in this analysis were developed by Miller Ecological Consultants, Inc. using data collected by Colorado Parks & Wildlife (CPW) in the Cache la Poudre River, an adjacent watershed similar to the St. Vrain (Miller and Swaim, 2011). The species and life stages analyzed in this study are juvenile and adult rainbow trout, juvenile and adult brown trout, longnose dace, and longnose sucker. 'Adults' were classified as having lengths greater than 150 mm. The hydraulic input for each species-specific habitat suitability equation included depth and depth-averaged velocity, and the output was a Habitat Suitability Indices (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 pre-defined 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 produced a *p*-value less than 0.05.

1.3 RESULTS

1.3.1 2-D and 3-D Hydraulic Variables

The modeled hydraulic conditions of the WWP pools were substantially different than the conditions in the natural pools. Also, a 2-D interpretation of hydraulic results painted a different picture of flow conditions than a 3-D interpretation. In all contour plots, flow is from left to right, in the positive *x*-direction.

Table 1.1 summarizes maximum values for the hydraulic metrics of depth, depth-averaged velocity, TKE, 3-D vorticity, and 2-D vorticity in WWP pools and natural pools for all flow rates. Discussion of these hydraulic metrics is reported in the following sub-sections.

Table 1.1. Maximum (a) flow depth, (b) depth-averaged velocity, (c) TKE, (d) 3-D vorticity, and (e) 2-D vorticity in WWP pools and natural pools for all flow rates.

(a) maximum flow depth in all pools (m)

Flow Rate	WWP Pools	Natural Pools
Low	1.5	0.6
Medium	1.8	0.9
High	2.1	1.1

(b) maximum depth-averaged velocity in all pools (m/s)

Flow Rate	WWP Pools	Natural Pools
Low	2.3	0.8
Medium	3.6	2.1
High	3.8	2.6

(c) maximum TKE (m^2/s^2) in all pools (s^{-1})

Flow Rate	WWP Pools	Natural Pools
Low	0.19	0.03
Medium	0.40	0.17
High	0.51	0.21

(d) maximum 3-D vorticity in all pools (s^{-1})

Flow Rate	WWP Pools	Natural Pools
Low	9.3	4.5
Medium	17.7	10.8
High	17.7	8.3

(e) maximum 2-D vorticity in all pools (s^{-1})

Flow Rate	WWP Pools	Natural Pools
Low	5.7	2.0
Medium	12.0	4.5
High	10.3	5.5

1.3.1.1 Depth

Model results showed 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 1.1).

1.3.1.2 Velocity

The maximum depth-averaged velocity was greater in the WWP pools than in the natural pools for all flow rates (Table 1.1). To show an example of the differences in velocity in a visual manner, two representative pools were chosen, one WWP pool (WWP2) and one natural pool (NR3). WWP2 was chosen because it had the most rapid and complex flow of any of the WWP pools, while NR3 was chosen because it was the deepest of the natural pools and provided the best comparison to the deeper WWP pools. Depth-averaged velocity for the two representative pools, WWP2 and NR3, is shown in Figure 1.2. The depth-averaged velocity in the thalweg in WWP2 was approximately 2.0 m/s, and the depth-averaged velocity in the thalweg in NR3 was approximately 1.9 m/s.

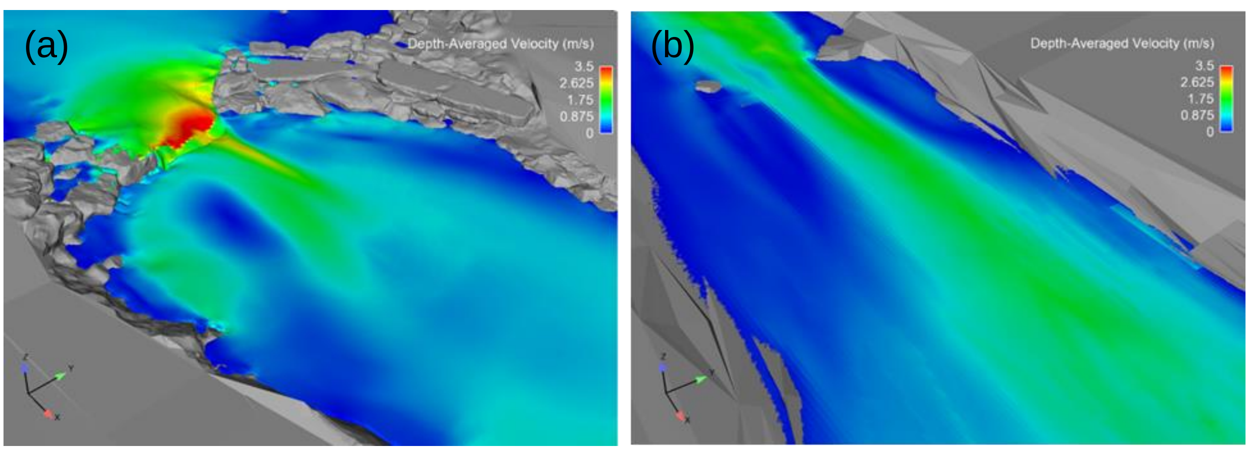


Figure 1.2. Depth-averaged velocity (m/s) in pools: (a) WWP2 and (b) NR3 at 4.25 cms (Kolden, 2013).

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 1.3b). 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 1.3a).

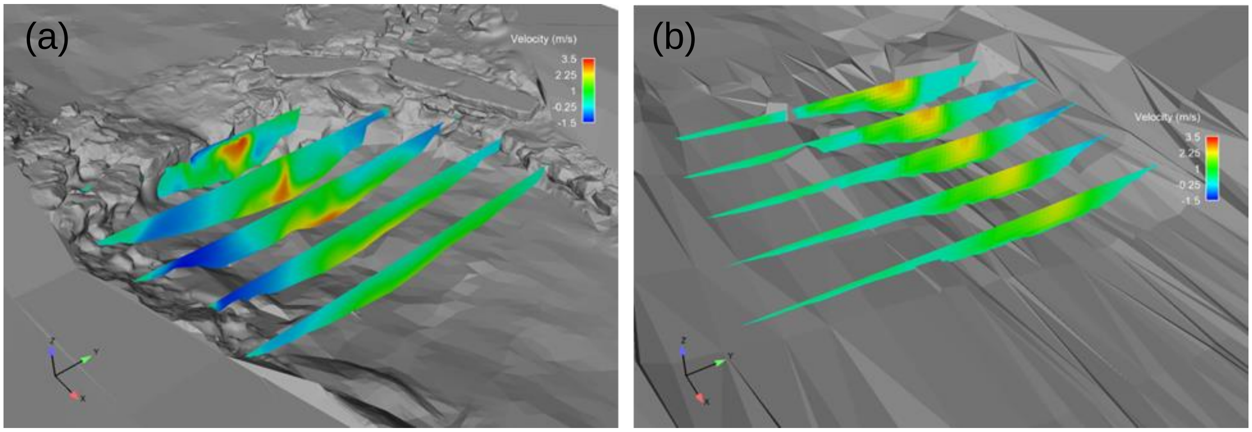


Figure 1.3. Cross sections showing the downstream velocity component (m/s) in pools: (a) WWP2 and (b) NR3 at 4.25 cms (Kolden, 2013).

1.3.1.3 TKE

The maximum TKE values for each flow rate were averaged for all the WWP pools and all the natural pools. TKE was consistently higher in the WWP pools than the natural pools, and increased with flow rate (Table 1.1). In the natural pool, areas with high turbulence were concentrated in the upper half of the water column in the thalweg, while in the WWP pool, areas of high turbulence were not confined to the thalweg and extended laterally across the pools.

1.3.1.4 Vorticity

The maximum 3-D vorticity and 2-D vorticity values for each flow rate were averaged for all the WWP pools and all the natural pools (Table 1.1). Both vorticity metrics were consistently higher in the WWP pools than 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).

There were clear differences between 2-D vorticity 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 calculations also overlooked a large area of vorticity downstream of the high-velocity jet, which was resolved by 3-D calculations. 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.

1.3.2 3-D Flow Patterns

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.

1.3.3 2-D Habitat Modeling

The 2-D habitat analysis resulted in few significant differences between the predicted habitat for WWP pools and natural pools. The depth limits for the habitat suitability criteria were exceeded in small areas of the WWP pools for native longnose dace and longnose sucker at all flow rates. Maximum depth-averaged velocity in small areas of the WWP pools exceeded the criteria limits for all species and all flow rates, while the maximum depth-averaged velocity in small areas of the natural pools exceeded criteria limits for all species at medium and high flow rates. The percentage of pool area with good habitat for each species life stage and flow rate is reported in Table 1.2.

Table 1.2. Percentage of pool area with good habitat (HSI > 0.5) for each species life stage and flow rate. Grey highlight indicates significant differences between WWP pools and natural pools (*p* < 0.05 for Wilcoxon and *t*-test).

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

1.3.3.1 Juvenile Brown Trout

Modeled 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, 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 1.2.

1.3.3.2 Adult Brown Trout

There was very little 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 1.4). The amount of habitat increased slightly with flow rate. Good habitat was minimal in the natural pools and did not change with flow rate. At low- and high-flow rates, there were no significant differences between the percentage of good adult brown trout habitat in the WWP pools and natural pools (Table 1.2). At medium flow rate, the WWP pools had significantly higher good habitat (8.8%) than the natural pools (0.9%) (*t*-test $p = 0.001$; Wilcoxon $p = 0.049$).

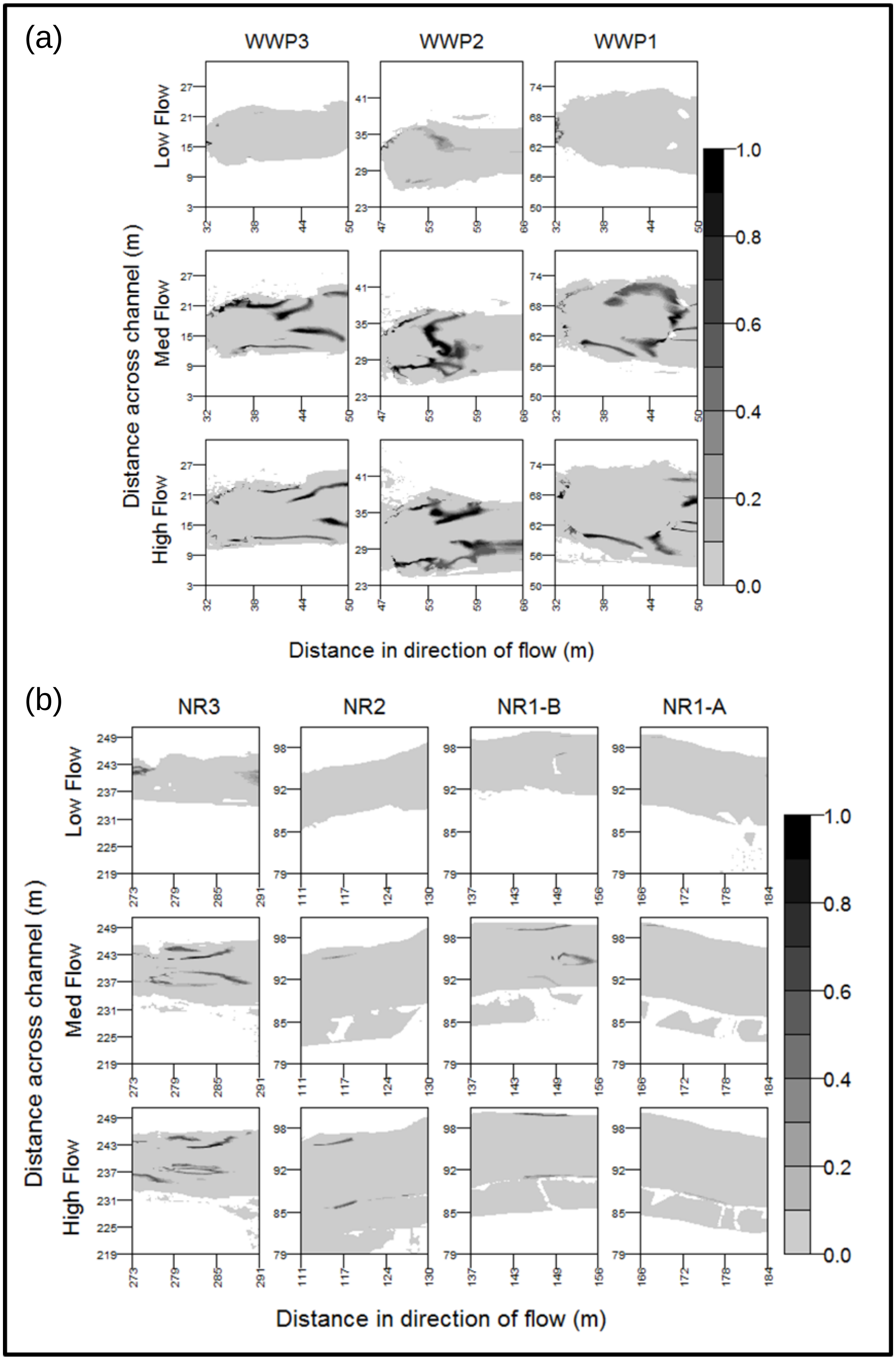


Figure 1.4. Habitat suitability results for adult brown trout in: (a) WWP pools and (b) natural pools (Kolden, 2013).

1.3.3.3 Juvenile Rainbow Trout

The 2-D habitat analysis showed that 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, 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 (Table 1.2).

1.3.3.4 Adult Rainbow Trout

In the WWP pools, adult rainbow trout habitat was concentrated in areas of higher depth, but as flow rate increased, habitat moved to the margins of jets and eddies, similar to adult brown trout habitat (Figure 1.5). The amount of habitat in the WWP pools generally increased with flow rate. There was minimal habitat available in the natural pools, and changes among flow rates were not apparent. 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 1.2).

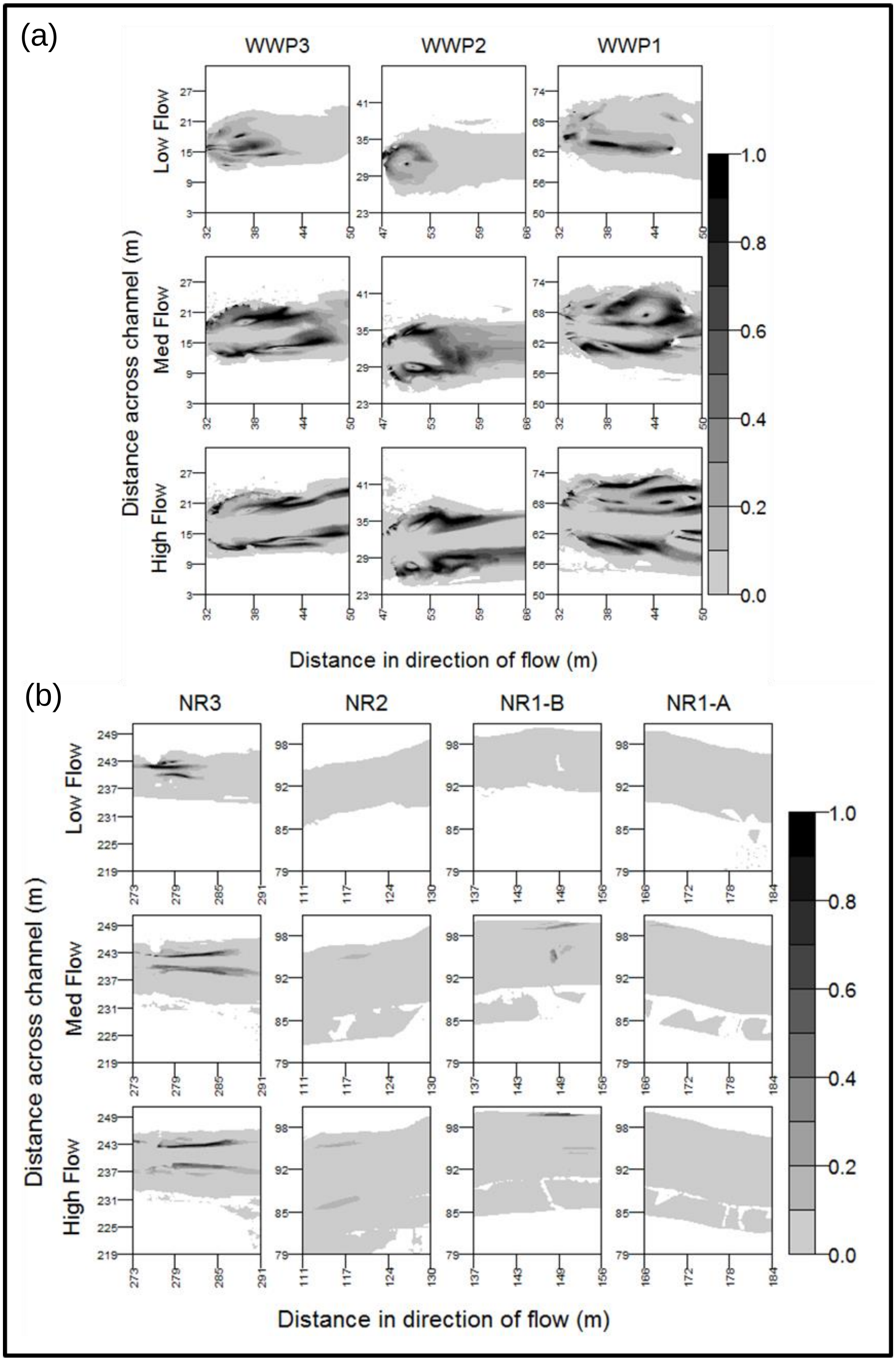


Figure 1.5. Habitat suitability results for adult rainbow trout in: (a) WWP pools and (b) natural pools (Kolden, 2013).

1.3.3.5 Longnose Dace

Predicted longnose dace habitat was abundant in the WWP pools, and occurred everywhere except for in the deepest part of the pools. The total amount of habitat decreased as flow increased, but the amount of good habitat was greatest at medium flow. In the natural pools, habitat was concentrated in the thalweg for low flow, and then moved to the margins as flow rate increased. Longnose dace was the only species that had a higher percentage of good habitat in the natural pools than in the WWP pools, though this was only true at low flow and was statistically significant for only one test (t-test $p = 0.002$; Wilcoxon $p = 0.057$) (Table 1.2). At medium flow, there was a higher percentage of good habitat in the WWP pools than in the natural pools at medium flows, but again, this was only statistically significant for one test (t-test $p = 0.04$; Wilcoxon $p = 0.057$).

1.3.3.6 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 1.2).

1.4 CASE STUDY: BIOMASS SURVEYS

CPW has an ongoing study to quantify biomass of introduced and native fishes in the North St. Vrain. They are surveying fish biomass in the same reaches and pools examined in this project. Beginning in Fall 2010, electroshocking surveys occurred each fall (in October or November) and spring (in April). Fall surveys were conducted during low flow and timed to coincide with brown trout spawning, while spring surveys corresponded with rainbow trout spawning. Spring and fall surveys occurred well before and after the summer period of heavy recreational use in the river.

The results of the Fall 2010 and Fall 2012 biomass surveys for adult brown trout (the most abundant fish species at the site) are shown in Figures 1.6 and 1.7. The 2011 results are not presented because they were affected by unusually prolonged high-flow rates that potentially confounded the field surveys. The capture probability in each pass during 2011 was insufficient for reliable population estimates (Kondratieff, 2013 pers. comm.). The Fall 2010 surveys followed a high flow year as well, but peak flow was short and did not extend into the fall. Fall 2012 surveys occurred after a period of spring and summer drought.

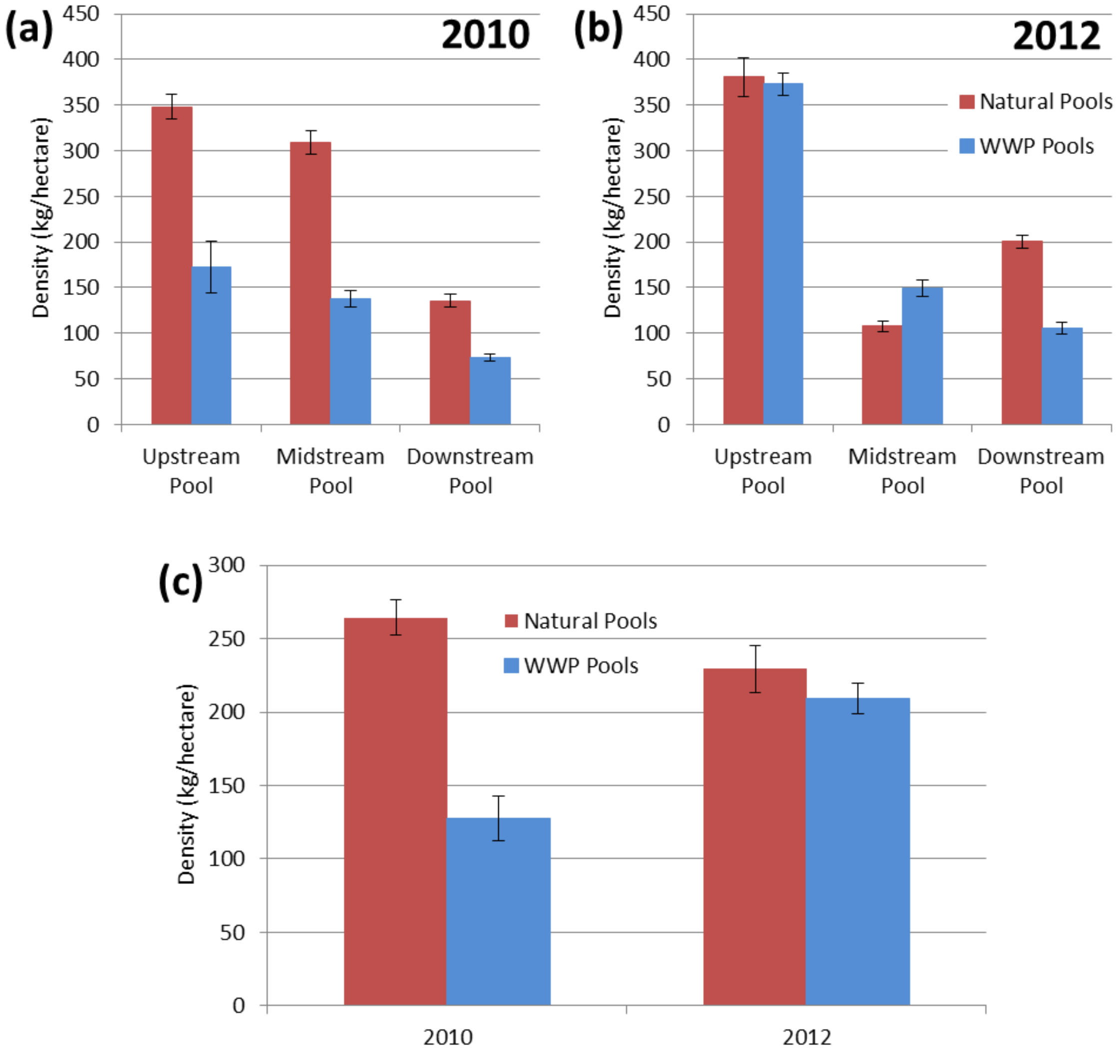


Figure 1.6. Adult brown trout biomass normalized by pool surface area: (a) biomass in each pool in 2010, (b) biomass in each pool in 2012, and (c) average biomass in WWP pools and natural pools in 2010 and 2012 (Kolden, 2013). Error bars represent 95% confidence intervals.

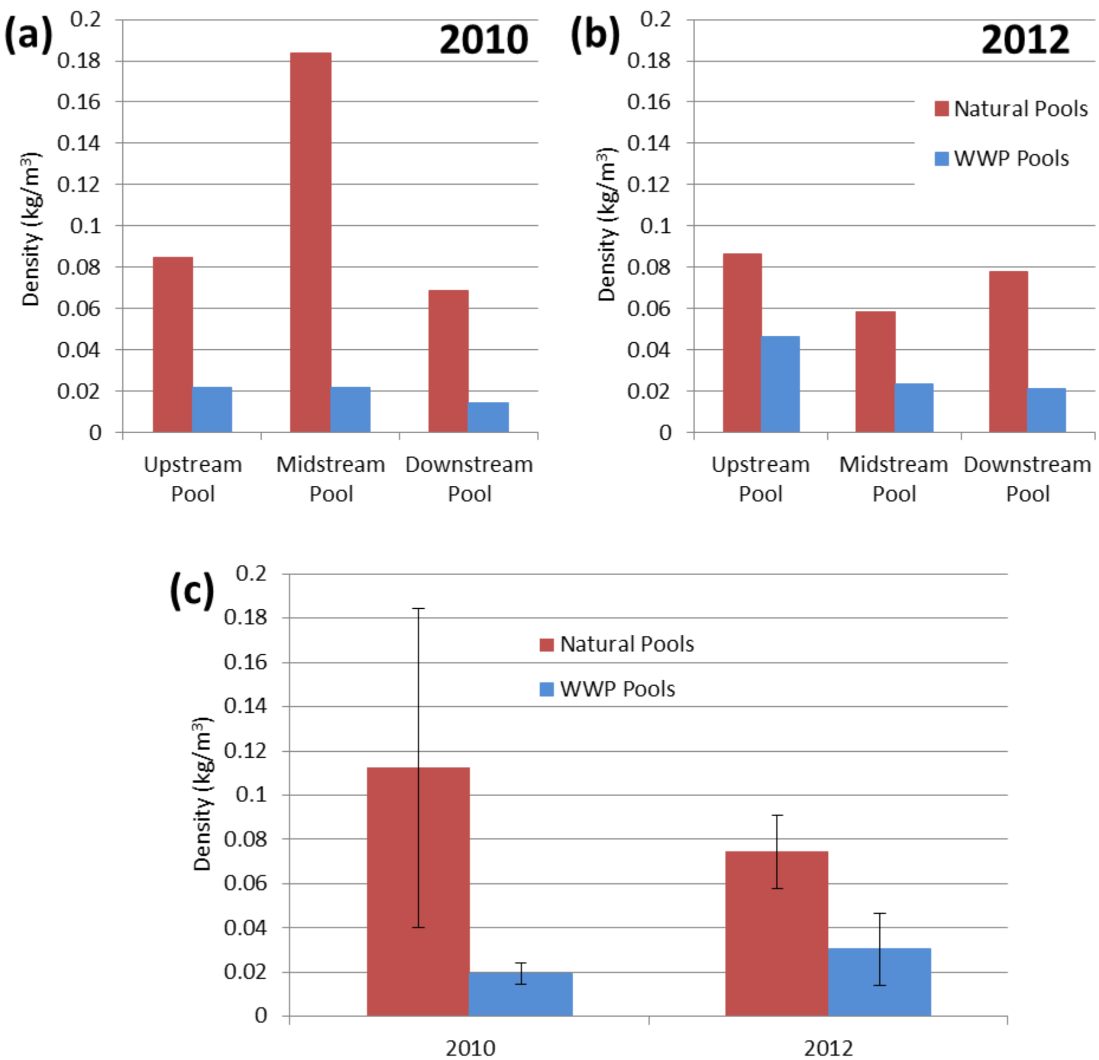


Figure 1.7. Adult brown trout biomass normalized by pool volume: (a) biomass in each pool in 2010, (b) biomass in each pool in 2012, and (c) average biomass in WWP pools and natural pools in 2010 and 2012 (Kolden, 2013). Error bars represent 95% confidence intervals.

When normalized by pool surface area, adult brown trout biomass was not significantly different in natural pools and WWP pools for either year (Figure 1.6c). However, when biomass was normalized by pool volume, biomass averages were significantly higher in the natural pools than the WWP pools for both years (Figure 1.7c). The per volume analysis accounts for the fact that the WWP pools are much deeper than the natural pools and, therefore, provide much more physical space for fish to inhabit.

The initial results of these biomass surveys caused concern among local fish biologists, and provided an impetus for further studies, including the modeling study presented here. Continuation and further analysis of the biomass surveys, including detailed methods, will be completed by CPW researchers and will be presented in a forthcoming publication.

1.5 DISCUSSION

1.5.1 Hydraulic Variables

Substantial differences were found between the hydraulic characteristics in WWP pools and natural pools. Depth, depth-averaged velocity, TKE, 2-D vorticity, and 3-D vorticity all had higher magnitudes in the WWP pools than in the natural pools. Pairing these results with the CPW biomass study results, which showed higher biomass per volume in the natural pools than the WWP pools, suggests that correlations could exist between these hydraulic variables 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 the natural pools, while biomass per volume is higher in the natural pools, which could 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 or river with very little complexity, depth-averaged velocity is a useful metric because the logarithmic velocity profile is very predictable. As described above (and shown in Figure 1.3) the WWP pools did not exhibit a logarithmic velocity profile. If the depth-averaged information was the only data available, one could erroneously assume that flow conditions were functionally the same and know nothing about the actual distribution of velocity beneath the water surface.

It is important to consider what conditions fish in this river are accustomed to, which in the case of velocity likely include 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 not be prepared for the high-velocity conditions at the bottom of a deep WWP pool. In a natural step-pool system, which would be found in streams with a higher gradient than the St. Vrain, fish might be more accustomed to the high velocities and complex flow patterns found in WWPs. Very similar flow patterns are 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 in this section of the St. Vrain, and there is reason to believe fish would not be accustomed 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, and again it can be assumed that fish in this region are accustomed to this pattern of vorticity distribution. 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, and exact values regarding fish preference are not known. It is possible that low levels of vorticity are tolerable and possibly even preferable to many fish, whereas high levels, above a certain threshold, are no longer suitable. 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. 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 river are accustomed 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 a large region of submerged, 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 spend significantly less time in 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 prevent migration (Silva *et al.*, 2012). Lacey *et al*. (2012) suggest that TKE not only influences fish directly through affecting swimming ability, but could also affect them indirectly through limiting food availability. This indirect effect could occur because food availability is influenced by local water velocity, which is often correlated with TKE. Since 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). More research is necessary to determine what meaningful threshold values might be.

1.5.2 2-D Habitat Models

The 2-D HSI analysis for adult brown and rainbow trout suggests that there was significantly more good habitat in the WWP pools than the natural pools for medium flow (brown and rainbow) and high flow (only rainbow) based on depth and depth-averaged velocity. When the brown trout results are compared to the results from the CPW biomass study, an interesting contradiction emerges. The 2-D HSI results predict almost no good adult brown trout habitat in all of the natural reaches (Figure 1.4), but surveys found more than twice as much average adult brown trout biomass per volume in the natural pools than in the WWP pools (Figure 1.7). Furthermore, in the WWP pools, the amount of predicted adult brown trout habitat was less than the amount predicted for any other species, which does not align with the fact that brown trout were by far the most abundant species in this stretch of river.

The lack of parallels between the 2-D HSI results and the biomass surveys could have many plausible explanations, and the truth likely lies in a combination of several factors. As explained above, 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 2-D parameters. The large differences between the 2-D and 3-D conditions pertaining to velocity, vorticity, and TKE were described above and are likely part of the explanation for the results of the biomass surveys. Also, the 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. Furthermore, fish habitat is not just affected by hydraulic conditions, but is also influenced by other physical factors such as substrate, bank complexity, and overhead cover, not to mention biological factors such as competition and predation. The presence of kayakers or other recreational users in the WWP pools will also have an effect on the ways fish use pool habitat, and is in no way accounted for in habitat modeling. Overall, 2-D hydraulic modeling can be a useful way to describe habitat conditions, but until researchers can be sure that the hydraulic metrics used in the models accurately correlate to habitat quality in regions of very complex 3-D flow and within biologically-complex systems, 2-D hydraulic modeling should not be used as the sole tool in habitat quality assessment.

1.5.3 Future Implications

Overall, it is clear that by ignoring the third dimension of flow in a 2-D hydrodynamic simulation, key information about hydraulic factors affecting habitat quality is being lost. 3-D modeling has the potential to be a very important tool for the future of WWP design. As understanding of how 3-D hydraulic variables influence aquatic habitat suitability increases, design modifications can be tested to minimize any negative effects of those hydraulics. However, as useful as 3-D modeling can be, 2-D modeling still has important utility. 2-D modeling is substantially cheaper than 3-D modeling in terms of software cost, computational power, required expertise, and time taken for data collection and modeling. The use of 2-D vs. 3-D modeling must be assessed on a case-by-case basis.

It is important to remember that this study represents one WWP in one river in Colorado, and cannot be used to make generalizations about the effects of WWPs on fish habitat in general, although it could inform future studies in parks with a similar size and geomorphic setting. Replications of the CFD process should be completed in other WWPs in order to understand general trends. Fish biomass studies should also be repeated in other parks, preferably with the inclusion of pre-construction baseline data.

Finally, before management decisions are made, it is important to consider the overall effects of WWPs and determine if the benefits outweigh the costs. The issue of habitat quality in WWPs does not have any right or wrong answers, and even if WWPs potentially impact habitat quality in a negative manner, there are other ways habitat can be improved. WWPs can increase community awareness of rivers and improve people's connection with the environment, which in turn could lead to habitat enhancement projects in other sections of river.

1.6 CONCLUSION

In this study, the effects of WWPs on aquatic habitat were examined using a 3-D hydrodynamic model. Two sections of a small river in Colorado were modeled for comparison: one relatively-natural section, and one section containing a WWP with three 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 and rainbow trout, longnose dace, and longnose sucker predicted higher habitat quality in the WWPs than the natural reaches for adult brown and rainbow trout at some flow rates, while in-stream surveys showed higher fish biomass per volume in the natural pools. There are many other factors besides 2-D hydraulic variables that impact habitat quality, including competition, predation, water quality, substrate, and cover. Another factor that is very important in WWPs but is often overlooked in habitat suitability analyses is the large amount of recreational use, which can scare fish and disrupt spawning grounds. 3-D hydraulic variables could also play an important role in determining habitat quality. In the WWP pools, 2-D model results did not describe the spatial distribution of flow characteristics or the magnitude of variables as well as 3-D results. The research presented in this study supports the use of 3-D modeling for complex flow found in WWPs, but projects should be evaluated case-by-case to determine if the simplified 2-D rendering of flow characteristics is acceptable. For 3-D modeling to be widely useful, improved understanding of linkages between 3-D aquatic habitat quality and hydraulic descriptors such as TKE, vorticity, and velocity is needed.

SECTION 2

ECO-HYDRAULIC EVALUATION OF WHITEWATER PARKS AS FISH PASSAGE BARRIERS

2.1 INTRODUCTION

Whitewater parks have become a popular recreational amenity in communities across the U.S. with Colorado being the epicenter of WWP design and construction. WWPs consist of one or more in-stream structures that create a hydraulic wave for recreational purposes. Originally WWPs were intended for use primarily by kayakers, although they have become increasingly popular destinations for swimmers and picnickers, while providing a “centerpiece” to many municipal park systems.

WWPs have been promoted as providing benefits for aquatic biota (McGrath, 2003) and are typically constructed with stated goals of improving fish habitat by creating large pools. In addition, WWPs are highly sought by communities as a means of providing a boost to local economies associated with an increase in tourism. A study of the WWP in Golden, Colorado (Hagenstad *et al*., 2000), found it generates approximately $1.36 to $2 million of economic benefit per year, and another report prepared for a proposed WWP in Fort Collins, Colorado, reported an estimated annual economic benefit of up to $750,000 (Loomis and McTernan, 2011). WWPs have also played an important role in the formation of “recreational in-channel diversions” (RICDs) in Colorado (Crow, 2008), which create a water right to maintain minimum discharges for recreational use.

Despite these assumed benefits, natural resource managers have raised concerns that WWPs may have adverse ecological effects. A pilot study conducted by CPW found low fish biomass within a WWP as compared to natural control (CR) reaches despite the presence of large constructed pools (Kondratieff, 2013 pers. comm.). Several hypotheses were developed for the cause of the reduced biomass, including impaired fish passage, degraded habitat conditions from interruption of sediment transport, and limited food production due to degraded riffles. Impaired fish passage was identified as a primary concern after measuring water velocities (>10 ft/s [3.05 m/s]) exceeding the swimming speed of several species and size classes of resident fishes. The presence of a passage barrier could potentially have effects extending beyond the local scale of a WWP (Lucas and Baras, 2001). These issues may become especially relevant in considering the construction of features for recreation purposes in an otherwise unfragmented and healthy river segment.

Ambiguities in decision-making arise from a lack of consensus regarding the potential effects of WWPs during the U.S. Army Corps of Engineers (USACE), Section 404 of the Clean Water Act permitting process. This process is intended to avoid, minimize, and mitigate impacts to the waters of the US, and also provides opportunity for state wildlife agencies to comment on the potential impacts of proposed projects. These permitting decisions can often be difficult because actual data on the effects of WWPs are unavailable. Without first understanding the significance of effects for a given action, speculation may lead to a potentially-biased regulatory permitting process by either allowing projects with unacceptable negative effects, or by stopping projects that may have minimal or no negative effect. Allowing the construction of WWPs, if they do in fact have adverse effects, may lead to projects that limit aquatic habitat and fish passage in otherwise unimpaired rivers. Disallowing the construction of WWPs, if they have minimal or no negative effect on aquatic habitat and fish passage, would unnecessarily prevent the completion of a project that would otherwise provide positive social and economic benefits to communities. Understanding the effects WWPs on fish passage and aquatic habitats are critical to better inform policy and decision-making for future WWPs, and provide local citizens and project sponsors with information to consider when weighing the potential benefits and adverse effects of WWPs.

Because impairment of upstream passage has the potential for the broadest impact on fish populations (Lucas and Baras, 2001), this issue has been identified by CPW as the most immediate concern and is the focus of this study. This study is the first to perform an investigation of how fish movement is affected by WWPs. ***The overarching goals of this research are to determine if, and to what extent, WWPs alter the upstream movement of fishes, and if there is an effect, to examine how the hydraulic conditions created from WWPs influence upstream movement of fishes.***

2.1.1 What is a WWP?

A WWP can be defined as any man-made in-stream structure designed with the intent of creating a hydraulic jump or wave for recreational purposes. While there is a wide variety of structure design techniques, field visits to eleven WWPs in Colorado and careful review of publically-available design plans suggest that this is typically accomplished by constriction of flow into a steep chute creating a hydraulic jump as it flows into a large downstream pool (Figure 2.1). A combination of such design features are often used by WWP designers to create structures that can be usable across a range of anticipated flows. Different types of waves can be constructed by manipulating the angle at which the flow from the chute enters the downstream pool. Steeper and shorter structures form what is considered a “hole,” while longer structures with flatter slopes form a “wave” (Figure 2.2). These differences in hydraulic jump types, described in Moore and Morgan (1959), are important to note because they affect the maximum velocity, structure length, turbulence, and other flow conditions related to fish passage.

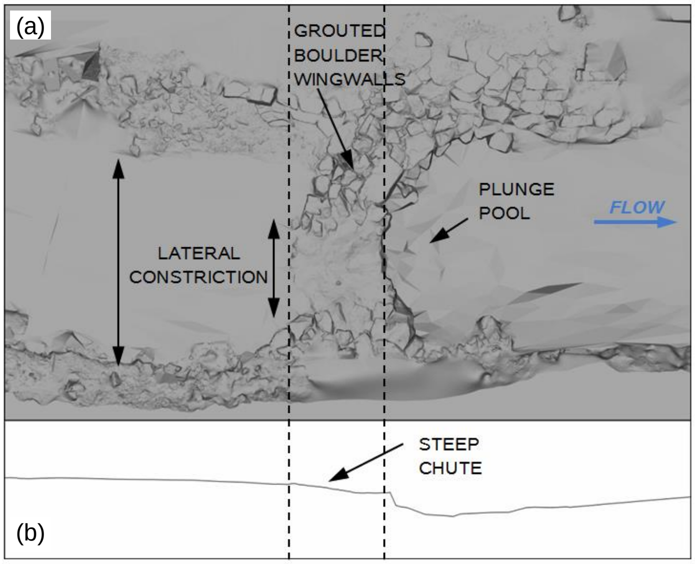


Figure 2.1: (a) Plan and (b) profile views of common design features found in WWPs (Fox, 2013).

(a) wave type (b) hole type

Figure 2.2: Typical (a) "wave" and (b) "hole" types of WWP structures (Fox, 2013).

Because all WWPs are built with the goal of creating a hydraulic jump, well-documented methods (Chow, 1959) based on changes in specific energy and Froude number (*Fr*) are available to characterize the general flow conditions required to form a hydraulic jump. This type of analysis is significant for describing fish passage conditions because it provides a simple method for estimating the general range of average flow velocity and depth regardless of any specific design characteristics. For a hydraulic jump to occur, flow must transition from a supercritical ($Fr > 1$) to subcritical ($Fr < 1$) specific energy state (Figure 2.3). Therefore, within any WWP structure that actually produces a jump, supercritical flow must exist and *Fr* must be greater than 1 along some part of the structure. Further, larger hydraulic jumps require a higher *Fr* within the supercritical section; therefore, larger jumps will require greater velocity and smaller flow depth within the supercritical section. The ranges of average flow velocity and depths are illustrated for a range of *Fr* and unit discharges (Figure 2.4) to provide a general estimate of hydraulic conditions occurring in the supercritical portion of a hydraulic jump (Moore and Morgan, 1959; Rajaratnam and Ortiz, 1977):

$$Fr = \frac{v}{\sqrt{gy}} \quad \textbf{(Eq. 2.1)}$$

$$q = vy \quad \textbf{(Eq. 2.2)}$$

$$v = \left(Fr^2 gq\right)^{1/3} \quad \textbf{(Eq. 2.3)}$$

$$y = \left(\frac{q^2}{gFr^2}\right)^{1/3} \quad \textbf{(Eq. 2.4)}$$

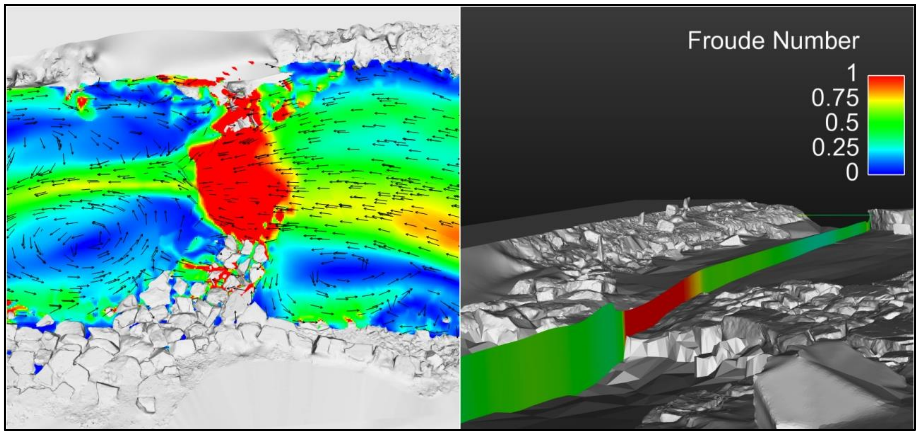
where

v = velocity $\left(\frac{\mathrm{L}}{\mathrm{T}}\right)$;

g = gravitational acceleration $\left(\frac{\mathrm{L}}{\mathrm{T}^2}\right)$;

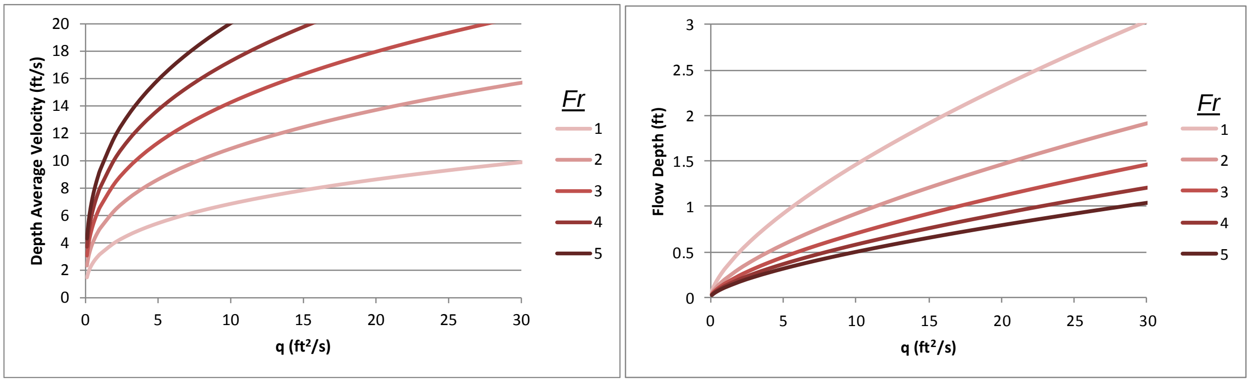
y = flow depth (L); and

q = unit discharge $\left(\frac{\mathrm{L}^2}{\mathrm{T}}\right)$.



(a) plan view (b) profile view

Figure 2.3: (a) Plan and (b) profile views of hydraulic jump-forming process in a "typical" WWP (Fox, 2013). Flow enters the structure as subcritical (*Fr* < 1) where specific energy is reduced to its minimum, or the critical flow condition (*Fr* = 1). From the location of critical depth, flow will continue as supercritical (*Fr* > 1) on a steep bed slope and form a jump at the subcritical (*Fr* < 1) tailwater.



(a) by unit discharge (b) by minimum depth

Figure 2.4: Depth-averaged flow velocity (a) by unit discharge and *Fr* estimating the lower range of maximum flow velocities and (b) minimum depth (Fox, 2013). Structures where a hydraulic jump is present will have conditions of *Fr* > 1, with jump height increasing with *Fr*.

This analysis indicates that consistent hydraulic conditions are required to produce the necessary changes in specific energy to form the hydraulic jump. These conditions include high-flow velocity, decrease in flow depth and large amounts of turbulence within the hydraulic jump. It should be emphasized that this analysis is a general characterization of the required spatially-averaged hydraulic conditions that are expected somewhere within the structure for a jump or wave to form. Site-specific design elements can cause a high degree of spatial variance in hydraulic characteristics within the structure. These design elements can include any physical feature that affects: (1) critical flow at the structure entrance, (2) Froude number of the supercritical flow, and (3) the rapid conversion from supercritical back to subcritical flow in the hydraulic jump. The effect of each design element will have a high degree of interaction and dependence with other design variables and discharge magnitude; therefore, WWPs must be evaluated on an individual basis to determine how site-specific conditions diverge from average conditions (Figure 2.4).

2.1.2 Objectives

A review of the physical features of WWPs indicates these in-stream features require large changes in flow velocity, depth, turbulence, and hydraulic drop to meet the recreational objectives of forming a hydraulic jump. All of these variables can pose a complete or partial barrier to upstream movement. In addition, it has been documented that structures producing similar hydraulic conditions were found to both impair and allow unimpeded movement. Because of the variability in spatial and temporal hydraulic conditions unique to individual structures, uncertainty in fish swimming data, and differences in passage success at similar structures, a simple comparison of the biologic and hydraulic metrics to evaluate fish passage at WWPs is unlikely to yield the type of information needed to inform policy and decision-making. To address these knowledge gaps and issues, we conducted a detailed field study that simultaneously observed fish movement and complex hydraulic conditions at a representative WWP site. Specific objectives were as follows:

- Determine if a representative WWP is a complete barrier to upstream movement for resident fishes using a novel combination of fish movement monitoring, detailed hydraulic measurements, and CFD modeling.
- Assess whether a representative WWP is a partial barrier to upstream movement for specific species and size classes.
- Assess the effects of spatial and temporal variation of flow velocity, depth, drop, and turbulence on successful fish passage.
- Determine if flow velocity is functioning as a burst swimming barrier for a range of fish size classes.
- Assess how results from the representative site can be transferred and applied to other WWPs.

2.2 METHODS

The introductory section underscores a clear need for improved understanding of fish movement within WWPs. A review of fish passage literature alone is inadequate to answer the questions posed by the research goal and it was determined a field study was necessary to understand how WWPs may be affecting fish passage.

The literature review indicates that the hydraulic environment of WWPs may be affecting fish movements; therefore, we sought to develop methods that could simultaneously monitor occurrences of fish movement and hydraulic conditions. These data would then lead to an integrated assessment to directly evaluate movement in WWPs and whether the structure hydraulics were a cause of impaired movement. The results of this assessment could be used to evaluate current fish passage conditions at existing WWPs and inform development of improved fish passage design criteria at proposed WWP locations.

This integrated assessment approach developed in our study followed the fishway evaluation methodology described by Castro-Santos *et al*. (2009). Such evaluations use integrated methods to assess the effectiveness of structures specifically designed for successful fish passage. In our study, these methods were applied in a context to assess limitations imposed by structures on upstream passage in what would otherwise be an unobstructed reach of river.

To meet the research goals and objectives, specific methods first required the selection of a representative field study site. A conceptual framework was then developed to assess hydraulic and biological variables affecting fish movement in WWPs. Fish movement was directly tracked using PIT tag telemetry at three WWP structures and three unaltered CR reaches to calculate movement probabilities, and a combination of field measurements and multidimensional hydraulic modeling was used to evaluate hydraulic conditions present in

WWPs. These data were then integrated into the assessment framework to evaluate the study objectives.

2.2.1 Site Description

The North Fork of the St. Vrain River in Lyons, Colorado, was selected as the location of the field study site (Figure 2.5). The study reach is located within the town of Lyons on the North Fork of the St. Vrain River. Geomorphically, this segment can be defined as a transition zone between typical mountain step-pool morphology and plains riffle-pool morphology, and is characterized by continuous steep riffles with very little pool habitat. The largest natural pools appear to occur in locations where rock or woody debris within the channel has caused local scour.

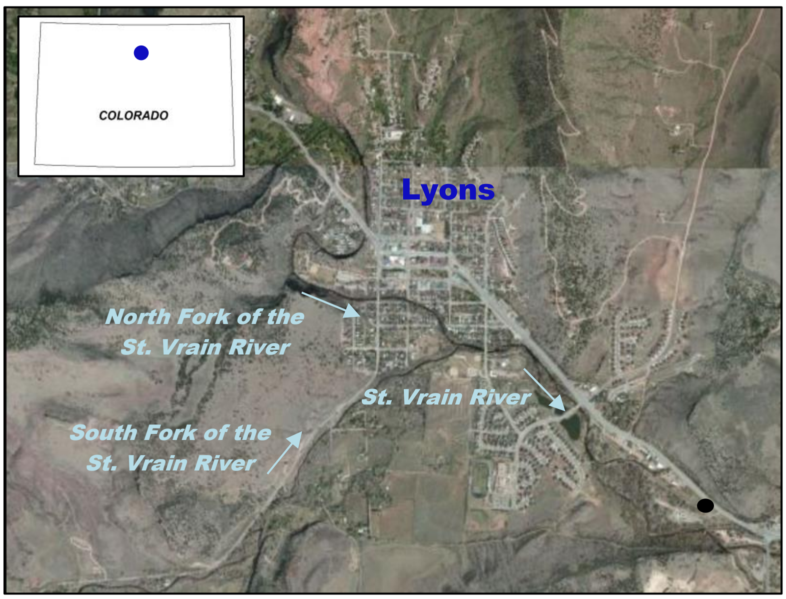


Figure 2.5: Location map of study site on the North Fork of the St. Vrain River, Lyons, Colorado (Fox, 2013).

A total of nine WWP structures were previously constructed in 2002 on the North Fork of the St. Vrain in Meadow Park, and an additional three structures were later built on the St. Vrain main stem near Highway 66. Three of the structures within Meadow Park and three CR sites were selected for the detailed movement study with PIT antennas (Figure 2.6(a)).

Figure 2.6: (a) Vicinity of study sites on the North Fork of the St. Vrain River, Lyons, Colorado; (b) location of three paired PIT arrays at control (CR) sites; (c) location of three paired PIT arrays at WWP sites; and (d) example of paired antenna installation (W3 and W4) (Fox, 2013).

The WWP study sites were selected to represent the range of physical design variables we had identified that may affect the hydraulic conditions at each of the sites. The CR sites were selected at natural riffle-pool sequences, and reflected a natural analog to the features in a WWP structure. The CR sites are located approximately 0.5 mi upstream from the WWP sites on private property. In addition, the CPW had previously conducted pilot studies of movement and abundance at these locations. This pilot study included the release of PIT tagged fishes, thereby allowing us to increase the sample size of the study by continued monitoring of previously-tagged individuals.

2.2.1.1 Hydrology

The site is typical of snowmelt hydrology systems of the southern Rocky Mountains. Peak runoff normally occurs during snowmelt runoff in late May or early June, but may also occur in late summer as a result of intense convective storm events. Existing stream gages are located on the main stem of the St. Vrain downstream of the confluence with the South Fork and upstream near the outlet of Button Rock Reservoir. As a result, existing gage data cannot directly be used to accurately quantify discharge at the sites. Accordingly, we used U.S. Geological Survey (USGS) regression equations (Capesius and Stephens, 2009) to estimate peak flow discharge and flow-duration probabilities for the site to evaluate the magnitude of the flow conditions observed during the study period (Tables 2.1 and 2.2).

Table 2.1: Flow-duration streamflow statistics for mountain region flow duration (Capesius and Stephens, 2009).

Statistic	Flow (cfs)	Prediction Error (%)
D10	271	19
D25	84.1	29
D50	32.7	29
D75	19.3	39
D90	13.8	72

Table 2.2: Annual peak flow (Capesius and Stephens, 2009).

Statistic	Flow (cfs)	Prediction Error (%)
PK2	655	82
PK5	1010	68
PK10	1280	64
PK25	1650	64
PK50	2070	63
PK100	2520	62
PK200	3530	66
PK500	3690	59

It should be noted that extreme flow events occurred the year prior to the study in 2011 when an extended high-water period occurred from May through August. In addition, an unusually low-water period occurred during the study, with the maximum discharge below 300 cfs.

Button Rock Reservoir is approximately 8 mi upstream from the study sites, and is the only major impoundment within the watershed. No major water diversions are located upstream from the study site, but several major irrigation canals divert water approximately 1.25 mi downstream. Additional water withdrawal from the river occurs from private pumping and by a single off-take structure located just upstream of the WWP sites. Because these are not major diversions and for private use only, it is assumed that these alterations have a negligible effect for the purposes of this study.

2.2.2 PIT Tag Telemetry Study

We quantified fish movement across WWP structures indirectly using PIT antenna arrays. Twelve Oregon Radio Frequency Identification (RFID) half-duplex (HDX) single antennas were installed to monitor movement across both the WWPs and CR sites (Figure 2.6). Nested pairs of antennas were placed upstream and downstream of each of the six site locations. Downstream antennas determine the presence of individuals available to move across a respective structure, and the upstream antennas determine the presence of an individual above a given structure. A sequenced detection from the downstream to upstream antenna indicates successful upstream movement of an individual across the structure.

Antenna configurations were designed to maximize the detection probability of tags, while minimizing safety risk to park users. Constraints for these goals include placement of antennas in locations of shallow flow depth to force passage a short distance to the antenna, and at locations away from high-velocity zones where entanglement in the antenna would create safety risk. Due to these constraints, the downstream antenna was placed at the pool tail of each site location and the upstream antenna placed approximately 20 ft upstream from the crest of the structures or riffles (Figure 2.6). This allowed for antennas to be located in relatively-shallow areas where read range and detection probability are maximized, and at a location away from any powerful hydraulic features where entanglement with antennas would be a safety concern.

A negative aspect of this antenna design is that detections do not occur within the portion of the structure where passage may be impaired. Movement across both antennas indicates a successful movement across the structure, but no information can be obtained regarding failed passage attempts, the number of attempts, and behavior as a fish is attempting to move across the structure.

Tags were introduced into the study by three different mark-release types (*MRT*) for six separate events (Figure 2.7). Rainbow trout (*Oncorhynchus mykiss*) and brown trout (*Salmo trutta*) were tagged using a combination of 32-mm and 23-mm HDX PIT tags inserted into the peritoneal cavity posterior to the pectoral fin using a hypodermic needle (Prentice *et al*., 1990; Acolas *et al*., 2007). Longnose sucker (*Catostomus catostomus*) and longnose dace (*Rhinichthys cataractae*) were tagged with 12-mm or 23-mm HDX PIT tags inserted in the same location, but these species were not tagged with a hypodermic needle. Instead, they were given a small incision, the tag was inserted into the peritoneal cavity, and the incision was sutured with methods described in Summerfelt and Smith (1990). Traditional surgery was used with these species to minimize the risks associated with using a tagging gun with fishes less than 120 mm in length (Baras *et al*., 1999). For each tagged individual the unique tag number, species, body length, and weight were recorded and entered into a database.

Figure 2.7: (a) Collection of fishes by electrofishing; (b) fish being PIT tagged; and (c) recording tag number, species, weight, and body length measurements of tagged fish (Fox, 2013).

The three *MRT*s include electrofishing study site residents, release of hatchery-reared fishes, and displacement of fishes below the study sites. The different *MRT*s were used to increase the sample size and motivation to move upstream. Electrofishing *MRT*s were performed at each of the six study sites on six occasions. These consisted of a three-pass removal effort with a shore-based electrofishing unit to collect and tag all available fishes within each of the study locations from approximately the downstream antenna to the base of the structure. Stocking *MRT*s consisted of releasing hatchery-reared rainbow trout (*Hofer x Harrison strains*) at each of the six study sites on two occasions. The displacement *MRT*s were performed on two occasions and consisted of sampling a location upstream from the WWP and CR reaches with a shore-based electrofishing unit to collect and tag all available fishes. These fishes were released in the WWP and CR reaches, below their respective lower structures. Previous research has noted a homing behavior to return to upstream capture sites after being displaced at a downstream site (Halvorsen and Stabell, 1990). The intent of the displacement *MRT*s was to increase the motivation of movement through each of the study sites.

Events 1 and 2 occurred as part of the CPW pilot study prior to the installation of the fixed PIT antennas; the subsequent four events occurred within the periods of PIT antenna operation. The fixed PIT antennas operated for approximately 14 months (October 12, 2011 – December 5, 2012). At the request of the property owner, the CR site antennas were removed between July 12 – September 12, 2012. No PIT data are available for the CR site during this period. Table 2.3 summarizes occurrences of each of the *MRT*s and events for the study.

Table 2.3: Summary of events and associated mark-release types (*MRTs*).

Event Number	Event Name	Mark-release Type (*MRT*)	CR DISP – POOL E	CR1 – POOL F	CR2 – POOL G	CR3 – POOL H	WWP DISP – POOL A	WWP1 – POOL B	WWP2 – POOL C	WWP3 – POOL D
1	Fall 2010	Electrofishing	–	11/10/10	11/10/10	11/9/10	–	11/8/10	11/8/10	11/8/10
		Stocking	–	11/10/10	11/10/10	11/9/10	–	11/8/10	11/8/10	11/8/10
2	Spring 2011	Electrofishing	–	4/15/11	4/15/11	4/15/11	–	4/15/11	4/15/11	4/15/11
10/12/2011 BEGIN PIT ANTENNA STUDY										
3	Fall 2011	Displacement (DISP)	11/16/11	–	–	–	11/16/11	–	–	–
		Electrofishing	11/16/11	11/15/11	11/15/11	11/15/11	–	11/14/11	11/14/11	11/14/11
		Stocking	–	10/12/11	10/12/11	10/12/11	–	10/12/11	10/12/11	10/12/11
4	Spring 2012	Electrofishing	–	4/11/12	4/11/12	4/10/12	–	4/10/12	4/10/12	4/10/12
5	October 2012	Displacement	10/5/12	–	–	–	10/5/12	–	–	–
		Electrofishing	–	10/4/12	10/4/12	10/4/12	–	10/5/12	10/5/12	10/5/12
6	November 2012	Electrofishing	–	11/8/12	11/8/12	11/8/12	–	11/6/12	11/6/12	11/6/12
12/5/2012 END PIT ANTENNA STUDY										

2.2.3 Hydraulics Evaluation

The goal of hydraulic data collection is to characterize the conditions that may be directly limiting the ability of individuals to move upstream in WWPs. Further, these data must be evaluated at spatial and temporal scales relevant to fish movement. To do this, we must be able to specify hydraulic values at all points potentially encountered by upstream migrating fishes, and at the full range of flows for each site. In practice, this can be accomplished through direct measurement or by the development of a hydraulic model.

Direct measurement methods are preferred because this method typically provides the most accurate data. However, the nature of WWPs poses several challenges to solely collecting data with field measurements. High-flow velocity at the site limits wading and, therefore, all parts of the channel cannot be accessed for detailed measurements. In addition, air entrainment, shallow depths, and high velocities create conditions that are unfavorable for accurate and reliable measurement (Craig Huhta, 2013 pers. comm.). Collecting a sufficient amount of data at spatial and temporal scales relevant to fish passage may also be impractical using conventional current flow meters.

CFD models can be used to evaluate the flow field at all discharges to obtain a large quantity of data over spatial and temporal scales not practical through the collection of field measurements. These models solve the governing physical equations for the conservation of mass, momentum, and energy to give a solution for the velocity components within the area of interest. While these data are only an approximation, they provide the best method for characterizing the hydraulic conditions to meet the goals of the project.

The project team collaborated in developing a computational model for this project using the commercial modeling software FLOW-3D. This software was used to create a fully 3-D non-hydrostatic model of each of the three WWP structures and three CR pools. Six different flow events (15, 30, 60, 100, 150, and 300 cfs) at the six study locations were modeled with FLOW-3D. Field data measurements of water-surface elevations, wetted perimeter, and point velocities were collected at a high- (150 cfs) and low-discharge (10 cfs) event to successfully validate the model output. Measured water-surface elevation profiles matched modeled data within 3 cm and velocity measurements were found to have an error of less than 16%. A detailed discussion of the model development procedures and validation process is given in Kolden (2013).

2.2.3.1 Discharge Rating Curve

We developed a discharge rating curve at the site to maintain a concurrent discharge record with fish movement data from the PIT antennas, and to link the hydraulic modeling data to observed occurrences of fish movement. HOBO® pressure transducers were installed at a location with uniform velocity patterns and set to record flow depth hourly. A total of eighteen discharge measurements were taken over a range of flows using a Sontek Flowtracker ADV to develop the stage-discharge relationship at the site. Because of the relatively-small range of flows encountered during the study period, a linear regression relationship was determined to be suitable for development of the stage-discharge relationship.

2.2.4 Data Analyses

2.2.4.1 PIT Data Analysis

We assessed raw PIT movement data to determine whether any of the structures posed a complete barrier to upstream movement for a given species or size class. This included an assessment of upstream movement of each individual from its initial release location, and assessment of movement for all individuals at all sites regardless of their initial release location. Any upstream movement occurring across a given location throughout the entire study period indicated that some level of successful passage was being achieved. Evaluation of partial barriers by size class was completed by comparing raw movement counts for fishes known to make upstream observations versus those that did not.

Further examination for the presence of any partial impairment to movement was completed through the development of a Cormack Jolly-Seber (CJS) regression model within program MARK (White and Burnham, 1999). The purpose of this model is to obtain least-biased estimates of upstream movement across WWP and CR sites by controlling for missed detections, *MRT*, events, species, and body length. This method can be viewed as an extension of binomial or logistic regression, where instead of estimating a single parameter of success vs. failure, a combined estimate of apparent success (Ψ) is modeled by:

$$\Psi = \phi * p \qquad \textbf{(Eq. 2.5)}$$

where

ϕ = probability of success; and
p = probability of encounter.

The success parameter that would be estimated using standard logistic regression is adjusted by a detection probability parameter that is determined from observations of missed detections. Specific procedures for the application of this modeling approach to predict unidirectional movement for fishes were developed by Burnham *et al*. (1987). This modeling approach calculates the probability of transition between two states and was originally applied to estimate survival probability of out-migrating smolts in the Columbia River basin.

This model was applied by evaluating movement success probability in the upstream direction for all individuals over the complete period of the study. In the context of our study, the success parameter (ϕ) can be interpreted as a combined estimate of movement and survival probability conditional that the individual was observed downstream of that site and alive. The general model that was fit to the data set is given:

$$
\begin{aligned}
logistic(\phi) = \beta_{INT} &+ \beta_1[MRT] + \beta_2[EVENT] + \beta_3[SPECIES] \\
&+ \beta_4[LENGTH] + \beta_5[LOCATION] \\
&+ \beta_6[LENGTH]*[SPECIES] + \beta_8[LOCATION]*[SPECIES] \\
&+ \beta_9[LOCATION]*[LENGTH]
\end{aligned}
\quad \textbf{(Eq. 2.6)}
$$

A candidate set of twenty-three possible models was selected by fixing the inclusion of *MRT* and *EVENT*, and nesting the remaining main effects and interactions. Interactions were not included in the candidate model set if the associated main effect was removed. *LOCATION* was modeled by using only sites (WWP and CR) and then by each of the three WWP structures and three CR pools.

2.2.4.2 Hydraulic Data Analysis

The full FLOW-3D model results were used to qualitatively evaluate and describe differences in flow conditions by discharge for each location. Full model results were reviewed to assess spatial variations in velocity, depth, hydraulic drop, and turbulence. Quantitative descriptors of the flow velocity were developed for the center chute portion of each WWP structure and upstream riffle at each CR pool. We sought to develop metrics to describe the range of velocity magnitudes encountered by upstream moving fishes that incorporated the spatial variations in the 3-D modeling data. To do this, we first extracted 2-D cross sections from the 3-D output in increments of 1 ft between the entry and exit portions of the center chute at WWP structures and riffle sections of the CR. A distribution of the velocity values within the 2-D plane were evaluated in SAS® using PROC UNIVARIATE to calculate area weighted summary values of velocity at each cross section. This result provided various estimates of not only the cross-section mean velocity, but also of minimum, maximum, 5th, 25th, 50th, 75th, and 95th percentile velocities within each cross section.

Because fish movement data are limited to ‘Yes/No’ for a specific discharge, we can use these aggregate quantifications of flow velocity to describe the range of potential conditions that may be encountered by upstream migrating fishes without knowledge of specific movement pathways. In particular, the quantile values provided a more-likely descriptor of actual velocities encountered by fishes as opposed to minimum velocities that may occur very near the channel bed and maximum velocity within the center of the channel. For example, the flow velocity specified as the 25th percentile within a cross section will indicate that 25% of the cross-section area contains a smaller velocity magnitude and 75% of the flow area contains a greater velocity magnitude. This type of quantification allows for simple metrics incorporating the spatial variation of velocity in both the cross-section and longitudinal dimensions that are potentially encountered by migrating fishes, however, it is noted that this method does not explicitly attempt to account for connectivity and flow paths between or within each of the cross sections.

2.2.4.3 Assessment of Burst Swimming Barrier

Without direct information on movement pathway, we further aggregated the velocity data to determine the maximum velocities among all cross sections at each location as a method to evaluate burst swimming barriers. For each location and discharge, the values of each cross-section minimum, maximum, 5th, 25th, 50th, 75th, and 95th percentile velocities were compared to find the respective maximum value. These maximum values among the cross sections represent the limiting condition for a burst swimming barrier, because they must be traversed for successful movement. While limitations to using these aggregate descriptors exist, they are the best available method for a direct quantification of flow velocity for binary movement. Additional data regarding movement pathways would be required to more precisely assess the effects of small-scale velocity variations of fish moving through the structure.

Because there were only six discrete flow events for which detailed hydraulic conditions were modeled, flow velocity was made continuous as a function of discharge by linearly interpolating for discharges that were not directly modeled in FLOW-3D. These values of velocity were then plotted against fish body length for all successful movement events occurring between 2/1/2013 – 7/15/2013 (data set 1) and 9/15/2013 – 12/5/2013 (data set 2). Restrictions by date range occur for periods when overall reader function was good and detection probability assumed to be very close to 1. This allowed for an unbiased comparison between WWP and CR sites with respect to detection probability.

2.3 RESULTS

2.3.1 PIT Data

2.3.1.1 Study Population Data

We tagged and released 1639 fishes within the WWP and CR sites that were included in the final analysis; of these, 87% were redetected at least once during the study (Table 2.4).

Table 2.4: Summary of total tagged individuals released over the duration of the study, and tags requiring removal (italic red-font values) from analysis.

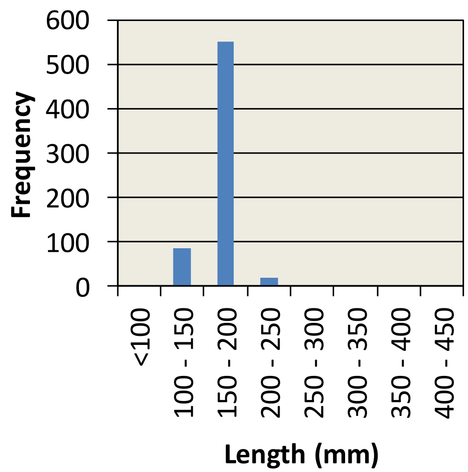
	Number of Fishes Tagged (*n*)
Released in WWP and CR over Study[1]	2268
Censored Tags	*-46*
CPW Pilot Study Non Encounters	*-583*
Tags in Analysis	1639
Tags Detections by PIT Antennas	1440
% Recapture by PIT Antennas	87%

[1]Includes all tags released during CPW pilot study.

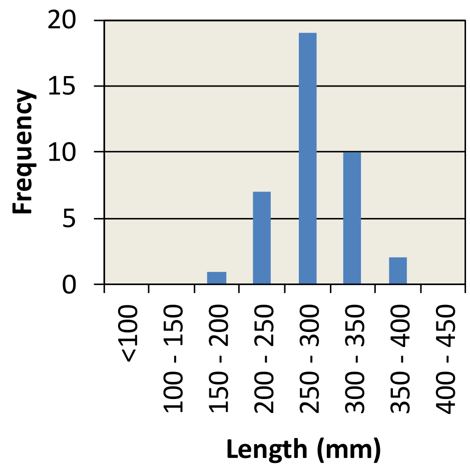
The numbers of tagged fishes released at each of the study sites are given (Table 2.5) for the six events. Distributions of the body lengths for tagged fishes are illustrated by species (Figure 2.8). Because of the small numbers of longnose sucker (LGS), longnose dace (LND), and rainbow trout (RBT) compared to brown trout (LOC), subsequent analyses group species as salmonid and non-salmonid as necessary.

Table 2.5: Summary of total fishes by species released at each site over the duration of the study; RBT – rainbow trout (*Oncorhynchus mykiss*), HOF – (*Hofer x Harrison strain*), LOC – brown trout (*Salmo trutta*), LGS – longnose sucker (*Catostomus catostomus*), and LND – longnose dace (*Rhinichthys cataractae*).

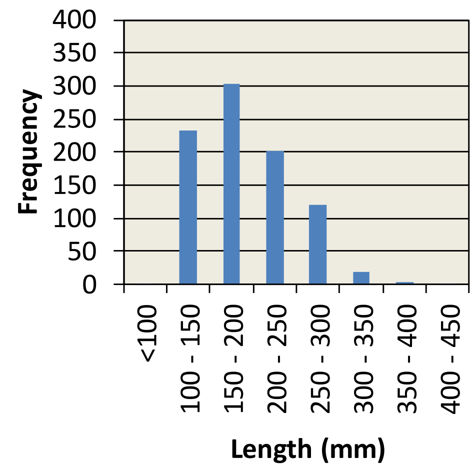
	Salmonid				Non-salmonid			Grand Total
	HOF	LOC	RBT	Total	LGS	LND	Total	
CR DISP – POOL E	0	118	2	*120*	0	0	*0*	**120**
CR1 – POOL F	109	81	2	*192*	0	7	*7*	**199**
CR2 – POOL G	109	99	3	*211*	0	12	*12*	**223**
CR3 – POOL H	111	222	25	*358*	8	16	*24*	**382**
WWP DISP – POOL A	0	108	2	*110*	0	0	*0*	**110**
WWP1 – POOL B	115	70	0	*185*	2	1	*3*	**188**
WWP2 – POOL C	104	64	2	*170*	0	5	*5*	**175**
WWP3 – POOL D	110	126	3	*239*	3	0	*3*	**242**
Grand Total	**658**	**888**	**39**	***1585***	**13**	**41**	***54***	**1639**



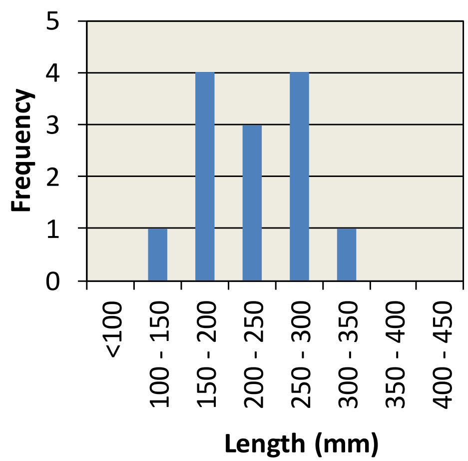
(a) HOF



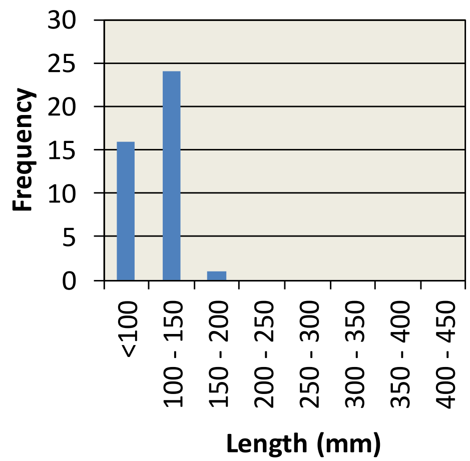
(b) RBT



(c) LOC



(d) LGS



(e) LND

Figure 2.8: Length (mm) frequency of entire study population (n = 1639) by species: (a) HOF – (*Hofer x Harrison strain*); (b) RBT – rainbow trout (*Oncorhynchus mykiss*); (c) LOC – brown trout (*Salmo trutta*); (d) LGS – longnose sucker (*Catostomus catostomus*); and (e) LND – longnose dace (*Rhinichthys cataractae*) (Fox, 2013).

2.3.1.2 Raw Movement Data

Counts of observed movement from the initial release location (Table 2.6) are given by species for all tagged (*n* = 1639) fishes. The total percentage of fish making at least one upstream movement from their release location ranged from 37 to 63% for the CR sites and 29 to 44% for the WWP sites. Counts of movement are also given (Table 2.7) for all individuals at all sites, conditional that the individual was observed downstream of a location and regardless of the location of initial release (*n* = 2648). The total percentage of fishes making at least one upstream movement across a given location after being observed downstream ranged from 48 to 72% for the CR sites and 40 to 44% for the WWP sites. Longnose dace was the only species found to not move across all of the structures (WWP1), but only a single individual was observed downstream.

Frequency of fishes that successfully moved upstream vs. those that did not show differences in movement success based on body length is plotted in Figures 2.9 and 2.10. These data are presented for all fishes in the study. As with raw data previously presented in Tables 2.6 and 2.7, these four categories of data are presented in terms of movement from the initial release location as well as movement of all individuals across all structures regardless of initial release location.

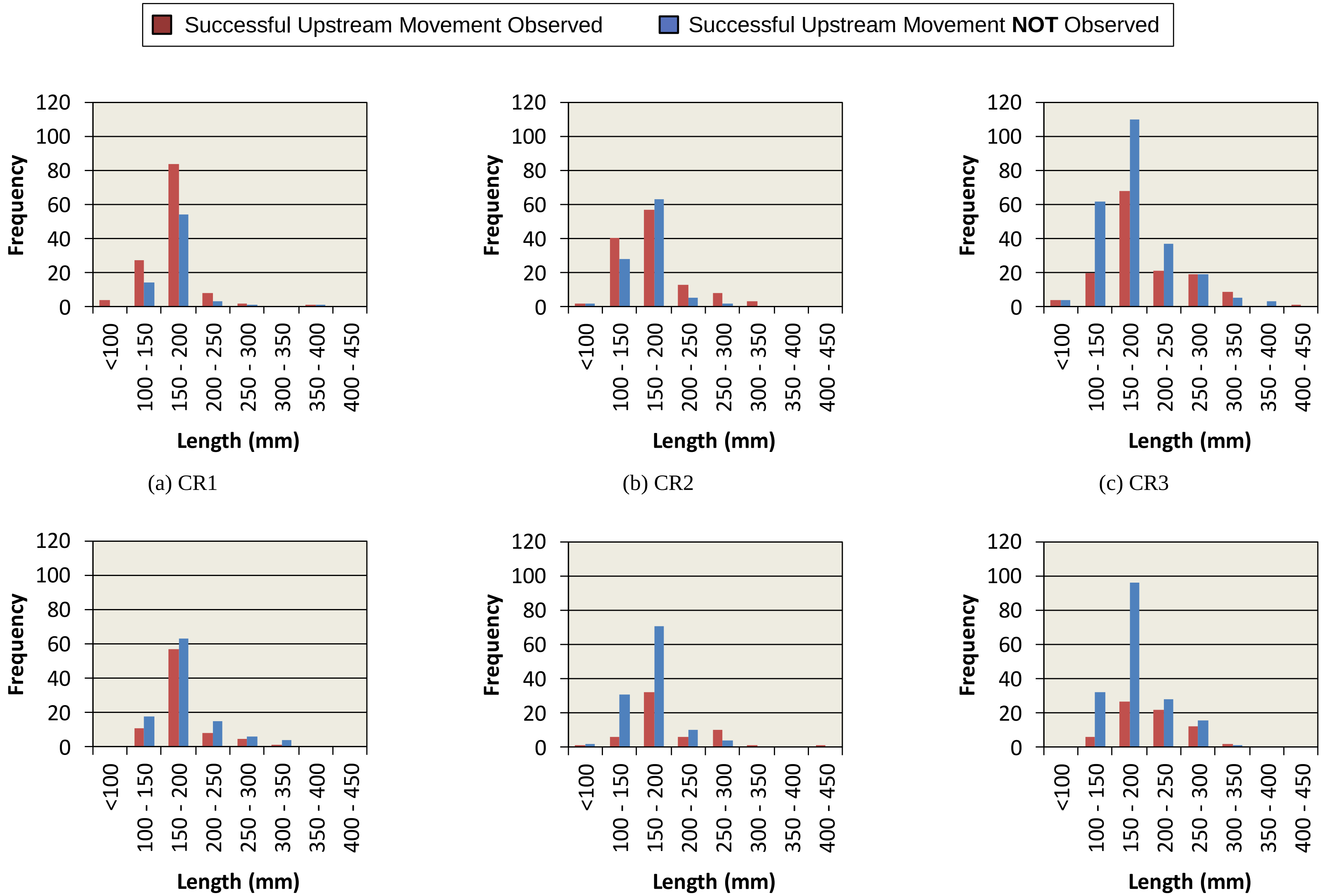
Total numbers of fishes (Figure 2.9) moving upstream from their initial release location, and total numbers of all fishes moving across all locations (Figure 2.10) indicate a trend that smaller fishes (<200 mm) are less likely to move across WWP1, WWP2, WWP3, and CR3; while greater numbers of all size classes are were able to move upstream in CR1 and CR2. This trend holds when reviewing both the initial movement (Figure 2.9) and all movement plots (Figure 2.10).

Table 2.6: Frequency of successful upstream movement from the initial release location (*n* = 1639).

	HOF			LGS			LND			LOC			RBT			TOTAL		
	Captured	Moved Upstream	%	Captured	Moved Upstream	%	Captured	Moved Upstream	%	Captured	Moved Upstream	%	Captured	Moved Upstream	%	Captured	Moved Upstream	%
WWP DISP	0	0	0%	0	0	0%	0	0	0%	108	90	83%	2	2	100%	110	92	84%
WWP1	115	58	50%	2	2	100%	1	0	0%	70	22	31%	0	0	0%	188	82	44%
WWP2	104	29	28%	0	0	0%	5	1	20%	64	27	42%	2	0	0%	175	57	33%
WWP3	110	24	22%	3	2	67%	0	0	0%	126	40	32%	3	3	100%	242	69	29%
CR DISP	0	0	0%	0	0	0%	0	0	0%	118	110	93%	2	1	50%	120	111	93%
CR1	109	60	55%	0	0	0%	7	6	86%	81	59	73%	2	1	50%	199	126	63%
CR2	109	48	44%	0	0	0%	12	6	50%	99	67	68%	3	2	67%	223	123	55%
CR3	111	43	39%	8	8	100%	16	8	50%	222	70	32%	25	13	52%	382	142	37%
																1639	**802**	**49%**

Table 2.7: Frequency of successful upstream movement of all fishes at all sites (*n* = 2648).

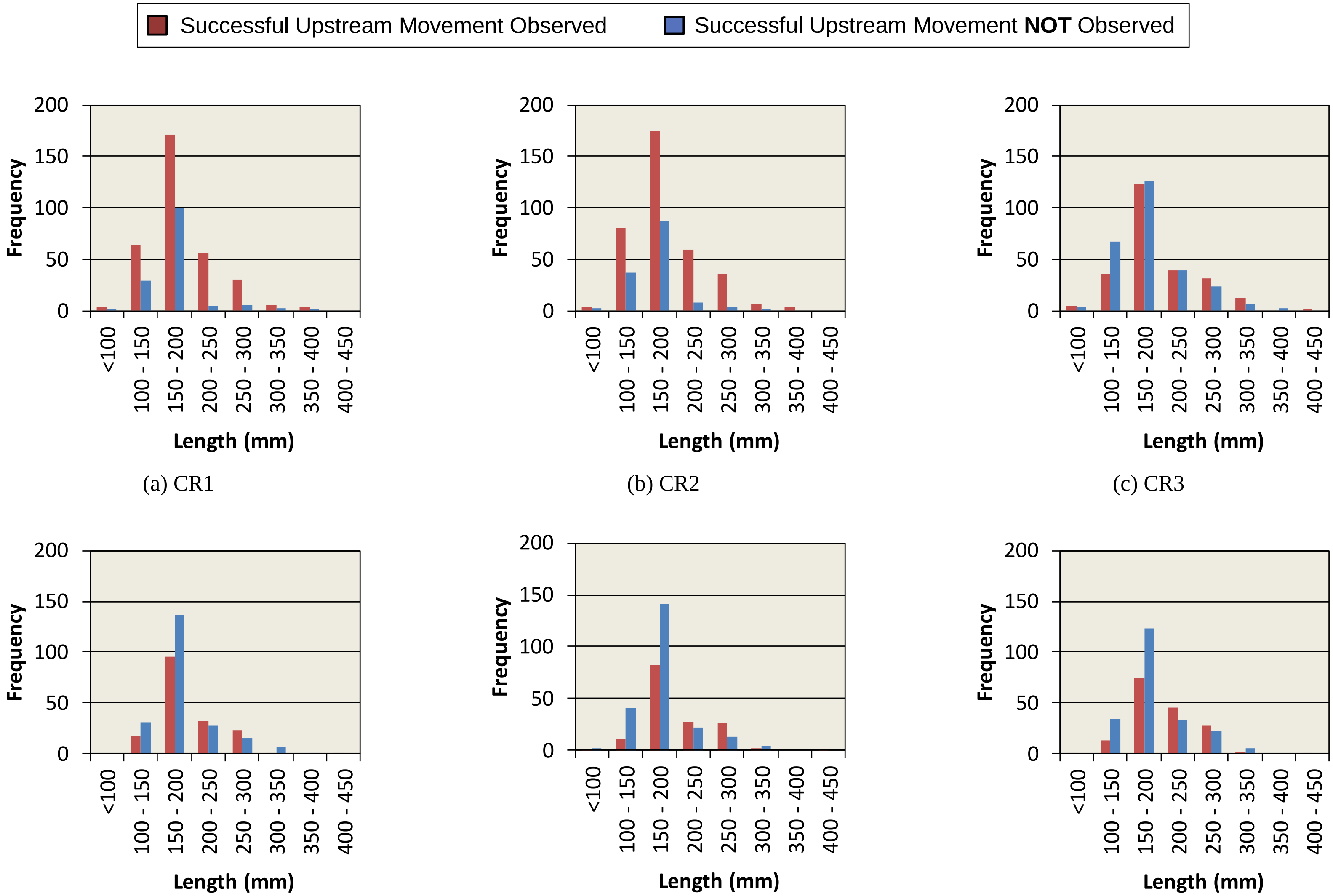
	HOF			LGS			LND			LOC			RBT			TOTAL		
	Captured	Moved Upstream	%	Captured	Moved Upstream	%	Captured	Moved Upstream	%	Captured	Moved Upstream	%	Captured	Moved Upstream	%	Captured	Moved Upstream	%
WWP1	207	82	40%	2	2	100%	1	0	0%	172	83	48%	8	4	50%	390	171	44%
WWP2	228	78	34%	4	3	75%	5	1	20%	128	66	52%	9	3	33%	374	151	40%
WWP3	185	70	38%	4	3	75%	1	1	100%	181	85	47%	10	5	50%	381	164	43%
CR1	202	104	51%	3	3	100%	12	7	58%	246	210	85%	17	11	65%	480	335	70%
CR2	203	126	62%	4	4	100%	17	11	65%	265	212	80%	16	12	75%	505	365	72%
CR3	158	80	51%	10	10	100%	18	10	56%	305	132	43%	27	15	56%	518	247	48%
																2648	**1433**	**54%**



(a) CR1 (b) CR2 (c) CR3

(d) WWP1 (e) WWP2 (f) WWP3

Figure 2.9: Frequency of fishes that successfully moved upstream from the initial release location vs. fishes that did not move upstream for all species and all *MRT* (*n* = 1639) (Fox, 2013).



(a) CR1 (b) CR2 (c) CR3

(d) WWP1 (e) WWP2 (f) WWP3

Figure 2.10: Frequency of fishes that successfully moved upstream at <u>each location</u> vs. fishes that did not move upstream for <u>all</u> species and <u>all</u> *MRT* (*n* = 2648) (Fox, 2013).

2.3.1.3 CJS Model Results

CJS model results include identification of the most parsimonious model in the candidate set using Akaike Information Criterion (AIC; Burnham and Anderson, 2002), and regression parameter estimates (Table 2.8) to indicate the magnitude of each effect in the selected model. Results for the final reduced model include: AIC weight = 0.67, model likelihood = 1; and the second-most supported model having a ΔAICc (corrected AIC) = 1.61, AICc weight = 0.3, model likelihood = 0.447; all remaining models have a ΔAICc > 8, AICc Weight < 0.01, model likelihood < 0.015.

Final form of the most supported model:

$$\begin{aligned} logistic(\phi) = \beta_{INT} &+ \beta_1[MRT] + \beta_2[EVENT] + \beta_3[SPECIES] \\ &+ \beta_4[LENGTH] + \beta_5[LOCATION] \\ &+ \beta_9[LOCATION]*[LENGTH] \end{aligned} \qquad \textbf{(Eq. 2.7)}$$

The selection of the final model (Eq. 2.7) over the candidate set models indicate that individual site location, body length, and species are all significant effects in estimating upstream movement probability. The calculated detection probabilities for each of the antennas in the final model averaged 0.84, ranged from a minimum of 0.74 to a maximum of 0.97, indicating very high rates of detection at each of the PIT antenna locations. The inclusion of the specific structure and pool location indicate that significant differences exist among these six locations. Further, the interaction of length and location indicates that fishes of different body lengths have different probabilities of moving across the different WWP structures and CR pools. This relationship (Figure 2.11) indicates that movement probability is very similar for fishes of all body lengths within CR1, CR2, CR3, and WWP3; larger fishes are more likely to move through WWP2, less likely to move through WWP1.

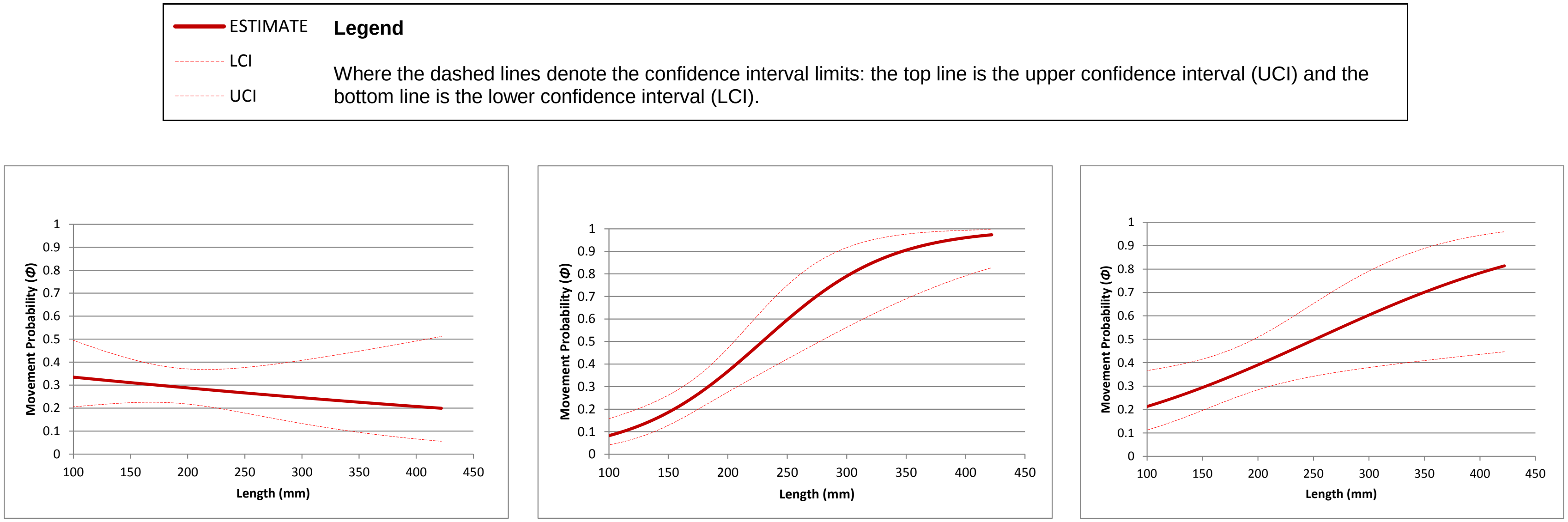
Because *MRT* and *EVENT* were fixed as additive effects in all candidate models, their inclusion in the final model does not necessarily indicate special significance over models without these variables. The additive effects or *MRT* show a strong positive effect to increase movement as compared to the reference category of electrofishing. In addition, a general effect of increased movement probability can be observed for release events occurring early in the study, with an exception occurring between Event 3 and Event 4. The negative effects of trout indicate the non-trout species are more likely to move upstream, but few numbers of non-trout within the WWP limit the application of this effect for that location.

Table 2.8: Regression parameter estimates given as log-odds ratios for the most supported model.

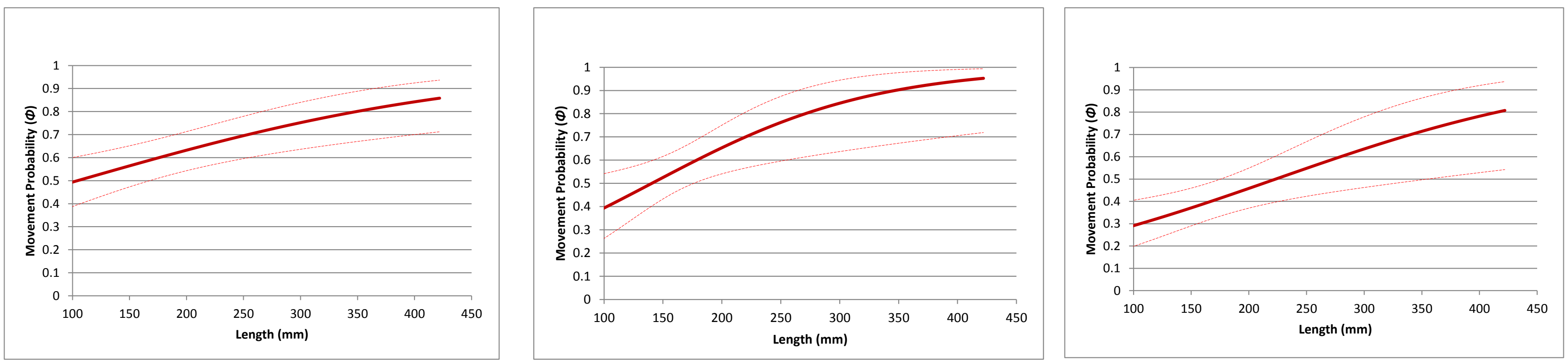
Beta	Variable	Category	Estimate	SE	LCI	UCI
0	[*INT*]	INT	0.509	0.414	-0.303	1.320
1	[*MRT*]	ELECTROFISHING	–	–	–	–
		STOCKING	**0.788**	**0.138**	**0.517**	**1.058**
		DISPLACEMENT	**1.666**	**0.154**	**1.365**	**1.967**
2	[*EVENT*]	**EVENT1**	**1.296**	**0.220**	**0.864**	**1.728**
		EVENT2	**1.557**	**0.257**	**1.053**	**2.062**
		EVENT3[1]	–	–	–	–
		EVENT4	**0.838**	**0.206**	**0.434**	**1.242**
		EVENT5	0.030	0.137	-0.238	0.297
		<u>EVENT6</u>	<u>-1.204</u>	<u>0.250</u>	<u>-1.695</u>	<u>-0.713</u>
3	[*SPECIES*]	<u>TROUT</u>	<u>-1.100</u>	<u>0.283</u>	<u>-1.655</u>	<u>-0.545</u>
		NON-TROUT[1]	–	–	–	–
4	[*LENGTH*]	**LENGTH**	**0.057**	**0.017**	**0.024**	**0.090**
5	[*LOCATION*]	WWP1	0.123	0.687	-1.223	1.470
		<u>WWP2</u>	<u>-3.685</u>	<u>0.816</u>	<u>-5.284</u>	<u>-2.085</u>
		<u>WWP3</u>	<u>-1.580</u>	<u>0.765</u>	<u>-3.080</u>	<u>-0.081</u>
		CR1[1]	–	–	–	–
		CR2	-0.904	0.745	-2.364	0.556
		CR3	-1.019	0.557	-2.111	0.072
6	[*LOCATION*]* [*LENGTH*]	<u>WWP1*LENGTH</u>	<u>-0.078</u>	<u>0.035</u>	<u>-0.147</u>	<u>-0.010</u>
		WWP2*LENGTH	**0.130**	**0.045**	**0.042**	**0.218**
		WWP3*LENGTH	0.030	0.039	-0.047	0.106
		CR1*LENGTH[1]	–	–	–	–
		CR2*LENGTH	0.050	0.044	-0.036	0.135
		CR3*LENGTH	0.015	0.030	-0.044	0.075

Definitions: LCI = lower confidence interval (0.05); SE = standard error; and UCI = upper confidence interval (0.95).

Font coding for values: plain values = no effect; bold values = positive effect; and underlined values = negative effect.



(a) WWP1 (b) WWP2 (c) WWP3



(d) CR1 (e) CR2 (f) CR3

Figure 2.11: Effects of continuous variable body length on probability of upstream movement, conditional that an individual was observed downstream at the specific location (parameter specification for ϕ estimates: *MRT* = electrofishing; *SPECIES* = TROUT; *EVENT* = 3) (Fox, 2013).

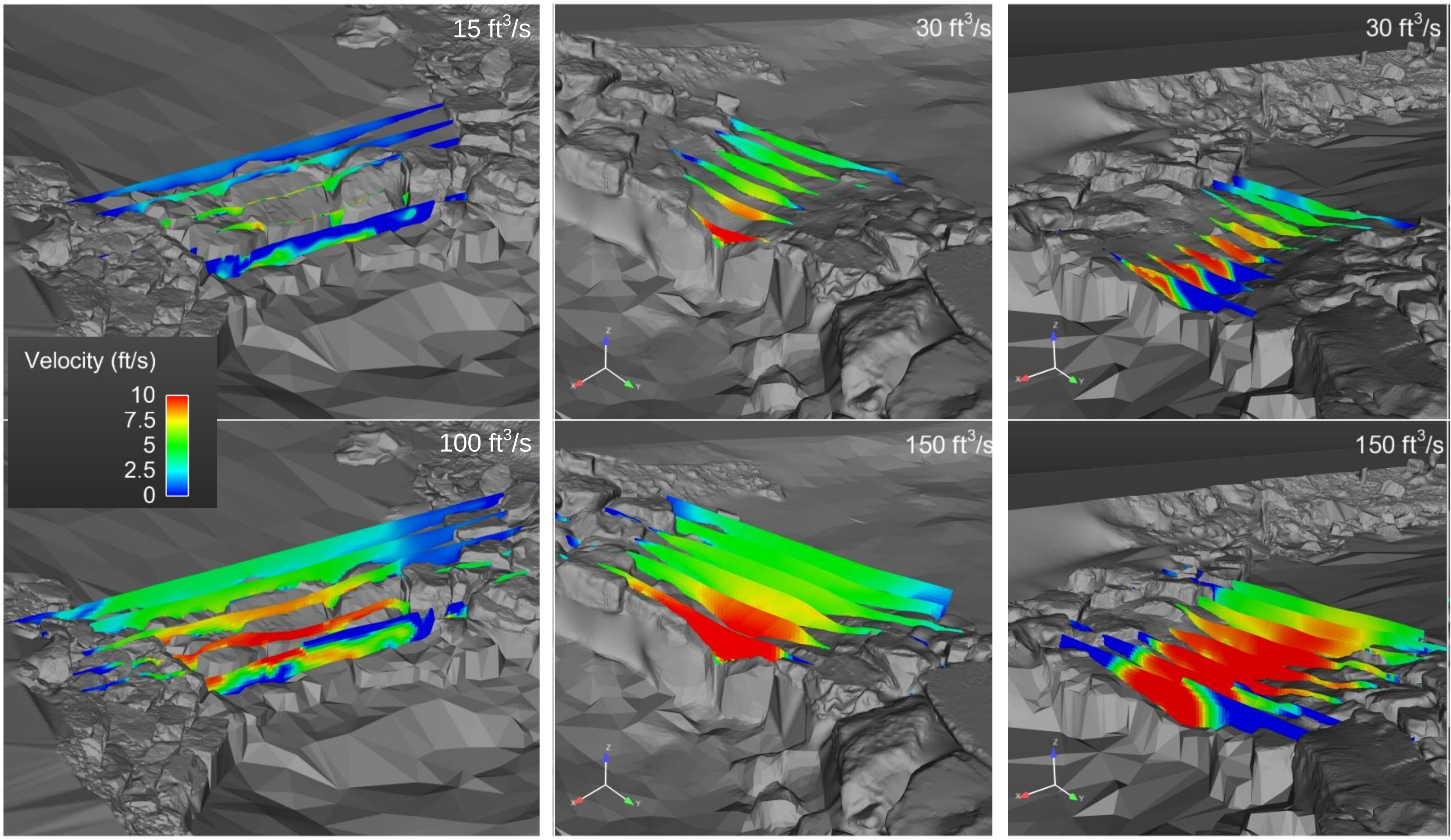
2.3.2 Hydraulic Results

2.3.2.1 Hydraulic Model Results and Observations

Model results for a low- and high-discharge event highlight differences between the WWP (Figure 2.12) and CR (Figure 2.13) sites. As expected, maximum flow velocities within the center chute of each of the WWP structures are significantly larger than those within the CR sites. The hydraulic model results also illuminated other interesting differences among the individual WWP structures caused by subtle variations in structure design elements.

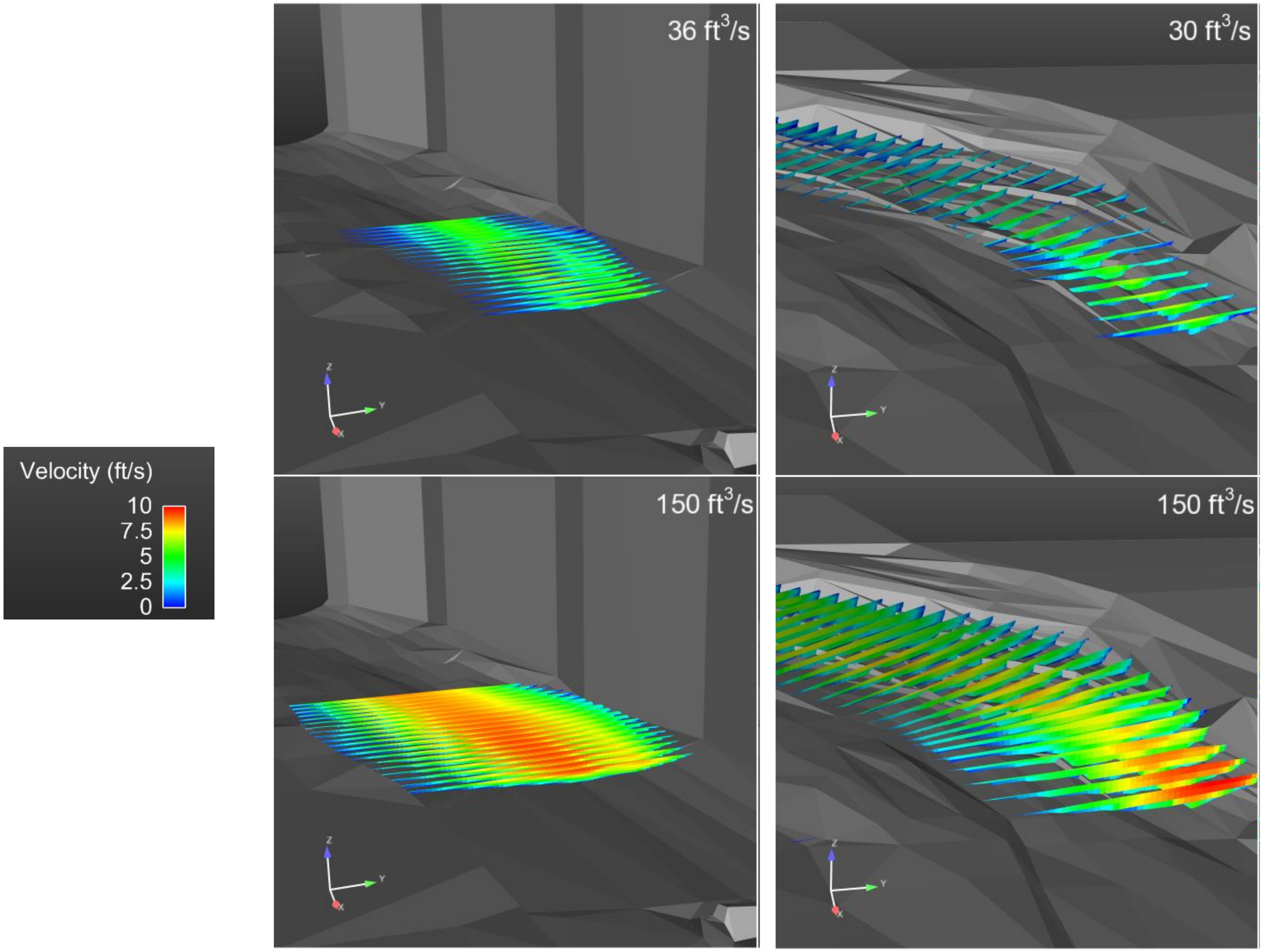
The 3-D model outputs were used to develop qualitative observations and descriptions of the hydraulic conditions at each location. Results for WWP1 show very complex flow conditions at all discharges due to non-uniformity on cross-sectional area. Large boulders were used to construct the short and steep center drop where flow vectors are concentrated; however, these boulders were placed in such a way that interstitial wetted spaces exist within the center chute and along the lateral margins. Smaller particles and grout were used to form the structure wingwalls and provide additional interstitial space during higher flows. During low discharges, the concentrated flow results in very shallow depths over the boulders composing the center chute; however, the interstitial spacing may be allowing potential passage routes. As discharge increases, the flow depth and velocity over the center of the structure also increase, and between 60- and 100-cfs complex flow patterns begin to develop over the wingwalls of the structure. The row of large boulders at the base of the drop is also noted because it may limit flow depth for a potential jumping attempt to below 2 ft at low-flow conditions and 4 ft at high-flow conditions.

WWP2 is a "wave" structure and consists of a longer sloping chute as opposed to the short steep drop found in WWP1. Model results for WWP2 show more uniform and consistent flow conditions due to these differences. At the low-discharge levels, the entire flow area of the channel is restricted to the center chute which is also the location of maximum velocity (8.5 ft/s). However, a very short distance upstream (≈ 4 ft), the flow velocity decreases to a cross-section median of 6 ft/s and then continues to decrease in the upstream direction toward the top of the structure. This indicates only a very short section of the structure contains extreme velocity magnitudes. Between 60 and 100 cfs, the center chute outlet velocity maintains a maximum of approximately 12 ft/s before flow begins to spill onto the side wingwalls, creating a very complex flow environment of micro-pools and low velocity. As the wingwalls are overtopped, additional passage routes become available to bypass the highest velocity zone of the structure occurring at the outlet of the center chute. It should also be noted that the maximum flow velocities encountered within the structure change very little once flow begins to spread out onto the wingwalls, indicating that maximum velocities are sustained at and beyond the discharge that fills the center chute.



(a) WWP1 (b) WWP2 (c) WWP3

Figure 2.12: Cross-sectional velocities for a low- and high-flow condition at: (a) WWP1; (b) WWP2; and (c) WWP3 (Fox, 2013).



(a) CR2

(b) CR3

Figure 2.13: Cross-sectional velocities for a low- and high-flow condition at: (a) CR2 and (b) CR3 (Fox, 2013).

WWP3 is also a "wave" structure and shares many similarities with WWP2. However, subtle differences between the structures may have effects on velocity conditions within the center chute. Unlike WWP2 which has a very confined outlet near the downstream plunge pool, WWP3 has a maximum flow area constriction near the middle of the center chute, and then expands laterally at the outlet. This feature allows for reverse flow eddies to form on the sides of the jump within the plunge pool, and is significant because it may provide a by-pass around the highest velocities of the structure for any upstream migrating fishes. However, the spatial extent of this high-velocity zone within this structure (8 to 12 ft) is larger, therefore, it may pose a greater challenge if the side eddies are not utilized.

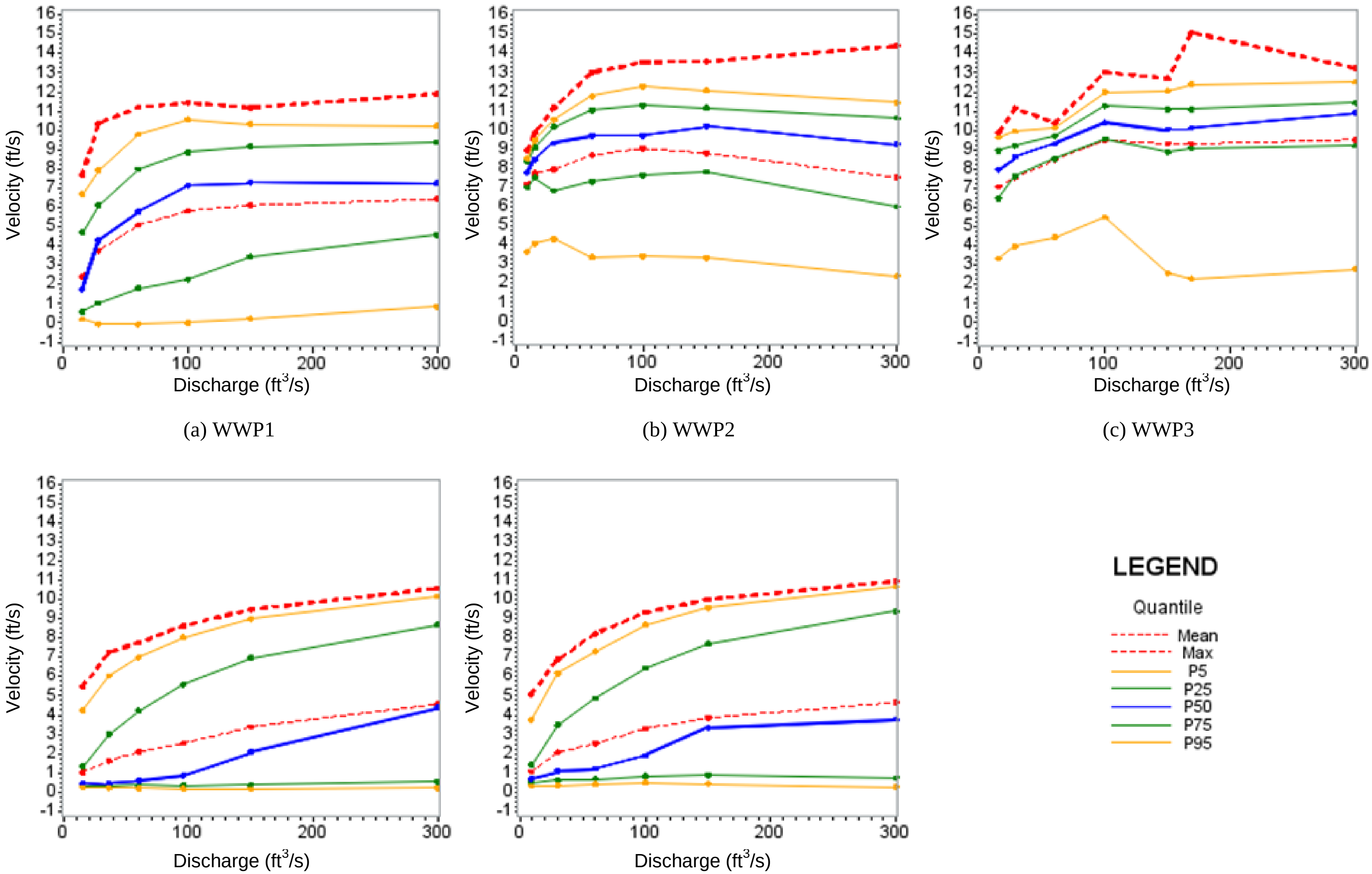
As expected, the results for CR2 showed very low overall velocity magnitudes as compared to those within the WWP. It also appears to provide a very wide range of velocity magnitudes at each cross section and no single location had a velocity challenge greater than the average conditions. At low discharges, approximately 75% of the flow area has a velocity of 5 ft/s or less. As discharge increases to 300 cfs, the model does show some areas of local velocity near 10 ft/s, but the majority of the flow area is still below 5 ft/s. This indicates the CR sites are maintaining substantial portions of low-velocity passage routes within the cross-sectional area.

CR3 provided the best natural hydraulic analog to WWPs because it consisted of a steep riffle flowing into a relatively-large natural pool. This site also shows relatively-uniform flow velocities along the channel, but the upper quartile velocities appear slightly larger than CR2. The lower quartiles of the velocity distribution are very stable in the CR sites, while the fluctuation occurs at the upper quartiles.

2.3.2.2 Limiting Velocity and Flow Depth Magnitudes

Summaries of the limiting cross-sectional velocity for burst swimming conditions (Figure 2.14) and flow depth (Figure 2.15) are presented as a function of discharge. The results of this analysis indicate large differences between CR and WWP in magnitude of velocity and flow depth that must be overcome for successful upstream movement.

Further comparisons among the individual WWP sites show variation in velocity and depth distributions. Within WWP2, upstream moving fishes must pass a cross section where 75% of the flow area is greater than 6 to 8 ft/s and 95% of the flow area is greater than 3 to 4 ft/s. WWP3 indicates that fishes successfully moving upstream must pass a cross section where 75% of the flow area is greater than 6 to 9 ft/s and 95% of the flow area is greater than 2 to 5 ft/s. While maximum velocities increase with discharge at the CR sites, a large portion of the flow area maintains low-velocity zones. In addition, there does not appear to be any particular cross-section location within the CR site that poses a significantly-higher velocity challenge than the observed average conditions along potential passage routes.



(a) WWP1

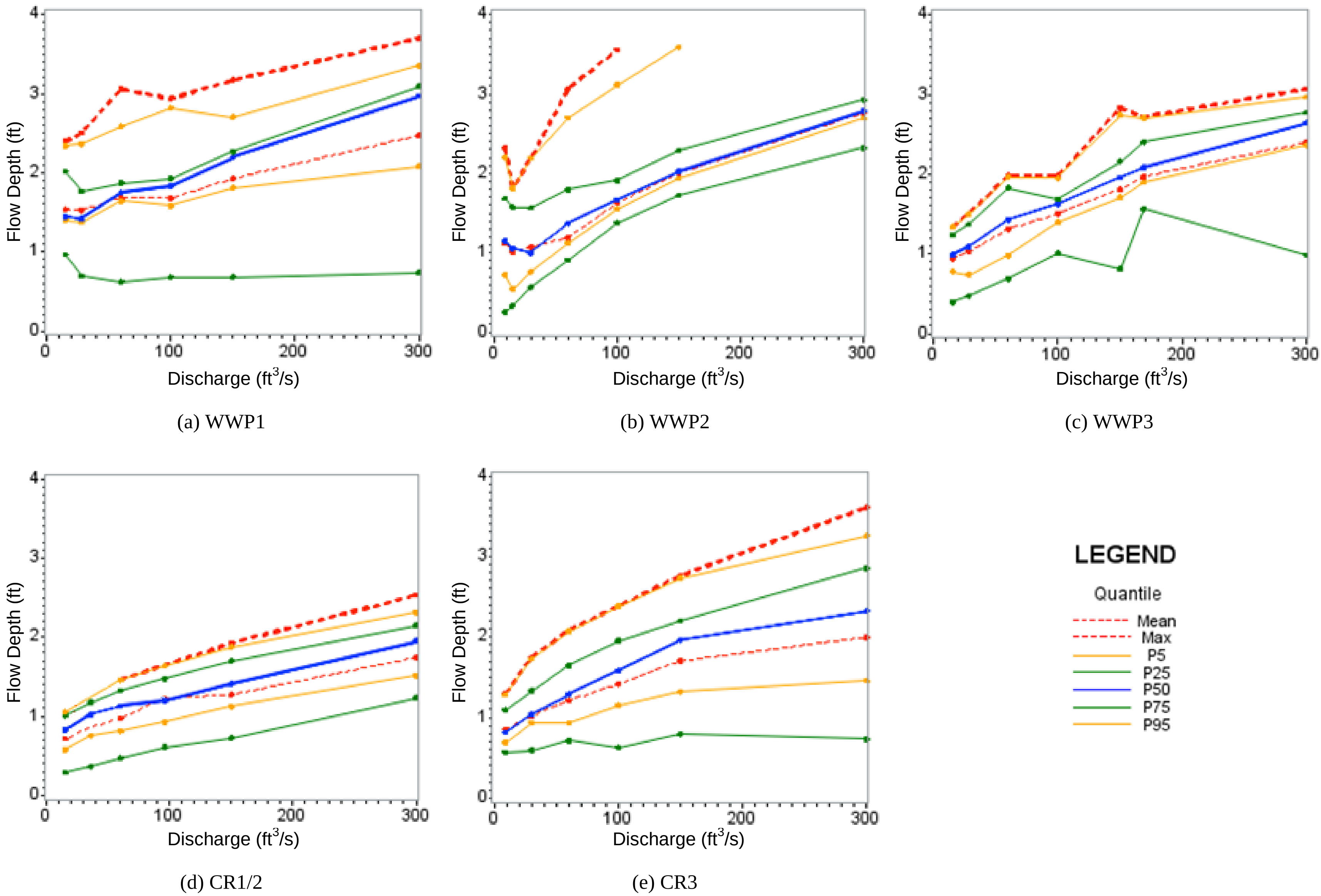
(b) WWP2

(c) WWP3

(d) CR1/2

(e) CR3

Figure 2.14: Limiting magnitudes of velocity within the zone of passage to assess burst swimming barriers (Fox, 2013).



(a) WWP1 (b) WWP2 (c) WWP3

(d) CR1/2 (e) CR3

Figure 2.15: Limiting magnitudes of flow depth within the zone of passage (Fox, 2013).

2.4 DISCUSSION

2.4.1 Review and Analysis of Findings

Rainbow and brown trout successfully completed upstream movements at all of the WWP and CR locations, strongly suggesting that the WWP in this study does not represent a complete barrier to movement over the range of flow conditions we monitored. However, results indicate that WWP structures can suppress movement by size class, and the magnitude of suppression appears to vary by WWP structure type and by CR pool location. Furthermore, this difference in movement may be related to the variation of hydraulic conditions among the WWP structures.

One of the most interesting results observed in both the raw movement data and CJS analysis suggest a relationship exists between body length and successful movement probability that is unique among each of the six locations. Given that body length is positively correlated with swimming ability (Beamish, 1978), a positive relationship between body length and movement probability could be interpreted that stronger swimming fishes are more likely to move upstream. This positive relationship was found at WWP2, while a negative relationship (larger fish less likely to move) was found in WWP1, and a positive but weaker relationship could be observed in WWP3.

Results for the limiting hydraulic conditions indicated that fish would need to pass velocities identified to be burst swimming barriers for brown trout (Peake *et al*., 1997). However, more recent studies (Castro-Santos *et al*., 2013) suggest that Peake *et al*. (1997) underestimated swimming ability for brown trout and velocities generated by the hydraulic model results suggest that these structures are not burst swimming barriers. An evaluation of maximum flow velocities encountered by fishes during successful passage events at each of the three WWP structures suggests that movement events rarely occurred where any portion of the cross-sectional flow velocities along the structure were greater than 25 BL/s. These results support findings from Castro-Santos *et al*. (2013) that 25 BL/s is a good predictor of brown trout maximum burst swimming capability. The absence of an observed threshold velocity for which movement of certain size classes are significantly reduced indicate that burst swimming barriers are not a likely major cause of impaired brown trout movement.

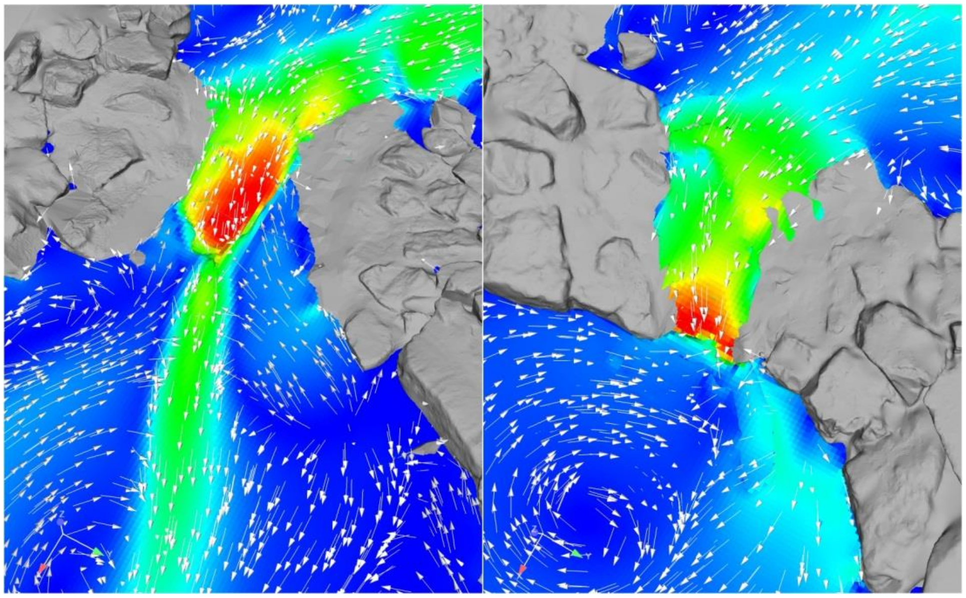
Given that both field data and laboratory studies (Castro-Santos *et al*., 2013) indicate these structures are not likely to be burst swimming barriers, a different mechanism may be causing the observed suppression of movement at the WWP sites. Other potential causes for the reduced movement may include an exhaustive swimming barrier, reduced flow depth, total hydraulic drop, highly-turbulent hydraulic conditions in the plunge pool, habitat quality, overall motivation, and/or differences in survival between WWP and CR sites.

Hydraulic modeling results for the WWP sites indicate an exhaustive swimming barrier to be unlikely. While all three structures showed zones of very high flow velocities, these were largely limited to the farthest downstream point of the center chute. Surprisingly, lower velocities (5 to 7 ft/s) can be observed at locations very close to the outlet and along the channel margins, indicating that if a fish can successfully negotiate the very short zone of high velocity, more favorable conditions exist throughout the remainder of the structure to facilitate good passage.

The effects of flow depth and total drop appeared to potentially play a direct role in limiting movement at only WWP1. Shallow flow depths can be attributed to the very steep center chute and the restriction of most of the flow area to a few small interstitial spaces present between larger boulders. While adequate depth is maintained within these interstitial pathways, it is unclear whether these small flow areas are affecting behavior and ability to locate the passage route. The presence of large boulders at the base of the jump may create complications to a leaping attempt by a larger fish in that they reduced the overall pool depth at locations which an individual fish could attempt to leap (Kondratieff and Myrick, 2006).

The larger turbulent energy dissipation within the hydraulic jump of each WWP structure is the most prominent hydraulic difference between WWP and CR sites. Kolden (2013) reported strong vorticity and large turbulent energy dissipation within the downstream plunge pools of these WWP structures, which may potentially reduce an individual fish's stability and swimming ability (Webb, 2002; Tritico and Cotel, 2010) as they attempt to enter the chute. This effect could present itself as an overall reduction of movement, but with no distinct relationship to the limiting velocity required to pass the chute, such as that observed within our data set. This hypothesis could also be used to infer the cause of the different movement probability among the WWP structures. For example, a fish moving upstream through WWP2 is required to pass through the highly-turbulent jump because of the constricted outlet flow area; while within WWP3 fishes may bypass the highest turbulent zones through the lateral eddies (Figure 2.16). The effects of turbulence within WWP1 are less clear because potential movement pathways are less defined, and turbulence effects will be largely dependent on the specific location a fish attempts to move upstream.

Habitat preference could also play an important role in determining motivation to move either upstream or downstream from a particular location (Lucas and Baras, 2001). If one assumes that WWPs are high-quality habitat, the suppressed movement within the WWP could be interpreted as fishes not motivated to leave these locations. However, biomass estimates were consistently higher within the CR than within the WWP (Kondratieff, 2013 pers. comm.), indicating that WWP were not preferred habitats despite larger pool volumes. Given these biomass estimates, it is unlikely that any suppression of movement in the WWPs is due to them being high-quality habitats.



(a) WWP3 (b) WWP2

Figure 2.16: (a) Modeling results for WWP3 indicates reverse flow around the high-velocity turbulent zones on the lateral margins of the hydraulic jump; and (b) modeling results for WWP2 indicate the highly-constricted outlet flow area limits potential passage routes through the highest velocity and turbulent sections of the flow field (Fox, 2013).

Additional factors that should be considered in this analysis are the selection of a previously-constructed WWP as a study site. The results of the displacement *MRT* group provided very interesting results by indicating reduced probabilities of movement at WWP1, and almost unimpaired movement through WWP2 and WWP3. This may indicate a selective effect of multiple inline WWP structures, in that fish that are able to pass upstream through the lower structure are high-performing individuals and are thus able to pass the remaining structures. If this is the case, then it might be expected that all fishes collected from the WWP sites during the electrofishing *MRT* are also high performers and have an increased ability to move across passage barriers. A similar study with pre- and post-monitoring of a constructed WWP or a separate study specifically designed to answer these questions would provide an interesting comparison to the selective effects observed in this study.

2.4.2 Design Guidance

Results from this study can be used to support management decisions for both existing and future WWPs. While suppression of movement may exist, the observations of successful movements indicate that WWPs producing hydraulic conditions within the range of those in our study have the potential to meet both recreational and fish passage goals for salmonids. However, the amount of suppressed movement that is acceptable for a given site is a question that must first be answered through criteria defined by natural resource managers, site-specific constraints and requirements of the target species. In addition, assessing the level of habitat impairment and fragmentation already existing from the presence of diversions, culverts, or other potential passage barriers may help assess the risk of adding a WWP with unknown passage effects. Selection of a site that already has degraded habitat conditions such as existing dams and urban environments where ecological improvement potential is limited (Kondolf and Yang, 2008) may be ideal locations for WWPs. However, without a clear understanding of what is an unacceptable level of impaired passage, it is difficult to objectively weigh the magnitude of any negative effect against the positive benefits of WWPs, and difficulties in decision-making will persist.

Assuming an acceptable location for a WWP can be found, results from our study can be applied to future designs to maximize the probability of successful upstream movement for fishes. Results from this study suggest that WWPs with laterally-constricted grouted chutes that are installed in streams of similar size and hydrologic characteristics appear to be able to function within the range of salmonid burst swimming abilities. Therefore, this suggests structures that maintain short high-velocity zones should be passable for species with similar swimming abilities, behavior, and motivation. In addition, lower velocity routes around high-velocity zones (side eddy zone within WWP3) and roughness elements on the lateral margins of the channel may improve passage success by reducing the length and magnitude of a potential velocity challenge. Flow depth also appears to be a concern on smaller rivers, as hydraulic modeling results from WWP1 suggest shallow flow depths during low-flow conditions restrict potential passage routes. However, without greater understanding of the specific mechanism causing the suppression of movement, developing detailed design guidelines will remain difficult.

Given the goals of WWPs have a general objective to create a hydraulic wave for recreational purposes; a broad range of potential design types exists. We examined a very narrow range of design types, but considering the requirement of supercritical specific energy ($Fr > 1$) within the structure, zones of high velocity (Figure 2.4(a)) must occur at some point within the structure. Additionally, the overall scale of the stream should be taken into consideration with the design type, as rivers with smaller mean discharges will require greater levels of lateral width constriction and vertical drop for the hydraulic wave to meet recreational goals. To fully evaluate the variations in design elements and discharge, a site-specific analysis would likely be required to determine if additional zones of lower velocity exist to allow potential upstream passage routes.

2.4.3 Future Research

We suggest future research efforts on fish passage in WWPs be focused toward two separate but related goals: (1) continued evaluation of movements by multiple species and life stage, and description of hydraulic conditions found at the range of existing WWP structures; and (2) further development of how specific design features and small-scale hydraulic conditions affect passage ability and behavior.

Additional studies to evaluate the broad range of structure types and how those designs influence diverse fish species and life stages for passage within WWP would provide additional data on overall passage efficiencies. The scope of the current study is limited since we evaluated only three structures and four species that are known to be strong swimmers on a single river system. Future studies should focus on identifying structures of different design types that may produce hydraulic conditions that differ from those found within our study sites. Because salmonids are strong swimmers, similar studies performed in locations where weaker swimming species are present would also be highly beneficial.

The second goal should focus on gaining a more accurate understanding of the small-scale hydraulic effects on movement, behavior, and ability of fishes attempting to move upstream across WWP structures. The results of the 3-D hydraulic modeling in the current study provided excellent qualitative descriptions of the flow fields and the ability to develop aggregate values describing flow conditions beyond spatial means. However, more detailed analysis of fish swimming pathways in conjunction with 3-D hydraulic data would allow for a more complete understanding of how hydraulics are affecting behavior and ability of fishes attempting to move upstream. A more rigorous framework for the statistical analysis of fish movement and hydraulic data may also be necessary before one can truly utilize these integrated assessment methods. In general, fish passage involves biological and hydraulic processes that are functions of the species characteristics, time, and location; rendering existing analysis methods difficult. Novel methods for assessing fish passage have been proposed using time-to-event analysis (Castro-Santos and Perry, 2012), but have so far only been intermittently applied in research settings. This type of study to integrate assessment with a robust statistical framework would contribute data and knowledge not only to understanding WWPs, but also be a significant contribution to the general body of fish passage literature where studies of behavior and hydraulic interactions are at the leading edge of fish passage research.

2.5 CONCLUSIONS

We performed the first field study of fish passage in WWPs by simultaneously tracking fish movement using PIT tag telemetry and evaluating hydraulic conditions with a high-resolution, 3-D hydraulic model. We found that WWP structures can incorporate a broad range of design types that affect small-scale hydraulics and potentially create unique hydraulic conditions that affect fish passage differently. Successful upstream movement of salmonids from 115 to 416 mm total length was observed at all of the WWP locations over the range of flows occurring during the study period, thus demonstrating that the WWPs in this study are not complete barriers to movement salmonids in these size ranges. However, results indicate that WWPs can suppress movement by size class, and the magnitude of this suppression appears to vary among different WWP structures and CR sites. Further, this difference in movement may be related to the variation of hydraulic conditions among the WWP structures, but does not appear to have a strong relationship with burst swimming abilities of salmonids. It is probable that the reduced movement may be attributed to other hydraulic and biologic variables such as turbulence, fish behavior, and motivation. Because of the small numbers of native species monitored in this study, no direct conclusions can be drawn on how this WWP affected their upstream movement ability. This study provided a starting point for understanding how WWPs affect fish movement. Future studies should focus on broadening structure type and species evaluated for passage, and perform more-detailed assessment of how hydraulic conditions other than velocity are affecting upstream movement behavior and motivation.

SECTION 3

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