IMPACTS OF ROCK WEIRS ON FISH SWIM PATH SELECTION AND FATIGUE LEVLES

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Abstract: The addition of rock weirs and other features is a common approach to stream restoration. We evaluate fish response to a pair of rock weirs installed in the Little Snake River, WY and explore the consequences of their presence in the stream in terms of fish movement and fish fatigue using a model. We model upstream fish movement of 5 size classes of salmonids, and use commonly accepted swim speeds and fatigue estimates to evaluate upstream movement. Fish can transition from a sustained to a prolonged or burst swim speed based on a local acceleration threshold. The flow field was computed using the model U2RANS and the resulting velocities averaged 1.4 m/s with a maximum of 3.8 m/s. We find that the largest fish are readily able to pass through the channel with low fatigue levels, while the smallest fish are unable to pass and have high fatigue levels. Moderate sized fish have two modes with some fish passing readily and with little fatigue while others don't pass and have high fatigue levels. The proportion of prolonged and burst swimming was highest for large fish. The results suggest that the rock weirs produce complex three-dimensional flow fields whose impacts depends on fish size and behaviour. Future work should focus on fish movement data collection near real stream restoration structures coupled with hydrodynamic modeling with U2RANS or other codes.

INTRODUCTION

Fragmentation and other effects of water resources development cause loss of populations and species of river fishes (Nilsson et al. 2005). Many species conservation and ecosystem restoration programs incorporate channel modifications such as rock weirs, intended to improve fish habitat, into their projects. Effective design criteria for incorporation of rock weirs into streams is based on stream stability and other engineering considerations and typically do not have a solid understanding of fish behavioral response to hydrodynamic consequences of rock weirs. Design criteria based solely on means of simple hydraulic variables may not capture the full behavioral repertoire of animals evolved to move in spatially and temporally complex aquatic environments. Rock weirs may be movement barriers to fish due to high velocities or excessive elevation change. If rock weirs are barriers to fish this may have fish population consequences because movement is disrupted or otherwise limited.

Fish employ at least three recognized swim behaviors during upstream migration: sustained, prolonged and burst swimming (Hoar and Randall 1978). Sustained swimming is generally employed over long time periods (hours, days) and is energetically efficient. Prolonged and burst swimming are short term (seconds, minutes) energy intensive behavior employed in high energy environments. Our goal is to mathematically represent upstream migration and quantify the

contribution of prolonged and burst swimming to passage by various sized fishes. We do this by: 1) using a computational fluid dynamics (CFD) CFD model of a restoration feature in a natural river; 2) simulating various sized fish implementing a mix of sustained and prolonger/burst swimming in complex hydraulic environments, and 3) analysis of resulting swim speeds, fatigue levels and passage success.

METHODS

A detailed CFD model is used to realistically simulate the hydrodynamic pattern in a selected section of river. The output of the CFD model is linked to a fish swim path selection model that creates virtual fish programmed to respond to hydrodynamic variables using Eulerian-Lagrangian-Agent Methods (ELAMs - Goodwin et al. 2006, 2013). The swim path selection model can be programmed with different behaviour rules that each represents a different assumption about the movement of observed fish. The outputs of competing movement rules can be evaluated for realism and explanatory power using techniques similar to those used for real fish. Virtual fish tracks can be analysed for swim distance, distance over ground, track complexity, track direction, passage rate past a fixed location (e.g. a fishway exit or an arbitrary finish line within the channel), and other useful descriptive measures. Species- and size-specific fatigue times based on swim speed and duration were derived from the literature.

Site Description and Computational Fluid Dynamics Model: We selected a 56-m long reach of the South Fork Little Snake River with a maximum width of about 5-m. This reach was characterized by steep slope, complex flow pattern (Figure 1A) with 3-D flow, two hydraulic jumps, and a wide range of depths and velocities created by a two u-shaped rock weirs (Figure 1B). To simulate this site, we used U^2RANS (Lai et al. 2003; Lai et al. 2004), a 3-D, unsteady, nonhydrostatic, model useful for simulating complex flow patterns in steep, geomorphically diverse river channels. The numerical mesh consists of about 160,000 cells with mixed hexahedrons and wedges. Maximum modeled pool depths are 1.6 m, maximum velocities at the weirs are greater than 3 m/s, and mean water velocities are 1.6 m/s (Figure 1).

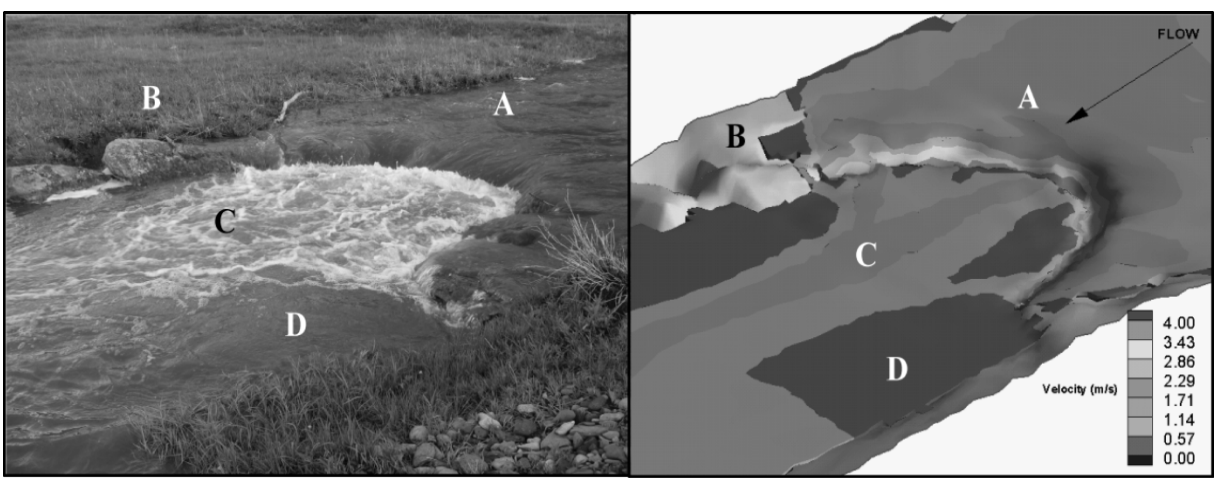

Figure 1 Photo and computational representation of the domain used to evaluate upstream fish movement. Point A shows approach to supercritical drop (height = 0.4 m) flow and velocities of 3 m/s. Point B shows complex rocks incorporated into the model. Point C is a high velocity jet of 2 m/s. Point D shows a low velocity zone (0.4 m/s).

Modeled Fish and Swimming Algorithm: We modelled fish with a default behavior of swimming upstream at a sustained speed of 2.0 body lengths per second (BL/s) using methods of Goodwin et al. (2006). Sustained upstream swimming is represented as a biased correlated random walk with turning angles drawn from a range of 0 to 5 degrees in the *xy* plane. We trigger a combined prolonged and burst swimming behavior (6 to 10 BL/s) using an acceleration threshold of 0.04 m/s^2. Both the sustained and prolonged/burst behaviors result in the fish swimming into the local flow vector. We manually calibrated the acceleration trigger by noting that a fish should implement swim strategies that minimize prolonged and burst swimming (to minimize fatigue) while still providing for upstream movement and ultimately passage through the domain.

One hundred fish per size class (0.38-, 0.52-, 0.63-, 0.73-, and 0.84-m) were parameterized with the size and swimming characteristics of upstream migrating steelhead (*Oncorhynchus mykiss*). A time step of 0.01 seconds was used because the domain is physically small and complex and larger time steps yield correspondingly less informative tracks. For example, given a time step of 0.1 seconds, a 0.84 m fish swimming at a maximum of speed of 10 BL/s can cover 0.84 m or roughly 20% of the channel width. The resulting swim path would miss much of the finer scale hydraulic complexity. Segments of virtual fish tracks exhibiting predicted swim velocities greater than 10 BL/s (occasionally occurs in small CFD domains for numerical reasons) were removed from the analysis during post processing. Simulation runs were terminated after 800 seconds because all fish had exited the model domain. Positions (*x*,*y*,*z*), swim speeds (BL/s and speed over ground (SOG), and the proportion of each behavior (sustained and prolonged/burst swimming) and fatigue (instantaneous and cumulative) were computed.

We estimated fatigue time using the well-known data on steelhead swimming and fatigue from Paulik et al (1957). Fatigue times are computed for modeled fish using estimates of swim speed (BL/s) as

$$lnT = -0.48 * swim\ speed \left(\frac{BL}{s}\right) + 6.466 \quad (1)$$

where *T* is fatigue time in seconds. The equation extends from approximately 1.5 to 7 BL/s. For speeds under 1.5 BL/s we specify *T* as 3600 seconds, or the upper time limit for sustained swimming. We extend the relationship beyond 7 BL/s to 10 BL/s. This does not imply that fish can only maintain sustained swimming for 3600 seconds. However, 3600 seconds yields a mathematically small estimate of fatigue for a given time interval suggesting long sustained swim times. Fatigue (%) for each time step was computed as

$$\left(\frac{t}{T}\right) \times 100 \quad (2)$$

where *t* is the model time interval in seconds. Cumulative fatigue time was simply the instantaneous fatigue time (%) summed over the intervals *t* by fish and stratified by fish size.

RESULTS

Mean cumulative fatigue varies by fish size with the larger fish accumulating the least fatigue and passing through the domain the fastest (Figure 2A). Larger fish, swimming at a sustained 2 BL/s, also have the highest mean SOG (Figure 2B). Larger fish have the highest passage rate

(~90%) while the smallest fish have the lowest (0%) (Table 1). Conversely, smaller fish implement the highest percentage of sustained swimming and the lowest percentage of prolonged/burst swimming (Table 1). This is due to the longer time smaller fish spend in the domain compared to larger fish (Figure 2C). To control for time and highlight the fatigue experienced by each size class of fish, we calculated the cumulative fatigue experienced by a fish per second and note that it is highest for the 0.38 size fish (Figure 2C).

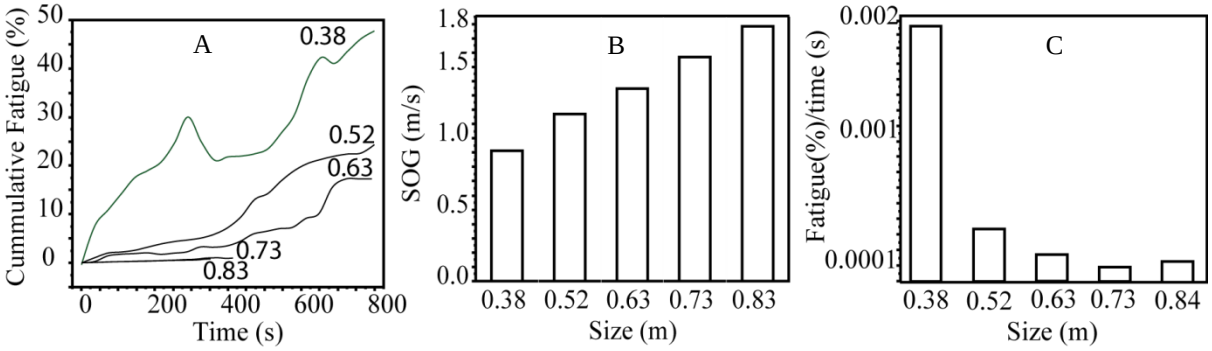

Figure 2 Mean cumulative fatigue (frame A), speed over ground (frame B), and accumulated fatigue per second (frame C) for each fish size class.

Table 1. The behavior and passage of the five size classes of fish

Size (m)	Sustained (%)	Prolonged/Burst (%)	Passage (%)
0.38	89	11	0
0.52	90	10	31
0.63	87	13	66
0.73	83	17	90
0.83	79	21	93

DISCUSSION

We show that it is possible to explore relationships among site specific geomorphology and hydraulic patterns with important biological attributes associated with fish behavior and fish passage. For example, larger fish pass at higher percentages and in shorter times than the smaller fish and the larger fish have higher SOG estimates than smaller fish. The inverse relationship between passage percentage and mean fatigue is also consistent with expectations as we would not expect fatigued fish to pass effectively. More subtlety, the simulation suggests that fatigue is not a simple correlate of swim speed. If it were, we would expect to observe that those fish that execute the most prolonged and burst swimming would also be the most fatigued. The smallest fish executed the least prolonged and burst swimming (Table 1) yet were the least successful at passage and were the most fatigued. We believe this reflects a complex dependency on fish size (and hence SOG) and the local hydraulic environment. We also note that there remains a basic question on how a fish decides, with incomplete knowledge of its environment, to transition from

sustained swimming to prolonged or burst swimming. Our premise was that prolonged and burst swimming should be not exceed the minimum needed to achieve passage. Embedded in this premise is the assumption that a fish knows the location and distance to the end point of the hydraulically challenging domain. This assumption may not be accurate, however. Improved methods of describing the decision process and behavior transitions and are needed.

Fatigue time analyses are common in the fish passage and fish swimming literature and are often used in conjunction with swimming speed information to estimate maximum distance a fish can swim in a given velocity field. Such analyses often assume uniform velocity such as might be found in a simple prismatic channel. With interest in complex natural fishways, stream restoration design and the burgeoning data available on fish movement via telemetry suggest that descriptions of fish behavior in complex, continuous velocity fields are needed. We have demonstrated one method that achieves the integration but acknowledge that much works remains to validate the approach.

Finally we note that the modelled river exhibited a range of hydraulic conditions with many point velocities exceeding the nominal swim speed criteria for adult steelhead of less than 0.6 m/s and vertical drops of 0.4 m (NMFS 2001). We demonstrated that passage was possible for some fish but not others in this environment. We conclude that simple velocity criteria may be difficult to apply in complex hydraulic environments with a wide range in velocities. Our results show that the combination of sustained and prolonged/burst swimming behaviour allows fish to pass through domains that simple criteria rule out. Further, it is possible to optimize the design using methods outlined in this study. This is a potentially important improvement over existing methods because rivers continue to be impacted by human activities and the need for effective mitigation has never been greater.

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