Evolution of an Innovative Fish Ladder Design to Address Issues of Perched Culverts

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ABSTRACT

This study evaluates the design of a new fish ladder for impassable perched culverts. The fish ladder and associated baffles were evaluated through the use of a 3-dimensional computational fluid dynamics model (Flow-3D). The new design termed the Duguay-Hannaford baffle consists of a lower and a higher passageway to accommodate fish passage over a wide range of seasonal flow rates. The numerical simulations were evaluated for barrier velocities, turbulence and maximum vertical drop between pools. Numerical results show that velocities at the passageways respect critical swim speeds for a wide range of fish species of socioeconomic importance to North America. The volumetric dissipative power is lower than maximum values suggested for salmonid species. The presence of adequate hydraulic refuge zones was also assessed. The Hannaford fish ladder shows promise as an easily transportable and effective solution to the problem of aquatic habitat fragmentation caused by perched culverts on remote and difficult to access terrain.

Keywords: Perched Culverts, Fish Passage, Fish Ladder, Numerical Modeling.

INTRODUCTION

The development of road infrastructure has fragmented the aquatic connectivity of inland streams and rivers. Perched culverts are often the result of incorrect installation or downstream sediment erosion and have been found to be a leading barrier to fish passage across North America. It has been estimated that more than 50% of impassable culverts are perched (Matthew et al. 2006). Fish ladders have long been a popular solution to address the problems of perched culverts and other vertical passage barriers such as dams and other in-stream structures.

In the early stages of fish ladder development designs were limited to timber and stone and were susceptible to the forces of nature thus requiring continual effort to maintain year-round functionality. Concrete fish ladders (permanent structures) appeared at the beginning of the 20^{th} century. Resource intensive fish ladders constructed of concrete require a considerable amount of site preparation and construction time which make them less attractive for use on rough terrain in remote locations. The narrow construction window typical of northern climates, followed by the limited resources at the disposal of transport agencies and the high costs associated with concrete fish ladder construction significantly reduces the number of perched culverts that can be addressed using this approach during a given fiscal year. Transportable Denil fish ladders constructed in aluminum were developed to respond to this need since they can be easily transported to and quickly installed on difficult terrain. However, the highly turbulent flow field developed in the Denil fish ladder and its lack of appropriate resting zones inhibits the passage of weaker fish species. A fish ladder designed specifically to develop resting areas of low turbulence and velocity much like the pools observed in natural streams would improve fish passage rates. Therefore, a light-weight fish ladder that is both adaptable to the site specific constraints of difficult terrains and rapidly installed by a small construction crew would be of great benefit to the aquatic habitat connectivity of inland streams.

Structural Plate Corrugated Steel Pipe (SPCSP) can easily be transported to and assembled at these remote locations. In addition to the low velocity resting zones observed in proximity to the corrugations (Ead et al. 2000), fabricated baffle forms can be fitted along the invert of the assembled culvert and used as a fish ladder. Recently, a thermoplastic co-polymer coating for SPCSP has been demonstrated to significantly increase service life under corrosive and abrasive conditions. Our study uses computational fluid dynamics (CFD) to investigate the flow field developed by an innovative fish baffle (*Duguay-Hannaford baffle*) placed within a half round polymer coated structural steel plate culvert. The numerical results demonstrate the baffle design performs similarly to that recommended by the Department of Fisheries and Oceans.

LITERATURE REVIEW

Fish passage stressors

The Department of Fisheries and Oceans (Canada) presents a list of stressors known to impede fish passage at in-stream structures (Savoie and Haché 2002). Among these stressors, a few are of particular importance for the design of a fish ladder; excessive velocities, elevated turbulence levels and substantial vertical drops. The flow field of the Duguay-Hannaford fish ladder will be evaluated for its response to these three stressors. Excessive velocities are characterized as those exceeding the *burst speed* of the target fish species. Burst speed is used by fish in nature normally only to evade predators and navigate rapid reaches of a river such as a choke or a low level cascade. Designs should limit the highest velocities to the burst speeds of the weakest swimming fish species in question. Figure 1 presents the burst speeds as well as the cruising and sustained speeds of a number of fish species common to North America.

Fish are known to prefer zones of low turbulence (Smith et al. 2005; Silva et al. 2012). Regions of excessive turbulence have been found to markedly reduce fish passage success rates in pool and weir fishways (Fouché and Heath 2013) (similar to the fish ladder studied herein). The volumetric dissipative power *VDP*, with units of W/m^3, gives a global evaluation of the turbulence within a region of flow. Recommended values of *VDP* vary between 150 W/m^3 and 200 W/m^3, depending on the size and species of the target fish (150 W/m^3 for trout and 200 W/m^3 for salmon) (Larinier et al. 1994). Equation 1 is used to calculate *VDP* (*Pv*) with ρ as density (kg/m^3), Q flow rate (m^3/s) and Δh being the elevation drop between the pools of the fish ladder. Fish ladder pools should be evaluated to ensure *VDP* is within reasonable limits.

$$P_v = \rho g Q \frac{\Delta h}{V} \tag{1}$$

Various researchers have investigated the jumping capacities of trout and salmon species (Lauritzen et al. 2005; Kondratieff and Myrick 2005; Brandt et al. 2005; Kondratieff and Myrick 2006; Lauritzen et al. 2010). Brandt et al. (2005) suggest that fish ladders designed for juvenile brook trout (*Salvelinus fontinalis*) should have a maximum drop height between pools of 0.1 *m* while Kondratieff and Myrick (2006) demonstrated that brook trout with body lengths between 0.10-0.15 *m* could jump 0.64 *m* and larger size fish could reach heights of 0.74 *m*. The DFO recommends values of Δh of 100 *mm* (between pools) for streams on small watersheds ($<2.5km^2$) and 200 *mm* for larger watersheds for use in baffle designs in road culverts (Savoie and Haché 2002). The Duguay-Hannaford baffle designed to be more passage friendly is assessed with these relevant research findings and the criteria of the DFO in mind.

THE DUGUAY-HANNAFORD BAFFLE

A 3D computational fluid dynamic model (CFD), *Flow-3D* by Flow science Inc., was employed to investigate the hydraulic characteristics of a new fish baffle geometry presented in Fig. 2. The current design of the Duguay-Hannaford baffle, was obtained after numerous simulations of various design modifications. The presented baffle design is not necessarily final, rather an acceptable geometry from which field verification can be performed to provide insights on possible modifications for improvements. The Duguay-Hannaford baffle consists of a lower principal passageway and a higher secondary passageway. The two passageways are separated by a convex arch which protrudes the water surface under all but the highest flow rates. In Fig. 2, θ and ϕ are the radii of the principal and secondary passageway, *Y* is the depth between the bottom of the baffle and the lowest point of the principal passageway, φ is the distance from the lowest point of the principal passageway and the highest point of the baffle, and finally *y* is the distance from the bottom of the baffle to the lowest point of the principal baffle. The front view of the downstream facing ramp is also shown in Fig. 2. The ramp respects a 2:1 slope beginning at the lowest point in the trough of the principal passageway and extends outwards by a distance of 0.2 *m*.

NUMERICAL MODEL

Model configuration

A computer assisted design (CAD) model of the fish ladder (see Fig. 3) was generated and imported into Flow-3D as a stereolithography file with the following dimensions; length of 10 m, diameter of 2.44 m and corrugations with pitch of 0.230 mm, depth of 0.064 mm and radius of 0.057 mm. The fish ladder was set at a slope of 8.5%. The dimensions of the numerical fish ladder were chosen to fit those needed to install a physical prototype ladder on an actual perched culvert located in Newfoundland. Baffles were spaced at 2.37 m starting at 0.75 m from the upstream end of the fish ladder. Baffle spacing was chosen to respect the 200 mm Δh suggested by the DFO (Savoie and Haché 2002). The principal passageway alternates position over the length of the fish ladder as seen in Fig. 3. The 0.200 m long ramp downstream of each principal passageway are also visible in Fig. 3.

Structured mesh blocks were used to discretize the computational domain as pictured in Fig. 4 and appropriate boundary conditions were employed for each mesh block. Porous flux surfaces were defined at each of the baffles to record the flow rates passing over each baffle at a given period in time. Flux surface data was used in conjunction with the mass averaged mean kinetic energy to determine when the simulation attained a steady-state solution.

Simulations

A second model was constructed and simulated using baffles having geometries respecting the DFO guidelines for baffles used in culverts (Savoie and Haché 2002) as pictured in Fig. 5. A number of simulations were performed to determine the flow rate causing the DFO slot to run at full capacity (i.e., water was just about to flow over the flanking weir portions adjacent to the slot). A flow rate of 0.0615 m^3/s was determined. The velocity and turbulent kinetic energy fields at the passageways as well as the *VDP* in the pools of both the Duguay-Hannaford design and the DFO design were compared at this flow rate. The Duguay-Hannaford design was further tested at a flow rate of 0.150 m^3/s an adequate flow rate to cause an appreciable amount of flow through the secondary passageway.

RESULTS AND DISCUSSION

Comparison with DFO baffle - low flow rate

Figures 6a and 6b present the near passageway surface velocity magnitude distributions at the 0.0615 m^3/s flow rate. Although the velocity vectors are not shown in Fig. 6 the flow direction at the passageways can be assumed to be approximately normal to the downstream baffle face. The velocities developed at the passageway for both the Duguay-Hannaford and DFO baffles are below the lower threshold of burst swim speeds for the majority of salmonid species presented in Fig. 1. However, juvenile individuals, weaker brown and cutthroat trout may encounter some difficulty at both the Duguay-Hannaford and the DFO baffle passageways. Further field testing of a full scale Duguay-Hannaford fish ladder is necessary to verify velocities over a range of common discharges.

The volumetric dissipative power of the Duguay-Hannaford baffle and the DFO baffles for each of the tested slopes and discharge configurations are presented in Table 1. Both baffle designs respect the VDP suggestions laid out by Larinier et al. (1994) for salmonids, with the Duguay-Hannaford baffle producing roughly half the value of VDP as the DFO baffle. The high arc of the

Duguay-Hannaford baffle helps retain water and builds depth in the pools at higher flow rates. This has the advantage of increasing the retained volume in the pool which in turn aids in the reduction of the VDP of the pool. Consequently, turbulence levels are expected to be lower in the Duguay-Hannaford fishway which may benefit fish by increasing the volume of refuge areas available in each pool.

At the low flow rate of 0.0615 m^3/s, the elevation difference between the downstream and upstream water levels for both baffles fluctuates near 0.2 *m* and is below the maximum jump height of 0.635 *m* demonstrated by Kondratieff and Myrick (2006) for brook trout with body lengths between 10-15 *cm*. This suggests that mature salmonid fish should demonstrate little difficulty jumping between successive pools.

Duguay-Hannaford baffle at high flow rate

Velocities at the primary and secondary passageways of the Duguay-Hannaford baffle for Q = 0.150 m^3/s are presented in Fig. 7 and are observed to fall within the range of 2 to 2.5 *m/s*. This range of velocity magnitudes still respects the burst swim speeds of the majority of fish species presented in Fig. 1 despite the relatively elevated flow rate. This suggests that the Duguay-Hannaford baffle develops low enough velocities at the passageways over a large range of seasonal flow rates to ensure fish passage. Figure 8 presents the streamline velocity distribution at the baffle and throughout the pool at the high flow rate of $Q = 0.150$ m^3/s. From Fig. 8, it can be seen that the regions of high velocity (>1 *m/s*) are relegated to the sides of the fish ladder in the wake of the principal and secondary jets. The remainder of the pool is characterized by velocity magnitudes <1 *m/s*. The areas of low velocity magnitudes will likely prove beneficial to fish as zones of hydraulic refuge, ideal for resting before attempting to overcome the next upstream passageway.

At the higher flow rate of 0.150 m^3/s the secondary passageway begins to develop enough flow to provide for fish passage. At the principal passageway, the Δh between the upstream and downstream water surface elevations is again approx. 0.2 *m*. At the secondary passageway the Δh is approx. 0.2 *m*, whereas the Δh between the downstream water surface elevation and the lowest elevation of the secondary baffle is approx. 0.1 *m*. These vertical drops are well below the maximum jump heights demonstrated for brook trout by Kondratieff and Myrick (2006). It is interesting to note that the downstream water surface level is higher than the lowest elevation of the primary passageway by 0.08 *m*. This can be seen in the profile section of the flow at the principal passageway in Fig. 9b and implies that weaker fish may swim directly between pools without the need to jump.

CONCLUSIONS

The Duguay-Hannaford baffle was shown to develop similar hydraulic characteristics to the baffle recommended by the Department of Fisheries and Oceans. The Duguay-Hannaford baffle developed lower values of VDP comparable to the DFO design and presents the advantage of confining the zones of high velocity magnitudes near the corrugations thus allowing a large and relatively tranquil recirculation zone to form in proximity to the passageways. The Δh values of the principal passageway were found to be below the reasonable limits for salmonid species during low flows. At high flows, the model results suggest that the principal passageway will be partially drowned so that fish will likely be able to swim directly between pools. The secondary passageway was also shown to develop adequate velocities and Δh values for use by fish during higher flow rates. Field verification and further testing of the Duguay-Hannaford fish ladder over a range of seasonal flow rates would provide insights into the general flow structure of the pools as well as an assessment/identification of velocity barriers. Studying the passage of live specimens indigenous to North America would be beneficial to evaluate the design's effectiveness for fish passage. The proposed polymer coated corrugated steel fish ladder equipped with the Duguay-Hannaford baffles provides a readily installed, lightweight and durable solution to fish habitat fragmentation issues at remote and limited access perched culverts and other suitable vertical barriers to fish passage.

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TABLE 1: VDP of the DFO and Duguay-Hannaford Baffle for at both slopes and discharges.

Baffle Type	Slope	Flow Rate (m^3/s)	VDP (W/m^3)
DFO	8.5%	0.062	125
Duguay-Hannaford	8.5%	0.062	60
Duguay-Hannaford	8.5%	0.150	117
Duguay-Hannaford	10%	0.062	70
Duguay-Hannaford	10%	0.150	140

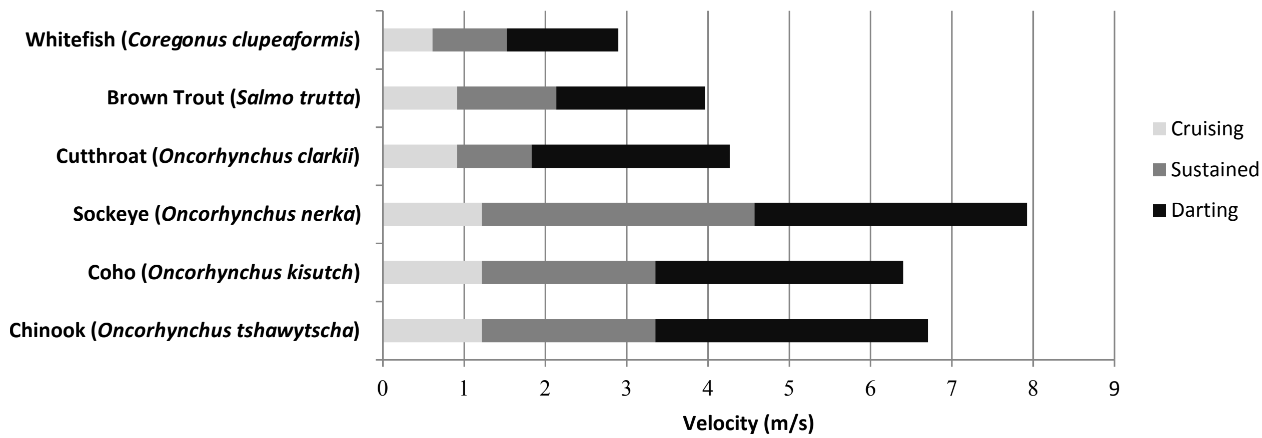

FIG. 1: Adult fish swimming speeds (data from Bell 1990).

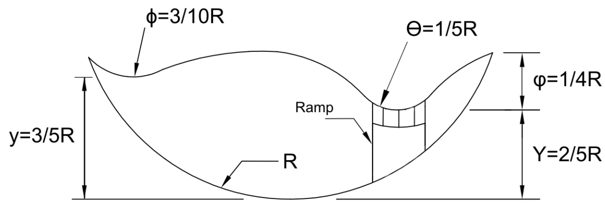

FIG. 2: Approximate dimensions of the Duguay-Hannaford baffle relative to the culvert radius, *R*.

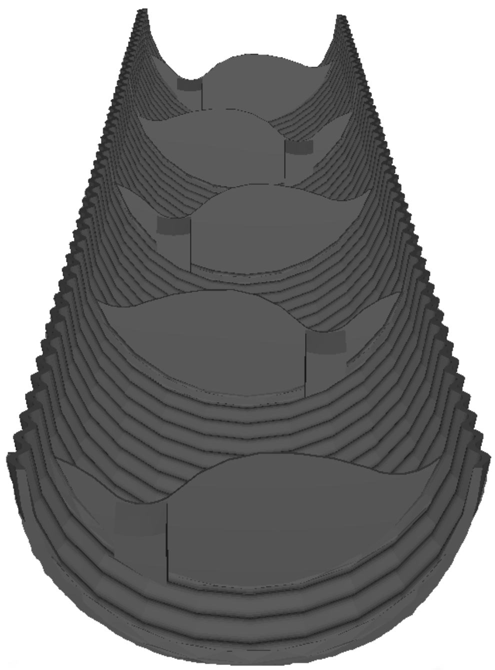

FIG. 3: CAD representation of the numerically simulated fish ladder.

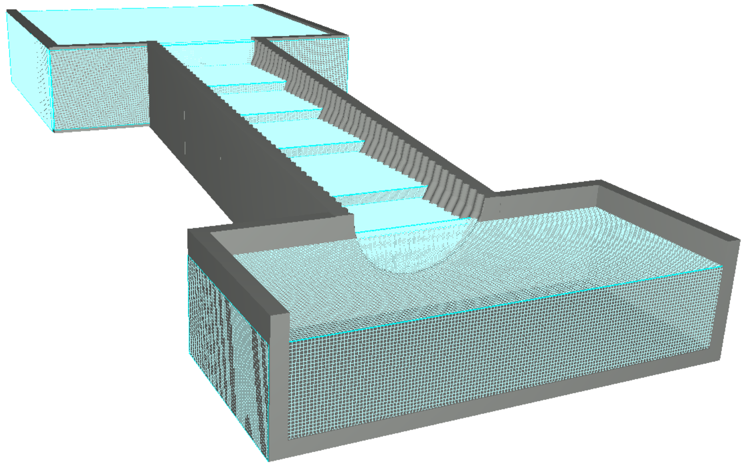

FIG. 4: Mesh details of the computational domain.

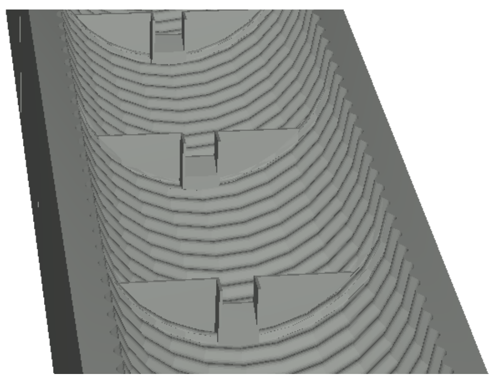

FIG. 5: CAD representation of the DFO baffle Design.

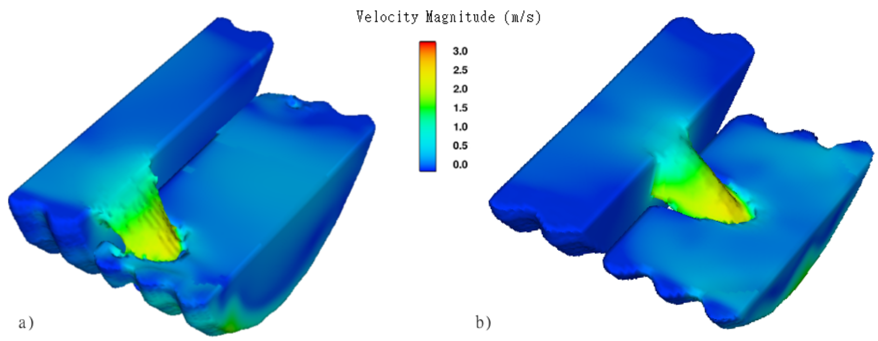

FIG. 6: Velocity distribution comparison at the passageways of the (a) Duguay-Hannaford baffle and the (b) DFO baffle at the low flow rate of 0.0615 m^3/s.

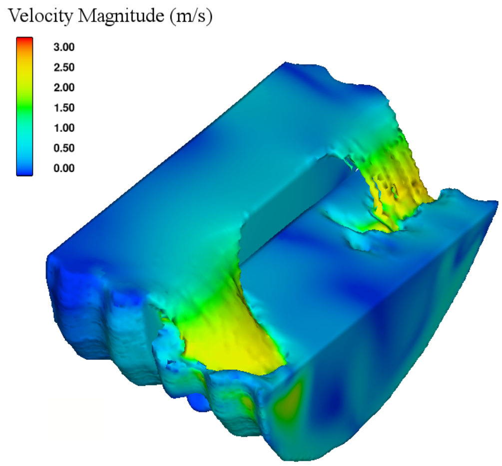

FIG. 7: Surface velocity distribution through the principal and secondary passageways at the high flow rate (Q = 0.150 m^3/s for the Duguay-Hannaford baffle).

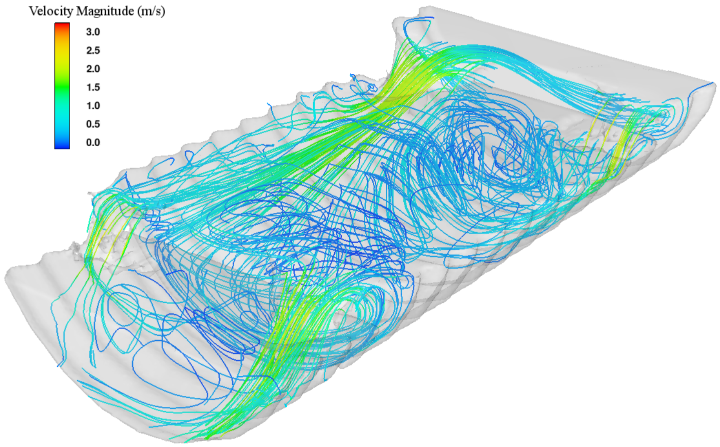

FIG. 8: Velocity distribution through the principal and secondary passageways along particle paths at the high flow rate (Q = 0.150 m^3/s).

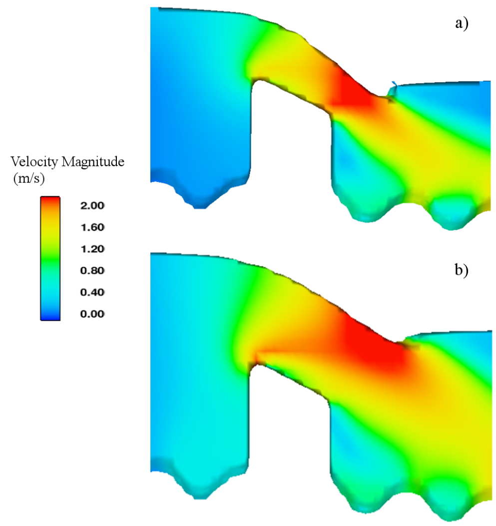

FIG. 9: Velocity at the center-line of the principal passageway of the Duguay-Hannaford baffle at (a) low flow and (b) and the high flow rate (Q = 0.150 m^3/s).