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Effects of whitewater parks on fish passage: a spatially explicit hydraulic analysis

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ABSTRACT

Evaluating and designing channel spanning structures for successful fish passage requires description of hydraulic conditions at scales meaningful to fish. We describe novel approaches combining fish movement data and hydraulic descriptions from a three-dimensional computational fluid dynamics model to examine the physical processes that limit upstream movement of trout across 3 unique in-stream structures at a whitewater park (WWP) in Lyons, Colorado. These methods provide a continuous and spatially explicit description of velocity, depth, vorticity, and turbulent kinetic energy along potential fish swimming paths in the flow field. Logistic regression analyses indicate a significant influence of velocity and depth on limiting passage success and accurately predict greater than 87% of observed fish movements. However, vorticity, turbulent kinetic energy, and a cost function do not significantly affect passage success. Unique combinations of depth and velocity at each WWP structure reflect variation in passage success. The methods described in this study provide a powerful approach to quantify hydraulic conditions at a scale meaningful to a fish and to mechanistically evaluate the effects of hydraulic structures on fish passage. The results of these analyses can be used for management and design guidance, and have implications for fishes with lesser swimming abilities.

1. Introduction

The reproductive success of migratory fishes and other organisms depends on the quantity, quality, and connectivity of available habitats that vary spatially and temporally across dimensions and scales (Frissel et al., 1986, 2001; Poff et al., 1997; Fausch et al., 2002). For example, many fishes migrate in search of optimal habitats for spawning, rearing, overwintering, and other life-cycle requirements (Schlosser and Angermeier, 1995). Human extraction of water resources has resulted in fragmentation of many rivers by dams, diversions, and other in-stream structures (Fagan, 2002; Nilsson et al., 2005; Perkin and Gido, 2012). When impassable, these structures cut-off necessary habitat linkages and migration routes of aquatic organisms, particularly fishes (Dudley and Platania, 2007; Fullerton et al., 2010; Walters et al., 2014). Successful passage for fishes of all life stages across barriers to migration is imperative to restore and maintain ecosystem function (Wohl et al., 2005; Beechie et al., 2010; Bunt et al., 2012).

In-stream structures must operate within the physiological limits of a fish's swimming abilities, and understanding how fish respond to micro-hydrodynamic and macro-hydrodynamic conditions within a structure is necessary to effectively design for passage success (Williams et al., 2012). However, structures are often designed and constructed without direct knowledge of fish passage success in response to altered hydraulic conditions.

Fish exhibit multiple modes of swimming when encountering different flow velocities in order to maximize ground speed and minimize energy expenditure (Beamish, 1978; Katopodis, 2005). Velocity can act as a burst swimming barrier in which the velocity of the water is greater than the fish's maximum swim speed. Velocity can also act as an exhaustive swimming barrier where a fish is unable to maintain positive ground speed over the required distance. Adequate depth is required for a fish to reach its full swimming potential (Webb, 1975). Insufficient depth to submerge a fish impairs its ability to generate thrust through body and tail

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movements, exposes the gills limiting oxygen consumption, and exposes the fish to physical trauma through contact with the channel bed (Dane, 1978).

Turbulence can increase or decrease a fish's swimming ability (Liao, 2007; Cotel and Webb, 2012; Lacey et al., 2012); however, high levels of turbulence pose a stability challenge to fish (Tritico and Cotel, 2010), and turbulence reduces fish swimming abilities at high current speeds (Pavlov et al., 2000; Lupandin, 2005). In particular, vorticity and turbulent kinetic energy (TKE) are recognized as meaningful measures of turbulence (Lacey et al., 2012).

Previous attempts to directly correlate fish passage with hydraulic variables yielded only poor predictors of passage success (Castro-Santos et al., 2009). Studies examining the effects of hydraulics on fish passage are constrained to laboratory settings or limited by scale, quantifying hydraulic conditions by point measurements or averaging over larger spatial scales (Crowder and Diplas, 2000, 2006; Cotel and Webb, 2012). Fish experience hydraulic conditions locally (Eulerian frame) and continuously along a movement path (Lagrangian frame) in a highly complex hydraulic environment (Goodwin et al., 2006).

A whitewater park (WWP) consists of one or more in-stream structures primarily constructed to create a hydraulic jump that is desirable to recreational kayakers and other boaters. The hydraulic jump is typically formed by grouting a laterally constricted chute over a steep drop into a downstream pool. WWPs provide a valuable recreational and economic resource (Hagenstad et al., 2000) that is rapidly growing in popularity. WWPs were originally thought to enhance aquatic habitat (McGrath, 2003); however, recent studies (Fox, 2013; Kolden, 2013) have shown that WWPs can act as a partial barrier to upstream migrating trout, and WWP pools may contain lower densities of fish compared to natural pools. Further, the magnitude of suppressed fish movement varies at different WWP structures and among size classes of fish. Higher velocities with larger spatial extents were recorded in WWPs compared to natural reaches, and unique hydraulic conditions exist at individual WWP structures as a result of seemingly subtle differences in their design and configuration. Concerns have arisen that the hydraulic conditions required to meet recreational needs are contributing to the suppression of movement of upstream migrating fishes and disruption of longitudinal connectivity. Without a direct understanding of the factors contributing to the suppression of movement in WWPs, making informed management and policy decisions regarding WWPs will continue to be difficult and could have unintended consequences.

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

1.1. Objectives

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

1. Use the results from a 3-D CFD model to provide a continuous and spatially explicit description of velocity, depth, vorticity, and TKE along the flow field at WWP structures containing PIT antennas.
2. Compare the magnitudes and distribution of velocity, depth, vorticity, and TKE among three unique WWP structures on the St. Vrain River in Colorado.
3. Determine the relationship between velocity, depth, vorticity, and TKE on the suppression of movement of upstream migrating fishes through statistical analysis of movement data from PIT-tag studies at the St. Vrain WWP.
4. Provide design recommendations and physically-based relationships that help managers better accommodate fish passage through WWP structures.

2. Methods

2.1. Study site

The North Fork of the St. Vrain River originates on the east slope of the Rocky Mountains where it flows east to the foothills region in the town of Lyons and its confluence with the South Fork of the St. Vrain River at 1637 m. The study site consists of nine WWP structures along a 400 m reach in Meadow Park. The natural river morphology at the study site can be described as the transition zone between a step-pool channel and a meandering pool-riffle channel with a slope of 1%. The natural river channel is characterized by riffles, runs, and shallow pools with cobble and boulder substrates. The North Fork of the St. Vrain River experiences a typical snowmelt hydrologic regime with a drainage area of 322 km^2 and peak flows occurring in late May to early June. In September 2013, the river was the site of massive catastrophic flooding (Gochis et al., 2014); field data collection was performed before this flooding occurred. A stage-discharge rating relationship was empirically developed at the site over the course of the study to provide a continuous record of discharges. Three of the nine WWP structures were selected for the study to represent the range of structure types and hydraulic conditions at the site. WWP1 is the downstream-most structure characterized by a short, steep drop constructed by large boulders. WWP2 is the middle structure producing a wave over a longer distance with the maximum constriction at the exit of the chute into the downstream pool. WWP3 is the upstream-most structure producing a wave similar to WWP2, but over a longer chute.

2.2. Fish movement data and hydraulic modeling results

2.2.1. Fish movement data

Fish passage was assessed at three WWP structures by obtaining 14 months of fish movement data from PIT-antenna arrays (Fox, 2013). Tagged rainbow trout (*Oncorhynchus mykiss Hofer x Harrison* strain) and brown trout (*Salmo trutta*) were included in the analysis totaling 536 tagged fish ranging in size from 115 to 435 mm as total length. Due to safety risks involving park users, PIT antennas were installed directly upstream of the WWP structures and in the tail-out of the pools directly downstream of the WWP structures (Fig. 1). The PIT-antenna configuration associated a time stamp and river discharge with a successful movement, but it did not provide information on individual fish that failed to cross the upstream antenna. Therefore, fish were classified as fish that did pass a structure versus fish that did not pass a structure.

Passage success was evaluated over four discrete time intervals based on marking/sampling events and times we expected target species (rainbow and brown trout) to be making a net upstream migration to access spawning habitat upstream: October 2011–March 2012, March 2012–October 2012, October 2012–November 2012, and November 2012–December 2012. The start of each time interval was defined by a stocking or electroshocking event in

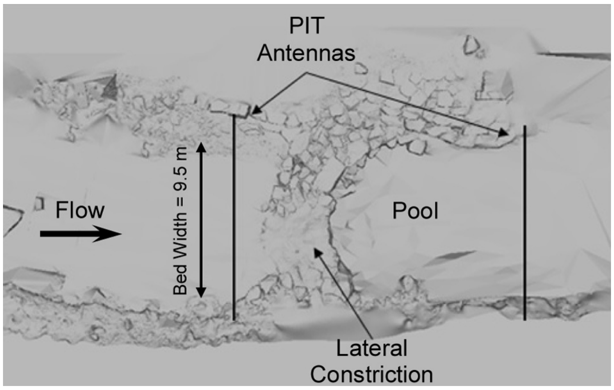

Fig. 1. Plan view of a WWP structure with PIT-antenna configuration.

which fish were observed in the pool directly below a structure. Movements were evaluated over the duration of that respective time interval. A successful movement across a structure was only included in the analysis if a fish was observed in the pool directly below that structure at the start of the time interval. This prevented overestimating passage success at structures where fishes with greater swimming abilities were able to migrate upstream crossing multiple structures over the duration of a time interval. There were 429 successful movements over the duration of all the time intervals.

2.2.2. Hydraulic modeling results

Seven discharges were modeled at three WWP structures containing PIT antennas using the 3-D CFD software FLOW-3D® v10.0 (Kolden, 2013). The modeled discharges include: 0.42, 0.85, 1.70, 2.80, 4.20, 4.80, and 8.50 cms, representing a range of flows that produce various habitats throughout the year. The annual flow duration exceedance probabilities for the modeled discharges range from 90% to less than 10% (Fox, 2013). FLOW-3D® described the flow field by solving the Reynolds-averaged Navier-Stokes (RANS) equations of fluid motion and a default renormalization group (RNG) turbulence closure with dynamically computed turbulent mixing length. The fluid domain was comprised of a series of discrete points making-up a mesh. The uniform grid sizes of the mesh ranged from 4 to 15 cm. The free surface was represented in the structured mesh by a process called volume of fluid (VOF; FLOW Science, 2009), and channel roughness elements were assumed to be adequately resolved through surveyed bathymetry obtained by a ground-based Light Detection and Ranging system (LiDAR), a Leica Total Station, and a Topcon® HiPer XT™ Global Positioning System (GPS) base and rover system (Kolden, 2013). A measured water surface elevation for each volumetric flow rate was used to specify a downstream pressure boundary. Field measurements of water surface elevations, velocity profiles, and wetted perimeter ensured the model was performing within an acceptable range of error (Kolden, 2013). Additional model validation was infeasible due to severe floods in September 2013 that significantly altered the channel geometry. Post-processing of the hydraulic results from the CFD model was performed using EnSight® Standard v10.1 (Computational Engineering International, Inc., 2013 https://www.ceisoftware.com).

2.3. Defining the flow field

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

EnSight® was used to create a flow volume consisting of the total modeled domain. Additional reduced flow volumes were created that consisted of the total modeled domain below a specified Froude number. The cross-sectional area of the reduced and total flow volumes were sampled at 8-cm longitudinal increments throughout the entire reach. A deviation in the cross-sectional area, between the total flow volume and the reduced flow volume, indicated areas with a Froude number greater than the thresholds used to define the boundaries of the analysis domain. This process was repeated for all modeled discharges at each structure. The upstream-most point for all discharges at which the cross-sectional areas diverged was used as the upstream boundary, and the downstream-most point at which the cross-sectional areas diverged was used as the downstream boundary. The Froude criteria were thoroughly analyzed to ensure the boundaries captured all features of the flow field relevant to fish passage.

2.4. Particle trace and potential movement path development

Releasing particle traces through the flow field and quantifying hydraulic variables along each trace provides a meaningful description of the hydraulic conditions a fish might encounter while migrating upstream. EnSight® was used to emit particle traces from nodes within the gridded mesh. A particle trace consists of a series of points that track a massless particle through both time and space in the fluid domain. The trajectory of the particle trace is parallel to the velocity vector field at that point and time. Particle traces were emitted forward and backward in time from volumes at the upstream and downstream boundaries encompassing important hydraulic features and the entirety of the flow field including eddies and zones of reverse flow.

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

To resolve this bias, particle traces that recirculated to the upstream or downstream boundary were divided at the point where they began to recirculate relative to the upstream/downstream directions. Two particle traces that do not make it through the entire flow volume result from each circulation. Each trace that did not make it through the entire volume (incomplete trace) was connected to a trace that did travel through the entire flow volume (complete trace) providing a path that represents the hydraulic conditions a fish might experience when migrating upstream. This task was accomplished by searching for the point within all the complete traces with the shortest Euclidean distance (maximum connection distance of 15 cm) to the terminus of an incomplete trace. The new trace consisted of the incomplete trace, the point of connection, and the needed portion of the complete trace to continue through the entire flow volume and account for recirculating particle traces. Approximately 6,500–20,000 particle traces were used to describe the flow field at each structure depending on the flow volume being analyzed.

2.5. Hydraulic conditions along potential movement paths

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

2.5.1. Velocity

The magnitude of a velocity vector was calculated as the root-mean-square (rms) of velocity in the *x*,*y*, and *z* planes with a directional component relative to the *x*-direction (Eq. (1)):

$$v_{\mathrm{rms}} = \sqrt{v_x^2 + v_y^2 + v_z^2} \cdot \left(\frac{|v_x|}{v_x}\right) \tag{1}$$

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

Velocity was used to define a variable that assesses the hydraulic environment relative to burst swimming ability. The velocity ratio is defined as the ratio of the local water velocity (v_{rms}) to the burst swimming ability (v_{burst}) of a particular fish (Eq. (2)):

$$\text{velocity ratio} = \frac{v_{\mathrm{rms}}}{v_{\mathrm{burst}}} \tag{2}$$

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

Velocity was also used to define a cost variable (Eq. (3)) in order to compare relative measures of cumulative energy expenditure through the length of a structure:

$$\text{cost} = \int v_{\mathrm{rms}}^2 \cdot d \cdot \left(\frac{v_{\mathrm{rms}}}{|v_{\mathrm{rms}}|}\right) \tag{3}$$

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

Table 1
Fraction of flow paths that exceed burst swimming abilities (25 BL/s) for each size class, discharge, and WWP structure (black (1) = no flow paths are available, white (0) = all flow paths are available). [1.5- or 2-column table; grayscale]

		Fish body length												
	Discharge (cms)	100 mm	125 mm	150 mm	175 mm	200 mm	225 mm	250 mm	275 mm	300 mm	325 mm	350 mm	375 mm	400 mm
WWP1	0.42	0.89	0.2	0.12	0.07	0.02	0.02	0	0	0	0	0	0	0
	0.85	1	0.44	0.12	0.08	0.01	0	0	0	0	0	0	0	0
	1.70	1	0.28	0.13	0.06	0.05	0	0	0	0	0	0	0	0
	2.80	1	0.95	0.21	0.07	0	0	0	0	0	0	0	0	0
	4.20	0.99	0.9	0.1	0.03	0.03	0	0	0	0	0	0	0	0
	4.80	0.98	0.86	0.35	0.09	0	0	0	0	0	0	0	0	0
	8.50	0.96	0.54	0.05	0.01	0	0	0	0	0	0	0	0	0
WWP2	0.42	1	0.85	0.11	0	0	0	0	0	0	0	0	0	0
	0.85	1	1	0.39	0.25	0.23	0.23	0.23	0.23	0.23	0.03	0.03	0.03	0
	1.70	1	1	1	0.19	0.01	0	0	0	0	0	0	0	0
	2.80	1	0.97	0.62	0.28	0.17	0	0	0	0	0	0	0	0
	4.20	1	0.76	0.62	0.15	0	0	0	0	0	0	0	0	0
	4.80	1	0.99	0.45	0.2	0.07	0	0	0	0	0	0	0	0
	8.50	1	0.98	0.23	0.03	0	0	0	0	0	0	0	0	0
WWP3	0.42	1	0.07	0	0	0	0	0	0	0	0	0	0	0
	0.85	1	0.07	0	0	0	0	0	0	0	0	0	0	0
	1.70	1	0.27	0	0	0	0	0	0	0	0	0	0	0
	2.80	1	0.83	0.36	0.01	0	0	0	0	0	0	0	0	0
	4.20	1	0.9	0.5	0	0	0	0	0	0	0	0	0	0
	4.80	0.57	0.55	0.27	0.07	0	0	0	0	0	0	0	0	0
	8.50	1	0.76	0.34	0.01	0	0	0	0	0	0	0	0	0

Ranges:	1	0.99 – 0.80	0.79 – 0.60	0.59 – 0.40	0.39 – 0.20	0.19 – 0.01	0

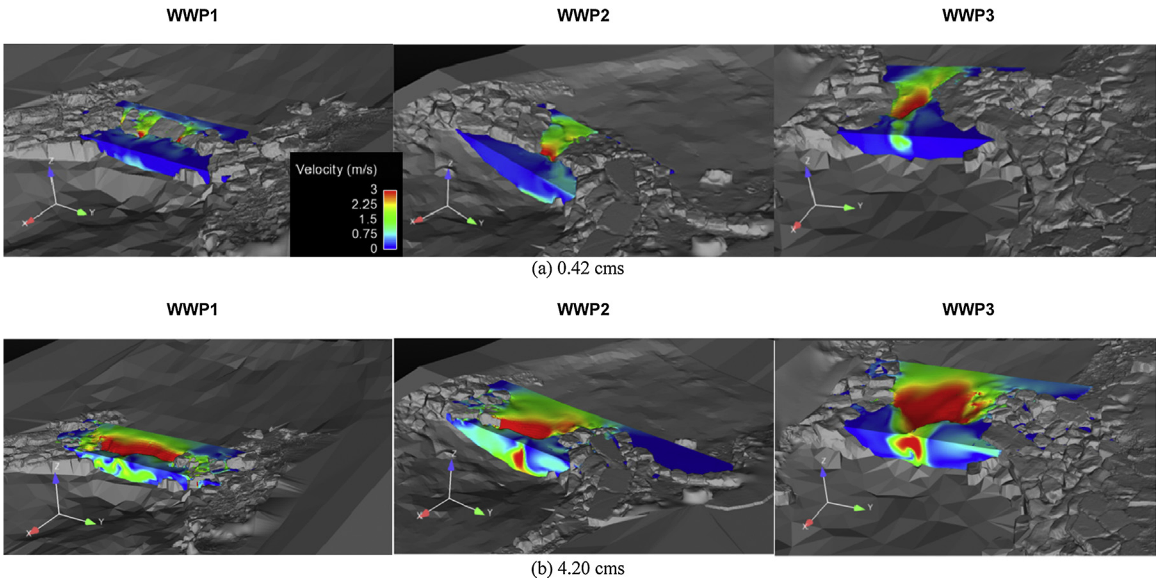

Fig. 2. Analysis flow volume at each WWP structure for (a) 0.42 cms and (b) 4.20 cms.

Cost is calculated over the distance in between nodes and summed along the length of the flow path. Therefore, the length of the hydraulic jump at a structure has a direct effect on cost.

2.5.2. Depth

A minimum of 0.18 m was used to evaluate depth as a barrier to upstream passage for this study. Without direct knowledge of fish body depths, 0.18 m provides an average minimum depth criterion (MDC) across the range of suggested values and fish size (Hotchkiss and Frei, 2007). Any location along a flow path where the fluid was less than 0.18 m was defined as a passage barrier. The minimum fluid depth along each flow path was evaluated, and the fraction of flow paths that did not maintain at least 0.18 m along the entire length of the path was determined (MDC). The MVR and MDC were also assessed in combination (MVR & MDC). If the minimum depth along a flow path was less than 0.18 m or the maximum velocity along the path was greater than a fish's swimming ability, the flow path was considered a passage barrier. Each flow path was evaluated, and the fraction of flow paths that exceeded a fish's burst swimming ability or did not provide adequate depth was determined.

2.5.3. Turbulence

Vorticity and TKE were selected as measures of turbulence meaningful to a fish. Vorticity is a vector representing the rotation rate of a small fluid element about its axis (Crowder and Diplas, 2002). EnSight® was used to calculate 3-D vorticity ($\bar{\xi}$) at each element within the gridded mesh (Eq. (4)):

$$\bar{\xi} = \left(\frac{\partial w}{\partial y} - \frac{\partial v}{\partial z}\right)\hat{i} + \left(\frac{\partial u}{\partial z} - \frac{\partial w}{\partial x}\right)\hat{j} + \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right)\hat{k} \qquad (4)$$

where u, v, and w are the x-, y-, and z-components of velocity, respectively, and i, j, and k are unit vectors in the x, y, and z directions, respectively. TKE is a measure of the increase in kinetic energy due to turbulent velocity fluctuations in the flow (Eq. (5)) (FLOW Science, 2009; Lacey et al., 2012):

$$\mathrm{TKE} = \frac{1}{2}(\sigma_u^2 + \sigma_v^2 + \sigma_w^2) \qquad (5)$$

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

The magnitudes of vorticity and TKE at each point along a flow path were summed over the length of the path quantifying the

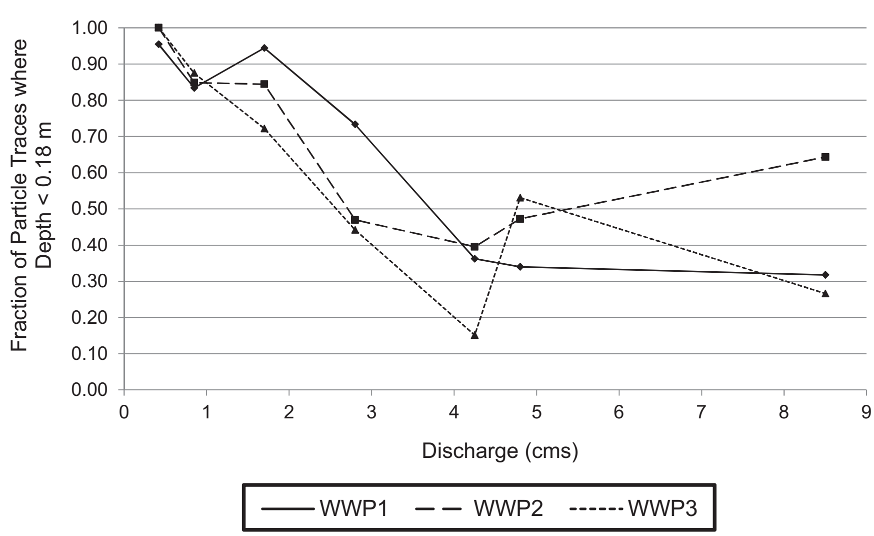

Fig. 3. The fraction of flow paths where the minimum depth is less than 0.18 m for each discharge and WWP structure.

Table 2
Fraction of flow paths that exceed burst swimming abilities (10 BL/s) for each size class, discharge, and WWP structure (black (1) = no flow paths are available, white (0) = all flow paths are available). [1.5- or 2-column table; grayscale]

	Discharge (cms)	Fish body length 100 mm	125 mm	150 mm	175 mm	200 mm	225 mm	250 mm	275 mm	300 mm	325 mm	350 mm	375 mm	400 mm
WWP1	0.42	1	1	1	1	1	0.93	0.89	0.75	0.53	0.16	0.12	0.12	0.11
	0.85	1	1	1	1	1	1	1	0.75	0.58	0.39	0.2	0.12	0.09
	1.70	1	1	1	1	1	1	1	0.99	0.96	0.26	0.17	0.13	0.12
	2.80	1	1	1	1	1	1	1	1	0.96	0.93	0.62	0.21	0.12
	4.20	1	1	1	1	1	1	0.99	0.94	0.92	0.86	0.48	0.1	0.07
	4.80	1	1	1	1	1	1	0.98	0.92	0.88	0.81	0.7	0.35	0.23
	8.50	1	1	1	1	1	0.99	0.96	0.84	0.62	0.44	0.18	0.05	0.01
WWP2	0.42	1	1	1	1	1	1	1	1	0.88	0.25	0.15	0.11	0.06
	0.85	1	1	1	1	1	1	1	1	1	1	0.45	0.39	0.28
	1.70	1	1	1	1	1	1	1	1	1	1	1	1	0.88
	2.80	1	1	1	1	1	1	1	0.99	0.98	0.71	0.69	0.62	0.47
	4.20	1	1	1	1	1	1	1	1	0.76	0.72	0.67	0.62	0.36
	4.80	1	1	1	1	1	1	1	1	1	0.6	0.58	0.45	0.32
	8.50	1	1	1	1	1	1	1	1	0.99	0.95	0.35	0.23	0.08
WWP3	0.42	1	1	1	1	1	1	1	0.51	0.14	0.01	0	0	0
	0.85	1	1	1	1	1	1	1	0.96	0.61	0	0	0	0
	1.70	1	1	1	1	1	1	1	0.68	0.65	0.04	0.01	0	0
	2.80	1	1	1	1	1	1	1	0.87	0.84	0.76	0.57	0.36	0.26
	4.20	1	1	1	1	1	1	1	0.98	0.96	0.74	0.64	0.5	0.1
	4.80	1	1	1	1	1	0.82	0.57	0.57	0.56	0.5	0.35	0.27	0.17
	8.50	1	1	1	1	1	1	1	1	0.81	0.74	0.67	0.34	0.24

Ranges: 1 | 0.99 – 0.80 | 0.79 – 0.60 | 0.59 – 0.40 | 0.39 – 0.20 | 0.19 – 0.01 | 0

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

2.6. Data analysis

Individual fish were designated as making a successful movement or an unsuccessful movement for each time interval.

Table 3
Fraction of flow paths that either exceed burst swimming abilities (25 BL/s) or do not provide adequate depth for each size class, discharge, and WWP structure (black (1) = no flow paths are available, white (0) = all flow paths are available). [1.5- or 2-column table; grayscale]

	Discharge (cms)	Fish body length 100 mm	125 mm	150 mm	175 mm	200 mm	225 mm	250 mm	275 mm	300 mm	325 mm	350 mm	375 mm	400 mm
WWP1	0.42	1	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
	0.85	1	0.98	0.88	0.87	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
	1.70	1	1	0.95	0.95	0.95	0.95	0.95	0.95	0.94	0.94	0.94	0.94	0.94
	2.80	1	0.99	0.78	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73
	4.20	1	0.99	0.39	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36
	4.80	1	0.96	0.55	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34
	8.50	1	0.73	0.36	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32
WWP2	0.42	1	1	1	1	1	1	1	1	1	1	1	1	1
	0.85	1	1	0.91	0.86	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
	1.70	1	1	1	0.89	0.85	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84
	2.80	1	1	1	0.72	0.64	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
	4.20	1	1	0.96	0.54	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
	4.80	1	1	0.9	0.66	0.55	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
	8.50	1	1	0.81	0.67	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64
WWP3	0.42	1	1	1	1	1	1	1	1	1	1	1	1	1
	0.85	1	0.88	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87
	1.70	1	0.92	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72
	2.80	1	1	0.78	0.45	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44
	4.20	1	1	0.65	0.16	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
	4.80	1	1	0.79	0.6	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53
	8.50	1	1	0.61	0.28	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27

Ranges: 1 | 0.99 – 0.80 | 0.79 – 0.60 | 0.59 – 0.40 | 0.39 – 0.20 | 0.19 – 0.01 | 0

Table 4
Fraction of flow paths that either exceed burst swimming abilities (10 BL/s) or do not provide adequate depth for each size class, discharge, and WWP structure (black (1) = no flow paths are available, white (0) = all flow paths are available). [1.5- or 2-column table; grayscale]

	Discharge (cms)	Fish body length 100 mm	125 mm	150 mm	175 mm	200 mm	225 mm	250 mm	275 mm	300 mm	325 mm	350 mm	375 mm	400 mm
WWP1	0.42	1	1	1	1	1	1	1	1	0.96	0.95	0.95	0.95	0.95
	0.85	1	1	1	1	1	1	1	1	1	0.97	0.88	0.88	0.87
	1.70	1	1	1	1	1	1	1	1	1	0.99	0.95	0.95	0.95
	2.80	1	1	1	1	1	1	1	1	0.99	0.98	0.87	0.78	0.74
	4.20	1	1	1	1	1	1	1	0.99	0.99	0.96	0.67	0.39	0.37
	4.80	1	1	1	1	1	1	1	1	0.98	0.93	0.86	0.55	0.45
	8.50	1	1	1	1	1	1	1	0.97	0.8	0.65	0.43	0.36	0.33
WWP2	0.42	1	1	1	1	1	1	1	1	1	1	1	1	1
	0.85	1	1	1	1	1	1	1	1	1	1	0.96	0.91	0.89
	1.70	1	1	1	1	1	1	1	1	1	1	1	1	0.96
	2.80	1	1	1	1	1	1	1	1	1	1	1	1	0.89
	4.20	1	1	1	1	1	1	1	1	1	1	1	0.96	0.7
	4.80	1	1	1	1	1	1	1	1	1	1	0.98	0.9	0.77
	8.50	1	1	1	1	1	1	1	1	1	0.99	0.92	0.81	0.7
WWP3	0.42	1	1	1	1	1	1	1	1	1	1	1	1	1
	0.85	1	1	1	1	1	1	1	1	0.96	0.88	0.87	0.87	0.87
	1.70	1	1	1	1	1	1	1	1	1	0.75	0.72	0.72	0.72
	2.80	1	1	1	1	1	1	1	1	1	0.99	0.97	0.78	0.68
	4.20	1	1	1	1	1	1	1	1	1	0.86	0.76	0.65	0.25
	4.80	1	1	1	1	1	1	1	1	1	0.97	0.87	0.79	0.7
	8.50	1	1	1	1	1	1	1	1	1	1	0.94	0.61	0.5

Ranges:	1	0.99 – 0.80	0.79 – 0.60	0.59 – 0.40	0.39 – 0.20	0.19 – 0.01	0

The hydraulic variables associated with a successful movement were determined based on the discharge at which the movement occurred. However, the hydraulic variables associated with an unsuccessful movement were determined based on the most frequent discharge that occurred during the respective time interval. Logistic regression was used to test for a significant influence of the hydraulic variables on passage success. Significance was evaluated using the chi-square (χ^2) statistic. Stepwise forward regression with a minimum Akaike information criterion (AIC) stopping rule was used to determine the hydraulic variables to include in logistic regression. Collinearity was assessed by examining the bivariate fits among the hydraulic variables. To avoid issues of collinearity, combinations of variables were manually selected to be tested for significance by stepwise forward regression. All statistical procedures were completed using JMP® Pro 11 (SAS Institute Inc., 2013).

3. Results

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

3.1. Hydraulic variables

3.1.1. Velocity and depth

The fraction of flow paths that exceed burst swimming abilities and/or do not provide adequate depth for a given discharge and body length varies appreciably among WWP structures (Table 1 through 4) as a result of subtle differences in their configuration. At lower discharges, continuous passage routes across WWP1 are only accessible through narrow chutes (less than 0.3 m) flowing in between boulders that may not provide adequate depth or flow area for larger fish, but do provide lower velocities accessible to smaller fish (Fig. 2). As discharge increases more flow paths might become available for larger fish, while smaller fish are inhibited by velocity. This is confirmed through the MVR, MDC, and observed passage success by size class. For example, the MVR_{25} at WWP1 indicates that there are more flow paths available (flow paths that are not barriers to migration) at 0.42 cms compared to 8.5 cms for a 125 mm fish (Table 1). In contrast, there are more flow paths available at 8.5 cms compared to 0.42 cms for a 150 mm fish. Depth presents the greatest challenge across all discharges at WWP1 (Fig. 3).

WWP2 constricts the flow to the center of the chute at lower discharges and forces fish to traverse shallow flow depths characterized by the highest velocities. This is reflected in the lack of flow paths meeting the MDC at 0.42 cms and the fraction of flow paths that exceed burst swimming ability for 25 BL/s at 0.85 cms. At 0.85 cms, the fraction of accessible flow paths is limited and similar among size classes for a 175–300 mm fish, indicating concentrated flow. When observing higher discharges and the fraction of available flow paths for 10 BL/s, there is a positive linear increase in the amount of available flow paths with fish size that is reflective of a linear increase in passage success (Table 2). As discharge increases, flow spills over the wing walls and a small zone adjacent to the left bank provides lower velocities (Fig. 2, and Tables 1 and 2).

In general, there are more available flow paths across discharges and size classes of fish at WWP3, with a majority of the flow paths becoming available for fish exceeding 150 mm in length (Table 1). At WWP3, recirculation zones exist adjacent to the main velocity jet. At lower flows these low-velocity zones may not provide adequate flow depth, forcing fish to pass through the main velocity jet (Figs. 2 and 3). As discharge increases, water spills over the wing walls, flow depths increase adjacent to the main velocity jet, and more flow paths become available to larger fish. These flow patterns are confirmed by examining the MVR_{10} & MDC. Depth appears to prevent passage at 0.42 cms, while passage is accessible

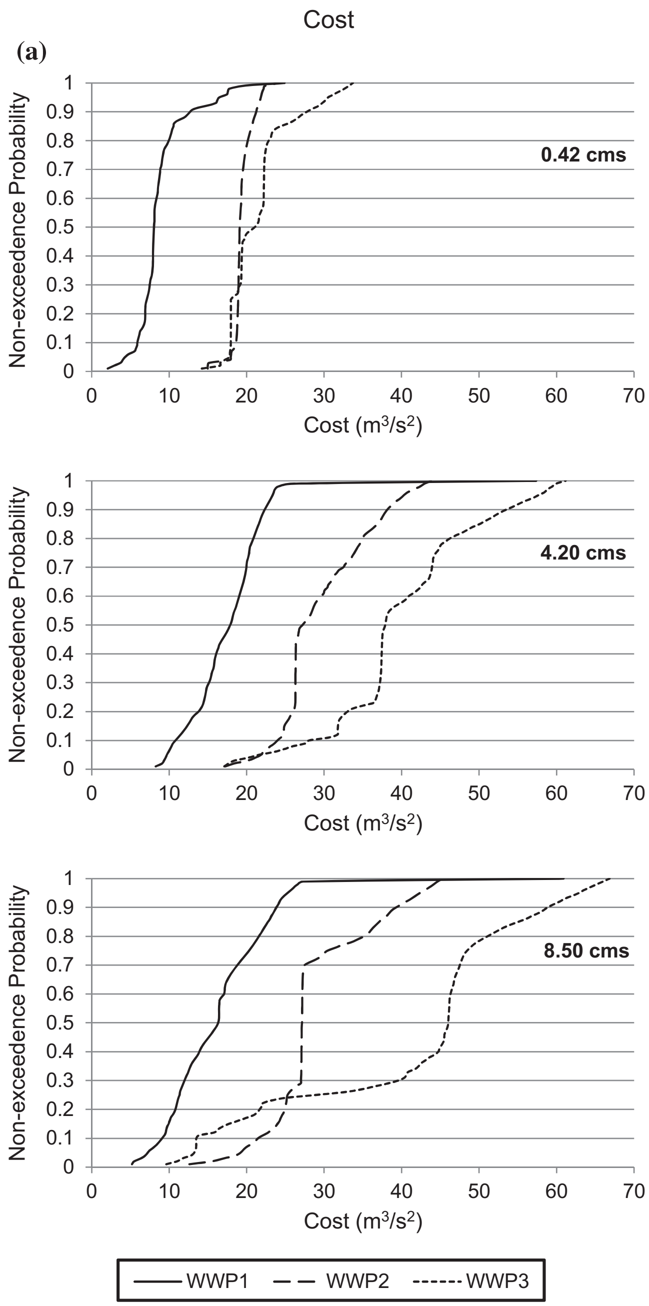

Fig. 4. (a) Non-exceedence probabilities for the cost along flow paths at each WWP structure for a low, intermediate, and high discharge. (b) Non-exceedence probabilities for the maximum vorticity and sum of vorticity along flow paths at each WWP structure for a low, intermediate, and high discharge. (c) Non-exceedence probabilities for the maximum TKE and sum of TKE along flow paths at each WWP structure for a low, intermediate, and high discharge.

to larger fish as discharge increases to 0.85 cms, indicating velocity as the limiting factor. A threshold appears in the MVR_{10} with a large fraction of flow paths becoming available at 0.42–1.70 cms.

According to the MVR, there is a general trend at all WWP structures for fish less than 175 mm in length that neither the lowest nor highest discharge presents the greatest challenge; rather, an intermediate discharge appears to be most limiting (Tables 1 and 2). Simultaneously examining the MVR_{25} and MDC shows that greater than 80% of the flow paths are inaccessible to fish of all size classes at flows less than 0.85 cms (Table 3). Additionally, combining the MVR_{10} and MDC as barriers to migration indicates that greater than 90% of the flow paths are unavailable for fish less than 300 mm in length (Table 4).

3.1.2. Cost

The magnitude and distribution of cost vary among WWP structures and discharges (Fig. 4a). The total length of the flow volume from the upstream boundary to downstream boundary was 3.4 m at WWP1, 5.0 m at WWP2, and 6.0 m at WWP3 (Fig. 2). The difference in the lengths of the flow volumes is a direct result of differences in the length of the hydraulic jump. The length of the hydraulic jump is greatest at WWP3, resulting in greater distances of supercritical flow and higher velocities. Consequently, WWP3 is characterized by the highest 50th percentile of cost. However, similar costs exist at WWP2 and WWP3 at lower flows. As discharge increases, lower velocities along the channel margins result in broader distributions of cost indicating greater hydraulic heterogeneity within the flow field. WWP1 consistently has a lower cost at all discharges.

3.1.3. Turbulence

The highest magnitudes and broader distributions of the maximum vorticity generally occur at the lowest discharge (0.42 cms). WWP3 has the greatest 50th percentile of maximum vorticity at 0.42 cms (Fig. 4b). The magnitude and distribution of the maximum vorticity is similar among WWP structures at discharges $\geq$4.20 cms. The maximum of the sum of vorticity along a flow path varies between WWP2 and WWP3 depending on the discharge and percentile being analyzed (Fig. 4b). However, there is a general trend that WWP1 contains the lowest sum of vorticity along a flow path. Additionally, narrow distributions of the sum of vorticity for each WWP structure exist at 0.42 and 8.50 cms.

The magnitude and distribution of the maximum TKE and the sum of TKE along a flow path also vary substantially among WWP structures and discharges (Fig. 4c). At a specific discharge, the maximum TKE among WWP structures depends on the percentile of the distribution. WWP2 has the greatest 50th percentile of the maximum TKE at all discharges except 0.42 cms (Fig. 4c). WWP3 appears to have a more narrow distribution of the maximum TKE at all discharges compared to WWP1 and WWP2. Similar trends in the relative magnitude of the 50th percentile of the sum of vorticity and TKE exist at each individual WWP structure (Fig. 4c). The 50th percentile of the sum of TKE is lowest at WWP1 for all discharges. However, WWP1 has the overall maximum of the sum of TKE along a flow path at 8.50 cms. Each structure is characterized by a narrower distribution of the sum of TKE at 0.42 cms.

3.2. Fish passage

Direct observations of fish movement obtained from the PIT-tag movement study (Fox, 2013) indicate that fish passage success varies among WWP structures and size classes of fish (Fig. 5). Passage success is greatest at WWP1 for fish 200 mm in length and smaller; however, passage success decreases as fish size increases at WWP1. WWP2 has the highest proportion passing for larger fish. Additionally, there appears to be a positive linear relationship with passage success and fish size. At WWP3, passage success increases from 28% to 80% when fish length exceeds 300 mm. Different fractions of successful movements at each WWP structure occurred over different discharges (Fig. 6). At 0–0.42 cms, the largest fraction of successful movements occurred at WWP2. There is a mode of successful movements for all WWP structures at 0.42–0.85 cms. Indeed, more than 80% of fish passage at WWP1 occurred at 0.42–0.85 cms, which has a much longer exposure time than the higher discharges we examined (Fig. 7). At 0.85–1.70 cms, a larger fraction of successful movements occurred at WWP3 compared to

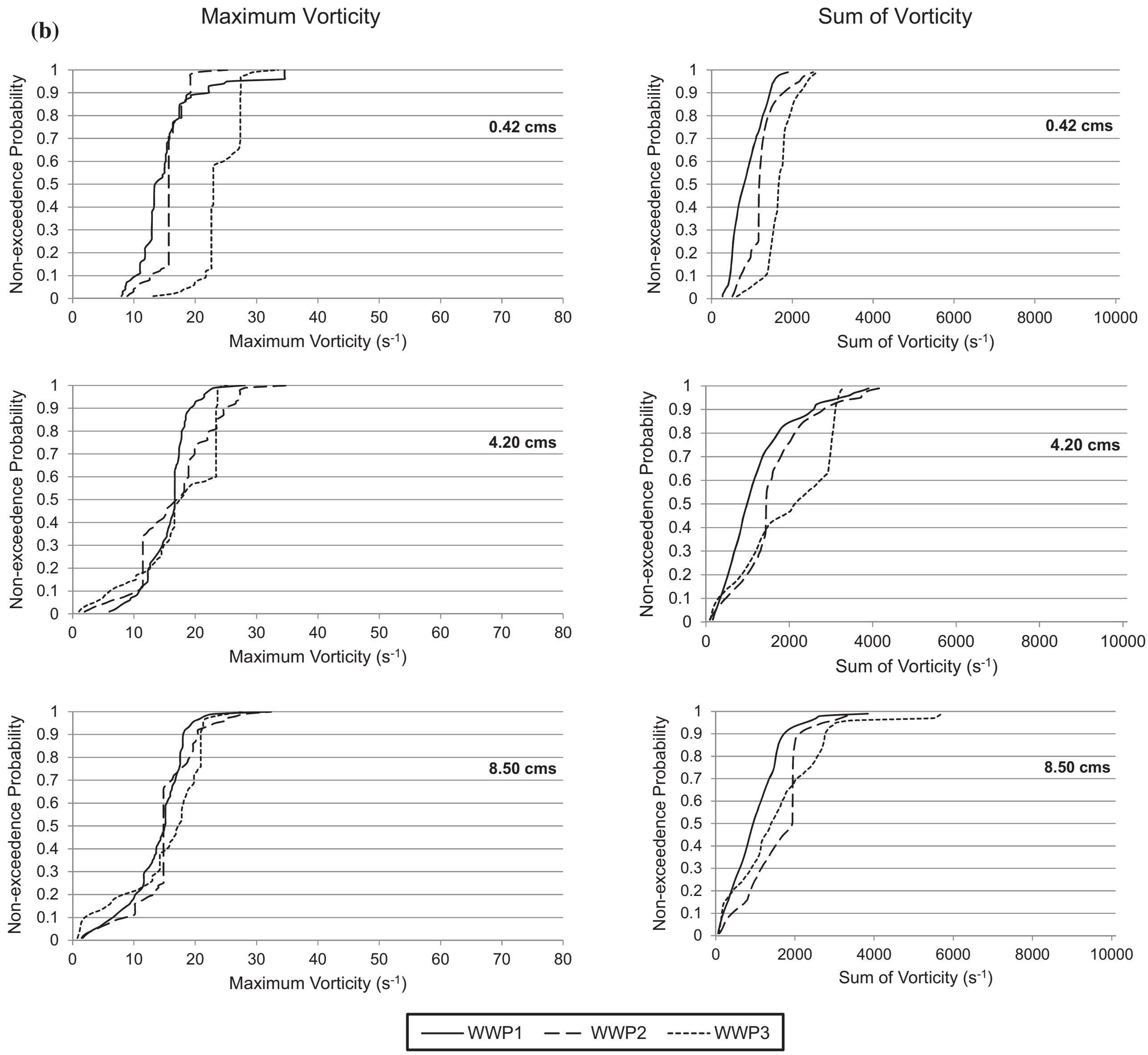

Fig. 4. (Continued)

WWP1 and WWP2. As discharge increases from 2.80 to 8.50 cms, the fraction of successful movements at each WWP structure greatly decreases as would be expected based on the frequency each discharge occurred.

3.3. Logistic regression analysis

Logistic regression analysis of hydraulic variables, i.e., the percentile of cost tested individually with the MVR_{10} and MVR_{25}, MDC, 50th percentile of the maximum vorticity, and 50th percentile of the maximum TKE consistently indicated that the MVR_{10}, MVR_{25}, and MDC were the best predictors of passage success across all WWP structures (Table 5). In contrast, the cost variable had an odds ratio close to 1 and was a poor predictor of passage success. Removing the cost variable from the logistic regression model does not have a significant effect on the model fit.

Model parameter estimates indicate that passage success decreases with increases in the fractions of flow paths that exceed burst swimming ability and do not meet the MDC (Table 5). A unit change in the MDC results in the greatest response in passage success compared to the MVR (odds ratio = 6.73×10^{-13}). The final model was highly significant ($p < 0.05$) with classification accuracies of 71.7 and 92.5 for successful and unsuccessful movements, respectively (Table 5).

Logistic regression analysis of each individual WWP structure shows a significant influence of different hydraulic variables at each structure. Depth is statistically significant at WWP1, depth and the MVR for 25 BL/s are significant at WWP2, and depth and the MVR for 10 BL/s are significant at WWP3. The parameter estimates and odds ratio for the hydraulic variables at each individual WWP structure show a decrease in the probability of success as the fraction of flow paths that exceed burst swimming ability increase (Table 5). The goodness-of-fit test at WWP1 indicates that more complex variables could be added to the model ($p < 0.05$). Despite the results from the goodness-of-fit test at WWP1, the likelihood ratio test indicates that the models predict passage success with high accuracy ($p < 0.05$) (Table 5). Additionally, the model correctly predicted 91.2% of the

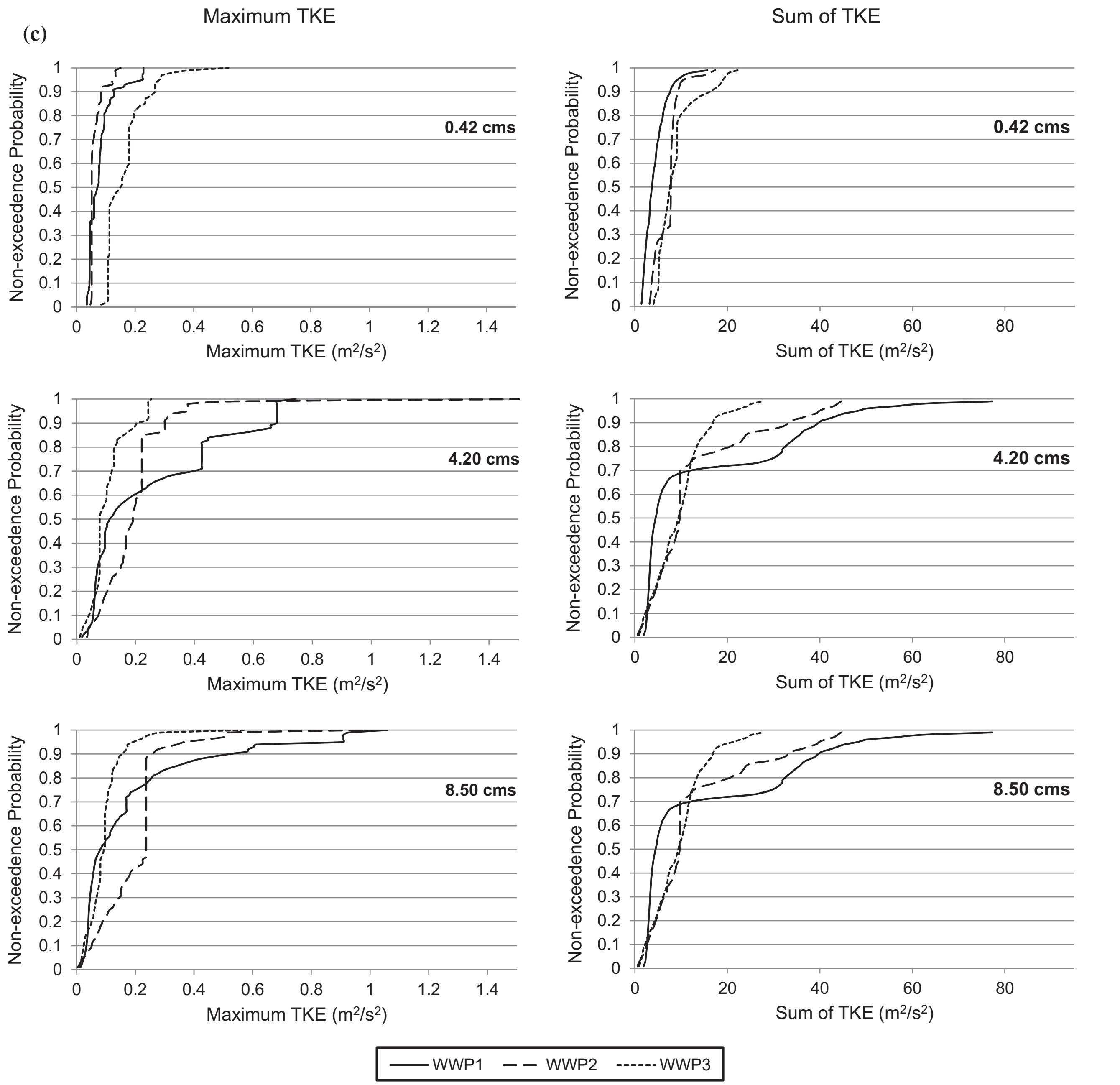

Fig. 4. (Continued)

observations. The logistic regression models accurately predicted 88.5% and 86% of the observations at WWP2 and WWP3, respectively (Table 5).

Logistic regression analysis of the MVR & MDC across all structures indicates a significant influence of the MVR_{25} & MDC; however, the MVR_{10} & MDC was not significant. The MVR_{25} & MDC has a negative parameter estimate and odds ratio less than 1, indicating that passage success decreases as the fraction of flow paths that exceed burst swimming ability (25 BL/s) or do not meet the MDC increases (Table 5). The likelihood ratio test indicates that the model predicted passage success with high accuracy ($p < 0.05$); however, the goodness-of-fit test indicates that additional variables could be added to improve the model fit. The model accurately predicted 87.5% of the observations (Table 5).

Logistic regression analyses of each individual structure indicated a significant influence of the MVR_{25} & MDC at WWP1 and WWP2, while MVR_{10} & MDC was significant at WWP3. According to the odds ratios and parameter estimates, passage success decreases with an increase in the fraction of traces that exceed burst swimming ability (10 and 25 BL/s) or do not meet the MDC (Table 5). The likelihood ratio test indicates that each model predicts passage success with high accuracy ($p < 0.05$) (Table 5). Additionally, the goodness-of-fit tests at WWP2 and WWP3 indicate that the inclusion of additional variables would not improve the model fit ($p > 0.05$); however, the addition of more complex variables at WWP1 might improve the model fit ($p < 0.05$). The model accurately predicted passage success for 90.7%, 87.5%, and 85.7% of the observations at WWP1, WWP2, and WWP3, respectively (Table 5).

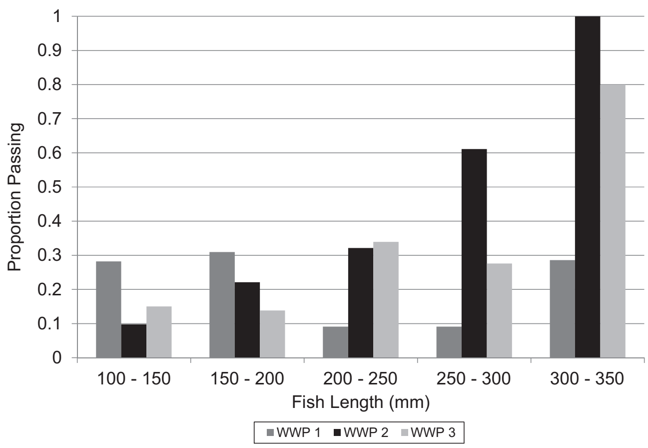

Fig. 5. The fraction of observed fish by size class at each WWP structure that successfully passed that structure.

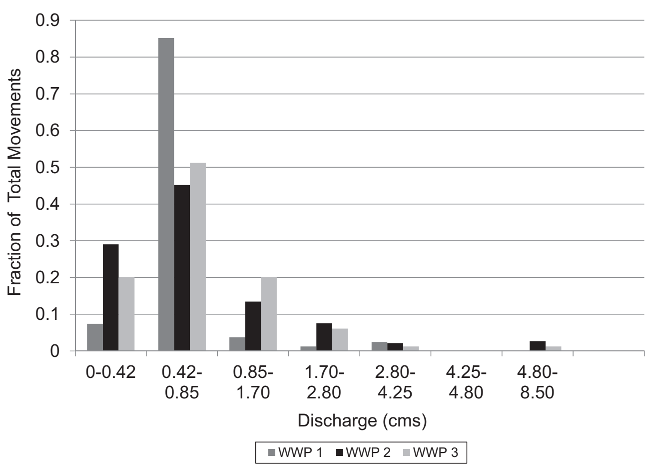

Fig. 6. The fraction of successful movements occurring over the range of modeled discharges at each WWP structure.

4. Discussion

The methods used in this study provide a novel and powerful approach to mechanistically evaluate fish passage over a wide range of hydraulic structure types. Describing the hydraulic conditions along potential fish movement paths continuously quantifies important flow features at a scale meaningful to a fish. Simply averaging the hydraulic conditions over large spatial scales or evaluating point measurements do not take into account the continuous complexity of the flow field along a fish's movement path. This is supported by evidence from a previous study that did not find maximum threshold velocities or burst swimming abilities as satisfactory predictors of passage success when quantified as cross-sectional velocity quantiles within the chute of WWP structures (Fox, 2013).

The logistic regression analyses indicate that the MVR_{10}, MVR_{25}, and MDC accurately predict passage success for over 87% of observed trout. The fraction of available flow paths that exceed a fish's burst swimming ability or do not provide adequate depth had a negative influence on passage success. This strongly suggests that both depth and velocity are contributing to the suppression of movement of upstream migrating salmonids. Logistic regression analysis indicates a significant influence of the MVR & MDC across all WWP structures and at each individual WWP structure. A potential movement path might meet the minimum depth criteria but serve as a velocity barrier and vice versa. This underscores the importance of concurrently considering depth and velocity as barriers to upstream migration. Additionally, evaluating velocity and depth concurrently and combining them into a single predictor variable allows for a simplified, but highly accurate, statistical analysis.

Although the MVR & MDC accurately captures the effects of velocity and depth, additional analyses of the variation in statistically significant hydraulic variables among WWP structures and across discharges highlights unique hydraulic characteristics at each WWP structure that affect passage success differently. For instance, depth presents a greater challenge at WWP1 as it is characterized by a shorter, steeper drop compared to WWP2 and WWP3. Velocity is more limiting at WWP2 and WWP3 compared to WWP1 due to longer chutes with minimal roughness and constricted flow. Variation among the chute configuration at similar structure types, such as WWP2 and WWP3, dictates variation in the magnitude of velocity vectors and heterogeneity within the flow field among structures. The evaluation of the MVR, MDC, and their combined influence on passage success by size class and discharge emphasizes the importance of site-specific characterization of subtle differences in structure design. However, depth has lowest odds ratio in all logistic regression analyses, suggesting it has the strongest effect on passage success.

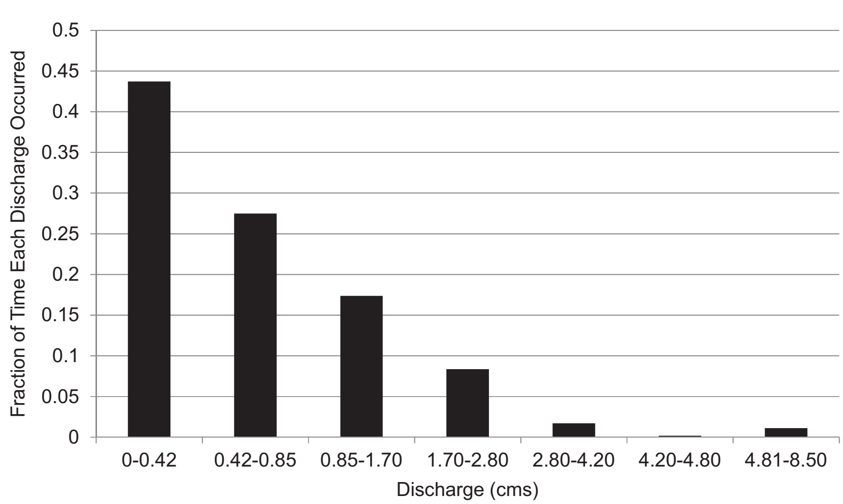

Fig. 7. The fraction of time each discharge occurred at the site over the course of the study.

Table 5
Logistic regression analysis for passage success. [1.5- or 2-column table; black and white]

Logistic regression model		Predicted logit of (passage success) =	Likelihood ratio test (p-value)	Goodness-of-fit test (p-value)	Predictor p-value	Odds ratio (e^{β})		Observations accurately predicted (%)
All WWP Structures		27.69 + (–2.422)*MVR_{10} + (–5.516)*MVR_{25} + (–28.03)*MDC	<0.0001	0.1222	0.0075	MVR_{10}	0.0888	87.5
					<0.0001	MVR_{25}	0.0808	
					<0.0001	MDC	6.73E-13	
All WWP Structures		24.67 + (–27.27)*MVR_{25} & MDC	<0.0001	<0.0001	<0.0001	MVR_{25} & MDC	1.44E-12	87.5
Individual Structures	WWP1	31.98 + (–36.32)*MDC	<0.0001	0.0068	<0.0001	MDC	1.69E-16	91.2
	WWP2	29.72 + (–4.874)*MVR_{25} + (–31.74)*MDC	<0.0001	0.9674	0.0038	MVR_{25}	7.64E-03	88.5
					<0.0001	MDC	1.64E-14	
	WWP3	26.81 + (–3.248)*MVR_{10} + (–26.22)*MDC	<0.0001	0.1389	<0.0001	MVR_{10}	3.89E-02	86.0
					<0.0001	MDC	4.09E-12	
Individual Structures	WWP1	45.01 + (–49.73)*MVR_{25} & MDC	<0.0001	<0.0001	<0.0001	MVR_{25} & MDC	2.51E-22	90.7
	WWP2	24.89 + (–27.00)*MVR_{25} & MDC	<0.0001	0.6235	<0.0001	MVR_{25} & MDC	1.88E-12	87.5
	WWP3	20.42 + (–22.61)*MVR_{10} & MDC	<0.0001	0.9513	<0.0001	MVR_{10} & MDC	1.51E-10	85.7

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

The goodness-of-fit test at WWP1 shows that more complex variables could improve the model fit. This suggests that additional variables to depth could be contributing to the suppression of movement at WWP1. A study examining the effects of turbulence on passage success in three different experimental pool-type fishways found that the fishway with the highest turbulence had the worst passage success, but passed smaller fish better than the other configurations (Silva et al., 2012). Similarly, WWP1 has the worst overall passage success; however, smaller fish experience higher success rates at WWP1 compared to larger fish. WWP1 is also characterized by the highest magnitudes and larger distribution of the maximum vorticity along flow paths at discharges when the majority of the movements occurred. This suggests that turbulence could be an additional factor affecting passage success at WWP1. Flow and interstitial space width may be limiting passage of larger fish (WWP1), as narrower widths have been shown to limit upstream passage success for brook trout (Brandt et al., 2005)

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

The cumulative effects of velocity a fish experiences while crossing a structure have the potential to influence passage success. Studies have shown that as the swim speed of a fish increases the time to fatigue decreases (Bainbridge, 1960; Peake et al., 1997). Considering a fish chooses the least cost path (McElroy et al., 2012) through a structure, it is unlikely that an exhaustive swimming barrier will exist. Additionally, lateral movements of fish linking low cost sections across several movement paths could substantially reduce the effective cost. Logistic regression analysis does not indicate a negative effect of cost on passage success; however, visual observations of failed attempts will reveal direct relationships on passage success and velocity as an exhaustive swimming barrier.

This study examines hydraulic conditions as physiological barriers to migration and does not take into account fish behavior. Accessible movement paths might exist at a structure. However, a fish might feel the cumulative effects of fatigue or lack motivation after several failed attempts to locate accessible movement paths (Castro-Santos et al., 2013). It is important to consider the timing of fish migrations and other life-cycle processes. Brown trout spawning migrations primarily occur in the fall when discharges are the lowest. However, rainbow trout spawning migrations primarily occur in the spring as discharge increases. The target species and local hydrologic regime could have implications for designing hydraulic structures to accommodate fish passage during critical seasons. Although higher discharges provide a higher fraction of accessible flow paths for fish at the Lyons WWP structures, discharges at 0.42–1.70 cms occur much more frequently throughout the year at the study site.

Despite the remaining uncertainties in additional factors that might be contributing to the suppression of movement, management guidance and design recommendations can be provided based on the strong relationship of passage success with velocity and depth. Care should be taken to ensure that velocity and depth requirements are met continuously along likely fish movement paths. Multiple field studies indicate that fish exploit boundary layers created by objects in the flow field (Fausch, 1993; Nestler et al., 2008). Interstitial spaces within the center of the chute may provide zones of lower velocity for smaller fish. Increasing the size of interstitial spaces to at least the body depth of the largest fish likely encountered at a WWP structure may provide adequate flow depth and lower velocities to accommodate a broader range of fish sizes. Increasing the width of interstitial spaces and passage routes could also prove beneficial for larger fish (Brandt et al., 2005). Continuous low-velocity zones along the margins of the chute with adequate flow depth should be provided, allowing fish to avoid the main velocity jet. Low-velocity zones along the channel margins can be achieved by allowing water to spill over the wing walls at all discharges. If the wing walls are not grouted they act as roughness elements providing flow refugia for fish. Large eddies that recirculate back into the chute at all discharges can provide additional low-velocity zones as seen at higher discharges at WWP3. These low-velocity recirculation zones should come up the sides of the main velocity jet as far as possible.

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

5. Conclusions

This study used the results from a 3-D CFD model to provide a continuous and spatially explicit description of the hydraulic conditions along potential fish movement paths and examine their influence on fish passage at a WWP on the St. Vrain River in Lyons, Colorado. Quantifying the hydraulic conditions in this manner captured important and unique hydraulic characteristics at each WWP structure, and described velocity and depth throughout the flow field at a scale meaningful to a fish. Logistic regression indicated a significant influence of velocity and depth on passage success, and accurately predicted 87% of individual fish movement observations. However, cost, vorticity, and TKE did not have a significant effect on passage success. Specific combinations of depth and velocity were statistically significant at individual WWP structures highlighting the effects of unique hydraulic conditions at each WWP structure on passage success. Further, a comparison of velocity and depth relative to a fish's swimming ability was reflective of the variation in passage success among WWP structures, across discharges, and among size classes of fish. The results indicate that additional variables such as turbulence might also be contributing to the suppression of movement. Further research is needed to examine the range of hydraulic conditions at existing hydraulic structures and their effects on native fishes with lesser swimming abilities. Additionally, studies involving flow/fish interactions are needed to evaluate fish behavior in response to hydraulic conditions and define turbulence at a scale relative to fish size. Similar hydraulic analyses coupled with fish movement data can be utilized to evaluate the effects of hydraulic conditions on passage success at other types and sizes of hydraulic structures. This study lays the groundwork for a novel and powerful approach to mechanistically evaluate the effects of hydraulic structures on fish passage. Further, the results of this study can serve as a reference for managers and policy makers, provide design guidance for future hydraulic structures, and be used to evaluate existing structures of similar size, design type, and hydrologic regime.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecoleng.2015.06.032.

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