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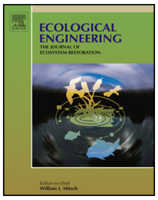

# Effects of whitewater parks on fish passage: a spatially explicit hydraulic analysis

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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