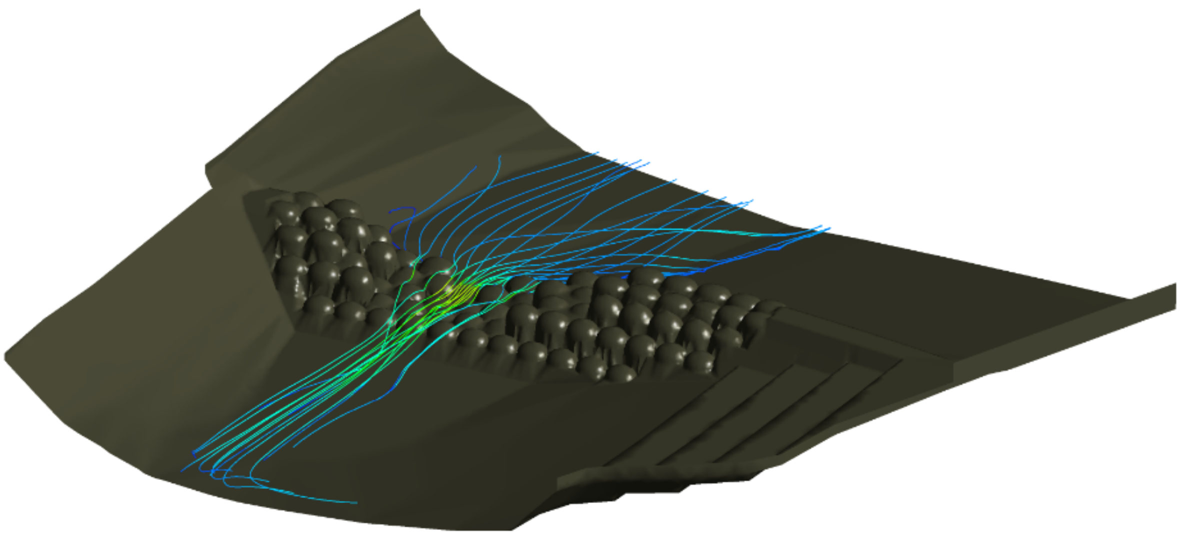
Computational Fluid Dynamics Study of Fish Passage and Aquatic Habitat for Redesigned Whitewater Structures in Meadow Park

September 29th, 2015



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Contents

Abstract

The September 2013 flood on the North St. Vrain River in Lyons, CO, largely destroyed the Meadow Park Whitewater Park. Prior to the flood, Colorado Parks and Wildlife (CPW) had conducted several studies at this site to investigate the impacts of existing whitewater park structures on fish passage and aquatic habitat. These studies identified characteristics of whitewater park structures that may negatively affect fisheries and proposed ways to mitigate these impacts. Meadow Park is currently being redesigned as part of the Lyons flood recovery process and the study presented herein was undertaken to evaluate proposed design alternatives prior to construction in order to optimize the redesigned structures for both fish passage and recreation opportunities.

This study analyzed four prototype whitewater structure geometries that included distinct characteristics intended to improve fish passage opportunities and habitat at the Meadow Park Whitewater Park. These characteristics included low and high slope roughened structures, a fish notch structure, and an alternating terrace structure.

A 3D Computational Fluid Dynamics (CFD) model was developed to compare hydraulic parameters between redesigned structure geometries and pre-flood whitewater structure geometries. Of the four geometries analyzed, the structure containing a fish notch in the center chute consistently produced the most desirable hydraulic conditions for fish passage, aquatic habitat, and recreational use at Meadow Park. The study also found that these results may not be universal, whitewater structure geometry selection is highly dependent on local site conditions. Though this study identified the Fish Notch geometry as the preferred alternative, site specific conditions such as channel geometries, hydrology, and 3D hydrodynamics may produce differing results in larger rivers and other locations.

The study also evaluated the whitewater characteristics of the structures with regards to recreational value to in-stream users. The revised structure geometries for the Meadow Park Whitewater Park redesign were selected based on physical and ecological criteria identified by CPW and are intended to meet both the needs of the recreationists as well as provide for fish passage and improve aquatic habitat.

Introduction

Whitewater Parks (WWPs) have become popular recreational amenities in cities across the United States. WWPs provide access to outdoor recreation, promote public interest in rivers, and generate economic revenue through tourism and the associated benefits to nearby businesses. Colorado has more WWPs than any other state in the nation and leads the way in WWP development with all of the Country's leading design firms based in the State.

Riverine WWPs typically consist of in-stream structures designed to create a hydraulic jump by modifying channel geometries to constrict flows and create a steep chute into a larger, downstream pool. Previous studies have identified four major hydraulic factors within WWPs that could directly limit upstream fish passage, including: velocity, depth, total drop and turbulence (Fox, 2013). The first whitewater parks were simple efforts designed to create robust structures that formed recreationally appealing hydraulics. These early parks were largely successful in their objectives and many of these early parks have become renowned attractions that draw boaters from around the world. Early WWP designs, such as those seen in the first iteration of Meadow Park in Lyons, Colorado, were of a simple design constructed using large amounts of concrete grout to form smooth monolithic structures. The field of WWP design has recently expanded to include moveable systems, pneumatic systems, and a variety of shapes and layouts. Despite the advances in design and construction of WWPs, and despite the aforementioned studies, little to no effort has been undertaken by designers to evaluate and tailor WWP designs to address potential ecological impacts.

The increasing prevalence of WWPs and the rapid evolution of new whitewater park design concepts has created concerns about the ecological impact of WWPs. Specifically, Colorado Parks and Wildlife (CPW) is concerned about the potential impact of WWPs on aquatic habitat and fish passage. This concern has led to several studies that investigate the relationships between WWP structure geometries, associated hydraulic conditions, and fisheries impacts. These studies can inform the field of WWP design, thereby creating more ecologically sound WWPs while simultaneously meeting the objectives of communities and recreationalists.

The original Meadow Park WWP was constructed in 2003 and consisted of nine river-wide grouted boulder structures within a 0.35 mile reach of the South St. Vrain River in Lyons, Colorado. In the years following its construction, CPW conducted a series of studies to evaluate the WWPs impacts to fish passage and aquatic habitat. During the flood of 2013, the Meadow Park WWP was largely destroyed. Since then the Town of Lyons has been pursuing the redesign and eventual reconstruction of the WWP and has thereby created an ideal location to compare before-and-after data with regards to fish passage. This study, in conjunction with the previous studies, has informed the redesign effort by identifying preferred design alternatives for the proposed WWP features at Meadow Park.

The overarching goal of the redesigned Meadow Park WWP is to improve fish passage and aquatic habitat, particularly during low flow periods identified by CPW, while simultaneously enhancing river-based recreation during the annual high water season. This study will assist in reaching the stated goals for Meadow Park by analyzing results obtained from a 3D Computational Fluid Dynamics (CFD) model, which calculates hydraulic conditions associated with structure geometries. Four separate proposed WWP structure geometries were evaluated at four different flow rates and compared to modeled results obtained from the earlier studies performed at Meadow Park.

The redesign and eventual reconstruction of the Meadow Park WWP, combined with the results outlined in the pre-flood studies completed by CPW, provides an ideal experimental set-up to evaluate the effects of WWP structure geometries on fish passage and aquatic habitat. The effects of WWP structure geometries on hydraulic conditions and subsequently their impacts to fish passage and aquatic habitat are analyzed in this study. Moreover, a framework for conducting before and after comparisons of the pre-flood and redesigned Meadow Park WWP are outlined herein.

Literature Review

Historically, there has been limited information regarding the impacts of WWPs on fisheries and aquatic ecosystem health. In an effort to fill this gap, Colorado State University (CSU) and CPW have undertaken a multi-year study to determine the effects of WWPs on fish habitat quality, stream connectivity, fish populations and fish passage at the Meadow Park WWP. To date, three separate studies based on the pre-flood configuration of the Meadow Park WWP have been completed. These pre-flood studies provide historical data for future studies such as the one presented herein.

Constructed in 2003, the Meadow Park WWP consisted of nine separate river wide structures, representing a range of physical geometries and associated recreational experiences. Three of the structures, along with three control reach (CR) sites, were selected for the studies completed by CSU/CPW. The WWP sites were identified as WWP1, WWP2, and WWP3. The CSU/CPW study area is shown below in Figure 1 and Figure 2.

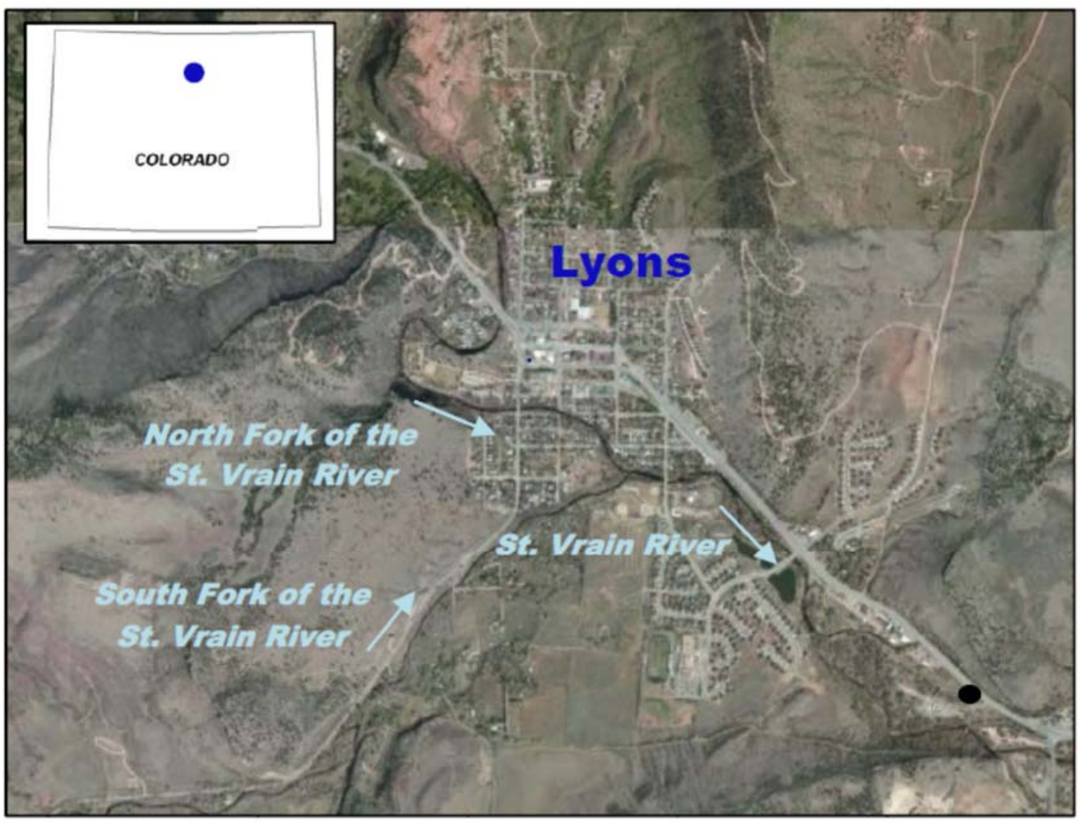


Figure 1: Study location, (Fox, 2013, p. 15).

Figure 2: Study Location, (Fox, 2013, p. 16)

The studies undertaken to date focus on altered hydraulic conditions at the WWP sites and rely on field data and 3D CFD modeling of the structures to assess impacts. A hydraulic dataset for the Meadow Park WWP was developed using FLOW-3D and this dataset was used to assess the effects of WWPs on fish passage (Fox, 2013) and habitat quality (Kolden, 2013). Stephens (2014) further used the results of the previous two studies to analyze the relationship between WWP hydraulics and fish passage. The selected control sites provided a baseline comparison for habitat and fish passage conditions.

Flow through a WWP structure is hydraulically complex and 3D modeling has the potential to be extremely useful in furthering our understanding of the effect of turbulence, vorticity and circulation on habitat quality (Kondratieff, 2013). The use of CFD modeling provides a powerful means of estimating the fine-scale hydrodynamic conditions through which fish passage must occur. Numerous studies have used CFD models to examine complex hydraulics related to fish passage and in-stream structures. Velocity, depth and turbulence have been used as variables to assess the hydraulic environment in the pre-flood studies. Vorticity and Turbulent Kinetic Energy (TKE) are measures of turbulence that influence fish movement. Vorticity is a pseudo vector representing the rotation rate of a small fluid element about its axis (Crowder DW, 2002). TKE is a measure of the increase in kinetic energy due to turbulent velocity fluctuations in the flow (Lacey RWJ, 2012); (Flow Science, 2009).

The study conducted by Brian Fox in 2013, *Eco-Hydraulic Evalution of Whitewater Parks as Fish Passage Barriers,* used a combination of fish movement monitoring and CFD modelling to assess if WWPs are barriers to upstream fish movement. CFD models provided detailed hydraulic conditions that were used to evaluate the flow field at all discharges over all modeled spatial and temporal fields.

Fox quantified fish movement across the Meadow Park WWP structures using Passive Integrated Transponder (PIT) telemetry system to track fish movement. Brown trout, rainbow trout, longnose sucker, and longnose dace were tagged and released for the study. Fixed PIT antennas were installed upstream and downstream of WWP structures along with the control sites to monitor fish movements. Raw PIT data were analyzed to determine if WWP structures posed a complete barrier to upstream movement for a given fish species or class size. Determination of partial barriers was completed by comparing raw movement counts for fishes known to make it upstream versus those that did not (Fox, 2013). This design measured successful passage across a structure, but did not quantify failed passage attempts, number of attempts, or behavior across the structure (Fox, 2013).

The commercially available software, FLOW-3D, was used to create 3D non-hydrostatic models of the each of the 3 WWP structures and three control sites. Six flow events (15, 30, 60, 100, 150 and 300 cfs) were modeled in FLOW-3D (Fox, 2013). 2D surfaces perpendicular to the flow were demarcated and the distribution of velocity values that described the range of potential flow conditions (Fox, 2013). The maximum, mean, 5^{th}, 25^{th}, 50^{th}, 75^{th} and 95^{th} percentile velocities were calculated within each cross section and used to assess opportunities for fish passage. This method does not account for connectivity and flow paths between or within the each of the cross sections.

Fox found that rainbow and brown trout were able to complete upstream movement across all WWP structures at nearly all flows studied. Fish body length, which is positively correlated with swimming ability, did not correlate with fish passage success across all three structures. Fox found a positive relationship between fish size and passage at WWP2, however, a negative relationship between movement and size existed at WWP1 (large fish were less likely to move), and a positive, but weak, relationship at WWP3. Further regression model analyses revealed that individual site location, body length, and species are all significant effects in estimating upstream movement probability (Fox, 2013). Furthermore, the interaction of length and location indicated that fishes of different body lengths have different probabilities of moving across various WWP structures and control pools. The inconsistency between fish size and passage is shown in Figur*e* 3, below, where it is evident that the trend between size and probability of movement varies between structures. These results suggest that there are factors other than size that influence the probability of fish passage at whitewater park structures and highlights the need for further studies to investigate the impacts of structure geometry on fish passage.

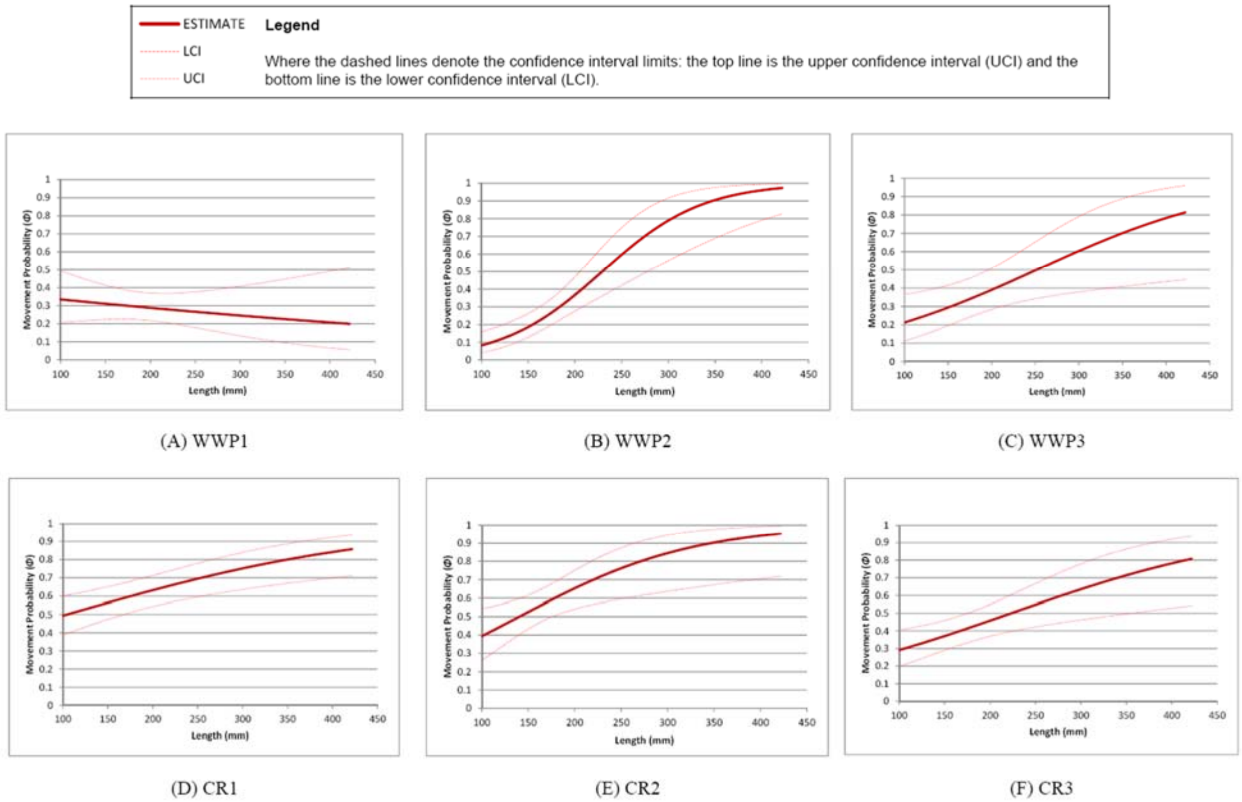


Figure 3: Effects of continuous variable body length on probability of upstream movement (Fox, 2013, p. 49).

Hydraulic modeling results were further used to evaluate and describe the flow velocity at each study site location. Flow velocity is a potential barrier to fish passage. Velocity can be either a burst swimming barrier, where the velocity exceeds a fish's maximum swimming speed, or an exhaustive swimming barrier, where a fish is unable to maintain positive ground over a given distance (Stephens, 2014).

The hydraulic modeling results, from Fox's report, show the range of velocities present at each WWP structures (Figure 4) and the Control Reaches (CR) (Figure 5). Fox (2013) further quantified velocities into 5th, 25th, 75th and 95th percentiles. For example, a flow classified at the 25th percentile indicates that 25% of the velocities sampled in the cross-section are less than or equal to the given velocity and the remaining 75% of the velocities sampled are greater than the given velocity.

The maximum velocities within the center chute of the WWP structures are significantly greater than those in the CR (Fox, 2013). The differences in velocities due to WWP structure geometries are seen below in Figure 4 and Figure 5. WWP1 is a short, steep drop, while WWP2 is a "wave" structure and consists of a longer, sloping chute with a confined outlet to the downstream plunge pool. WWP1 shows complex flow conditions due to the non-uniformity on the cross-sectional area. During low flows, the concentrated flow results in shallow depths, however the interstitial spacing may allow for potential passage routes. At WWP2 the entire flow area of the channel is restricted to the center chute at low discharges, however, there is only a very short section of the structure that contains high velocity magnitudes. WWP3 is also a "wave" structure, however, unlike WWP2, WWP3 has a maximum flow area constriction near the middle of the center chute and then expands laterally. This allows for reverse eddies to form on the sides of the jump of the plunge pool, possibly providing a by-pass around the high center velocities. These results highlight the influence of WWP structure geometry and design on velocity and fish passage.

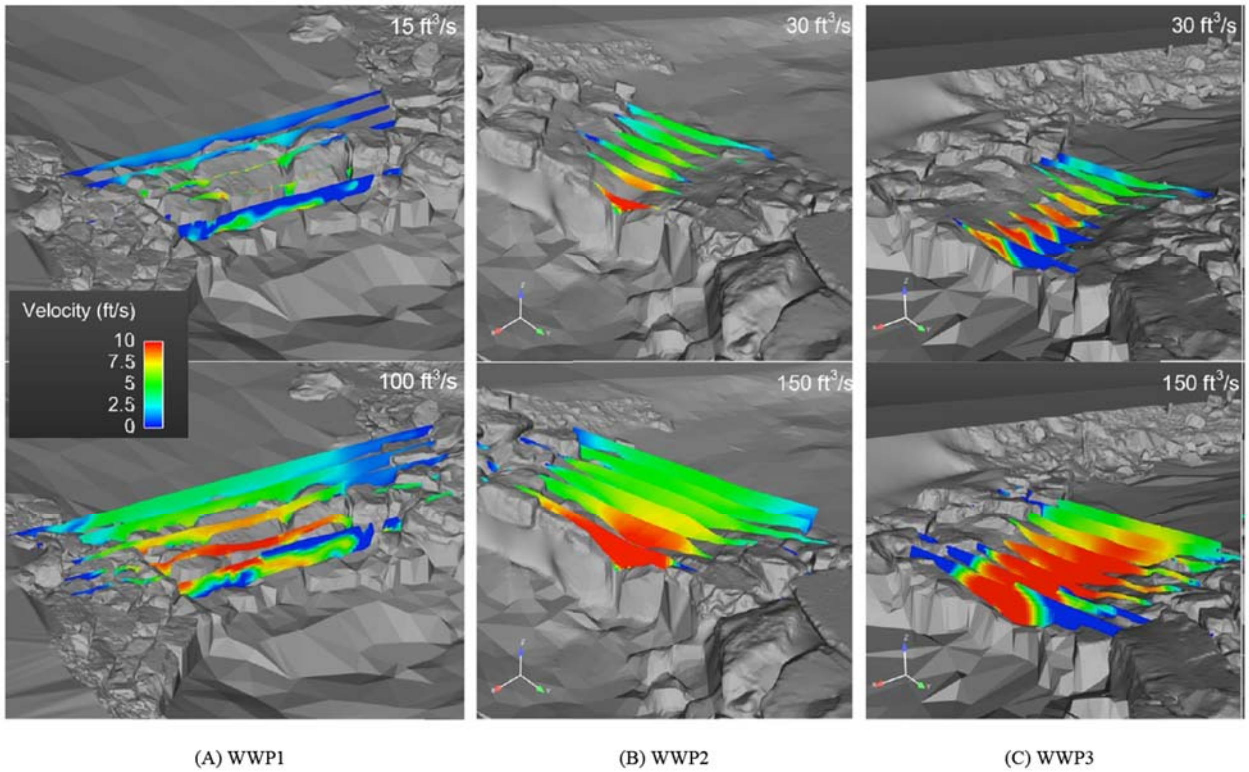


Figure 4: Cross sectional velocities for a low and high flow condition at (A) WWP1; (B) WWP2; (C) WWP3 (Fox, 2013, p. 52)

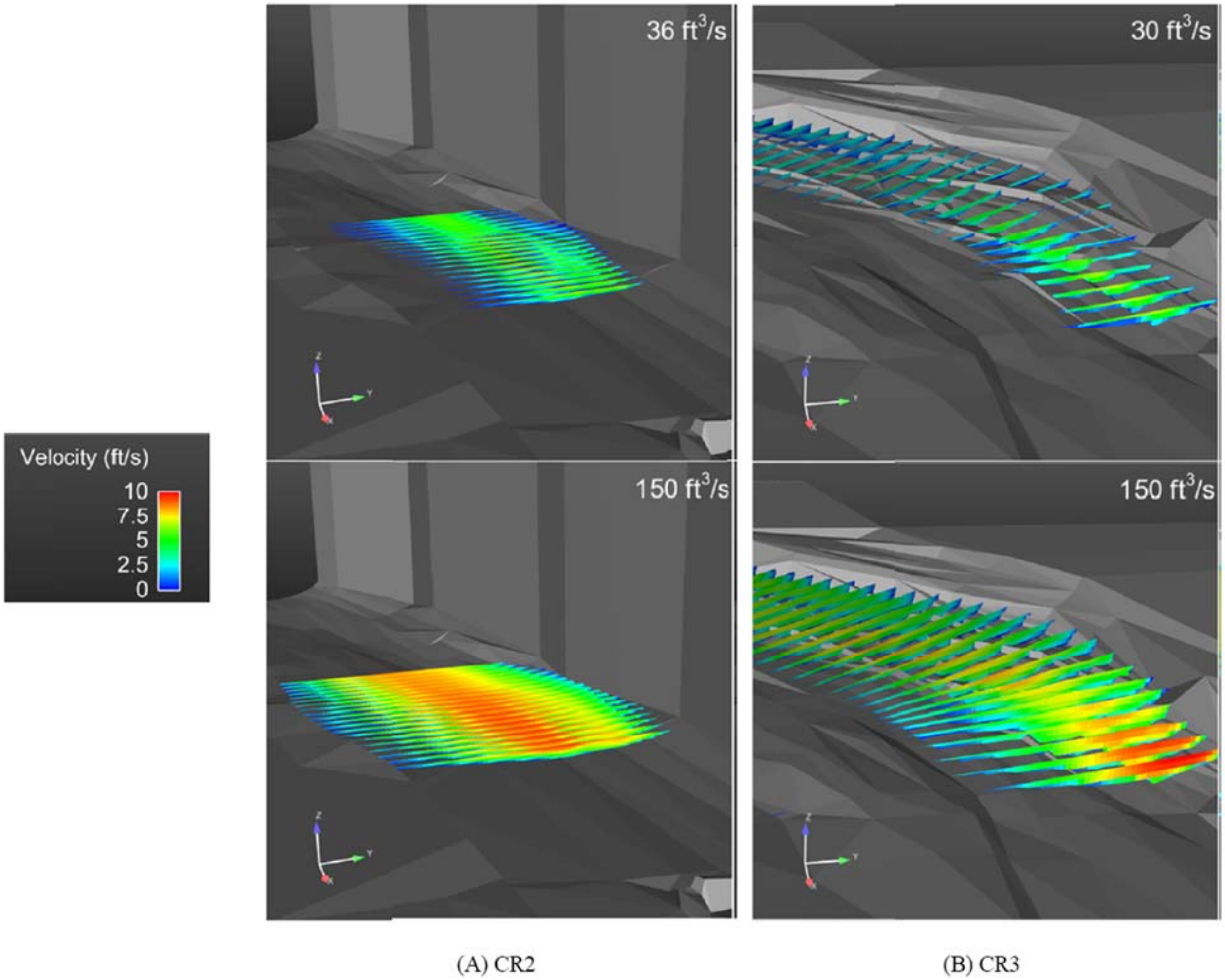


Figure 5: Cross-sectional velocities for a low and high flow condition at: (A) CR2 and (B) CR3 (Fox, 2013).

The burst swimming abilities of fish species coupled with the velocities generated by the WWP structures can influence the upstream mobility of fishes at Meadow Park. Castro-Santos (2013) suggests that brown trout have greater burst swimming abilities (up to 25 body lengths/s) than previously found by Peake (1997) (10 body lengths/second). Based on this study, a burst swimming barrier was assessed by considering the maximum velocity at each cross-section. The maximum velocities are considered the limiting condition burst swimming barrier.

The velocities calculated by the hydraulic models were typically less than calculated burst velocities, further suggesting that there are other factors that may explain the lack of correlation between fish size and passage at the studied WWP structures. While the study showed that cross-sectional velocity for burst swimming conditions shows large differences between CR and WWPs in the magnitude of velocity that must be overcome however, the velocities found in the WWP structures are likely not burst swimming barriers to salmonids despite flow velocities greater than 10 ft/s within each of the WWP structures (Fox, 2013). Figure 6, below, illustrates the velocity distributions through the WWP structures and the control reaches.

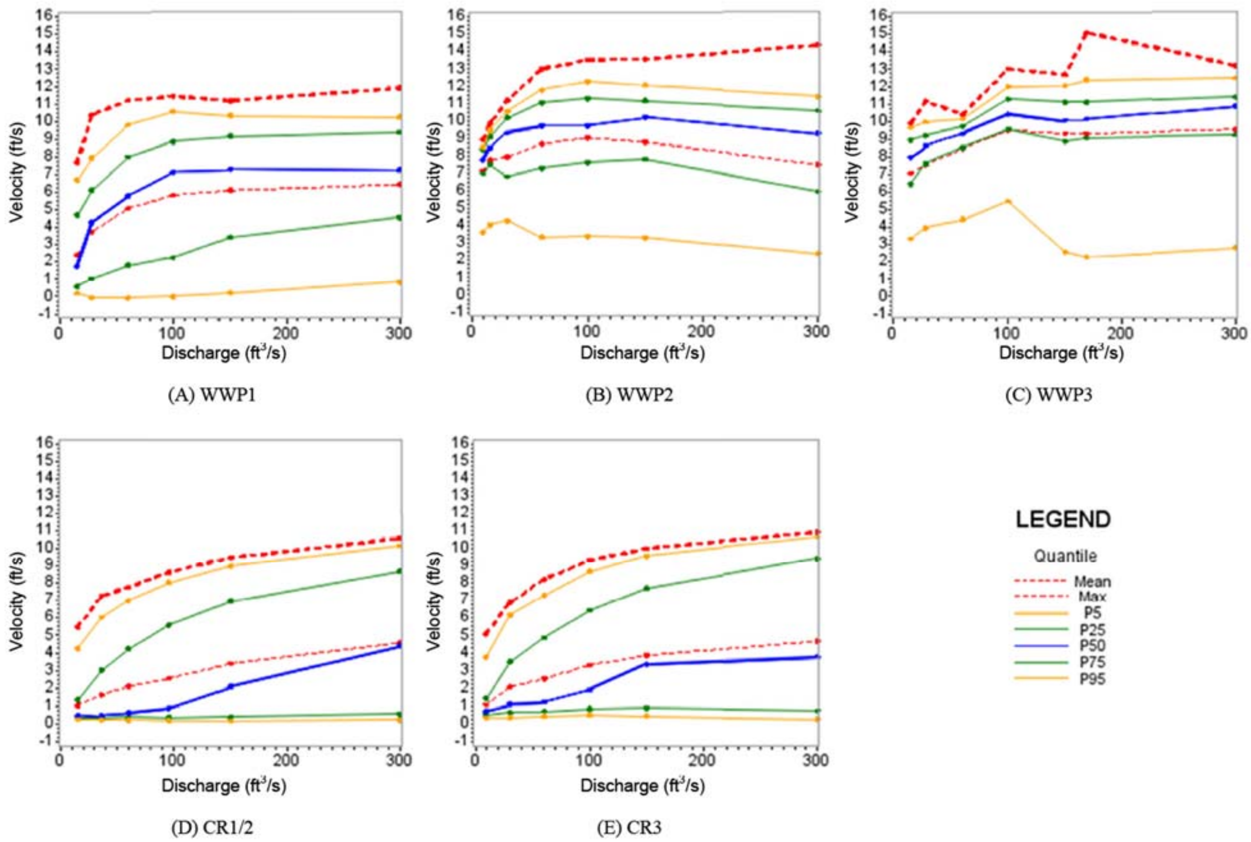


Figure 6: Limiting magnitudes of velocity within the zone of passage to assess burst swimming barriers (Fox, 2013, p. 57).

Successful movement was observed within WWP sites where fish were able to overcome velocities ranging from 8 ft/s in the 25th percentile to 12 ft/s in the 95th percentile (Fox, 2013). The control sites maintained lower velocities within 25-50% of the cross-sectional area, but the maximum flow velocities were nearly as high as those in the WWP sites.

Rainbow and brown trout were successfully able to pass each WWP structure, suggesting that the WWP does not represent a complete barrier to upstream movement (Fox, 2013). Results pertaining to native fish were less conclusive due to the relatively small sample sizes utilized in the study conducted by Fox. However, successful passage of longnose dace was observed at two of the three WWP structures studied and successful passage of longnose suckers was observed at all three of the WWP structures studied. Other potential causes for reduced fish movement include: an exhaustive swimming barrier, reduced flow depth, total hydraulic drop, turbulence, habitat quality, fish behavior, and/or differences in survival between WWP and CR sites.

Modeling results indicated that an exhaustive swimming barrier is unlikely. While all three structures show zones of high-flow velocities, these are generally limited to the downstream point of the center chute. Lower velocities can be observed at locations close to the outlet and along the channel margins, providing favorable conditions for the remainder of the passageway (Fox, 2013). Despite the higher velocities at the WWP sites, there was not a significant trend between passage and body length (Fox, 2013).

In the Discussion Section of Fox's study he recommends certain guidelines for the design of WWP structures, which include: structures that maintain short, high-velocity zones should be passable for species of similar swimming abilities; the presence of lower velocity routes around high velocity zones and roughness elements on the lateral margins of the channel also may improve fish passage success by reducing and magnitude of a potential velocity challenge.

A study conducted by Eleanor Kolden, *Modeling in a Three-Dimensional World: Whitewater Park Hydraulics and Their Impact on Aquatic Habitat in Colorado* (2013), described and compared fish habitat quality in the Meadow Park WWP and Control Reaches using 3D CFD modeling and traditional 2D habitat suitability criteria. Kolden (2013) modeled the same reaches along the North St. Vrain River as described in the study by Fox (2013). Using 3D CFD models, hydraulic conditions at each of the three WWP structures studied by Fox were modeled by Kolden and the calcualted hydraulic parmeters were used as inputs for the 2D habitat suitibility indeces.

Habitat sutabitlity models typically relate 2D hydraulic variables of depth and depth averaged velocity to habitat suitibility indices for specific species and lifestages. However, the 2D simplification of hydraulic conditions ignores the effects of vertical velocity components and gradients in the water column (Crowder DW, 2002), a factor that is of key importance at WWP structures due to the complexity of the associated hydraulic conditions. Furthermore, there is limited information on the correlations between ecological functions and 3D hydrodynamics, including turbulence, vorticity and circulation (Pasternack, 2008). Kolden (2013) modeled a range of discharges using FLOW-3D that are intended to represent the range of flows that occur over a typical year in the South St Vrain. The coresponding results for velocities, depths, vorticities and TKE are presented in the discussion and provide comparisons to the results of this study.

Habitat suitibility analyses were performed for brown and rainbow trout, longnose dace, and longnose sucker. These analyses predicted substantially higher habitat quality in WWPs as compared to natural reaches for both adult brown and rainbow trout, however, instream surveys completed by CPW showed higher fish biomass per volume in natural pools (Kolden, 2013). The discrepancy between these results indicates the need for additional studies, as well as the need to include other possible variables, such as competition, predation, food availablity, water quality and recreational use.

Kolden (2013) further investigated the differences between the 2D and 3D vorticity and TKE. In the 2D rendering, vorticity in and around the eddy was almost completely damped out, indicating that the vorticity in that area was not in the horizontal plane. Similarly, at the center jet, the 2D rendering did not show the large area of higher vorticity downstream of the jet, despite the clear presence of churning and boils from field surveys (Kolden, 2013). These differences indicate the advantages of 3D modeling to relate vorticity and TKE within WWP structures to fish habitat.

Kolden's (2013) report suggested possible connections between modeled hydraulic conditions and biomass. TKE, 2D voriticity, and 3D vorticity measurements were all higher in the WWP pools, while the biomass was lowest in the WWP pools. 3D modeling was shown to be important in this study for determining velocity distribution in the water column and vorticity. Due to the geometries of the WWP structures studied, the velocities tended to be highest near the bottom of the water column and slower near the surface, the opposite of what is generally observed. This can have implications on fish movement, as some species are adapted to swimming near the bottom where the velocities tend to be slower. This study highlights the need for further information on the impact of TKE and vorticity on fish behavior.

Timothy Stephens completed a study, *Effects of Whitewater Parks on Fish Passage: A Spatially Explicit Hydraulic Analysis* (2014), which combined observed fish movement data and 3D hydraulic modeling results to examine the physical processes that may limit the upstream movement of trout at the Meadow Park WWP. The methods used provide a continuous and spatially explicit description of velocity, depth, voticity and TKE along potential fish swimming pathways within the flow field. Using the results from the 3D modeling described above, Stephens (2014) identified a relationship between velocity, depth, vorticity and TKE on the suppression of movement of upstream migrating fish through statistical analysis of movement data from PIT-tagged studies at the Meadow Park WWP.

Stephans (2014) found that both the magnitude and distribution of TKE and vorticity varied substantially among WWP structures and discharges, as shown below in Figure 7, Figure 8, and Figure 9 (Stephens, 2014).

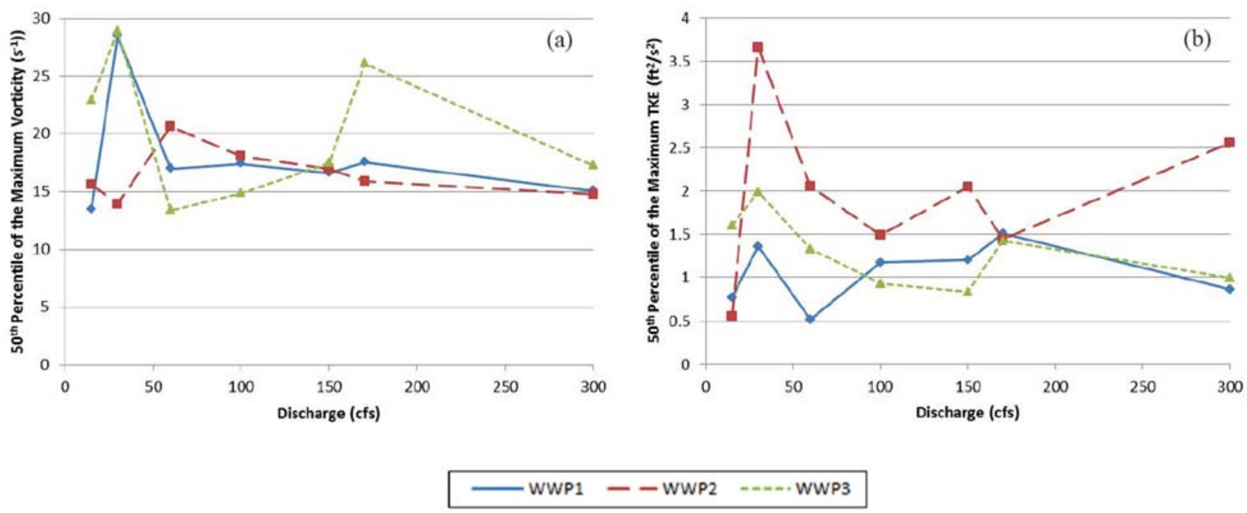


Figure 7: 50th percentile of (a) maximum vorticity and (b) maximum TKE along a flow path for each WWP structure and discharge (Stephens, 2014, p. 32)

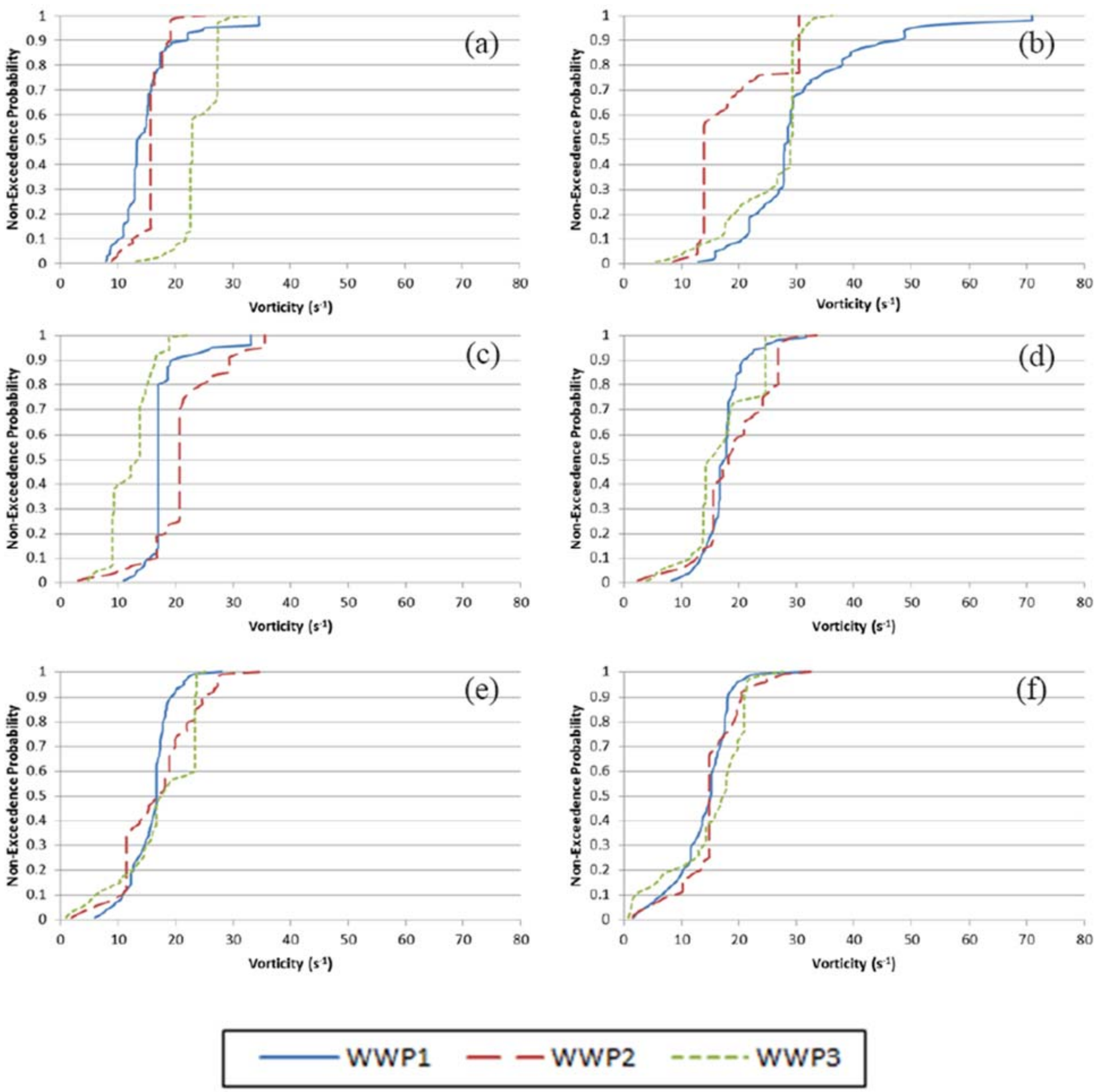


Figure 8: Non-exceedence probabilities for maximum vorticity along flow paths at each WWP structure for: (a) 15 cfs, (b) 30 cfs, (c) 60 cfs, (d) 100 cfs, (e) 150 cfs, and (f) 300 cfs (Stephens, 2014, p. 33)

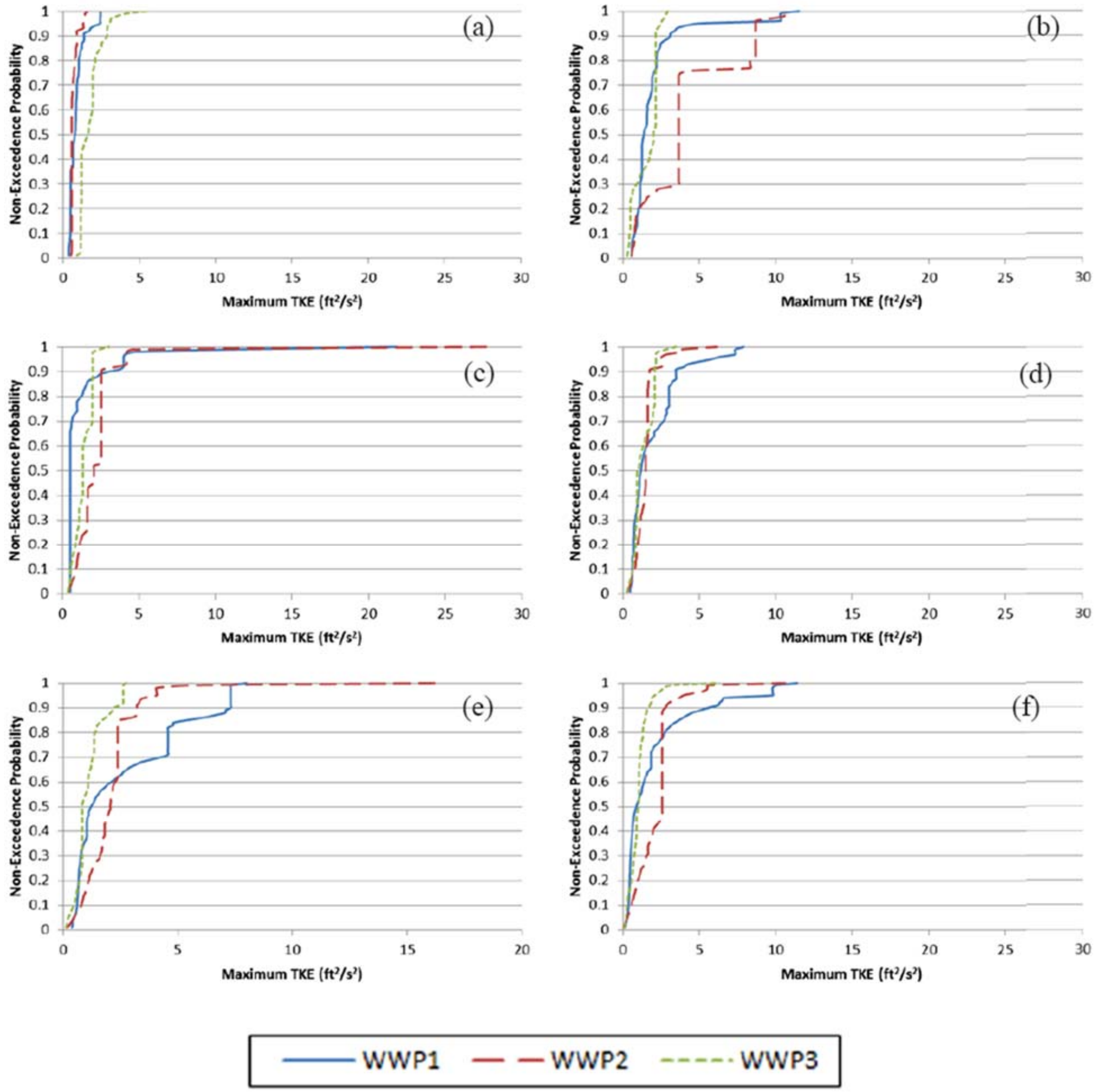


Figure 9: Non-exceedence probabilities for the maximum TKE along flow paths at each WWP structure for: (a) 15 cfs, (b) 30 cfs, (c) 60 cfs, (d) 100 cfs, (e) 150 cfs, and (f) 300 cfs (Stephens, 2014, p. 34)

Stephens (2014) also found that velocity, depth, and body length all have a signficant influence on passage success. Depth was the primary limiting factor at WWP1, while both velocity and depth have signficant influences at WWP2 and WWP3. Regression analysis demonstrated the influence of the combined variables of maximum velocity (25 BL/s) and minimum depth across all WWP structures. These results may be applied broadly across other WWPs, however, additional investigations of WWPs of various sizes and hydrologic regimes should be investigated (Stephens, 2014). This demonstrates the importance of considering depth and velocity jointly when evaluating barriers to upstream passage (Stephens, 2014).

The significance of velocity as an influence on fish passage differs from Fox's study which did not find velocity to have a clear effect on passage success. This contradiction may be attributed to the difference in scales over which velocities were calculated. Fox (2013) calculated cross sectional velocity quantiles within the chute of the WWP, not accounting for discontinuities in acceptable velocities along the movement path (Stephens, 2014). This indicates that secondary pathways can be designed that allow for fish passageway.

All three studies demonstrate a clear need for better understanding of how design-specific features and small scale hydraulics affect fish passage and behavior and provide insight into ways that WWPs can be designed to improve fish passage and aquatic habitat. The following study utilized the results of these studies to create an experiment that evaluated varying designs with the intent of maximizing fish passage and fish habitat through the use of metrics identified in these studies.

Methods

Study Site

The North St. Vrain River begins as snowmelt, in the Front Range of the Colorado Rockies, along the east side of the Continental Divide. It descends rapidly through high alpine glacial valleys and entrenched bedrock canyons to an elevation of 5,374 ft at its confluence within the South St. Vrain River. The Meadow Park WWP is located within the Town of Lyon, CO, approximately 0.5 miles upstream from the confluence of the North and South St. Vrain Rivers. The existing channel morphology of the 0.35 mile Meadow Park WWP reach is primarily single-thread with alternating step/pool bed sequences created from the construction of nine separate whitewater structures. Bed slopes within this reach typically range from 1 to 1.5 percent, with locally steeper slopes observed within the WWP structures. The valley floor is flanked by large sandstone escarpments on both sides, which impose geologic controls on the river channel, thereby limiting its ability to meander.

This study focused modeling efforts on a single WWP structure, described as WWP3 in the previous CPW studies. This study compared hydraulic conditions calculated for four different proposed geometries at the WWP3 structure, which currently exists at the Meadow Park WWP.

Hydrology

The hydrology of the North St. Vrain River is primarily snowmelt dominated. However, high intensity convective thunderstorms, typically occurring in mid to late summer, can generate extreme flood events such as those seen in 2013.

The hydrology for the study was developed based on direction provided by CPW and a separate analysis of stream gage data on the North St. Vrain River, post 1965, following the construction of the Button Rock Dam. Average mean daily flow rates for the North St. Vrain River were calculated using 33 years of stream gaging records on the St. Vrain River and four years of data measured on the South St. Vrain River (Figure 10). A percent reduction factor was calculated using years where gaging records overlapped between the South St. Vrain and the main stem. This reduction factor was then multiplied by the flows measured in the main stem on years where no flows were measured in the North St. Vrain to calculate flows.

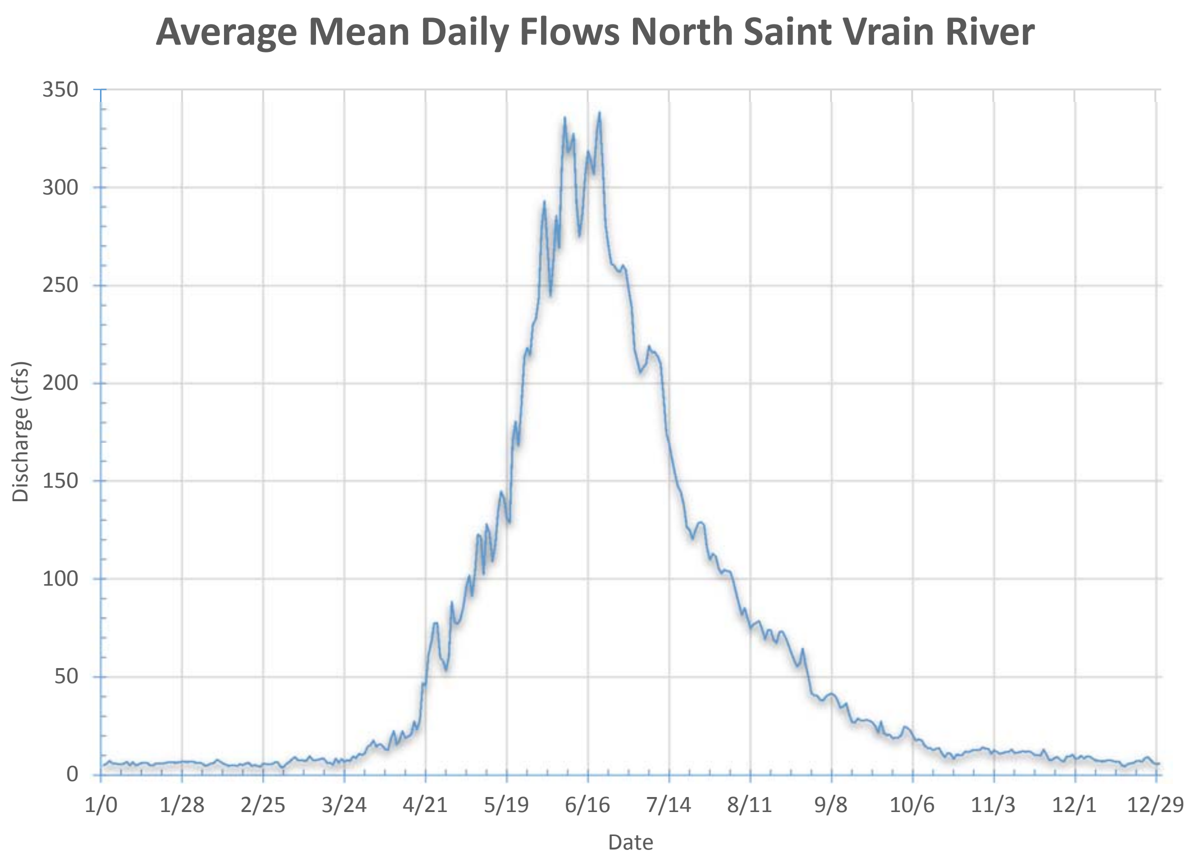


Figure 10: Hydrograph showing the calculated average of mean daily flows for the North St. Vrain River, following the construction of Button Rock Dam.

Based on the calculated average of mean daily flows for the North St. Vrain, four different flow rates were selected for this study. These flows included: base flows, spawning flows, recreational flows and peak flows (Table 1).

Table 1: Study Flow Rates

	Base Flows	Spawning Flows	Recreational Flows	Bank Full Flows
Time Period	Oct 15-Nov 15	April 1-April 30	June 1 - June 30	2 Yr Flow
Average Flow (cfs)	11.8	32.5	289.9	NA
Maximum Flow (cfs)	14.2	77.6	338.5	NA
Minimum Flow (cfs)	8.2	11.1	244.7	NA
Study Flow (cfs)	10.0	30.0	300.0	600.0

Base Flows

Discussions with CPW revealed that October 15th-November 15th is a critical time period for fish passage in the St. Vrain River system. Using the calculated average of mean daily flows for the North St. Vrain

River, the average flow for this period was determined to be 11.8 cfs while the minimum and maximum flows for the period were determined to be 8.2 cfs and 14.2 cfs respectively. A second time period between January 1st and March 31st was also evaluated. This period shows even lower flows than the October 15th through November 15th window. The average, minimum, and maximum flows calculated during this period were 6.4 cfs, 4.1 cfs, and 10.8 cfs respectively. Given the variability of low flows in the North St. Vrain between October and March a Base Flow of 10 cfs was proposed for the CFD modeling study.

Spawning Flows

CPW also specified the period between April 1st and April 30th as a second critical window for spawning in the North St. Vrain. Using the calculated average of mean daily flows the average, minimum, and maximum flows for this period were determined to be 32.5 cfs, 11.1 cfs, and 77.6 cfs respectively. Based on this analysis a Spawning Flow of 30 cfs was proposed for this study.

Recreational Flows

Recreational flows were also identified in this study to determine the effects of various fish passage treatments on the anticipated recreational opportunities to occur at the modeled drop structure. The period between June 1st and June 30th was identified as a critical window for recreation in Meadow Park. Using the average of mean daily flows, an average flow of 290 cfs was calculated for this period. The minimum and maximum flows for the same period were calculated as 245 cfs and 339 cfs respectively. Based on this analysis a Recreational Flow of 300 cfs was proposed for this study.

Bank Full Flows

Bank full flows are also proposed for this study to evaluate the hydraulic conditions generated by the structures during high probability flood events where the river accesses its primary floodplain. For this analysis, the 2 year recurrence interval was proposed as the flow in which the river stage exceeds its banks. Using a similar methodology to the calculation of the average of mean daily flows, peak flow data were obtained for the main stem of the St. Vrain River in Lyons then reduced by a calculated percentage of flow as determined from stream flows measured in the South St. Vrain River. Using the Weibull plotting position formula these corrected peak flow data were then used to obtain the probability of occurrence and recurrence interval. This analysis yielded a flow of 608 cfs for a 2 year recurrence interval. Based on this analysis a Bank Full flow of 600 cfs was proposed for the CFD model.

Experimental Setup

Four different prototype geometric configurations were developed for the proposed WWP3 structure redesign. The four identified flow rates were modeled within the prototype structures to characterize associated hydraulic conditions and their implications to fish passage, aquatic habitat, and recreation. Structure geometries varied to include the range of cross sectional differences, longitudinal slopes, wing configurations and boulder edges shown in Table 2. Structure geometries were developed in AutoCAD Civil3D as Triangular Irregular Networks (TIN), for export to ANSYS CFX. The prototype geometries studied are listed below:

Roughened Ramp 16%

The Roughened Ramp 16% (RR16) geometry has a 16.6% (6H:1V) low flow ramp slope, symmetrical wing elevations, staggered boulder edges along the margins, and boulder roughness elements intended to simulate a recessed grout line relative to the top of boulder (Figure 11 and Figure 12). This design was used to investigate the effect of surface roughness on modeled hydraulic conditions.

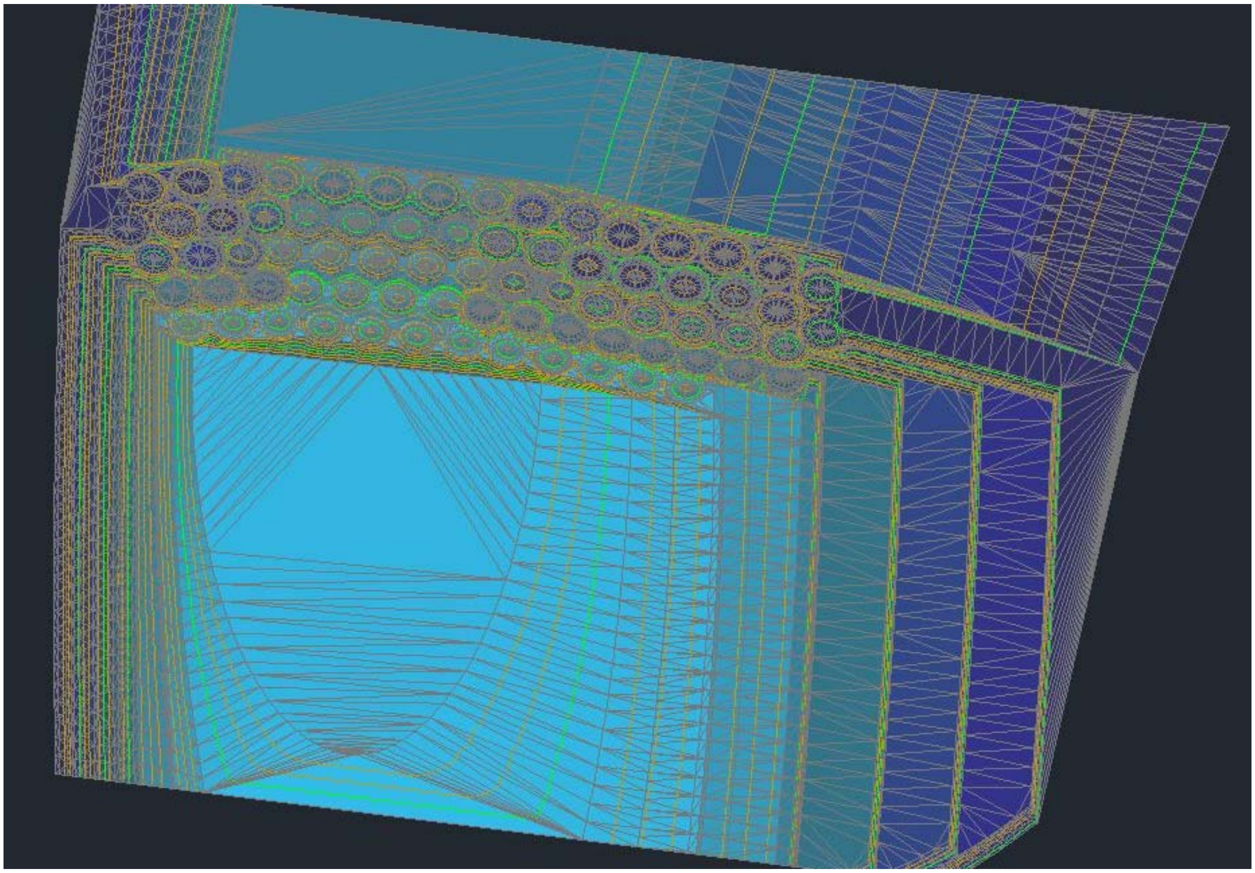


Figure 11: Planview of the Roughened Ramp 16% geometry

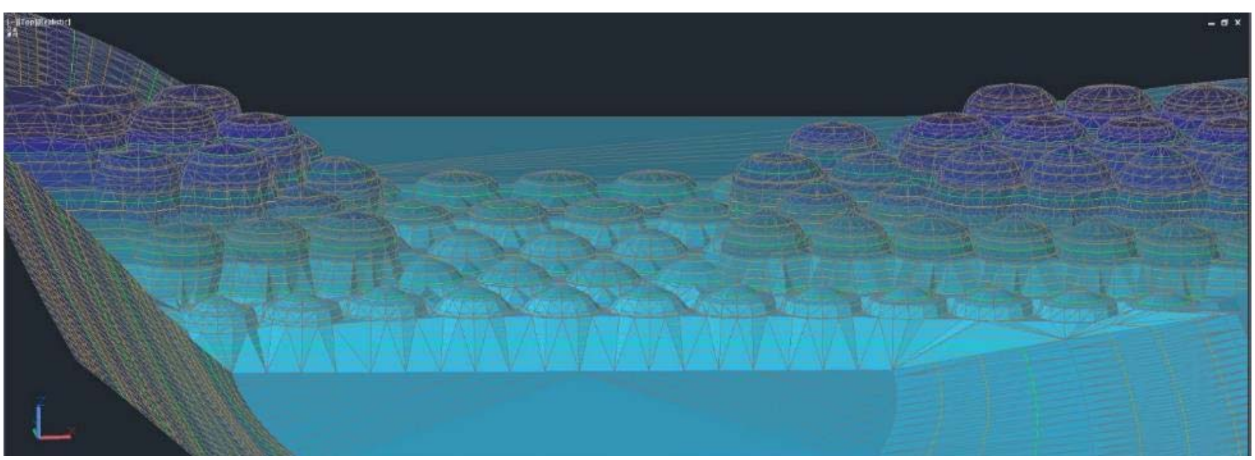


Figure 12: Looking upstream through the throat of the Roughened Ramp 16% geometry.

Roughened Ramp 12%

The Roughened Ramp 12% (RR12) geometry has a 12.5% (8H:1V) low flow ramp slope, symmetrical wing elevations, staggered boulder edges along the margins, and boulder roughness elements (Figure 13 and Figure 14). This design allowed for the investigation of the effect of reduced bed slopes on modeled hydraulic conditions.

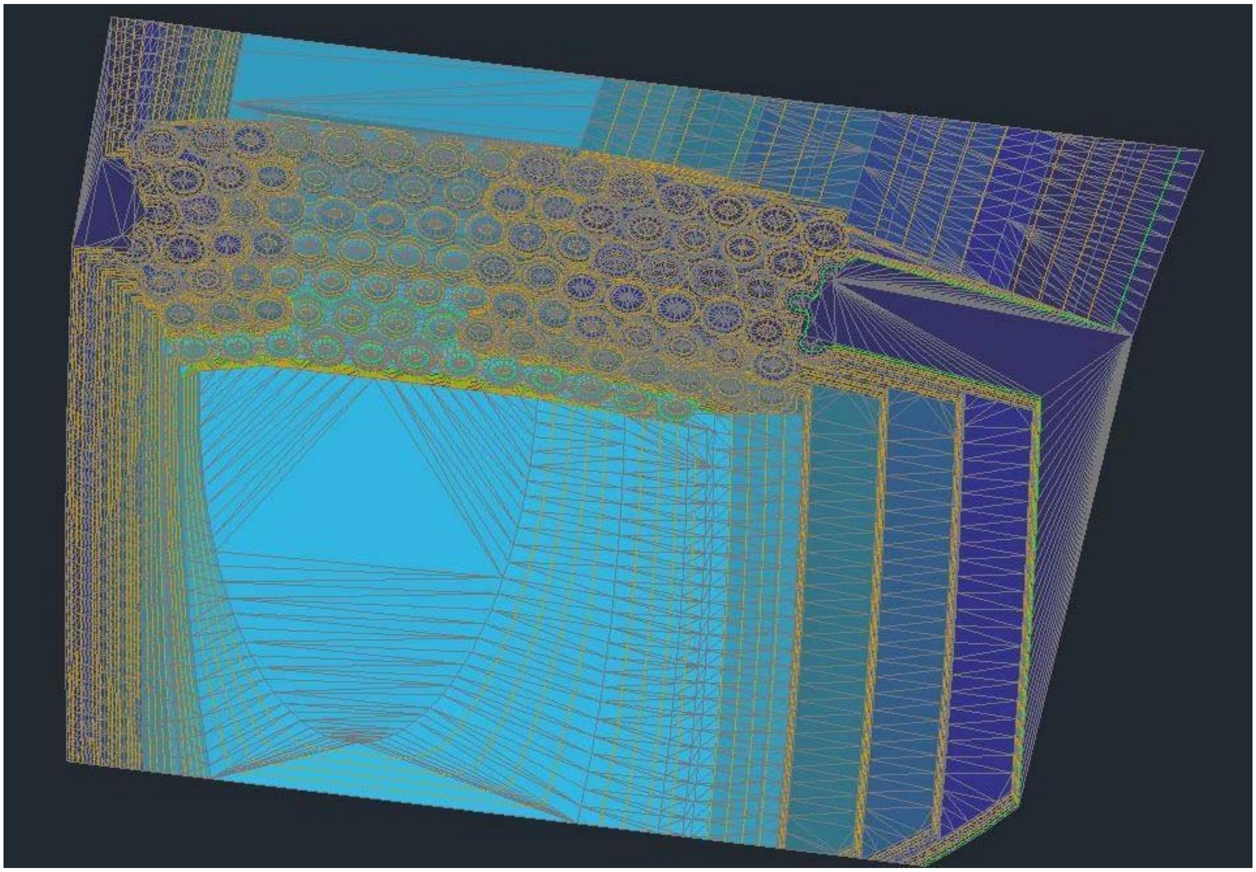


Figure 13 Planview of the Roughened Ramp 12% geometry.

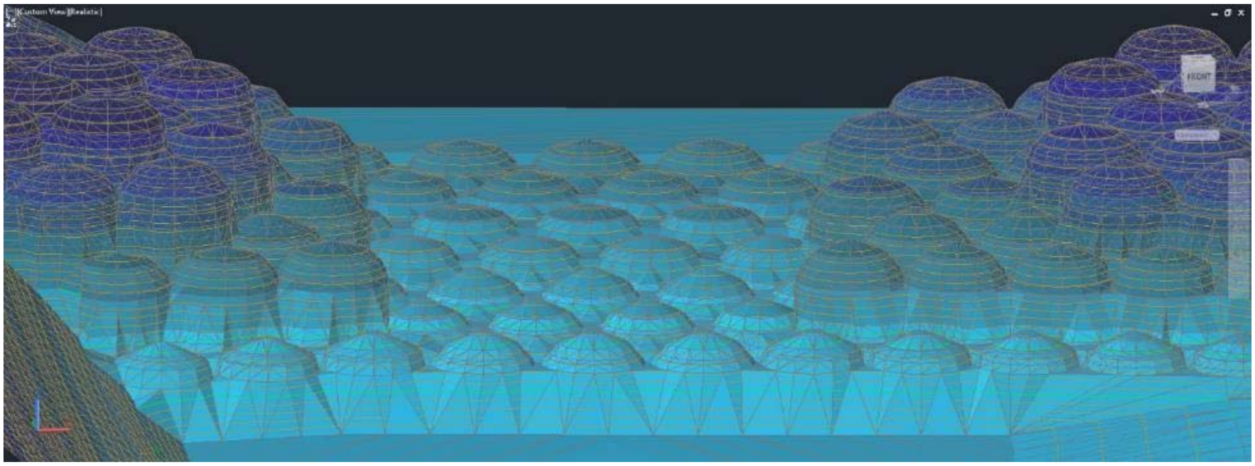


Figure 14: Looking upstream through the throat of the Roughened Ramp 12% geometry.

Alternating Terrace

The Alternating Terrace (AT) geometry has a 16.6% (6H:1V) low flow ramp slope, alternating staggered wing elevations, staggered boulder edges along the margins, and boulder roughness elements (Figure 15 and Figure 16). This geometry was investigated to determine how alternating terrace depths affect small scale hydrodynamics.

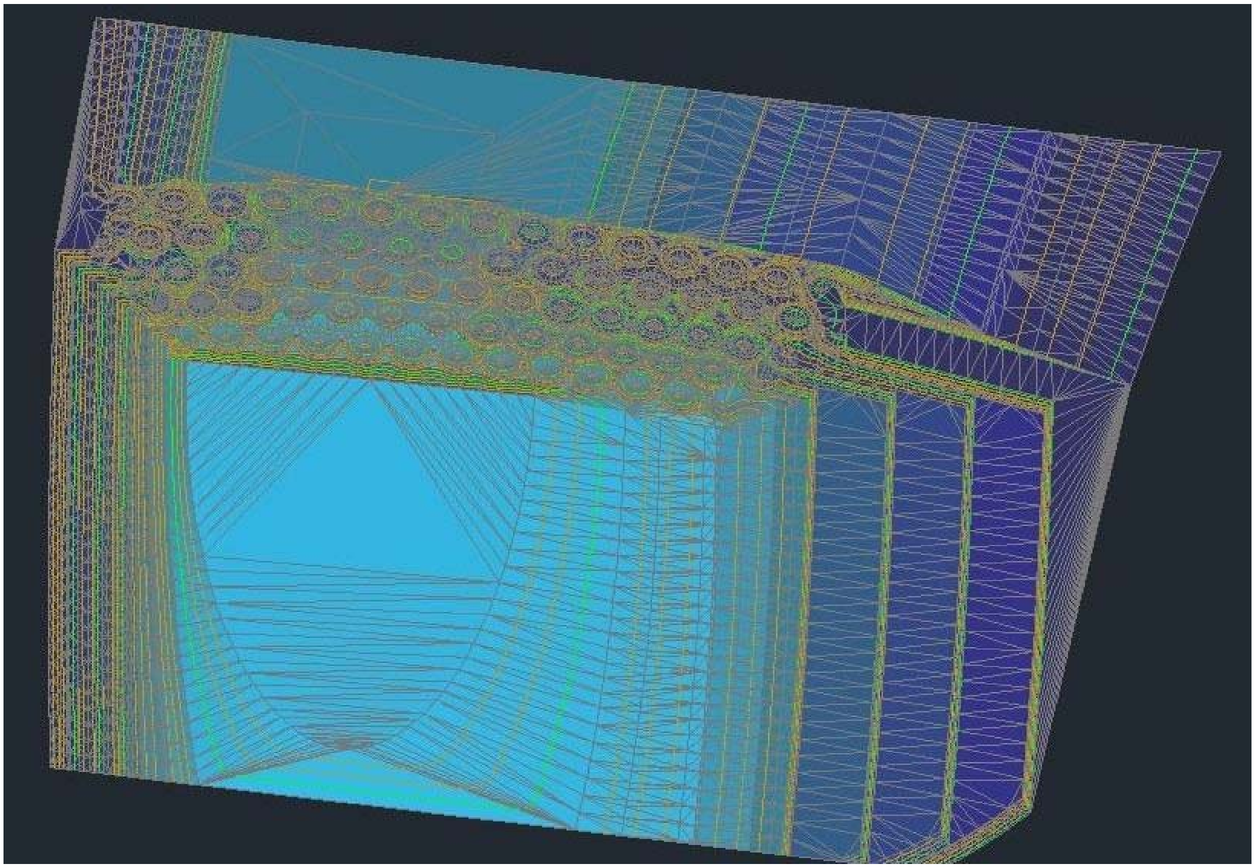


Figure 15: Planview of the Alternating Terrace geometry.

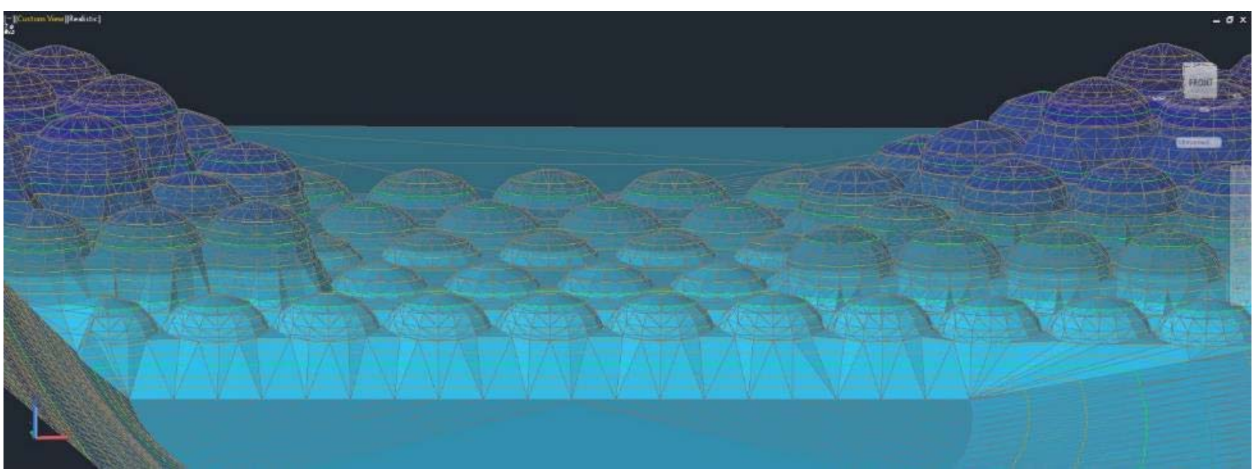


Figure 16: Looking upstream through the throat of the Alternating Terrace geometry.

Fish Notch

The Fish Notch (FN) geometry has a central notch 5.5% (18H:1V), a 16.6% (6H:1V) low flow ramp slope, symmetrical wing elevations, staggered boulder edges along the margins, and boulder roughness elements (Figure 17 and Figure 18). This geometry was investigated to see how a low slope centered notch effect hydraulic conditions, particularly at lower flows.

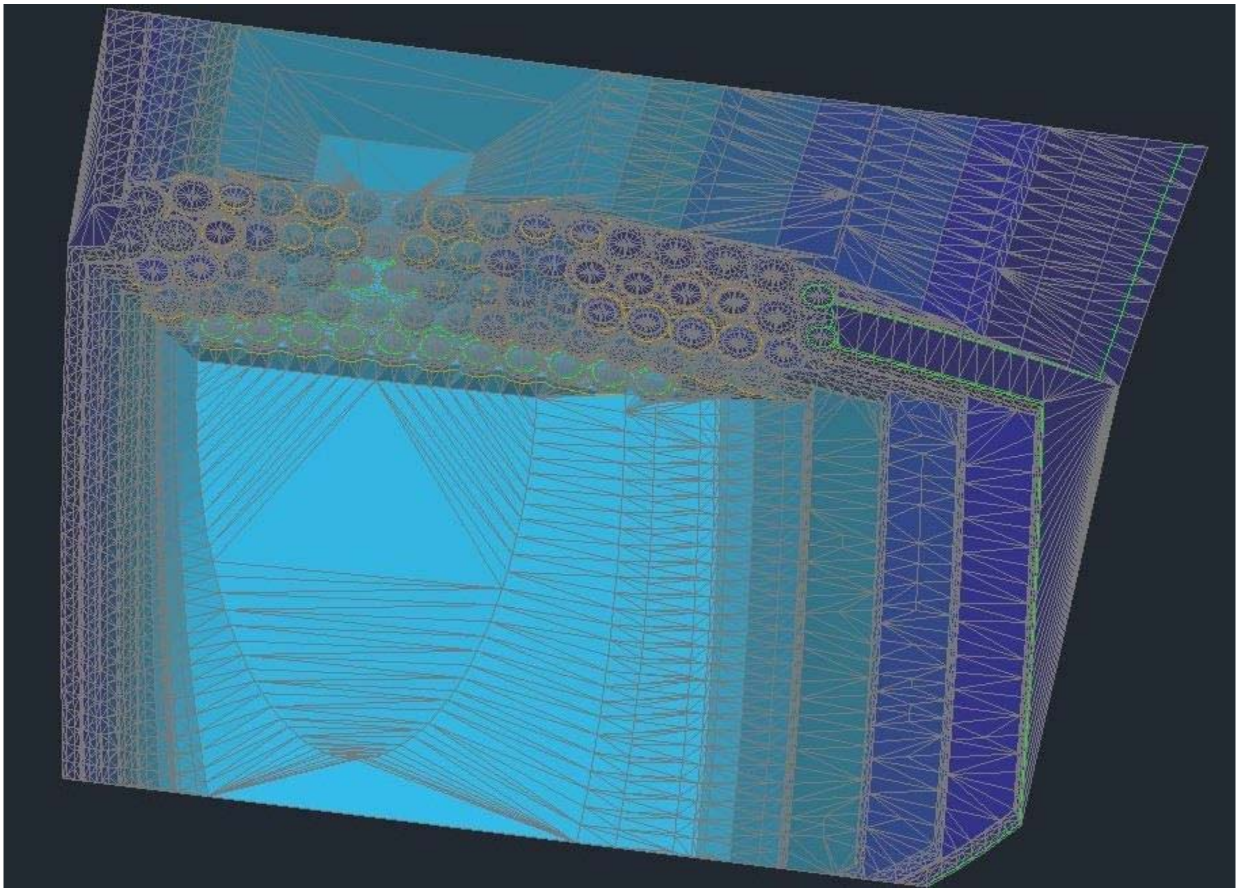


Figure 17: Planview of the Fish Notch geometry.

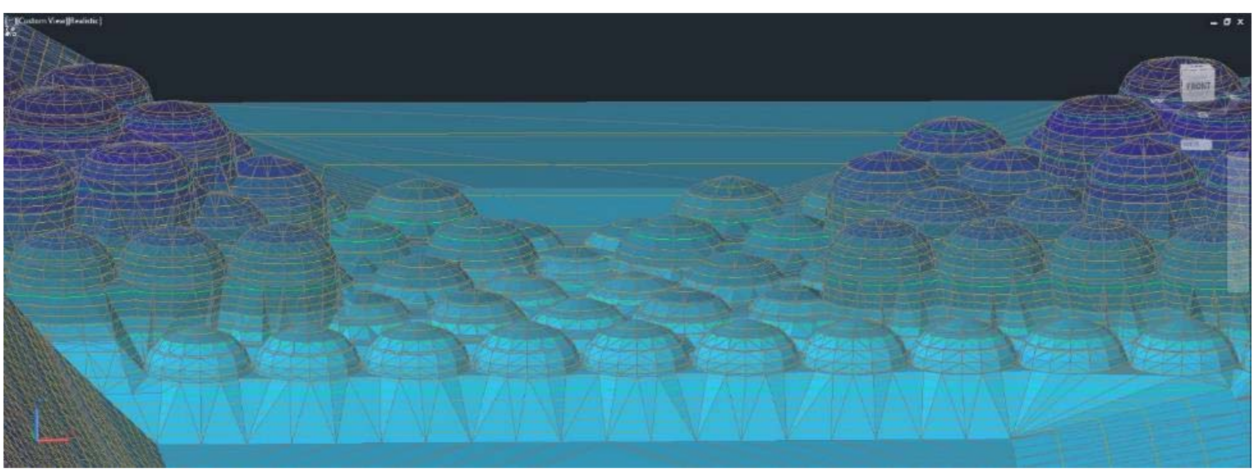


Figure 18: Looking upstream through the throat of the Fish Notch geometry.

Table 2: Four geometry types studied to evaluate associated hydraulic conditions and their potential Implications to fish passage and aquatic habitat.

Geometry Name	Ramp Slope	Wing Elevation	Boulder Edge
Roughened Ramp 16%, RR16	16.6% (6H:1V) Low Flow Ramp Slope	Symmetrical Wing Elevations	Staggered
Roughened Ramp 12%, RR12	12.5% (8H:1V) Low Flow Ramp Slope	Symmetrical Wing Elevations	Staggered
Alternating Terrace, AT	16.6% (6H:1V) Low Flow Ramp Slope	Alternating Staggered Wing Elevations	Staggered
Recessed Fish Notch, FN	5.5% (18H:1V) Fish Notch Ramp Slope, 16.6% (6H:1V) Low Flow Ramp Slope	Symmetrical Wing Elevations	Staggered

Modeling

Terrain Modeling

Survey data were collected by a professionally licensed surveyor, sufficient to describe the existing (post flood) topography and bathymetry of the Meadow Park WWP. These data included spot elevations with descriptions, breaklines, and channel cross sections. AutoCAD Civil 3D 2014 was used to generate a Triangular Irregular Network (TIN) from the survey data for the purpose of creating a baseline Digital Terrain Model (DTM) of the project site. The DTM was created in the Colorado State Plane Coordinate System, US foot (COHP-NF). The vertical datum of the DTM is the North American Vertical Datum of 1988 (NAVD 88).

Boundary Conditions Modeling

A one-dimensional (1D) steady flow model of the Meadow Park WWP was created using the publically available HEC-RAS flood modeling software created by the US Army Corps of Engineers. This model was used to characterize existing and proposed 1D hydraulic conditions within the reach. The existing conditions model describes streamflow in the downstream direction, along a defined channel alignment. Channel cross sections were cut perpendicular to the alignment, sampling the DTM at locations of interest along the reach. Hydraulic roughness coefficients (Manning's n) were assigned to the model based on observed conditions and standard tables presented in the HEC-RAS User's Manual.

Two separate flow paths were identified at an island just upstream of the WWP3 structure. A split flow model was developed to better characterize flows in this sub-reach. Within the HEC-RAS model options, flow optimization was performed to iteratively determine the portion of the total discharge to be assigned to each flow path. Using the split flow optimization, HEC-RAS creates a water surface profile based on the initial trial flows. Using results from the computed profile, new flows are calculated at the junctions and the profiles are subsequently recalculated. This process continued until the calculated and assumed flows matched within a given tolerance (Brunner, 2002). Downstream of the confluence of these two separate flow paths, the model returned to a single thread geometry.

A proposed conditions model was created based on modifications to the existing conditions model, sufficient to describe proposed geometric changes to the channel, banks, and whitewater structures as well as hydraulic roughness coefficients. This model was then used to develop and analyze hydraulic conditions resulting from the proposed changes to the Meadow Park WWP and to assign boundary conditions for the 3D CFD modeling.

Three-Dimensional CFD Modeling

Each of the four whitewater structure geometries described above were developed as geometric inputs into four separate 3D CFD models. Modeling was completed using ANSYS CFX, a 3D Computational Fluid Dynamics simulations software.

The individual CFD model geometries were created in the ANSYS WorkBench geometry editor by importing and subtracting each unique boulder geometry from the associated riverbed geometry (Figure 19).

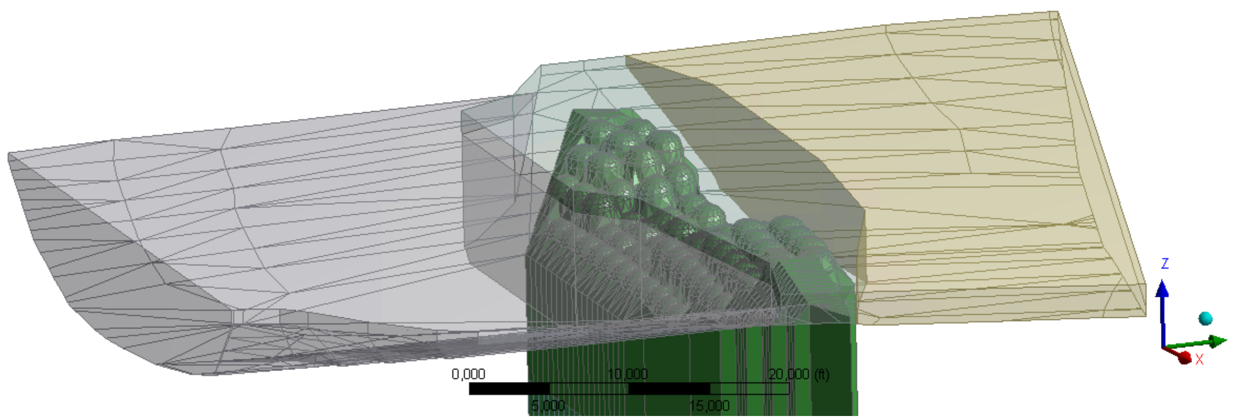


Figure 19: Geometry created by subtracting boulders (green color) from riverbed geometry (gray color).

Consecutive meshing was performed using ANSYS Meshing toolbox (Figure 20). A tetrahedral cell geometry with typical element sizes of 0.25 ft (min size), 0.5 ft and 1 ft (max size) were used.

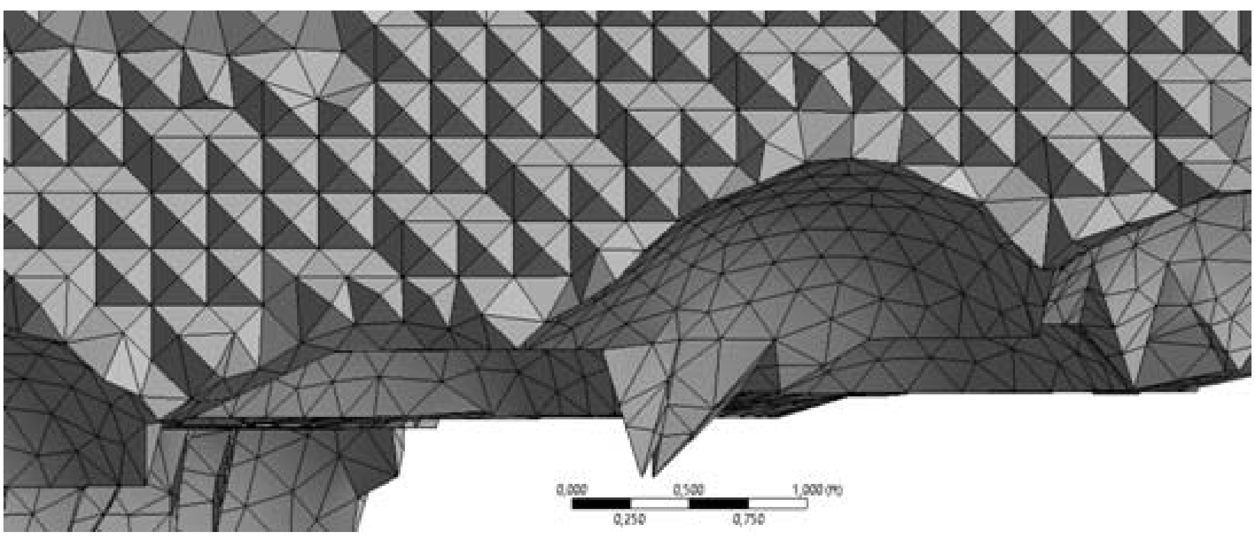


Figure 20: Minimum mesh element size (0.25 ft).

The number of elements varied according to each of the four structure geometries and flow rates studied. Between 2 million and 3 million elements were used for smaller flows, while larger elements were used for higher flows. Element spacing also increased with elevation and distance from the physical structure, necessary to reduce the total number of computational nodes, thereby improving model stability and reducing computational requirements (Figure 21).

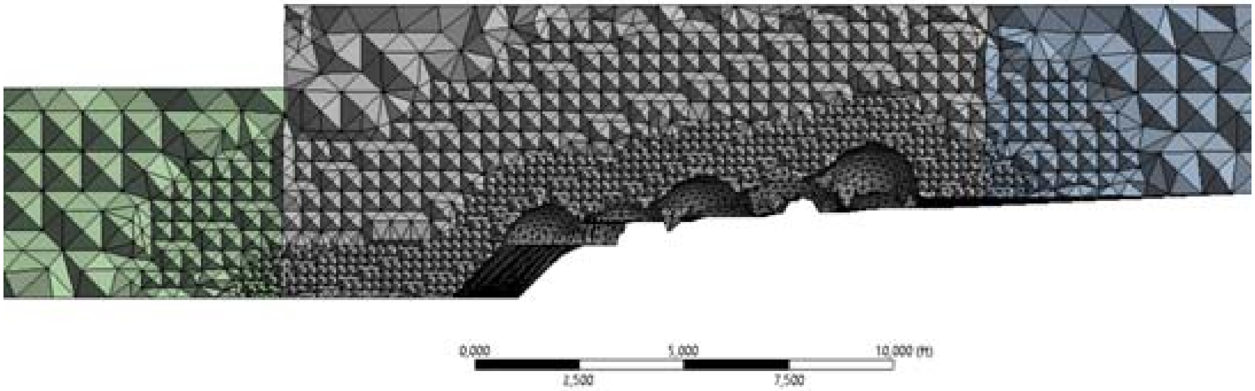


Figure 21: Maximum mesh size element (1 ft), medium size element (0.5 ft) and minimum mesh element size (0.25 ft).

The following settings for the CFX Solver (ANSYS) were used: a homogeneous model (2 phase - water and air) with a standard Free Surface Model; turbulence was modeled using a standard k-epsilon model with a standard wall function.

The upstream and downstream boundary conditions were developed based on the outputs from the 1-D HEC-RAS model for given cross section (Figure 22). The water intake boundary condition was defined using the given flow rates. The outlet boundary condition was defined as pressure outlet with a specified water surface elevation. The channel bottom was set up as a solid surface with assigned roughness elements.

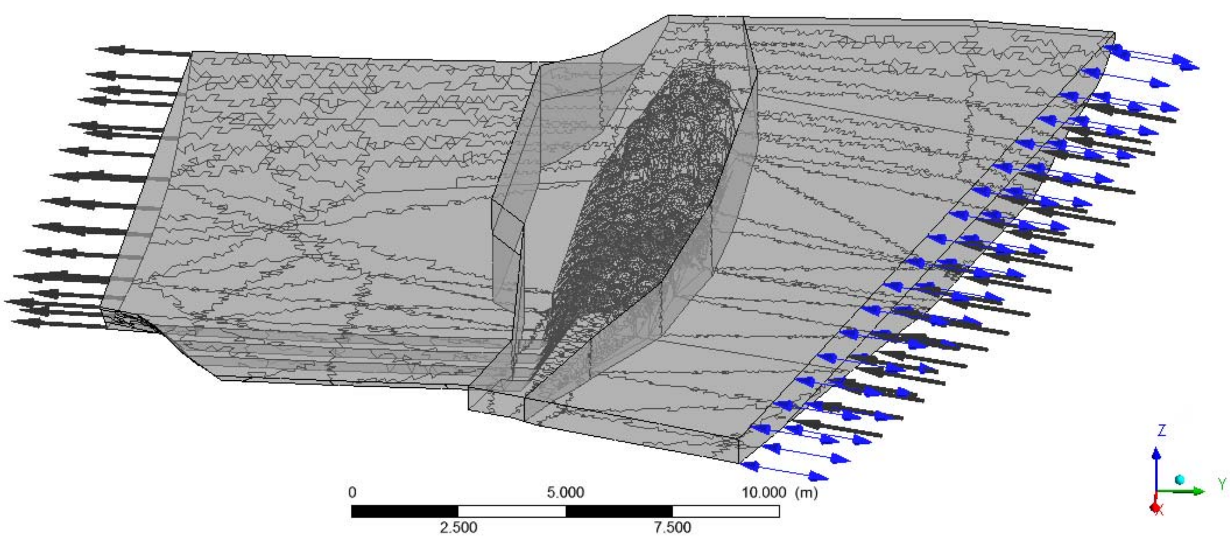


Figure 22: Boundary conditions; black arrow right - water intake (flow rate), blue arrow right - air intake, black arrow left – outlet.

Convergence controls were limited to a maximum of 1000 iterations and monitored with the stabilization of flow rate within the computational domain (Figure 23).

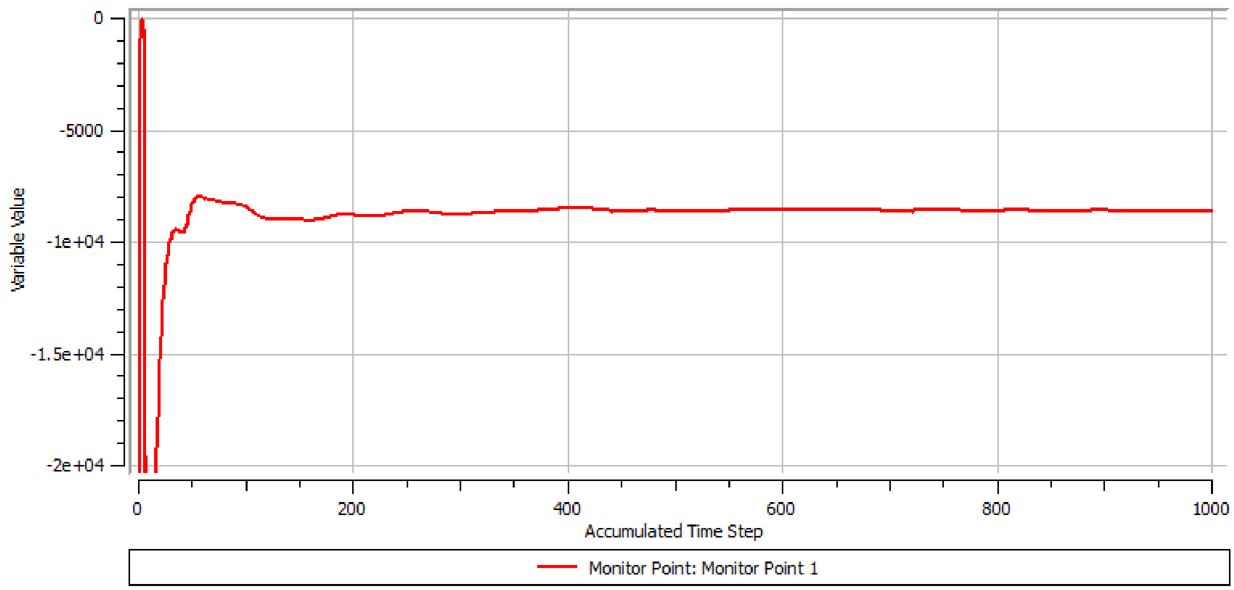


Figure 23: Monitoring of stabilization of flow rate.

Results

Results describing the hydraulic conditions calculated for each of the structure geometries and flow rates are outlined in the following sections. Numerical outputs for cross-sectional velocities, depths, vorticity, and TKE are presented below and include maximum, mean, 5^{th}, 25^{th}, 50^{th}, 75^{th}, and 95^{th} quantile values. Graphical results are presented for the 5^{th}, 25^{th}, and 50^{th} quantiles of velocity and the 50^{th}, 75^{th}, and 95^{th} quantiles of depth to highlight specific metrics of importance to the study.

The geometries of the WWP structures studied create unique hydraulic conditions as compared to the natural pool/riffle sequences found in the St. Vrain River. The distribution of flows over a whitewater structure affects the availability of fish passage routes and the predominant mechanisms by which passage is limited. During low flows, slower more shallow water is typically concentrated in the center portion of the ramp while at higher flows, deeper more rapid water spreads out laterally over the entire structure. Because fish seek the most energy efficient pathway for passage, it stands to reason that at high flows fish will seek out pathways in the lower velocity zones near the margins of the channel, while at lower flows fish are forced into fewer flow pathways with sufficient depth for passage. In this way fish passage can be depth limited at low flows whereas at high flows it may be velocity limited. For this reason, it is assumed that the 5^{th} quantile for velocity, TKE, and vorticity during higher flows is the threshold that must be crossed by the fish to complete a successful passage through the structure.

At low flows, when water is concentrated in the center portion of the ramp, the total number of continuous passage routes is reduced as lower velocity zones along the channel bottom and margins become depth limited. For this reason, it is assumed that fish passing upstream must navigate zones of higher relative velocity due to the reduced number of continuous passage routes. Based on this assumption, results from the 50th quantile of velocity, TKE, and vorticity are considered to act as thresholds for fish passage at lower flows.

Depth

Depth measurements were determined for all four of the whitewater structures at each specified flow rate using the 3D CFD models described above. 2D cross sections were cut along the longitudinal profile at 1 foot increments from the upstream subcritical pool, through the super critical structure throat, and downstream into the subcritical pool (stations 93.2-58.2). Along these cross sections, 2D depths were sampled at every tenth of a foot across the wetted channel.

Statistical analyses were performed on these data to describe the maximum depth sampled at each cross section, mean depth sampled at each cross section, 5th percentile (95% of the flow depths sampled greater than the given value), 25th percentile (75% of the flow depths sampled greater than the given value), 50th percentile (50% of the flow depths sampled greater than the given value), 75th percentile (25% of the flow depths sampled greater than the given value), and the 95th percentile (5% of the flow depths sampled greater than the given value).

Similar to the methodology described in the study by Fox (2013), it was assumed that a fish passing upstream over the whitewater structure must pass through each cross section. This allowed for the most difficult hydraulic conditions faced by an individual fish to be identified by classifying the limiting depths to passage within each cross section, despite not knowing the exact pathway to be followed by a given fish. Table 3 describes the limiting depths for each structure geometry at each flow rate based on the minimum value of maximum depths sampled for the maximum, mean, 5th, 25th, 50th, 75th, and 95th quantiles, calculated from the 2D cross sections sampled along the longitudinal profile.

Table 3: Describes the minimum value of maximum depths sampled for the maximum, mean, 5th, 25th, 50th, 75th, and 95th quantiles for each structure geometry at each flow rate.

Geometry Type	Flow, Q	Max Depth	Mean Depth	5th PCTL	25th PCTL	50th PCTL	75th PCTL	95th PCTL
	ft^3/s	ft	ft	ft	ft	ft	ft	ft
Fish Notch	10	0.8	0.3	0.0	0.1	0.2	0.6	0.7
Roughened Ramp 12%	10	0.4	0.2	0.0	0.1	0.1	0.2	0.3
Roughened Ramp 16%	10	0.5	0.2	0.0	0.1	0.1	0.3	0.5
Alternating Terrace	10	0.5	0.2	0.0	0.1	0.1	0.3	0.5
Fish Notch	30	1.1	0.5	0.0	0.1	0.3	0.7	1.1
Roughened Ramp 12%	30	0.7	0.4	0.0	0.3	0.4	0.5	0.6
Roughened Ramp 16%	30	0.7	0.4	0.0	0.3	0.4	0.5	0.7
Alternating Terrace	30	0.8	0.4	0.0	0.2	0.4	0.6	0.8
Fish Notch	300	2.7	1.0	0.0	0.2	0.5	1.9	2.5
Roughened Ramp 12%	300	2.6	0.7	0.0	0.1	0.2	0.9	2.4
Roughened Ramp 16%	300	2.9	0.8	0.0	0.1	0.2	1.0	2.5
Alternating Terrace	300	2.5	0.9	0.0	0.1	0.3	1.6	2.2
Fish Notch	600	3.9	1.2	0.2	0.4	0.6	1.4	3.6
Roughened Ramp 12%	600	3.7	1.2	0.1	0.3	0.5	1.3	3.4
Roughened Ramp 16%	600	3.8	1.1	0.2	0.4	0.6	1.5	3.5
Alternating Terrace	600	3.7	1.3	0.2	0.4	0.7	1.6	3.4

Limiting depths for the 25th, 50th, 75th, and 95th quantiles are shown graphically below in Figure 24. At the 25th and 50th quantiles, we do not see much difference between measured depth values across the range of structure geometries and flowrates. However, at the 75th and 95th quantiles we see that the Fish Notch geometry produces greater limiting depths as compared to the other structure geometries studied, particularly during critical base and fish flows. Moreover, because the critical depth threshold of 0.6 ft, utilized by Stephens (2014), is surpassed in both the 75th and 95th quantiles at both 10 and 30 cfs, as compared to the three other structure geometries, which only exceed the 0.6 ft threshold in the 95th quantile for the same flows, we can see that a significantly greater portion of the flow area is available for passage within the Fish Notch geometry during these critical low flow periods.

At 300 cfs no structure geometry achieves the limiting depth condition of 0.6 ft prior to the 75th quantile however, the magnitude of limiting depth produced by the Fish Notch geometry is significantly greater than the other geometries studied at this flow rate. At 600 cfs we see three of the four geometries studied produce limiting depths equal to or greater than 0.6 ft, within 50% of the cross sectional area sampled. Because these threshold depths are generated by the Fish Notch within both a greater portion of the cross sectional area sampled as well as during the lower flow periods studied, this geometry type appears to produce the most favorable limiting depth conditions for all structure geometries studied.

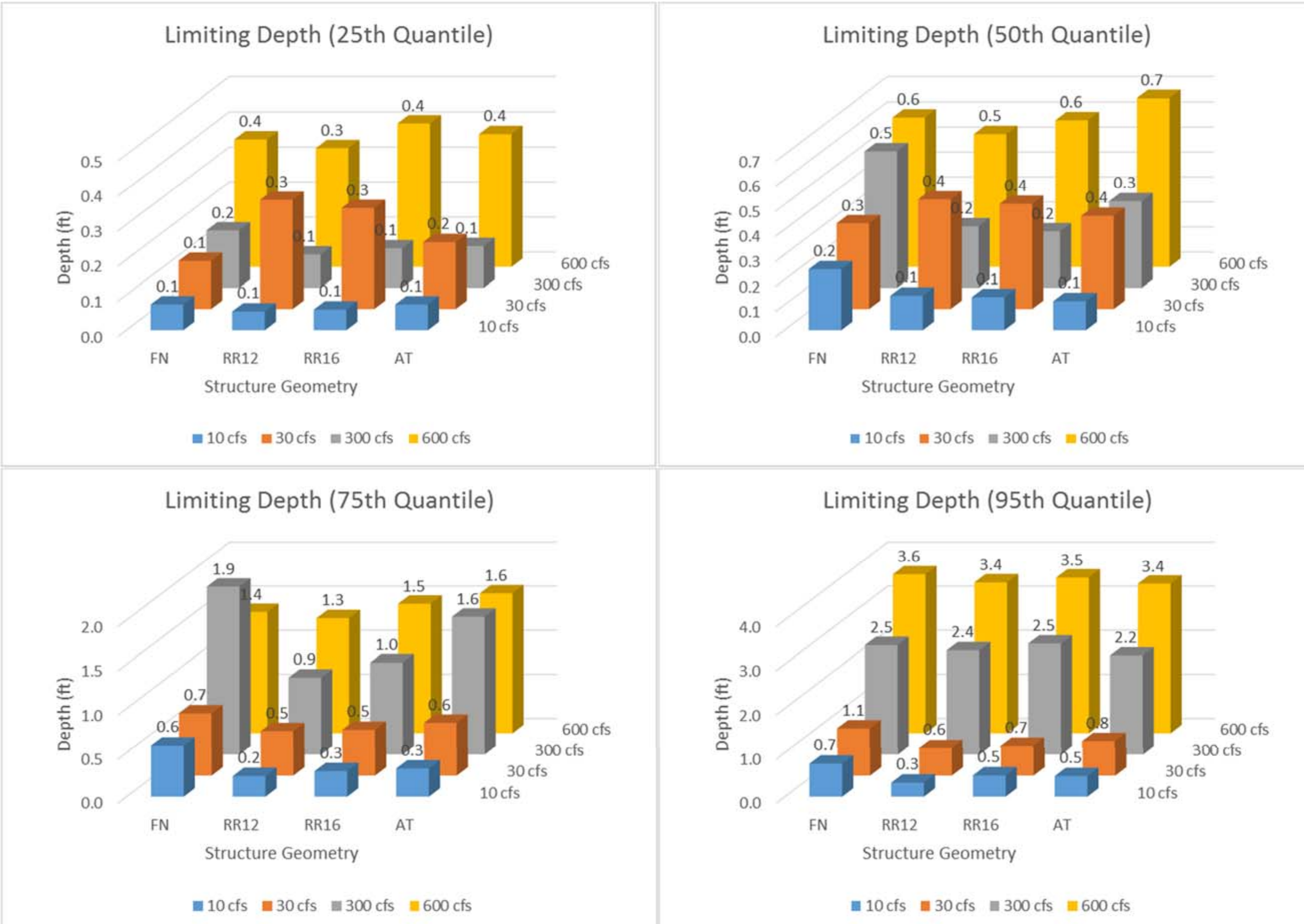


Figure 24: 25th, 50th, 75th, and 95th quantiles of limiting depth

Velocity

Cross sectional velocities were also sampled at each of the four whitewater structures geometries at each specified flow rate. Using the same cross sections cut along the longitudinal profile, velocity values were sampled at each computational node within the 2D plane. Statistical analyses were performed on these data to describe the maximum, mean, 5th, 25th, 50th, 75th, and 95th quantile velocities.

In the same way as limiting depth, it was assumed that the cross sections containing the greatest values of velocity would act as limiting velocities to upstream fish passage. Table 4 describes the limiting velocities for each structure geometry at each flow rate based on the maximum velocities sampled for the maximum, mean, 5th, 25th, 50th, 75th, and 95th quantiles.

Table 4: Describes the maximum velocities sampled for the maximum, mean, 5th, 25th, 50th, 75th, and 95th quantiles for each structure geometry at each flow rate.

Geometry Type	Flow, Q	Max Velocity	Mean Velocity	5th PCTL	25th PCTL	50th PCTL	75th PCTL	95th PCTL
	ft^3/s	ft/s	ft/s	ft/s	ft/s	ft/s	ft/s	ft/s
Fish Notch	10	5.2	3.6	2.1	2.9	3.8	4.2	5.0
Roughened Ramp 12%	10	5.9	4.6	3.1	3.9	4.8	5.4	5.7
Roughened Ramp 16%	10	6.4	4.3	2.8	3.8	4.5	4.9	5.9
Alternating Terrace	10	5.6	4.3	3.1	3.9	4.4	4.9	5.4
Fish Notch	30	6.9	4.6	2.8	3.9	4.9	5.7	6.7
Roughened Ramp 12%	30	8.2	5.7	3.0	5.1	6.4	7.4	7.9
Roughened Ramp 16%	30	8.3	6.2	5.4	5.9	6.3	7.4	8.1
Alternating Terrace	30	7.3	5.8	4.7	5.4	5.8	6.7	7.0
Fish Notch	300	13.4	8.1	2.0	5.7	10.4	11.2	12.3
Roughened Ramp 12%	300	14.7	7.1	1.9	3.7	7.3	12.1	13.1
Roughened Ramp 16%	300	14.8	8.7	2.2	6.6	10.4	11.6	12.7
Alternating Terrace	300	14.9	8.1	2.0	5.8	9.8	11.9	13.3
Fish Notch	600	13.5	7.8	1.6	5.2	8.7	10.6	11.8
Roughened Ramp 12%	600	13.2	7.6	1.9	4.9	8.3	11.0	12.0
Roughened Ramp 16%	600	12.7	8.3	1.7	6.4	9.1	10.9	11.9
Alternating Terrace	600	13.2	7.1	1.5	4.4	8.1	10.4	11.7

The results shown in Table 4 have been distilled to look at the limiting velocities for the 5th, 25th, 50th, and 75th quantiles (Figure 25). At the lower more critical fish passage flows of 10 and 30 cfs, the Fish Notch geometry produces the least limiting velocities of 2.1 ft/s and 2.8 ft/s respectively in the 50th quantile. At higher more recreationally desirable flows, when the fish have increased passage options, it can be seen that fairly uniformly low flow velocities are seen across all geometries at the Recreational Flows while the Alternating Terrace and Fish Notch geometries show the lowest velocities at Bankfull Flow levels. Because the Fish Notch geometry creates the lowest limiting velocities during the low flow periods while not producing significant differences during high flow periods, this geometry type appears to produce the most favorable hydraulic conditions for both fish passage and recreation in the structure.

Figure 25: 5th, 25th, 50th, and 75th quantiles of limiting velocity.

3D Vorticity

Without direct knowledge of the mechanisms through which vorticity within the structure ramp impacts fish passage, this parameter was analyzed in a similar manner to velocity to look for trends between prototype structure geometries and flows. Using the same 2D cross sections sampled at 1 foot increments along a longitudinal profile, 3D vorticity was sampled at each computational node. Statistical analyses were performed to describe the maximum, mean, 5th, 25th, 50th, 75th, and 95th quantiles of sampled vorticities, within each cross section. Table 5 describes the limiting 3D vorticities for each structure geometry at each flow rate based on the maximum 3D vorticity sampled for the maximum, mean, 5th, 25th, 50th, 75th, and 95th quantiles.

Table 5: Describes the maximum 3D vorticity sampled for the maximum, mean, 5th, 25th, 50th, 75th, and 95th quantiles for each structure geometry at each flow rate.

Geometry Type	Flow, Q	Max Vorticity	Mean Vorticity	5th PCTL	25th PCTL	50th PCTL	75th PCTL	95th PCTL
	ft^3/s	1/s	1/s	1/s	1/s	1/s	1/s	1/s
Fish Notch	10	11.6	5.6	1.5	3.2	5.5	7.7	10.4
Roughened Ramp 12%	10	16.5	5.4	3.2	4.4	5.3	7.1	9.1
Roughened Ramp 16%	10	19.5	6.8	4.4	6.0	6.8	9.2	13.3
Alternating Terrace	10	16.8	6.8	1.9	4.2	7.1	9.8	13.2
Fish Notch	30	19.0	5.3	1.6	3.1	4.3	7.3	12.2
Roughened Ramp 12%	30	22.8	6.7	3.1	4.3	6.4	8.7	13.1
Roughened Ramp 16%	30	16.5	6.5	3.1	4.2	6.0	9.8	13.0
Alternating Terrace	30	19.7	5.4	2.9	4.0	5.4	7.1	13.9
Fish Notch	300	30.3	6.9	0.7	2.7	5.9	11.2	17.5
Roughened Ramp 12%	300	60.8	8.4	1.5	5.1	8.3	11.3	17.8
Roughened Ramp 16%	300	44.6	9.7	1.7	5.1	8.2	13.2	23.0
Alternating Terrace	300	30.6	7.9	1.3	3.8	7.2	11.6	16.8
Fish Notch	600	35.0	9.1	0.9	4.5	8.3	12.7	20.5
Roughened Ramp 12%	600	38.7	9.0	0.6	4.1	7.9	12.7	21.6
Roughened Ramp 16%	600	37.1	10.3	0.9	4.7	9.4	14.9	23.1
Alternating Terrace	600	32.5	8.1	0.8	3.7	7.3	11.7	19.3

At Base Flows the Fish Notch geometry produced the lowest limiting 3D vorticities in the 5th and 25th quantiles, while the Roughened Ramp 12% geometry produced the lowest limiting 3D vorticities in the 50th and 75th quantiles (Figure 26). At Fish Flows the Fish Notch geometry produced the lowest limiting 3D vorticities at the 5th, 25th, 50th, and 75th quantiles. At recreation Flows the Fish Notch Geometry once again produced the lowest limiting 3D vorticities at the 5th, 25th, 50th, and 75th quantiles. At Bank Full Flows the Roughened Ramp 12% geometry produced the lowest limiting 3D vorticities in the 5th quantile while the Alternating Terrace geometry produced the lowest limiting 3D vorticities in the 25th, 50th, and 75th quantile.

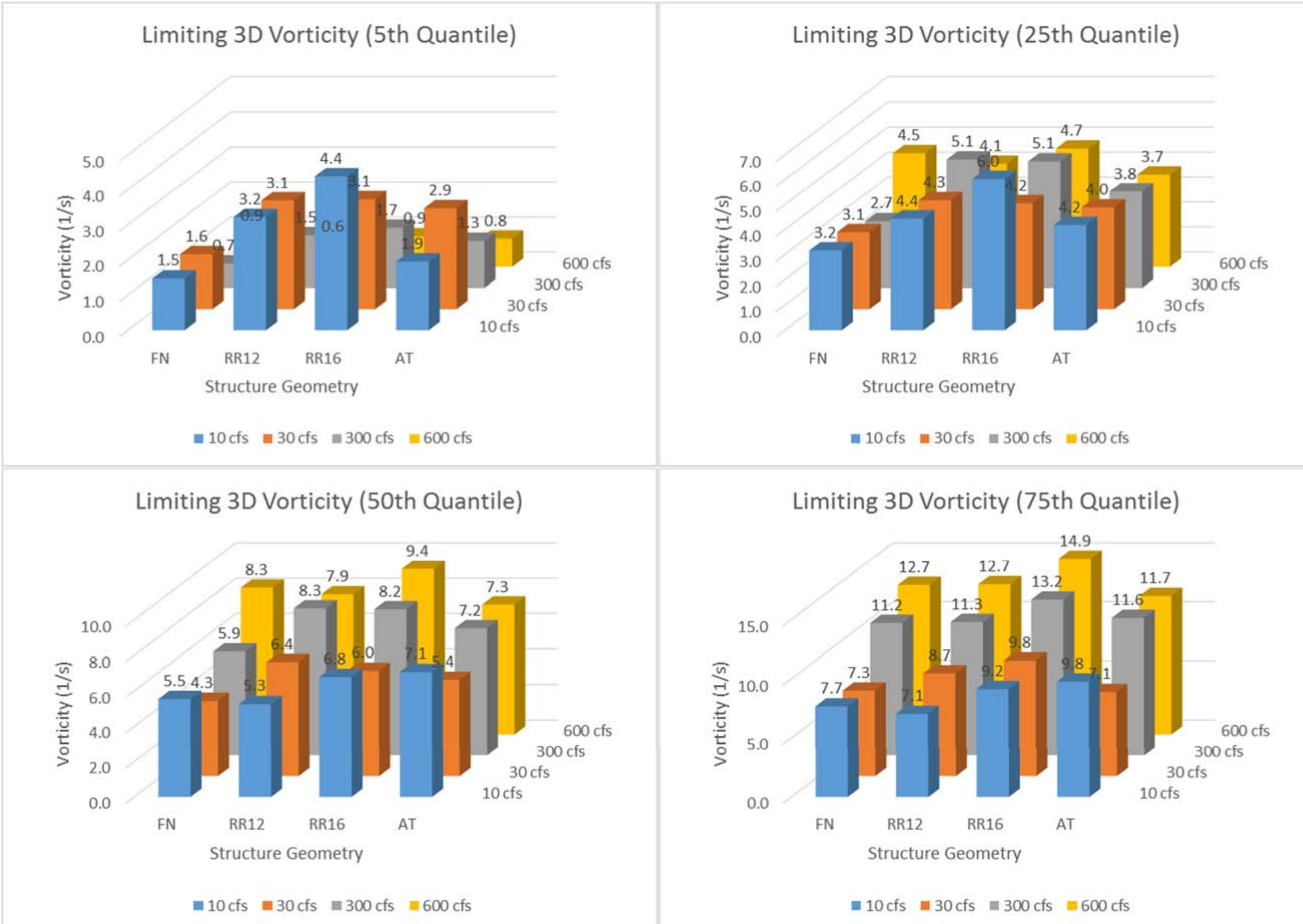


Figure 26: 5th, 25th, 50th, and 75th quantiles of limiting 3D vorticity.

TKE

Turbulent Kinetic Energy (TKE) was also analyzed using 2D cross sectional data, in order to describe limiting TKEs to upstream fish passage. Using the same 2D cross sections located at 1 foot increments along a longitudinal profile, TKE was sampled at each computational node. Statistical analyses were also performed to describe the maximum TKE sampled for the maximum, mean, 5th, 25th, 50th, 75th, and 95th quantiles, within each cross section (Table 6)

Table 6: Describes the maximum TKE sampled for the maximum, mean, 5th, 25th, 50th, 75th, and 95th quantiles for each structure geometry at each flow rate.

Geometry Type	Flow, Q	Max TKE	Mean Velocity	5th PCTL	25th PCTL	50th PCTL	75th PCTL	95th PCTL
	ft^3/s	ft^2/s^2	ft^2/s^2	ft^2/s^2	ft^2/s^2	ft^2/s^2	ft^2/s^2	ft^2/s^2
Fish Notch	10	0.9	0.3	0.0	0.1	0.3	0.5	0.7
Roughened Ramp 12%	10	1.5	0.5	0.1	0.2	0.5	0.8	1.2
Roughened Ramp 16%	10	1.7	0.4	0.1	0.2	0.4	0.6	1.2
Alternating Terrace	10	1.3	0.5	0.1	0.2	0.5	0.7	1.0
Fish Notch	30	1.4	0.3	0.1	0.1	0.2	0.4	0.9
Roughened Ramp 12%	30	2.0	0.4	0.1	0.1	0.3	0.5	1.2
Roughened Ramp 16%	30	2.6	0.5	0.1	0.2	0.3	0.7	1.6
Alternating Terrace	30	1.8	0.5	0.1	0.2	0.3	0.7	1.4
Fish Notch	300	5.3	0.5	0.0	0.1	0.2	0.5	2.7
Roughened Ramp 12%	300	7.3	0.5	0.0	0.1	0.3	0.6	1.9
Roughened Ramp 16%	300	6.2	0.5	0.0	0.1	0.2	0.5	2.2
Alternating Terrace	300	7.7	0.4	0.0	0.1	0.2	0.4	2.5
Fish Notch	600	5.6	0.7	0.0	0.1	0.4	1.0	2.8
Roughened Ramp 12%	600	6.9	0.6	0.0	0.1	0.3	0.7	2.2
Roughened Ramp 16%	600	5.9	0.8	0.0	0.1	0.4	1.1	2.9
Alternating Terrace	600	7.0	0.6	0.0	0.1	0.4	0.9	2.6

At recreational and bankfull flows, all geometries show relatively low TKE values, with RR12 being the lowest at both flows. The Fish Notch resulted in the lowest 5th percentile values of TKE at base flows and fish flows. At base flows and fish flows, TKE is lowest at the Fish Notch geometry. The 50$^{\%}$ TKE is very similar across all geometries at recreational lows, and lowest at RR12 during bankfull flows. TKE is consistently lowest at the Fish Notch during the lower flows across all quantiles. At higher flows there is a not a single geometry that produces consistently lower values than the others, but there TKE do not differ significantly between the structures.

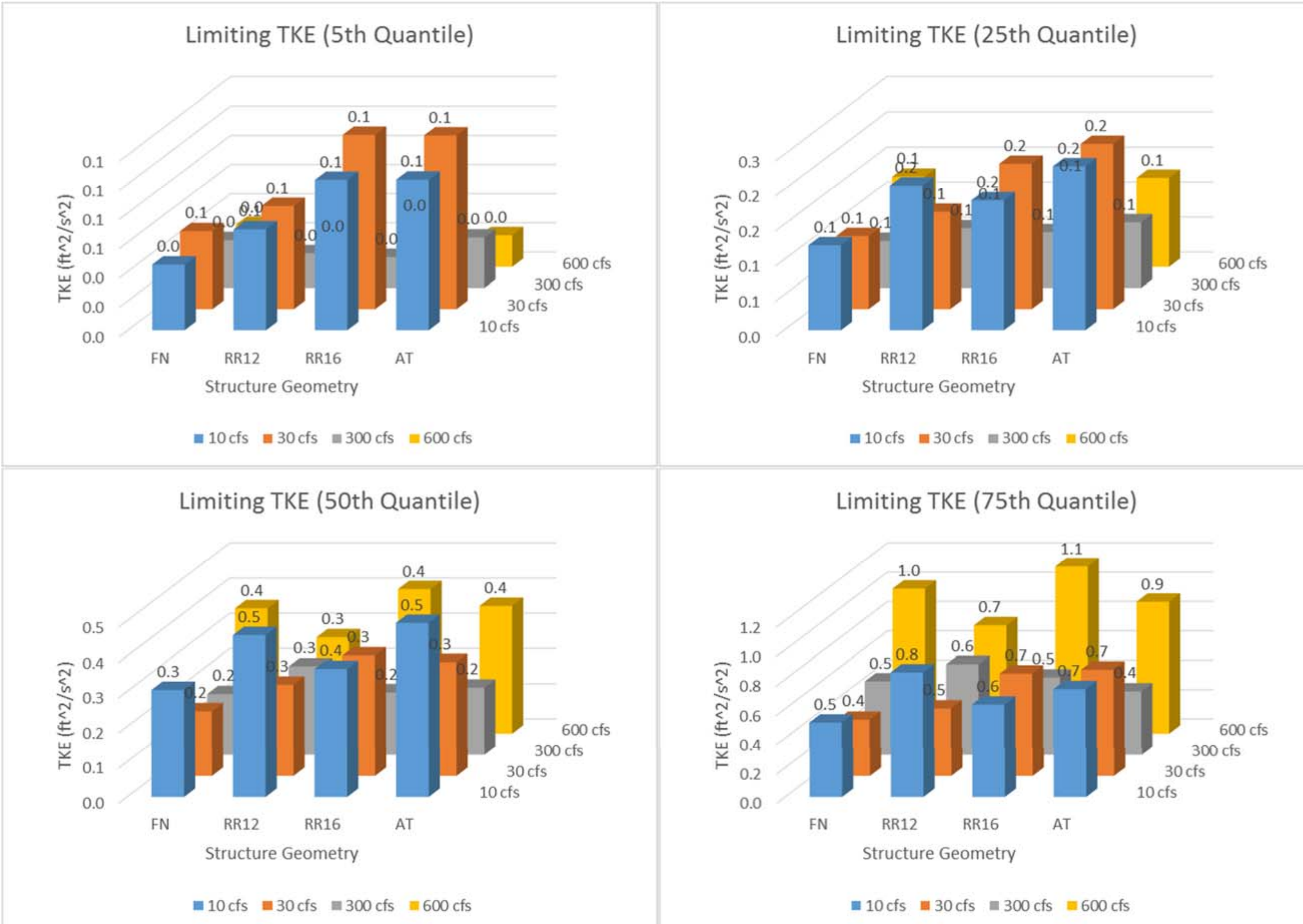


Figure 27: 5th, 25th, 50th, and 75th quantiles of limiting TKE.

Discussion

For the purposes of identifying the structure geometries that produce the least limiting hydraulic conditions as well as relating hydraulic conditions between this study and previous studies, internal comparisons between results from this study and external comparisons between results from different studies were both performed. Internal comparisons include evaluations of the limiting hydraulic conditions, and depths as well as a combination approach intended to identify potential opportunities for fish passage within each studied structure geometry at each identified flow rate. External comparisons were also made to assess of limiting velocities, structure geometries and pool turbulence to results presented in the previous studies at Meadow Park.

Limiting Hydraulic Conditions

A comparison of the results for the 95th quantiles for each hydraulic parameter sampled is shown below in Table 7. For the purposes of describing the limiting conditions for each structure geometry and flow rate, it was assumed that the 95th quantile represented a statistically significant portion of the sampled cross sectional area. The maximum values were not chosen for comparison, as they may represent more extreme observations and as such, are less representative of the sampled data sets.

Table 7: Comparison of the 95th quantiles of limiting velocities, depths, vorticities and TKE.

Geometry Type	Flow, Q	Limiting Velocity	Limiting Depth	Limiting Vorticity	Limiting TKE
	ft^3/s	ft/s	ft	s^{-1}	ft^2/s^2
Fish Notch	10	5.0	0.7	10.4	0.7
Roughened Ramp 12%	10	5.7	0.3	9.1	1.2
Roughened Ramp 16%	10	5.9	0.5	13.3	1.2
Alternating Terrace	10	5.4	0.5	13.2	1.0
Fish Notch	30	6.7	1.1	12.2	0.9
Roughened Ramp 12%	30	7.9	0.6	13.1	1.2
Roughened Ramp 16%	30	8.1	0.7	13.0	1.6
Alternating Terrace	30	7.0	0.8	13.9	1.4
Fish Notch	300	12.3	2.5	17.5	2.7
Roughened Ramp 12%	300	13.1	2.4	17.8	1.9
Roughened Ramp 16%	300	12.7	2.5	23.0	2.2
Alternating Terrace	300	13.3	2.2	16.8	2.5
Fish Notch	600	11.8	3.6	20.5	2.8
Roughened Ramp 12%	600	12.0	3.4	21.6	2.2
Roughened Ramp 16%	600	11.9	3.5	23.1	2.9
Alternating Terrace	600	11.7	3.4	19.3	2.6

As shown in Table 7, the Fish Notch geometry consistently produces the lowest limiting velocities, vorticities and TKEs along with the greatest limiting depths for all scenarios at 10 and 30 cfs, other than the vorticity observation at 10 cfs, where the Roughened Ramp 12% produces a lower limiting vorticity value. As flows increase to recreationally desirable levels, between 300 and 600 cfs, it can be seen that the Fish Notch geometry no longer produces the lowest limiting conditions for all hydraulic parameters measured and generally produces very comparable limiting values of velocity, depth, vorticity, and TKE between all structure geometries studied.

These results demonstrate the ability of the Fish Notch geometry to produce the least limiting hydraulic conditions during the more critical lower flow periods, while producing very similar hydraulic conditions during recreationally important flows. These results suggest that when each hydraulic parameter is analyzed independently, the Fish Notch geometry appears to produce the most conducive hydraulic conditions for fish passage at lower flows while simultaneously producing very similar hydraulic conditions at higher flows.

Limiting Depth

Stephens used a minimum value of 0.6 ft to define a depth limiting fish passage barrier, and any location along a flow path where the water column was less than 0.6 ft was defined as such. Without direct knowledge of fish body depths, 0.6 ft provides an average minimum depth criterion across the range of suggested values and fish size (Hotchkiss and Frei, 2007).

The results of this study, shown in Table 7, demonstrate how the more traditional ramp geometries, such as the Roughened Ramp 12%, Roughened Ramp 16% and Alternating Terrace, can create limiting depths for fish passage, particularly during critical low flow periods. Of the four geometry types studied only the Fish Notch generates limiting depths greater than 0.6 ft at 10 cfs, suggesting that this geometry type would not limit passage as a function of depth. As flows increase to 30 cfs, all four structure geometries create depths equal to or greater than 0.6 ft no longer creating a depth limiting scenario for fish passage.

Comparison of Limiting Velocities

Limiting velocities were compared between the Fish Notch geometry and the pre-flood geometries presented by Fox (2013). The Fish Notch geometry was selected for comparison because it consistently produced the lowest limiting conditions of the four geometry types studied and was selected as the preferred geometry for the structure redesigns at Meadow Park.

A comparison of the maximum velocity, mean velocity, 5th, 25th, 50th, 75th, and 95th velocity quantiles, shown in Table 8, demonstrates the Fish Notch geometry's ability to produce significantly lower velocity values when compared to pre-flood geometries, WWP2 and WWP3, at both 10 and 30 cfs. When compared to the WWP1 geometry, the Fish Notch geometry produces lower maximum velocities as well as 75th, and 95th velocity quantiles at both 10 and 30 cfs. However, as flows increase to 300 cfs, the Fish Notch geometry produces very similar velocities to all pre-flood structure geometries, suggesting that at recreationally desirable levels, the Fish Notch geometry is capable of producing equivalent and even superior recreational opportunities.

Table 8: Comparison of velocity results for pre-flood geometries and proposed Fish Notch geometry at WWP3.

Geometry Type	Flow, Q	Max Velocity	Mean Velocity	5th Percentile	25th Percentile	50th Percentile	75th Percentile	95th Percentile
	ft^3/s	ft/s	ft/s	ft/s	ft/s	ft/s	ft/s	ft/s
Fish Notch	10	5.2	3.6	2.1	2.9	3.8	4.2	5.0
Fox WWP1	15	7.6	2.4	0.1	0.5	1.7	4.6	6.6
Fox WWP2	15	9.7	7.7	4.0	7.4	8.3	9.0	9.3
Fox WWP3	15	9.8	7.0	3.3	6.4	7.9	8.8	9.6
Fish Notch	30	6.9	4.6	2.8	3.9	4.9	5.7	6.7
Fox WWP1	30	10.3	3.7	0.0	1.0	4.3	6.1	7.9
Fox WWP2	30	11.0	7.8	4.3	6.7	9.2	10.0	10.4
Fox WWP3	30	11.1	7.4	3.9	7.5	8.5	9.0	9.9
Fish Notch	300	13.4	8.1	2.0	5.7	10.4	11.2	12.3
Fox WWP1	300	11.8	6.4	0.8	4.5	7.2	9.3	10.1
Fox WWP2	300	14.2	7.5	2.3	5.9	9.2	10.5	11.3
Fox WWP3	300	13.1	9.4	2.7	9.1	10.8	11.3	12.4

Combination of Limiting Depth and Velocity

Stephens (2014) describes a method to evaluate fish passage opportunities at a given WWP structure based on a combination of limiting depth and velocity. A similar approach has been taken within this study to evaluate passage opportunities at WWP3 for all four prototype structure geometries, albeit without performing the calculations explicitly along streamlines.

For this analysis a ratio of the limiting velocity to maximum burst speed was developed for each structure geometry at each flow rate. The 95th quantile describing both depth and velocity was assumed to conservatively represent limiting hydraulic conditions for this analysis. The maximum burst speeds were calculated based on the burst swimming abilities of 25 body lengths/s described by Castro-Santos (2013) and further validated by Stephens (2014). All calculated ratios of limiting velocity to maximum burst speed greater than 1.00 were assumed to produce velocity limiting conditions for fishes of a given size class and are represented in Table 9 with a by a red shaded cell. A secondary depth limiting condition of calculated depths less than 0.6 ft was then superimposed on top of the calculated ratios to further define fish passage limitations. Depth limited values are described by the value within the cell being crossed out. Both yellow and green shaded cells, without crossed out values, represent opportunities for passage of fishes of the indicated size class. Yellow shaded cells contain calculated ratio values between 0.99 and 0.50, while green shaded cells contain calculated ratio values less than 0.49.

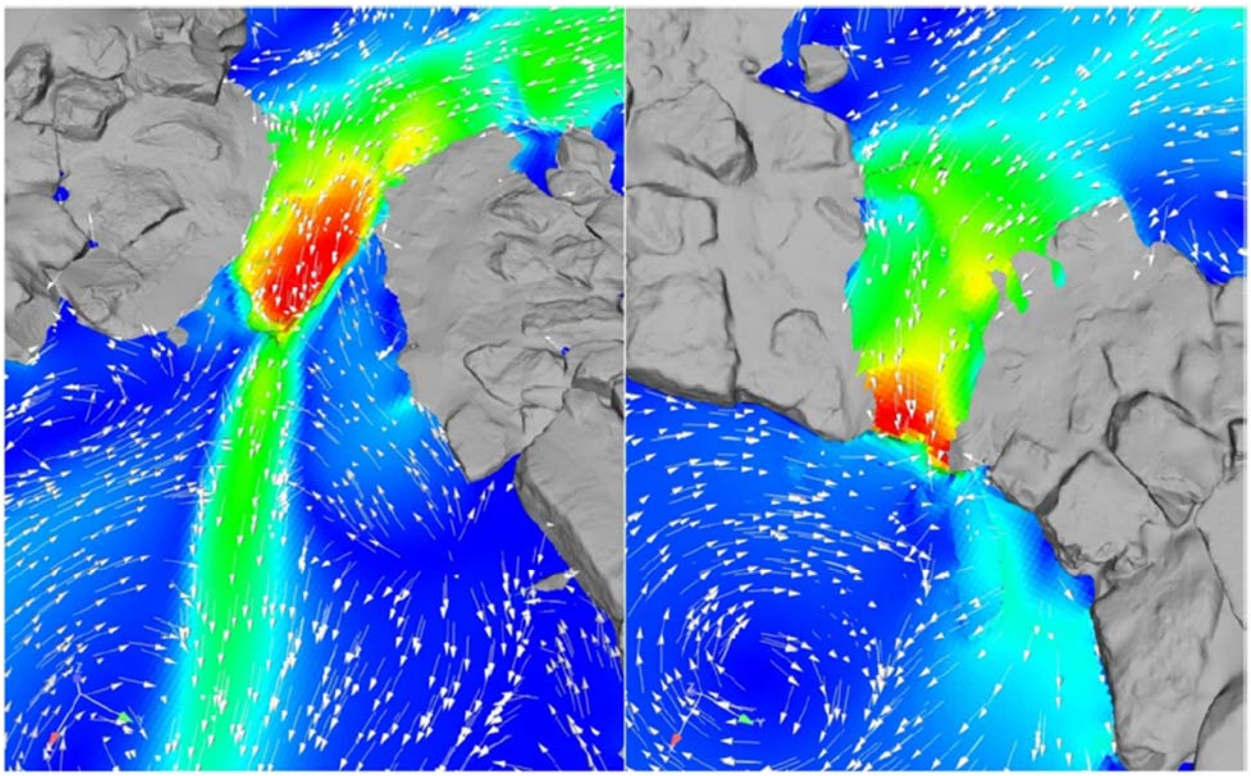
The results of this analysis, shown in Table 9, demonstrate the Fish Notch geometries ability to produce the lowest ratios of limiting velocity to maximum burst speed during the critical fish passage periods. Although all four geometries do not produce velocity limiting conditions for fish larger than 75 mm at 10 cfs, when the depth limiting condition is superimposed, we see that only the Fish Notch geometry will allow for passage of fishes 75 mm and greater, due to depth limiting conditions.

Table 9: Ratio of limiting velocity to maximum burst speed along with superimposed depth limiting condition.

		Fish Body Length (mm)												
		50	75	100	125	150	175	200	225	250	275	300	325	350
Base Flow (10 cfs)	Fish Notch	1.22	0.81	0.61	0.49	0.41	0.35	0.30	0.27	0.24	0.22	0.20	0.19	0.17
	Roughened Ramp 12%	~~1.38~~	~~0.92~~	~~0.69~~	~~0.55~~	~~0.46~~	~~0.39~~	~~0.34~~	~~0.31~~	~~0.28~~	~~0.25~~	~~0.23~~	~~0.21~~	~~0.20~~
	Roughened Ramp 16%	~~1.43~~	~~0.95~~	~~0.71~~	~~0.57~~	~~0.48~~	~~0.41~~	~~0.36~~	~~0.32~~	~~0.29~~	~~0.26~~	~~0.24~~	~~0.22~~	~~0.20~~
	Alternating Terrace	~~1.31~~	~~0.87~~	~~0.66~~	~~0.52~~	~~0.44~~	~~0.37~~	~~0.33~~	~~0.29~~	~~0.26~~	~~0.24~~	~~0.22~~	~~0.20~~	~~0.19~~
Fish Flow (30 cfs)	Fish Notch	1.63	1.09	0.81	0.65	0.54	0.47	0.41	0.36	0.33	0.30	0.27	0.25	0.23
	Roughened Ramp 12%	1.92	1.28	0.96	0.77	0.64	0.55	0.48	0.43	0.38	0.35	0.32	0.30	0.27
	Roughened Ramp 16%	1.98	1.32	0.99	0.79	0.66	0.56	0.49	0.44	0.40	0.36	0.33	0.30	0.28
	Alternating Terrace	1.70	1.14	0.85	0.68	0.57	0.49	0.43	0.38	0.34	0.31	0.28	0.26	0.24
Recreation Flow (300 cfs)	Fish Notch	3.01	2.01	1.50	1.20	1.00	0.86	0.75	0.67	0.60	0.55	0.50	0.46	0.43
	Roughened Ramp 12%	3.19	2.13	1.60	1.28	1.06	0.91	0.80	0.71	0.64	0.58	0.53	0.49	0.46
	Roughened Ramp 16%	3.10	2.07	1.55	1.24	1.03	0.89	0.78	0.69	0.62	0.56	0.52	0.48	0.44
	Alternating Terrace	3.24	2.16	1.62	1.29	1.08	0.92	0.81	0.72	0.65	0.59	0.54	0.50	0.46
Bankfull Flow (600 cfs)	Fish Notch	2.89	1.93	1.44	1.16	0.96	0.83	0.72	0.64	0.58	0.53	0.48	0.44	0.41
	Roughened Ramp 12%	2.93	1.96	1.47	1.17	0.98	0.84	0.73	0.65	0.59	0.53	0.49	0.45	0.42
	Roughened Ramp 16%	2.90	1.93	1.45	1.16	0.97	0.83	0.73	0.64	0.58	0.53	0.48	0.45	0.41
	Alternating Terrace	2.85	1.90	1.42	1.14	0.95	0.81	0.71	0.63	0.57	0.52	0.47	0.44	0.41

Structure Geometries

All three previous studies have noted that a highly constricted outlets at the exit of the structure could limit potential fish passage routes by forcing fish to pass through the highest velocity and most turbulent sections of the flow field. However, no specific hydraulic parameters were used to describe this effect. Fox stated that “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. 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” (Figure 28).



(A) WWP3 (B) WWP2

Figure 28: (A) Modeling results for WWP3 indicates reverse flow around the high-velocity turbulent zones on lateral margins of the hydraulic jump; and (B) modeling results for WWP2 indicate highly-constricted outlet flow area limits potential passage routes through the highest velocity and turbulent sections of the flow field (Fox, 2013, p. 69).

Figure 29 and Figure 30, shown below, demonstrate how the redesigned structures at Meadow Park can minimize this affect by altering the geometry of the structure to allow for backwatering of the ramp at critical fish passage flows. Furthermore, the inclusion of roughness elements on the structure bed and edges along with hydraulically designed structure geometries, allows for the structure to drive flows through critical depth during periods of flow when whitewater recreation is occurring in the reach, while simultaneously limiting flow choking at lower flows when fish passage needs are more critical.

A comparison of these figures demonstrates the ability of the Fish Notch geometry, relative to the other geometries analyzed, to create the lowest velocity zones through the throat and along the lateral margins of the structures during both the 10 and 30 cfs simulations. It is assumed that these reduced margin and terrace velocities along with the more focused turbulent zone at the structure exit will result in increased pathways and subsequent increased passage success.

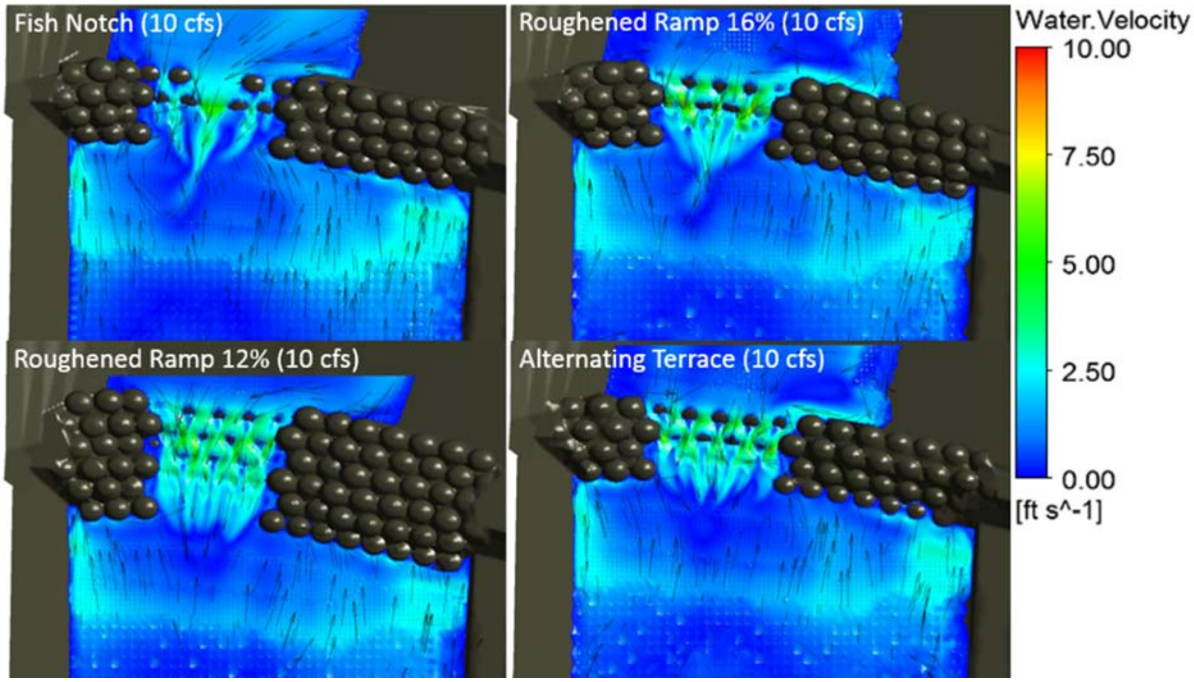


Figure 29: Turbulent high velocity zones at 10 cfs along the lateral margins of revised study geometries.

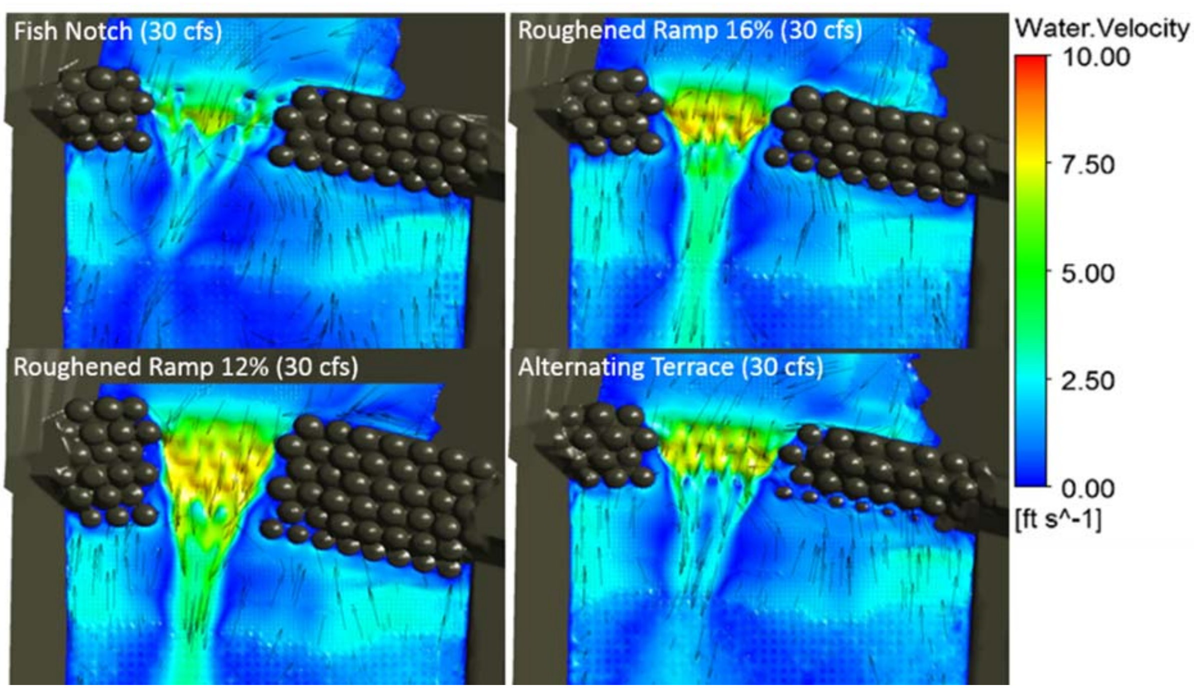


Figure 30: Turbulent high velocity zones at 30 cfs along the lateral margins of revised study geometries.

Pool Turbulence

Kolden compared modeled aquatic habitat quality to field measurements of fish biomass to examine the applicability of 3D modeling to assess habitat suitability. The primary zones of interest studied by Kolden were the scour pools, downstream of the whitewater structures. Maximum depth, vorticity and TKE were averaged across all four pool cross-sections and compared to the results reported by Kolden (2013) for both WWP pools and natural pools. Results presented by Kolden were averaged across the pools of all three whitewater structure geometries studied, while our results are presented as averages for each individual study geometry. Kolden compared hydraulic variables at WWP pools and natural pools for Low (15 cfs) Medium (150 cfs) and High flow rates (300 cfs). Because our study did not analyze flows at 150 cfs, results are only presented for the Low and High flows described by Kolden. Hydraulic conditions created by flows at 10 and 15 cfs are assumed to be similar thereby allowing for a comparison of the Base flows calculated in this study and the Low flows analyzed by Kolden.

TKE

Average maximum pool TKE results for all structure geometries modeled were lower than the WWP values reported by Kolden (2013) at both Low and High flows (Table 10). At Low flows, Kolden reported 2.0 and 0.3 ft^2/s^2 for the average of the WWP pools and the Natural Pools, respectively. At High Flows, Kolden reported 5.5 and 2.3 ft^2/s^2 for the average of the WWP pools and the Natural Pools, respectively. Of the four geometries modeled in this study, RR12 resulted in the lowest TKE values at base flows, while both the RR16 and Alternating Terrace geometries resulted in the lowest TKE values at recreational flows. In all cases the Fish Notch geometry produced significantly lower TKE values when compared to WWP pool values presented by Kolden (2013).

Table 10: Average maximum pool TKE (ft^2/s^2).

	Kolden (2013)		**S2o (2015)**			
	WWP	Natural	Fish Notch	Roughened Ramp 12%	Roughened Ramp 16%	Alternating Terrace
Low (10-15 cfs)	2.0	0.3	0.8	0.7	0.8	0.8
High (300 cfs)	5.5	2.3	1.9	2.9	1.6	1.6

Depth

All modeled structure geometries resulted in shallower pool depths than those reported by Kolden (2013) for the WWP pools (Table 11). All four geometries modeled in this study resulted in very similar depths (within 0.1 ft) at base flows, with the Fish Notch having the greatest depth. At Low flows, Kolden reported the natural pool as having the shallowest depth, at 2.0 ft, while the average WWP pool had a depth of 4.9 ft. At High Flows, the redesigned structure geometry pools produced significantly lower depths than those reported by Kolden (2013) for the WWP pools.

Table 11: Average maximum pool depths (ft).

	Kolden (2013)		S2o (2015)			
	WWP	Natural	Fish Notch	Roughened Ramp 12%	Roughened Ramp 16%	Alternating Terrace
Low (10-15 cfs)	4.9	2.0	3.1	3.1	3.0	3.0
High (300 cfs)	6.9	3.6	4.4	4.4	4.4	4.3

Vorticity

Average maximum 3D pool vorticity for the revised structure geometries was also much lower than those reported by Kolden (2013) (Table 12). At Low flows, Kolden found maximum vorticities of 9.3/s and 4.5/s in the WWP and natural pools, respectively. At High flows, Kolden found maximum vorticities of 17.7 /s and 8.3 /s in the WWP and natural pools, respectively. The Alternating Terrace geometry resulted in the lowest maximum vorticities for both Base and Recreational Flows. The Fish Notch geometry also produced significantly lower average pool 3D vorticity values when compared to both the WWP and natural pools studied by Kolden (2013).

Table 12: Maximum 3D pool vorticity (/s).

	Kolden (2013)		S2o (2015)			
	WWP	Natural	Fish Notch	Roughened Ramp 12%	Roughened Ramp 16%	Alternating Terrace
Low (10-15 cfs)	9.3	4.5	3.3	2.8	3.2	2.7
High (300 cfs)	17.7	8.3	7.6	8.0	7.6	6.9

Overall, all four proposed geometries resulted in lower average maximum TKE and vorticity values at both base flows and recreational flows as compared to the pre-flood structures presented in Kolden's 2013 study. The proposed geometries also had lower depths when compared to Kolden's WWP results. These results suggest that alterations to structure geometries can successfully reduce pool turbulence and subsequently improve aquatic habitat in WWP pools.

Recreation

The modeling of recreation at a whitewater structure can be subjective and is generally based on associating quantitative measurements and qualitative visual assessments of the modeled hydraulic jump to existing WWP features of a known character. Specific parameters used in this study to assess the recreational quality of the four geometry types modeled include:

- Depth over the structure;
- Shape of the wave surface;
- Eddy function and velocity; and
- Overall character of hydraulic jump.

Depth over Structure

The depth of flow over the structure is one of the most critical factors to downstream recreational use of a WWP. Though freestyle kayakers will typically have a higher standard for use for a WWP, often requiring waves and holes of substantial size and power, slalom boaters and tubers will often use WWPs at much lower flows. It is feasible that these downstream users could potentially use the park at flows as low as 30 cfs, which would only require adequate depth to float over a structure without coming into physical contact with it. Similar to upstream fish passage, the limiting cross section for downstream recreational use will contain the minimum value of maximum depths observed. As presented above, the limiting depth in the Fish Notch geometry, at 30 cfs, is 1.1 ft, whereas the other three geometries produce significantly lower values of limiting depths. Figure 31, below, shows how the Fish Notch geometry provides a deeper flow path through the low flow notch, which is anticipated to increase the duration of potential downstream use of the WWP.

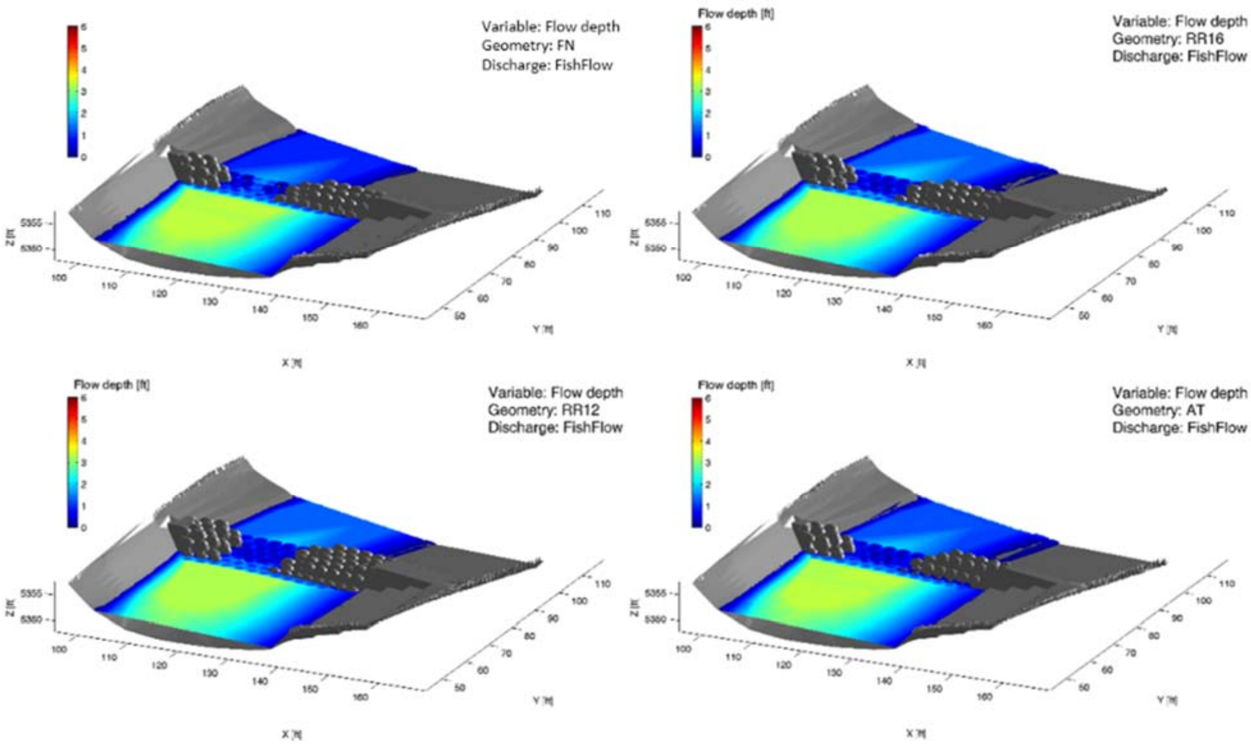


Figure 31: Water depths over the structure throat during Fish Flows (30 cfs).

Shape of Wave Surface

The overall shape of the wave surface is one of the most critical factors for freestyle use of a whitewater structure. For this study, the shape of the wave surface was generally broken into three defining factors including: formation and height of a pile; symmetry of the wave trough; and abruptness of the transition between supercritical and subcritical flows at the hydraulic jump.

Freestyle use of the Meadow Park WWP will largely hinge on the availability to adequate flows in the North St. Vrain River. Using the Recreational Flows (300 cfs) as a general measure of the necessary flow to create good recreation, Figure 32 below, shows that the Fish Notch geometry creates the greatest modeled height of the pile as well as uniformity of pile shape. The increased pile height also translates to lower velocities within the pile, suggesting a more desirable hydraulic conditions for freestyle kayaking.

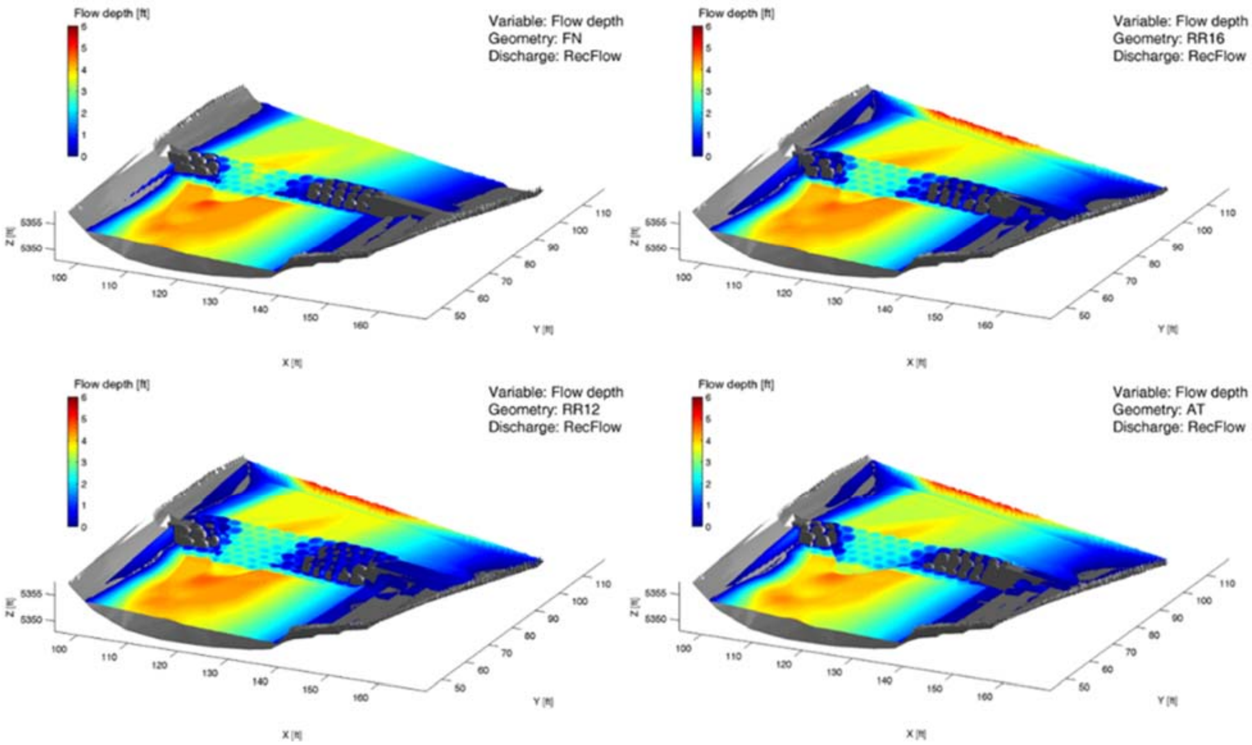


Figure 32: Water depths over the structure throat during Rec Flows (300 cfs).

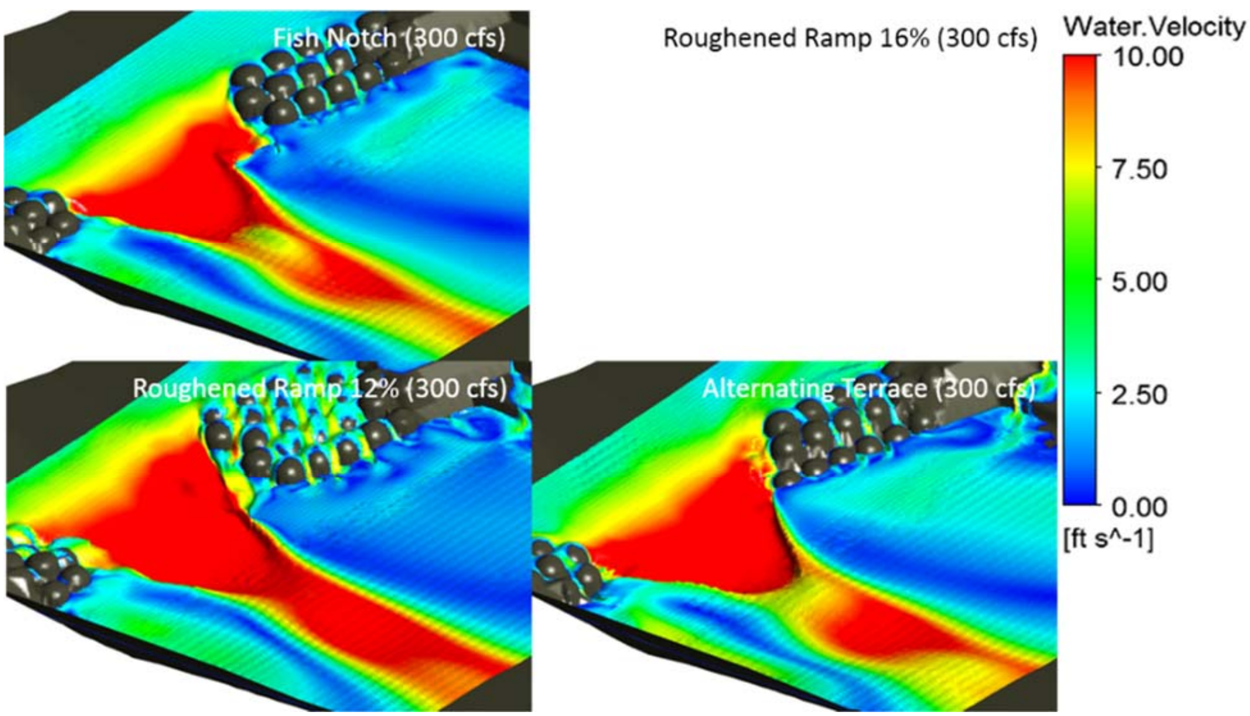


Figure 33: Isometric view of wave troughs and associated velocities for the four structure geometries studied.

The Fish Notch geometry also appears to create the most symmetrical wave trough (Figure 33). At 300 cfs, all four geometries create relatively smooth transitions between supercritical and subcritical flows, though the Alternating Terrace geometry creates the most abrupt transition along the left edge of the wave. It can also be seen that the lower bed slopes of the Roughened Ramp 12% do not generate the desired pile or wave shape as compared to the other geometry types studied. The Fish Notch geometry appears to create the most attractive wave shape from a qualitative standpoint.

Eddy Function

Park and play freestyle kayaking requires both the formation of desirable wave shapes and the creation of feeder eddies to allow for continued use of the feature without having to exit ones kayak to return to the wave. Eddies should provide adequate recirculation to attain back to the wave without generating excessive velocities, which can result in reduced function by pulling freestyle uses toward the feature while waiting their turn in line. It should also be noted that eddy velocities can be too low as well. In this scenario excess sedimentation can occur in the pools outside the primary jet, limiting the functional use of the waves. Figure 34 shows the eddy circulation patterns, at 300 cfs, for all four geometries studied. It can be seen that the Alternating Terrace geometry produces the greatest eddy velocities along both the left and right banks of the pools. Furthermore, the Fish Notch geometry appear to produce the greatest amount of pool surface area at relatively low velocities where freestyle users can wait their turn in line, without generating excessively low velocities such as the Roughened Ramp 12% geometry, which could result in increased sedimentation in the pool.

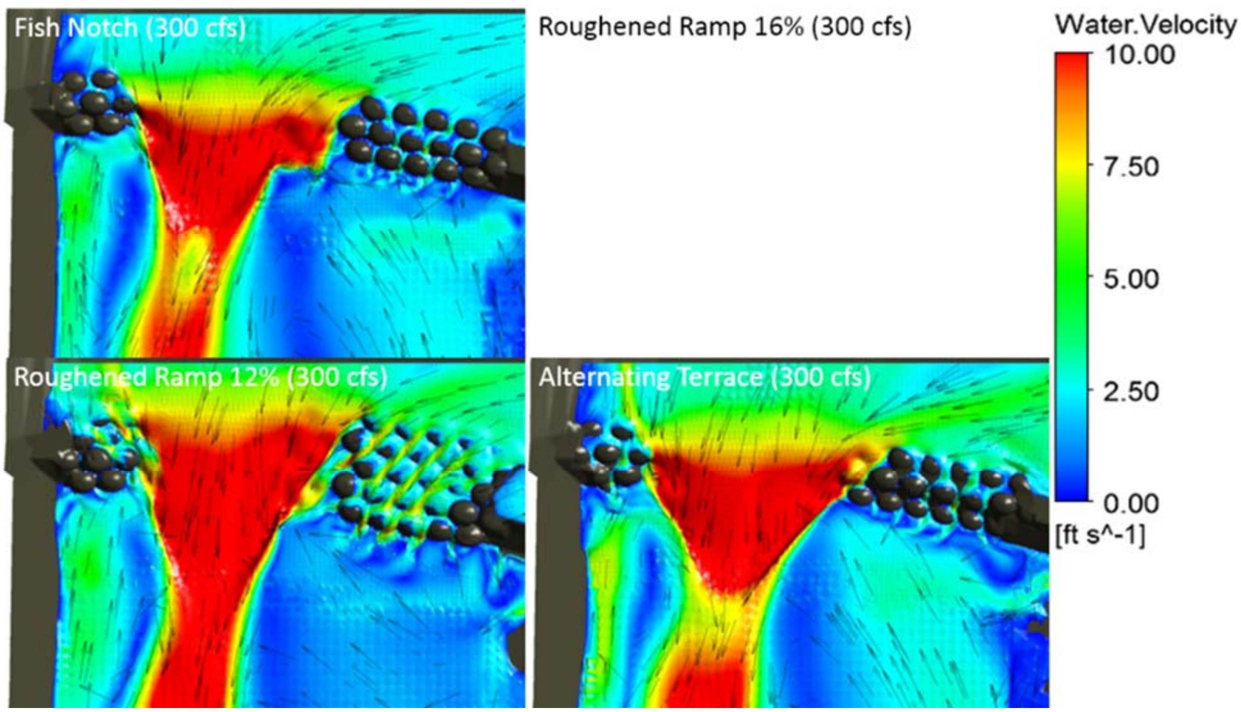


Figure 34: Planview of the modeled hydraulic jumps and velocity vectors at each studied geometry type studied.

Character of Hydraulic Jump

The character of a hydraulic jump in this study is generally defined as a combination of the magnitude and direction of the velocity vectors produced within the wave and pile. Traditional analyses of hydraulic jumps in rectangular channels produces a general classification of hydraulic jumps as a function of Froude Numbers, as shown in Figure 35.

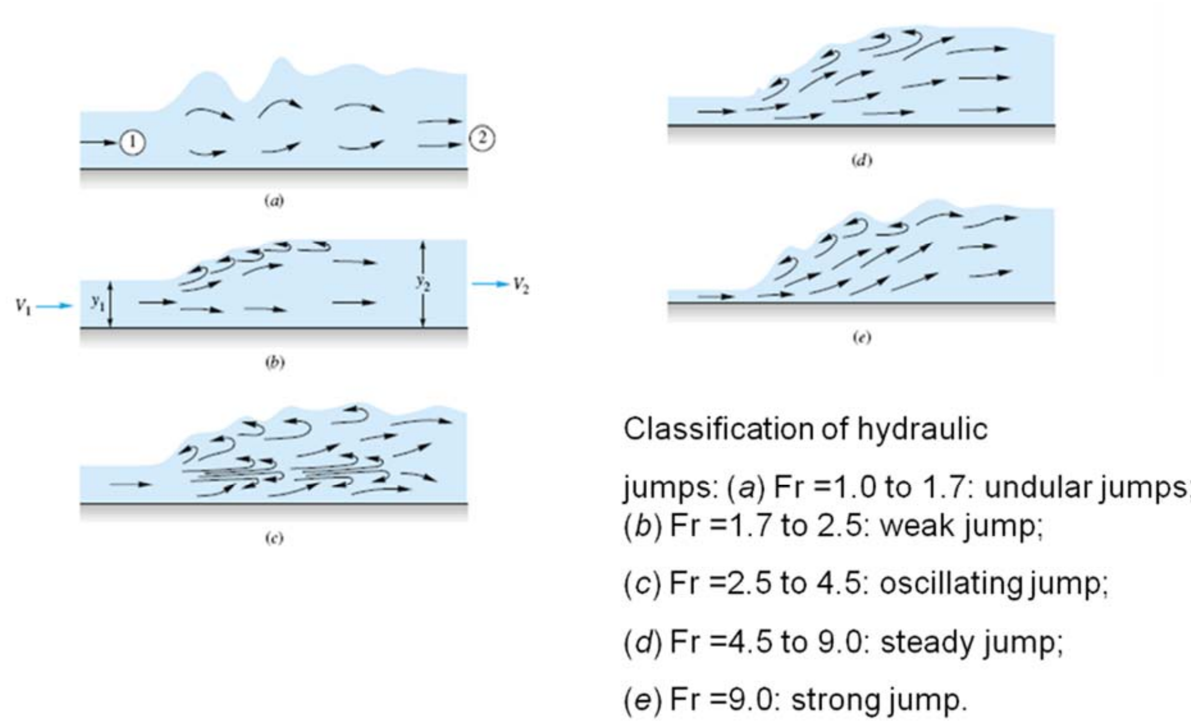


Figure 35: Traditional classification of hydraulic jumps in a rectangular channel (optimist4u.blogspot.com, 2015).

For recreational applications, a wave resembling a weak or oscillating hydraulic jump is typically preferable, though a direct comparison of hydraulic jumps occurring in natural channels versus rectangular flumes is not always advisable. Weaker hydraulic jumps such as those formed in an oscillating jump are not generally preferable as they do not effectively dissipated their energy in the primary jump and form apparent wave trains downstream in the pool, which often does not produce desirable recreational features and can lead to excessive downstream erosion. On the other end of the spectrum, both steady and strong hydraulic jumps can be overly retentive resulting in potentially dangerous waves that do not allow for sufficient egress from the wave. Working within this general framework for hydraulic jumps, Figure 36 shows that the Alternating Terrace and Fish Notch geometries appear to produce hydraulic jumps of appropriate character, while the Roughened Ramp 12% and Roughened Ramp 16% geometries appear to produce more defined wave trains with extended zones of downstream energy dissipation. All hydraulic jumps appear to be safe and do not suggest that they will produce dangerous conditions at Bank Full flows, the greatest flow rates modeled.

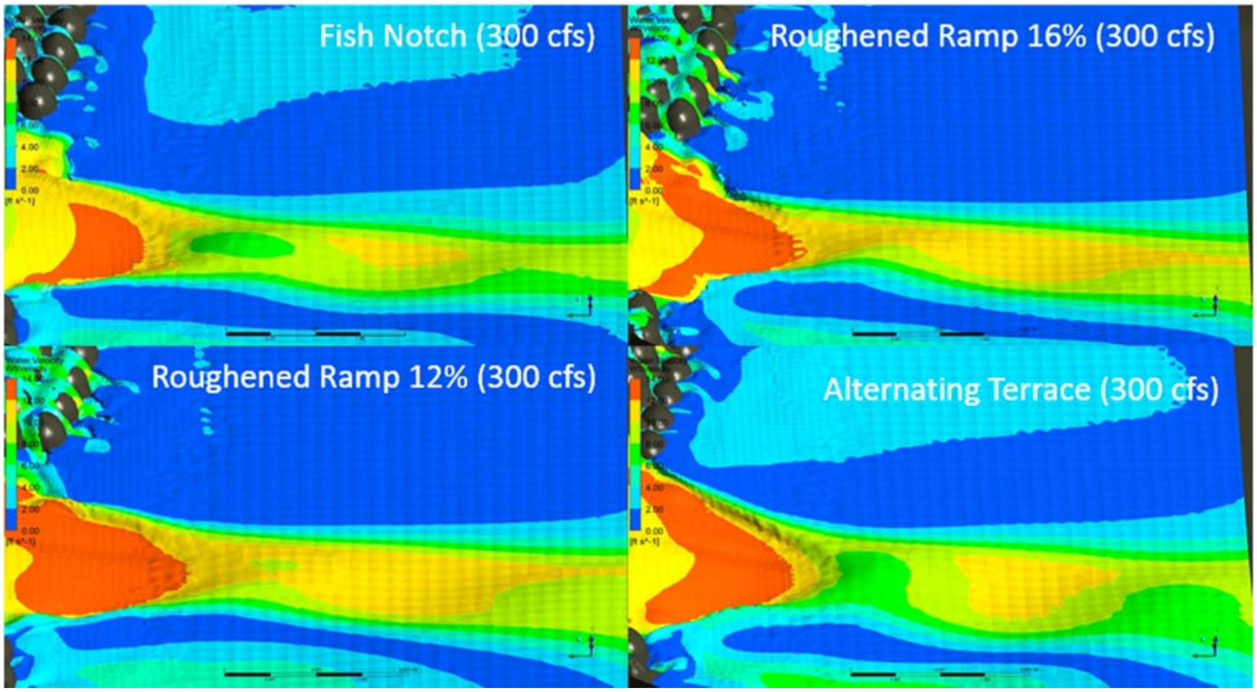


Figure 36: View of the modeled hydraulic jumps and pools occurring at each studied geometry type.

Conclusion

The redesign effort along with the previous pre-flood studies completed by CPW at Meadow Park, provided the ideal study setting to analyze the effects of different WWP structure geometries on hydraulic conditions that can effect fish passage and aquatic habitat. In total, four structure geometries were analyzed for the redesign effort and 3D CFD modeling was used to assess differences in associated hydraulic conditions.

The Meadow Park WWP has been the site of three prior studies, two of which analyzed fish passage over WWP structures and one that looked at aquatic habitat in the downstream pools of the pre-flood structures. This study has been conducted to analyze the effects of new structure geometries on hydraulic conditions for the proposed reconstruction of the Meadow Park WWP in 2015. Four separate structure geometries were modeled at the WWP3 site. The results were used to characterize the effects of structure geometry on hydraulic conditions and subsequently fish passage limitations and downstream aquatic habitat. The structures were evaluated over a range of flows that were determined to be representative of the typical flow variation seen during the course of a year and were identified as critical to fish passage and recreation. Hydraulic conditions created by each different structure geometry were compared to one another to identify which geometries created the least limiting hydraulic conditions and subsequently the preferred structure designs for the proposed Meadow Park WWP reconstruction. Hydraulic conditions calculated for the preferred design approaches were then compared to results presented in previous studies to better understand the implications of the revised geometries on fish passage and habitat.

The results of this study suggest that changing WWP structure geometries can significantly affect calculated hydraulic conditions and subsequently improve fish passage and aquatic habitat without compromising recreational opportunities. Though all revised structure geometries created hydraulic conditions, at 10 cfs, which suggests they may act as fish passage barriers to fishes less than 75 mm, the Fish Notch geometry is the only structure studied that does not create a depth limiting condition during this critical low flow period. Of the four geometries analyzed, the Fish Notch consistently resulted in the lowest velocities, vorticities and TKE at 10 and 30 cfs. At recreationally desirable flows, the Fish Notch produced very comparable limiting velocity, depth, TKE, and 3D vorticity values. The revised structure geometries also drastically reduce calculated turbulence in the scour pools downstream of the WWP structures when compared to the pre-flood geometries analyzed by Kolden (2013). These results further demonstrate the ability of the revised design approaches, particularly the Fish Notch geometry, to meet both the needs of the recreationists as well as to facilitate fish passage and aquatic habitat.

When hydraulic conditions generated by the Fish Notch geometry are compared to results from previous studies, the differences suggest that this is not only the best structure geometry of the four analyzed, but that the fish notch treatment option, when designed correctly, can greatly improve fish passage opportunities within similar WWPs elsewhere. However, because of the complexity of 3D flows over whitewater structures, the fish notch may not be applicable to significantly higher volume rivers. The other treatment options evaluated in this study, including the use of roughened edges along the lateral margins, varying ramp slopes, non-symmetrical wing terraces, and recessed notches, may provide additional fish passage treatment options for bypass channel solutions in larger river settings.

This study provides a framework for conducting before and after comparisons of the pre-flood and redesigned Meadow Park WWP. The redesign and eventual reconstruction of the Meadow Park WWP, combined with the results outlined in the pre-flood studies completed by CPW, provides an ideal experimental set-up to evaluate the effects of WWP structure geometries on fish passage and aquatic habitat. It is anticipated that future studies of Meadow Park, following its reconstruction in 2015, will be used to further assess the success of design and analytical methodologies outlined herein.

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