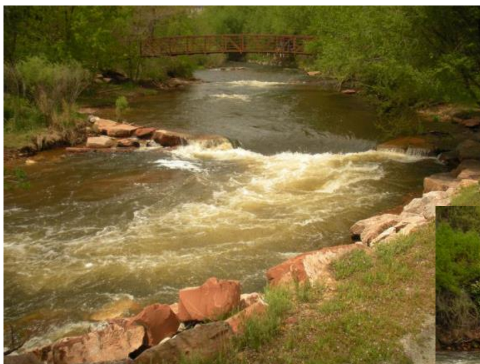
INVESTIGATION OF THE EFFECTS OF WHITEWATER PARKS ON AQUATIC RESOURCES IN COLORADO

Prepared for the

Colorado Water Conservation Board



Prepared by

Brian P. Bledsoe, Brian D. Fox, Timothy A. Stephens, Eleanor Kolden, and Erin R. Ryan

September 2014

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EXECUTIVE SUMMARY

Whitewater parks (WWPs) have become a popular recreational amenity in cities 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. 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 opinions without having any concrete studies to inform those opinions. 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 three major sections of this report provide condensed versions of three complementary Colorado State University theses focused on the effects of WWPs on aquatic resources in Colorado.

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 summarized studies (Fox, 2013; Kolden, 2013; Stephens 2014). 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 River, and they have performed fish biomass surveys in the same reaches and pools described in this study. 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. 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.

Kolden (2013) modeled two sections of the North St. Vrain River in Lyons, Colorado: 1) one natural section, and 2) one section containing a WWP with three engineered drop structures. A two-dimensional (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. 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.

The three-dimensional (3-D) computation fluid dynamics (CFD) software FLOW-3D® v10.0 was used to model each of the reaches. 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 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.

A continuous and spatially-explicit hydraulic model was created by Stephens (2014) to further analyze the data from the North St. Vrain WWP. The model describes hydraulic conditions along potential fish movement paths and examines their influence on fish passage. Quantifying the hydraulic conditions in this manner captured important and unique hydraulic characteristics at each WWP, and described velocity and depth throughout the flow field at a scale meaningful to fish. Logistic regression indicated that both depth and velocity were major predictors of passage success, and underlined the importance of jointly considering hydraulic variables when assessing the probability of passage success. This model accurately predicted over 87% of non-movements and over 92% of upstream movements in the WWP based on individual fish PIT observations.

Seven different discharges, ranging from 15 to 300 cfs, were used in the model, and it was found that neither the highest nor lowest discharges presented the greatest challenge for passage. While the higher discharges provide a larger fraction of accessible flow paths for fish, discharges at 15 to 60 cfs occur much more frequently throughout the year at the study site. Both interstitial spaces and recirculation eddies were found to create important zones of lower velocity and improve fish passage throughout the range of discharges.

DESIGN RECOMMENDATIONS

Knowledge gained from these studies of the WWP structures on the North St. Vrain River 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 amount of acceptable suppressed movement is a question that should be answered by natural resource managers on a case-by-case basis. Criteria to consider when assessing passage requirements include the previous fragmentation of the system (existing diversions, barriers, etc.), site-specific constraints, target species, and potential benefits due to increased community awareness and personal connection to the environment.

The hydraulic analysis and statistical model developed by Stephens (2014) shows that flow depth is critical in determining the probability of fish passage success. This study strongly suggests that flow depths greater than 0.6 ft should be maintained for all expected discharges. The hydraulic modeling and subsequent statistical analysis also show that velocity is a key factor affecting fish passage. However, hydraulic nuances exist for each type of WWP structure and, therefore, velocity thresholds vary with each design type. The passable velocity also varies with the size class of fish attempting to move upstream. Without site-specific analysis, it is recommended that velocities remain under 10 to 25 BL/s. Care should be taken to ensure that *both depth and velocity requirements are met continuously along likely fish movement paths*.

Evidence from the North St. Vrain WWP studies also underscores the importance of providing continuous zones of lower velocity, away from the main velocity jet, as alternate passage routes. The use of non-grouted wingwalls provides interstitial spaces where smaller bodied fishes (with inherently lesser swimming abilities) can pass the structures through lower velocity paths. These interstitial spaces should have a range of sizes comparable to the expected body sizes of the fish population. A design with non-grouted wingwalls also creates additional roughness elements along the channel margins, providing refugia for fishes attempting to move upstream. Large eddies that reach as far as possible up the sides of the main velocity jet also provide low-velocity zones, especially during high discharges. The recommended non-grouted wingwall design should allow water to spill over the wingwalls at some location, with adequate flow depth, even at base flow discharges.

It is worth noting that the resulting recommendations are best applied to a system of geomorphic class, hydrologic regime, and scale similar to the study reach. 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. 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 either case, 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 adequate zones of lower velocity would exist to allow potential upstream passage routes. It is likely that a site-specific analysis would also be required to determine if an existing WWP needed to be modified to provide additional zones of lower velocity. However, without greater understanding of the specific mechanism(s) causing the suppression of movement, developing detailed design guidelines will remain challenging.

Although suppression of fish movement exists at the WWP evaluated in this study, the observations of successful movements indicate that WWPs producing hydraulic conditions within the range of those described in this study have the potential to meet both recreational and fish passage goals for salmonids. 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.

The research described in this report provides a foundation for understanding how and why WWPs affect fish movement, yet new questions and uncertainties have emerged. Important areas for future study include: the minimum resolution of hydraulic models needed to characterize fish passage potential and habitat suitability in WWP pools; further analysis of the mechanisms causing upstream movement suppression through WWPs; cumulative effects of inline structures; transferability of results from the North St. Vrain WWP studies; and the impact of WWPs on native non-salmonid species. As the popularity of WWPs continues to grow in Colorado and elsewhere, it is imperative to also continue increasing our knowledge base concerning the design and potential impacts of these recreational structures.

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Symbols:

d	=	distance between two nodes
df	=	statistical term: degrees of freedom
D10, D25, D50, D75, D90	=	flow-duration streamflow statistics
e^{β}	=	statistical term: odds ratio
EVENT	=	CJS variable: tag release events
Fr	=	Froude number
g	=	gravitational acceleration (L/T^2)
i, *j*, *k*	=	unit vector in the x,y, and z directions, respectively
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
p	=	statistical term: p-value
PK2, PK5, PK10, PK25, PK50, PK100, PK200, PK500	=	annual peak flow statistics
q	=	unit discharge (L^2/T)
rms	=	root-mean-square
SE	=	statistical term: standard error
SPECIES	=	CJS variable: trout/non-trout
u, v, w	=	x, y, and z components of velocity, respectively
UCI	=	statistical term: upper confidence interval

v	=	velocity (L/T)
v_{burst}	=	burst swimming velocity
v_{rms}	=	average *rms* velocity between two nodes
v_x, v_y, v_z	=	velocity in the x-plane, y-plane, z-plane orientation, respectively
x, y, z	=	planes with an axis in the longitudinal, lateral, and vertical directions, respectively
y	=	flow depth (L)
β	=	statistical term: beta
β_1, β_2, β_3, β_4, β_5, β_6, β_8, β_9, β_{INT}	=	CJS regression parameters
$\bar{\xi}$	=	3-D vorticity
σ	=	standard deviation
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
χ^2	=	statistical term: significance was evaluated using the chi-square statistic
Ψ	=	apparent successful upstream movement

Units of Measure:

BL	body length(s)
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
ft^2	square feet
ft^2/s^2	square feet per square second
ft^3/s^2	cubic feet per square second
km	kilometer(s)
km^2	square kilometer(s)

L, L^2	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, T^2	time dimension

Abbreviations:

1-D, 2-D, 3-D	one-, two-, and three-dimensional, respectively
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)
CR1, CR2, CR3	control site designations
CR DISP	control site displacement designation
DISP	displacement
GPS	Global Positioning System
HDX	half-duplex
HOF	Hofer x Harrison strain
HSI	Habitat Suitability Indices
IPOS	intensity, periodicity, orientation, and scale
LGS	longnose sucker
LIDaR	LIght Detection and Ranging
LND	longnose dace
LOC	brown trout

MRT	mark-release types
NOAA	National Oceanic and Atmospheric Administration
NR1, NR2, NR3	natural reach designations
NR1-2	natural reach designation (includes natural reaches NR1-A, NR1-B, and NR2)
pers. comm.	personal communication
PHABSIM	Physical HABitat SIMulation
PIT	passive integrated transponder
RBT	rainbow trout
®	registered
RANS	Reynolds-Averaged Navier-Stokes
RFID	Radio Frequency Identification
RICDs	recreational in-channel diversions
RNG	renormalization group
TI	turbulent intensity
TKE	turbulent kinetic energy
™	trademark
U. S.	United States
USA	United States of America
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
VOF	volume of fluid
W3, W4	paired antenna installation designations
WWP1, WWP2, WWP3	whitewater park reach designations
WWP DISP	whitewater park reach displacement designation
WWPs	whitewater parks
x, X, y, Y, z, 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, 2000a). 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, 2000a). 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, 2000a) 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.

1.1.1 Objectives

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.

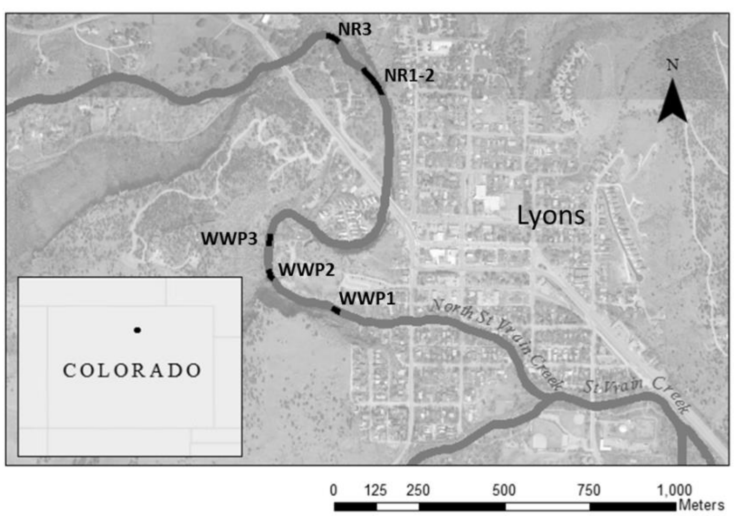
The topic of fish passage in WWPs is addressed in Section 2 of this report (Fox, 2013).

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 (0.125 to 0.5 ft), 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})

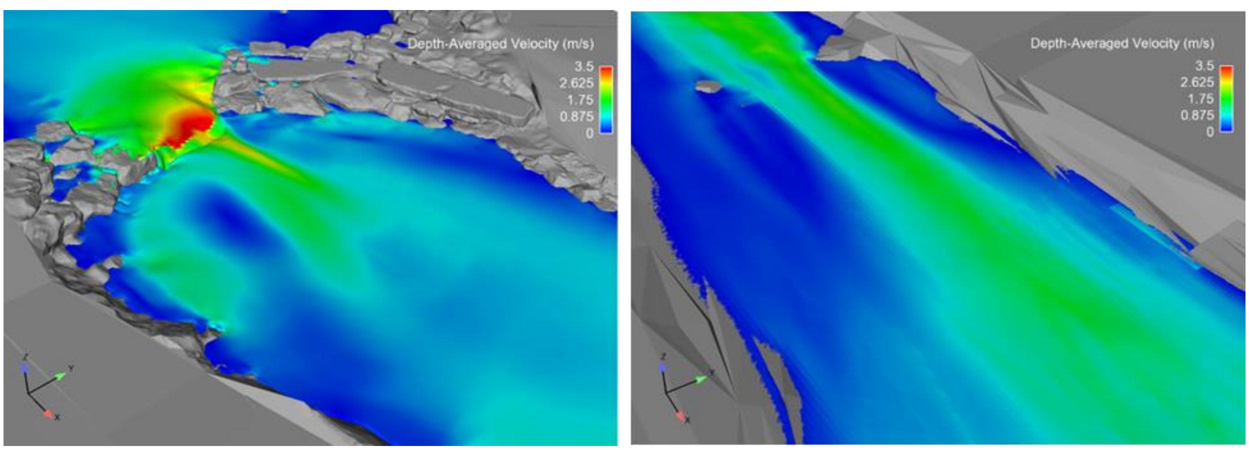
Flow Rate	WWP Pools	Natural Pools
Low	5.7	2.0
Medium	12.0	4.5
High	10.3	5.5

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

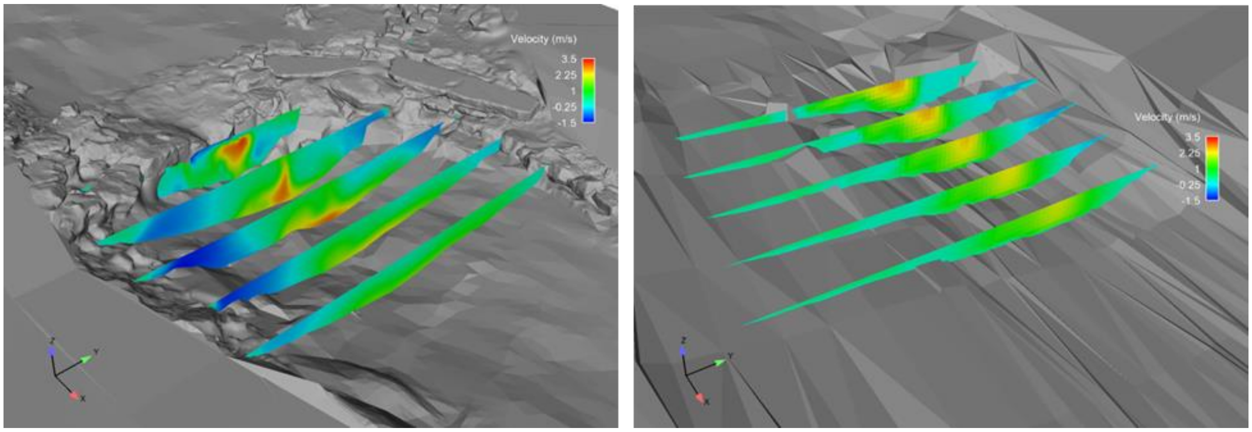
The maximum depth-averaged velocity was greater in the WWP pools than in the natural pools for all flow rates (Table 1.1). To show an example of the differences in velocity in a visual manner, two representative pools were chosen, one WWP pool (WWP2) and one natural pool (NR3). WWP2 was chosen because 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.



(a) WWP2 (b) NR3

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).



(a) WWP2 (b) NR3

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-highlighted values indicate significant differences between WWP pools and natural pools ($p < 0.05$ for Wilcoxon and t-test).

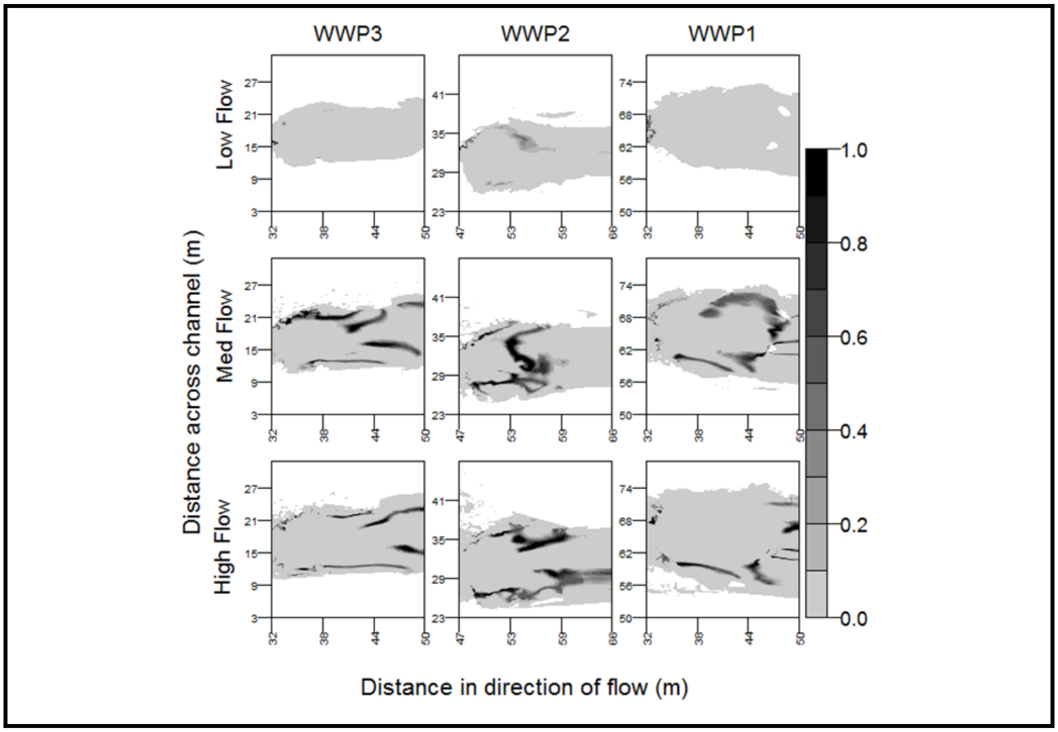
Flow (cms)	Juvenile Brown		Adult Brown		Juvenile Rainbow		Adult Rainbow		Dace		Sucker	
	WWP	Natural	WWP	Natural	WWP	Natural	WWP	Natural	WWP	Natural	WWP	Natural
0.42	14.1	16.3	0.3	0.2	37.5	19.6	3.6	0.8	5.2	25.5	21.8	36.5
4.25	9.6	8.6	8.8	0.9	18.7	15.3	17.6	0.7	40.7	15.3	42.0	42.8
8.5	7.7	8.6	6.2	0.9	13.0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

1.3.3.1 Juvenile Brown Trout

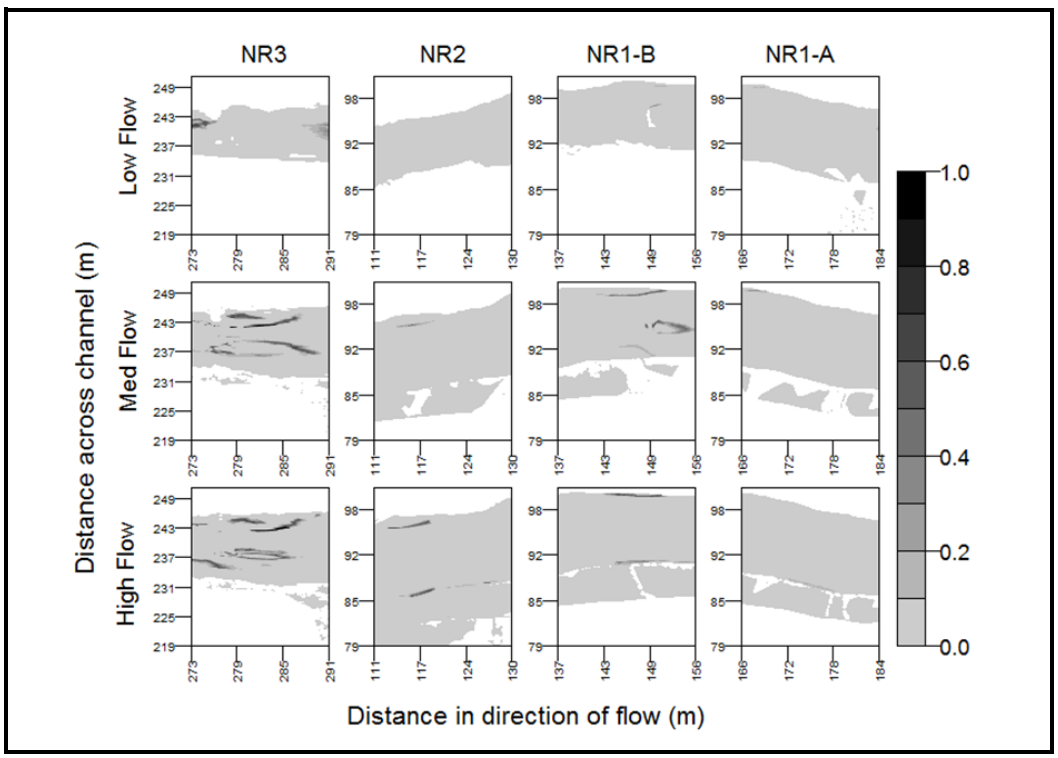
Modeled juvenile brown trout habitat was concentrated around the margins of the WWP pools and decreased as the flow rate increased. At low flow in the natural pools, habitat was concentrated in the thalweg, but moved to the margins of the channel as flow increased. When the average percentage of good 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).



(a) WWP pools



(b) natural pools

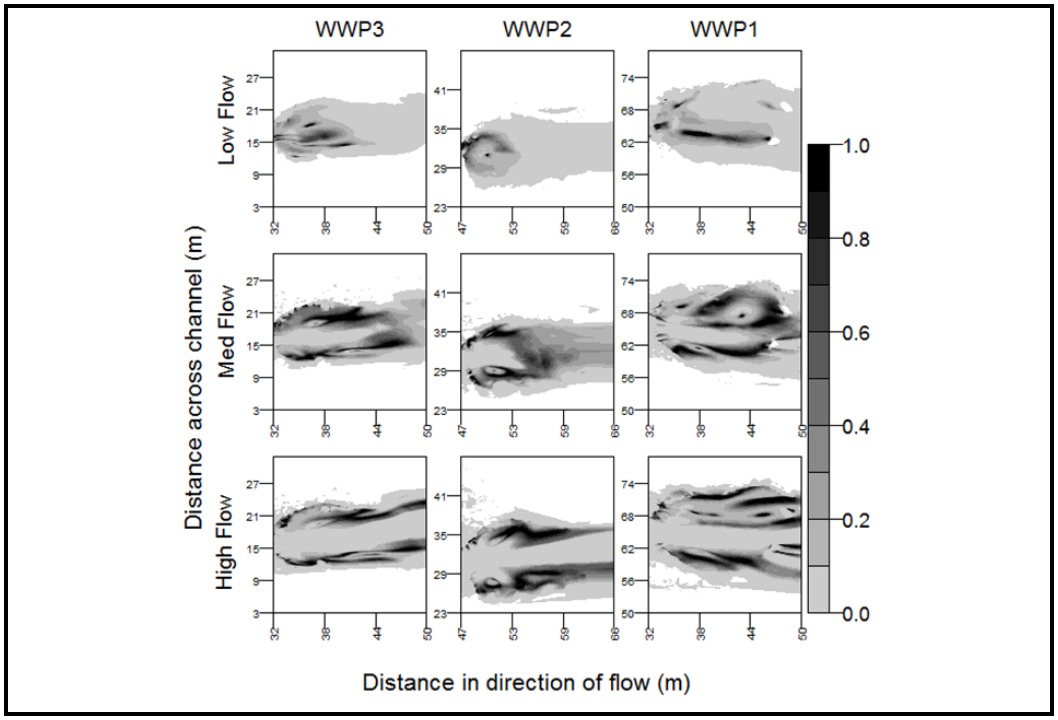
Figure 1.4. Habitat suitability results for adult brown trout in: (a) WWP pools and (b) natural pools (Kolden, 2013).

1.3.3.3 Juvenile Rainbow Trout

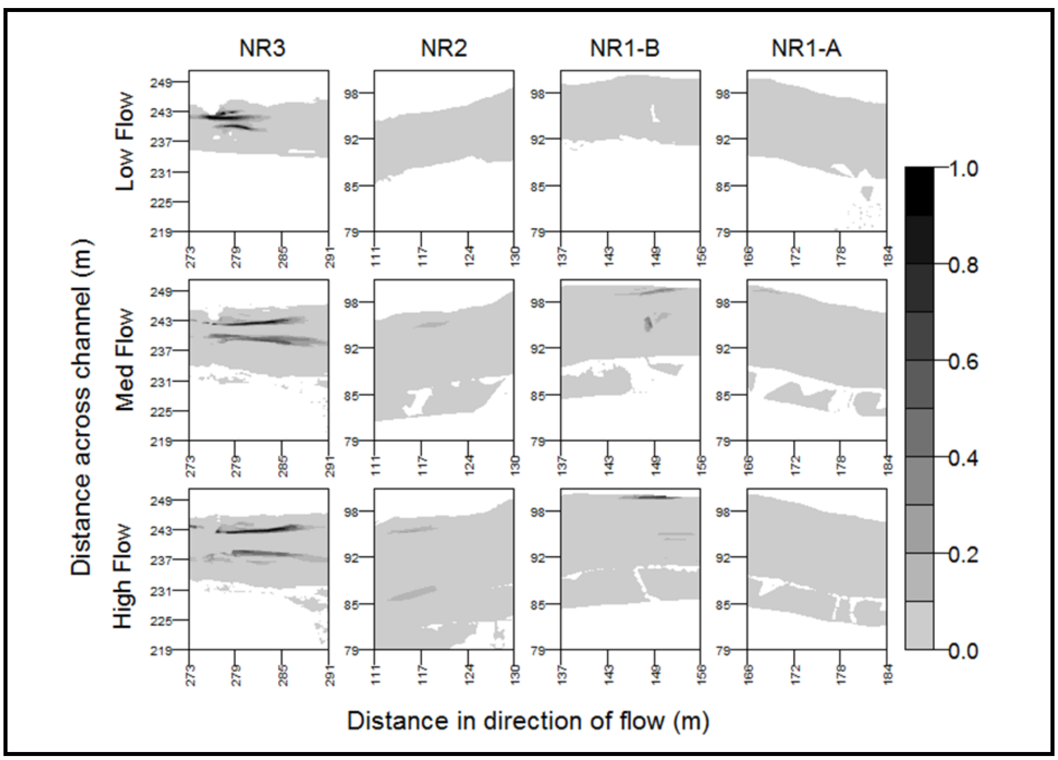
The 2-D habitat analysis showed that juvenile rainbow trout habitat was high in the WWP pools and found everywhere except for the deepest parts of the pools. The amount of good habitat decreased as the flow rate increased, but remained above 13% of area. At low flow in the natural reaches, juvenile rainbow 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).



(a) WWP pools



(b) natural pools

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 $p = 0.057$).

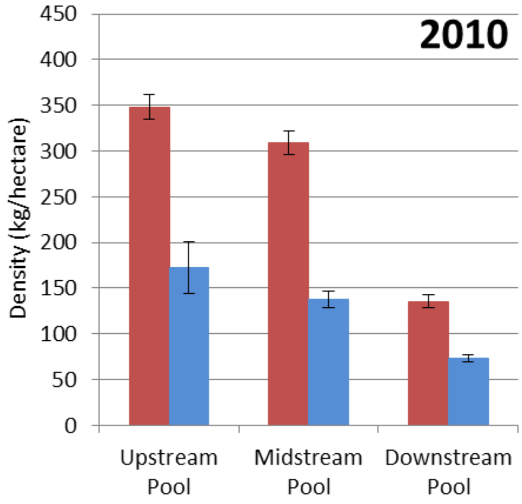
1.3.3.6 Longnose Sucker

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).

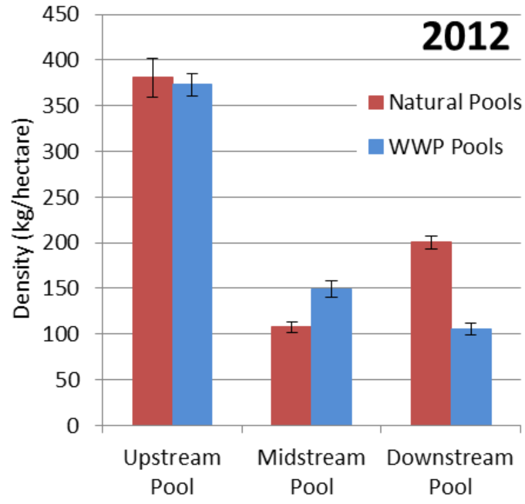
1.4 CASE STUDY: BIOMASS SURVEYS

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.

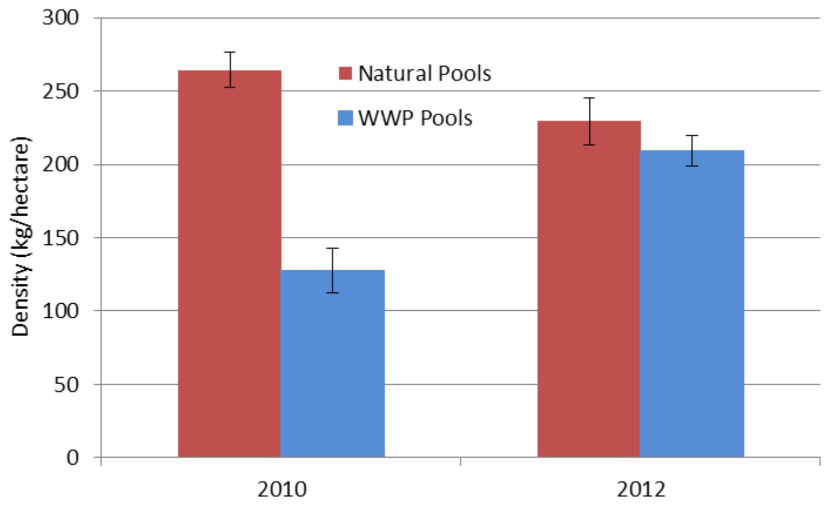
The results of the Fall 2010 and Fall 2012 biomass surveys for adult brown trout (the most abundant fish species at the site) are shown in Figures 1.6 and 1.7. The 2011 results are not presented because they were affected by unusually prolonged high-flow rates that potentially confounded the field surveys. 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.



(a) biomass in each pool in 2010

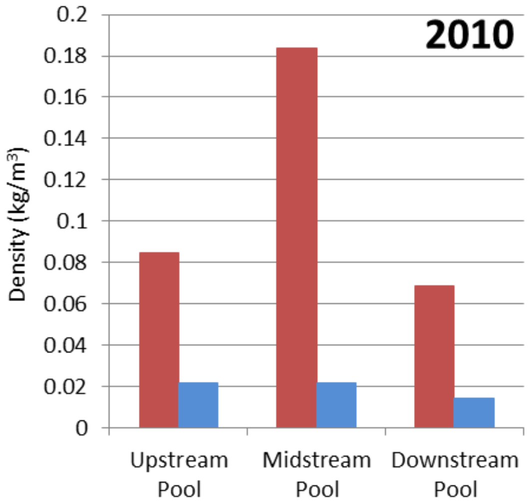


(b) biomass in each pool in 2012

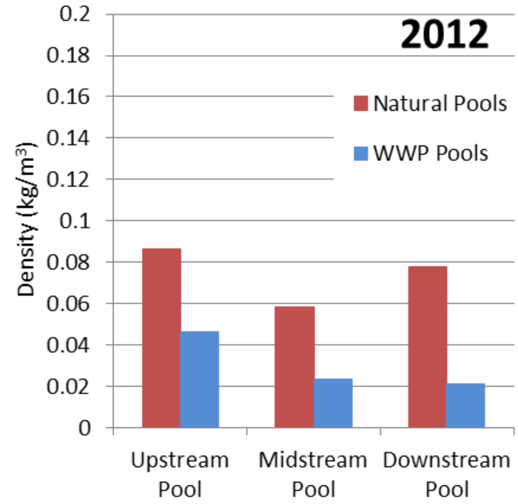


(c) average biomass in WWP pools and natural pools in 2010 and 2012

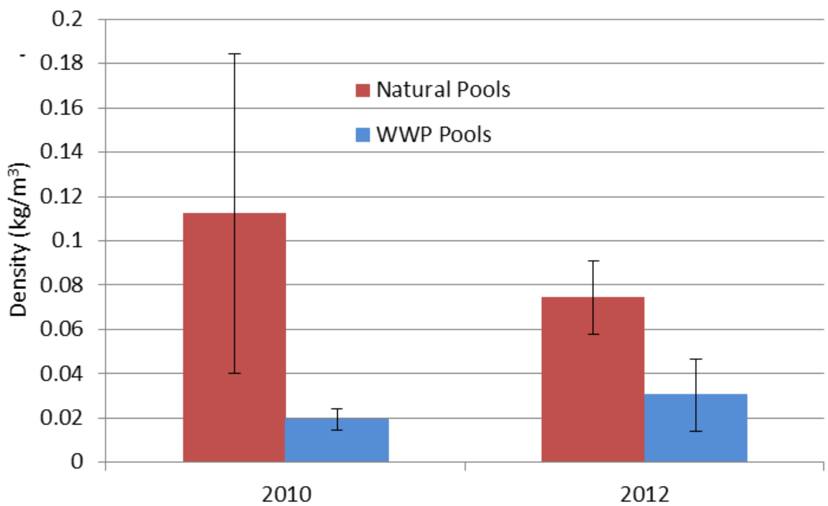
Figure 1.6. Adult brown trout biomass normalized by pool surface area: (a) biomass in each pool in 2010, (b) biomass in each pool in 2012, and (c) average biomass in WWP pools and natural pools in 2010 and 2012 (Kolden, 2013). Error bars represent 95% confidence intervals.



(a) biomass in each pool in 2010



(b) biomass in each pool in 2012



(c) average biomass in WWP pools and natural pools in 2010 and 2012

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 U. S., 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.

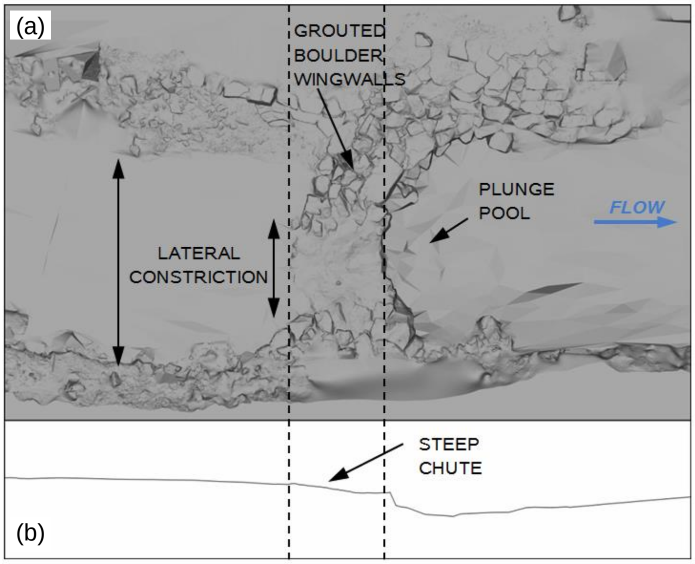


Figure 2.1. (a) Plan and (b) profile views of common design features found in WWPs (Fox, 2013).

(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):

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

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

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

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

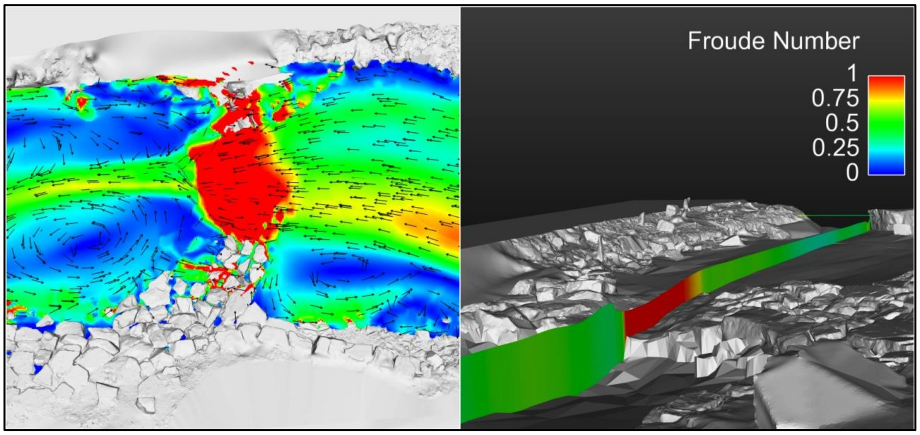
where

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

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

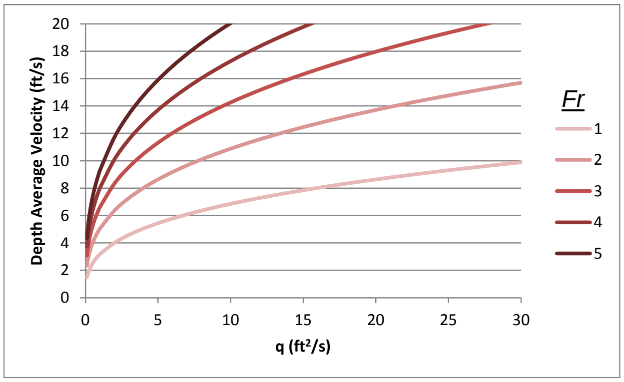
y = flow depth (L); and

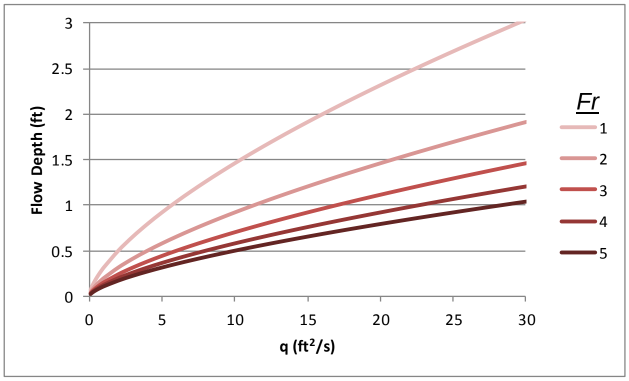
q = unit discharge $\left(\frac{\mathrm{L}^2}{\mathrm{T}}\right)$.



(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 passive integrated transponder (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.

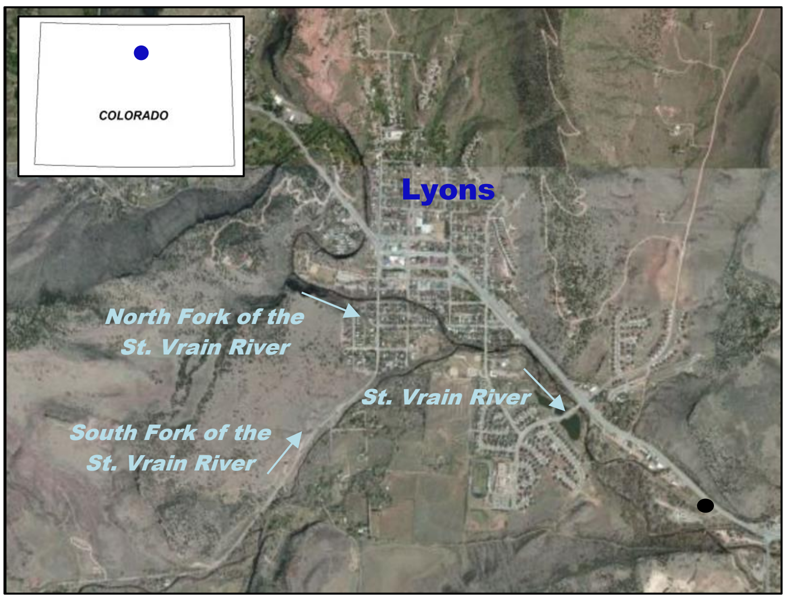


Figure 2.5. Location map of study site on the North Fork of the St. Vrain River, Lyons, Colorado (Fox, 2013).

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 statistics (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 MRTs include electrofishing study site residents, release of hatchery-reared fishes, and displacement of fishes below the study sites. The different MRTs were used to increase the sample size and motivation to move upstream. Electrofishing MRTs 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 MRTs consisted of releasing hatchery-reared rainbow trout (*Hofer x Harrison strains*) at each of the six study sites on two occasions. The displacement MRTs 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 MRTs 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:

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

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**

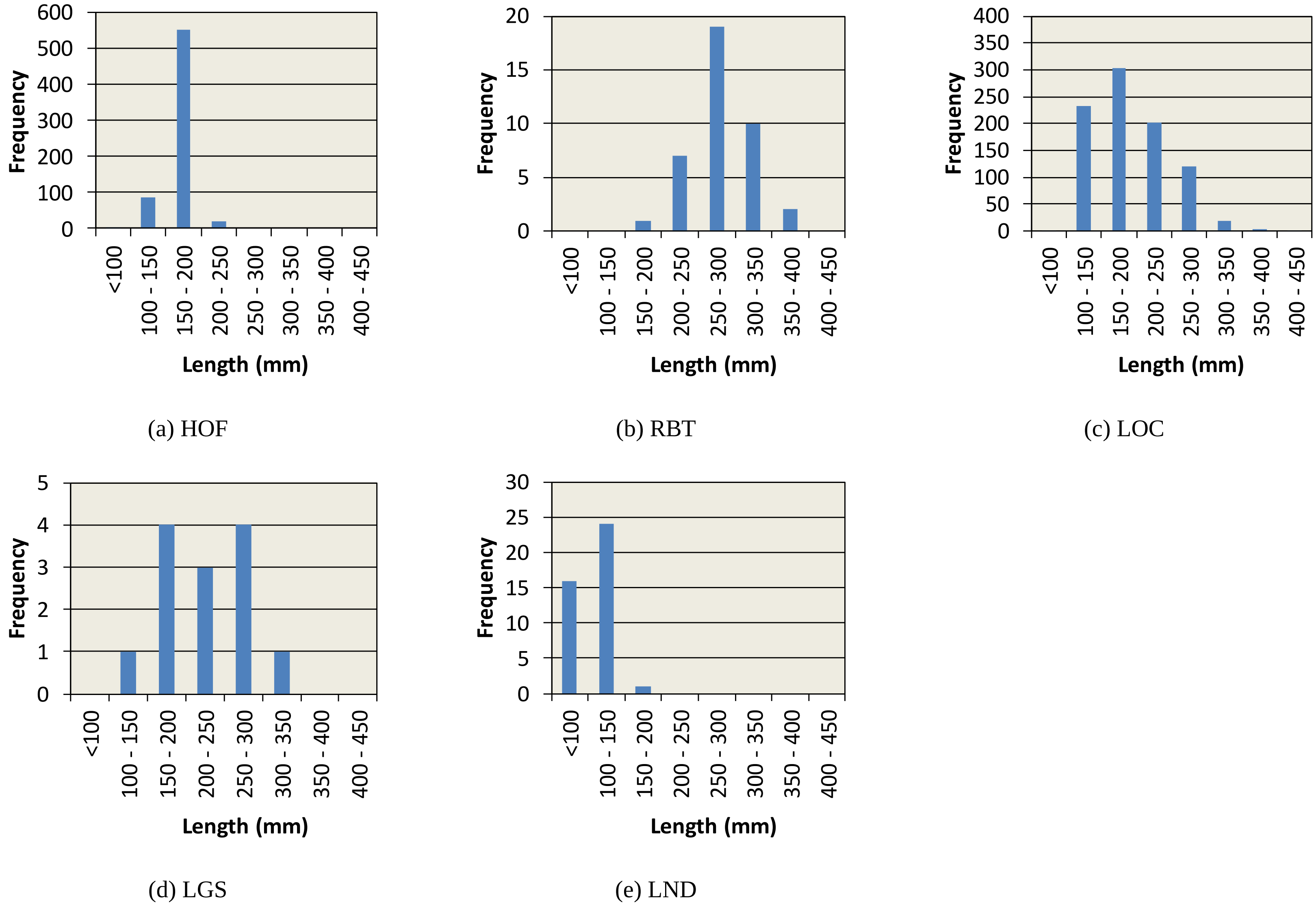


Figure 2.8. Length (mm) frequency of entire study population (*n* = 1639) by species: (a) HOF – (*Hofer x Harrison strain*); (b) RBT – rainbow trout (*Oncorhynchus mykiss*); (c) LOC – brown trout (*Salmo trutta*); (d) LGS – longnose sucker (*Catostomus catostomus*); and (e) LND – longnose dace (*Rhinichthys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

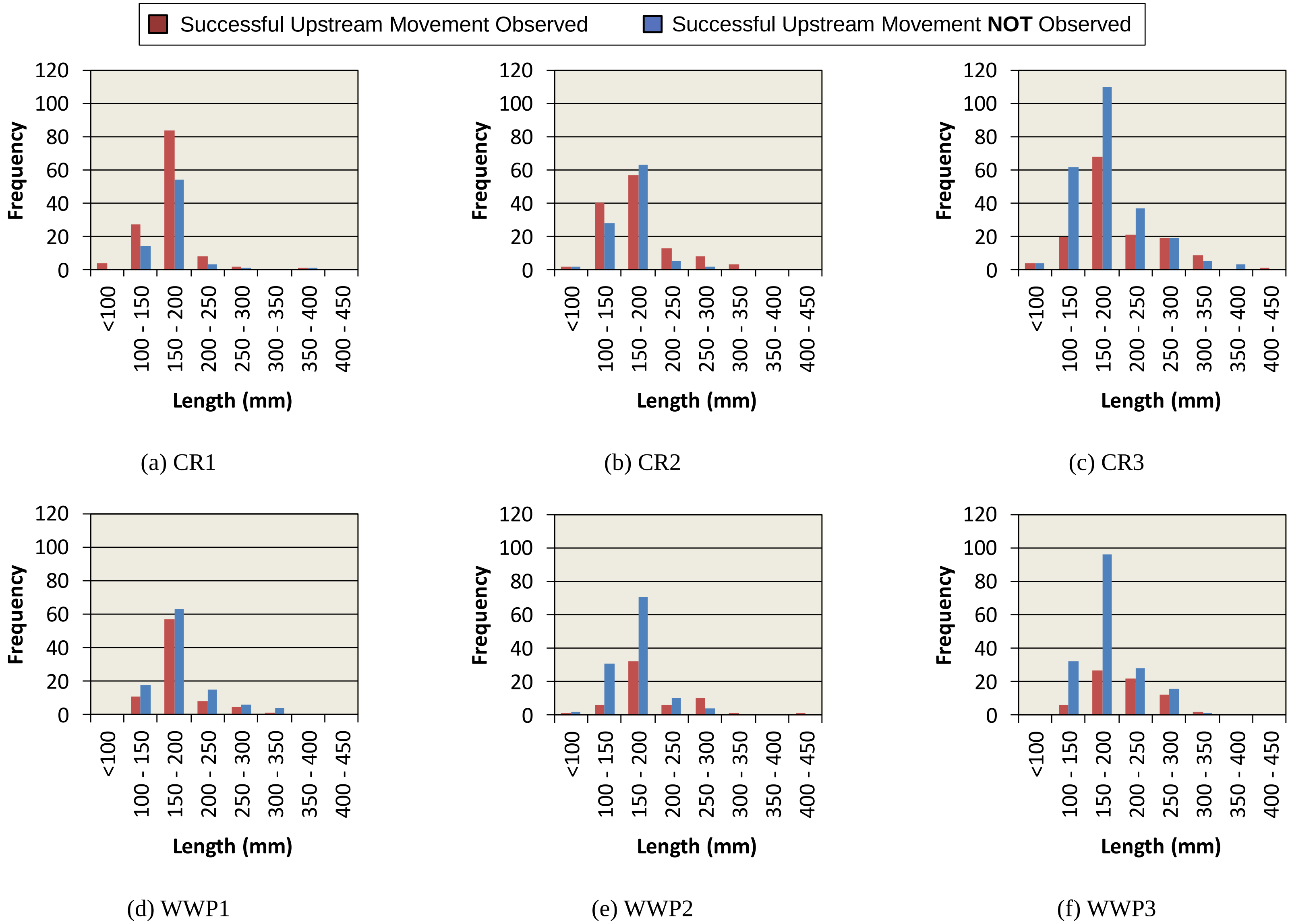
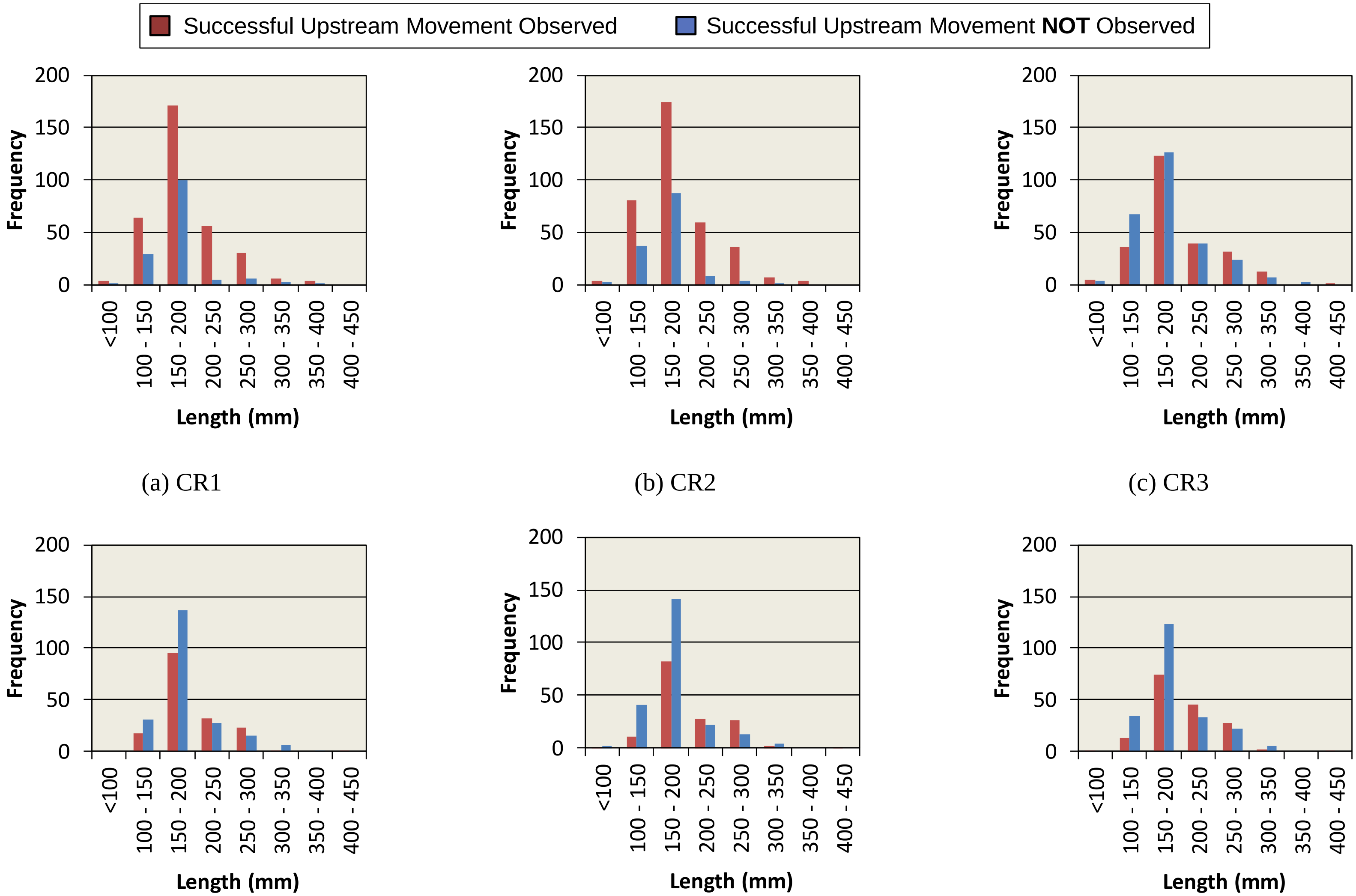


Figure 2.9. Frequency of fishes that successfully moved upstream from the <u>initial</u> release location vs. fishes that did not move upstream for <u>all</u> species and <u>all</u> *MRT* (*n* = 1639) (Fox, 2013).



(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 △AICc (corrected AIC) = 1.61, AICc weight = 0.3, model likelihood = 0.447; all remaining models have a △AICc > 8, AICc weight < 0.01, model likelihood < 0.015.

Final form of the most supported model:

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

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.

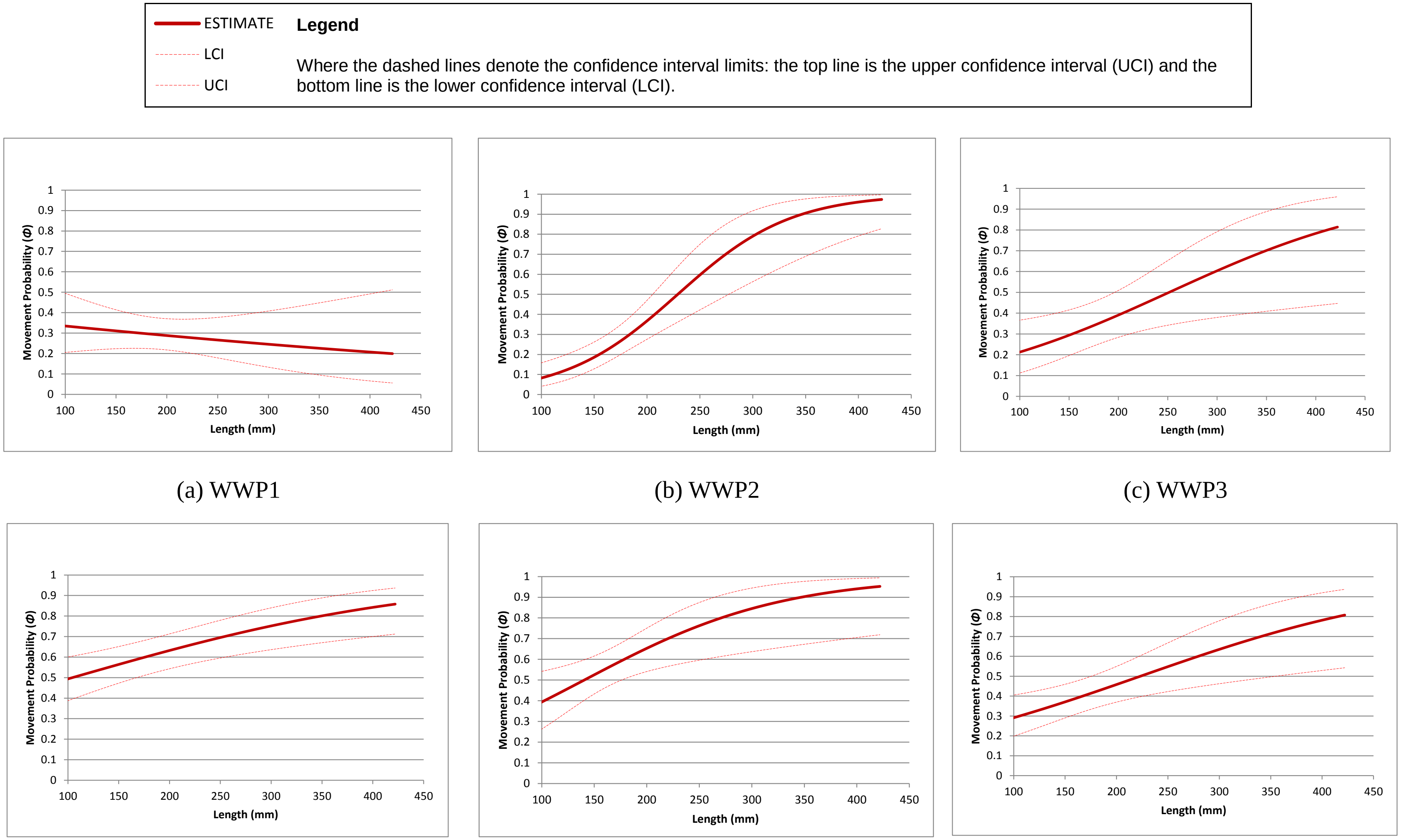
Because *MRT* and *EVENT* were fixed as additive effects in all candidate models, their inclusion in the final model does not necessarily indicate special significance over models without these variables. The additive effects or *MRT* show a strong positive effect to increase movement as compared to 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
		EVENT6	-1.204	0.250	-1.695	-0.713
3	[*SPECIES*]	TROUT	-1.100	0.283	-1.655	-0.545
		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
		WWP2	-3.685	0.816	-5.284	-2.085
		WWP3	-1.580	0.765	-3.080	-0.081
		CR1[1]	–	–	–	–
		CR2	-0.904	0.745	-2.364	0.556
		CR3	-1.019	0.557	-2.111	0.072
6	[*LOCATION*]* [*LENGTH*]	WWP1*LENGTH	-0.078	0.035	-0.147	-0.010
		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).

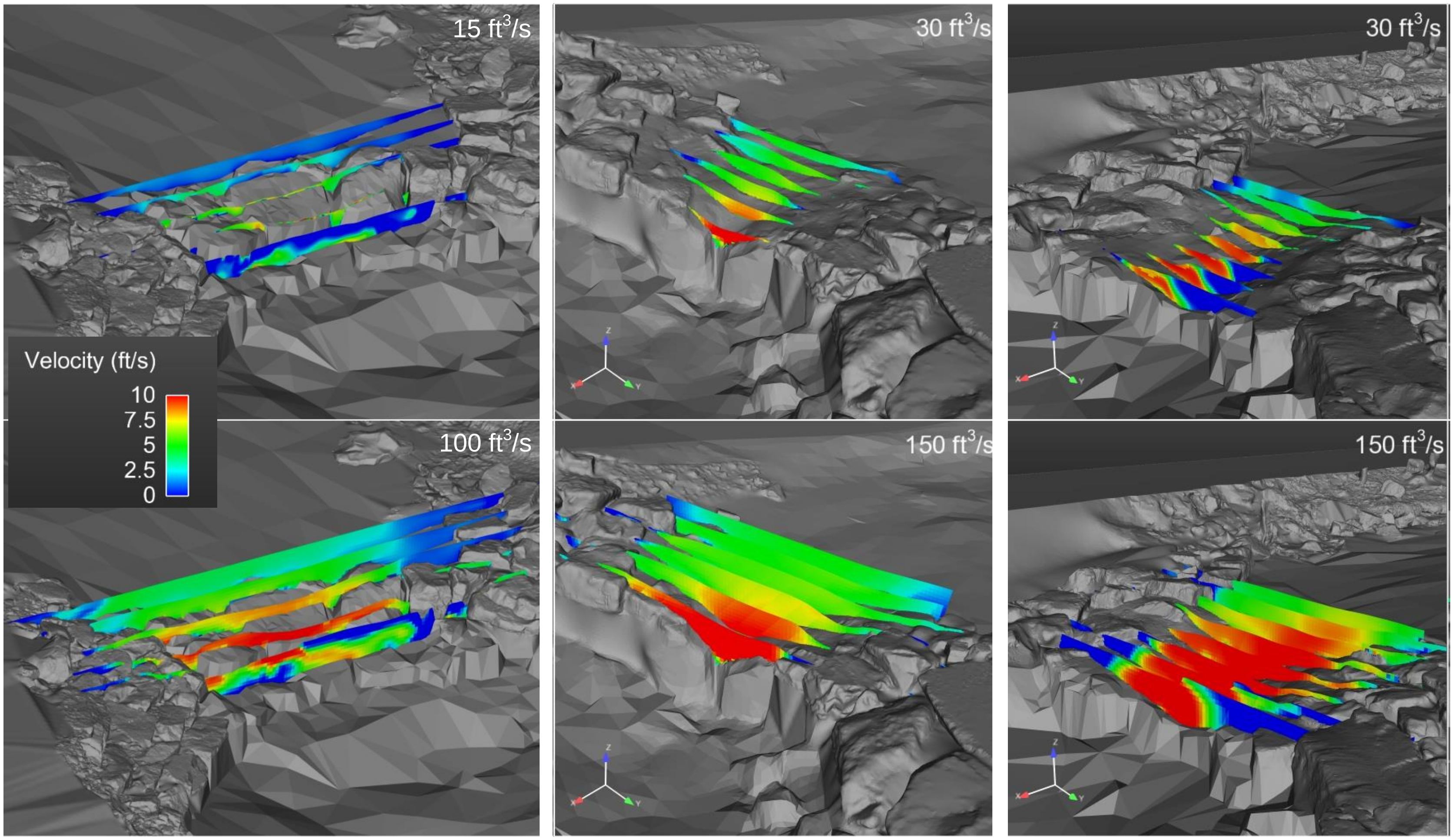
2.3.2 Hydraulic Results

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.

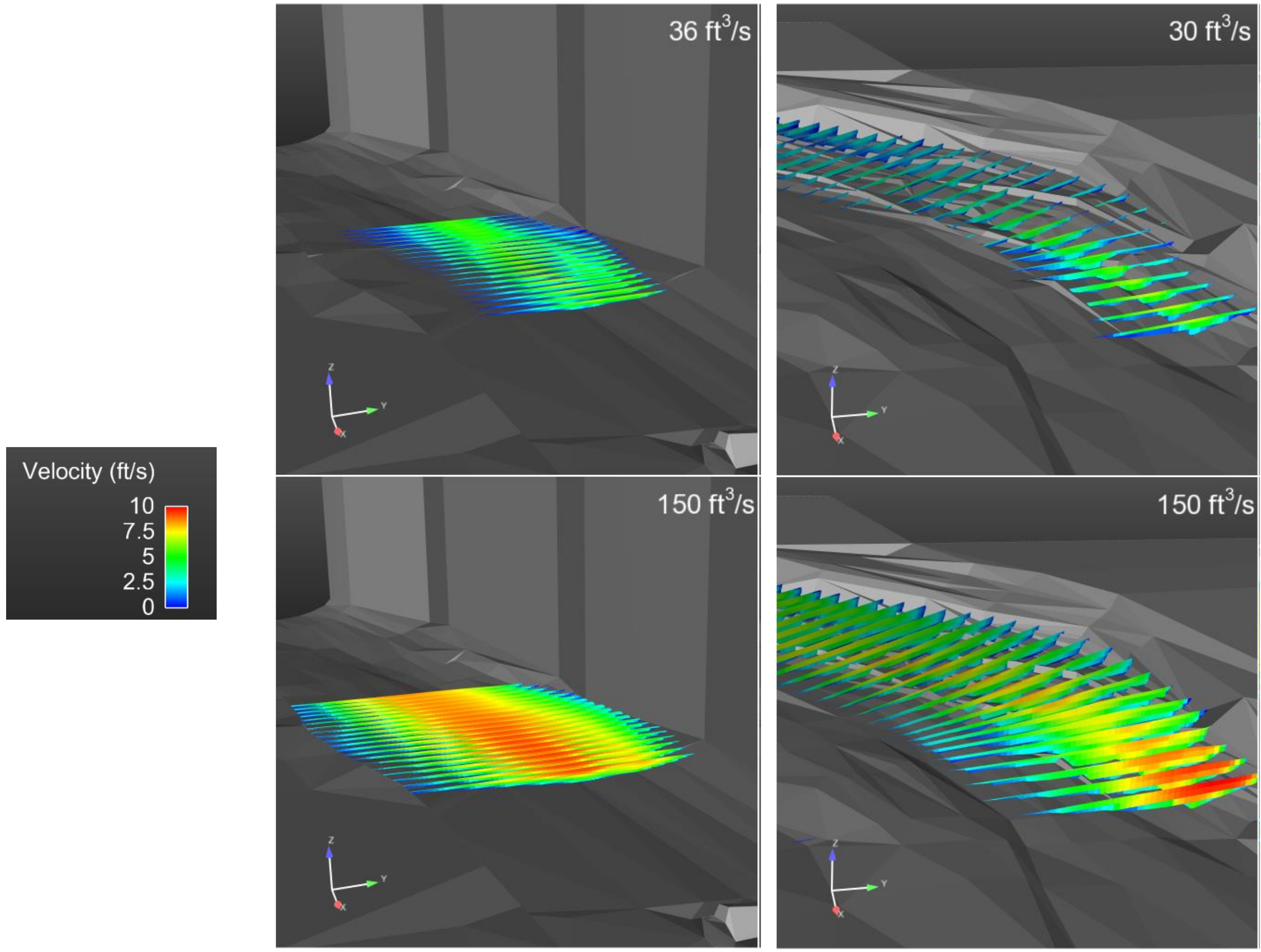
The 3-D model outputs were used to develop qualitative observations and descriptions of the hydraulic conditions at each location. Results for WWP1 show very complex flow conditions at all discharges due to non-uniformity on cross-sectional area. Large boulders were used to construct the short and steep 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.

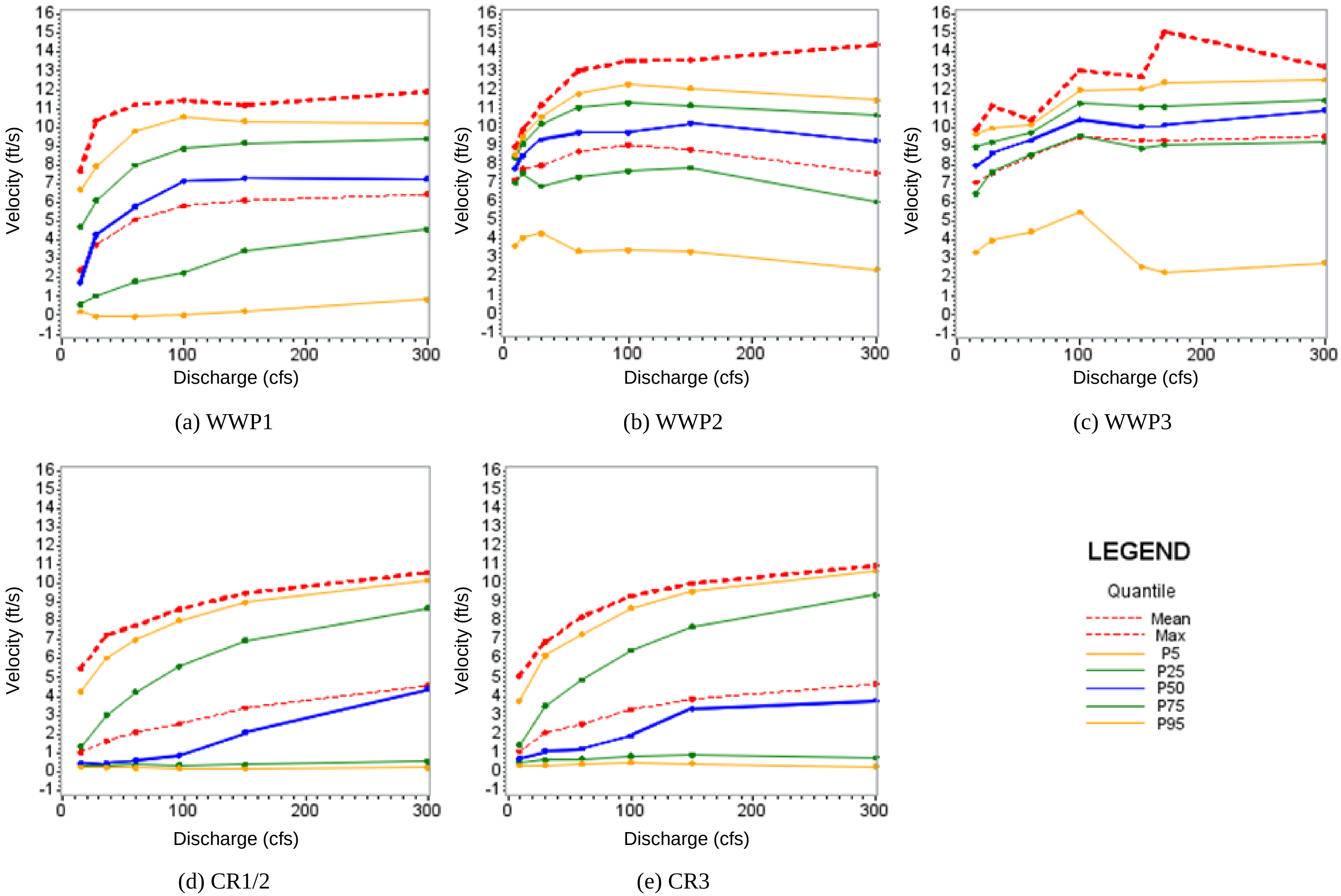
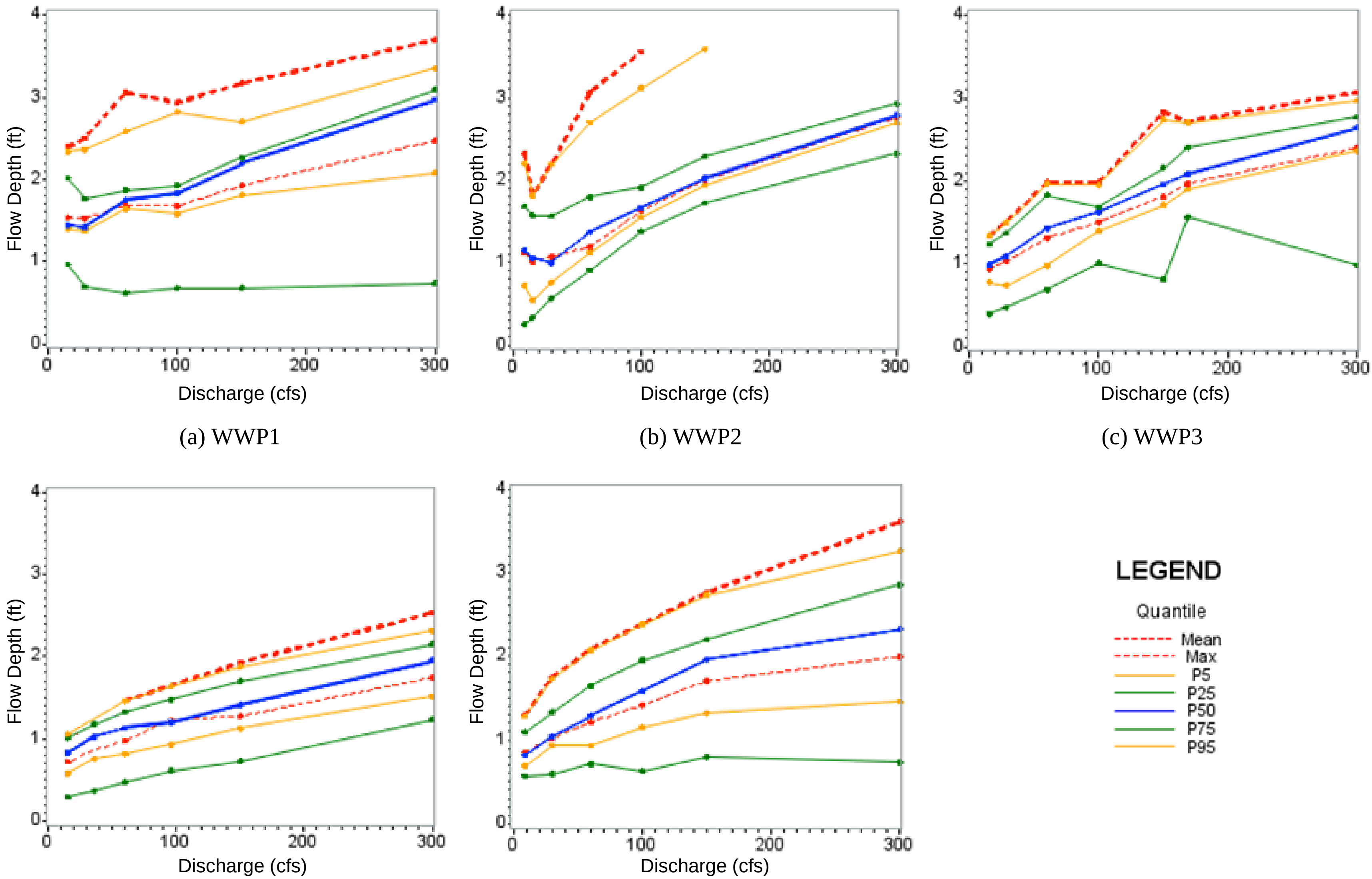


Figure 2.14. Limiting magnitudes of velocity within the zone of passage to assess burst swimming barriers (Fox, 2013).



(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.

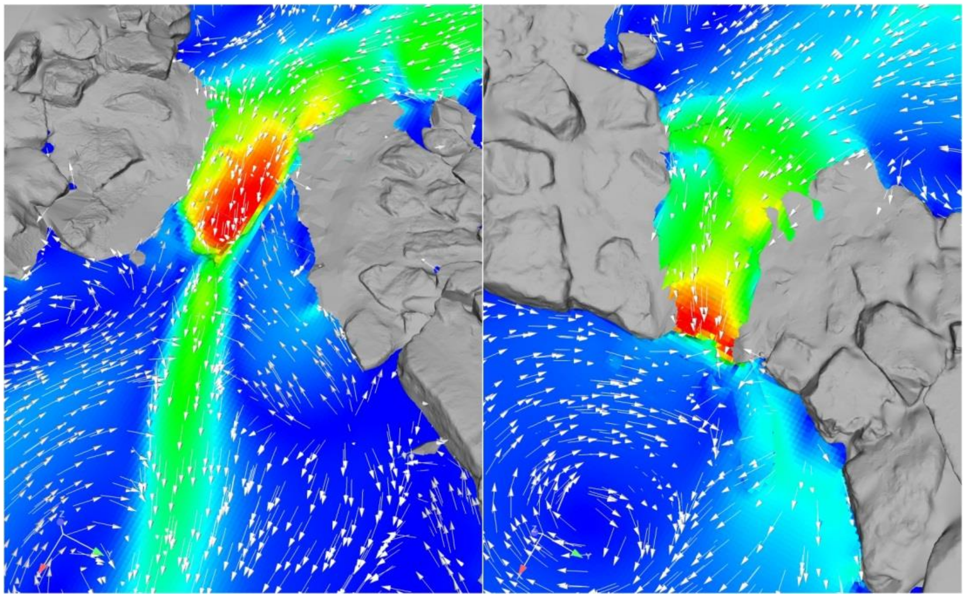
Given that both field data and laboratory studies (Castro-Santos *et al*., 2013) indicate these structures are not likely to be burst swimming barriers, a different mechanism may be causing the observed suppression of movement at the WWP sites. Other potential causes for the reduced movement may include 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 CONCLUSION

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

EFFECTS OF WHITEWATER PARKS ON FISH PASSAGE: A SPATIALLY EXPLICIT HYDRAULIC ANALYSIS

3.1 INTRODUCTION

3.1.1 Whitewater Parks and Water Resources

Riverine biota have evolved to inhabit highly complex hydraulic environments formed through natural hydrologic variability and geomorphic response (Poff *et al*., 1997; Nestler *et al*., 2012; Thorp *et al*., 2006). Aquatic organisms exploit habitats that vary spatially and temporally across dimensions and scales, thus highlighting the need for connectivity of the river landscape (Fausch *et al*., 2002; Frissel *et al*., 1986). For example, many fishes migrate in search of optimal habitats for spawning, rearing, overwintering, and other life-cycle processes (Schlosser and Angermeier, 1995). The reproductive success of migratory fishes and other organisms is dependent on the quantity, quality, and connectivity of available habitats from large-scale systems as they vary slowly and are disrupted infrequently, down to smaller habitat patches that are disturbed and change more frequently (Frissel *et al*., 2001).

Anthropogenic needs require the extraction of water resources resulting in fragmentation of many rivers by dams, diversions, and other in-stream structures. When impassable, these structures cut-off necessary habitat linkages and migration routes of aquatic organisms, particularly fishes (Dudley and Platania, 2007; Fullerton *et al*., 2010; Walters *et al*., 2014). There is a strong interdependence among organisms within an ecosystem, and the extirpation of a species could alter the entire ecosystem energy flow and composition (Baxter *et al*., 2004). Successful passage for fishes of all life stages across barriers to migration is imperative to restore and maintain ecosystem function (Beechie *et al*., 2010; Bunt *et al*., 2012; Wohl *et al*., 2005). In-stream structures must operate within the physiological limits of a fish's swimming abilities, and understanding how fish respond to micro-hydrodynamic and macro-hydrodynamic conditions within a structure is necessary to effectively design for passage success (Williams *et al*., 2012).

However, structures are designed and constructed without direct knowledge of fish passage success in response to altered hydraulic conditions. A whitewater park (WWP) consists of one or more in-stream structures primarily constructed to create a hydraulic jump that is desirable to recreational kayakers and other boaters. The hydraulic jump is typically formed by grouting a laterally constricted chute over a steep drop into a downstream pool. WWPs provide a valuable recreational and economic resource (Hagenstad *et al*., 2000) that is rapidly growing in popularity throughout communities in the U. S., with Colorado being an epicenter of WWP design and construction (Fox, 2013). Currently there are 22 constructed and 12 proposed WWPs in the state of Colorado (Kondratieff, pers. comm.). WWPs were originally thought to enhance aquatic habitat (McGrath, 2003); however, recent studies (Fox, 2013; Kolden, 2013) have shown that WWPs can act as a partial barrier to upstream migrating trout, and WWP pools may contain lower densities of fish compared to natural pools. Further, the magnitude of suppressed fish movement varies at different WWP structures and among size classes of fish. Higher velocities with larger spatial extents were recorded in WWPs compared to natural reaches, and unique hydraulic conditions exist at individual WWP structures as a result of seemingly subtle differences in their design and configuration. Concerns have arisen that the hydraulic conditions required to meet recreational needs are contributing to the suppression of movement of upstream migrating fishes, and disruption of longitudinal connectivity.

3.1.2 Fish Swimming Abilities

Fish exhibit multiple modes of swimming when encountering different flow velocities in order to maximize ground speed and minimize energy expenditure (Beamish, 1978; Katopodis, 2005). Additionally, the swimming ability of fishes is directly related to fish body length (BL) (Beamish, 1978; Castro-Santos *et al*., 2013; Peake *et al*., 1997; Webb, 1998). Velocity can act as a burst swimming barrier in which the velocity of the water is greater than the fish's maximum swim speed. Velocity can also act as an exhaustive swimming barrier where a fish is unable to maintain positive ground speed over the required distance. Previous laboratory studies have observed burst swimming abilities of 10 to 15 BL/s (Beamish, 1978; Peake *et al*., 1997); however, a more recent study observed burst swimming abilities of brook trout (*Salvelinus fontinalis*) and brown trout (*Salmo trutta*) of up to 25 BL/s (Castro-Santos *et al*., 2013).

Adequate depth is required for a fish to reach its full swimming potential (Webb, 1975). Minimum flow depths in a WWP are often located in zones of supercritical flow where velocities are greatest. Insufficient depth to submerge a fish impairs its ability to generate thrust through body and tail movements, exposes the gills limiting oxygen consumption, and exposes the fish to physical trauma through contact with the channel bed (Dane, 1978). Minimum depth recommendations for fish passage through culverts vary from 1.5 to 2.5 times the body depth of a fish depending on the species of interest, life stage, and regulating agency (Hotchkiss and Frei, 2007). For non-anadromous salmonids, typical depth recommendations range from 0.4 to 0.8 ft (Fitch, 1995; Hotchkiss and Frei, 2007; Kilgore *et al*., 2010; National Oceanic and Atmospheric Administration (NOAA), 2001).

Current knowledge of turbulence and its effects on fish swimming abilities suggests that turbulence might be contributing to the suppression of movement in WWPs. In particular, vorticity and TKE are recognized as meaningful measures of turbulence (Lacey *et al*., 2012), and higher magnitudes of vorticity and TKE were observed in WWP pools compared to natural pools (Kolden, 2013). Numerous studies have investigated the effects of turbulence metrics such as TKE, turbulent intensity (TI), Reynolds' shear stress, and vorticity on fish swimming abilities. Turbulence can increase or decrease a fish's swimming ability (Cotel and Webb, 2012; Lacey *et al*., 2012; Liao, 2007); however, high levels of turbulence pose a stability challenge to fish (Tritico and Cotel, 2010), and turbulence reduces fish's swimming abilities at high current speeds (Lupandin, 2005; Pavlov *et al*., 2000). Fish migrating upstream through an experimental pool-type fishway appear to prefer locations of lower turbulence and velocity (Silva *et al*., 2012).

Despite current knowledge of fish passage and hydraulics, there is little understanding of the factors contributing to the suppression of fish movements in WWPs. Previous attempts to directly correlate fish passage with hydraulic variables yielded only poor predictors of passage success (Castro-Santos *et al*., 2009). Studies examining the effects of hydraulics on fish passage are limited by scale. Fish experience hydraulic conditions locally (Eulerian frame) and continuously along a movement path (Lagrangian frame) in a highly complex hydraulic environment (Goodwin *et al*., 2006). Studies employing Particle Image Velocimetry have the capability of quantifying hydraulics continuously along fish movement paths; however, the majority of these studies are limited to laboratory settings that constrain the transferability of results to natural environments (Cotel and Webb, 2012). Additional studies are limited to 3-D point measurements or averaging over larger spatial scales that do not capture the continuous small-scale hydraulic heterogeneity important to a fish (Crowder and Diplas, 2000b, 2006).

Consequently, the factors contributing the suppression of movement of upstream migrating fish in WWPs have not been mechanistically explained. Managers and policy makers are forced to make decisions and review designs regarding WWPs without sound scientific evidence. This problem has the potential to impose negative environmental impacts if a WWP that greatly disrupts the longitudinal connectivity of a river is approved. Alternatively, if a WWP does not pose a threat to the environment and is disapproved, a valuable recreational and economic opportunity will be missed. Without a direct understanding of the factors contributing to suppression of movement in WWPs, making informed management and policy decisions regarding WWPs will continue to be difficult and could have unintended consequences.

In order to determine the effect of hydraulic conditions on passage success, detailed fish movement data must be assessed in conjunction with hydraulic characteristics at a scale meaningful to a fish (Williams *et al*., 2012). Advancements in quantifying fish movement through PIT tags have increased our ability to monitor and evaluate passage success. Additionally, CFD models provide a powerful means of estimating the fine-scale hydrodynamic conditions through which fish pass.

3.1.3 Objectives

We describe novel approaches combining fish movement data and hydraulic results from a 3-D computational fluid dynamics model to examine the physical processes that limit upstream movement of trout in an actual WWP in Lyons, Colorado. The objectives of this study are as follows:

- Use the results from a 3-D CFD model to provide a continuous and spatially explicit description of velocity, depth, vorticity, and TKE along the flow field.
- Compare the magnitudes and distribution of velocity, depth, vorticity, and TKE among three unique WWP structures on the St. Vrain River, Colorado, USA.

- Determine the relationship between velocity, depth, vorticity, and TKE on the suppression of movement of upstream migrating fishes through statistical analysis of movement data from PIT-tag studies at the St. Vrain WWP.
- Provide design recommendations and physically-based relationships that help managers better accommodate fish passage through WWP structures.

3.2 METHODS

3.2.1 Site Description

Fish movement data and the results from a 3-D CFD model were available at a WWP located on the North Fork of the St. Vrain River in Lyons, Colorado (Fox, 2013; Kolden, 2013). The North Fork of the St. Vrain River originates on the east slope of the Rocky Mountains where it flows east to the foothills region in the town of Lyons and its confluence with the South Fork of the St. Vrain River. The study site consists of nine WWP structures along a 1,300-ft reach in Meadow Park. The natural river morphology at the study site can be described as the transition zone between a step-pool channel and a meandering pool-riffle channel. The natural river channel is characterized by riffles, runs, and shallow pools with cobble and boulder substrates. The North Fork of the St. Vrain River experiences a typical snowmelt hydrologic regime with peak flows occurring in late May to early June. Accurate USGS gage data were unavailable for the site due to a reservoir located approximately 8 mi upstream; however, a stage-discharge rating relationship was developed over the course of the study to provide a continuous record of discharges for the site (Fox, 2013).

3.2.2 Fish Movement Data

Fish passage was assessed at three WWP structures by obtaining 14 months of fish movement data from PIT-antenna arrays (Fox, 2013). Tagged rainbow trout (*Oncorhynchus mykiss* and *Hofer x Harrison* strain) and brown trout (*Salmo trutta*) were included in the analysis totaling 536 tagged fishes ranging in size from 115 to 435 mm. Due to safety risks involving park users, PIT antennas were installed directly upstream of the WWP structures and in the tail-out of the pools directly downstream of the WWP structures (Figure 3.1). The PIT-antenna configuration associated a time stamp and river discharge with a successful movement, but it did not provide information on failed attempts of individual fish. Therefore, fish were classified as fish that did pass a structure versus fish that did not pass a structure.

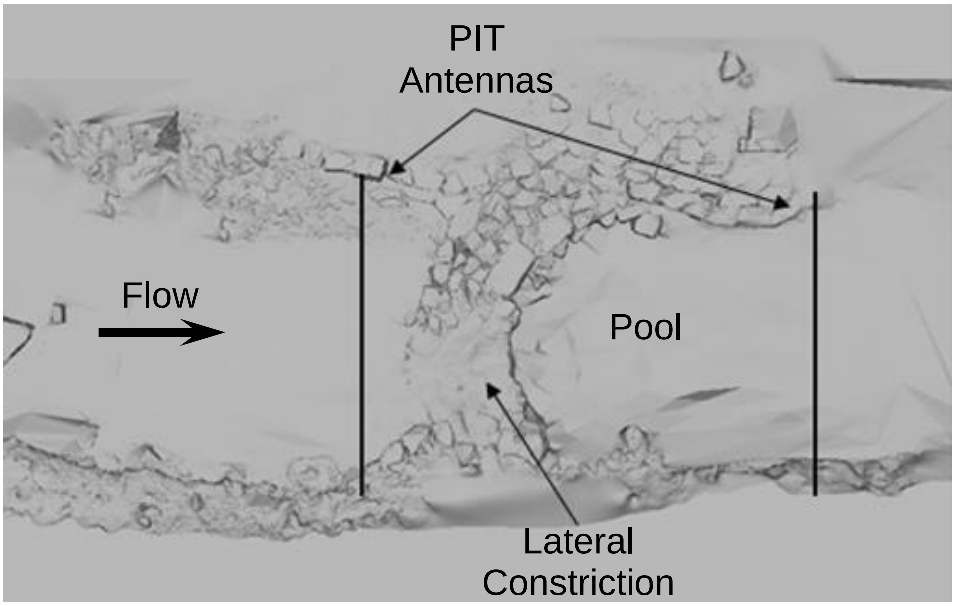


Figure 3.1. Plan view of a WWP structure with PIT-antenna configuration (Stephens, 2014).

Passage success was evaluated over four discrete time windows: October 2011 – March 2012, March 2012 – October 2012, October 2012 – November 2012, and November 2012 – December 2012. The start of each time window was defined by a stocking or electroshocking event in which fish were observed in the pool directly below a structure. Movements were evaluated over the duration of that respective time window. A successful movement across a structure was only included in the analysis if a fish was observed in the pool directly below that structure at the start of the time window. This prevented over-estimating passage success at structures where fishes with greater swimming abilities were able to migrate upstream crossing multiple structures over the duration of a time window. There were 429 successful movements over the duration of all the time windows.

3.2.3 Hydraulic Modeling Results

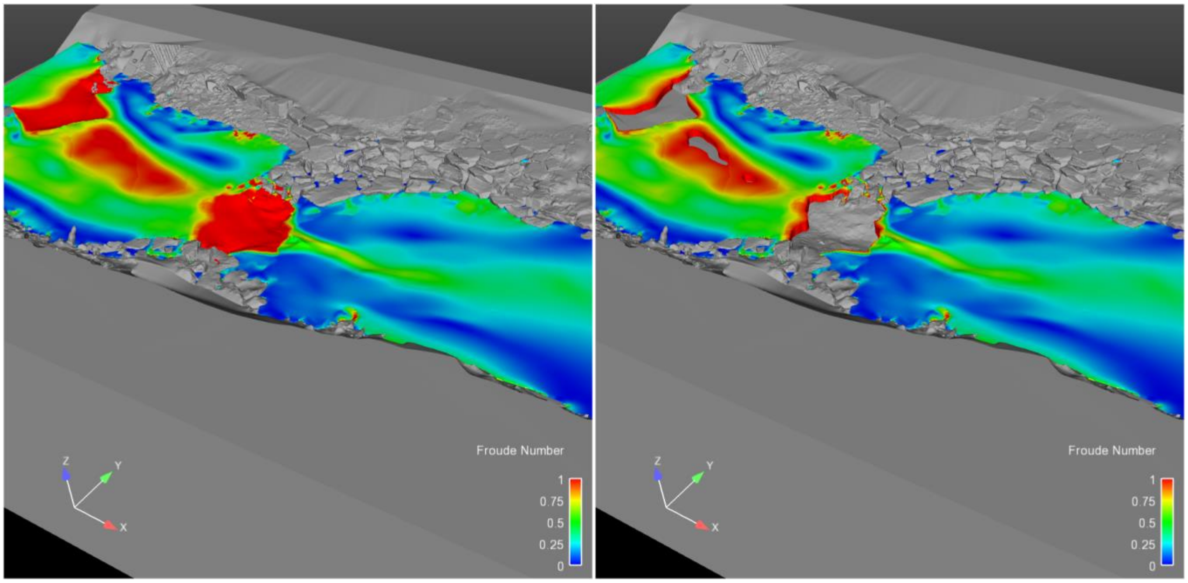
Seven discharges were modeled at three WWP structures containing fish-tracking data using the 3-D CFD software FLOW-3D v10.0 (Kolden, 2013). The modeled discharges include: 15, 30, 60, 100, 150, 170, and 300 cfs, representing a range of flows that produce various habitats throughout the year. FLOW-3D described the flow field by solving the Reynolds-Averaged Navier-Stokes (RANS) equations of fluid motion and a default RNG turbulence closure with dynamically-computed turbulent mixing length. The fluid domain was comprised of a series of discrete points making-up a mesh. The uniform grid sizes of the mesh ranged from 0.125 to 0.5 ft (3.81 to 15.24 cm). The free surface was represented in the structured mesh by a process called volume of fluid (VOF) (FLOW Science, 2009), and channel roughness elements were assumed to be adequately resolved through surveyed bathymetry. Model validation through field measurements ensured the model was performing within an acceptable range of error

(Kolden, 2013). Additional model validation was infeasible due to severe floods in September 2013 that significantly altered the channel geometry. Post-processing of the hydraulic results from the CFD model was performed using EnSight Standard v10.0.3.

3.2.4 Defining the Flow Field

In order to equally compare the hydraulics among WWP structures and across a range of discharges within WWP structures, a physically-based criterion was needed to define the upstream and downstream boundaries of the analysis domain. The Froude number provided a physically meaningful criterion for establishing boundary conditions that captured the full extent of potential hydraulic barriers to fish passage. The upstream and downstream boundaries were defined by a Froude number of 1 and 0.8, respectively. The upstream boundary condition includes supercritical flow and the most challenging velocities that must be traversed by a fish at all discharges. The downstream boundary encompasses the hydraulic jump from supercritical flow to subcritical flow and the highest levels of turbulence.

EnSight was used to create a flow volume consisting of the total modeled domain. Additional, reduced flow volumes were created that consisted of the total modeled domain below a specified Froude number (Figure 3.2). The cross-sectional area of the reduced and total flow volumes were sampled at 0.25-ft longitudinal increments throughout the entire reach. A deviation in the cross-sectional area, between the total flow volume and the reduced flow volume, indicated areas with a Froude number greater than the thresholds used to define the boundaries of the analysis domain (Figure 3.3). This process was repeated for all modeled discharges at each structure. The upstream-most point for all discharges at which the cross-sectional areas diverged was used as the upstream boundary, and the downstream-most point at which the cross-sectional areas diverged was used as the downstream boundary. The Froude criteria were thoroughly analyzed to ensure the boundaries captured all features of the flow field relevant to fish passage.



(a) total flow volume (b) reduced flow volume

Figure 3.2. (a) Total flow volume, and (b) the reduced flow volume of all Froude numbers less than 1 (Stephens, 2014).

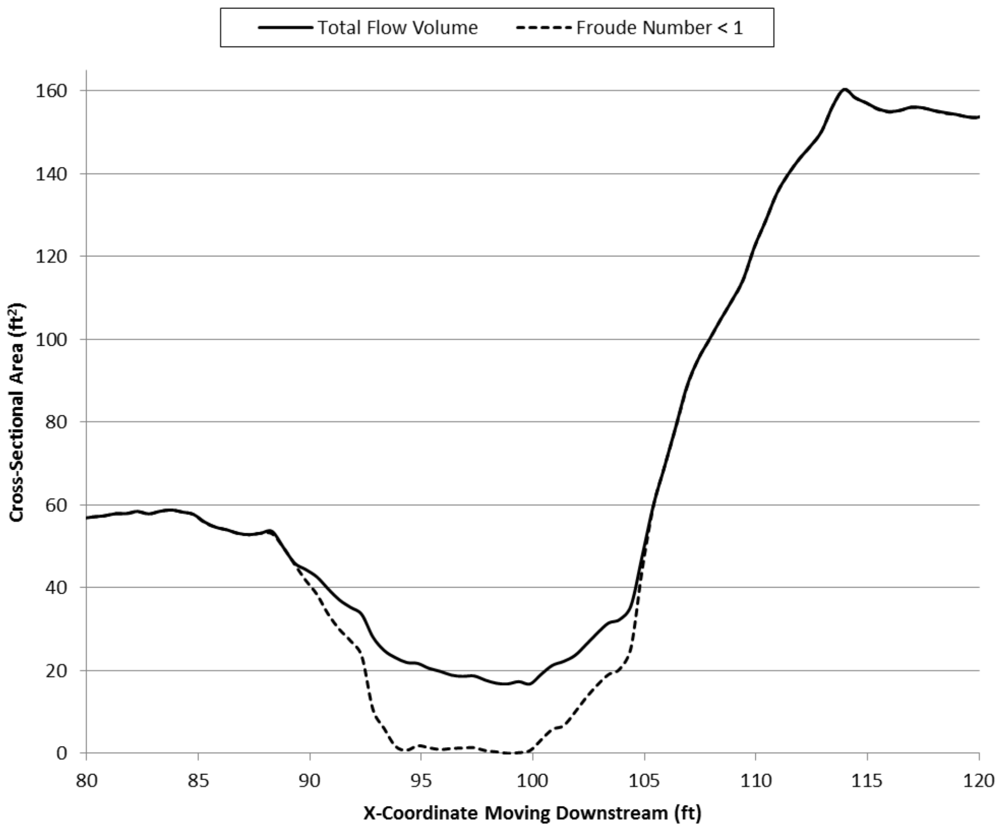
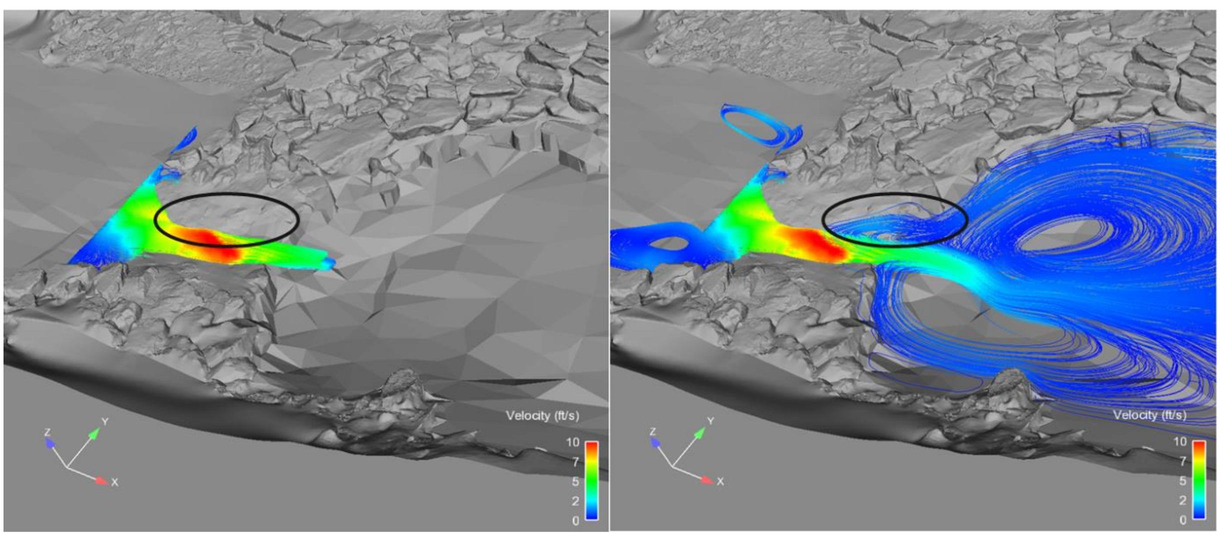


Figure 3.3. Example of longitudinal changes in cross-sectional area of the total flow volume versus the reduced flow volume comprised of Froude numbers less than 1 (Stephens, 2014).

3.2.5 Particle Trace and Potential Swimming Path Development

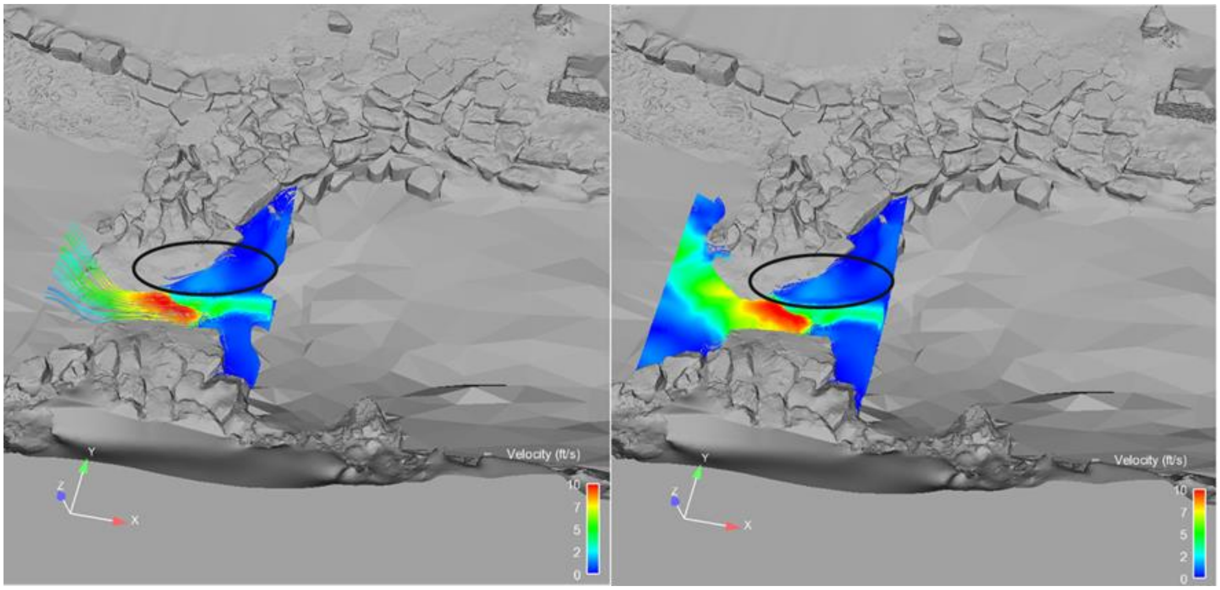
Releasing particle traces through the flow field and quantifying hydraulic variables along each trace provides a meaningful description of the hydraulic conditions a fish might encounter while migrating upstream. EnSight was used to emit particle traces from nodes within the gridded mesh. A particle trace consists of a series of points that track a massless-particle through both time and space in the fluid domain. The trajectory of the particle trace is parallel to the velocity vector field at that point and time.

Releasing particle traces from a cross section at the upstream boundary limits the number of particle traces to the number of nodes that make-up the cross section; however, particle traces can be emitted from a volume to greatly increase the number of nodes from which particle traces can be emitted. Additionally, releasing particle traces forward in time through the defined flow volume stops the particle traces at the downstream boundary. This excludes eddies and zones of reverse flow where a particle trace would continue past the downstream boundary and then recirculate back upstream into the defined flow volume (Figure 3.4). Therefore, particle traces were emitted forward and backward in time from volumes at the upstream and downstream boundaries encompassing important hydraulic features and the entirety of the flow field (Figure 3.5).



(a) to downstream boundary (b) through entire reach

Figure 3.4. (a) Particle traces released forward in time from an upstream cross section traveling to the downstream boundary, and (b) particle traces released forward from an upstream cross section traveling through the entire reach (Stephens, 2014). A reference recirculation zone is highlighted by a circle.



(a) at the downstream boundary both forward and backward in time

(b) at the upstream and downstream boundaries both forward and backward in time

Figure 3.5. (a) Particle traces released from a volume at the downstream boundary both forward and backward in time, and (b) particle traces released from volumes at the upstream and downstream boundaries both forward and backward in time (Stephens, 2014). A reference recirculation zone is highlighted by a circle.

A portion of the particle traces released from volumes at the upstream and downstream boundaries both forward and backward in time nevertheless stopped prematurely and did not reach the opposite boundary. A particle trace stopped prematurely if the trace moved outside the space in which the vector field was defined or the particle trace entered a location where the velocity was zero (Computational Engineering International, Inc., 2013). Additional particle traces existed that recirculated in an eddy before stopping prematurely or continuing through the flow field. Particle traces that stopped prematurely or recirculated within the flow volume introduce bias when quantifying hydraulic variables along each particle trace and assessing the conditions a fish might experience as it swims upstream.

To resolve this bias, particle traces that recirculated to the upstream or downstream boundary were divided at the point where they began to recirculate relative to the upstream/downstream directions. Two particle traces that do not make it through the entire flow volume result from each circulation. Each trace that did not make it through the entire volume (incomplete trace) was connected to a trace that did travel through the entire flow volume (complete trace) providing a path that represents the hydraulic conditions a fish might experience when migrating upstream. This task was accomplished by searching for the point within all the complete traces with the shortest Euclidean distance to the terminus of an incomplete trace. The new trace consisted of the incomplete trace, the point of connection, and the needed portion of the complete trace to continue through the entire flow volume. The new trace was added to the list of complete traces and made available for connecting to additional incomplete traces. A maximum connection distance of 0.5 ft was established to prevent excessive interpolation and an unrealistic hydraulic representation of the flow field. If the closest connection point for an incomplete trace was greater than 0.5 ft, connecting that particular incomplete trace was re-attempted after all the incomplete traces were cycled through. After the first iteration, the allowable connection distance was adjusted to 1 ft and the process was repeated until the minimum connection distance was greater than 1 ft or there were no more incomplete traces. The distance of each particle trace was determined along with the maximum distance between nodes along each trace to validate the modified particle traces. Approximately 6,500 to 20,000 particle traces were used to describe the flow field at each structure depending on the flow volume being analyzed.

3.2.6 Particle Trace Evaluation

Each particle trace was evaluated as a potential fish movement path (flow path). Velocity, depth, vorticity, and TKE were defined in 3-D at every point along a flow path and used to define hydraulic variables that relate to fish swimming abilities. The maximum velocity relative to fish swimming ability, a cumulative cost in terms of energy and the drag force on a fish, the minimum depth, and the sum and maximum vorticity and TKE were quantified along the entire length of each flow path providing a distribution of hydraulic variables for each modeled discharge. The magnitude and distribution of these hydraulic variables were compared among WWP structures.

3.2.6.1 Velocity

The magnitude of a velocity vector was calculated as the root-mean-square (*rms*) of velocity in the *x*, *y*, and *z* planes with a directional component relative to the *x*-direction (Eq. 3.1):

$$v_{rms} = \sqrt{v_x^2 + v_y^2 + v_z^2} \times \left(\frac{|v_x|}{v_x} \right) \qquad \textbf{(Eq. 3.1)}$$

By definition, the *rms* of velocity is always positive and does not take into account the direction of flow. This is important because a velocity vector with a resultant in the positive upstream direction might be advantageous to a fish migrating upstream. Therefore, positive and negative signs were assigned to the v_{rms} based on the velocity in the downstream (v_x) and upstream directions, respectively (Figure 3.6). A positive value indicates a resultant in the downstream direction, while a negative value indicates a resultant in the upstream direction. Velocity vectors that were limited to the *y* (v_y) and *z* (v_z) planes were assigned a positive value.

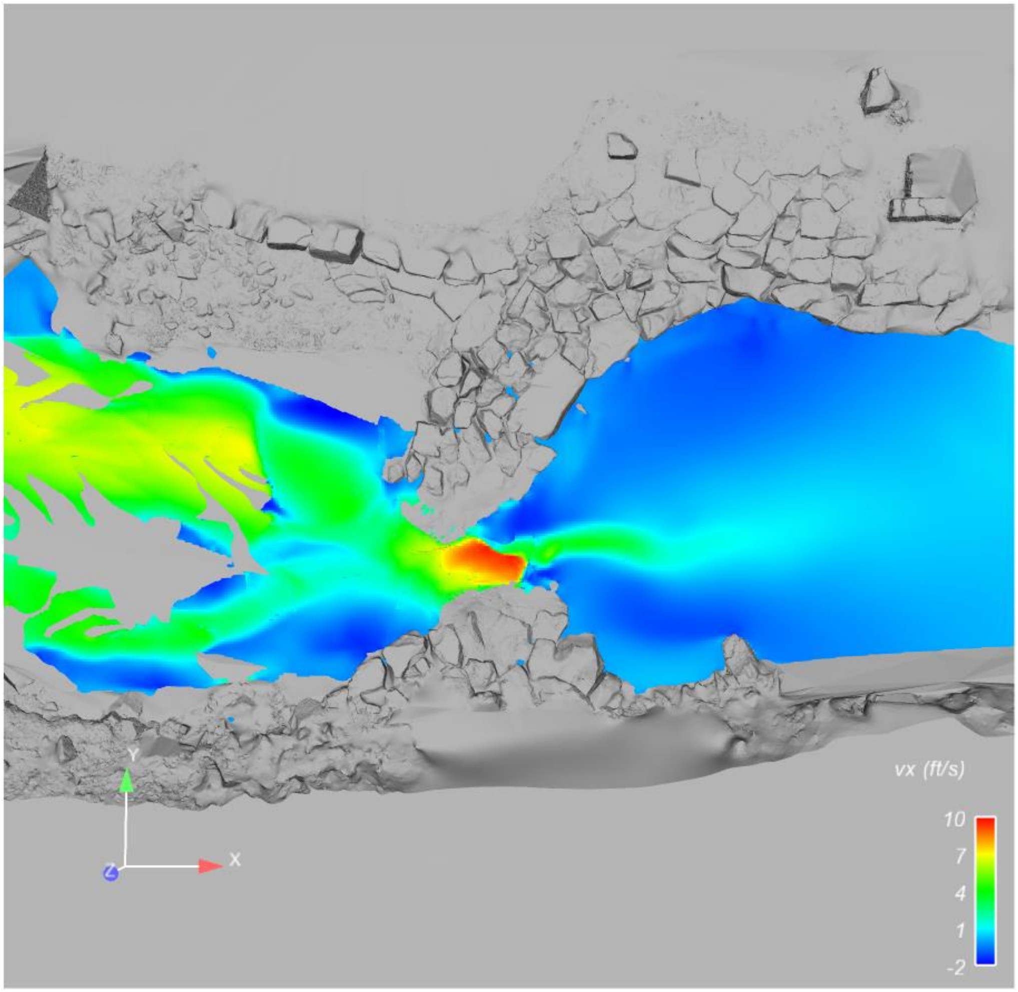


Figure 3.6. Plan view of a WWP structure colored by velocity along the *x*-axis indicating flow moving upstream or downstream (Stephens, 2014).

Velocity was used to define a variable that assesses the hydraulic environment relative to burst swimming ability. The velocity ratio is defined as the ratio of the local water velocity (v_{rms}) to the burst swimming ability (v_{burst}) of a particular fish (Eq. 3.2):

$$\text{velocity ratio} = \frac{v_{rms}}{v_{burst}} \qquad \textbf{(Eq. 3.2)}$$

This variable is evaluated at every point along a flow path. If the ratio is ≥ 1, theoretically the fish cannot traverse that point. The maximum velocity ratio was determined along each flow path and the fraction of traces with a maximum velocity ratio ≥ 1 was determined. If this fraction equals 1, every trace contains a point greater than a fish's burst swimming ability. If this fraction is 0, theoretically, none of the flow paths are greater than a fish's burst swimming ability. The maximum velocity ratio was determined for 100- to 400-mm fish with burst swimming abilities of 10 and 25 BL/s (Peake *et al*., 1997; Castro-Santos *et al*., 2013).

Velocity was also used to define a cost variable (Eq. 3.3) in order to compare relative measures of cumulative energy expenditure through the length of a structure:

$$\text{Cost} = \int v_{rms}^2 \cdot d \cdot \left(\frac{v_{rms}}{|v_{rms}|} \right) \qquad \textbf{(Eq. 3.3)}$$

where v_{rms} is the average *rms* velocity between two nodes; and d is the distance between two nodes. The square of velocity is proportional to energy and the drag force on a fish (Chow, 1959; McElroy *et al*., 2012). The distance term accounts for the length over which a fish might experience those velocities. By squaring the v_{rms}, it is always positive; thus, the fraction term containing the v_{rms} adds a directional component to the cost based on the upstream/downstream directions. If the flow is traveling downstream, the cost between nodes will be positive as a fish will have to expend more energy to swim against the flow and vice versa. Cost is calculated over the distance in between nodes and summed along the length of the flow path. Therefore, the length of the hydraulic jump at a structure has a direct effect on cost.

3.2.6.2 Depth

A minimum of 0.6 ft was used to evaluate depth as a barrier to upstream passage for this study. Without direct knowledge of fish body depths, 0.6 ft provides an average minimum depth criterion across the range of suggested values and fish size (Hotchkiss and Frei, 2007). Any location along a flow path where the fluid was less than 0.6 ft was defined as a passage barrier. The minimum fluid depth along each flow path was evaluated, and the fraction of flow paths that did not maintain at least 0.6 ft along the entire length of the path was determined. The maximum velocity ratio and depth were also assessed in combination. If the minimum depth along a flow path was less than 0.6 ft or the maximum velocity along the path was greater than a fish's swimming ability, the flow path was considered a passage barrier. Each flow path was evaluated, and the fraction of flow paths that exceeded a fish's burst swimming ability or did not provide adequate depth was determined.

3.2.6.3 Turbulence

Vorticity and TKE were selected as measures of turbulence meaningful to a fish. Vorticity is a vector representing the rotation rate of a small fluid element about its axis (Crowder and Diplas, 2002; Kolden, 2013). EnSight was used to calculate 3-D vorticity at each element within the gridded mesh (Eq. 3.4):

$$\bar{\xi} = \left(\frac{\partial w}{\partial y} - \frac{\partial v}{\partial z} \right)\hat{i} + \left(\frac{\partial u}{\partial z} - \frac{\partial w}{\partial x} \right)\hat{j} + \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right)\hat{k} \qquad \textbf{(Eq. 3.4)}$$

where u, v, and w are the x-, y-, and z-components of velocity, respectively, and i, j, and k are unit vectors in the x, y, and z directions, respectively. TKE is a measure of the increase in kinetic energy due to turbulent velocity fluctuations in the flow (Eq. 3.5) (Lacey *et al.*, 2012; FLOW Science, 2009):

$$\text{TKE} = \frac{1}{2}\left(\sigma_u^2 + \sigma_v^2 + \sigma_w^2\right) \qquad \textbf{(Eq. 3.5)}$$

where σ_u, σ_v, and σ_w are the standard deviations of velocity in the x, y, and z directions, respectively.

The magnitudes of vorticity and TKE at each point along a flow path were summed over the length of the path quantifying the cumulative effect of vorticity and TKE a fish might experience. Additionally, the maximum vorticity and TKE along the length of a path was determined to examine the largest magnitudes of vorticity and TKE a fish might experience. Specific thresholds of turbulence relative to fish swimming abilities are unknown; therefore, we are limited to a relative comparison of turbulence among WWP structures and passage success. Examining the cumulative effect and maximum magnitudes of vorticity and TKE along each flow path highlights potential barriers due to turbulence cumulatively through the flow volume and in locations characterized by the highest levels of turbulence.

3.2.7 Data Analysis

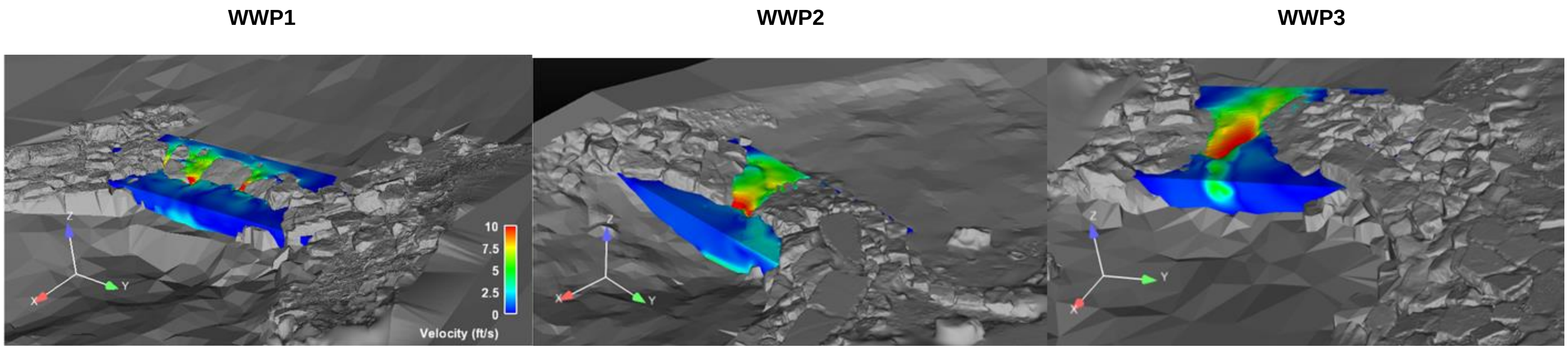
Individual fish were designated as making a successful movement or an unsuccessful movement for each time window. The hydraulic variables associated with a successful movement were determined based on the discharge at which the movement occurred. However, the hydraulic variables associated with an unsuccessful movement were determined based on the most frequent discharge that occurred during the respective time window. Logistic regression was used to test for a significant influence of the hydraulic variables on passage success. Significance was evaluated using the chi-square statistic. Stepwise forward regression with a minimum AIC stopping rule was used to determine the hydraulic variables to include in logistic regression. Collinearity was assessed by examining the bivariate fits among the hydraulic variables. To avoid issues of collinearity, combinations of variables were manually selected to be tested for significance by stepwise forward regression. All statistical procedures were completed using JMP® Pro 11 (SAS Institute Inc., 2013).

3.3 RESULTS

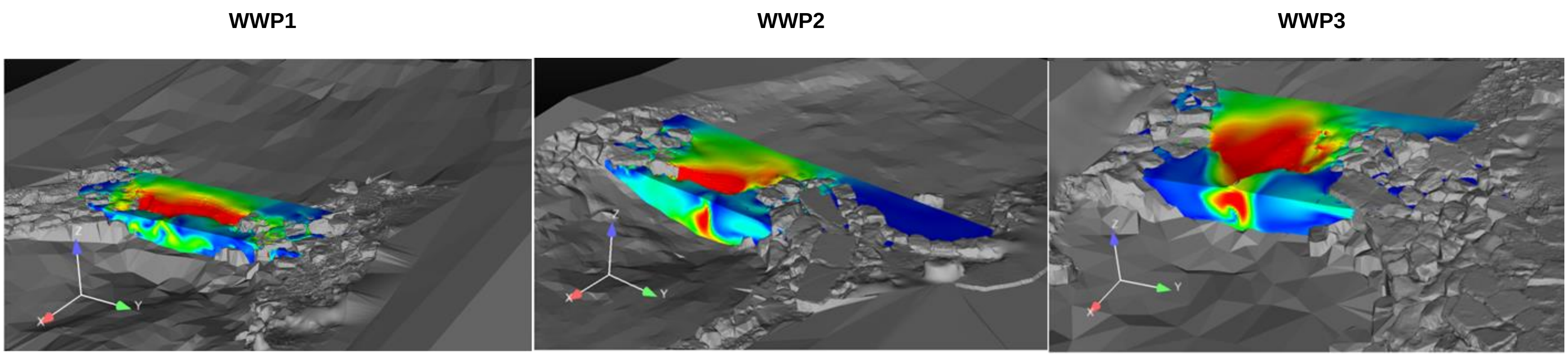
Quantifying the hydraulic conditions along potential fish swimming paths highlights the magnitude and distribution of potential barriers to upstream migrating trout at each WWP structure. The magnitude and distribution of the hydraulic variables vary among WWP structures, relative to each size class of fish, and across discharges, similar to passage success. Further, logistic regression shows a statistically significant influence of specific hydraulic variables on passage success.

3.3.1 Hydraulic Variables

WWP1 is the most downstream structure characterized by a short-steep drop constructed by large boulders. WWP2 is the middle structure producing a wave over a longer distance with the maximum constriction at the exit of the chute into the downstream pool. WWP3 is the most upstream structure producing a wave similar to WWP2 but over a longer chute. The total length of the flow volume from the upstream to downstream boundary was 11 ft at WWP1, 16.5 ft at WWP2, and 19.6 ft at WWP3 (Figure 3.7).



(a) 15 cfs



(b) 150 cfs

Figure 3.7. Analysis flow volume at WWP1, WWP2, and WWP3 for (a) 15 cfs, and (b) 150 cfs (Stephens, 2014).

3.3.1.1 Maximum Velocity Ratio

The fraction of flow paths that exceed a fish's burst swimming ability varies among WWP structures, different size classes of fish, and across discharges (Tables 3.1 and 3.2). For example, assuming a burst velocity of 25 BL/s at WWP1 indicates that there are more flow paths available (flow paths that are not barriers to migration) at 15 cfs compared to 300 cfs for a 125-mm fish. In contrast, there are more flow paths available at 300 cfs compared to 15 cfs for a 150-mm fish. This relationship varies among structures, where there are more flow paths available at 15 cfs compared to 300 cfs for a 150-mm fish at WWP2 and WWP3 (Table 3.1). This variability is also present for burst swimming abilities of 10 BL/s (Table 3.2).

The results for 25 BL/s indicate that a majority of the flow paths are available at all discharges for 175-mm fish and larger (Table 3.1). Though few flow paths are available, WWP1 provides the most available flow paths for the smallest size class of fish compared to WWP2 and WWP3, with a majority of the traces becoming available for fish 150 mm and larger. At WWP2, greater than 20% of the flow paths at 30 cfs exceed the swimming ability of fish up to 300 mm in length. A large number of flow paths become available for fish exceeding 175 mm in length across all discharges at WWP2, with the exception of 30 cfs. In general, there are more available flow paths across discharges and size classes of fish at WWP3, with a majority of the flow paths becoming available for fish exceeding 150 mm in length. WWP2 appears to present the fewest available flow paths. There is a general trend at all WWP structures for fish less than 175 mm in length that neither the lowest nor highest discharge presents the greatest challenge; rather, an intermediate discharge appears to be most limiting.

Table 3.1. Fraction of traces that exceed burst swimming abilities (25 BL/s) for each size class, discharge, and WWP structure.

		Fish Body Length												
	Discharge (cfs)	100 mm	125 mm	150 mm	175 mm	200 mm	225 mm	250 mm	275 mm	300 mm	325 mm	350 mm	375 mm	400 mm
WWP1	15	0.89	0.2	0.12	0.07	0.02	0.02	0	0	0	0	0	0	0
	30	1	0.44	0.12	0.08	0.01	0	0	0	0	0	0	0	0
	60	1	0.28	0.13	0.06	0.05	0	0	0	0	0	0	0	0
	100	1	0.95	0.21	0.07	0	0	0	0	0	0	0	0	0
	150	0.99	0.9	0.1	0.03	0.03	0	0	0	0	0	0	0	0
	170	0.98	0.86	0.35	0.09	0	0	0	0	0	0	0	0	0
	300	0.96	0.54	0.05	0.01	0	0	0	0	0	0	0	0	0
WWP2	15	1	0.85	0.11	0	0	0	0	0	0	0	0	0	0
	30	1	1	0.39	0.25	0.23	0.23	0.23	0.23	0.23	0.03	0.03	0.03	0
	60	1	1	1	0.19	0.01	0	0	0	0	0	0	0	0
	100	1	0.97	0.62	0.28	0.17	0	0	0	0	0	0	0	0
	150	1	0.76	0.62	0.15	0	0	0	0	0	0	0	0	0
	170	1	0.99	0.45	0.2	0.07	0	0	0	0	0	0	0	0
	300	1	0.98	0.23	0.03	0	0	0	0	0	0	0	0	0
WWP3	15	1	0.07	0	0	0	0	0	0	0	0	0	0	0
	30	1	0.07	0	0	0	0	0	0	0	0	0	0	0
	60	1	0.27	0	0	0	0	0	0	0	0	0	0	0
	100	1	0.83	0.36	0.01	0	0	0	0	0	0	0	0	0
	150	1	0.9	0.5	0	0	0	0	0	0	0	0	0	0
	170	0.57	0.55	0.27	0.07	0	0	0	0	0	0	0	0	0
	300	1	0.76	0.34	0.01	0	0	0	0	0	0	0	0	0

Table 3.2. Fraction of traces that exceed burst swimming abilities (10 BL/s) for each size class, discharge, and WWP structure.

	Discharge (cfs)	Fish Body Length 100 mm	125 mm	150 mm	175 mm	200 mm	225 mm	250 mm	275 mm	300 mm	325 mm	350 mm	375 mm	400 mm
WWP1	15	1	1	1	1	1	0.93	0.89	0.75	0.53	0.16	0.12	0.12	0.11
	30	1	1	1	1	1	1	1	0.75	0.58	0.39	0.2	0.12	0.09
	60	1	1	1	1	1	1	1	0.99	0.96	0.26	0.17	0.13	0.12
	100	1	1	1	1	1	1	1	1	0.96	0.93	0.62	0.21	0.12
	150	1	1	1	1	1	1	0.99	0.94	0.92	0.86	0.48	0.1	0.07
	170	1	1	1	1	1	1	0.98	0.92	0.88	0.81	0.7	0.35	0.23
	300	1	1	1	1	1	0.99	0.96	0.84	0.62	0.44	0.18	0.05	0.01
WWP2	15	1	1	1	1	1	1	1	1	0.88	0.25	0.15	0.11	0.06
	30	1	1	1	1	1	1	1	1	1	1	0.45	0.39	0.28
	60	1	1	1	1	1	1	1	1	1	1	1	1	0.88
	100	1	1	1	1	1	1	1	0.99	0.98	0.71	0.69	0.62	0.47
	150	1	1	1	1	1	1	1	1	0.76	0.72	0.67	0.62	0.36
	170	1	1	1	1	1	1	1	1	1	0.6	0.58	0.45	0.32
	300	1	1	1	1	1	1	1	1	0.99	0.95	0.35	0.23	0.08
WWP3	15	1	1	1	1	1	1	1	0.51	0.14	0.01	0	0	0
	30	1	1	1	1	1	1	1	0.96	0.61	0	0	0	0
	60	1	1	1	1	1	1	1	0.68	0.65	0.04	0.01	0	0
	100	1	1	1	1	1	1	1	0.87	0.84	0.76	0.57	0.36	0.26
	150	1	1	1	1	1	1	1	0.98	0.96	0.74	0.64	0.5	0.1
	170	1	1	1	1	1	0.82	0.57	0.57	0.56	0.5	0.35	0.27	0.17
	300	1	1	1	1	1	1	1	1	0.81	0.74	0.67	0.34	0.24

When examining burst swimming abilities of 10 BL/s, greater than 90% of the flow paths exceed a fish's burst swimming ability at all structures for fish 200 mm and smaller (Table 3.2). WWP1 and WWP2 vary in the fraction of available flow paths depending on the discharge and size class of fish; however, there is a general tendency that fewer flow paths are available at WWP2 compared to WWP1. At WWP2, there are no available flow paths for fish $\leq$ 325 mm at 30 cfs and $\leq$ 375 mm at 60 cfs. Larger fish consistently have the most available flow paths at WWP3. A threshold appears at WWP3 with a large fraction of flow paths becoming available at 15 to 60 cfs. Again, there is a general tendency that neither the lowest nor the highest discharge presents the greatest challenge.

3.3.1.2 Depth

The fraction of flow paths that do not provide adequate depth for fish passage varies among WWP structure and discharge; however, low flows appear to be the most limiting (Figure 3.8). At 15 cfs, WWP2 and WWP3 do not have any flow depths greater than 0.6 ft, while greater than 90% of the flow paths contain depths less than 0.6 ft at WWP1. WWP1 poses the greatest depth challenge at intermediate flows with greater than 60% of the flow paths inaccessible due to depth. At high flows, the fraction of available flow paths increase at WWP1 and WWP3 reducing the likelihood of depth as a passage barrier. At WWP2, the fraction of flow paths acting as a depth barrier increases from 40% at 150 cfs to 65% at 300 cfs.

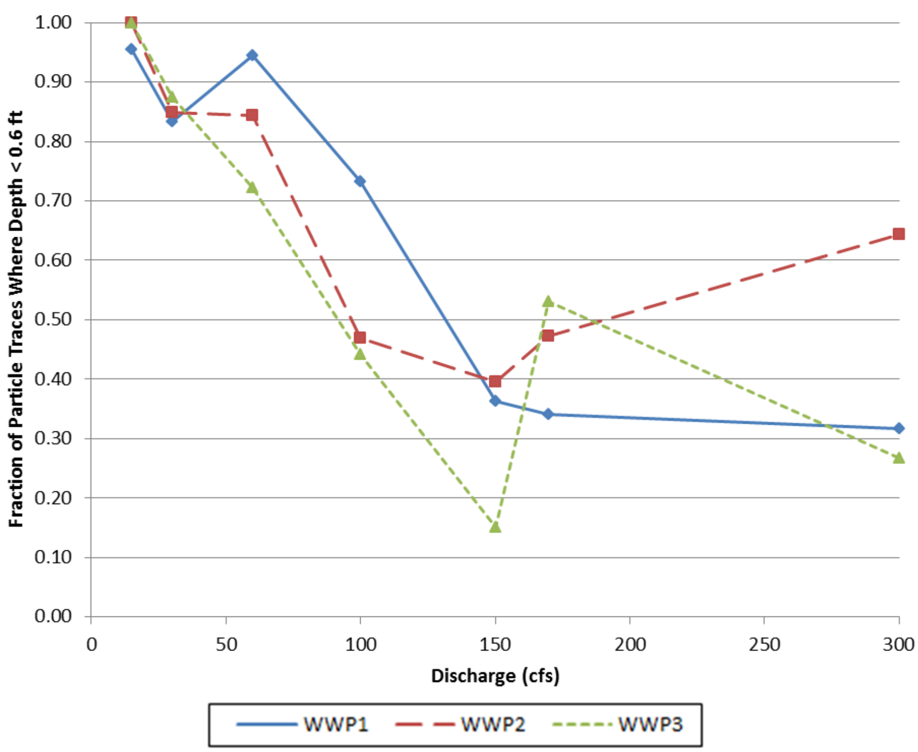


Figure 3.8. The fraction of flow paths where the minimum depth is less than 0.6 ft for each discharge and WWP structure (Stephens, 2014).

3.3.1.3 Maximum Velocity Ratio and Depth Combined

The fraction of flow paths that either exceed a fish's burst swimming ability or do not provide adequate flow depth varies among WWP structure, size class of fish, and across discharges. Simultaneously examining the maximum velocity ratio for 25 BL/s and depth shows that greater than 80% of the flow paths are inaccessible to fish of all size classes at flows less than 30 cfs (Table 3.3). In general, WWP1 provides the most available flow paths for fish 150 mm in length and less. WWP1 has the largest fraction of available flow paths at 15 and 30 cfs while WWP3 has the least available flow paths. Flows greater than 150 cfs provide the most available flow paths at all structures.

Table 3.3. Fraction of traces that exceed burst swimming abilities based on the minimum depth criterion and maximum velocity ratio (25 BL/s) for each size class, discharge, and WWP structure.

	Discharge (cfs)	Fish Body Length												
		100 mm	125 mm	150 mm	175 mm	200 mm	225 mm	250 mm	275 mm	300 mm	325 mm	350 mm	375 mm	400 mm
WWP1	15	1	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
	30	1	0.98	0.88	0.87	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
	60	1	1	0.95	0.95	0.95	0.95	0.95	0.95	0.94	0.94	0.94	0.94	0.94
	100	1	0.99	0.78	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73
	150	1	0.99	0.39	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36
	170	1	0.96	0.55	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34
	300	1	0.73	0.36	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32
WWP2	15	1	1	1	1	1	1	1	1	1	1	1	1	1
	30	1	1	0.91	0.86	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
	60	1	1	1	0.89	0.85	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84
	100	1	1	1	0.72	0.64	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
	150	1	1	0.96	0.54	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
	170	1	1	0.9	0.66	0.55	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
	300	1	1	0.81	0.67	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64
WWP3	15	1	1	1	1	1	1	1	1	1	1	1	1	1
	30	1	0.88	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87
	60	1	0.92	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72
	100	1	1	0.78	0.45	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44
	150	1	1	0.65	0.16	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
	170	1	1	0.79	0.6	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53
	300	1	1	0.61	0.28	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27

Combining the minimum flow depth and the maximum velocity ratio for 10 BL/s as barriers to migration indicates that greater than 90% of the flow paths are unavailable for fish less than 300 mm in length (Table 3.4). In general, WWP2 provides the fewest number of available flow paths. Excluding 15 cfs, there is an evident threshold at WWP3 that all flow paths are inaccessible for fish 300 mm in length and smaller. At WWP1 and WWP2, a clear threshold for the size class of fish at which flow paths become accessible is less apparent as discharge varies.

Table 3.4. Fraction of traces that exceed burst swimming abilities based on the minimum depth criterion and maximum velocity ratio (10 BL/s) for each size class, discharge, and WWP structure.

		Fish Body Length												
	Discharge (cfs)	100 mm	125 mm	150 mm	175 mm	200 mm	225 mm	250 mm	275 mm	300 mm	325 mm	350 mm	375 mm	400 mm
WWP1	15	1	1	1	1	1	1	1	1	0.96	0.95	0.95	0.95	0.95
	30	1	1	1	1	1	1	1	1	1	0.97	0.88	0.88	0.87
	60	1	1	1	1	1	1	1	1	1	0.99	0.95	0.95	0.95
	100	1	1	1	1	1	1	1	1	0.99	0.98	0.87	0.78	0.74
	150	1	1	1	1	1	1	1	0.99	0.99	0.96	0.67	0.39	0.37
	170	1	1	1	1	1	1	1	1	0.98	0.93	0.86	0.55	0.45
	300	1	1	1	1	1	1	1	0.97	0.8	0.65	0.43	0.36	0.33
WWP2	15	1	1	1	1	1	1	1	1	1	1	1	1	1
	30	1	1	1	1	1	1	1	1	1	1	0.96	0.91	0.89
	60	1	1	1	1	1	1	1	1	1	1	1	1	0.96
	100	1	1	1	1	1	1	1	1	1	1	1	1	0.89
	150	1	1	1	1	1	1	1	1	1	1	1	0.96	0.7
	170	1	1	1	1	1	1	1	1	1	1	0.98	0.9	0.77
	300	1	1	1	1	1	1	1	1	1	0.99	0.92	0.81	0.7
WWP3	15	1	1	1	1	1	1	1	1	1	1	1	1	1
	30	1	1	1	1	1	1	1	1	0.96	0.88	0.87	0.87	0.87
	60	1	1	1	1	1	1	1	1	1	0.75	0.72	0.72	0.72
	100	1	1	1	1	1	1	1	1	1	0.99	0.97	0.78	0.68
	150	1	1	1	1	1	1	1	1	1	0.86	0.76	0.65	0.25
	170	1	1	1	1	1	1	1	1	1	0.97	0.87	0.79	0.7
	300	1	1	1	1	1	1	1	1	1	1	0.94	0.61	0.5

3.3.1.4 Cost

The magnitude and distribution of cost vary among WWP structures and discharges (Figure 3.9). WWP1 consistently has a lower cost at all discharges. WWP2 and WWP3 have similar magnitudes of cost at 15 and 30 cfs. The distribution of cost is much narrower at 15 cfs. WWP3 has the maximum 50th percentile of cost at all discharges except 60 cfs (Figure 3.10). At 100 cfs, the range of costs at WWP3 increases and indicates greater hydraulic heterogeneity within the flow field. The maximum cost at WWP2 occurs at 30 cfs. At 150 and 300 cfs, the maximum cost at WWP1 greatly increases.

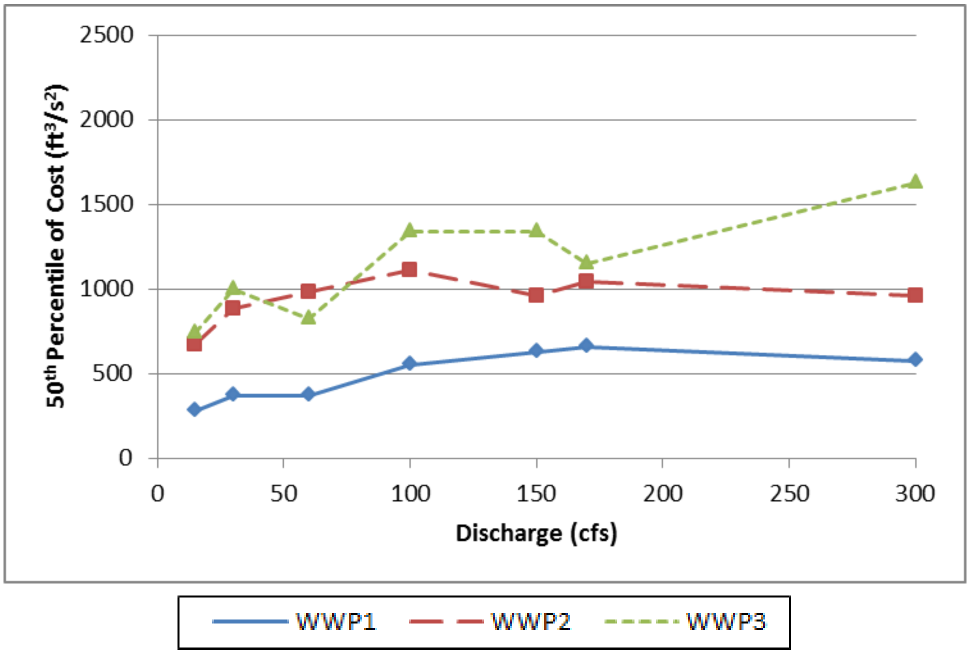


Figure 3.9. 50th percentile of cost for each WWP structure and discharge (Stephens, 2014).

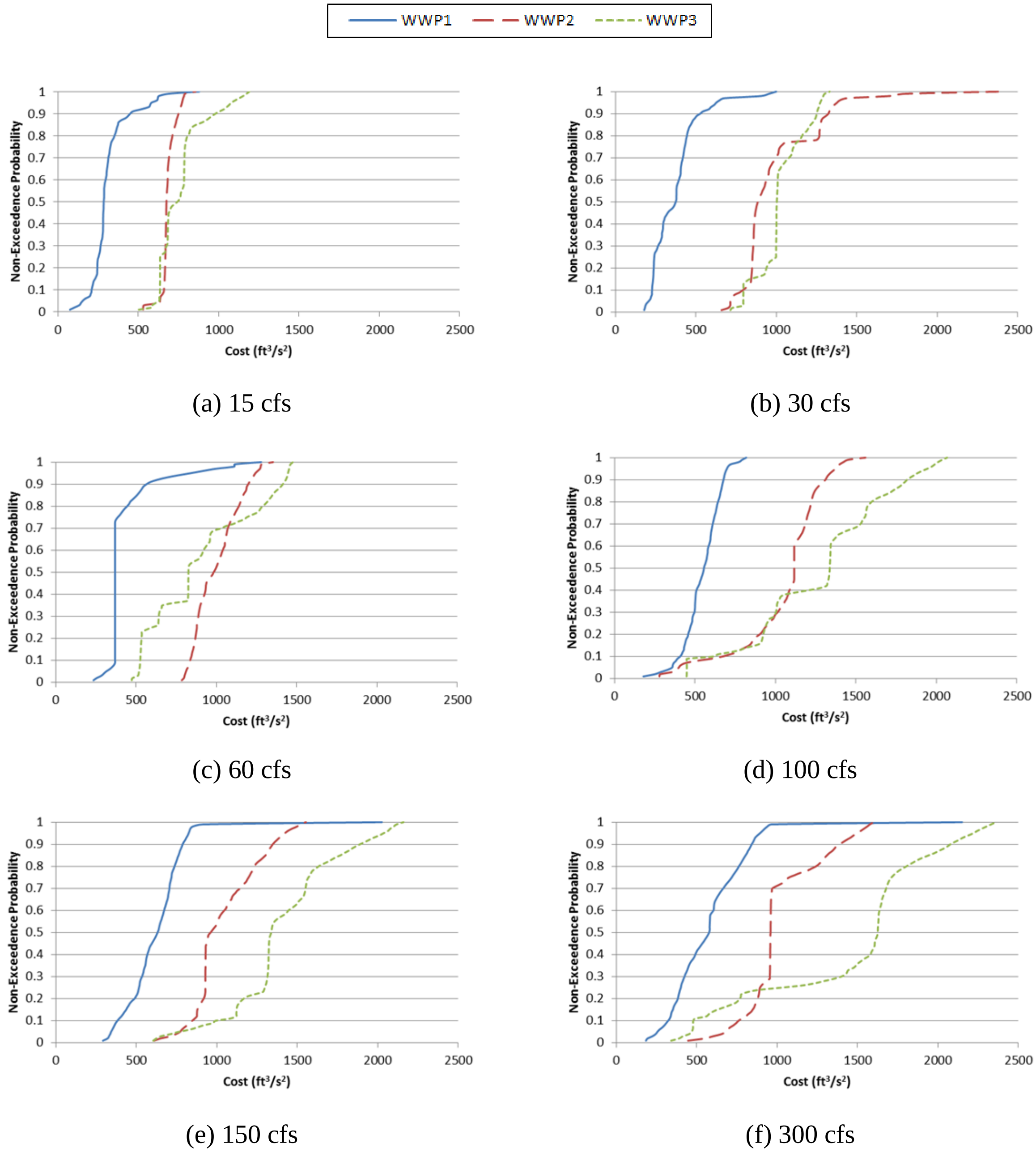
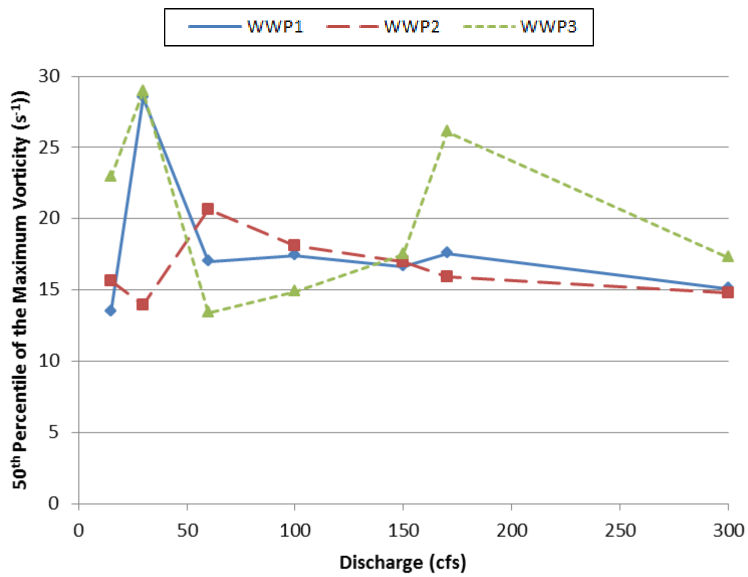


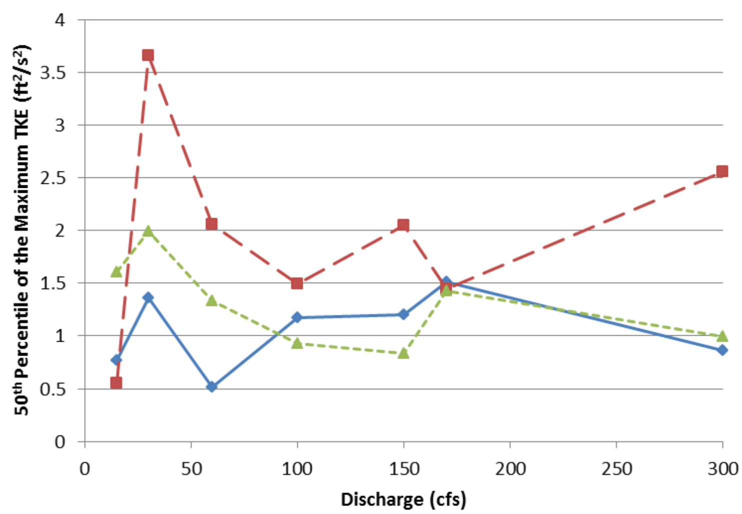
Figure 3.10. Non-exceedence probabilities for the cost along flow paths at each WWP structure for: (a) 15 cfs, (b) 30 cfs, (c) 60 cfs, (d) 100 cfs, (e) 150 cfs, and (f) 300 cfs (Stephens, 2014).

3.3.1.5 Turbulence

The highest magnitudes and broader distributions of the maximum vorticity generally occur at the lowest discharges (15 and 30 cfs). WWP3 has the greatest 50th percentile of maximum vorticity at 15 and 30 cfs (Figure 3.11); however, WWP1 has the highest overall maximum vorticity value at 30 cfs (Figure 3.11). The magnitude and distribution of the maximum vorticity is similar among the WWP structures at discharges ≥ 100 cfs.



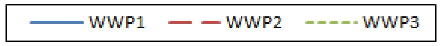
(a) maximum vorticity

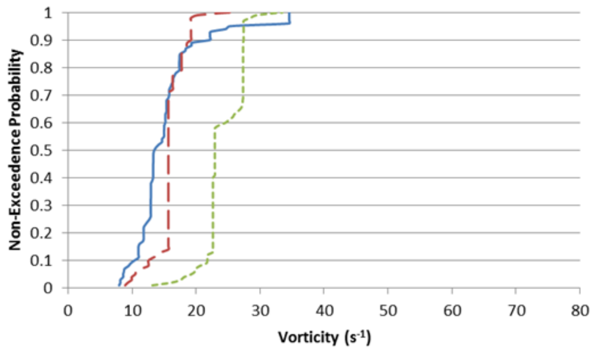


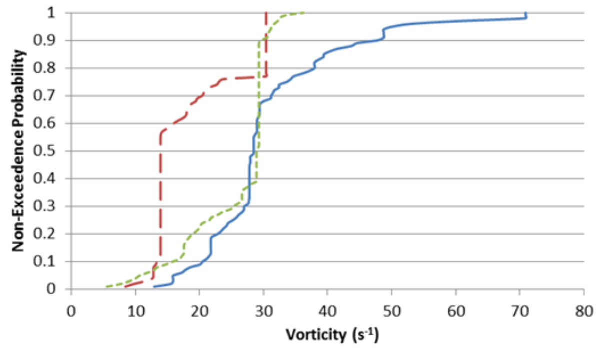
(b) maximum TKE

Figure 3.11. 50th percentile of the (a) maximum vorticity, and (b) maximum TKE along a flow path for each WWP structure and discharge (Stephens, 2014).

The magnitude and distribution of the maximum TKE along a flow path also vary substantially among WWP structures and discharges (Figure 3.12). At a specific discharge, the maximum TKE among the WWP structures depends on the percentile of the distribution. WWP1 has the highest maximum TKE at 30, 100, and 300 cfs. WWP2 has the greatest 50th percentile of TKE at all discharges except 30 cfs (Figure 3.13). WWP3 appears to have a more narrow distribution of TKE at all discharges compared to WWP1 and WWP2. The maximum 50th percentile of TKE occurs at 30 cfs at WWP2 and WWP3, and 170 cfs at WWP1.

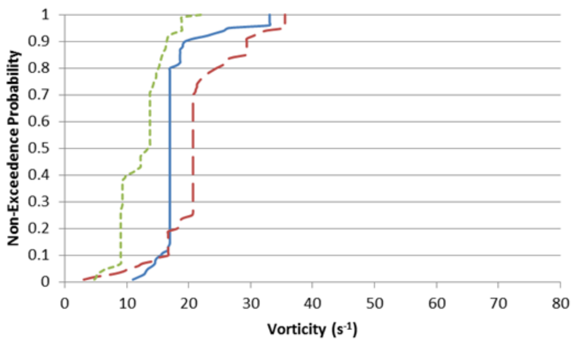


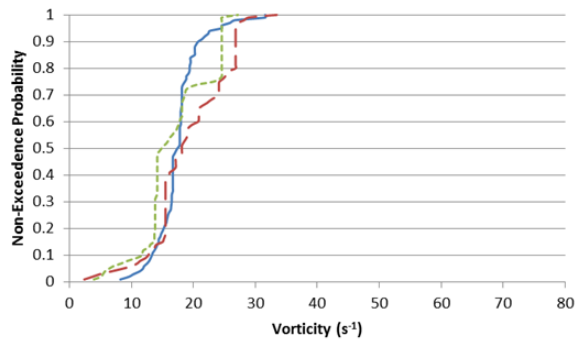




(a) 15 cfs

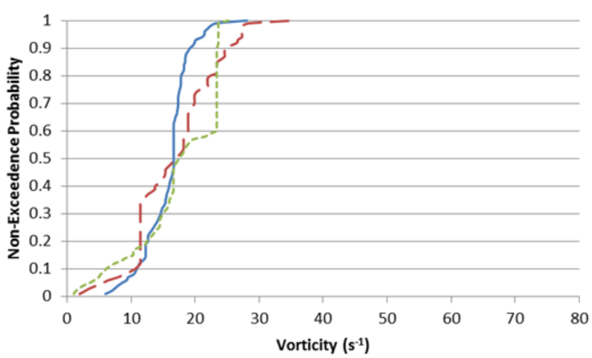
(b) 30 cfs

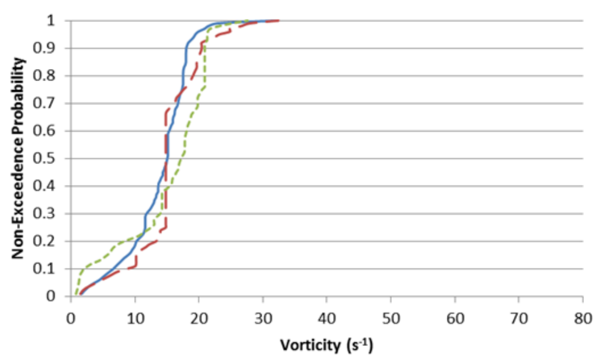




(c) 60 cfs

(d) 100 cfs





(e) 150 cfs

(f) 300 cfs

Figure 3.12. Non-exceedence probabilities for maximum vorticity along flow paths at each WWP structure for: (a) 15 cfs, (b) 30 cfs, (c) 60 cfs, (d) 100 cfs, (e) 150 cfs, and (f) 300 cfs (Stephens, 2014).

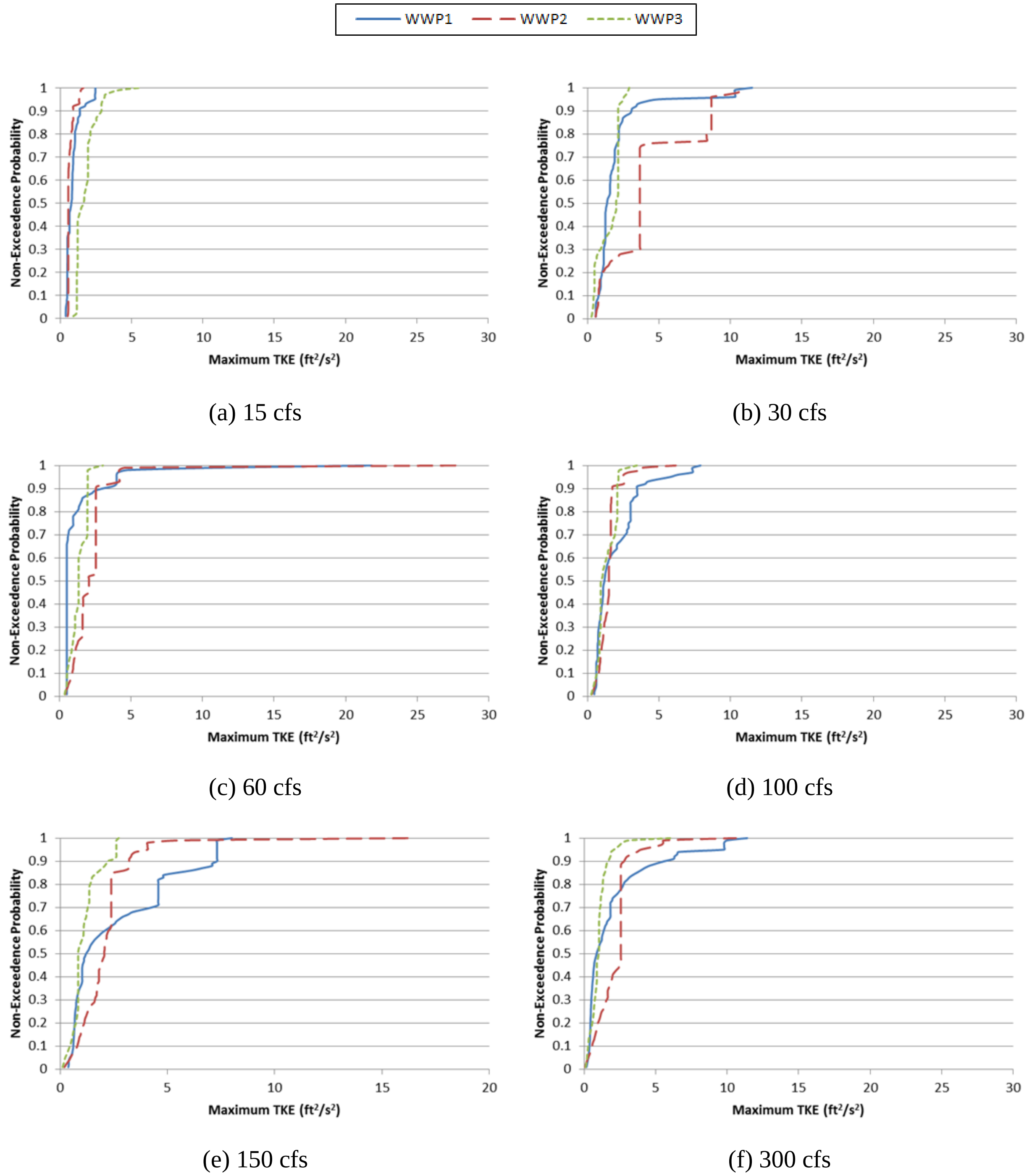
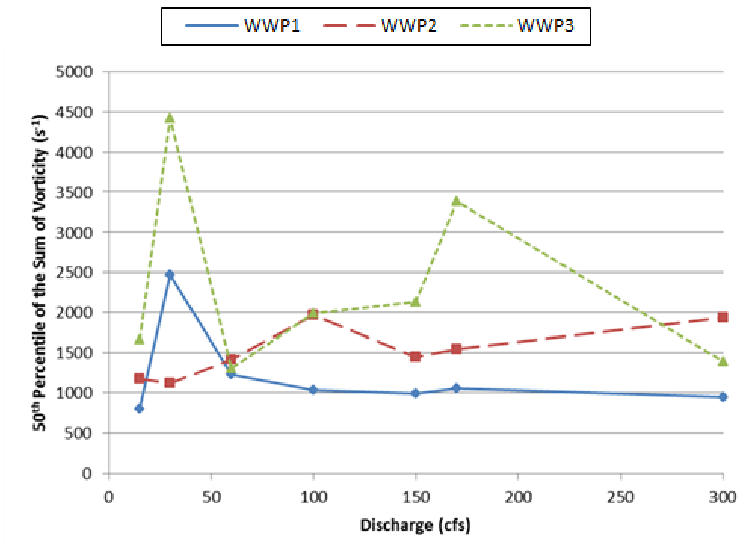
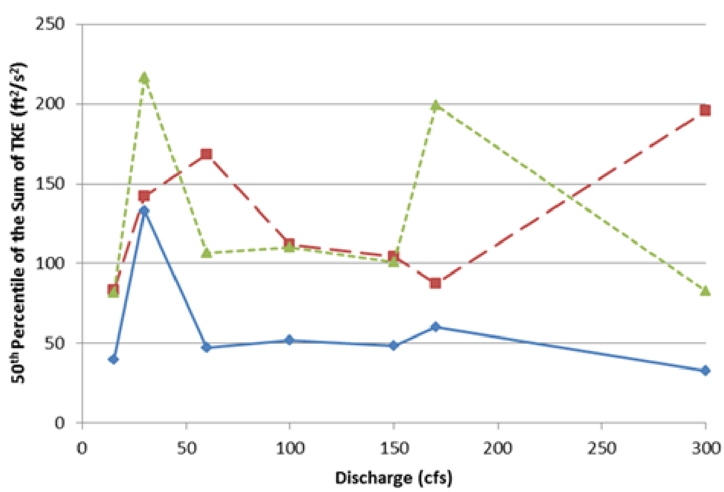


Figure 3.13. Non-exceedence probabilities for the maximum TKE along flow paths at each WWP structure for: (a) 15 cfs, (b) 30 cfs, (c) 60 cfs, (d) 100 cfs, (e) 150 cfs, and (f) 300 cfs (Stephens, 2014).

The magnitude and distribution of the sum of vorticity along a flow path vary among WWP structures and discharges (Figure 3.14). The maximum 50th percentile of the sum of vorticity along a flow path occurs at 30 cfs for WWP1 and WWP3, and 100 cfs for WWP2 (Figure 3.14). WWP3 has the highest 50th percentile of the sum of vorticity with the exception of 60 and 100 cfs. The maximum of the sum of vorticity along a flow path varies between WWP2 and WWP3 depending on the discharge and percentile being analyzed. There is a general trend that WWP1 contains the lowest sum of vorticity along a flow path. Additionally, narrow distributions for each WWP exist at 15, 150, and 300 cfs.



(a) sum of vorticity



(b) TKE

Figure 3.14. 50th percentile of the (a) sum of vorticity, and (b) TKE along a flow path for each WWP structure and discharge (Stephens, 2014).

The magnitude and distribution of the sum of TKE along a flow path varies among WWP structures and discharges (Figure 3.15). The maximum 50th percentile of the sum of TKE occurs at 30 cfs for WWP1 and WWP3, and 300 cfs for WWP2 (Figure 3.16). Similar trends in the relative magnitude of the 50th percentile of the sum of vorticity and TKE exist at each individual WWP structure. The 50th percentile of the sum of TKE is lowest at WWP1 for all discharges. However, WWP1 has the overall maximum of the sum of TKE along a flow path at 150 and 300 cfs, while WWP2 had the overall maximum at 30 to 100 cfs. WWP3 has the overall maximum of the sum of TKE along a flow path at 15 cfs. Each structure is characterized by a narrower distribution of the sum of TKE at 15 cfs.

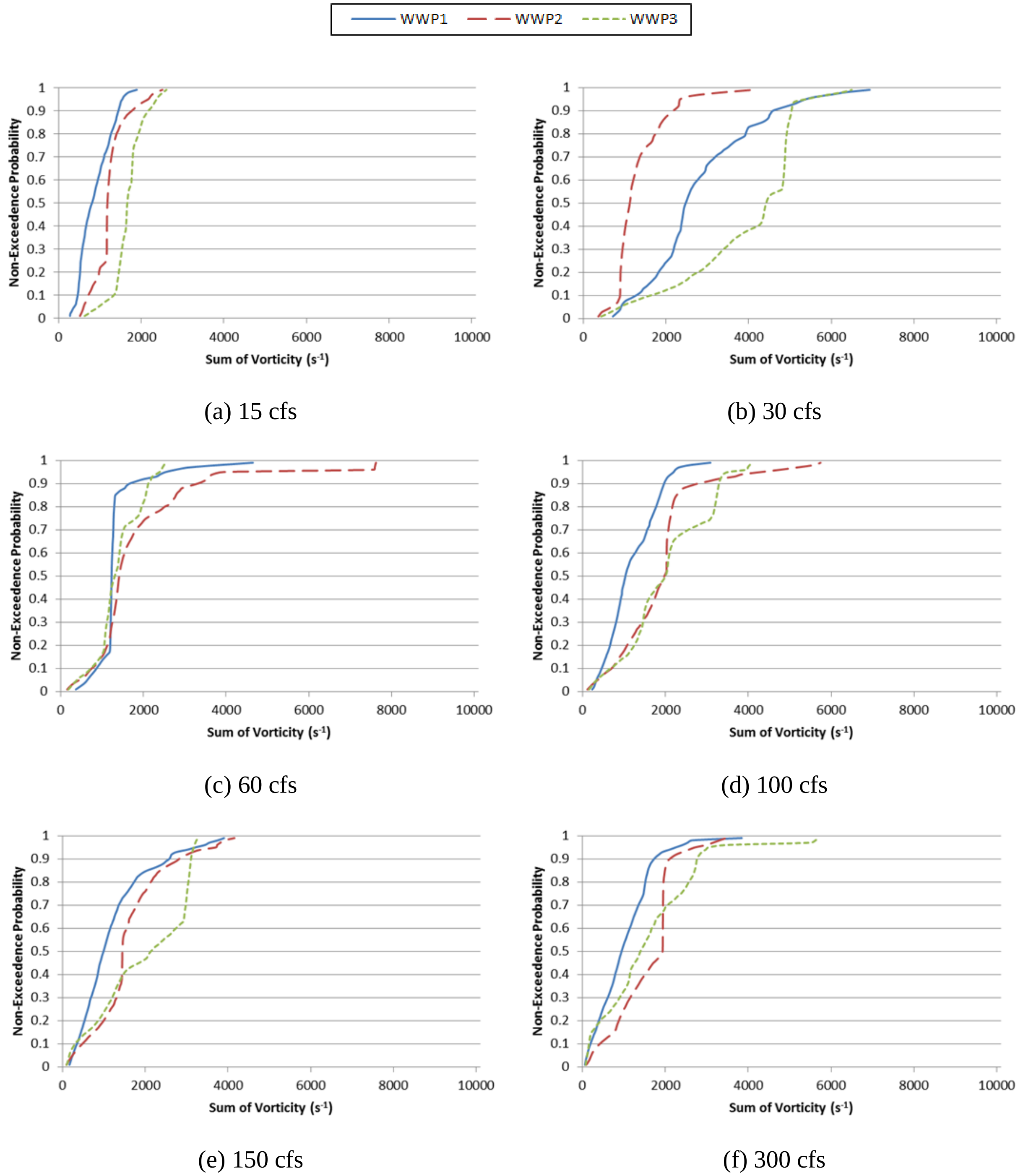
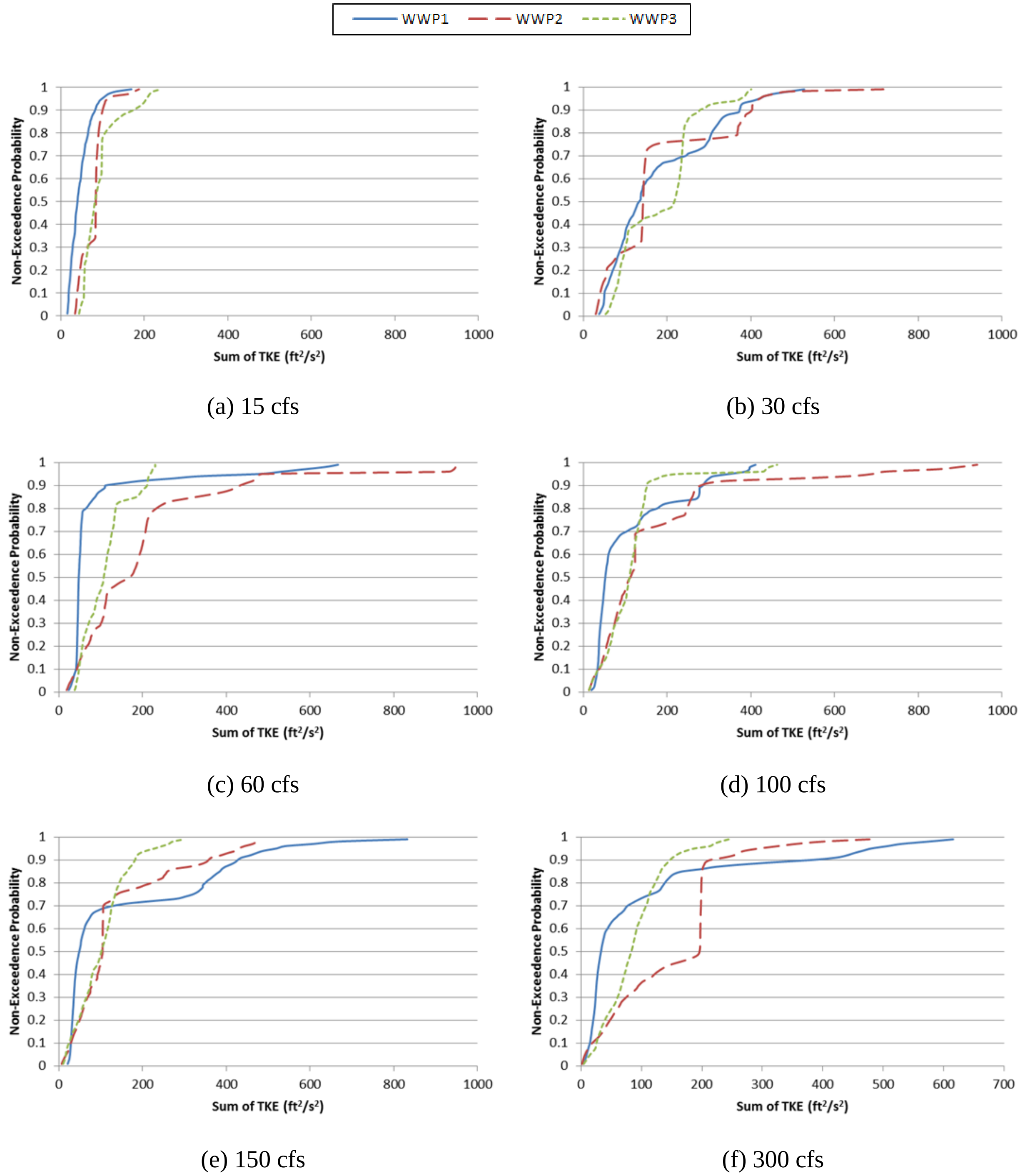


Figure 3.15. Non-exceedence probabilities for sum of vorticity along flow paths at each WWP structure for: (a) 15 cfs, (b) 30 cfs, (c) 60 cfs, (d) 100 cfs, (e) 150 cfs, and (f) 300 cfs (Stephens, 2014).



(a) 15 cfs (b) 30 cfs

(c) 60 cfs (d) 100 cfs

(e) 150 cfs (f) 300 cfs

Figure 3.16. Non-exceedence probabilities for the sum of TKE along flow paths at each WWP structure for: (a) 15 cfs, (b) 30 cfs, (c) 60 cfs, (d) 100 cfs, (e) 150 cfs, and (f) 300 cfs (Stephens, 2014).

3.3.2 Fish Passage

Fish passage success varies among WWP structures and size classes of fish (Figure 3.17). Passage success is greatest at WWP1 for fish 200 mm in length and smaller; however, passage success decreases as fish size increases at WWP1. WWP2 has the highest success rate for larger fish. Additionally, there appears to be a positive linear relationship with passage success and fish size. At WWP3, passage success increases from 28% to 80% when fish length exceeds 300 mm. Different fractions of successful movements at each WWP structure occurred over different discharges (Figure 3.18). At 15 cfs, the largest fraction of successful movements occurred at WWP2. There is a mode of successful movements for all WWP structures at 30 cfs. Indeed, more than 80% of fish passage at WWP1 occurred at 30 cfs. At 60 cfs, a larger fraction of successful movements occurred at WWP3 compared to WWP1 and WWP2. As discharge increases from 100 to 300 cfs, the fraction of successful movements at each WWP greatly decreases.

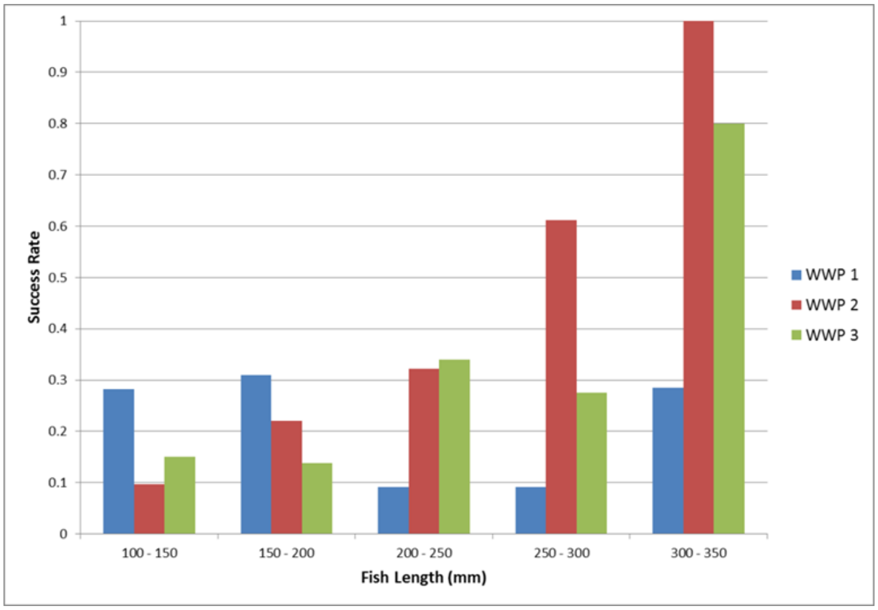


Figure 3.17. The fraction of observed fish by size class at each WWP structure that successfully passed that structure (Stephens, 2014).

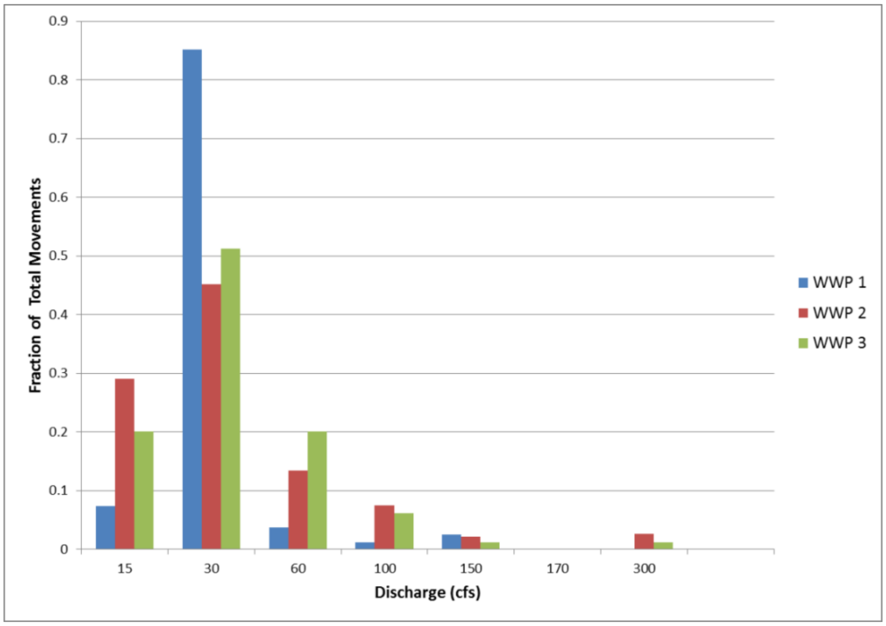


Figure 3.18. The fraction of successful movements occurring over the range of modeled discharges at each WWP structure (Stephens, 2014).

3.3.3 Logistic Regression Analysis

Logistic regression analysis of hydraulic variables, i.e., percentile of cost tested individually with the maximum velocity ratio for 25 and 10 BL/s, the minimum depth criterion, the 50^{th} percentile of the maximum vorticity, and the 50^{th} percentile of the maximum TKE consistently indicated that maximum velocity ratio for 25 and 10 BL/s, and the minimum depth criterion were the best predictors of passage success across all WWP structures (Table 3.5). In contrast, the cost variable was a poor predictor of passage success. Removing the cost variable from the logistic regression model does not have a significant effect on the model fit.

Model parameter estimates indicate that passage success decreases with increases in the fractions of flow paths that exceed burst swimming ability and the minimum depth criterion (Table 3.5). A unit change in the minimum depth criterion results in the greatest response in passage success compared to the maximum velocity ratio (odds ratio = 6.73×10^{-13}). The final model was highly significant ($p < 0.05$) with classification accuracies of 71.7 and 92.5 for successful and unsuccessful movements, respectively (Table 3.6).

Table 3.5. Logistic regression analysis for passage success across all WWP structures.

Predictor	β	SE β	χ^2	df	p	odds ratio (e^{β})
Constant	27.6948	2.2348	153.5700	1	<0.0001	–
Maximum Velocity Ratio (10 BL/s)	-2.4217	0.9061	7.1400	1	0.0075	0.0888
Maximum Velocity Ratio (25 BL/s)	-2.5155	0.5742	19.1900	1	<0.0001	0.0808
Minimum Depth Criterion	-28.0266	2.1821	164.9700	1	<0.0001	6.73E-13
Test			χ^2	**df**	**p**	
Overall model evaluation:						
Likelihood ratio test			271.7842	3	<0.0001	
Goodness-of-fit test			147.8854	3	0.1222	

Table 3.6. The observed and predicted frequencies for passage success across all WWP structures.

	Predicted		
Observed	Pass	Did Not Pass	% Correct
Pass	114	45	71.7%
Did Not Pass	37	458	92.5%
Overall % Correct			87.5%

Logistic regression analysis of each individual structure shows a significant influence of different hydraulic variables at each structure. Depth is statistically significant at WWP1, depth and the maximum velocity ratio for 25 BL/s are significant at WWP2, and depth and the maximum velocity ratio for 10 BL/s are significant at WWP3. The parameter estimates and odds ratio for the hydraulic variables at each individual structure show a decrease in the probability of success as the fraction of flow paths that exceed burst swimming ability increase (Table 3.7). The goodness-of-fit test at WWP1 indicates that more complex variables could be added to the model ($p < 0.05$). Despite the results from the goodness-of-fit test at WWP1, the likelihood ratio test indicates that the models predict passage success with high accuracy ($p < 0.05$) (Table 3.7). Additionally, the model correctly predicted 76.14% of the observations. The logistic regression models accurately predicted 88.5% and 86% of the observations at WWP2 and WWP3, respectively (Table 3.8).

Table 3.7. Logistic regression analysis for passage success at each WWP structure.

	Predictor	β	SE β	χ^2	df	p	odds ratio (e^β)
WWP1	Constant	31.9771	3.8436	69.2100	1	<0.0001	–
	Minimum Depth Criterion	-36.3190	4.2438	73.2400	1	<0.0001	1.69E-16
WWP2	Constant	29.7199	4.6198	41.3900	1	<0.0001	–
	Maximum Velocity Ratio (25 BL/s)	-4.8744	1.6846	8.3700	1	0.0038	7.64E-03
	Minimum Depth Criterion	-31.7426	4.6872	45.8600	1	<0.0001	1.64E-14
WWP3	Constant	26.8093	3.4570	60.1400	1	<0.0001	–
	Maximum Velocity Ratio (10 BL/s)	-3.2481	0.6892	22.2100	1	<0.0001	3.89E-02
	Minimum Depth Criterion	-26.2229	3.3716	60.4900	1	<0.0001	4.09E-12
	Test			χ^2	**df**	**p**	
WWP1	Overall model evaluation:						
	Likelihood ratio test			119.3776	1	<0.0001	
	Goodness-of-fit test			9.9828	1	0.0068	
WWP2	Overall model evaluation:						
	Likelihood ratio test			89.4292	2	<0.0001	
	Goodness-of-fit test			21.2561	2	0.9674	
WWP3	Overall model evaluation:						
	Likelihood ratio test			92.7136	2	<0.0001	
	Goodness-of-fit test			33.8460	2	0.1389	

Table 3.8. The observed and predicted frequencies for passage success at each individual WWP structure.

		Predicted		
	Observed	**Pass**	**Did Not Pass**	**% Correct**
WWP1	Pass	8	10	44.4%
	Did Not Pass	37	142	79.3%
	Overall % Correct			76.1%
WWP2	Pass	35	15	70.0%
	Did Not Pass	7	135	95.1%
	Overall % Correct			88.5%
WWP3	Pass	41	14	74.5%
	Did Not Pass	22	181	89.2%
	Overall % Correct			86.0%

Logistic regression analysis of the combined variable for the maximum velocity ratio and minimum depth criterion indicate a significant influence of the maximum velocity ratio for 25 BL/s and the minimum depth criterion; however, the maximum velocity ratio for 10 BL/s and the minimum depth criterion was not significant. The combined variable has a negative parameter estimate and odds ratio < 1, indicating that passage success decreases as the fraction of flow paths that exceed burst swimming ability (25 BL/s) or do not meet the minimum depth criterion increases (Table 3.9). The likelihood ratio test indicates that the model predicted passage success with high accuracy ($p < 0.05$); however, the goodness-of-fit test indicates that additional variables could be added to improve the model fit. The model accurately predicted 87.5% of the observations (Table 3.10).

Table 3.9. Logistic regression analysis for passage success across all WWP structures for the combined variable (maximum velocity ratio of 25 BL/s and the minimum depth criterion).

Predictor	β	SE β	χ^2	df	p	odds ratio (e^{β})
Constant	24.6694	2.0324	147.34	1	<0.0001	–
Maximum Velocity Ratio (25 BL/s) and the Minimum Depth Criterion	-27.2676	2.1608	159.24	1	<0.0001	1.44E-12
Test			χ^2	**df**	**p**	
Overall model evaluation:						
Likelihood ratio test			228.7675	1	<0.0001	
Goodness-of-fit test			81.9267	1	<0.0001	

Table 3.10. The observed and predicted frequencies for passage success across all WWP structures for the combined variable (maximum velocity ratio of 25 BL/s and the minimum depth criterion).

	Predicted		
Observed	**Pass**	**Did Not Pass**	**% Correct**
Pass	108	51	67.9%
Did Not Pass	31	464	93.7%
Overall % Correct			87.5%

Logistic regression analyses of each individual structure indicated a significant influence of the combined variable for the maximum velocity ratio of 25 BL/s and the minimum depth requirement. According to the odds ratios and parameter estimates, passage success decreases with an increase in the fraction of traces that exceed burst swimming ability (25 BL/s) or do not meet the minimum depth criterion increases (Table 3.11). The likelihood ratio test indicates that each model predicts passage success with high accuracy ($p < 0.05$) (Table 3.11). Additionally, the goodness-of-fit test at WWP2 and WWP3 indicates that the inclusion of additional variables would not improve the model fit ($p > 0.05$); however, the addition of more complex variables at WWP1 might improve the model fit ($p < 0.05$). The model accurately predicted passage success for 90.7%, 87.5%, and 85.7% of the observations at WWP1, WWP2, and WWP3, respectively (Table 3.12).

Table 3.11. Logistic regression analysis for passage success at each WWP structure for the combined variable (maximum velocity ratio of 25 BL/s and the minimum depth criterion).

	Predictor	β	SE β	χ^2	df	p	odds ratio (e^{β})
WWP1	Constant	45.0055	5.5986	64.62	1	<0.0001	–
	Maximum Velocity Ratio (25 BL/s) and the Minimum Depth Criterion	-49.7348	6.0592	67.37	1	<0.0001	2.51E-22
WWP2	Constant	24.8876	3.6464	46.58	1	<0.0001	–
	Maximum Velocity Ratio (25 BL/s) and the Minimum Depth Criterion	-27.0016	3.7769	51.11	1	<0.0001	1.88E-12
WWP3	Constant	20.4209	2.9188	48.95	1	<0.0001	–
	Maximum Velocity Ratio (10 BL/s) and the Minimum Depth Criterion	-22.6106	3.0498	54.96	1	<0.0001	1.51E-10

	Test	χ^2	df	p
WWP1	Overall model evaluation:			
	Likelihood ratio test	104.3809	1	<0.0001
	Goodness-of-fit test	38.4229	1	<0.0001
WWP2	Overall model evaluation:			
	Likelihood ratio test	80.308	1	<0.0001
	Goodness-of-fit test	13.6666	1	0.6235
WWP3	Overall model evaluation:			
	Likelihood ratio test	71.7071	1	<0.0001
	Goodness-of-fit test	0.0999	1	0.9513

Table 3.12. The observed and predicted frequencies for passage success at each individual WWP structure for the combined variable (maximum velocity ratio of 25 BL/s and the minimum depth criterion).

		Predicted		
	Observed	Pass	Did Not Pass	% Correct
WWP1	Pass	43	11	79.6%
	Did Not Pass	8	142	94.7%
	Overall % Correct			90.7%
WWP2	Pass	33	17	66.0%
	Did Not Pass	7	135	95.1%
	Overall % Correct			87.5%
WWP3	Pass	34	21	61.8%
	Did Not Pass	16	187	92.1%
	Overall % Correct			85.7%

3.4 DISCUSSION

The methods used in this study provide a novel and powerful approach to evaluate fish passage at hydraulic structures. Describing the hydraulic conditions along potential fish movement paths continuously quantifies important flow features at a scale meaningful to a fish. The logistic regression analyses indicate that the maximum velocity ratio for burst swimming abilities of 25 and 10 BL/s and the minimum depth criterion accurately predict passage success for over 87% of observed trout. Additionally, the model accurately predicted over 92% of the observations of no movement. The fraction of available flow paths that exceed a fish's burst swimming ability or do not provide adequate depth had a negative influence on passage success. This strongly suggests that both depth and velocity are contributing to the suppression of movement of upstream migrating salmonids. These results contrast with a previous study that did not find velocity to have an evident effect on passage success (Fox, 2013). This contradiction is likely the result of the difference in scale over which velocities were quantified, as the previous study calculated cross-sectional velocity quantiles within the chute of WWP structures not accounting for discontinuities in acceptable velocities along a movement path.

Logistic regression analysis indicates a significant influence of the combined variable for the maximum velocity ratio (25 BL/s) and the minimum depth criterion across all WWP structures and at each individual WWP structure. This underscores the importance of jointly considering depth and velocity as barriers to upstream migration. Additionally, combining velocity and depth into a single variable allows for a simplified, but highly accurate, statistical analysis. Quantifying a single variable provides a means to assess passage success with fewer observed movements. This could have implications for future projects where time and cost are limiting factors.

Although the combined variable accurately captures the effects of velocity and depth, additional analyses of the variation in statistically significant hydraulic variables among WWP structures highlights unique hydraulic characteristics at each WWP structure that affect passage success differently. Depth is the primary limiting factor contributing to the suppression of movement at WWP1, while both velocity and depth have significant influences at WWP2 and WWP3. The evaluation of the maximum velocity ratio, depth, and their joint influence on passage success by size class and discharge emphasizes the importance of site-specific characterization of subtle differences in structure design. However, depth has lowest odds ratio in all logistic regression analyses suggesting it has the strongest effect on passage success.

At lower discharges, continuous passage routes across WWP1 are only accessible through narrow chutes (< 1 ft) flowing in between boulders that may not provide adequate depth or flow area for larger fish, but do provide lower velocities accessible to smaller fish. This is confirmed through logistic regression, the maximum velocity ratio and depth variables, and observed passage success by size class. Depth presents the greatest challenge across discharges at WWP1, and examining the maximum velocity ratio for burst swimming abilities of 10 BL/s and depth concurrently indicates that WWP1 provides the most available flow paths for smaller fish. Depth is the only statistically significant variable influencing passage success at WWP1, and higher success rates are observed for smaller fish compared to larger fish at WWP1.

WWP2 constricts the flow to the center of the chute at lower discharges and forces fish to traverse shallow flow depths characterized by the highest velocities. This is reflected in the lack of available flow paths exceeding 0.6 ft at 15 cfs and the fraction of flow paths that exceed burst swimming ability for 25 BL/s at 30 cfs. At 30 cfs, the fraction of accessible flow paths is limited and similar among size classes for a 175- to 300-mm fish indicating concentrated flow. When observing higher discharges and the fraction of available flow paths for 10 BL/s, there is a positive linear increase in the amount of available flow paths with fish size that is reflective of a linear increase in passage success. Further, logistic regression confirms depth and velocity as significant influences on passage success at WWP2. As discharge increases, flow spills over the wing walls and a small zone adjacent to the left bank provides lower velocities.

At WWP3, recirculation zones exist adjacent to the main velocity jet. At lower flows these low-velocity zones may not provide adequate flow depth, forcing fish to pass through the main velocity jet. These flow patterns are confirmed by examining the aggregate effect of the maximum velocity ratio for 10 BL/s and depth. Depth appears to prevent passage at 15 cfs, while passage is accessible to larger fish as discharge increases to 30 cfs indicating velocity as the limiting factor. Fish movement data show a similar threshold of increased passage success for larger fish at WWP3. However, as discharge increases, water spills over the wing walls, flow depths increase adjacent to the main velocity jet, and more flow paths become available to larger fish. Logistic regression verifies depth and velocity as significant influences on passage success at WWP3.

It is interesting that the maximum velocity ratios for burst swimming abilities of 10 and 25 BL/s are both statistically significant. Fish naturally vary in their physical capabilities much like humans (Williams *et al*., 2012). Thus, a variation in physical capabilities among fish is likely illustrated through the inclusion of the maximum velocity ratio for burst swimming abilities of 10 and 25 BL/s. This is consistent with a previous study examining passage success through fishways, where not all fish were able to pass a structure equally well (Caudill *et al*., 2007). Additionally, burst swimming abilities of 10 and 25 BL/s agree with the different findings of previous laboratory studies (Beamish, 1978; Peake *et al*., 1997; Castro-Santos *et al*., 2013). Further, a mixed population of hatchery fish and naturally producing fish supports the inclusion of different burst swimming abilities. It has been shown that hatchery rearing can alter the behavior and swimming ability of fish (Duthie, 1987; Peake *et al*., 1997). The inclusion of the maximum velocity ratio for different burst swimming abilities at individual structures could also indicate the influence of additional hydraulic variables, such as depth or turbulence, to reduce a fish's swimming ability.

The goodness-of-fit test at WWP1 shows that more complex variables could improve the model fit. This suggests that additional variables to depth could be contributing to the suppression of movement at WWP1. A study examining the effects of turbulence on passage success in three different pool-type fishways found that the fishway with the highest turbulence had the worst passage success, but passed smaller fish better than the other configurations (Silva *et al*., 2012). Similarly, WWP1 has the worst overall passage success; however, smaller fish experience higher success rates at WWP1 compared to larger fish. WWP1 is also characterized by the highest magnitudes and larger distribution of the maximum vorticity along flow paths at discharges when the majority of the movements occurred. This suggests that turbulence could be an additional factor affecting passage success at WWP1.

The fact that our models did not identify turbulence as a significant influence could be an issue of scale. It has been suggested that the intensity, periodicity, orientation, and scale (IPOS) of turbulence should be considered in conjunction when relating turbulence to fish swimming abilities (Lacey *et al*., 2012). The magnitude or intensity of vorticity and TKE do not account for the spatial scale at which fish experience turbulent eddies relative to body length. Turbulent eddies that are small compared with the fish scale lack momentum required to negatively affect a fish, and in some cases assist in forward movement (Haro *et al*., 2004, Hinch and Rand, 2000; Lacey *et al*., 2012). Turbulent eddies with a diameter close to the length of a fish can pose stability challenges and reduce a fish's swimming ability (Lupandin, 2005; Pavlov *et al*., 2000; Tritico and Cotel, 2010). However, examining these relationships remains difficult without direct observations of flow/fish interactions and established thresholds of the effects of turbulence on fish swimming abilities.

The cumulative effects of velocity a fish experiences while crossing a structure have the potential to influence passage success. Studies have shown that as the swim speed of a fish increases the time to fatigue decreases (Bainbridge, 1960; Peake *et al*., 1997). The difference in the lengths of the flow volumes is a direct result of differences in the length of the hydraulic jump at each structure. The length of the hydraulic jump is greatest at WWP3, resulting in greater distances of supercritical flow and higher velocities. Consequently, WWP3 is characterized by the highest 50th percentile of cost with the exception of 60 cfs. However, similar costs exist at WWP2 and WWP3 at lower flows. As discharge increases, lower velocities along the channel margins at WWP3 provide similar costs between WWP3 and WWP2 below the 50th percentile. Considering a fish chooses the least cost path (McElroy *et al*., 2012) through a structure, it is unlikely that an exhaustive swimming barrier will exist. Logistic regression analysis does not indicate a negative effect of cost on passage success; however, visual observations of failed attempts will reveal direct relationships on passage success and velocity as an exhaustive swimming barrier.

Passage success across barriers to migration is a function of the behavior and physiological limits of a fish (Castro-Santos *et al*., 2013). This study examines hydraulic conditions as physiological barriers to migration and does not take into account fish behavior. Accessible movement paths might exist at a structure. However, a fish might feel the cumulative effects of fatigue or lack motivation or willingness after several failed attempts to locate accessible movement paths (Castro-Santos *et al*., 2013). It is important to consider the timing of fish migrations and other life-cycle processes. Although higher discharges provide a higher fraction of accessible flow paths for fish, discharges at 15 to 60 cfs occur much more frequently throughout the year at the study site.

Despite the remaining uncertainties in additional factors that might be contributing to the suppression of movement, management guidance and design recommendations can be provided based on the strong relationship of passage success with velocity and depth. Care should be taken to ensure that velocity and depth requirements are met continuously along likely fish movement paths. Multiple field studies indicate that fish exploit boundary layers created by objects in the flow field (Fausch, 1993; Nestler *et al*., 2008). Interstitial spaces within the center of the chute may provide zones of lower velocity for smaller fish. Increasing the size range of the interstitial spaces to at least the body depth of largest fish likely encountered may provide adequate flow depth and lower velocities to accommodate a broader size class of fish size. Continuous low-velocity zones along the margins of the chute with adequate flow depth should be provided, allowing fish to avoid the main velocity jet. Low-velocity zones along the channel margins can be achieved by allowing water to spill over the wing walls at all discharges. If the wing walls are not grouted they act as roughness elements providing flow refugia for fish. Large eddies that recirculate back into the chute at all discharges can provide additional low-velocity zones as seen at higher discharges at WWP3. These low-velocity recirculation zones should come up the sides of the main velocity jet as far as possible.

Quantifying hydraulic conditions along potential fish movement paths provides a novel and powerful approach to mechanistically evaluate the effects of hydraulics on fish passage over a wide range of hydraulic structure types. When assessing WWP designs, it is important to describe the hydraulic conditions at scales that fish experience them. Simply averaging the hydraulic conditions over large spatial scales or evaluating point measurements do not take into account the continuous complexity of the flow field along a fish's movement path. It is also important to consider the interaction between multiple hydraulic variables such as depth and velocity to ensure all conditions are met for successful passage.

The results of this study are potentially limited in their transferability to assessing passage success of salmonids at WWPs of similar size, design type, and hydrologic regime. Similar hydraulic analyses can provide information on the effects that velocity and depth might have on passage success at additional WWPs. Evaluating additional WWPs is highly recommended to determine the range of hydraulic conditions that fish are required to pass. Further, assessing passage success of non-salmonid fishes with different swimming abilities or behaviors could highlight the need for lower velocity zones or higher topographic diversity within WWP chutes. A more in-depth analysis of turbulence incorporating flow/fish interactions could reveal new thresholds and additional factors that affect passage success. Additionally visual observations of successful and failed attempts of individual fish will allow for a more-detailed comparison of the hydraulic conditions that effect passage success and shed light on behavioral limitations.

3.5 CONCLUSION

This study used the results from a 3-D CFD model to provide a continuous and spatially explicit description of the hydraulic conditions along potential fish movement paths and examine their influence on fish passage at an actual WWP on the St. Vrain River in Lyons, Colorado. Quantifying the hydraulic conditions in this manner captured important and unique hydraulic characteristics at each WWP, and described velocity and depth throughout the flow field at a scale meaningful to a fish. A comparison of velocity and depth relative to a fish's swimming ability was reflective of the variation in passage success among WWP structures and size classes of fish. Logistic regression indicated a significant influence of velocity and depth on passage success, and accurately predicted 87% of individual fish observations. Specific combinations of depth and velocity were statistically significant at individual WWP structures highlighting the effects of unique hydraulic conditions at each WWP on passage success. The results indicate that additional variables such as turbulence might also be contributing to the suppression of movement. Further research is needed to examine the range of hydraulic conditions at existing WWPs and the effects of WWPs on native fishes with lesser swimming abilities. Additionally, studies involving flow/fish interactions are needed to evaluate fish behavior in response to hydraulic conditions and define turbulence at a scale relative to fish size. Similar hydraulic analyses coupled with fish movement data can be utilized to evaluate the effects of hydraulic conditions on passage success at other types and sizes of WWPs. This study lays the groundwork for a novel and powerful approach to mechanistically evaluate the effects of hydraulic structures on fish passage. Further, the results of this study can serve as a reference for managers and policy makers, provide design guidance for future WWPs, and be used to evaluate existing WWPs of similar size, design type, and hydrologic regime.

SECTION 4

CLOSING REMARKS

Kolden (2013) modeled both WWP pools and natural pools on the North St. Vrain River to look at habitat quality for juvenile and adult brown trout (*Salmo trutta*), rainbow trout (*Oncorhychus mykiss*), longnose dace (*Rhinichthys cataractae*), and longnose sucker (*Catostomus catostomus*). Both 2-D and 3-D methods were used to model velocity components, TKE, and vorticity. TKE results were not available with the 2-D method and important aspects of the velocity and vorticity distributions were missed due to depth-averaging. Although this study supported the use of 3-D modeling for complex flow found in WWPs, 2-D modeling still has important utility and is less costly and time consuming. Other projects should be evaluated case-by-case to determine if the simplified 2-D rendering of flow characteristics is acceptable. The analysis showed much higher values of all hydraulic components in the WWP pools, and indicated that better habitat quality existed in the WWP pools. However, a biomass study, performed in conjunction with CPW, showed that fish biomass per volume was much higher in the natural pools. This contradiction suggests that correlation exists between biomass and hydraulic variables and provides a change to investigate the yet-undetermined links between TKE, 2-D or 3-D vorticitiy, and habitat suitability.

The novel combination of fish movement and hydraulic data collected by Fox (2013) at three WWP structures on the North St. Vrain River show that while there is suppression of upstream movement to some extent, the WWP structures are not acting as a complete barrier to fish passage for brown or rainbow trout. However, due to small sample sizes there is still limited information available about the effect in-stream recreational structures have on the upstream movement of native species such as longnose dace and longnose sucker. The amount of suppression for the adult and juvenile of these two species varies both with structure design type and fish body length. Fox (2013) hypothesizes that flow depth plays a critical role in whether or not passage is successful, and that turbulence within the WWP pools is somehow affecting fish stability and therefore passage success. Visual observations suggest that the placement of large boulders near the chute may be hindering the leaping ability of adult fishes. The interstitial spaces in the WWP structures seem to allow necessary alternate passage routes with lower velocity, though the size of these spaces must be appropriate for the body size of the fish attempting to pass.

Continuing the analysis of data collected on the North St. Vrain, Stephens (2014) developed a spatially explicit hydraulic model which accurately predicted over 87% of non-movements and over 92% of upstream movements through WWP. A logistic linear regression model showed that both depth and velocity were major predictors of passage success, and underlined the importance of jointly considering hydraulic variables when assessing the probability of passage success. Interestingly, neither turbulence nor cost (accounting for cumulative effects as fish stage multiple attempts or attempt to pass multiple structures) were found to be statistically significant in the model. Visual observations and a look at the passage variability at each WWP structure suggest that turbulence really is affecting passage. This discrepancy is likely an issue of scale, as turbulence was not described at a scale meaningful to fish relative to body size. The current cost function was also not scaled to body length, and a recalculation may give more insight into cumulative effects. Nuances in hydraulic characteristics were found at each different WWP structure type which affected passage in different ways. Both interstitial spaces and recirculation eddies were found to create zones of lower velocity and improve fish passage. Seven different discharges, ranging from 15 to 300 cfs, were used in the model, and it was found that neither the highest nor lowest discharges presented the greatest challenge for passage. While the higher discharges provide a larger fraction of accessible flow paths for fish, discharges at 15 to 60 cfs occur much more frequently throughout the year at the study site.

4.1 DESIGN GUIDELINES

Knowledge gained from these investigations of WWP structures on the North St. Vrain River provide a valuable starting point for advising the design of future WWPs with fish passage in mind. It is worth noting that the resulting recommendations are best applied to a system of geomorphic class, hydrologic regime, and scale similar to the study reach. In order to achieve the necessary hydraulic jump on rivers larger than the one examined in these studies, it is possible that higher velocities, which exceed salmonid burst swimming abilities, might be required within the chute to generate a wave that achieves recreational objectives. 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. 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. The hydraulic analysis model and statistical model developed by Stephens (2014) shows that flow depth is critical in determining the probability of fish passage success. This study strongly suggests that flow depths greater than 0.6 feet should be maintained for all expected discharges. The hydraulic modeling and subsequent statistical analysis also show that velocity is a key factor affecting fish passage. However, hydraulic nuances exist for each type of WWP structure and therefore velocity thresholds vary with each design type. The passable velocity also varies with the size class of fish attempting to move upstream. Without site specific analysis, it is recommended that velocities remain under 10 to 25 BL/s. Care should be taken to ensure that *both depth and velocity requirements are met continuously along likely fish movement paths.*

Evidence from the North St. Vrain WWP studies also underscores the importance of providing continuous zones of lower velocity, away from the main velocity jet, as alternate passage routes. The use of non-grouted wingwalls provides interstitial spaces where smaller bodied fishes (with inherently lesser swimming abilities) can pass the structures through lower velocity paths. These interstitial spaces should have a range of sizes comparable to the expected body sizes of the fish population. A design with non-grouted wingwalls also creates additional roughness elements along the channel margins, providing refugia for fishes attempting to move upstream. Large eddies that reach as far as possible up the sides of the main velocity jet also provide low velocity zones, especially during high discharges. The recommended non-grouted wingwall design should allow water to spill over the wingwalls at some location, with adequate flow depth, even at base flow discharges.

Although suppression of fish movement exists at the WWP evaluated in this study, the observations of successful movements indicate that WWPs producing hydraulic conditions within the range of those described in this study have the potential to meet both recreational and fish passage goals for salmonids. The amount of acceptable suppressed movement is a question that should be answered by natural resource managers on a case-by-case basis. Criteria to consider when assessing passage requirements include the previous fragmentation of the system (existing diversions, barriers, etc.), site-specific constraints, target species, and potential benefits due to increased community awareness and personal connection.

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

4.2 FUTURE RESEARCH OPPORTUNITIES

The research described in this report provides a foundation for understanding how and why WWPs affect fish movement, yet new questions and uncertainties have emerged. Important areas for future study include: the minimum resolution of hydraulic models needed to characterize fish passage potential and habitat suitability in WWP pools, further analysis of the mechanisms causing upstream movement suppression through WWPs, cumulative effects of the inline structures, transferability of results from the North St. Vrain WWP studies, and the impact of WWPs on native non-salmonid species. As the popularity of WWPs continues to grow in Colorado and elsewhere, it is imperative to also continue increasing our knowledge base concerning the design and potential impacts of these recreation structures.

Although significantly more fish biomass per volume was found in the natural control pools, the habitat suitability analysis by Kolden (2013) showed that the WWP pools provided much better habitat. The hydraulic variables of TKE, 2-D vorticity, and 3-D vorticity were also found to be much higher in the WWP pools. The biomass contradiction paired with the difference in hydraulic variable distribution suggests that correlations could exist between the two. The results provide a starting point for examining the effects of these flow characteristics on habitat quality and the necessary resolution needed to characterize them. Another factor that is very important in WWPs but is often overlooked in habitat suitability analyses is the large amount of recreational use. A future study could also be improved by the inclusion of a recreational use variable which looks at how rates and patterns of usage affect the quality of aquatic habitat in WWP pools.

The hydraulic model developed by Stephens (2014) suggests that inclusion of more complex variables could improve the model fit. The investigation of variables corresponding to fish behavior would be a good starting point. The model could also benefit from the inclusion of a chute margin variable to look at zones where fish are most likely to attempt passage. Although the current model didn't find turbulence to be significant, an inspection of passage variability at each structure suggests that turbulence could still be an additional factor affecting successful fish passage through a WWP. The current vorticity and TKE variables (representations of turbulence) are not described at the spatial scale, relative to fish body length, that fish encounter turbulent eddies. Depending on this relative size, turbulent eddies might negatively or potentially positively affect a fish's swimming ability and therefore passage success. However, visual observations of flow/fish interactions and deeper analysis are vital to further understanding any meaningful thresholds for these hydraulic/behavioral variables.

Many WWPs incorporate a series of structures to create the desirable length and variation of wave types for boaters. When attempting to pass multiple inline structures, a fish is likely to suffer from cumulative effects influencing complete passage success. Therefore, a structure that may not be an exhaustive swimming barrier by itself might become one when combined with other structures. A more in-depth analysis of the cost associated with traversing an entire WWP will provide additional data on overall passage efficiencies. A good place to begin would be a recalculation of the cost metric included in the Stephens (2014) hydraulic model. Linear regression analysis of the current cost variable did not indicate a negative effect on passage success. However, a slight variation in the calculation method to include fish body length should help shed light on visual observations of failed attempts and provide a more accurate estimation of cumulative effects on passage success.

The results from the North St. Vrain are likely transferrable to systems with very similar characteristics. Yet, the looming question remains of whether or not they are appropriate to use with a larger/smaller river system or with different WWP structure types. A future study should be conducted to classify the broad range of existing structure types and evaluate how hydraulic behavior varies between design types. This will allow for a better understanding of when and where results from this and other WWP studies can accurately be applied. An investigation of how hydraulic behavior for a single type of structure varies as the scale of the river system changes is also important for assessing the passage likelihood of future WWP projects or modifications.

Currently, large gaps remain in the knowledge base concerning the swimming abilities and passage implications for native non-salmonid species. One reason for this paucity is the difficulty in obtaining a large enough sample size of native fishes to make statistically significant conclusions. A study with the explicit objective of understanding more about the effect of WWPs on native species will prove greatly beneficial. When doing so, obtaining baseline data of pre-construction fish movement is imperative to assess level of suppression. It would also be interesting to look at the effect of WWPs on multiple life-stages of these fishes, which have differing swimming abilities.

An abundance remains to be learned about how WWP structures affect the upstream movement of fish populations. A replication of the studies conducted on the North St. Vrain River at different locations where the system and structure characteristics vary will provide information on general trends of the influence WWPs have on both fish passage and habitat quality. Additionally, several suggestions for continuing the work started on the North St. Vrain, transferring the results to other projects, and following up on questions that have developed from these studies have been outlined in this report. By better understanding and reporting on the relationships between WWP design and fish passage, we can better merge the management of aquatic ecosystems with the meeting of recreational human objectives.

SECTION 5

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