THESIS

# ECO-HYDRAULIC EVALUATION OF WHITEWATER PARKS AS FISH PASSAGE BARRIERS

Submitted by

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ABSTRACT

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Whitewater parks (WWPs) have become a popular recreational amenity in cities across the United States with Colorado being the epicenter of WWP design and construction. Whitewater parks consist of one or more in-stream structures that create a hydraulic wave for recreational purposes. A wave is typically created by constricting flow into a steep chute creating a hydraulic jump as it flows into a large downstream pool. Concerns have been raised that high velocities, resulting from the constricted flow at these structures, may be inhibiting movement of certain fish species at different times of year.

I 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 (*Salmo trutta*), rainbow trout (*Oncorhynchus mykiss*), longnose sucker (*Catostomus catostomus*), and longnose dace (*Rhinichthys cataractae*) 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 three-dimensional hydraulic model using FLOW-3D®.

Results show that this WWP is not a complete barrier to upstream movement, but differences in passage efficiency from release location range from 29 to 44% in WWP sites and 37 to 63% for control sites indicating a suppression of movement within WWPs. Further, this suppression of movement appears to be related to fish body length. Results from the hydraulic models indicate that these are not likely burst swimming barriers to salmonids despite flow velocities greater than 10 ft/s within each of the WWP structures. Hydraulic model results provided insight in identifying other possible causes of the suppressed movement and guidance for future research efforts.

# ACKNOWLEDGMENTS

The completion of this study is the end of a long journey, and along the way I have gained an incredible amount of knowledge, insight, and advice from more people than I could ever thank. I would first like to thank my advisor, Brian Bledsoe; co-advisor, Chris Myrick; and committee member Karan Venayagamoorthy for valuable guidance and encouragement throughout the process.

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Finally, I would like to thank my wife, Dana, who not only endured the many hours this study required me to be away from home, but provided invaluable encouragement along the way.

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| | | |
|---|---|---|
| *B* | = | behavior = species-specific passage strategies that affect ability to traverse a potential obstacle. These may include but are not limited to path selection, swimming vs. jumping, maximal effort, and motivation. |
| *E* | = | environmental factors = additional variables that may influence physiological ability and motivation (temperature, pollutants, human presence, etc.) |
| *EVENT* | = | CJS variable: tag release events |
| *Fr* | = | Froude number |
| *g* | = | gravitational acceleration $\left(\frac{\mathrm{L}}{\mathrm{T}^2}\right)$ |
| *H* | = | hydraulic conditions = a specific hydraulic variable affecting the ability, motivation, or behavior of a fish attempting to move upstream. These may include but are not limited to velocity, depth, hydraulic drop, and turbulence. The magnitude, timing, rate of change, duration, and frequency of these variables may also affect upstream movement. |
| *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 |
| *M* | = | motivation = species-specific behavior that directs movements to optimal spawning, feeding, and refugia habitats during various temporal periods |
| *MRT* | = | CJS variable: three mark-release types |

| | | |
|---|---|---|
| $n$ | = | number of fishes |
| $p$ | = | probability of encounter |
| $P$ | = | physiological ability = species-specific swimming ability to successfully traverse a given hydraulic environment. This may include but is not limited to maximum swimming or leaping ability, endurance and stability within turbulent environments. |
| $q$ | = | unit discharge $\left(\frac{L^2}{T}\right)$ |
| $r^2$ | = | statistical term: coefficient of determination |
| SE | = | statistical term: standard error |
| *SPECIES* | = | CJS variable: trout/non-trout |
| UCI | = | statistical term: upper confidence interval |
| $v$ | = | velocity $\left(\frac{L}{T}\right)$ |
| $y$ | = | flow depth (L) |
| $\beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \beta_8, \beta_9, \beta_{INT}$ | = | CJS regression parameters |
| $\phi$ | = | 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 |
| $\Psi$ | = | apparent successful upstream movement |

## UNITS OF MEASURE

| | |
|---|---|
| BL/s | body length(s) per second |
| cm | centimeter(s) |
| cfs, $ft^3/s$ | cubic feet per second |
| ft | foot or feet |
| ft/s | feet per second |
| L | length dimension |
| m | meter(s) |
| m/s | meter(s) per second |
| mi | mile(s) |
| mm | millimeter(s) |
| % | percent |
| T | time dimension |

# CHAPTER 1 INTRODUCTION

Whitewater parks (WWPs) have become a popular recreational amenity in communities across the United States (US) 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 Colorado Parks & Wildlife (CPW) found low fish biomass within a WWP as compared to natural control (CR) reaches despite the presence of large constructed pools (Kondratieff, 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 United States Army Corps of Engineers (USACE), Section 404 of the Clean Water Act permitting process. This process is intended to avoid, minimize, and mitigate impacts to the waters of the US, and also provides opportunity for state wildlife agencies to comment on the potential impacts of proposed projects. These permitting decisions can often be difficult because actual data on the effects of WWPs are unavailable. Without first understanding the significance of effects for a given action, speculation may lead to a potentially-biased regulatory permitting process by either allowing projects with unacceptable negative effects, or by stopping projects that may have minimal or no negative effect. Allowing the construction of WWPs, if they do in fact have adverse effects, may lead to projects that limit aquatic habitat and fish passage in otherwise unimpaired rivers. Disallowing the construction of WWPs, if they have minimal or no negative effect on aquatic habitat and fish passage, would unnecessarily prevent the completion of a project that would otherwise provide positive social and economic benefits to communities. Understanding the effects WWPs on fish passage and aquatic habitats are critical to better inform policy and decision-making for future WWPs, and provide local citizens and project sponsors with information to consider when weighing the potential benefits and adverse effects of WWPs.

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

The next section provides a brief literature review of the physical characteristics of WWPs and pertinent fish passage concepts as they relate to the physical design elements of WWPs and identification of key characteristics that may be affecting successful upstream fish passage. Because direct data on fish movement within actual WWPs from other studies are unavailable, I also reviewed fish passage studies conducted at different types of in-stream structures that are hydraulically comparable to evaluate how they relate to WWPs and their associated effects on fish passage. Finally, the concepts developed within this literature are used to provide context for the development of the specific study objectives.

## 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 suggests 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 1.1). 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 1.2). 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.

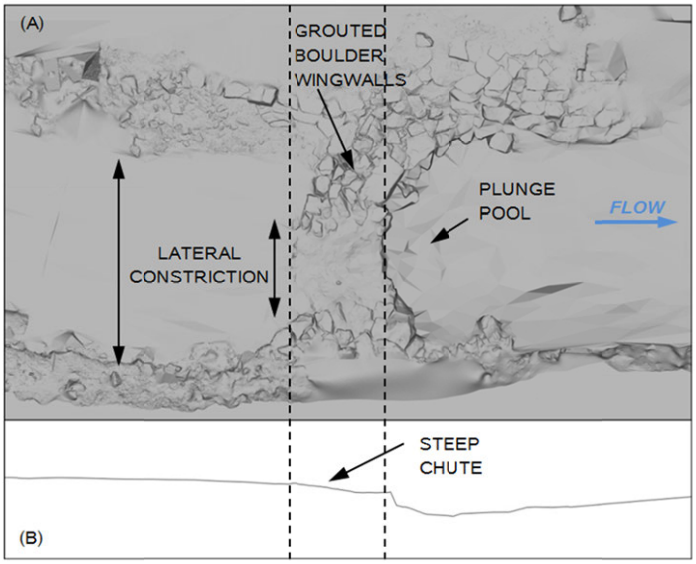



**Figure 1.1: (A) Plan and (B) profile views of common design features found in WWPs.**

(A) wave type (B) hole type

**Figure 1.2: Typical (A) "wave" and (B) "hole" types of WWP structures.**

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 1.3). 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 1.4) 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):

$$Fr = \frac{v}{\sqrt{gy}} \qquad \textbf{(Eq. 1.1)}$$

$$q = vy \qquad \textbf{(Eq. 1.2)}$$

$$v = \left(Fr^2 gq\right)^{1/3} \qquad \textbf{(Eq. 1.3)}$$

$$y = \left(\frac{q^2}{gFr^2}\right)^{1/3} \qquad \textbf{(Eq. 1.4)}$$

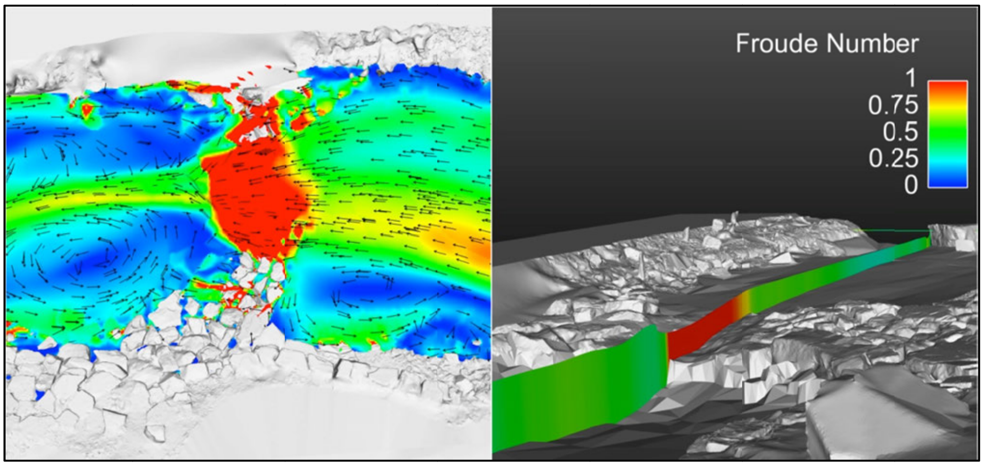
where

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

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

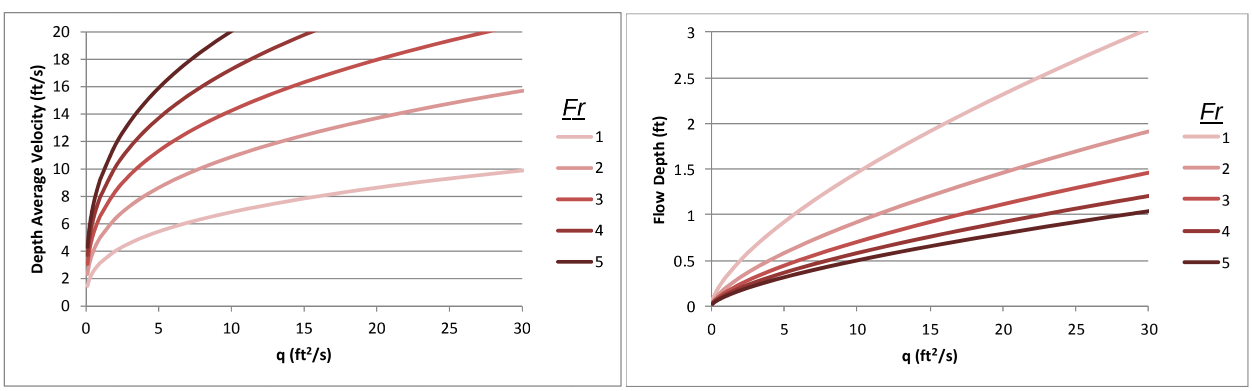
$$y \;=\; \text{flow depth (L); and}$$

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




(A) plan view (B) profile view

**Figure 1.3: (A) Plan and (B) profile views of hydraulic jump-forming process in a "typical" WWP. 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 1.4: Depth-averaged flow velocity (A) by unit discharge and *Fr* estimating the lower range of maximum flow velocities and (B) minimum depth. 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 1.4).

## 1.2 Fish Passage Data Review for WWPs

For this study, I define an optimal fish passage structure as one that is "transparent" to individuals moving in both directions, and has no effect on the life-cycles of migrating fishes (Castro-Santos *et al*., 2009). The successful structure should have no effect on passage success, frequency, delay, and timing of movement; and results in no increase in energy cost, predation, and overall stress associated with passage. Numerous factors must be considered in assessing overall fish passage success; however, many of these are behavioral in nature, difficult to evaluate, and necessarily beyond the scope of this study. I focus on evaluating direct passage success as influenced by the altered hydraulic conditions as a starting point for understanding fish passage within WWPs. The four major types of hydraulic factors that could directly limit upstream passage are velocity, depth, total drop, and turbulence.

### *1.2.1 Velocity Barrier*

Average flow velocity is a widely-used metric for fish passage assessment and design, and is typically applied by assessing whether the current velocity is a burst or exhaustive swimming barrier. A burst swimming barrier occurs when the flow velocity is greater than the maximum swimming speed of the fish and an exhaustive barrier occurs if a fish cannot maintain a positive ground speed for an adequate duration to move through a velocity challenge prior to exhaustion (Beamish, 1978). A review of the physical characteristics of WWP structures shows that they tend to be relatively short structures with distinct spatial zones of high-flow velocity, indicating a high potential for burst swimming barriers. While an exhaustive swimming barrier is possible, its occurrence will largely depend on site-specific design characteristics such as length of structure.

Swimming data used for identifying potential burst swimming barriers for specific fish species are available from several types of laboratory-derived studies, the most common being the critical velocity and fixed velocity methods developed by Brett (1964). Using these methods, the maximum burst swimming speed of fishes is typically estimated in the range of 10 to 15 body lengths (BL)/s (Beamish, 1978). More recent studies using volitional swimming flumes, producing observed fish sprint speeds as high as 20 BL/s (Haro *et al.*, 2004). Specific studies of brook trout (*Salvelinus fontinalis*) and brown trout (*Salmo trutta*) (Castro-Santos *et al.*, 2013), using the volitional swimming flume method, found maximum swim speed of these two species to be approximately 25 BL/s. Using an estimate from the range of flow velocities likely at WWPs (Figure 1.4(A)) of 10 ft/s, these data indicate a burst swimming barrier exists for a brown trout less than 125 mm (Castro-Santos *et al*., 2013) or less than 300 mm in length (Peake *et al*., 1997) (Table 1.1). It should be noted that while general estimates of burst swimming speed can be given in terms of BL/s (Videler, 1993), maximum absolute swim speed increase less rapidly for larger fishes. Therefore, these estimates may tend to overestimate swimming speed for larger individuals (>200 mm).

**Table 1.1: Predicted maximum burst speed for brown trout (*Salmo trutta*) by body length using estimates of 10 BL/s (Peake *et al*., 1997) and 25 BL/s (Castro-Santos *et al*., 2013).**

| Length<br>m (ft) | 10 BL/s<br>m/s (ft/s) | 25 BL/s<br>m/s (ft/s) |
|---|---|---|
| 0.100 (0.3) | 1.00 (3.3) | 2.50 (8.2) |
| 0.125 (0.4) | 1.25 (4.1) | 3.13 (10.3) |
| 0.150 (0.5) | 1.50 (4.9) | 3.75 (12.3) |
| 0.175 (0.6) | 1.75 (5.7) | 4.38 (14.4) |
| 0.200 (0.7) | 2.00 (6.6) | 5.00 (16.4) |
| 0.225 (0.7) | 2.25 (7.4) | 5.63 (18.5) |
| 0.250 (0.8) | 2.50 (8.2) | 6.25 (20.5) |
| 0.275 (0.9) | 2.75 (9.0) | 6.88 (22.6) |
| 0.300 (1.0) | 3.00 (9.8) | 7.50 (24.6) |
| 0.325 (1.1) | 3.25 (10.7) | 8.13 (26.7) |
| 0.350 (1.1) | 3.50 (11.5) | 8.75 (28.7) |
| 0.375 (1.2) | 3.75 (12.3) | 9.38 (30.8) |
| 0.400 (1.3) | 4.00 (13.1) | 10.00 (32.8) |

### *1.2.2 Flow Depth*

A functional fish passage structure should maintain an adequate depth for a fish to swim upstream through the structure (Castro-Santos *et al*., 2009). The preliminary hydraulic analysis of WWPs shows that the flow depth within WWPs is often substantially reduced in sections of supercritical flow and increased velocity. This decrease in flow depth may pose problems for fish passage in structures on small rivers or during low-flow periods when small unit discharges (Figure 1.3(B)) occur within the structure. However, it should be emphasized that flow depth exhibits site-specific spatial variability in non-uniform channels.

### *1.2.3 Hydraulic Drop*

The direct effects of a hydraulic drop on successful fish passage will also be highly dependent on whether passage is attempted by leaping or swimming. Longer structures will likely require fishes to pass by swimming, while steep structures with short horizontal distance may be more conducive to a leaping attempt. Leaping information for fishes is somewhat limited, but it can often be correlated to burst swimming speed using the projectile equation (Aaserude and Orsborn, 1985). Kondratieff and Myrick (2006) performed an extensive laboratory assessment of brook trout jumping abilities. They observed jumping over waterfalls heights ranging from 43.5 to 73.5 cm, with the maximum jump height of an individual increasing with pool depth, fish body length, and condition.

### *1.2.4 Turbulence*

The effects of turbulent environments on fish behavior and swimming ability are at the forefront of eco-hydraulic research priorities. Liao (2007) provided an in-depth review of fish swimming mechanics and behavior in turbulent flows. Studies on the effects of turbulence on swimming ability have shown it can both increase (Liao *et al*., 2003) and decrease swimming ability (Webb, 2002; Tritico and Cotel, 2010; Enders *et al*., 2003; Smith *et al*., 2005), and may interact with flow velocity in determining passage success.

Characterizing turbulence effects on fish passage is difficult because turbulence is a highly-complex and poorly-understood phenomenon by itself (Ferziger, 2005). Coupling the uncertainty associated with the basic understanding of turbulence with an additional level of uncertainty in how it would affect fish behavior and swimming ability, it is not often utilized as a practical metric for passage assessment. Lacey *et al*. (2012) proposed a framework for incorporating turbulence in fish swimming studies, but existing data that can be applied in a practical setting are largely unavailable. Despite limited knowledge of how turbulence may affect fish passage, the presence of all four characteristics (intensity, periodicity, orientation, and scale) of turbulence (Lacey *et al*., 2012) are present within WWPs, and their effects should at least be considered when evaluating passage results in WWPs.

### *1.2.5 Analogous Studies*

Due to the lack of information regarding fish passage at WWPs, studies concerning fish passage across similar structures were reviewed as analogs. Studies examining the effects of culverts (Belford and Gould, 1989; Burford *et al*., 2009) on fish passage are useful because these structures can produce similar hydraulic conditions found within WWPs. Other types of structures that have hydraulic similarity to WWPs include the rock vortex weir structures widely used in stream rehabilitation. A study evaluating passage success over a series of these structures using Passive Integrated Transponder (PIT) antennas found that movement of juvenile rainbow trout across structures was delayed during low-flow conditions when compared to movement of adults (Martens and Connelly, 2010). Specific hydraulic conditions were not evaluated to determine how their effects may interact with fish body length and swimming ability.

Thomas *et al*. (2011) provided a review of several related studies to evaluate grade control structures (GCS) in western Iowa as upstream movement barriers. They assessed how the design characteristics and hydraulic conditions of these structures affected the ability of fishes to move upstream. Using mark-recapture techniques they found that as structure slope increased from 6 to 8%, the passage success decreased. The hydraulic analysis of the steeper structures found the depth and velocity exceeded criteria for passage of target species within their study sites.

## 1.3 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, I conducted a detailed field study that simultaneously observed fish movement and complex hydraulic conditions at a representative WWP site. Specific objectives were as follows:

1. 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 computational fluid dynamics (CFD) modeling.
2. Assess whether a representative WWP is a partial barrier to upstream movement for specific species and size classes.
3. Assess the effects of spatial and temporal variation of flow velocity, depth, drop, and turbulence on successful fish passage.
4. Determine if flow velocity is functioning as a burst swimming barrier for a range of fish size classes.

5. Assess how results from the representative site can be transferred and applied to other WWPs.

# CHAPTER 2 METHODS

The introductory chapter 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, I 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 my 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 my study, these methods were applied in a context to assess limitations imposed by structures on upstream passage in what would otherwise be an unobstructed reach of river.

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

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

## 2.1 Site Description

The North Fork of the St. Vrain River in Lyons, Colorado, was selected as the location of the field study site (Figure 2.1). 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.

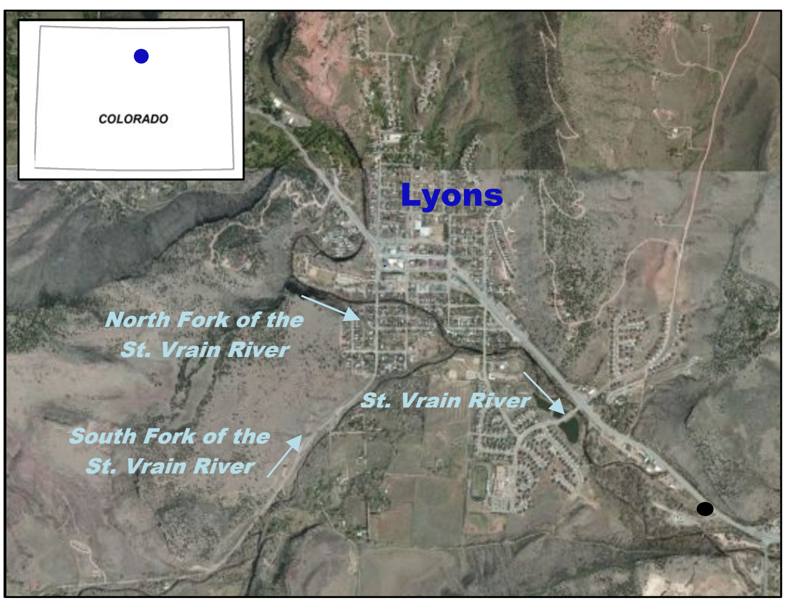



**Figure 2.1: Location map of study site on the North Fork of the St. Vrain River, Lyons, Colorado.**

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 2.2(A)).


**Figure 2.2: (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).**

The WWP study sites were selected to represent the range of physical design variables I 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 me to increase the sample size of the study by continued monitoring of previously tagged individuals.

### *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, I used United States Geological Survey (USGS) regression equations (Capesius and Stephens, 2009) to estimate peak flow discharge and flow-duration probabilities for the site to evaluate the magnitude of the flow conditions observed during the study period (Tables 2.1 and 2.2).

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

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

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

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

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

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

## 2.2 Assessment Framework

A conceptual understanding of the variables related to fish passage in WWPs was provided in the literature review and used to guide the development of field data collection and analysis. This review states the probability of a successful upstream movement of a fish across any given discrete location ($\phi$) is a highly complex response variable that is a function of multiple biotic and abiotic predictor variables. I identified five separate categories of hydraulic and biological variables to potentially quantify the response variable $\phi$:

$$\phi = f\left[H, P, M, B, E\right] \qquad \textbf{(Eq. 2.1)}$$

where

$\phi$ = 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.

$H$ = hydraulic conditions = a specific hydraulic variable affecting the ability, motivation, or behavior of fishes attempting to move upstream. These may include but are not limited to velocity, depth, hydraulic drop, and turbulence. The magnitude, timing, rate of change, duration, and frequency of these variables may also affect upstream movement (Poff *et al*., 1997).

$P$ = physiological ability = species-specific swimming ability to successfully traverse a given hydraulic environment. This may include but is not limited to maximum swimming or leaping ability, endurance, and stability within turbulent environments.

$M$ = motivation = species-specific behavior that directs movements to optimal spawning, feeding, and refugia habitats during various temporal periods.

$B$ = behavior = species-specific passage strategies that effect ability to traverse a potential obstacle. These may include but are not limited to path selection, swimming vs. jumping, maximal effort, and motivation.

$E$ = environmental factors = additional variables that may influence physiological ability and motivation (temperature, pollutants, human presence, etc.).

This conceptual diagram shows that upstream movement is related to many complex processes that vary spatially, temporally, and among individual fishes. An optimal study design quantifies these variables to develop a model of how each predictor effects the movement probability ($\phi$). This is beyond the scope and ability of this study. Because I believe the hydraulic conditions are the factor that most likely will affect movement, data collection and analysis will focus on evaluating the relationship between $\phi$ and $H$. The upstream movement rate ($\phi$) was quantified using a PIT tag telemetry system, and the hydraulic conditions ($H$) were evaluated using a 3-D hydraulic model which are discussed in Chapters 3 and 4.

## 2.3 PIT Tag Telemetry Study

I 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 2.2). 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 2.2). 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 2.3). 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 2.3: (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.**

The three *MRT*s include electrofishing study site residents, release of hatchery-reared fishes, and displacement of fishes below the study sites. The different *MRT*s were used to increase the sample size and motivation to move upstream. Electrofishing *MRT*s were performed at each of the six study sites on six occasions. These consisted of a three-pass removal effort with a shore-based electrofishing unit to collect and tag all available fishes within each of the study locations from approximately the downstream antenna to the base of the structure.

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

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

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

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

Site visits were typically conducted on a weekly basis to change batteries, synchronize reader clocks, download data, tune antennas, test antenna read range, and ensure proper operation was being maintained. Antennas were routinely inspected to ensure that they were firmly fixed to the stream bed and no potential for entrapment hazard existed.

A summary of individual reader performance over the study period is illustrated in Appendix A. Antennas were not operational during periods of power loss and equipment malfunction. Data loss also occurred from corrupted data storage disks within the PIT reader units. A database application was constructed in MS Access® to compile data and prepare formats for assessment in program MARK. Data from each of the six events and twelve PIT antennas were loaded and organized within this application to produce capture histories for each individual.

Data quality-control procedures were developed to assess PIT data, and individual tags were removed from study for analysis because of unresolved crosstalk, death, tag loss, and non-encounters for fishes from the CPW pilot study. Crosstalk is the occurrence of a false positive detection due to close proximity of two or more PIT antennas (Warren Leach, pers. comm.). The occurrence of this can be observed by near simultaneous detection of a single tag on more than one antenna. Movement records were evaluated for crosstalk by identifying physically-impossible or unrealistic movement duration between antenna stations, read counts, and past detection history. Where possible, encounter histories were edited to remove these occurrences. When crosstalk appeared to be present but unresolvable, the tags were removed from the study for analysis. Tags released during the CPW pilot study that were never detected by PIT antennas or recaptured during subsequent events were assumed to no longer be available for capture and were removed from consideration in the analysis.

## 2.4 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, I 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, 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.

I collaborated with Kolden (2013) in developing a computational model for this project using the commercial modeling software FLOW-3D® v10.0 (Flow Science, 2009; hereafter referred to as 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).

#### *2.4.1 Discharge Rating Curve*

I 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 Acoustic Doppler Velocimeter (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.

### 2.5 Data Analyses

#### *2.5.1 PIT Data Analysis*

I 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 ($\Psi$) is modeled by:

$$\Psi = \phi * p \qquad \textbf{(Eq. 2.2)}$$

where

$\phi$ = 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 my study, the success parameter ($\phi$) can be interpreted as a combined estimate of movement and survival probability conditional that the individual was observed downstream of that site and alive. A detailed description of the model parameters and development procedures are given in Appendix B. The general model that was fit to the data set is given:

$$\begin{aligned} logistic(\phi) = \beta_{INT} &+ \beta_1[MRT] + \beta_2[EVENT] + \beta_3[SPECIES] \\ &+ \beta_4[LENGTH] + \beta_5[LOCATION] \\ &+ \beta_6[LENGTH]*[SPECIES] + \beta_8[LOCATION]*[SPECIES] \\ &+ \beta_9[LOCATION]*[LENGTH] \end{aligned} \quad \textbf{(Eq. 2.3)}$$

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.

### *2.5.2 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. I 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, I first extracted two-dimensional (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, 5$^{th}$, 25$^{th}$, 50$^{th}$, 75$^{th}$, and 95$^{th}$ percentile velocities within each cross section.

Because fish movement data are limited to 'Yes/No' for a specific discharge, I 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 25$^{th}$ 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.

### *2.5.3 Assessment of Burst Swimming Barrier*

Without direct information on movement pathway, I 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, 5$^{th}$, 25$^{th}$, 50$^{th}$, 75$^{th}$, and 95$^{th}$ percentile velocities were compared to find the respective maximum value. These maximum values among the cross-sections represent the limiting condition for a burs swimming barrier, because they must be traversed to 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.

# CHAPTER 3 RESULTS

## 3.1 PIT Data

### *3.1.1 Study Population Data*

I 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 3.1).

**Table 3.1: 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 3.2) for the six events. Distributions of the body lengths for tagged fishes are illustrated by site and by species (Figures 3.1 through 3.3). 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 3.2: 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** |

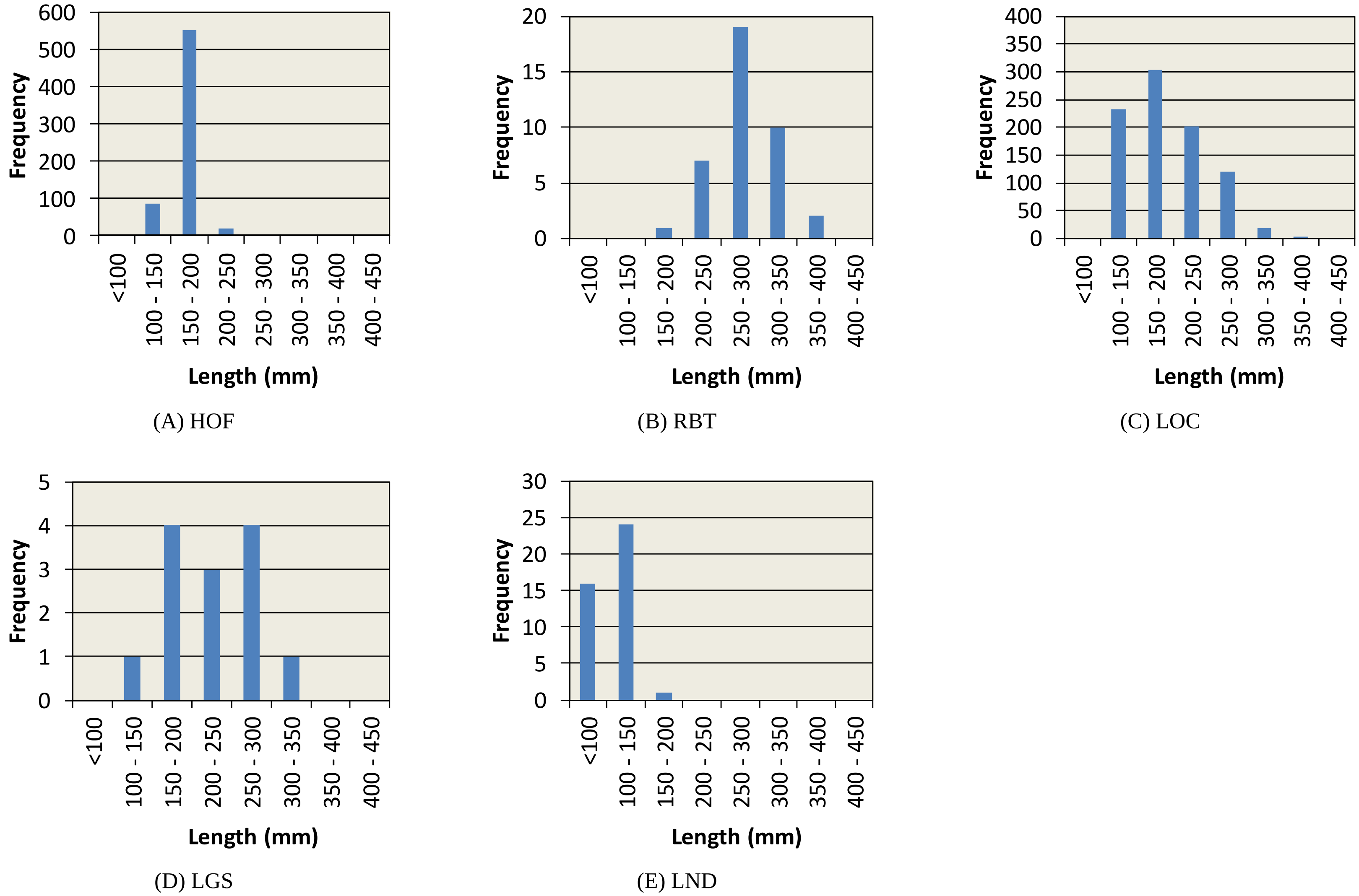
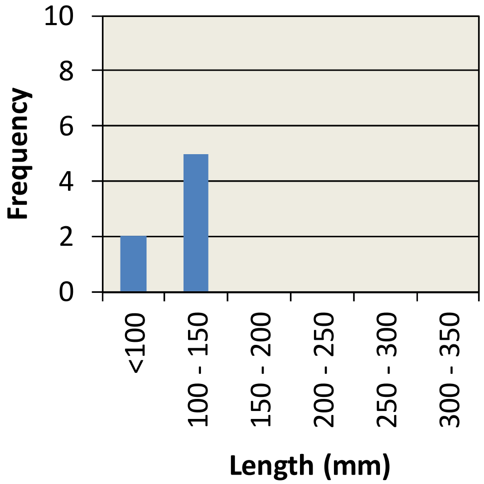
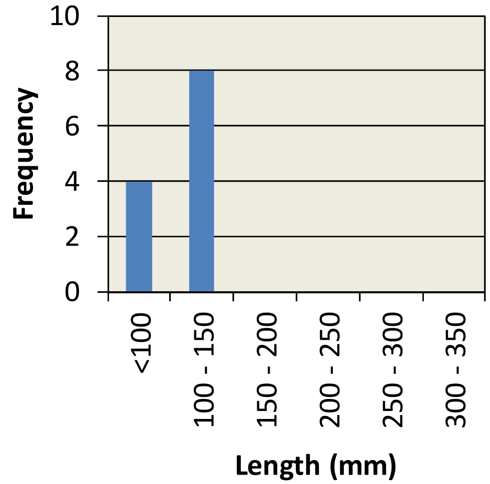


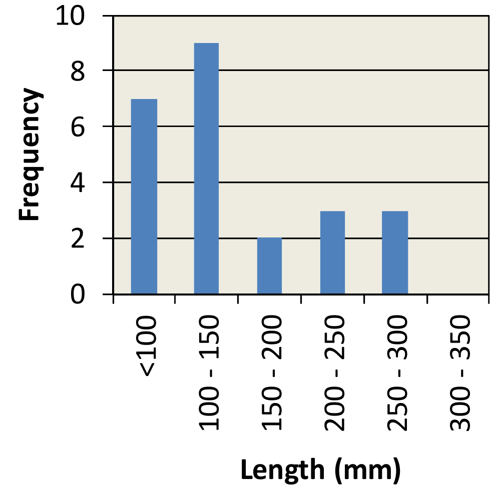

**Figure 3.1: Length (mm) frequency of entire study population (*n* = 1639) by species: (A) HOF – (*Hofer x Harrison strain*); (B) RBT – rainbow trout (*Oncorhynchus mykiss*); (C) LOC – brown trout (*Salmo trutta*); (D) LGS – longnose sucker (*Catostomus catostomus*); and (E) LND – longnose dace (*Rhinichthys cataractae*).**



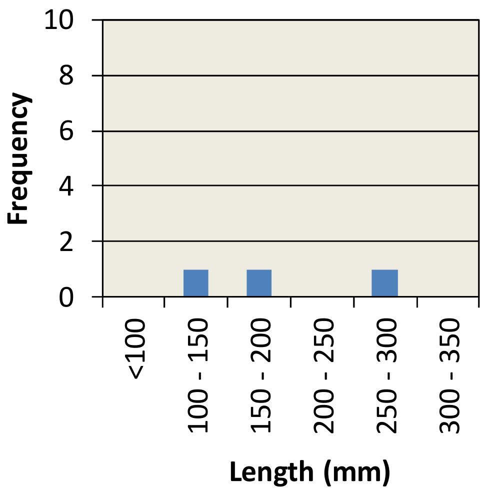

(A) CR1



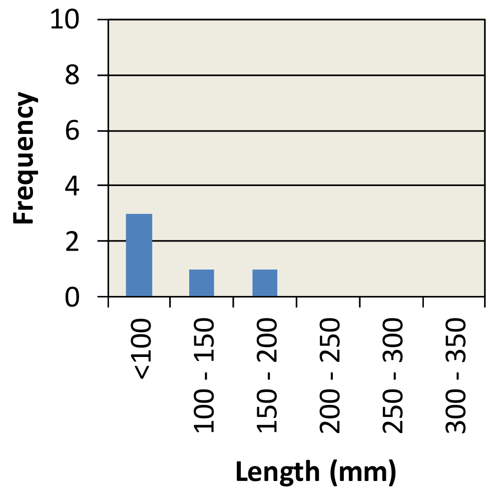

(B) CR2



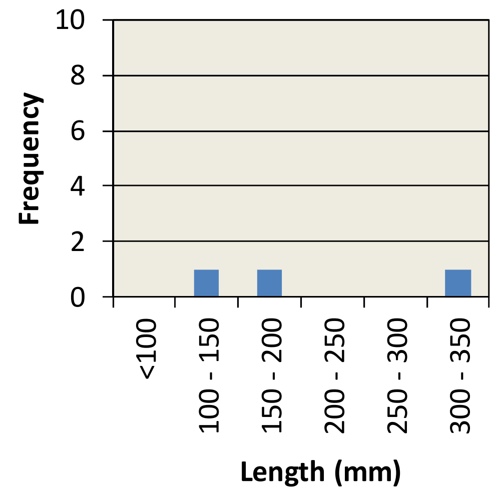

(C) CR3




(D) WWP1

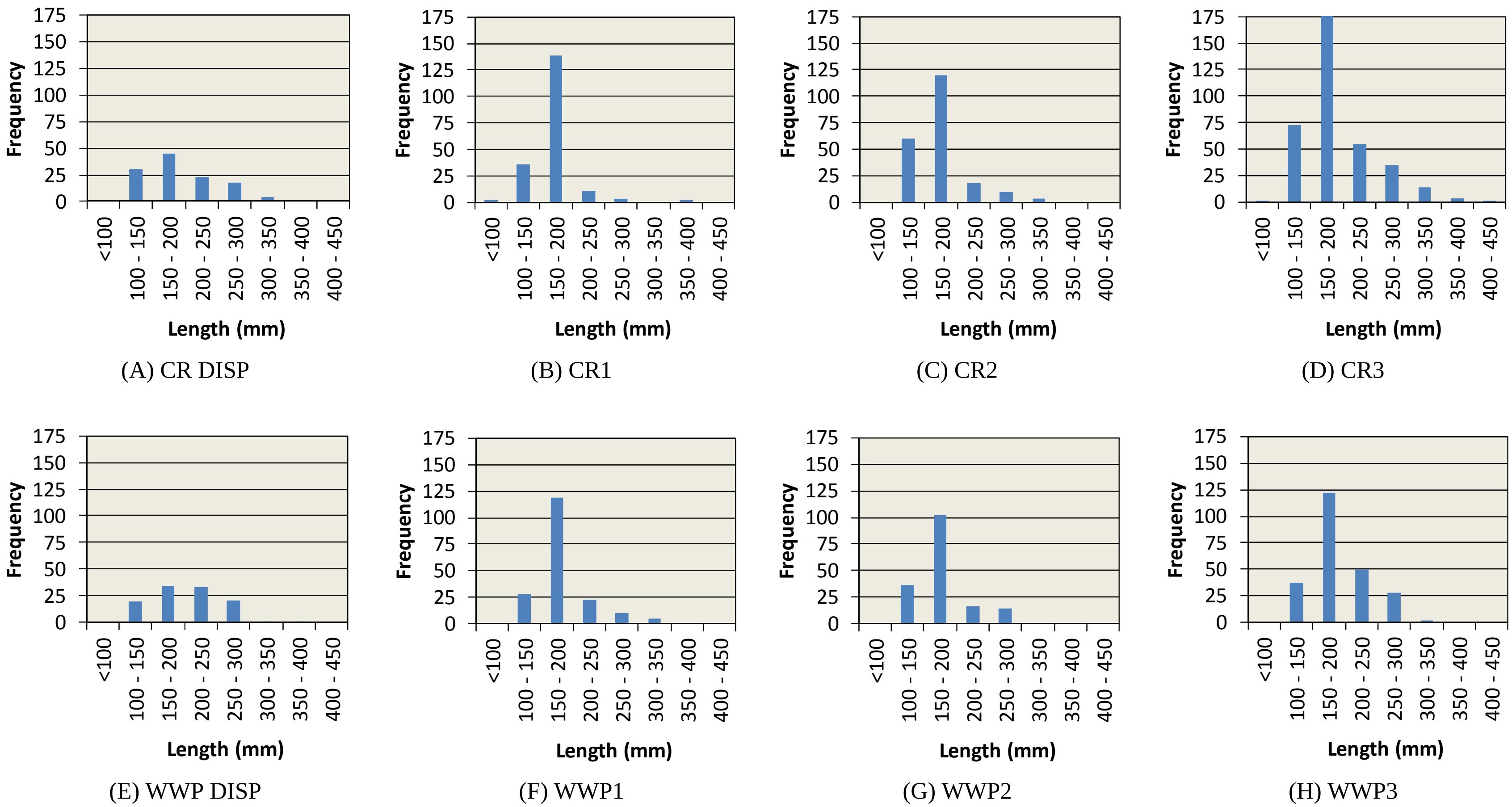



(E) WWP2




(F) WWP3

**Figure 3.2: Length (mm) frequency of tagged non-salmonids at release locations.**




(A) CR DISP (B) CR1 (C) CR2 (D) CR3

(E) WWP DISP (F) WWP1 (G) WWP2 (H) WWP3

**Figure 3.3: Length (mm) frequency of tagged salmonids at release locations.**

### *3.1.2 Raw Movement Data*

Counts of observed movement from the initial release location (Table 3.3) 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 3.4) 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 plots of fishes that successfully moved upstream vs. those that did not depict differences in movement success based on body length (Figures 3.4 through 3.11). These data are first presented for all fishes in the study (Figures 3.4 and 3.5), followed by separate evaluations for each *MRT*: electrofishing (Figures 3.6 and 3.7), stocking (Figures 3.8 and 3.9), and displacement (Figures 3.10 and 3.11) types. As with raw data previously presented in Tables 3.3 and 3.4, 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.

## Table 3.3: Frequency of successful upstream movement from the initial release location (*n* = 1639).

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

## Table 3.4: Frequency of successful upstream movement of all fishes at all sites (*n* = 2648).

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

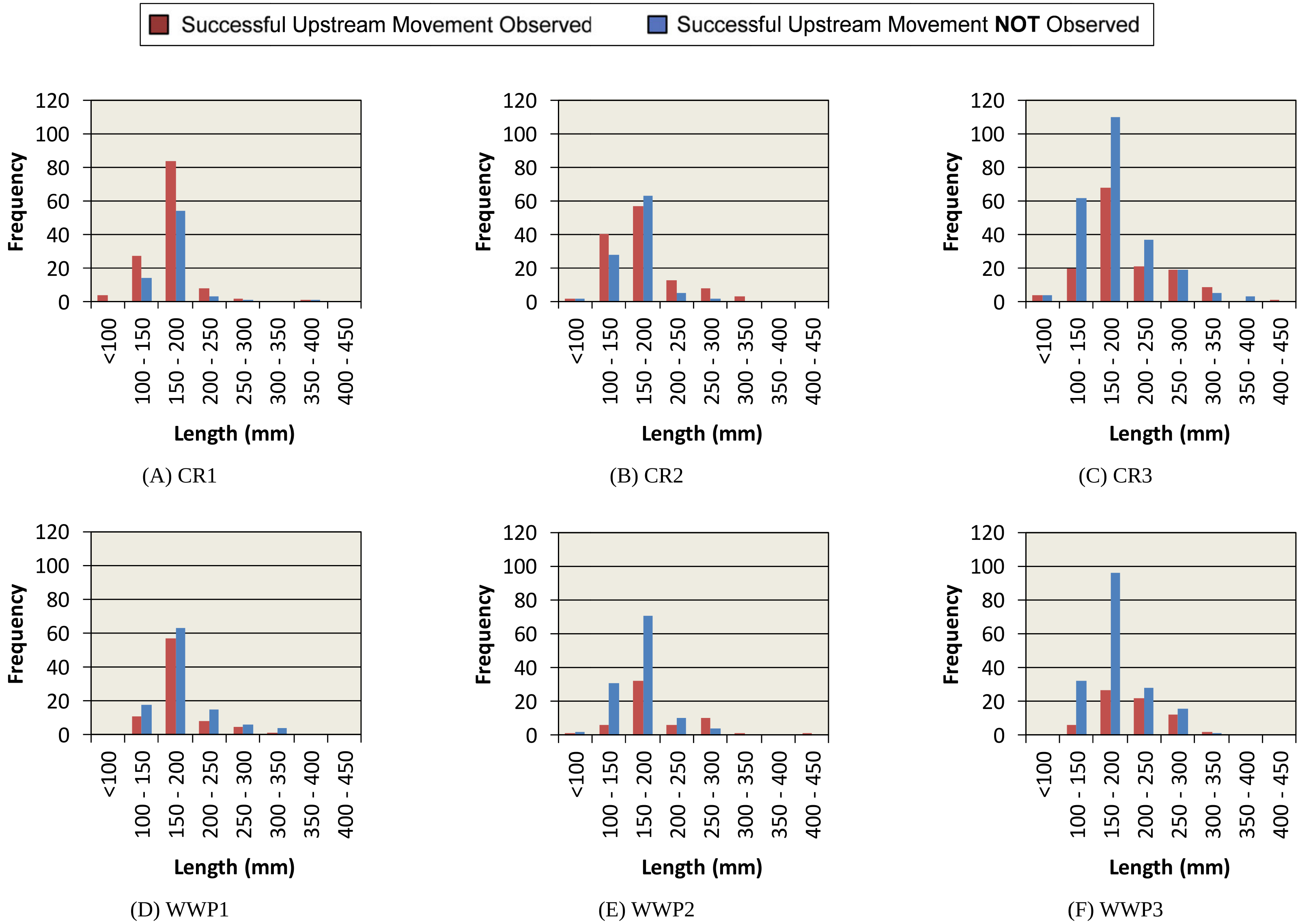



**Figure 3.4: Frequency of fishes that successfully moved upstream from the <u>initial</u> release location vs. fishes that did not move upstream for <u>all</u> species and <u>all</u> *MRT* (*n* = 1639).**

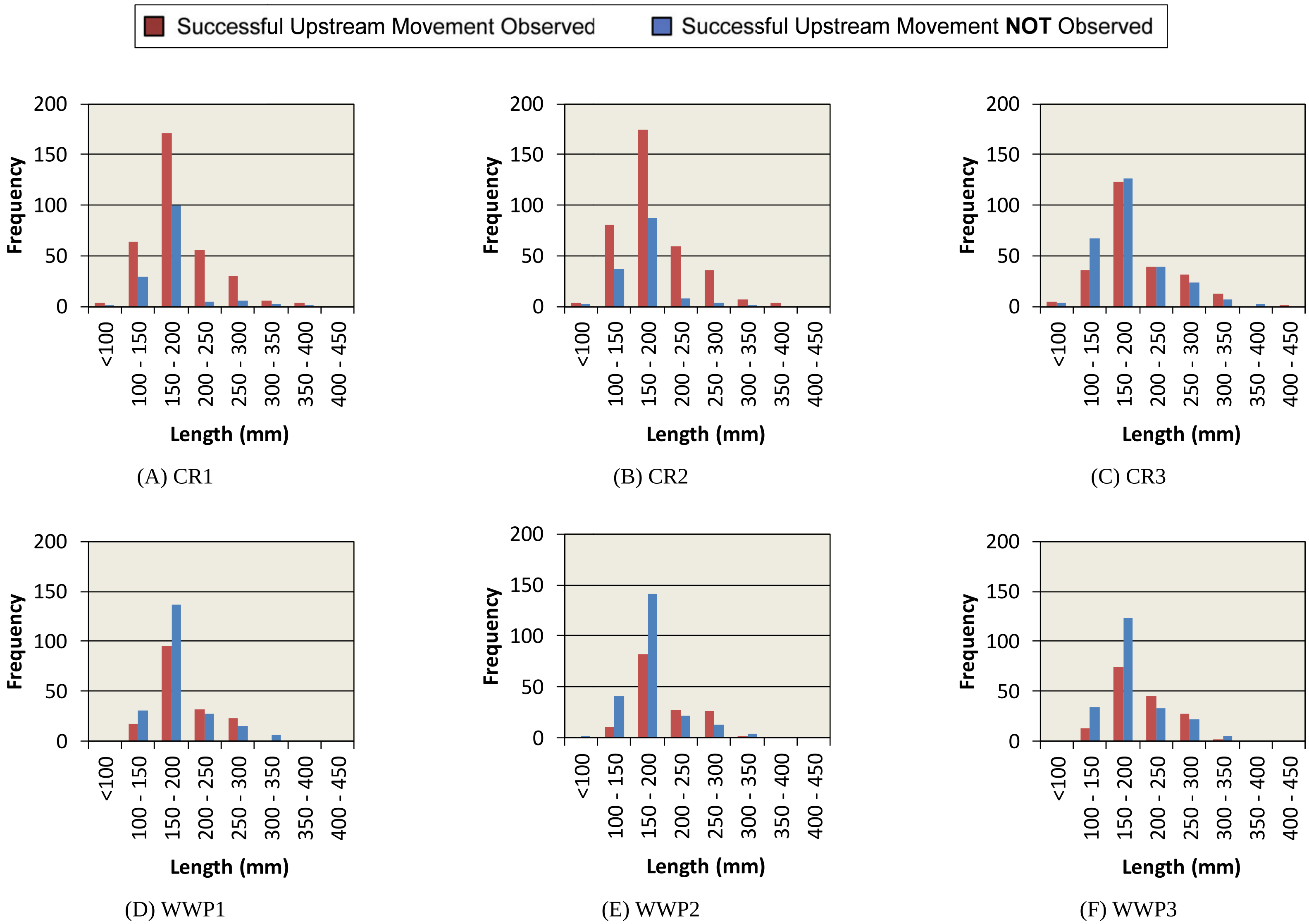
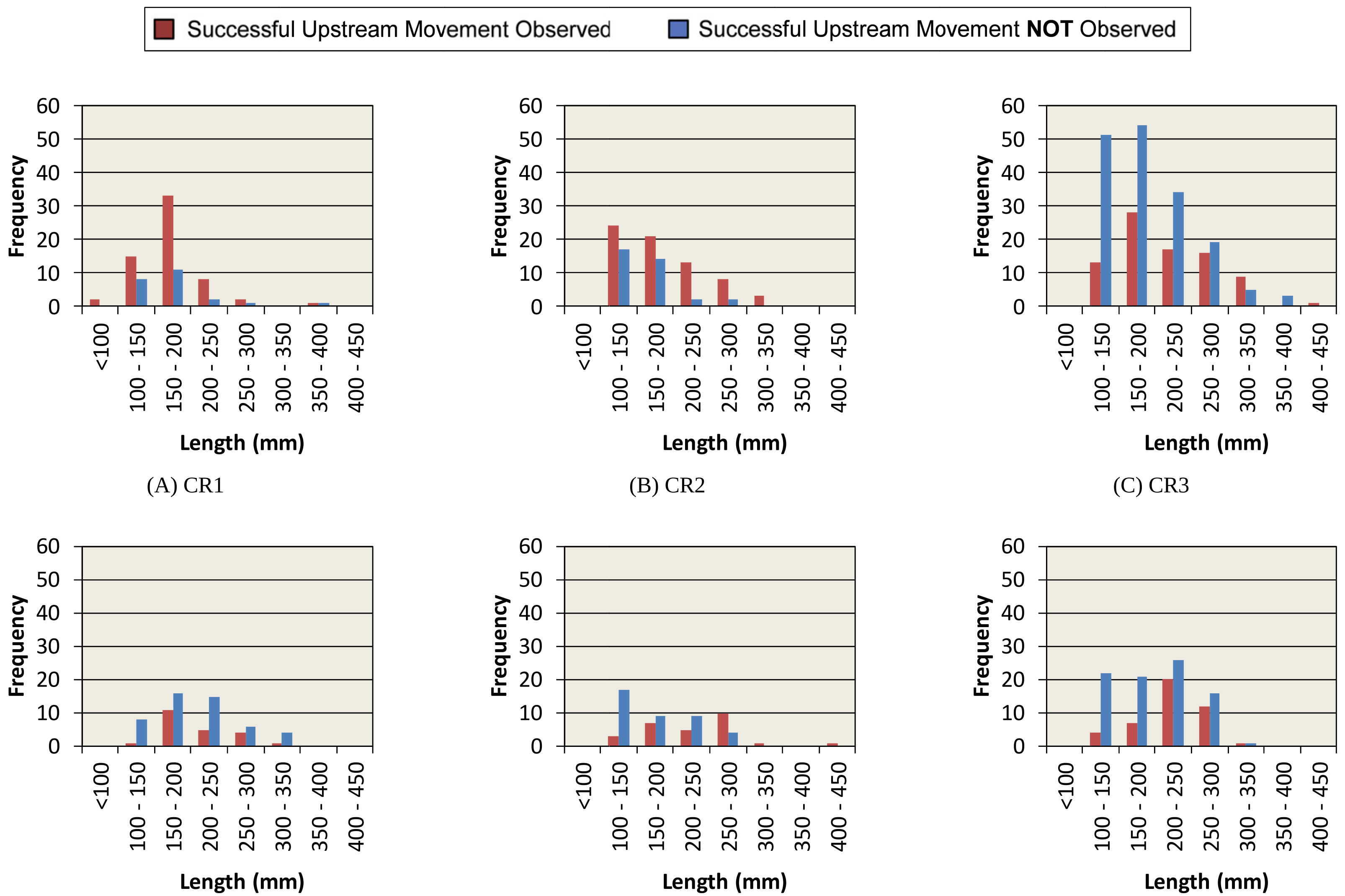


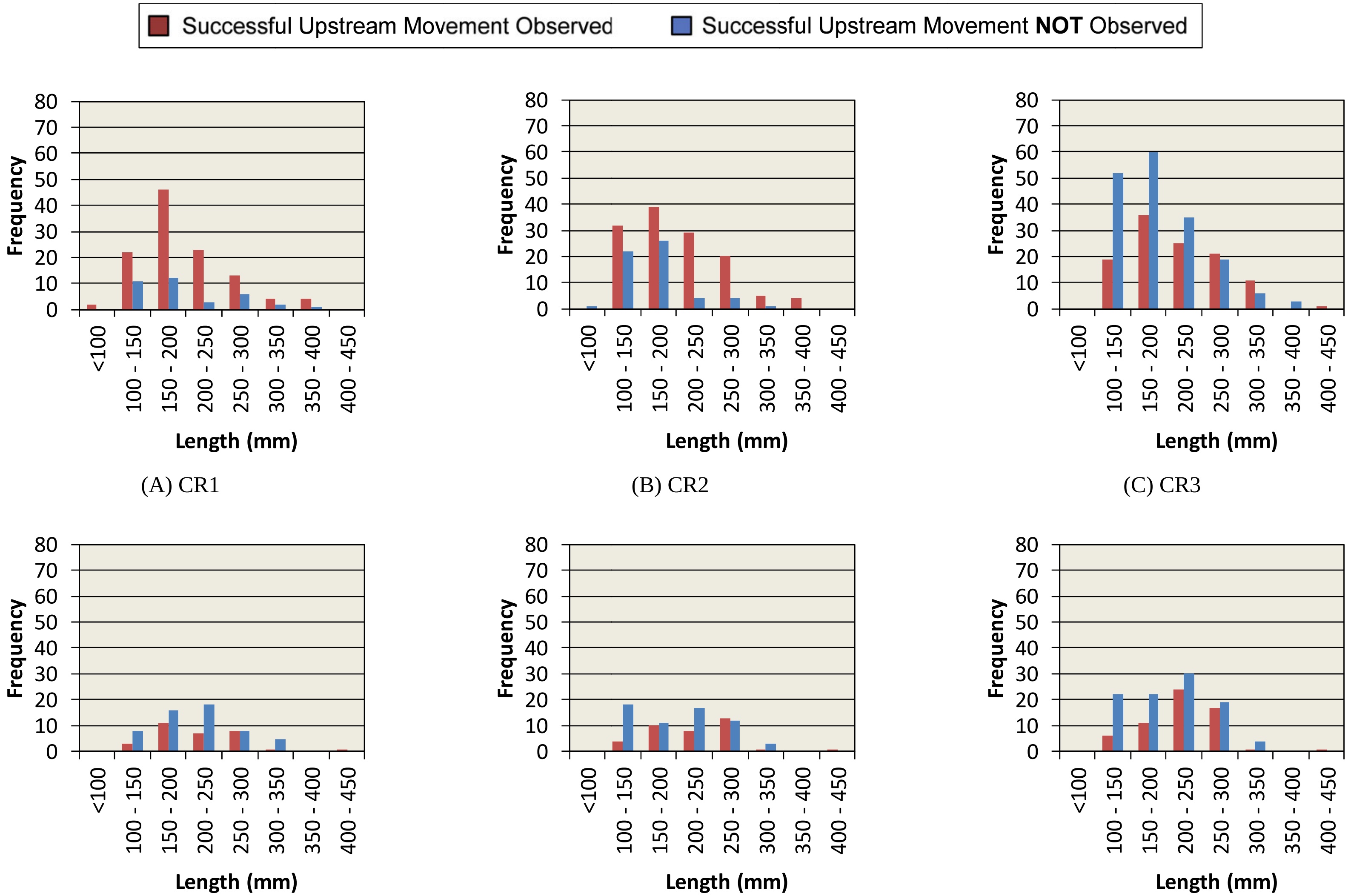

**Figure 3.5: Frequency of fishes that successfully moved upstream at <u>each location</u> vs. fishes that did not move upstream for <u>all</u> species and <u>all</u> *MRT* (*n* = 2648).**




(A) CR1 (B) CR2 (C) CR3

(D) WWP1 (E) WWP2 (F) WWP3

**Figure 3.6: Frequency of fishes that successfully moved upstream from the <u>initial</u> release location vs. fishes that did not move upstream for <u>salmonid</u> species and <u>electrofishing</u> *MRT* (*n* = 705).**




(A) CR1 (B) CR2 (C) CR3

(D) WWP1 (E) WWP2 (F) WWP3

**Figure 3.7: Frequency of fishes that successfully moved upstream at <u>each location</u> vs. fishes that did not move upstream for <u>salmonid</u> species and <u>electrofishing</u> *MRT* (*n* = 965).**

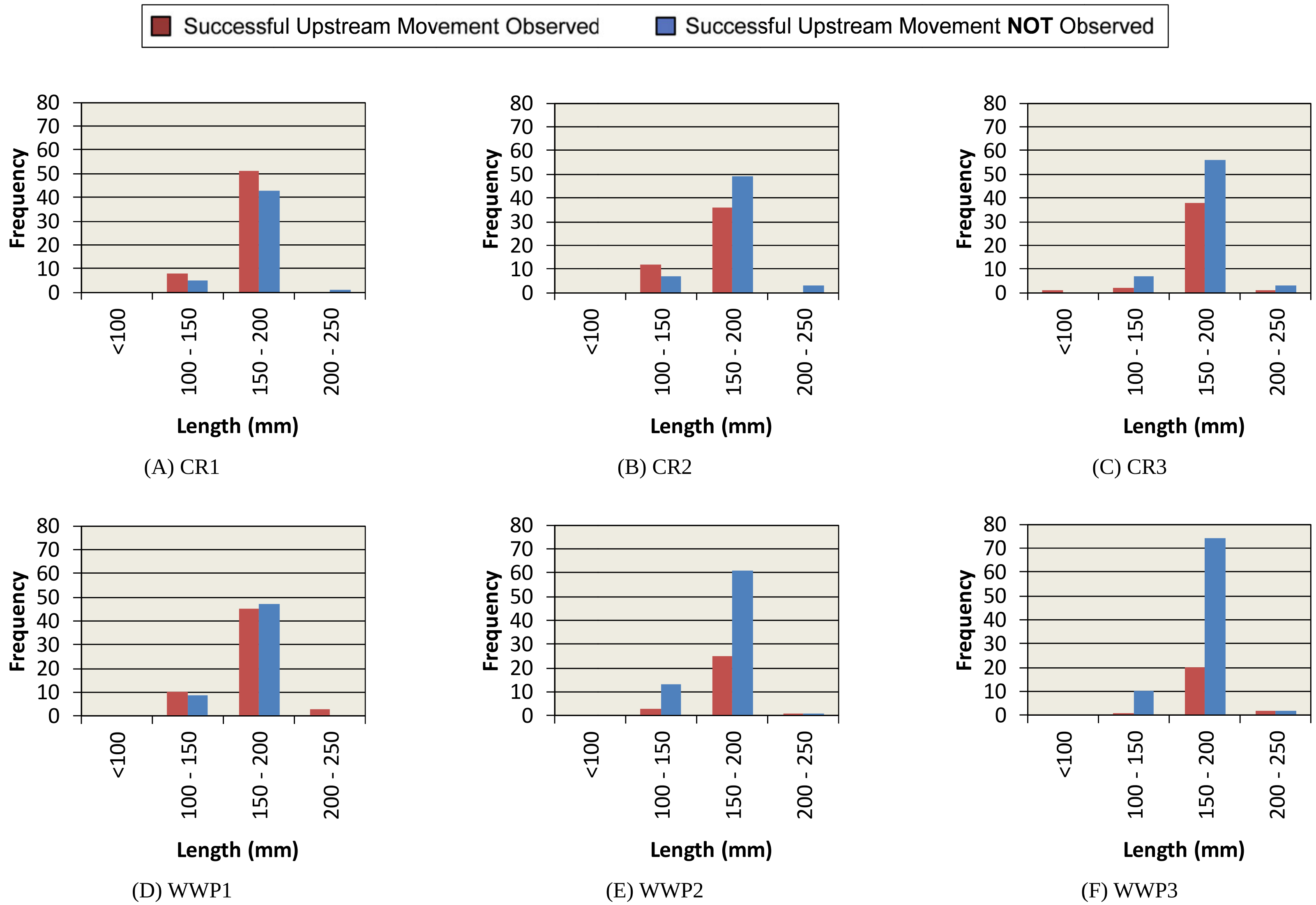
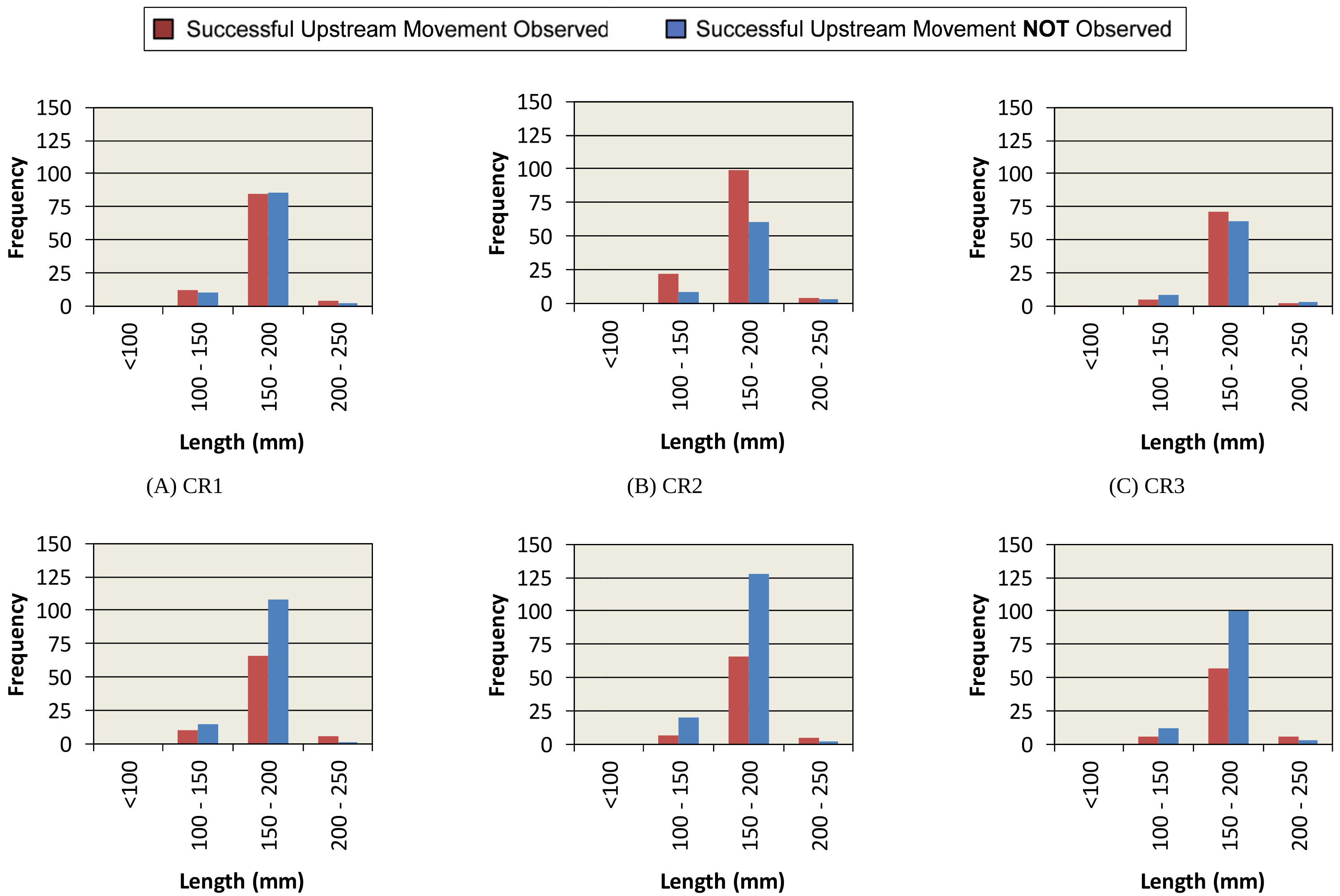


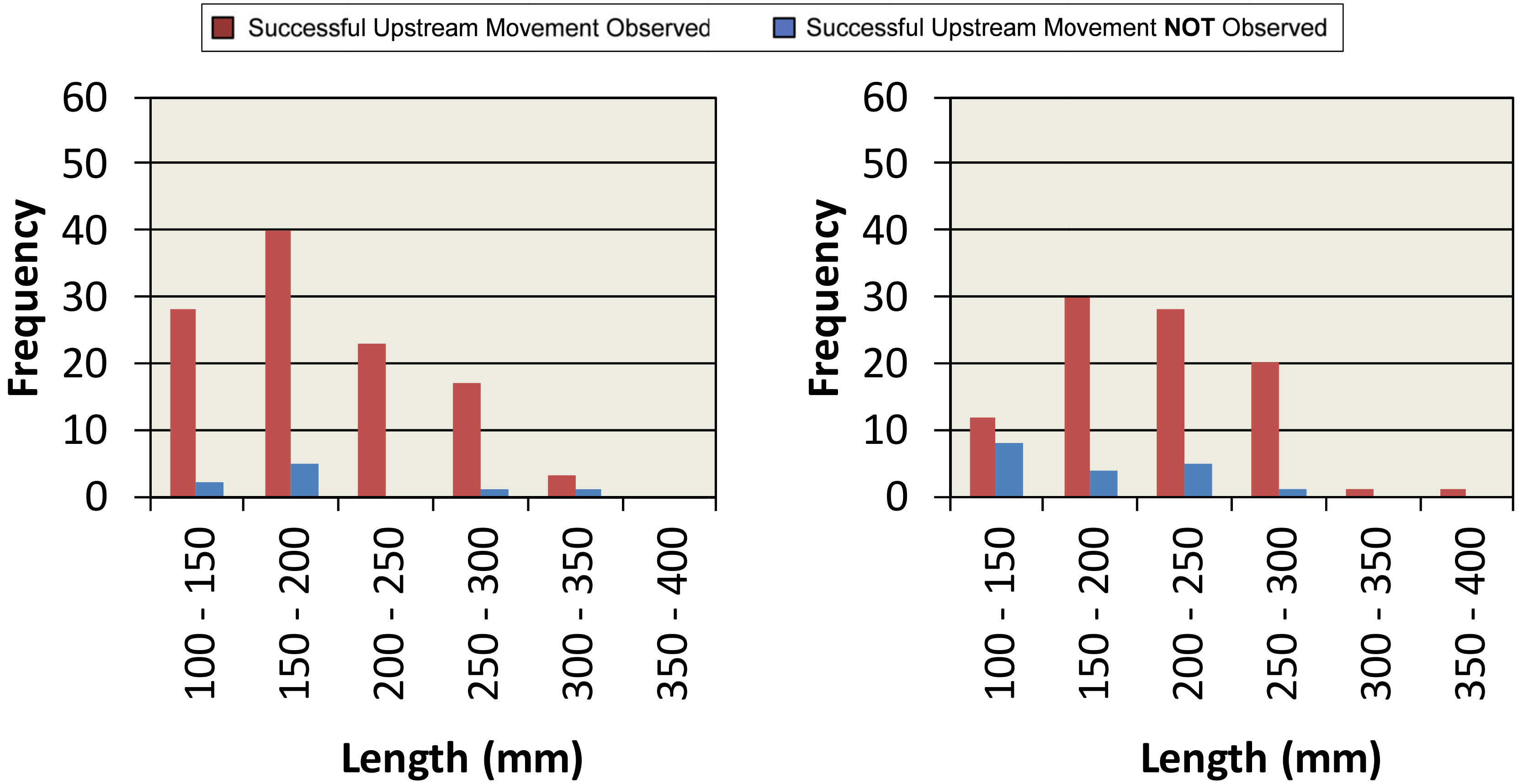

**Figure 3.8: Frequency of fishes that successfully moved upstream from the <u>initial</u> release location vs. fishes that did not move upstream for <u>HOF</u> species and <u>stocking</u> *MRT* (*n* = 650).**




(A) CR1 (B) CR2 (C) CR3

(D) WWP1 (E) WWP2 (F) WWP3

**Figure 3.9: Frequency of fishes that successfully moved upstream at <u>each location</u> vs. fishes that did not move upstream for <u>HOF</u> species and <u>stocking</u> *MRT* (*n* = 1170).**




(A) CR DISP

(B) WWP DISP

**Figure 3.10: Frequency of fishes that successfully moved upstream from the <u>initial</u> reach displacement location vs. fishes that did not move upstream for <u>salmonid</u> species and <u>displacement</u> *MRT* (*n* = 230).**

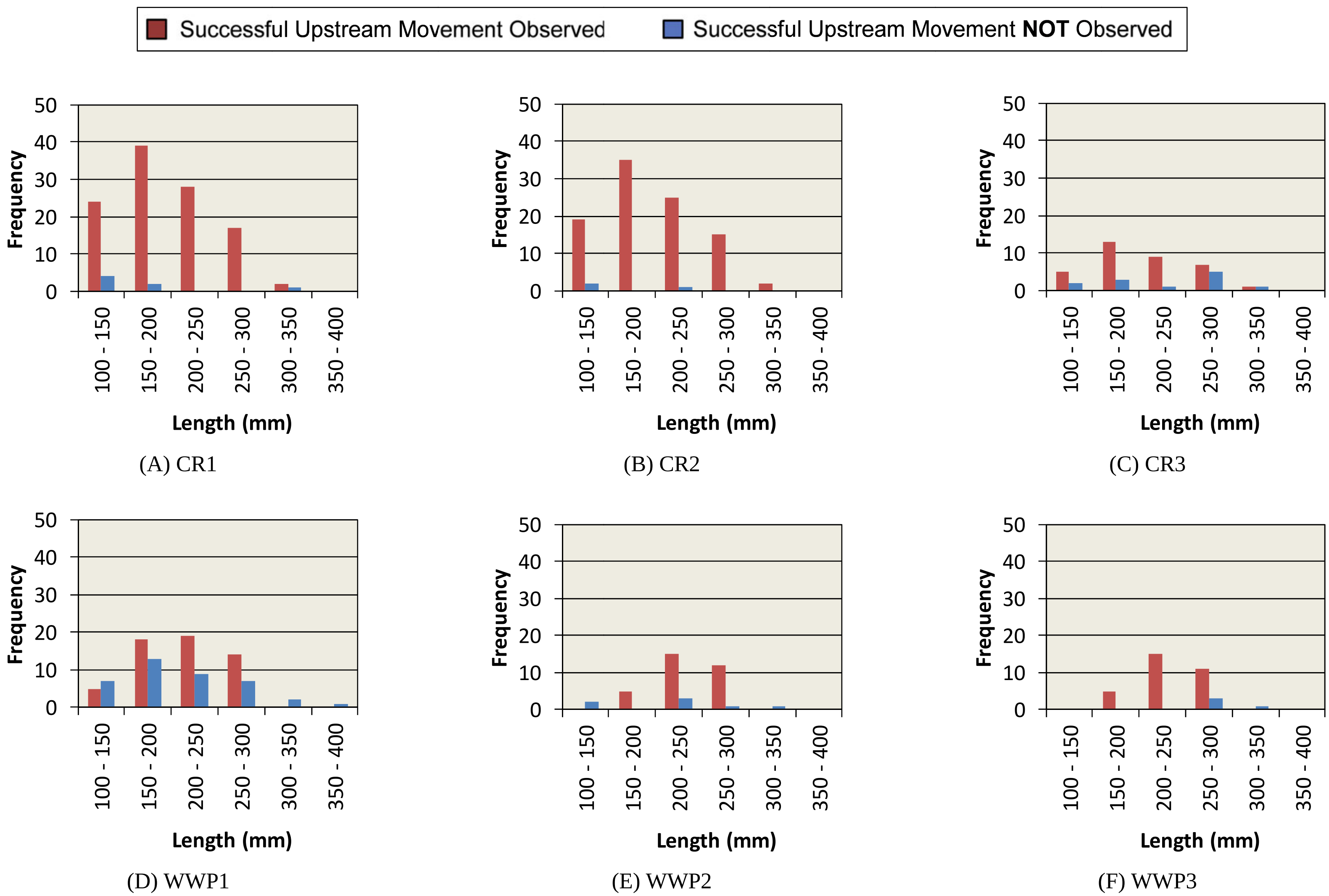



**Figure 3.11: Frequency of fishes that successfully moved upstream at <u>each location</u> vs. fishes that did not move upstream for <u>salmonid</u> species and <u>displacement</u> *MRT* (*n* = 432). Within the displacement MRT, a possible upstream movement attempt at locations 2 and 3 within the WWP and CR sites is conditional on previous upstream passage success at their respective downstream locations.**

Total numbers of fishes (Figure 3.4) moving upstream from their initial release location, and total numbers of all fishes moving across all locations (Figure 3.5) 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 3.4) and all movement plots (Figure 3.5). For fishes only within the electrofishing *MRT*, similar trends are maintained but observations of very large numbers of fishes not moving through CR3 are more evident. Analysis of the stocking *MRT* also indicate smaller fishes are less likely to move upstream at the WWPs sites, and results for CR3 appear similar to CR1 and CR2. The displacement *MRT* indicates that there were large numbers of fishes not successfully moving upstream through WWP1, but very high success for fishes that successfully moved upstream to WWP2 and WWP3 (Figures 3.10 and 3.11). Conversely, larger proportions of displacement *MRT* fishes moved through all of the CR sites successfully. Data for non-salmonids are not reported by length because of small frequency of observations for these species throughout the study.

### *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 3.5) 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 $\Delta$AICc (corrected AIC) = 1.61, AICc weight = 0.3, model likelihood = 0.447; all remaining models have a $\Delta$AICc > 8, AICc Weight < 0.01, model likelihood < 0.015.

Final form of the most supported model:

$$
\begin{aligned}
logistic(\phi) = \beta_{INT} &+ \beta_1[MRT] + \beta_2[EVENT] + \beta_3[SPECIES] \\
&+ \beta_4[LENGTH] + \beta_5[LOCATION] \\
&+ \beta_9[LOCATION]*[LENGTH]
\end{aligned}
\qquad \textbf{(Eq. 3.1)}
$$

**Table 3.5: Regression parameter estimates given as log-odds ratios for the most supported model.**

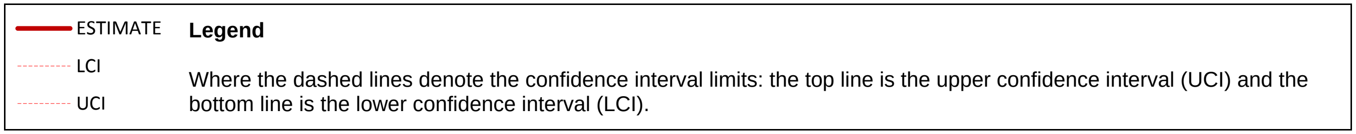
| Beta | Variable | Category | Estimate | SE | LCI | UCI |
|---|---|---|---|---|---|---|
| 0 | [*INT*] | INT | 0.509 | 0.414 | -0.303 | 1.320 |
| 1 | [*MRT*] | ELECTROFISHING | – | – | – | – |
| | | **STOCKING** | **0.788** | **0.138** | **0.517** | **1.058** |
| | | **DISPLACEMENT** | **1.666** | **0.154**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

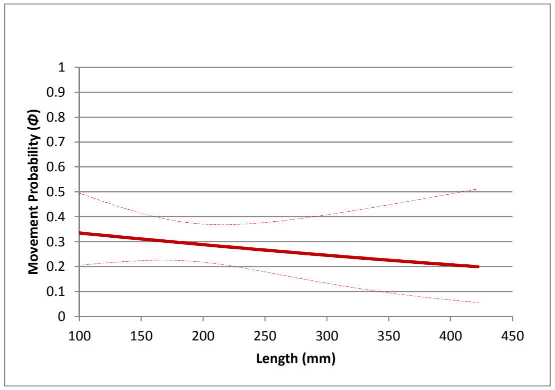
Definitions: LCI = lower confidence interval (0.05); SE = standard error; and UCI = upper confidence interval (0.95).

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

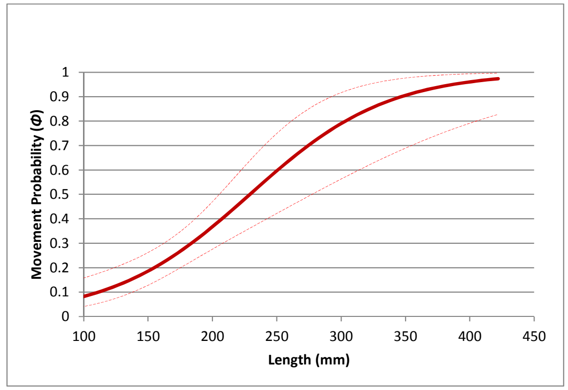
The selection of the final model (Eq. 3.1) over the candidate set models indicate that individual site location, body length, and species are all significant effects in estimating upstream movement probability. The calculated detection probabilities (Appendix B) for each of the antennas in the final 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 indicate that fishes of different body lengths have different probabilities of moving across the different WWP structures and CR pools. This relationship (Figure 3.12) 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.

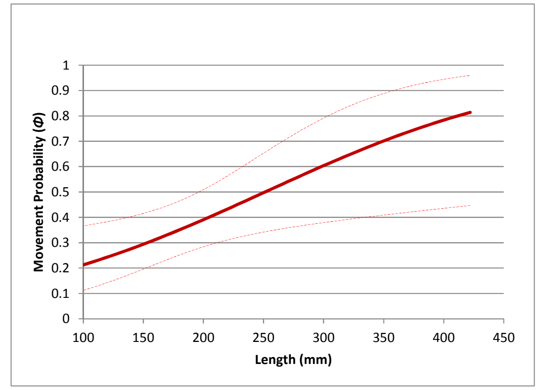


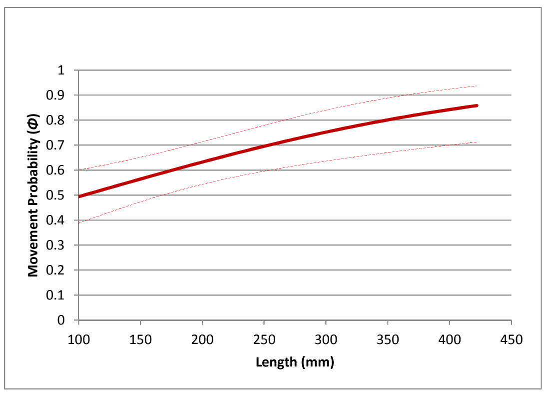

(A) WWP1



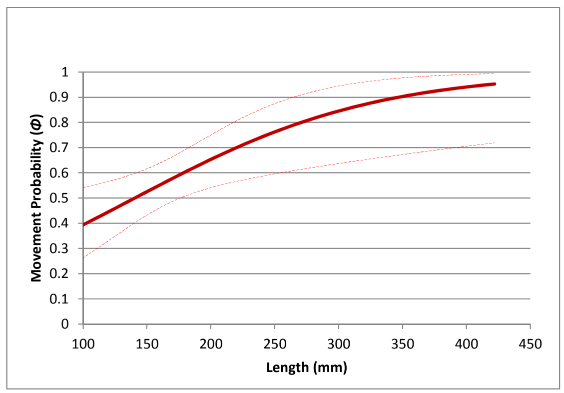

(B) WWP2



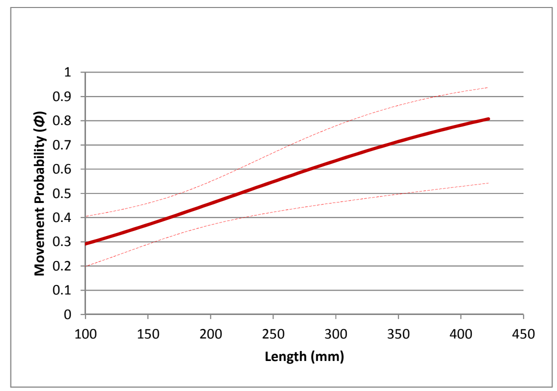

(C) WWP3




(D) CR1




(E) CR2




(F) CR3

**Figure 3.12: 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 $\phi$ estimates: *MRT* = electrofishing; *SPECIES* = TROUT; *EVENT* = 3).**

## 3.2 Hydraulic Results

### *3.2.1 Stage-discharge Relationship*

The eighteen discharge measurements were used to construct a stage-discharge relationship for all sites (Figure 3.13). The maximum discharge directly measured in the field was 172 cfs and the minimum measured was 8 cfs. Because of the atypical low-flow conditions experienced during 2012, water-surface levels remained largely within the channel banks and linear regression produced the best fit ($r^2$ = 0.98) over power functions for the stage-discharge relationship. A continuous hydrograph for the complete study period is provided in Appendix A.

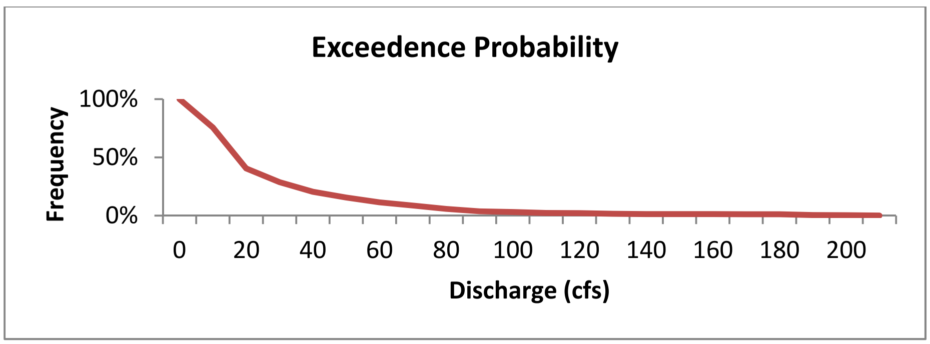
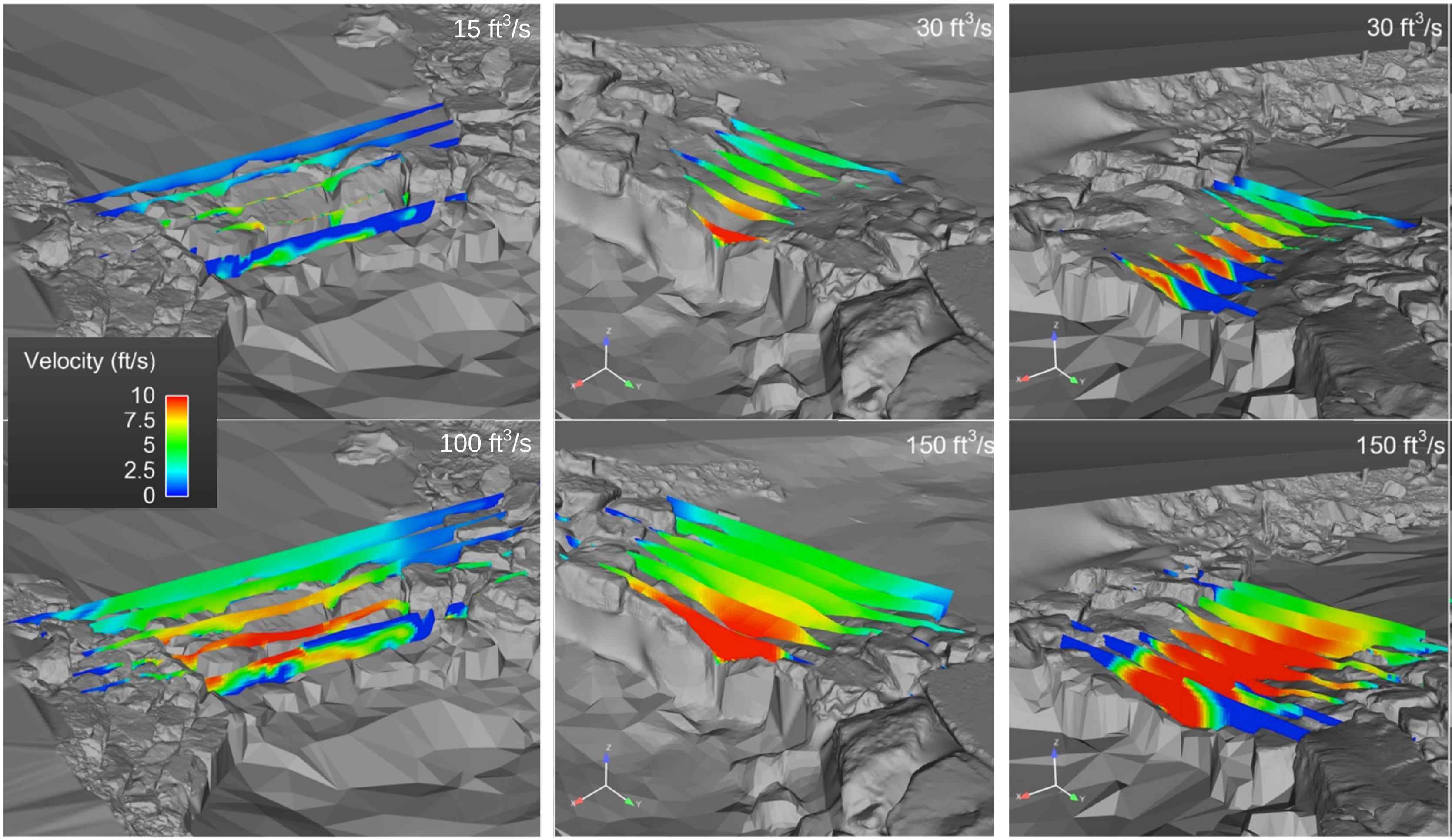



**Figure 3.13: Flow exceedence probability during study period.**

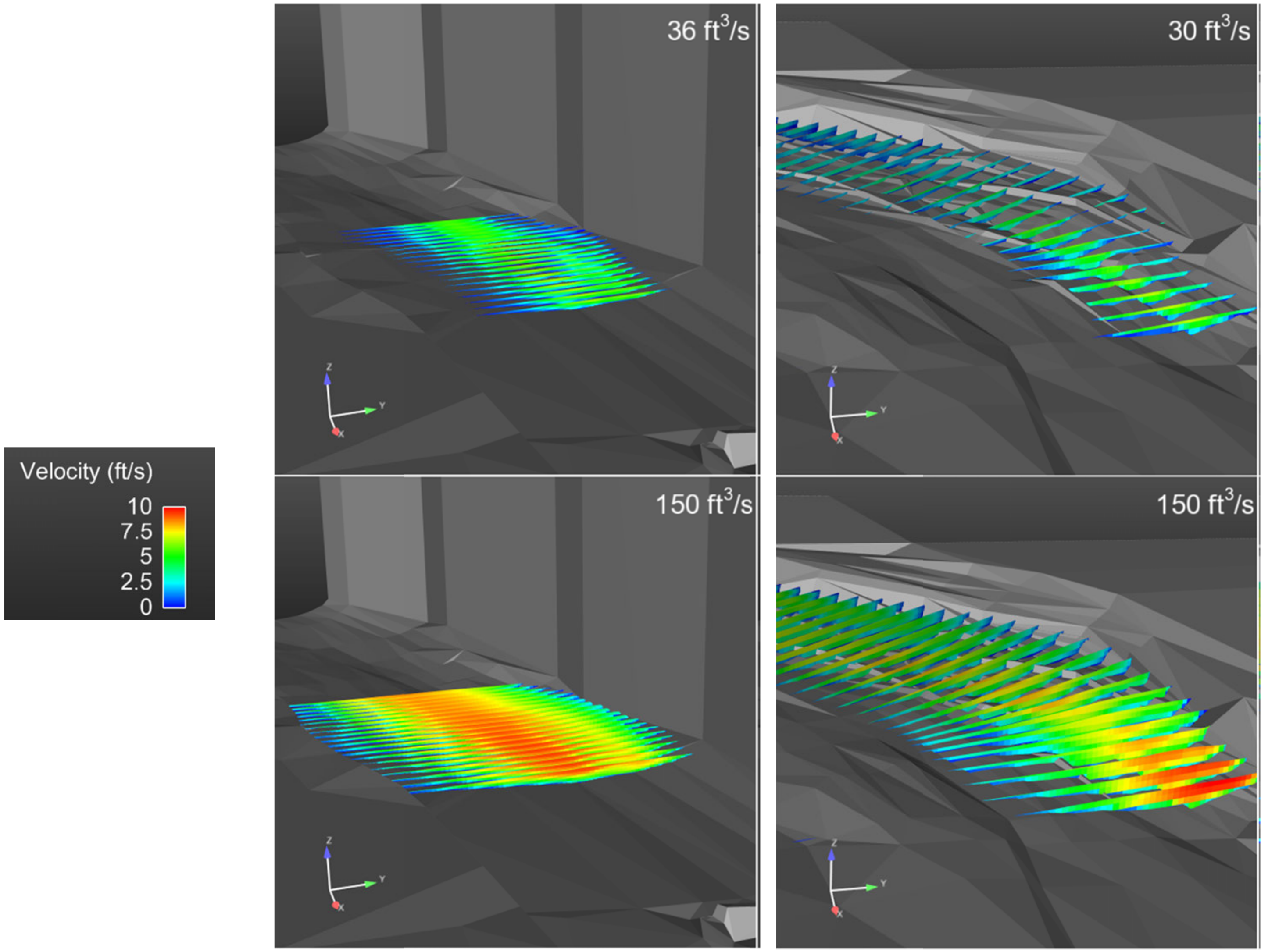
### *3.2.2 Hydraulic Model Results and Observations*

Detailed results of the 3-D hydraulic characterizations developed for the WWP and CR sites using FLOW-3D are presented in Appendix C. Illustrations of cross-sectional velocities and calculated cross-section velocity quantiles are presented for each of the six model discharges and each location (Appendix C). Model results for a low and high discharge event highlight differences between the WWP (Figure 3.14) and CR (Figure 3.15) 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.




(A) WWP1 (B) WWP2 (C) WWP3

**Figure 3.14: Cross-sectional velocities for a low- and high-flow condition at: (A) WWP1; (B) WWP2; and (C) WWP3.**




(A) CR2 (B) CR3

**Figure 3.15: Cross-sectional velocities for a low- and high-flow condition at: (A) CR2 and (B) CR3.**

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 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.

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.

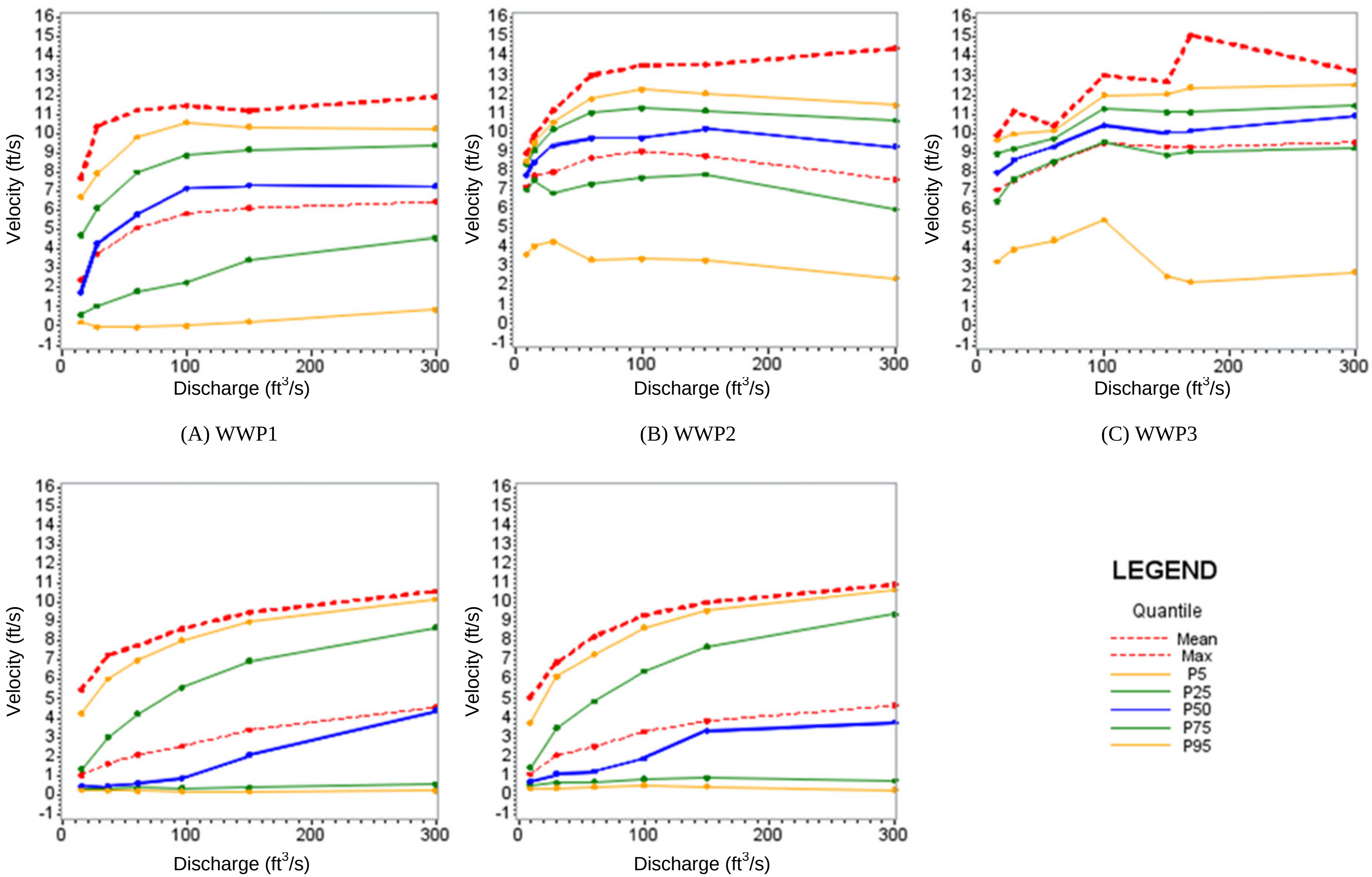
As expected, the results for CR2 showed very low overall velocity magnitudes as compared to those within the WWP. It also appears to provide a very wide range of velocity magnitudes at each cross section and no single location had a velocity challenge greater than the average conditions. At low discharges, 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.

### *3.2.3 Limiting Velocity and Flow Depth Magnitudes*

Summaries of the limiting cross-sectional velocity for burst swimming conditions (Figure 3.16) and flow depth (Figure 3.17) are presented as a function of discharge. The results of this analysis indicate large differences between CR and WWP in magnitude of velocity and flow depth that must be overcome for successful upstream movement.

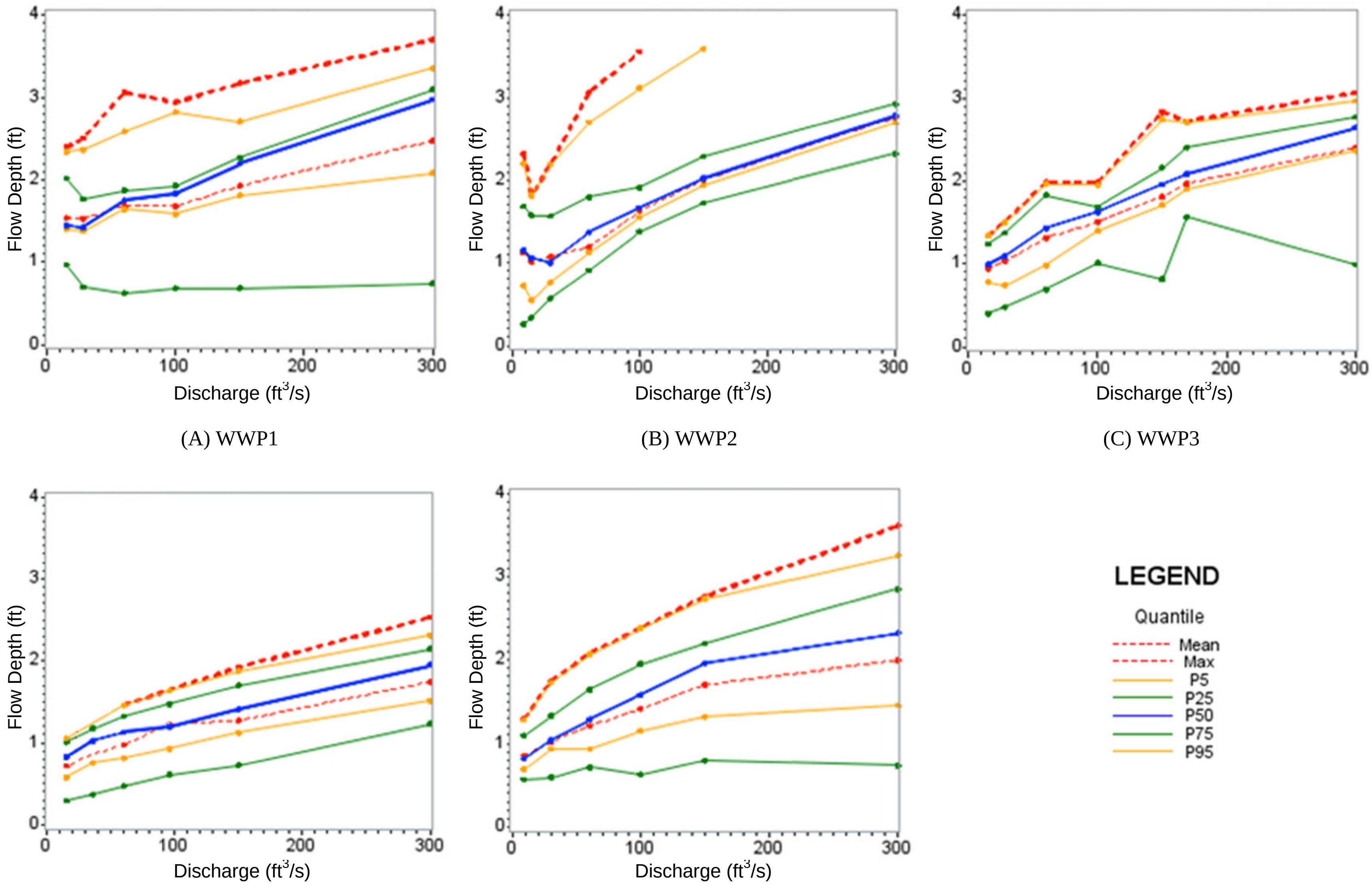
Further comparisons among the individual WWP sites show variation in velocity and depth distributions. Within WWP2, upstream moving fishes must pass a cross section where 75% of the flow area is greater than 6 to 8 ft/s and 95% of the flow area is greater than 3 to 4 ft/s. WWP3 indicates that fishes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




(A) WWP1 (B) WWP2 (C) WWP3

(D) CR1/2 (E) CR3

**Figure 3.16: Limiting magnitudes of velocity within the zone of passage to assess burst swimming barriers.**




(A) WWP1

(B) WWP2

(C) WWP3

(D) CR1/2

(E) CR3

**Figure 3.17: Limiting magnitudes of flow depth within the zone of passage.**

### 3.3 Velocity vs. Body Length of Moving Fish

Relationships between fish body length and limiting flow velocities for observations of successful movement are illustrated for the 25$^{th}$, 50$^{th}$, and 95$^{th}$ cross-sectional percentiles (Figures 3.18 through 3.23). Reference lines for the prediction of maximum burst speed are given for 10 BL/s (Peake *et al*., 1997) and 25 BL/s (Castro-Santos *et al*., 2013). Successful movement occurred within WWP sites where fishes were required to overcome velocities of 8 ft/s within the 25$^{th}$ quartile, 10 ft/s in the 50$^{th}$ percentile, and 12 ft/s in the 95$^{th}$ percentile. These results show that all passage events occurring within the CR sites maintained lower flow velocities within 25 and 50% of the cross-sectional area, but near maximum flow velocities (95$^{th}$ percentile) were nearly as high as those within the WWP sites. Despite the much higher velocities found with the WWP sites, no significant thresholds or trends indicate a strong relationship between successful passage and fish body length are observed.

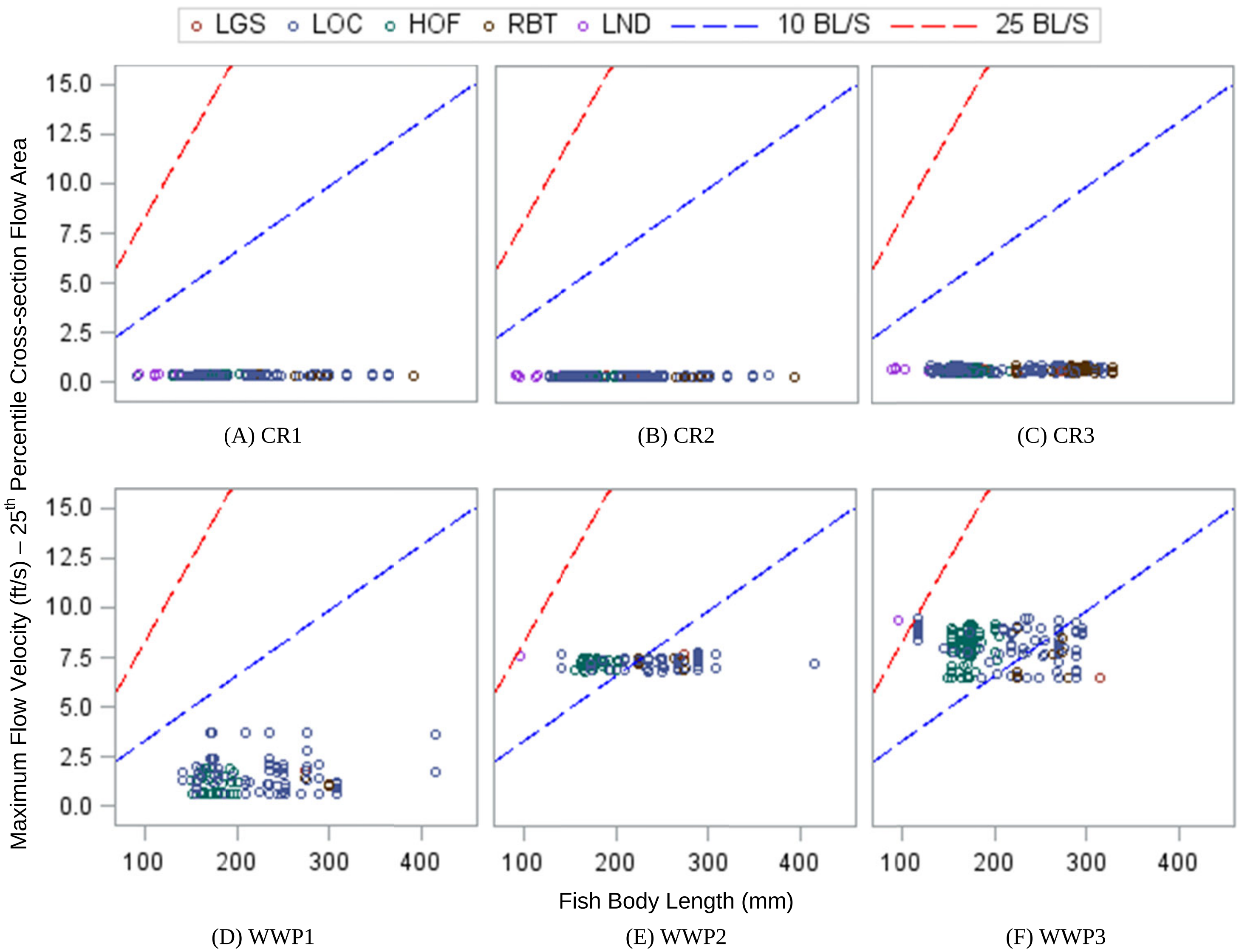



**Figure 3.18: Comparison of fish body length vs. maximum 25$^{th}$ percentile cross-sectional velocity for successful upstream movement that occurred during 2/1/2012 – 7/13/2013 (*n* = 1460).**

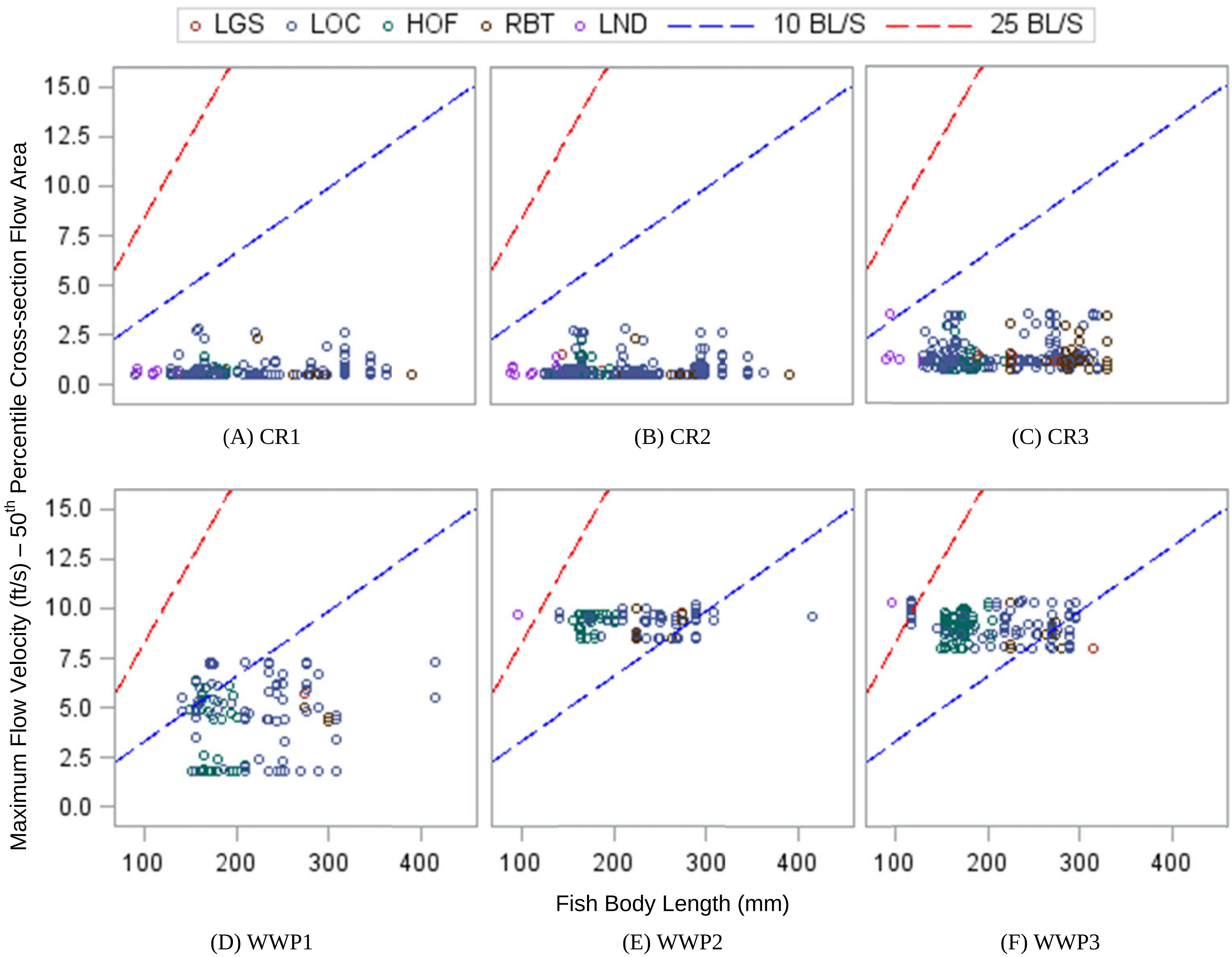



**Figure 3.19: Comparison of fish body length vs. maximum 50$^{th}$ percentile cross-sectional velocity for successful upstream movement that occurred during 2/1/2012 – 7/13/2013 (*n* = 1460).**

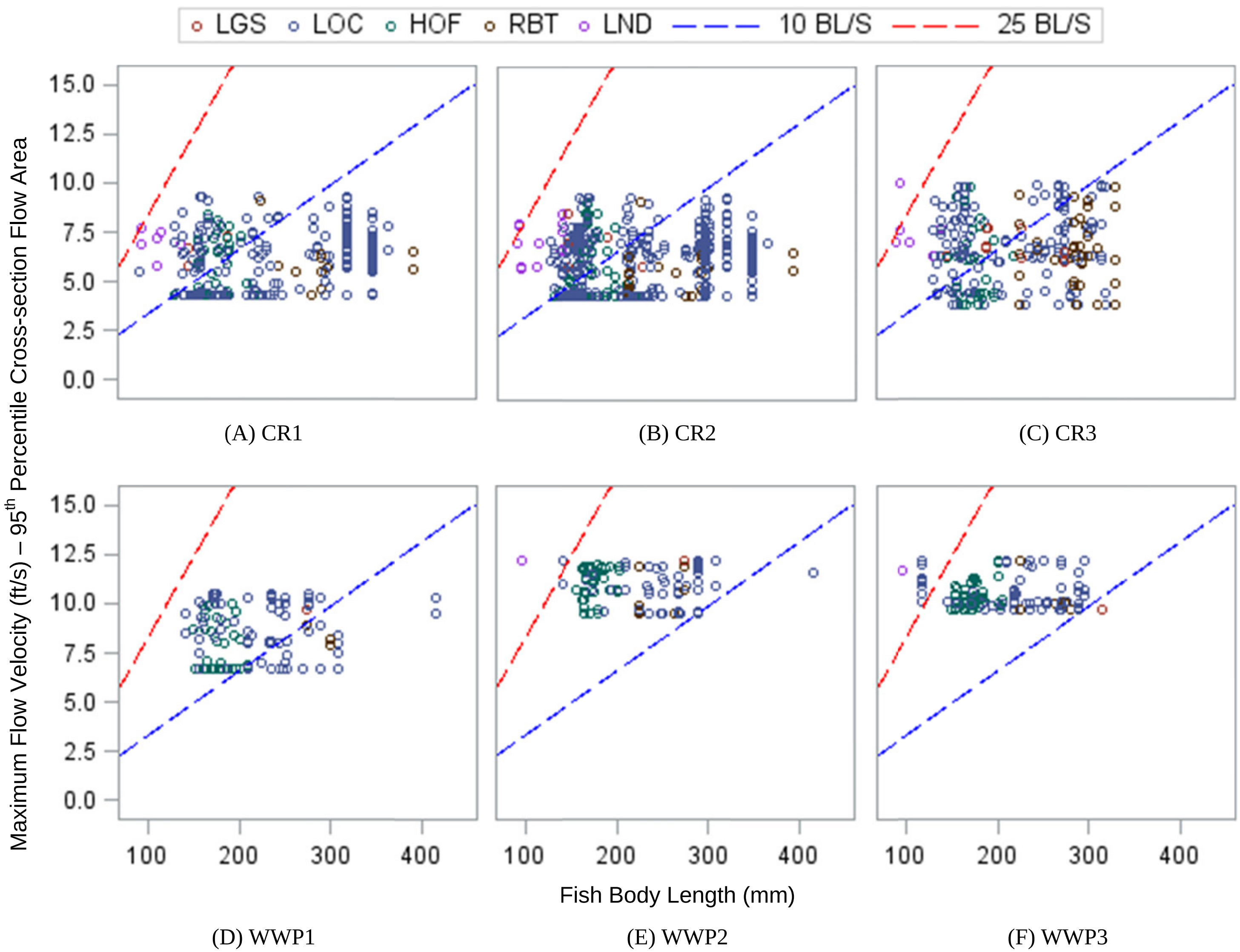



**Figure 3.20: Comparison of fish body length vs. maximum 95$^{th}$ percentile cross-sectional velocity for successful upstream movement that occurred during 2/1/2012 – 7/13/2013 ($n$ = 1460).**

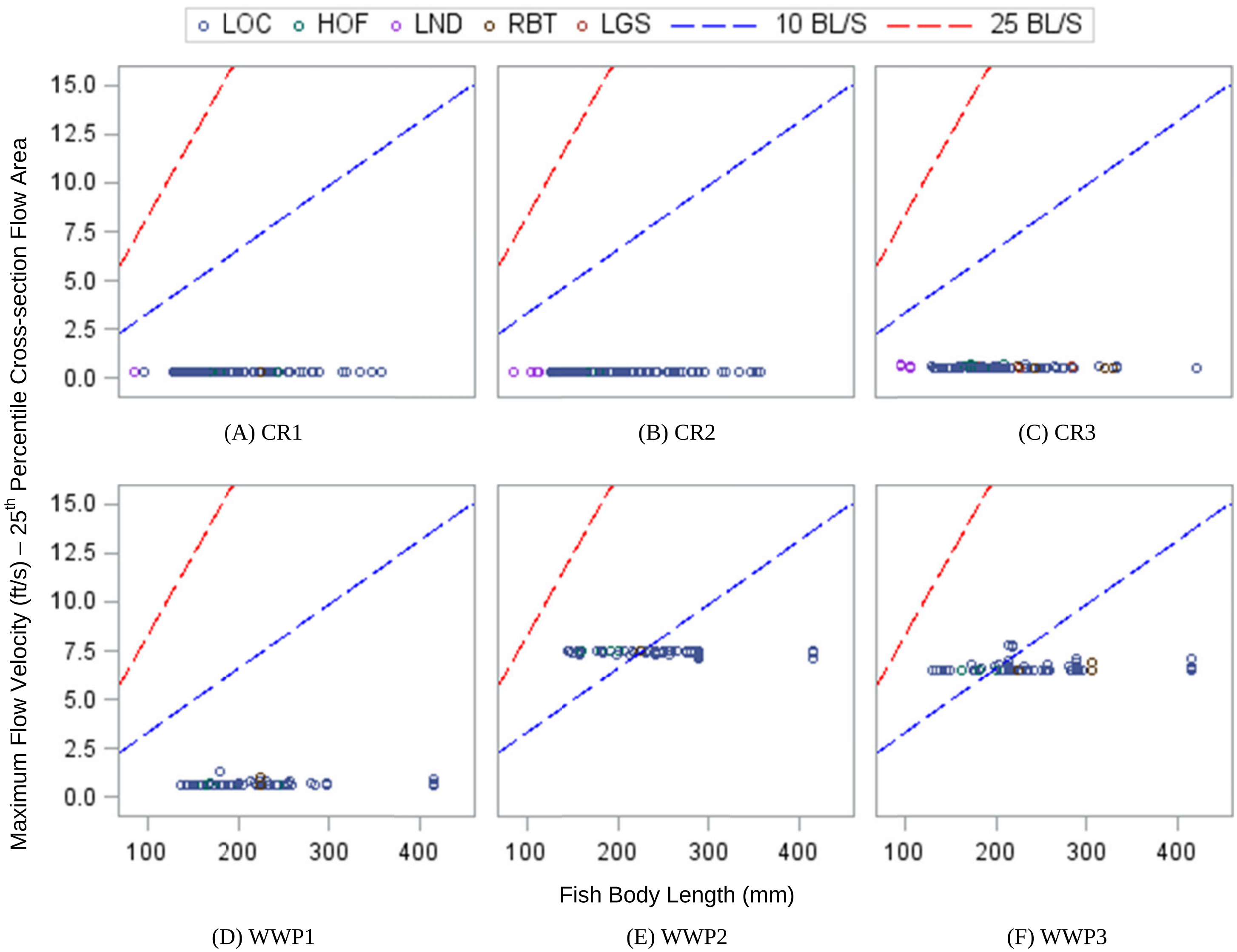



**Figure 3.21: Comparison of fish body length vs. maximum 25th percentile cross-sectional velocity for successful upstream movement that occurred during 9/12/2012 – 12/5/2013 (*n* = 947).**

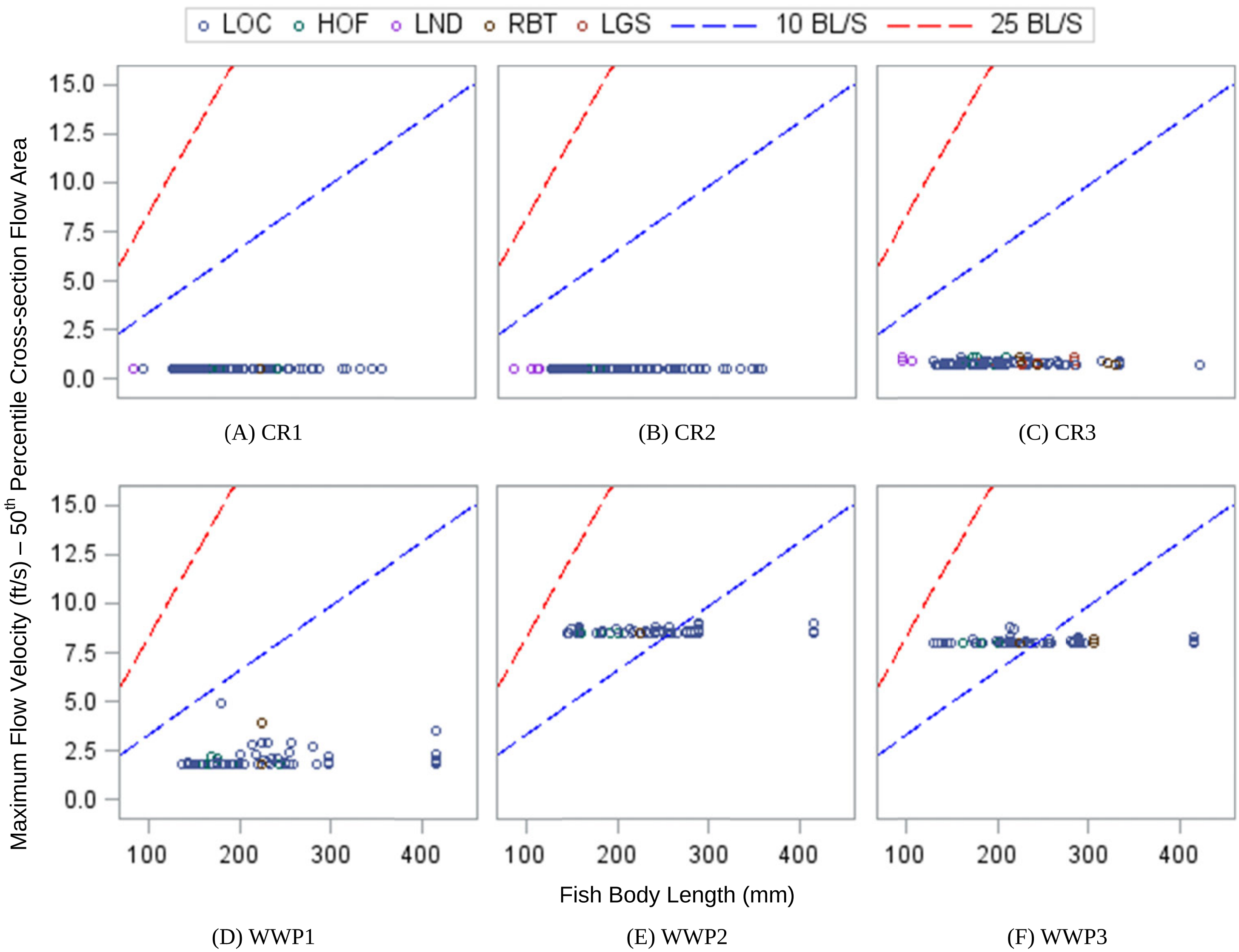
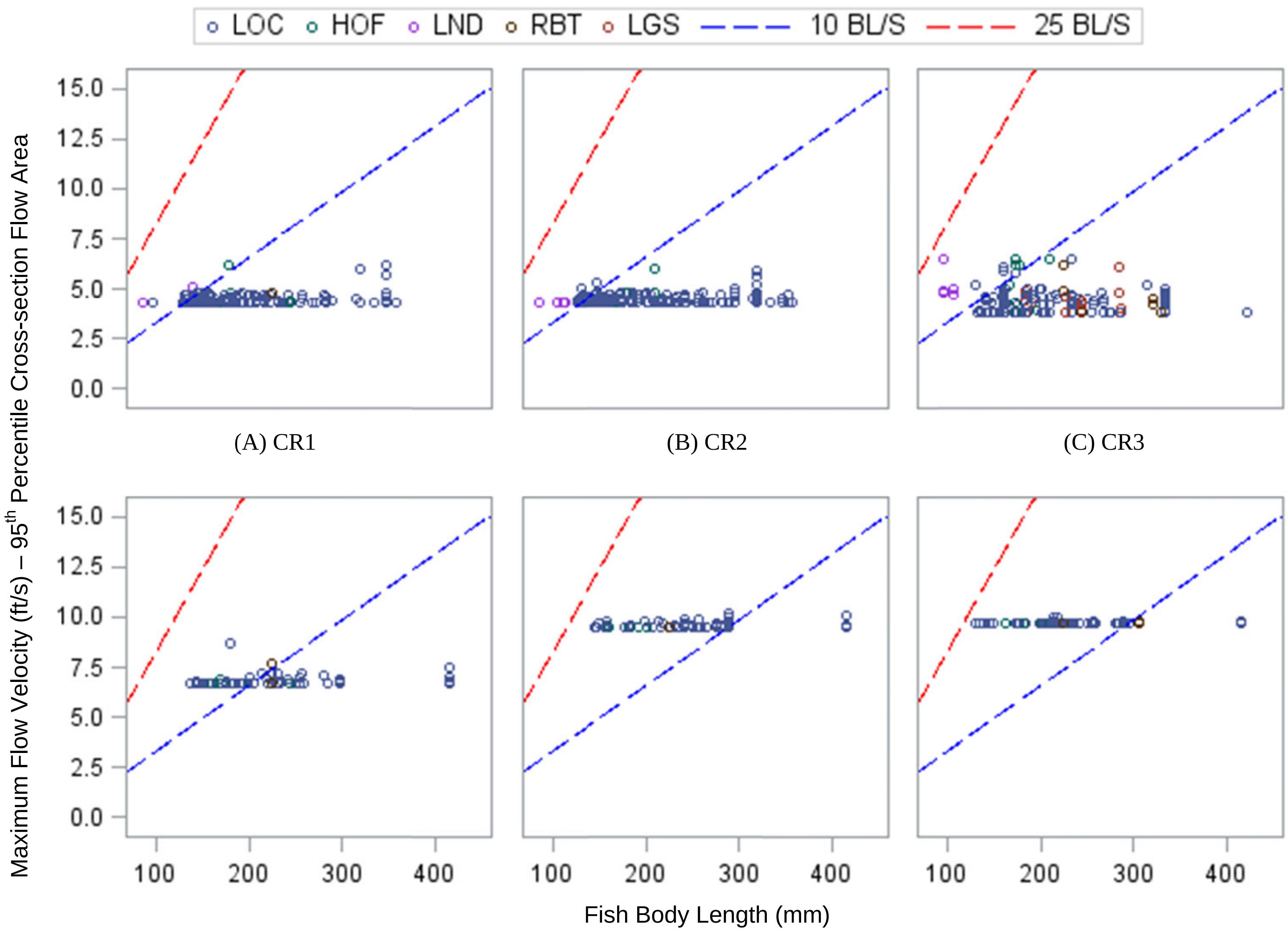



**Figure 3.22: Comparison of fish body length vs. maximum 50th percentile cross-sectional velocity for successful upstream movement that occurred during 9/12/2012 – 12/5/2013 (*n* = 947).**




(D) WWP1 (E) WWP2 (F) WWP3

**Figure 3.23: Comparison of fish body length vs. maximum 95$^{th}$ percentile cross-sectional velocity for successful upstream movement that occurred during 9/12/2012 – 12/5/2013 (*n* = 947).**

# CHAPTER 4 DISCUSSION

## 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

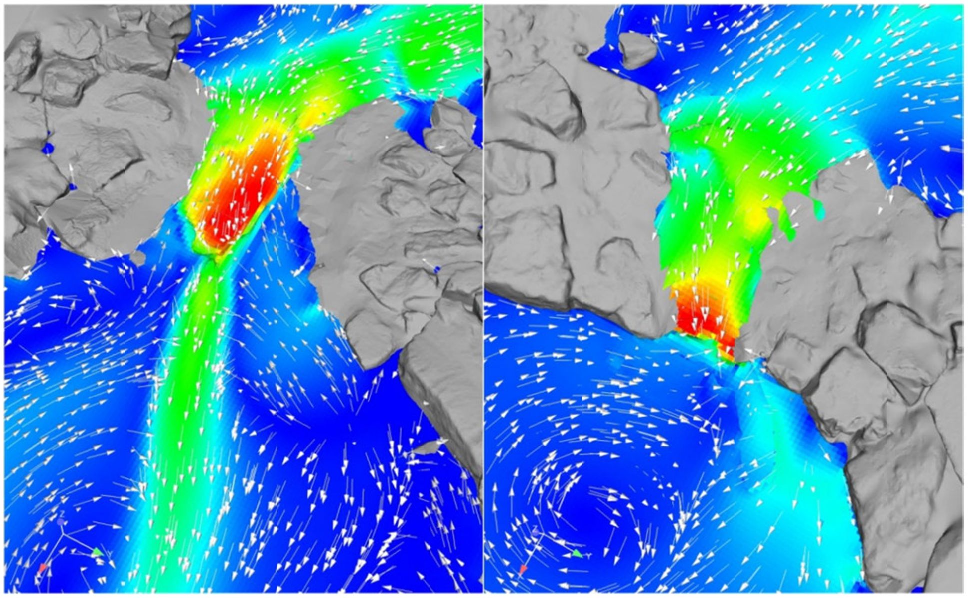
(Figures 3.18 through 3.23) suggests that movement events rarely occurred where any portion of the cross-sectional flow velocities along the structure were greater than 25 BL/s. These results support findings from Castro-Santos *et al*. (2013) that 25 BL/s is a good predictor of brown trout maximum burst 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 closely 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 my 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 4.1). 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.



(A) WWP3 (B) WWP2

**Figure 4.1: (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.**

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, 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.

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 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.

## 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 my 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 my 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 restricts 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 1.4(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.

### 4.3 Future Research

I 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 I 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 my 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.

# CHAPTER 5 CONCLUSIONS

I 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. I 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.

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# APPENDIX A TIME LINE

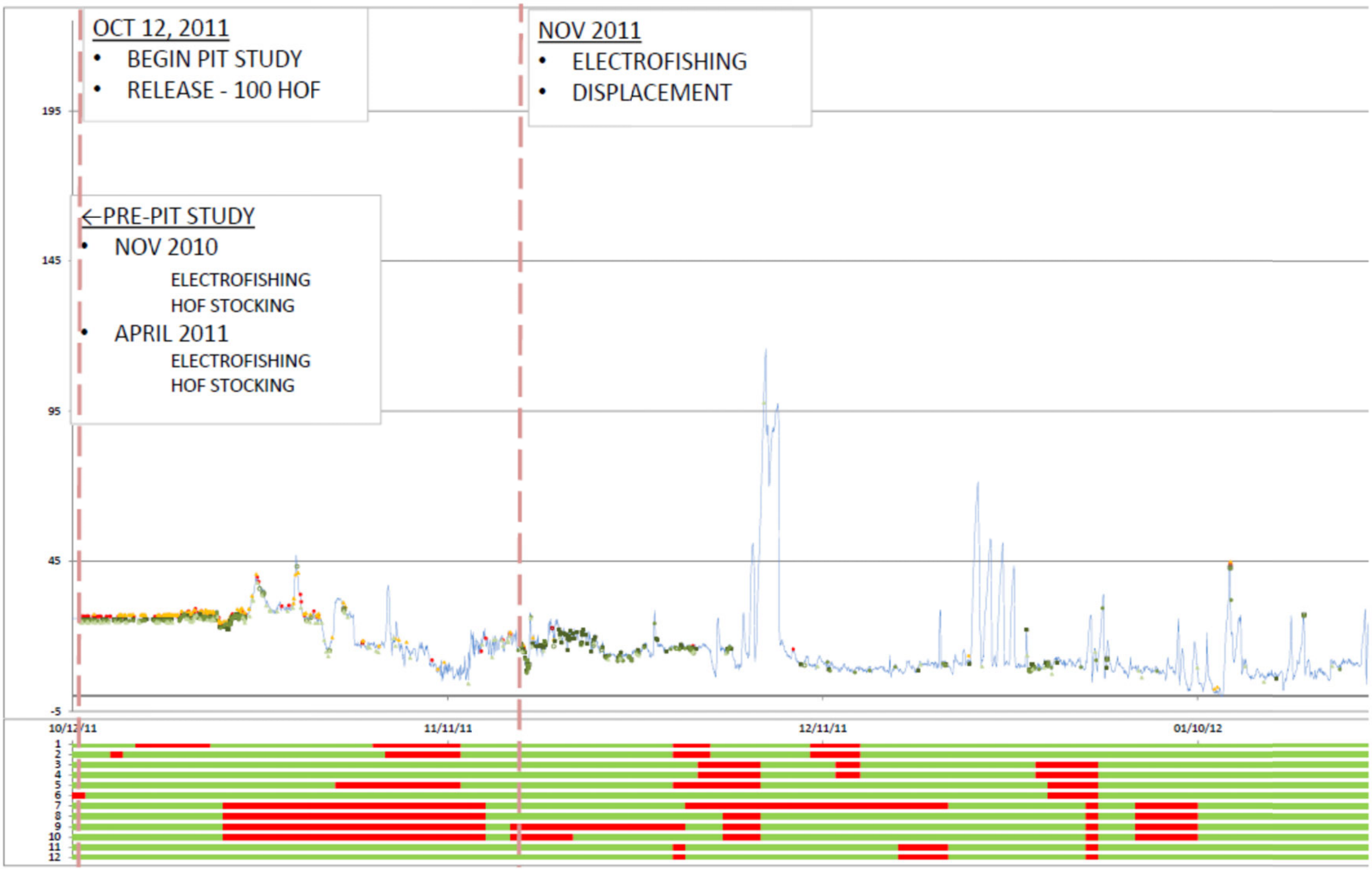



**Figure A.1: First segment of the continuous hydrograph for the complete study period.**


**Figure A.2: Second segment of the continuous hydrograph for the complete study period.**


**Figure A.3: Third segment of the continuous hydrograph for the complete study period.**

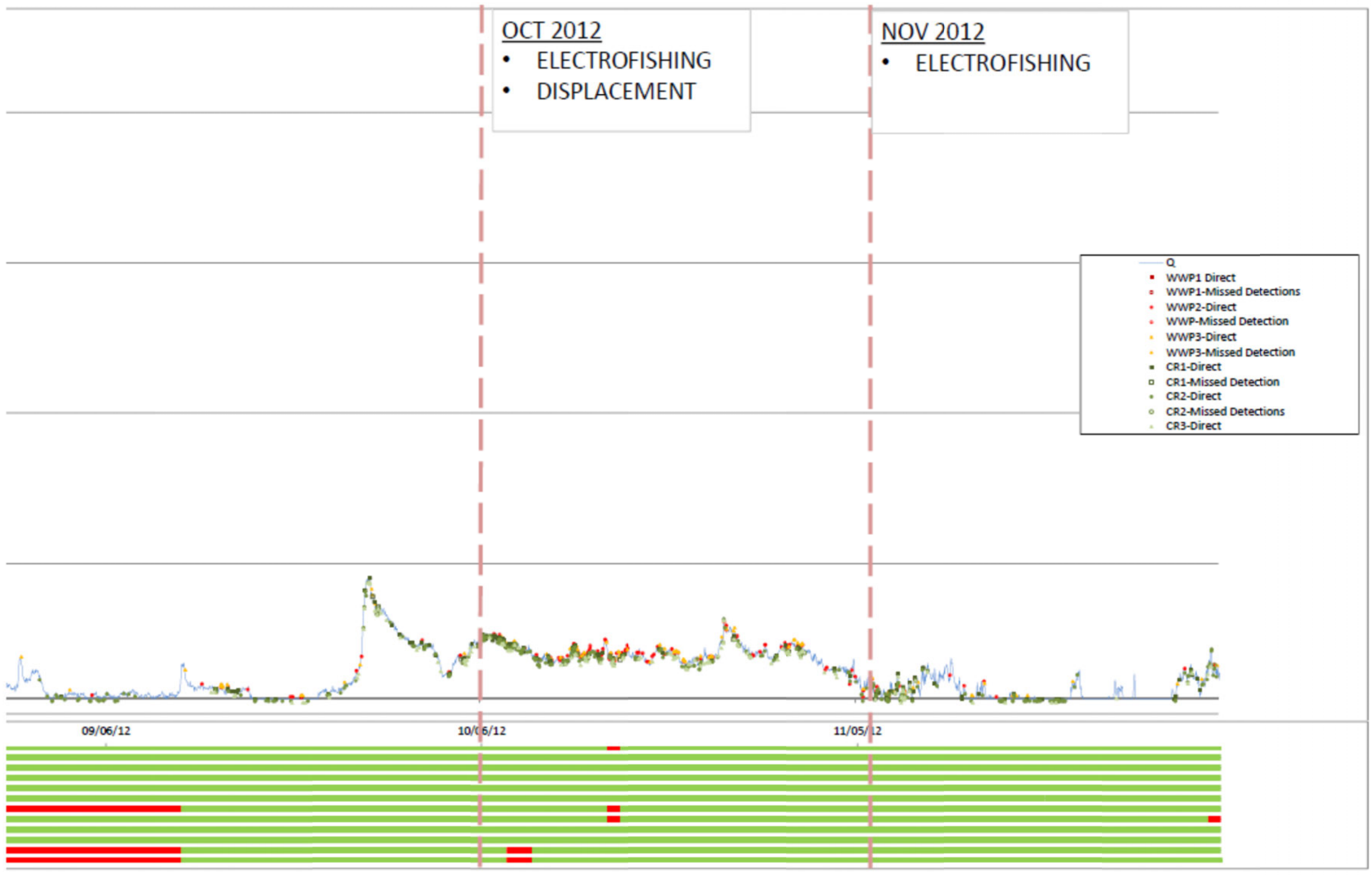



**Figure A.4: Fourth segment of the continuous hydrograph for the complete study period.**

# APPENDIX B CJS MODEL PROCEDURES AND RESULTS

## GENERAL MODEL

$$\phi = \beta_{INT} + \beta_1[MRT] + \beta_2[EVENT] + \beta_3[SPECIES] + \beta_4[LENGTH] + \beta_5[LOCATION] + \beta_6[LENGTH]*[SPECIES] + \beta_8[LOCATION]*[SPECIES] + \beta_9[LOCATION]*[LENGTH] \quad \textbf{(Eq. B.1)}$$

## FIVE MAIN EFFECTS

- *MRT*: Three mark-release types
- *EVENT*: Six separate sampling occasions for the *MRT*
- *LOCATION*: Six possible sites within the two reaches
- *SPECIES*: Identified as Trout/Non-Trout
- *LENGTH*: Body length of the fish at time of tagging

## THREE POSSIBLE INTERACTIONS

- *LENGTH*SPECIES*
- *LOCATION*LENGTH*
- *LOCATION*SPECIES*

## MAIN EFFECT: MARK-RELEASE TYPE (*MRT*)

***Type:*** Categorical

***Domain:***

- Electrofishing
- Stocking
- Displacement

***Modeled Effect:***

- Behavior
- Motivation
- Species (indirectly)

***Description:***

Mark-release types (*MRTs*) are the methods by which fishes were introduced into the study for detection on a PIT antenna. There are three distinct tag and release methods which may potentially result in different motivation and behavior for these individuals.

- **Electrofishing –** Capture and release of individuals each of the six study site locations. Individuals from this group are considered to have typical motivation and behavior of native in-stream residents.
- **Displacement –** Individuals were collected from a location upstream of each reach and re-released below the respective lower structure. The intent of the displacement was to increase motivation under the assumption that individuals will instinctually move back upstream to their capture location. Individuals from this group are expected to have higher movement rates than those from the electrofishing group.
- **Stocking –** Release of hatchery raised HOF. Unknown as to what their behavior or movement motivations may be.

**MAIN EFFECT: *EVENT***

***Type:*** Categorical

***Domain:***

**Table B.1: Summary of tag release events.**

| *EVENT* No. | *EVENT* Name | *MRT* Mark-Release Type |
|---|---|---|
| 1 | Fall 2010 | Electrofishing |
| | | Stocking |
| 2 | Spring 2011 | Electrofishing |
| | BEGIN PIT 10/2011 | |
| 3 | Fall 2011 | Displacement |
| | | Electrofishing |
| | | Stocking |
| 4 | Spring 2012 | Electrofishing |
| 5 | October 2012 | Displacement |
| | | Electrofishing |
| 6 | November 2012 | Electrofishing |
| | END PIT 12/2012 | |

***Modeled Effect:***

- Movement likelihood from the increased duration available for movement during the study.

***Description:***

Six separate events, with two occurring before the start of the PIT antenna installation. Note that not all *MRT*s occurred during each event. This parameter is entered to account for differences in movement probability associated with how long the fish has had a tag and was present within the river. For example, it is likely that a fish that has been in the river for 1 year has a higher probability of moving over the course of the study than a fish that has only been tagged and available for movement for a period of 1 month. This effect controls for variability due to experimental methods, and not intended to test or support any biological hypothesis related to passage in WWPs.

## MAIN EFFECT: *LOCATION*

***Type:*** Two levels of Categorical

- Reach: WWP, CR
- SITE: DISP, 1, 2, 3

***Domain:***

**Table B.2: Summary of encounter locations used to model upstream movement.**

| CJS Occasion | Movement Parameter | Reach | Encounter Method | Description | Interpreted Successful Upstream Movement |
|---|---|---|---|---|---|
| 1 | NA | WWP | DISP RELEASE | Release of displacement below W1 | NONE |
| 2 | $\psi_1$ | WWP | W1 OR POOL B | Move from WWP DISP in position below WWP1 | DUMMY |
| 3 | $\psi_2$ | WWP | W2 | Move across WWP1 structure | WWP1 |
| 4 | $\psi_3$ | WWP | W3 OR POOL C | Move in position below WWP2 | DUMMY |
| 5 | $\psi_4$ | WWP | W4 | Move across WWP2 structure | WWP2 |
| 6 | $\psi_5$ | WWP | W5 OR POOL D | Move in position below WWP3 | DUMMY |
| 7 | $\psi_6$ | WWP | W6 | Move across WWP3 structure | WWP3 |
| 8 | $\psi_7$ | CR | DISP RELEASE | Release of displacement below C1, no possible movement detection | DUMMY |
| 9 | $\psi_8$ | CR | C1 OR POOL E | Move from CR DISP in position below CR1 | DUMMY |
| 10 | $\psi_9$ | CR | C2 | Move across CR1 | CR1 |
| 11 | $\psi_{10}$ | CR | C3 OR POOLF | Move in position below CR2 | DUMMY |
| 12 | $\psi_{11}$ | CR | C4 | Move across CR2 structure | CR2 |
| 13 | $\psi_{12}$ | CR | C5 OR POOL E | Move in position below CR3 | DUMMY |
| 14 | $\psi_{13}$ | CR | C6 | Move across CR3 structure | CR3 |

NA = not applicable

***Modeled Effect:***

- Difference in movement probabilities between WWP/CR.

***Description:***

Possible encounters occurred at twenty possible locations during electrofishing, stocking, displacement, and fixed PIT antenna detection. A paired detection between two antennas represented a movement, with the sequence of detection determining directionality. Because my primary interest is in identifying upstream movement, the pool detection locations downstream of each site and the downstream antenna for each respective site can be combined. Encounter at either of these locations can be interpreted as presence below a given structure and that upstream movement is possible. A paired detection with either of these downstream antennas with an upstream antenna can then be interpreted as an upstream movement across a structure. This pooling allowed for the reduction of encounter occasions to 14 within the CJS model (twelve PIT antennas, two DISP locations).

Each of the different movement parameters needs to be understood to accurately interpret movement. There are several natural groupings among these parameters to test the difference among the control and treatment. Interpretation of each of the movement parameters was given in the description of the *LOCATION* variable, and separated into four groups

- 1,8 – Movement back upstream from the displacement group
- 2,4,6 – Movement across WWP
- 9,11,13 – Movement across CR
- 3,5,10,12 – Movement to a lower antenna (treated as a dummy variable)

Parameters representing the movement across the WWP and CR are the only ones of interest. The dummy variables include information to adjust capture probabilities that will affect the upstream movement parameters, but no direct interpretation of the value of the dummy variables should be made.

**MAIN EFFECT: *SPECIES***

***Type:*** Categorical

***Domain:***

- Trout
- Non-Trout

***Modeled Effect:***

- Behavior
- Swimming ability

***Description:***

This variable is used to identify effects of any species-specific behavior, motivation, and swimming ability. All individuals will be coded as either trout or non-trout. Almost all fishes within the study are brown trout with small numbers of wild rainbow trout, longnose dace, and longnose sucker.

It would be reasonable to pool the brown and wild rainbow trout as their swimming ability are similar. Differences may exist between behavior and motivation, but such low numbers of RBT will prevent any meaningful assessment of this effect. HOF can be evaluated separately by looking only at release group.

Likewise LGS and LND will be pooled as a non-trout covariate because of low capture numbers. It is not exactly clear if they are similar in swimming ability and behavior, but will provide an interesting comparison with the trout group.

**MAIN EFFECT: *LENGTH***

***Type:*** Continuous

***Domain:*** 100 mm – 400 mm

***Model Effect:***

- Swimming ability
- Behavior

***Description:***

It is well known that swimming ability and maximum swim speed is correlated with body length. Therefore, an increase in body length will result in an increase in hypothetical swimming ability and increase in the ability to traverse a potential velocity barrier.

**INTERACTION: *LOCATION*SPECIES***

***Modeled Effect***:

Any interaction of a main effect modeling swimming behavior with location will indicate the potential for a hydraulic of specific effect of treatment/control on movement ability.

*SPECIES* is modeling differences in behavior and swimming ability. A significant effect from *SPECIES*LOCATION* would suggest that swimming ability or species-specific behavior is effecting the ability to move upstream at a given location. Analysis of the regression parameter beta can be used to determine the magnitude and direction of the interaction effect.

**INTERACTION: *LOCATION*LENGTH***

***Modeled Effect***:

Any interaction of a main effect modeling swimming behavior with location will indicate the potential for a hydraulic of specific effect of treatment/control on movement ability.

*LENGTH* is modeling differences in behavior and swimming ability. A significant effect from *LENGTH*LOCATION* would suggest that swimming ability is affecting the ability to move upstream at a given location. Analysis of the regression parameter beta can be used to determine the magnitude and direction of the interaction effect.

## INTERACTION: *LENGTH*SPECIES*

***Modeled Effect***:

Both of these are modeling swimming ability. It is possible that each species' ability has a different response to changes in length. This would be captured by including this effect in the model. However, I am suspicious that this effect can be identified by the collected data. A more appropriate parameterization would be to include these as additive effects. Or include possible model swimming ability as such *SPECIES* + *SPECIES***LENGTH*, and not include an additive length effect.

## SCHEMATIC OF CJS MODEL SETUP

Each $\phi$ defines the meaning of each movement parameter in the CJS model. $\phi 2$ is an upstream movement across WWP1. $\phi 3$ is a dummy parameter defining movement between structures that is not part of the analysis. This is included for requirements to estimate parameters at other locations. Figure B.1 is a schematic of the CJS model setup.

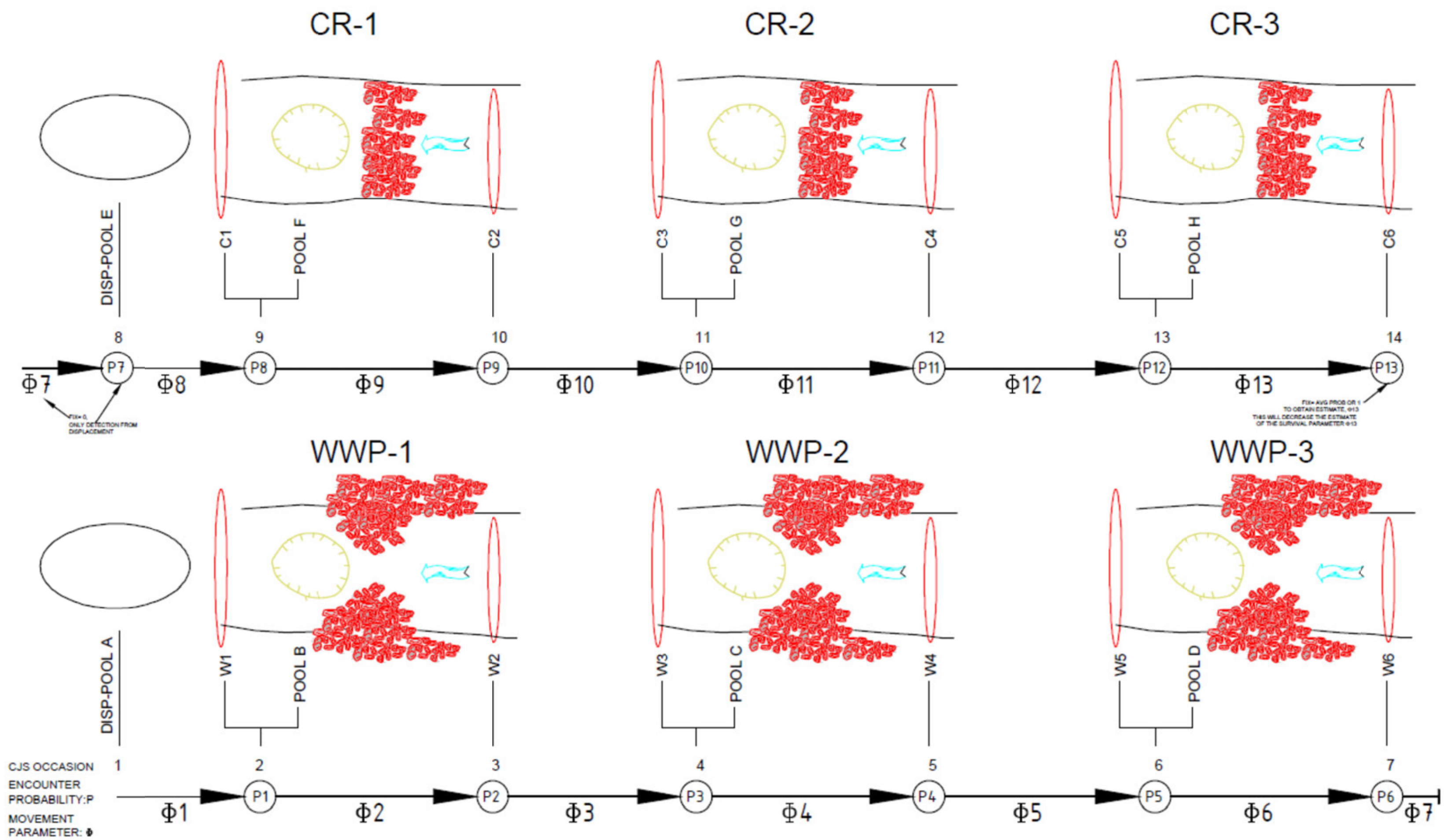



**Figure B.1: Schematic of the CJS model setup.**

**Table B.3: CJS model selection.**

| Model | AICc | ΔAICc | AICc Weights | Model Likelihood | Number of Parameters | Deviance |
|---|---|---|---|---|---|---|
| {[SITE_ONLY]+[LENGTH]+[TROUT]+[SITE*LENGTH]} | 4714.75 | 0.00 | 0.671 | 1.00 | 38 | 4637.81 |
| {[SITE_ONLY]+[LENGTH]+[TROUT]+[TROUT*LENGTH]+[SITE*LENGTH]} | 4716.36 | 1.61 | 0.300 | 0.45 | 39 | 4637.37 |
| {[SITE_ONLY]+[LENGTH]+[TROUT]+[SITE*TROUT]+[SITE*LENGTH]} | 4723.14 | 8.39 | 0.010 | 0.02 | 43 | 4635.95 |
| {[SITE_ONLY]+[LENGTH]+[TROUT]} | 4724.47 | 9.73 | 0.005 | 0.01 | 33 | 4657.77 |
| {FULL_MODEL} | 4724.73 | 9.99 | 0.005 | 0.01 | 44 | 4635.49 |
| {[SITE_ONLY]+[LENGTH]+[TROUT]+[TROUT*LENGTH]} | 4725.80 | 11.05 | 0.003 | 0.00 | 34 | 4657.05 |
| {[SITE_ONLY]+[LENGTH]+[SITE*LENGTH]} | 4728.77 | 14.02 | 0.001 | 0.00 | 37 | 4653.88 |
| {[REACH_ONLY]+[TROUT]+[LENGTH]} | 4730.60 | 15.86 | 0.000 | 0.00 | 29 | 4672.06 |
| {[SITE_ONLY]+[LENGTH]+[TROUT]+[SITE*TROUT]} | 4732.01 | 17.26 | 0.000 | 0.00 | 38 | 4655.08 |
| {[REACH_ONLY]+[TROUT]+[LENGTH]+[REACH*SPECIES]} | 4732.16 | 17.42 | 0.000 | 0.00 | 30 | 4671.58 |
| {[REACH_ONLY]+[TROUT]+[LENGTH]+[TROUT*LENGTH]} | 4732.27 | 17.53 | 0.000 | 0.00 | 30 | 4671.69 |
| {[REACH_ONLY]+[TROUT]+[LENGTH]+[REACH*LENGTH]} | 4732.47 | 17.72 | 0.000 | 0.00 | 30 | 4671.88 |
| {[SITE_ONLY]+[LENGTH]+[TROUT]+[TROUT*LENGTH]+[SITE*TROUT]} | 4733.43 | 18.69 | 0.000 | 0.00 | 39 | 4654.45 |
| {[REACH_ONLY]+[TROUT]+[LENGTH]+[TROUT*LENGTH]+[REACH*SPECIES]} | 4733.66 | 18.92 | 0.000 | 0.00 | 31 | 4671.04 |
| {[REACH_ONLY]+[TROUT]+[LENGTH]+[REACH*LENGTH]+[REACH*SPECIES]} | 4734.11 | 19.36 | 0.000 | 0.00 | 31 | 4671.48 |
| {[REACH_ONLY]+[TROUT]+[LENGTH]+[TROUT*LENGTH]+[REACH*LENGTH]} | 4734.11 | 19.36 | 0.000 | 0.00 | 31 | 4671.48 |
| {REACH_ONLY_FULL_MODEL} | 4735.60 | 20.86 | 0.000 | 0.00 | 32 | 4670.94 |
| {[REACH_ONLY]+[LENGTH]} | 4740.22 | 25.48 | 0.000 | 0.00 | 28 | 4683.71 |
| {[REACH_ONLY]+[LENGTH]+[REACH*LENGTH]} | 4741.89 | 27.14 | 0.000 | 0.00 | 29 | 4683.34 |
| {[REACH_ONLY]+[TROUT]} | 4767.62 | 52.88 | 0.000 | 0.00 | 28 | 4711.11 |
| {[REACH_ONLY]+[TROUT]+[REACH*SPECIES]} | 4769.32 | 54.58 | 0.000 | 0.00 | 29 | 4710.78 |
| {[REACH_ONLY]} | 4769.71 | 54.97 | 0.000 | 0.00 | 27 | 4715.24 |
| {[SITE_ONLY]+[TROUT]+[SITE*TROUT]} | 4769.95 | 55.21 | 0.000 | 0.00 | 37 | 4695.07 |

## FINAL REDUCED MODEL

$$\phi = \beta_{INT} + \beta_1[MRT] + \beta_2[EVENT] + \beta_3[SPECIES] + \beta_4[LENGTH] + \beta_5[LOCATION] + \beta_9[LOCATION]*[LENGTH] \quad \textbf{(Eq. B.2)}$$

**Table B.4: Beta parameter estimates for top model.**

| Index | Label | Estimate | SE | LCI | UCI |
|---|---|---|---|---|---|
| 1 | INT | 0.509 | 0.414 | -0.303 | 1.320 |
| 2 | STOCKING | 0.788 | 0.138 | 0.517 | 1.058 |
| 3 | DISP | 1.666 | 0.154 | 1.365 | 1.967 |
| 4 | EVENT1 | 1.296 | 0.220 | 0.864 | 1.728 |
| 5 | EVENT2 | 1.557 | 0.257 | 1.053 | 2.062 |
| 6 | EVENT4 | 0.838 | 0.206 | 0.434 | 1.242 |
| 7 | EVENT5 | 0.030 | 0.137 | -0.238 | 0.297 |
| 8 | EVENT6 | -1.204 | 0.250 | -1.695 | -0.713 |
| 9 | TROUT | -1.100 | 0.283 | -1.655 | -0.545 |
| 10 | LENGTH | 0.057 | 0.017 | 0.024 | 0.090 |
| 11 | DUMMY-W1 | -0.489 | 0.330 | -1.137 | 0.159 |
| 12 | DUMMY-W3 | -1.751 | 0.258 | -2.256 | -1.245 |
| 13 | DUMMY-W5 | 0.110 | 0.431 | -0.735 | 0.956 |
| 14 | DUMMY-DISPCR | -3.057 | 0.288 | -3.621 | -2.493 |
| 15 | DUMMY-C1 | 0.808 | 0.542 | -0.255 | 1.871 |
| 16 | DUMMY-C3 | 0.978 | 0.365 | 0.262 | 1.694 |
| 17 | DUMMY-C5 | -1.774 | 0.203 | -2.173 | -1.376 |
| 18 | SITE-WWP1 | 0.123 | 0.687 | -1.223 | 1.470 |
| 19 | SITE-WWP2 | -3.685 | 0.816 | -5.284 | -2.085 |
| 20 | SITE-WWP3 | -1.580 | 0.765 | -3.080 | -0.081 |
| 21 | SITE-CR2 | -0.904 | 0.745 | -2.364 | 0.556 |
| 22 | SITE-CR3 | -1.019 | 0.557 | -2.111 | 0.072 |
| 23 | SITE-WWP1*LENGTH | -0.078 | 0.035 | -0.147 | -0.010 |
| 24 | SITE-WWP2*LENGTH | 0.130 | 0.045 | 0.042 | 0.218 |
| 25 | SITE-WWP3*LENGTH | 0.030 | 0.039 | -0.047 | 0.106 |
| 26 | SITE-CR2*LENGTH | 0.050 | 0.044 | -0.036 | 0.135 |
| 27 | SITE-CR3*LENGTH | 0.015 | 0.030 | -0.044 | 0.075 |
| 28 | Detection Prob W1 | 3.435 | 0.715 | 2.033 | 4.837 |
| 29 | Detection Prob W2 | 1.894 | 0.357 | 1.194 | 2.593 |
| 30 | Detection Prob W3 | 1.565 | 0.380 | 0.819 | 2.310 |
| 31 | Detection Prob W4 | 2.070 | 0.335 | 1.413 | 2.727 |
| 32 | Detection Prob W5 | 1.061 | 0.294 | 0.484 | 1.637 |
| 33 | Detection Prob W6 | 1.101 | 0.339 | 0.437 | 1.766 |
| 34 | Detection Prob CR-DISP | 0.000 | 0.000 | 0.000 | 0.000 |
| 35 | Detection Prob CR1 | 1.482 | 0.224 | 1.042 | 1.922 |
| 36 | Detection Prob CR2 | 2.194 | 0.220 | 1.763 | 2.625 |
| 37 | Detection Prob CR3 | 1.269 | 0.178 | 0.920 | 1.619 |
| 38 | Detection Prob CR4 | 2.046 | 0.263 | 1.531 | 2.562 |
| 39 | Detection Prob CR5/CR6 | 1.528 | 0.258 | 1.022 | 2.033 |

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

**Table B.5: Example of real parameter estimates for top model and specified covariate/parameter set.**

| Parameter | Value |
|---|---|
| EVENT1 | 0 |
| EVENT2 | 0 |
| EVENT4 | 0 |
| EVENT5 | 1 |
| EVENT6 | 0 |
| LENGTH | 15 |
| TROUT | 1 |

| Index | Label | Estimate | SE | LCI | UCI |
|---|---|---|---|---|---|
| 1 | Phi | 0.450 | 0.083 | 0.298 | 0.612 |
| 2 | Phi | 0.317 | 0.052 | 0.225 | 0.426 |
| 3 | Phi | 0.188 | 0.040 | 0.122 | 0.278 |
| 4 | Phi | 0.191 | 0.036 | 0.130 | 0.271 |
| 5 | Phi | 0.598 | 0.103 | 0.391 | 0.775 |
| 6 | Phi | 0.300 | 0.059 | 0.199 | 0.426 |
| 7 | Phi | 0.059 | 0.016 | 0.034 | 0.100 |
| 8 | Phi | 0.750 | 0.099 | 0.516 | 0.894 |
| 9 | Phi | 0.572 | 0.048 | 0.475 | 0.663 |
| 10 | Phi | 0.780 | 0.060 | 0.642 | 0.875 |
| 11 | Phi | 0.533 | 0.049 | 0.437 | 0.625 |
| 12 | Phi | 0.184 | 0.030 | 0.133 | 0.250 |
| 13 | Phi | 0.378 | 0.045 | 0.295 | 0.469 |
| 14 | Phi | 0.636 | 0.072 | 0.488 | 0.762 |
| 15 | Phi | 0.498 | 0.049 | 0.403 | 0.594 |
| 16 | Phi | 0.331 | 0.049 | 0.242 | 0.433 |
| 17 | Phi | 0.334 | 0.042 | 0.258 | 0.420 |
| 18 | Phi | 0.761 | 0.074 | 0.589 | 0.876 |
| 19 | Phi | 0.478 | 0.063 | 0.358 | 0.600 |
| 20 | Phi | 0.118 | 0.027 | 0.074 | 0.182 |
| 21 | Phi | 0.865 | 0.060 | 0.701 | 0.946 |
| 22 | Phi | 0.740 | 0.031 | 0.676 | 0.796 |
| 23 | Phi | 0.883 | 0.034 | 0.799 | 0.935 |
| 24 | Phi | 0.709 | 0.036 | 0.633 | 0.774 |
| 25 | Phi | 0.326 | 0.034 | 0.263 | 0.395 |
| 26 | Phi | 0.564 | 0.043 | 0.479 | 0.646 |
| 27 | Phi | 0.812 | 0.045 | 0.708 | 0.885 |
| 28 | Phi | 0.711 | 0.048 | 0.610 | 0.795 |
| 29 | Phi | 0.551 | 0.059 | 0.435 | 0.661 |
| 30 | Phi | 0.555 | 0.057 | 0.442 | 0.662 |
| 31 | Phi | 0.887 | 0.042 | 0.775 | 0.948 |
| 32 | Phi | 0.694 | 0.061 | 0.565 | 0.799 |
| 33 | Phi | 0.249 | 0.054 | 0.159 | 0.368 |
| 34 | Phi | 0.941 | 0.028 | 0.856 | 0.977 |
| 35 | Phi | 0.876 | 0.021 | 0.828 | 0.912 |
| 36 | Phi | 0.949 | 0.017 | 0.905 | 0.974 |

**Table B.5 (continued).**

| Index | Label | Estimate | SE | LCI | UCI |
|---|---|---|---|---|---|
| 37 | Phi | 0.858 | 0.025 | 0.801 | 0.900 |
| 38 | Phi | 0.545 | 0.046 | 0.455 | 0.632 |
| 39 | Phi | 0.763 | 0.038 | 0.680 | 0.829 |
| 40 | p | 0.969 | 0.022 | 0.884 | 0.992 |
| 41 | p | 0.869 | 0.041 | 0.768 | 0.930 |
| 42 | p | 0.827 | 0.054 | 0.694 | 0.910 |
| 43 | p | 0.888 | 0.033 | 0.804 | 0.939 |
| 44 | p | 0.743 | 0.056 | 0.619 | 0.837 |
| 45 | p | 0.750 | 0.063 | 0.607 | 0.854 |
| 46 | p | 0.000 | 0.000 | 0.000 | 0.000 |
| 47 | p | 0.815 | 0.034 | 0.739 | 0.872 |
| 48 | p | 0.900 | 0.020 | 0.854 | 0.932 |
| 49 | p | 0.781 | 0.031 | 0.715 | 0.835 |
| 50 | p | 0.886 | 0.027 | 0.822 | 0.928 |
| 51 | p | 0.822 | 0.038 | 0.735 | 0.884 |
| 52 | p | 0.822 | 0.038 | 0.735 | 0.884 |

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

# APPENDIX C HYDRAULIC MODEL RESULTS: CROSS-SECTION NORMAL VELOCITY

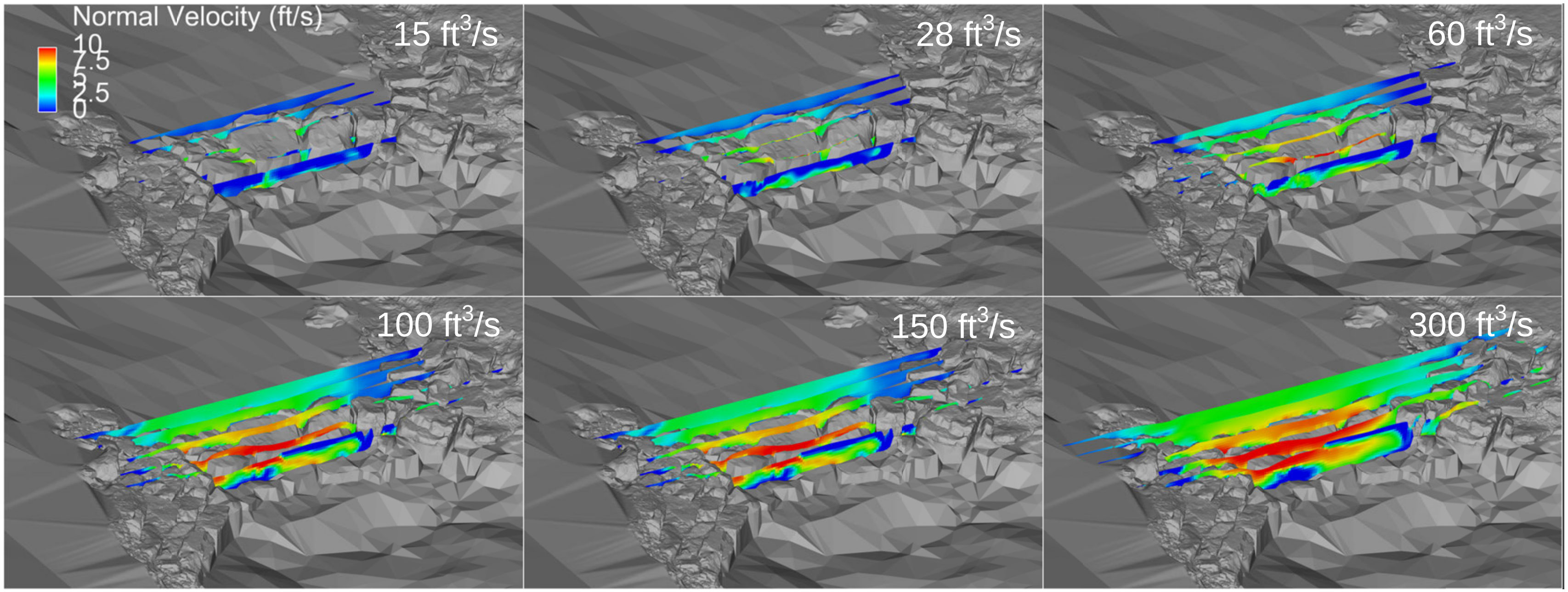
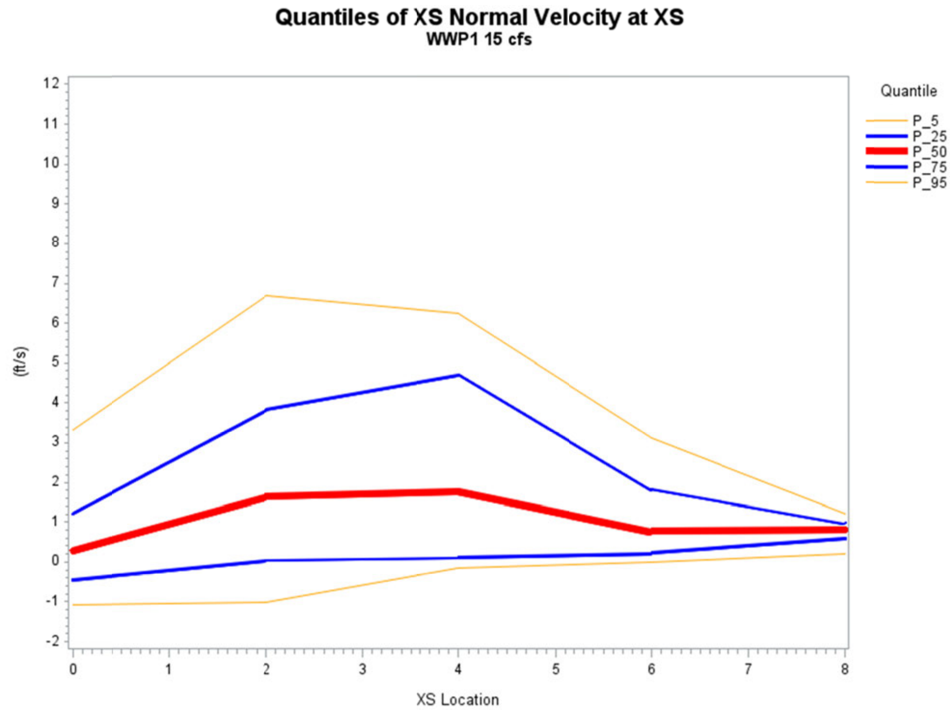
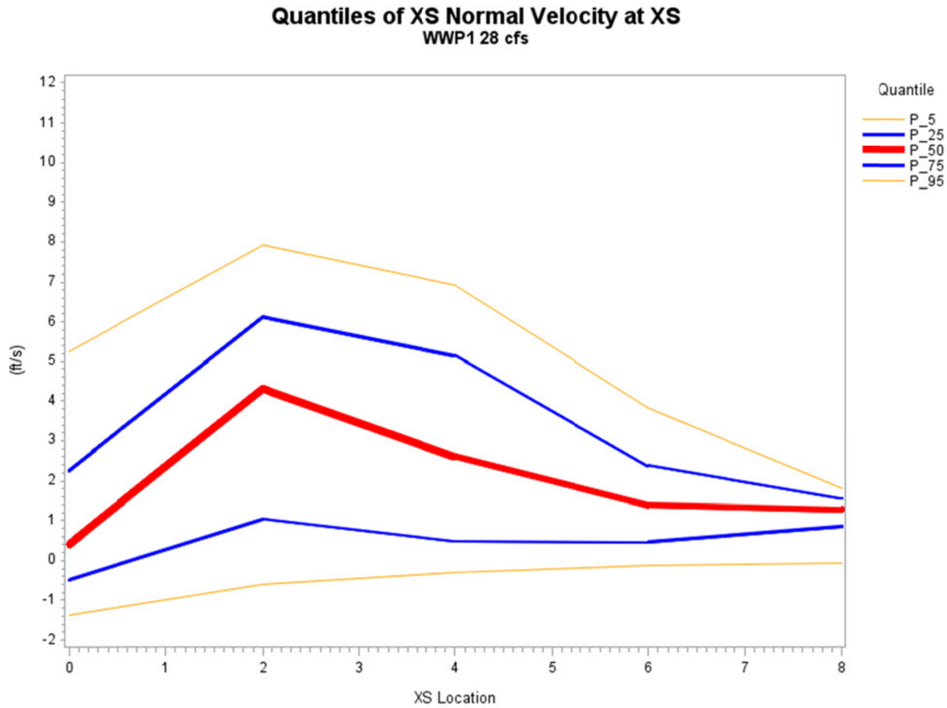



**Figure C.1: Detailed hydraulic model output of WWP1 for six discharges.**

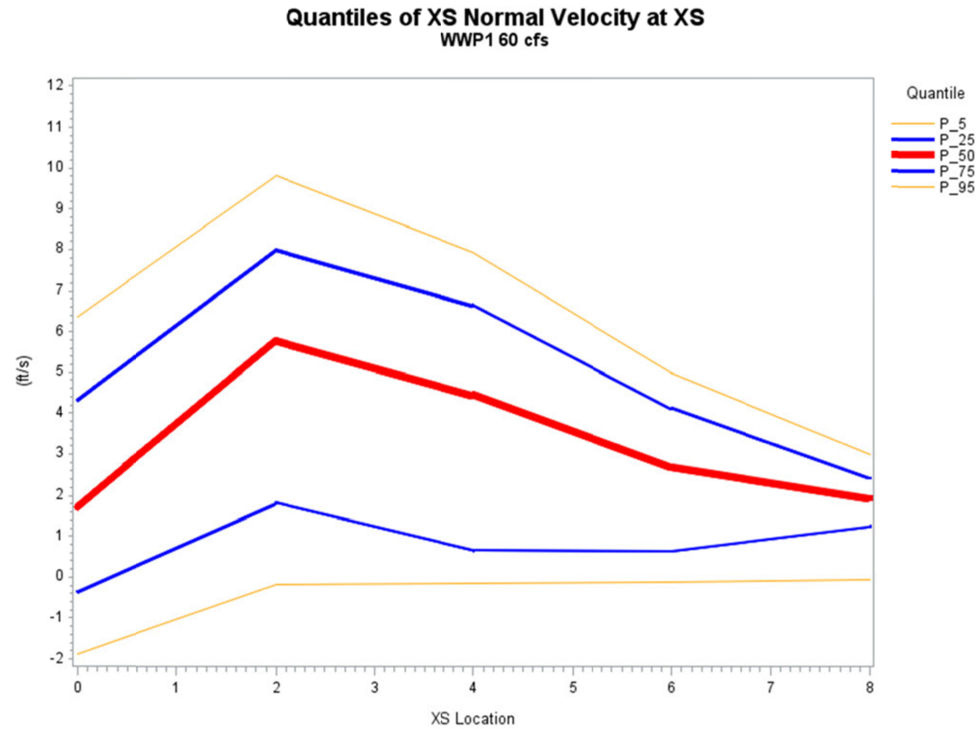



(A) 15 cfs

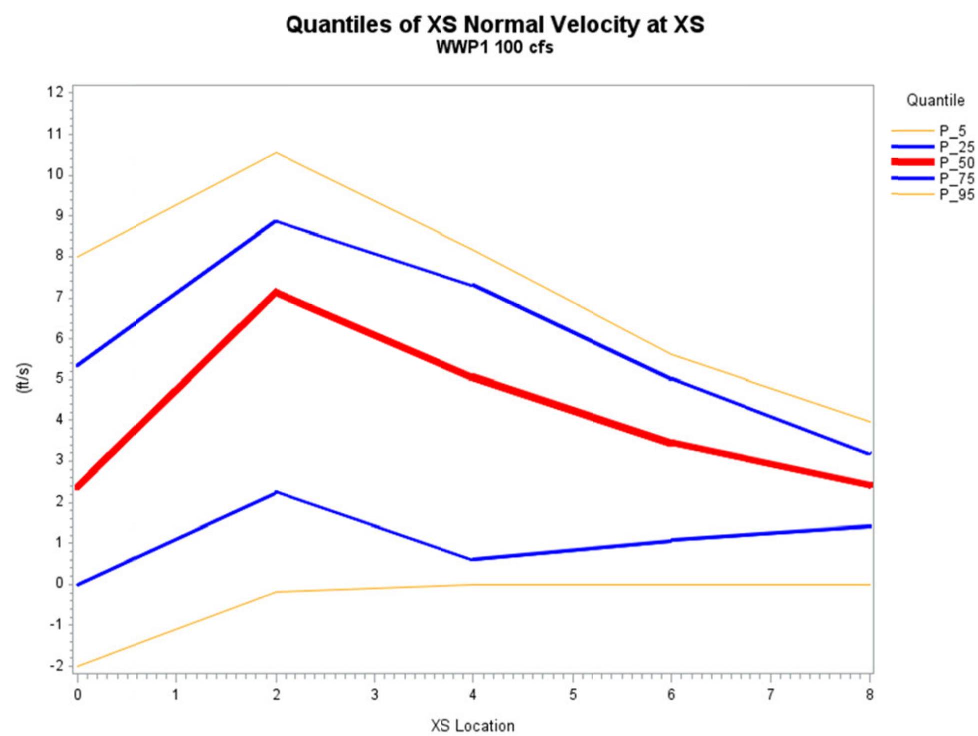



(B) 28 cfs

**Figure C.2: Analysis of WWP1 cross-sectional flow velocity by percentile flow area: (A) 15 cfs; (B) 28 cfs; (C) 60 cfs; (D) 100 cfs; (E) 150 cfs; and (F) 300 cfs.**

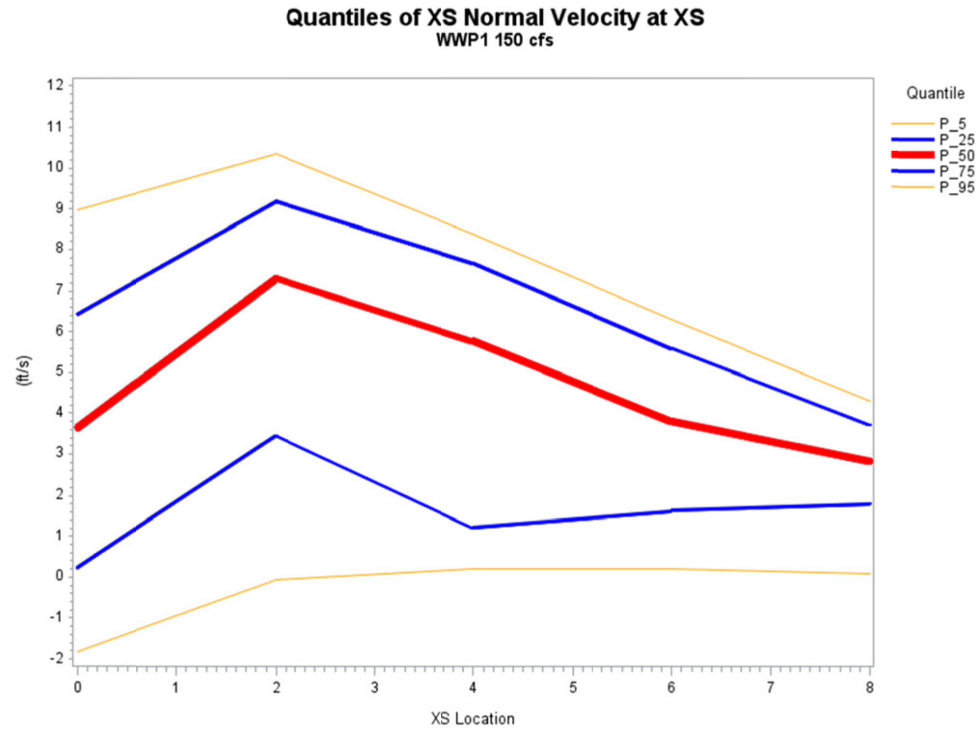



(C) 60 cfs

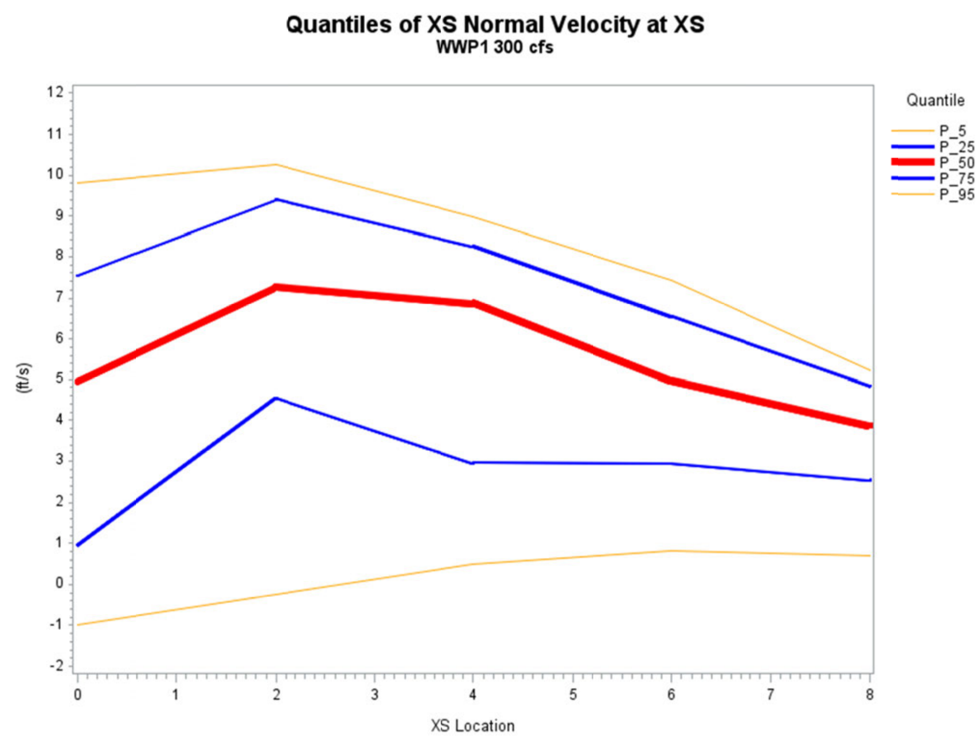



(D) 100 cfs

**Figure C.2 (continued).**




(E) 150 cfs




(F) 300 cfs

**Figure C.2 (continued).**

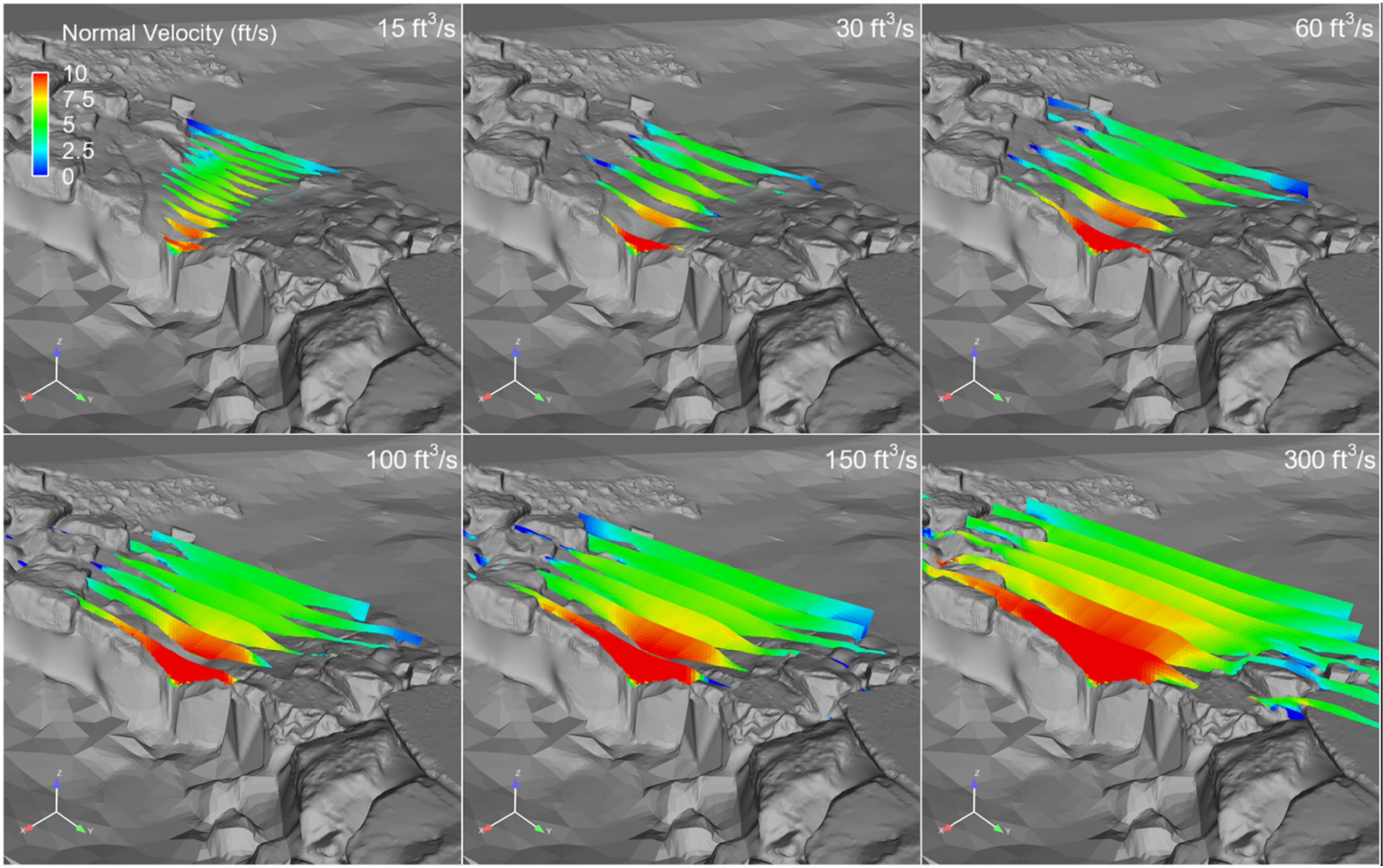
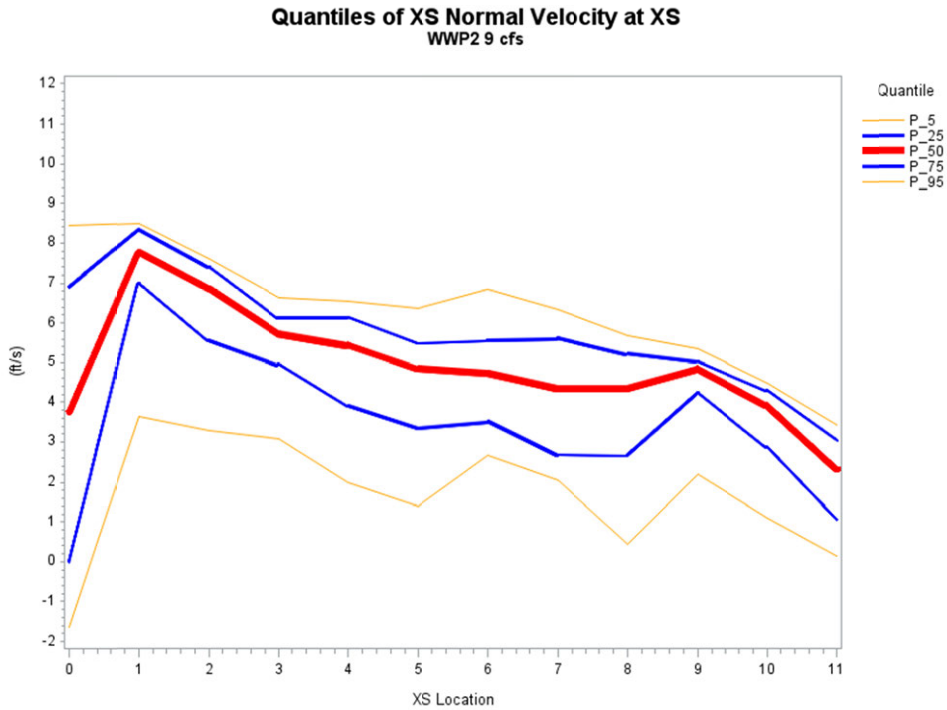
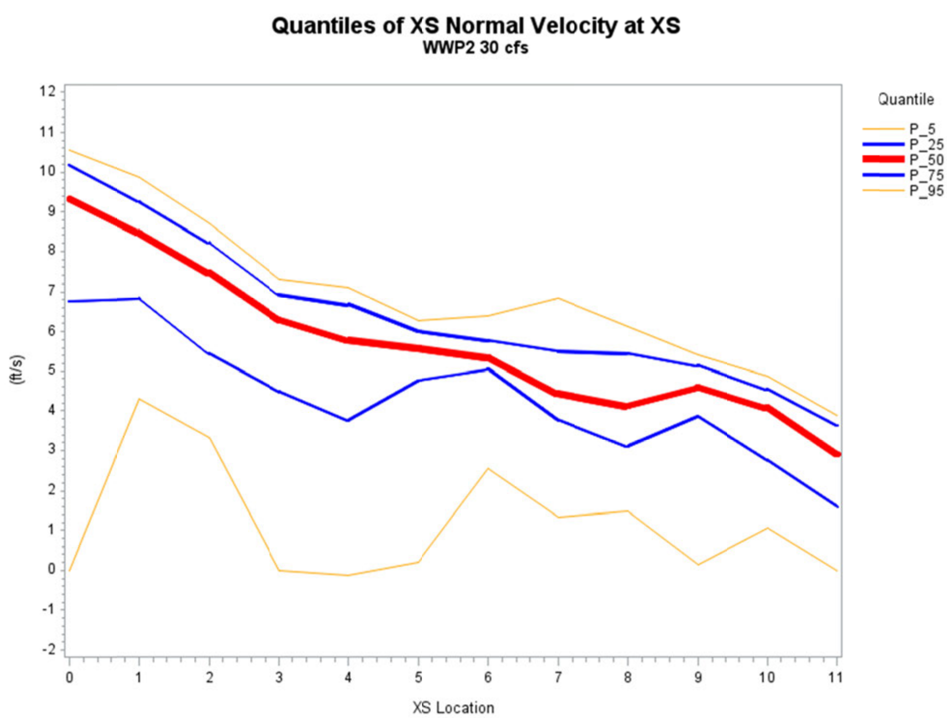



**Figure C.3: Detailed hydraulic model output of WWP2 for six discharges.**

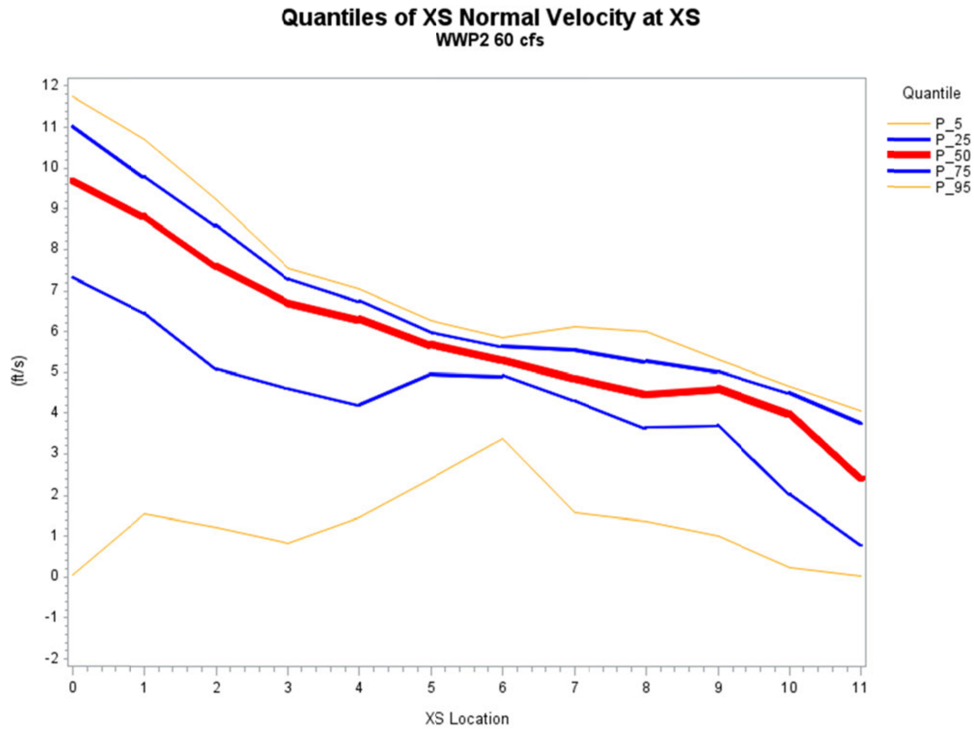



(A) 9 cfs

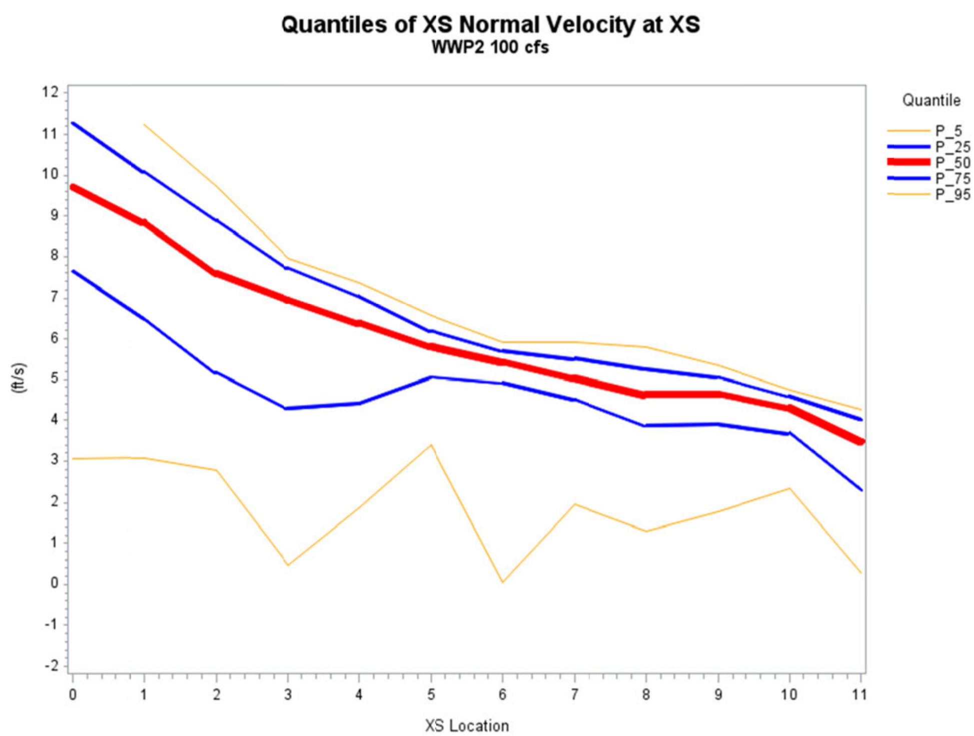



(B) 30 cfs

**Figure C.4: Analysis of WWP2 cross-sectional flow velocty by percentile flow area: (A) 9 cfs; (B) 30 cfs; (C) 60 cfs; (D) 100 cfs; (E) 150 cfs; and (F) 300 cfs.**

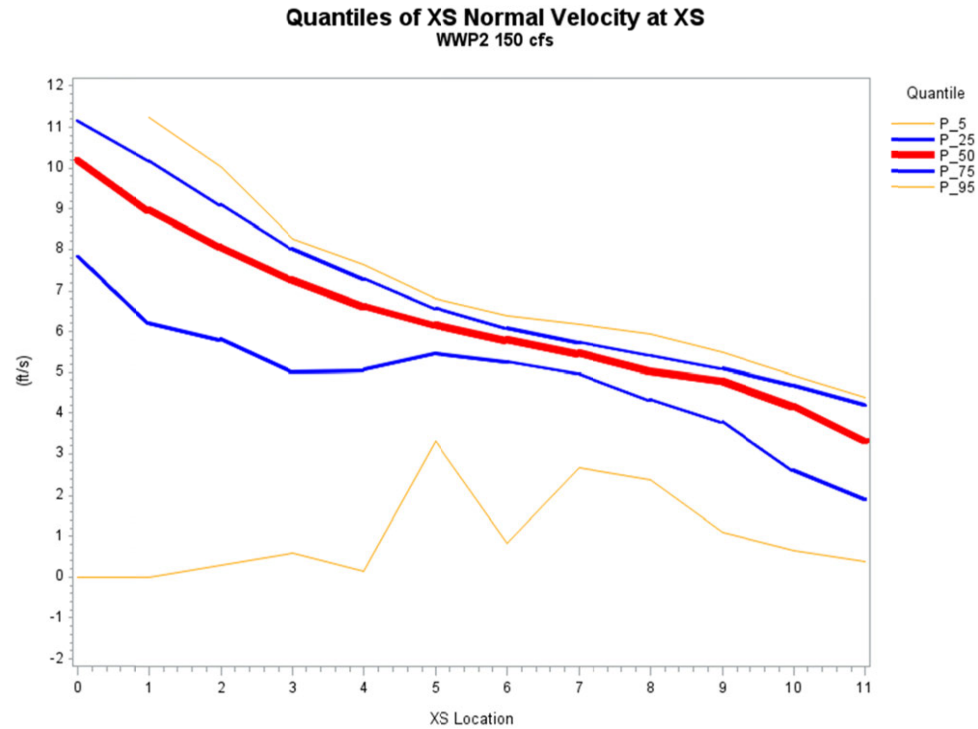



(C) 60 cfs

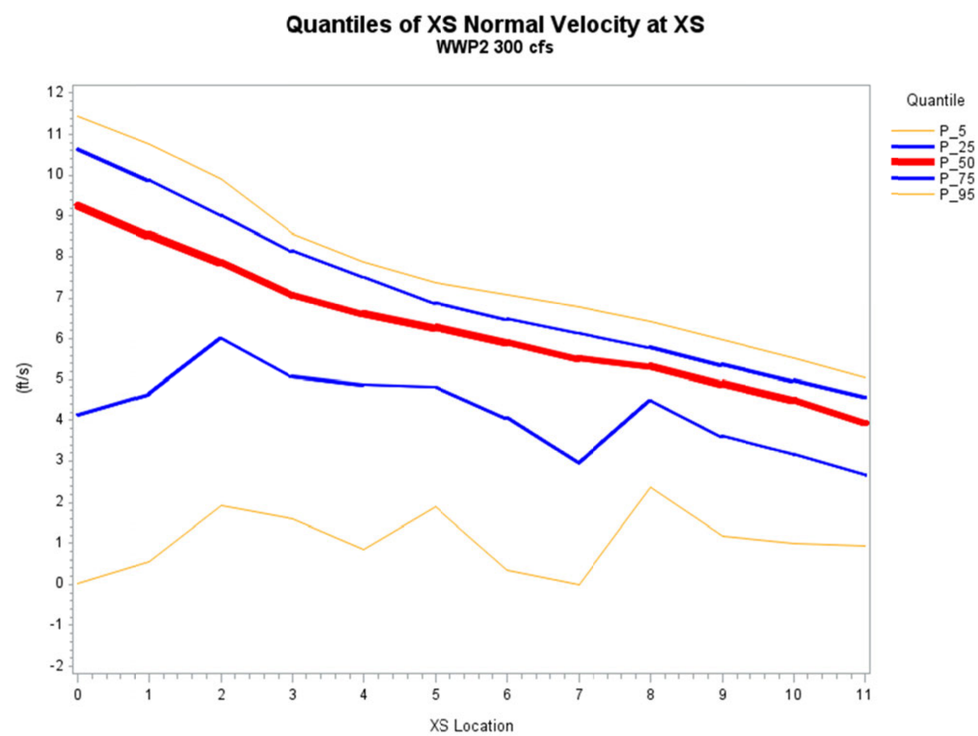



(D) 100 cfs

**Figure C.4 (continued).**




(E) 150 cfs




(F) 300 cfs

**Figure C.4 (continued).**

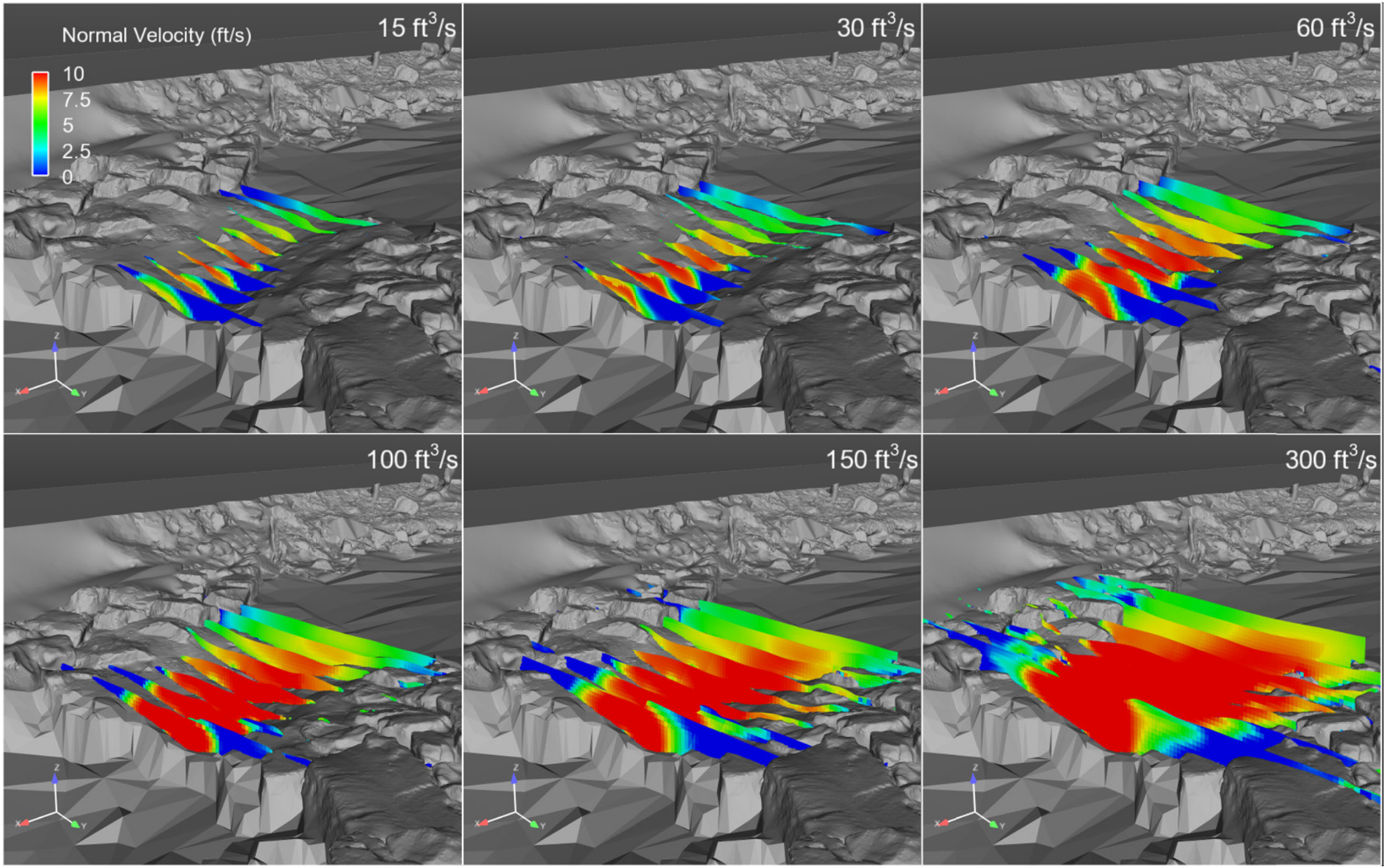
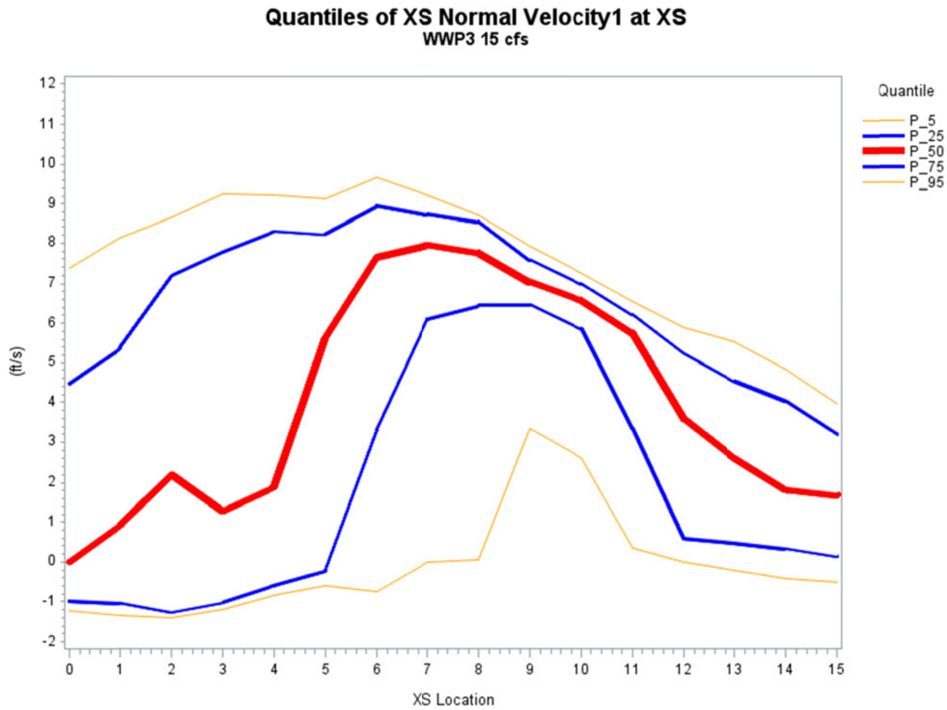
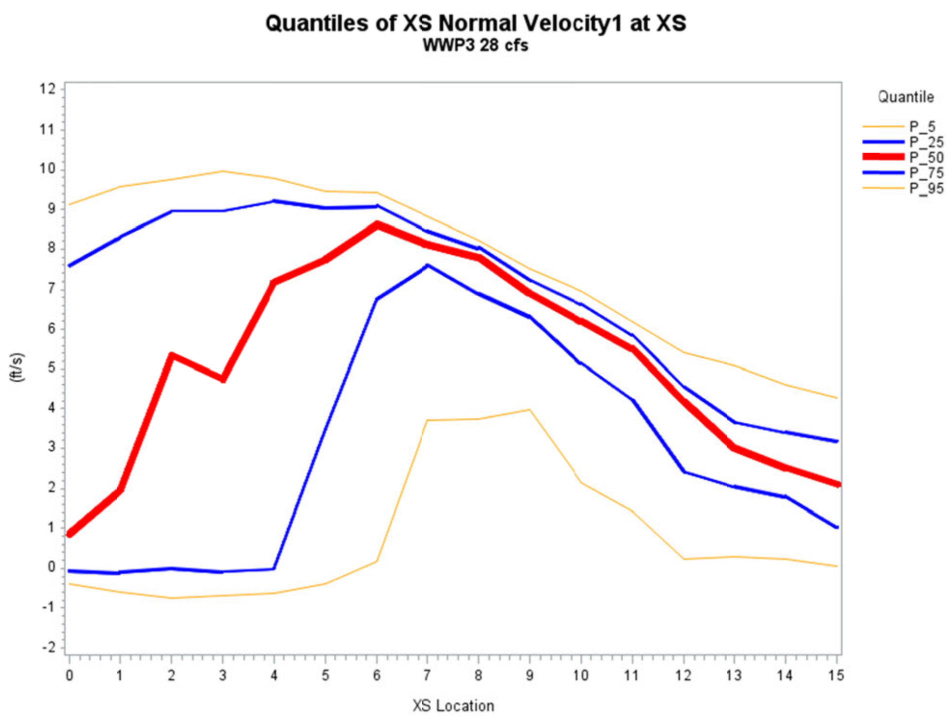



**Figure C.5: Detailed hydraulic model output of WWP3 for six discharges.**

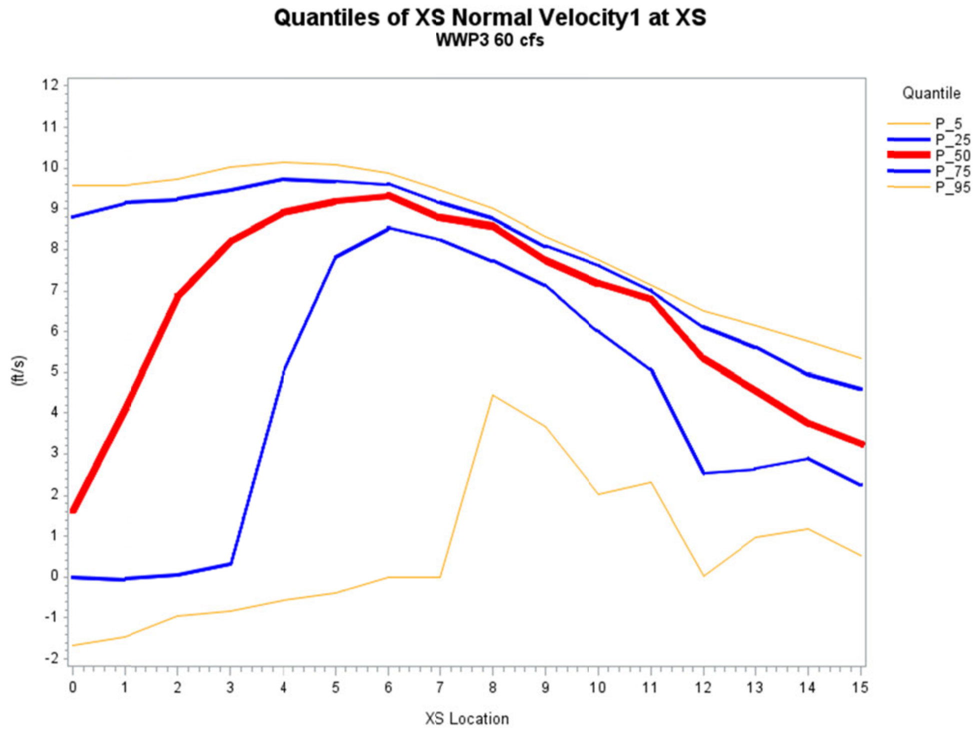



(A) 15 cfs

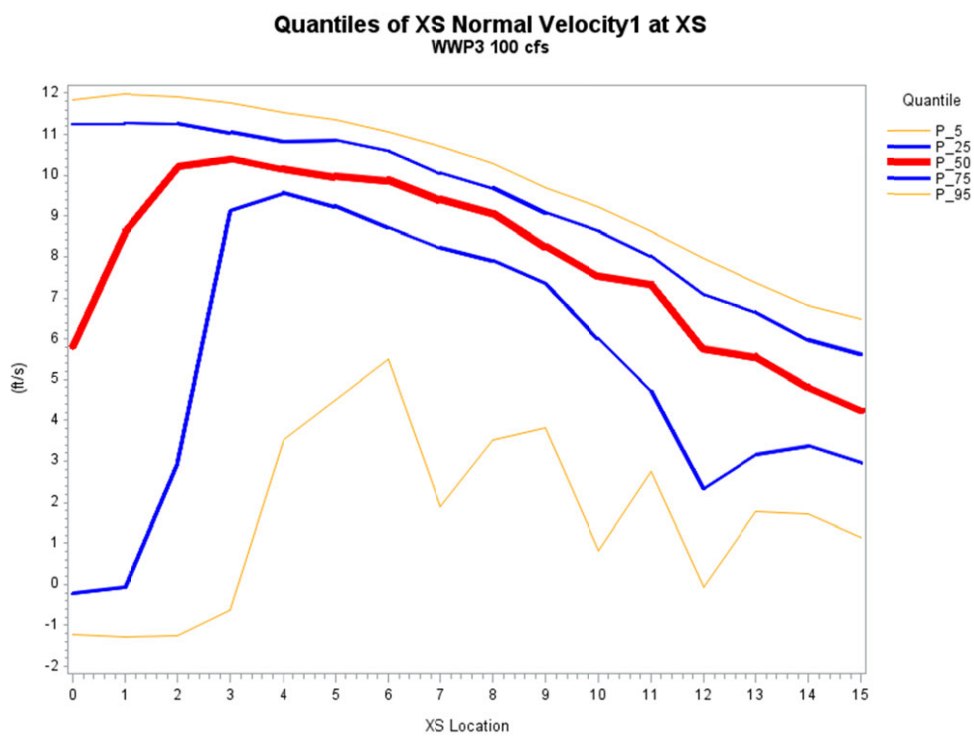



(B) 28 cfs

**Figure C.6: Analysis of WWP3 cross-sectional flow velocty by percentile flow area: (A) 15 cfs; (B) 28 cfs; (C) 60 cfs; (D) 100 cfs; (E) 150 cfs; and (F) 300 cfs.**

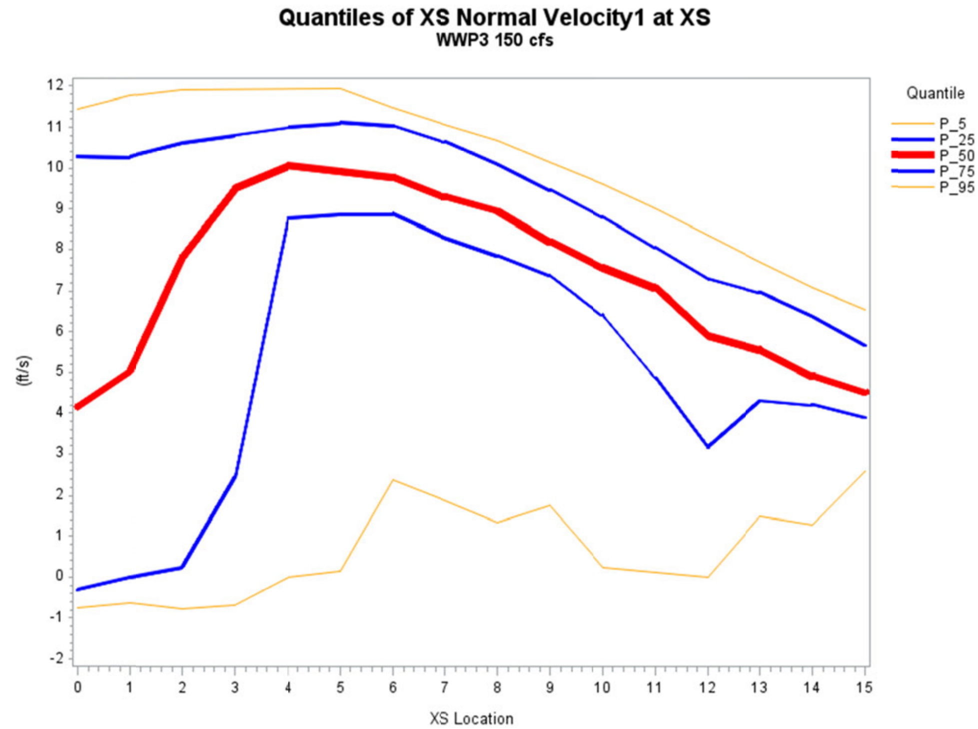



(C) 60 cfs

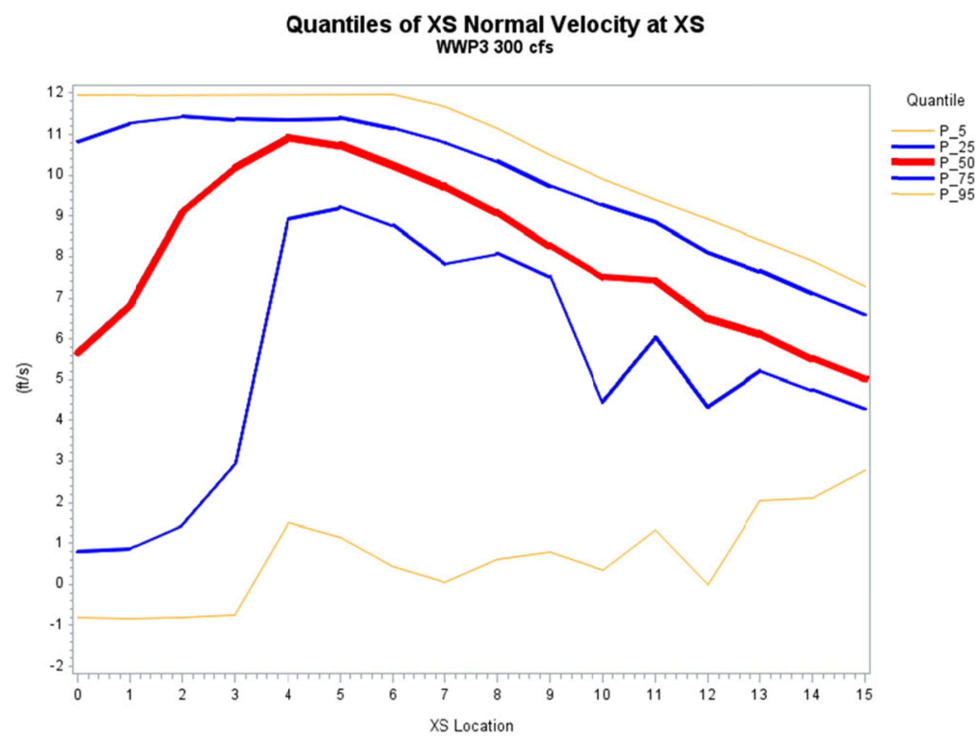



(D) 100 cfs

**Figure C.6 (continued).**




(E) 150 cfs




(F) 300 cfs

**Figure C.6 (continued).**

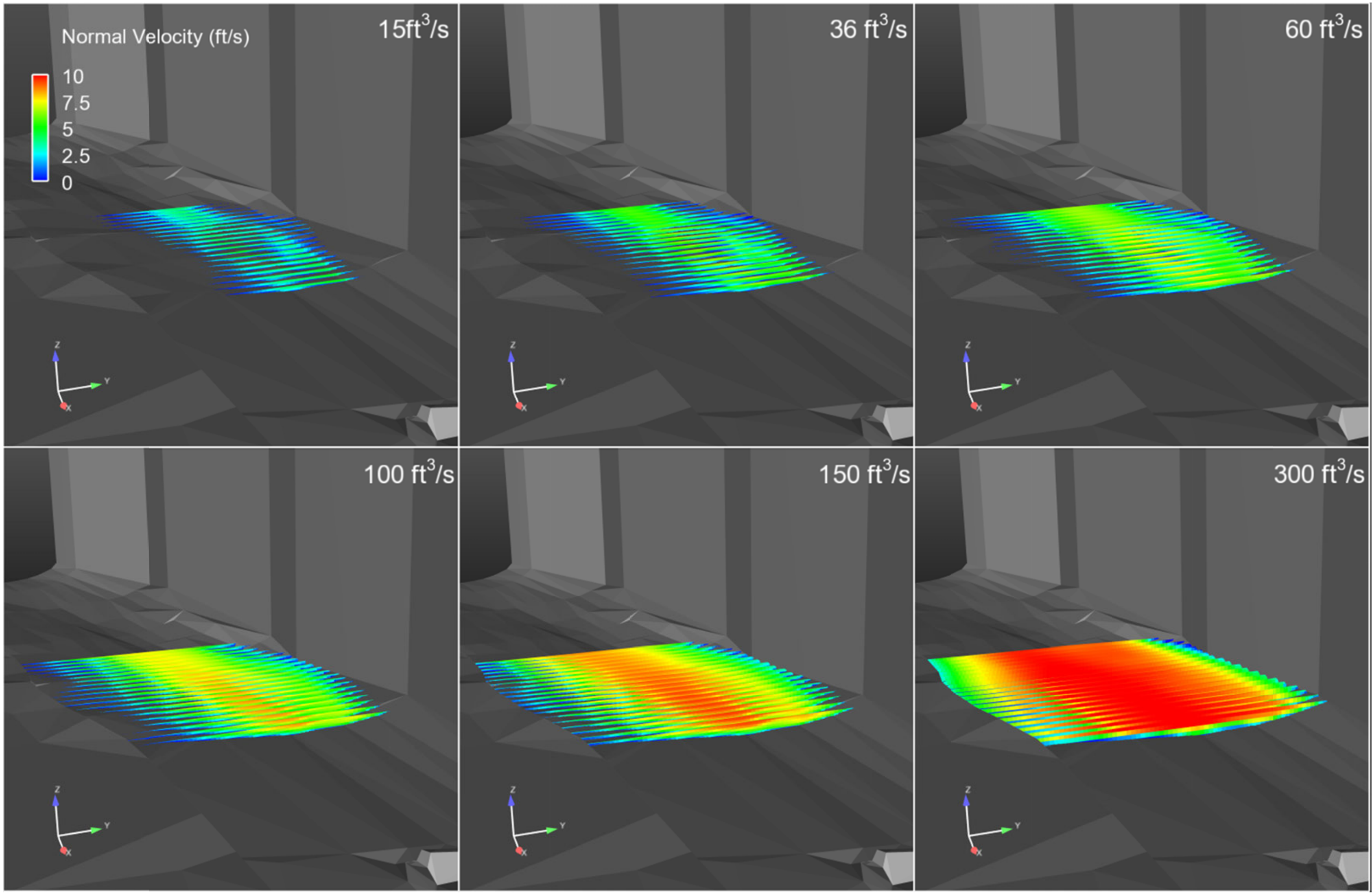
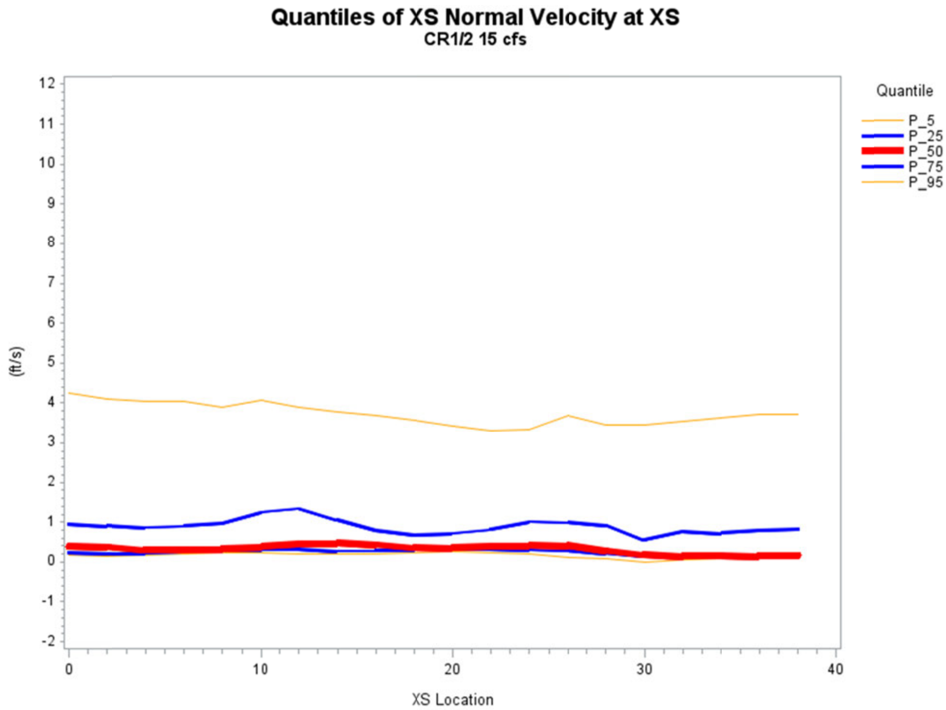
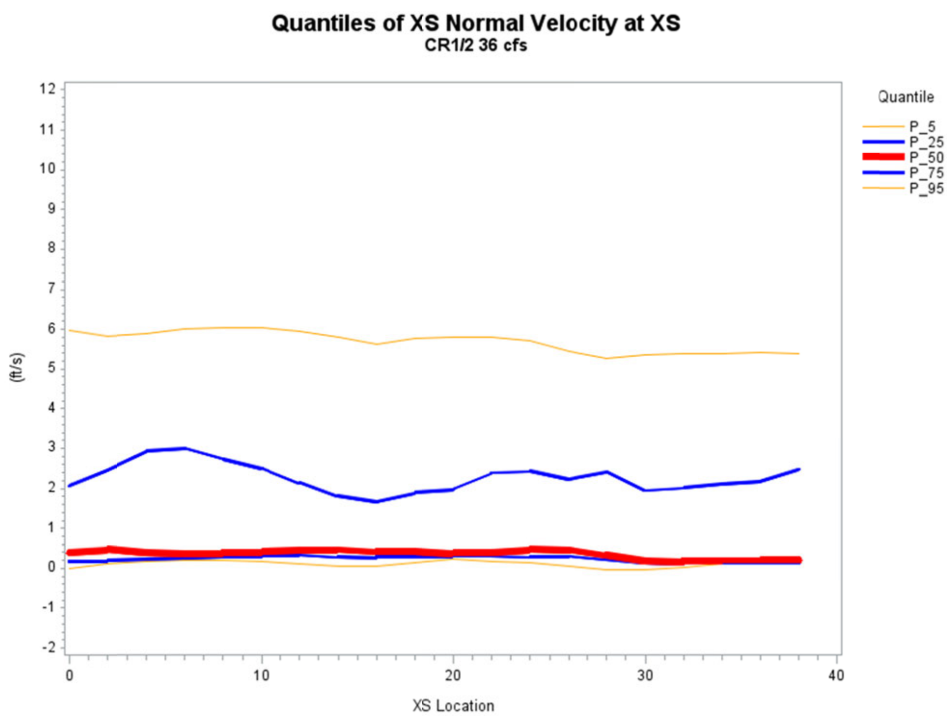



**Figure C.7: Detailed hydraulic model output of CR2 for six discharges.**

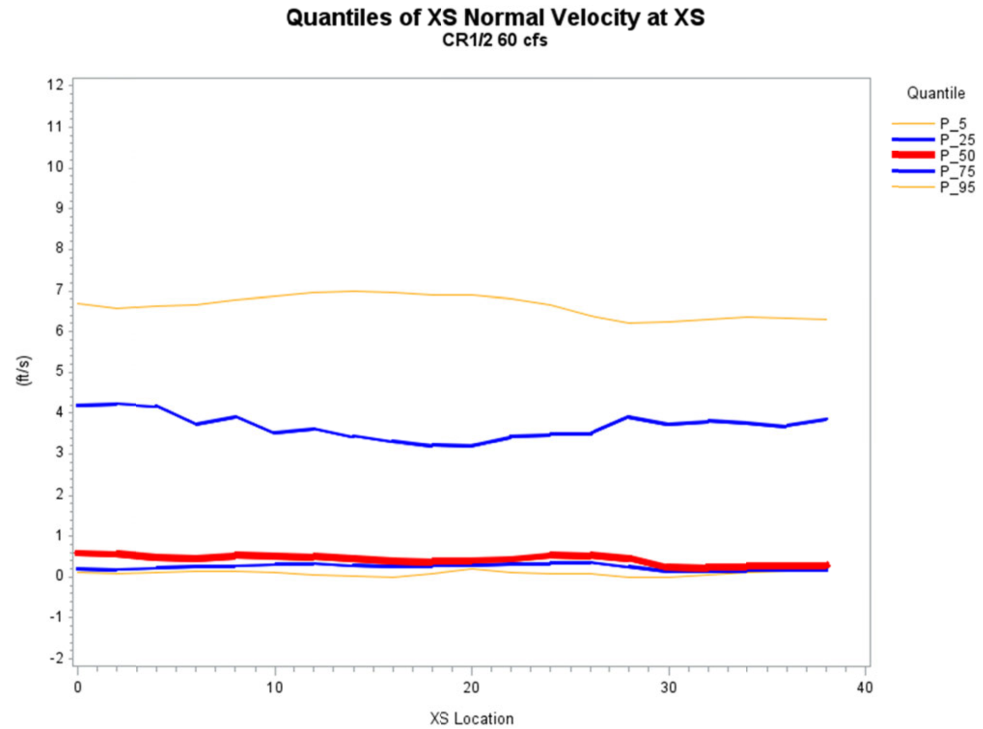



(A) 15 cfs

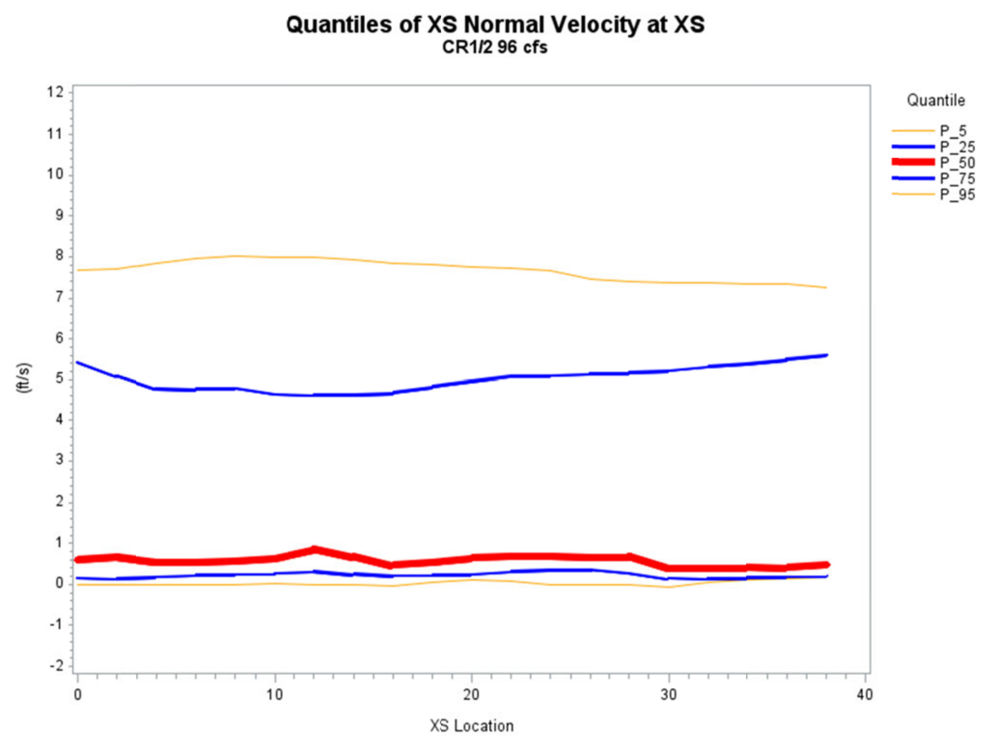



(B) 36 cfs

**Figure C.8: Analysis of CR2 cross-sectional flow velocty by percentile flow area: (A) 15 cfs; (B) 36 cfs; (C) 60 cfs; (D) 96 cfs; (E) 150 cfs; and (F) 300 cfs.**

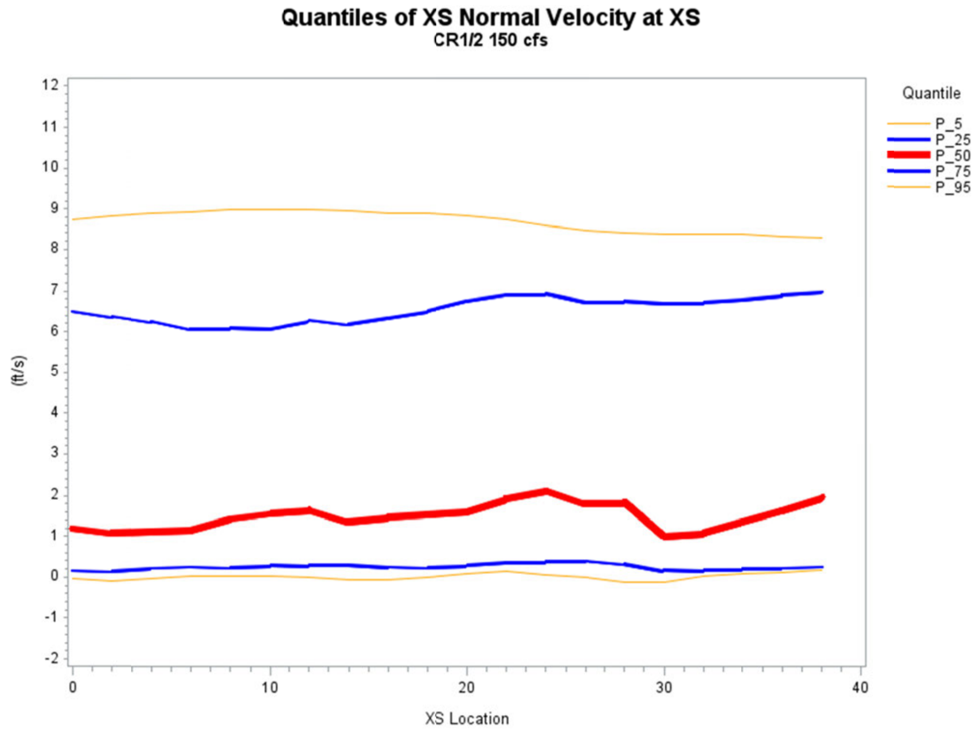



(C) 60 cfs

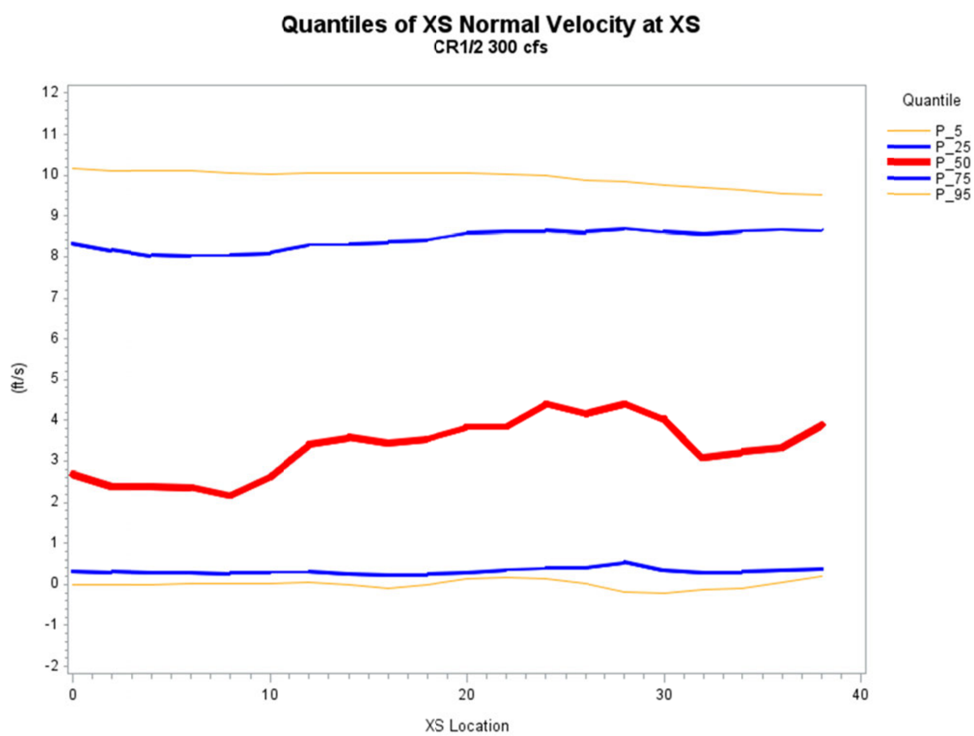



(D) 96 cfs

**Figure C.8 (continued).**




(E) 150 cfs




(F) 300 cfs

**Figure C.8 (continued).**

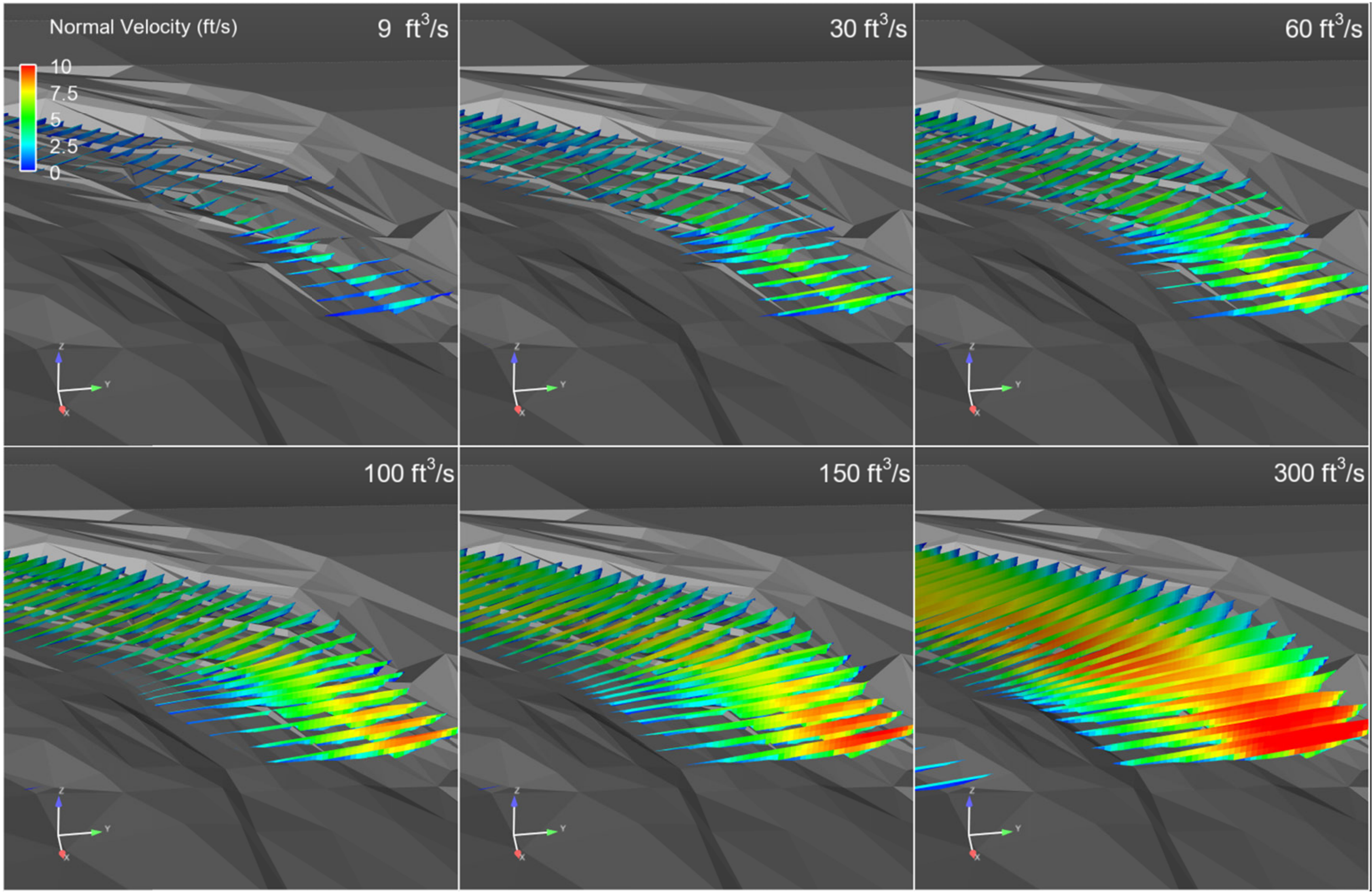
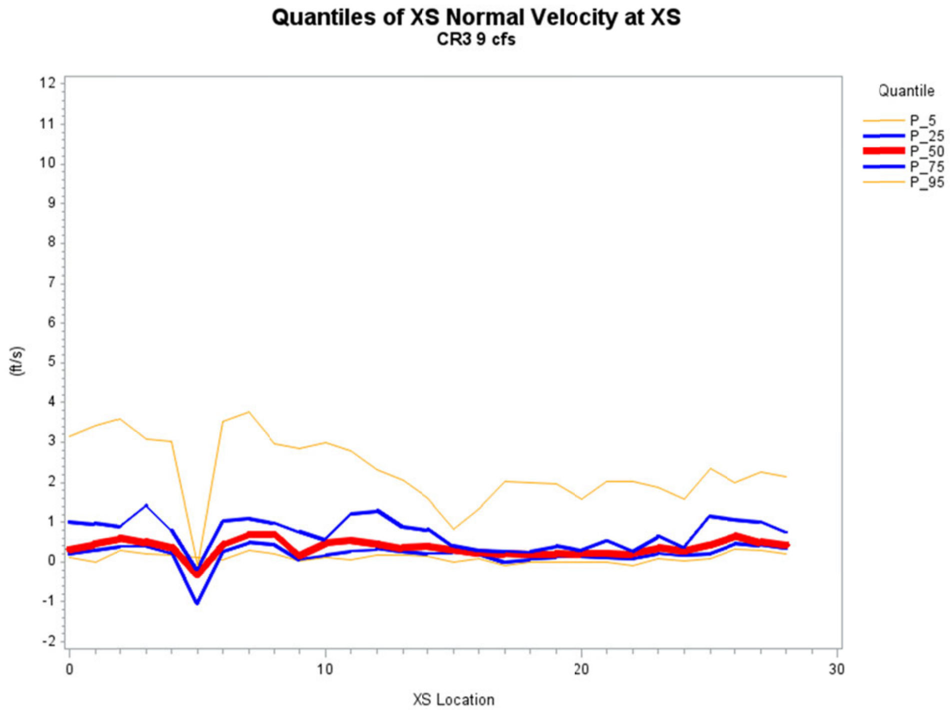
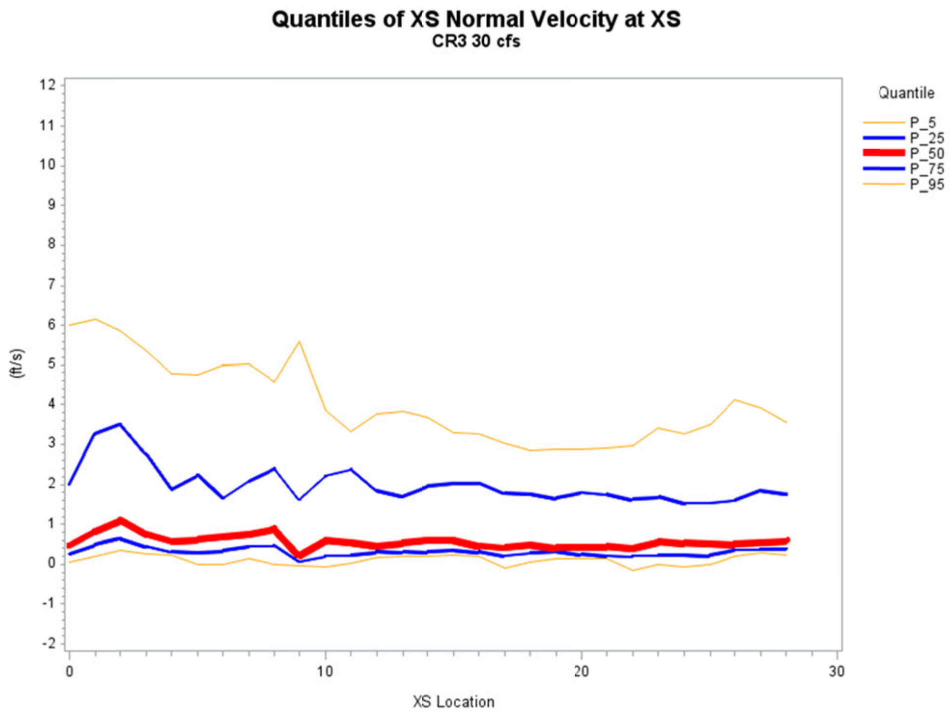



**Figure C.9: Detailed hydraulic model output of CR3 for six discharges.**

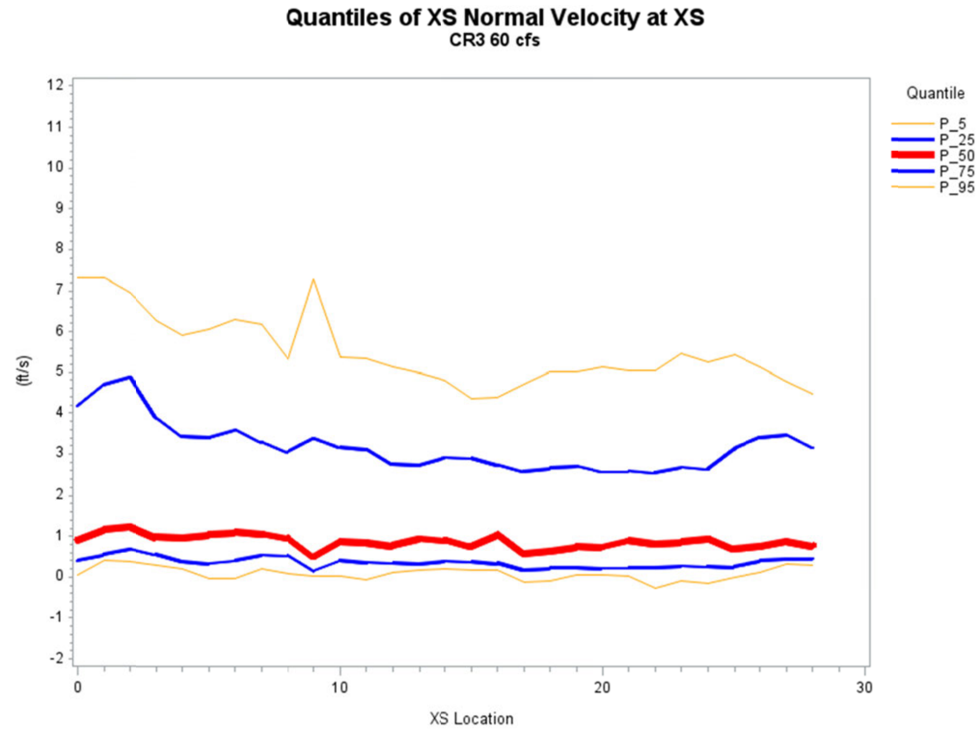



(A) 9 cfs

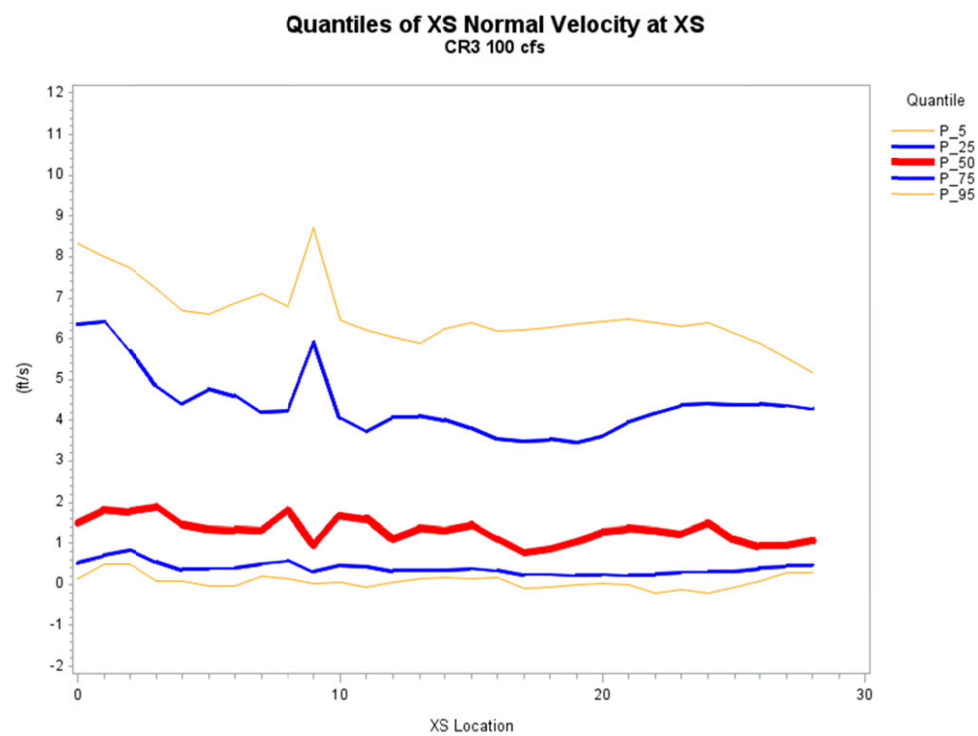



(B) 30 cfs

**Figure C.10: Analysis of CR3 cross-sectional flow velocty by percentile flow area: (A) 9 cfs; (B) 30 cfs; (C) 60 cfs; (D) 100 cfs; (E) 150 cfs; and (F) 300 cfs.**

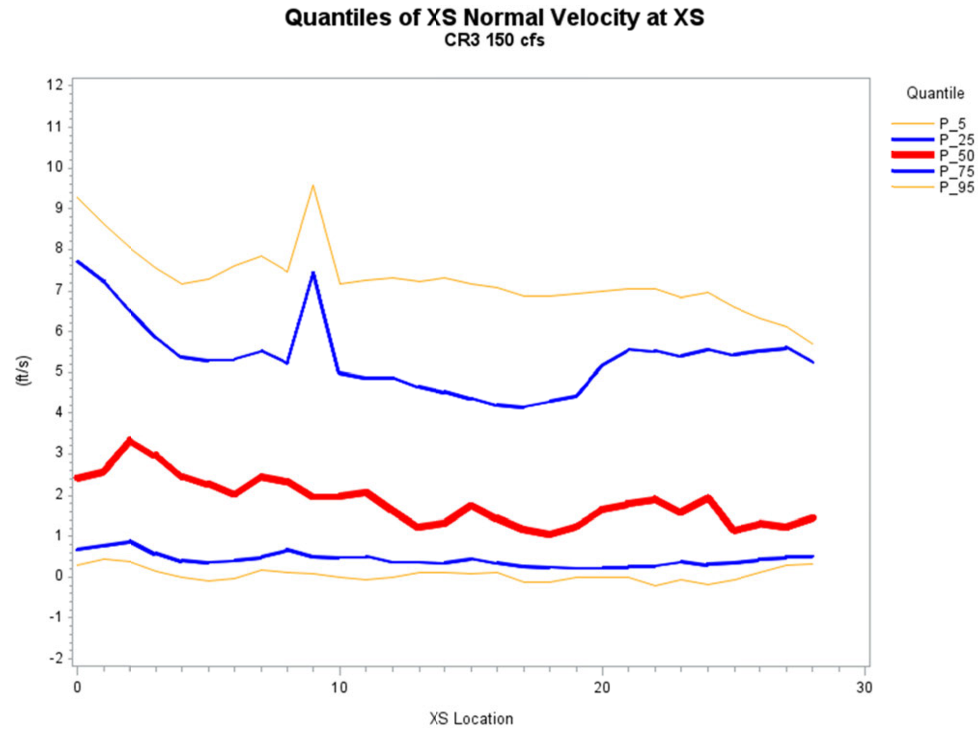



(C) 60 cfs

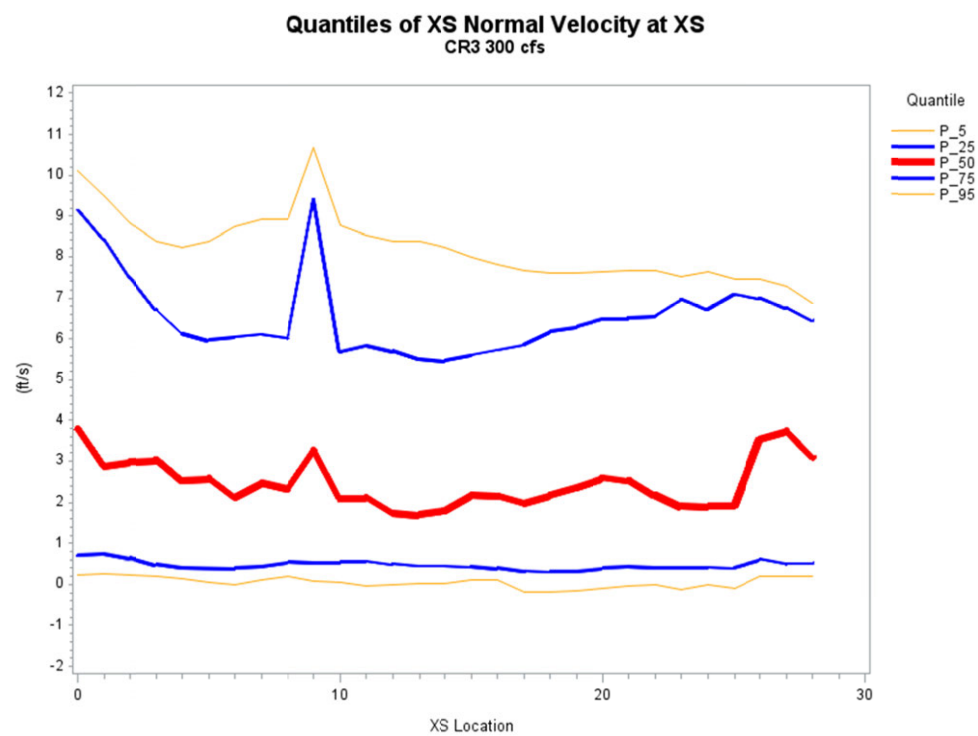



(D) 100 cfs

**Figure C.10 (continued).**




(E) 150 cfs




(F) 300 cfs

**Figure C.10 (continued).**

# LIST OF ABBREVIATIONS

| | |
|---|---|
| 2-D | two-dimensional |
| 3-D | three-dimensional |
| ADV | Acoustic Doppler Velocimeter |
| AIC | Akaike Information Criterion |
| AICc | corrected Akaike Information Criterion |
| CFD | computational fluid dynamics |
| CJS | Cormack Jolly-Seber |
| CPW | Colorado Parks & Wildlife |
| CR | control (sites) |
| DISP | displacement |
| GCS | grade control structures |
| HDX | half-duplex |
| HOF | Hofer x Harrison strain |
| LGS | longnose sucker |
| LND | longnose dace |
| LOC | brown trout |
| MRT | mark-release types |
| NA | not applicable |
| PIT | passive integrated transponder |
| ® | registered |
| RBT | rainbow trout |
| RFID | Radio Frequency Identification |
| RICDs | recreational in-channel diversions |

| | |
|---|---|
| US | United States |
| USACE | United States Army Corps of Engineers |
| USGS | United States Geological Survey |
| WWPs | whitewater parks |
| XS | cross section |