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Improvement of fish passage in culverts using CFD

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ABSTRACT

Upstream migration of fish through circular culverts is often prevented by velocities in the barrel being higher than that of the natural channel. In this investigation a computational fluid dynamic (CFD) model has been used to test the effects of various spoiler baffle geometries in culverts of varying size to reduce water velocity and increase water depth and thus increase the upstream passage of small fish species. Results indicated that standard baffles designed for specific fish species or groups could be successfully retrofitted to culverts of varying dimensions. Subsequent field tests have confirmed the effectiveness of the design.

1. Introduction

Un-impeded passage both in upstream and downstream direction is mandatory for diadromous fish species since they need to migrate between freshwater and the sea to reach rearing and/or spawning grounds (e.g. Haro et al., 2009). With catchment developments, the upstream migration is often blocked by anthropogenic obstructions notably weirs, dams and culverts. Although the passage of large migratory species with strong commercial value has received much attention in the past, accommodating movements of a wide range of species and sizes of fishes, as well as other aquatic fauna, is now recognised as being equally important (Mallen-Cooper and Stuart, 2007). The problem caused by migration barriers is common throughout the world with much research now focussing on prioritising the obstacles for remediation and designing ways of facilitating fish passage at barriers (e.g. Bell, 1986; Clay, 1995; Kroes et al., 2006; Barton et al., 2009; Kemp and O'Hanley, 2010). Unfortunately, when designing new culverts at stream crossings engineers still tend to focus on maximising the hydraulic efficiency of the structure and minimising cost and pay little attention to habitat and passage needs of fish and invertebrates (Baker and Votapka, 1990; Warren and Pardew, 1998; Blakely et al., 2006). Whether a culvert is a barrier or not is dependent on a number of factors including water velocities within the structure, and size specific swimming ability of the target fish (Starrs et al., 2011). Availability of low velocity refugia for resting is also an important factor to consider in fast flow environments (MacDonald and Davies, 2007). Therefore, the solution proposed to facilitate the upstream passage of fish at an in-stream barrier, has to be optimised for the local conditions and the fish species or group that is required to pass through the structure.

Fish tend to be able to travel long distance without rest when travelling at a low swimming speed (sustained speed) but generally, the higher the water velocity the smaller the maximum distance they can cover without resting notably when travelling at burst/darting speed (Boubée et al., 1999). Mitchell (1989) tested the swimming performance of a variety of small freshwater fish species that commonly occur in Australia and New Zealand, and found that their performance was similar with sustained swimming speeds in the order of 0.2–0.3 m/s. Burst/darting speed is essentially related to fish length and time and using the relationship described by Boubée et al. (1999) it is possible to calculate, for example, that a 70 mm long *Galaxias maculatus* (also known as the Common Jollytail in Australia, Inanga in New Zealand, Paye and Ao in Chile and Puyen in Argentina) can swim at 0.87 m/s for 5 s before needing to rest.

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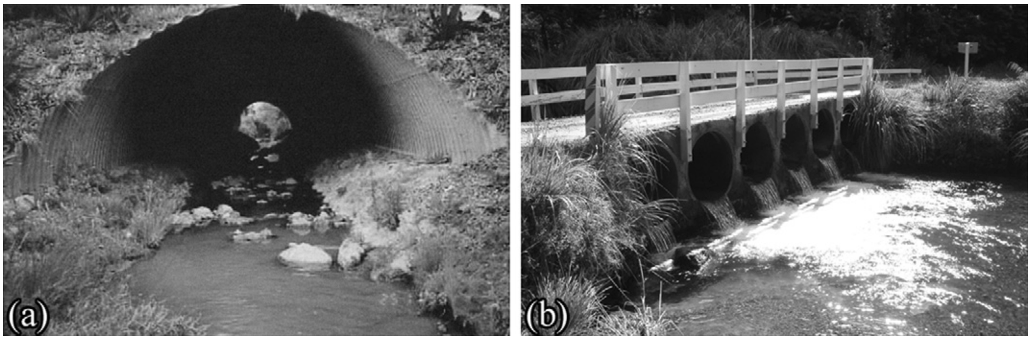

Fig. 1. (a) Ideal culvert design (from Boubée et al., 1999); (b) example of an impassable culvert caused by an overhung outlet.

In many situations it will not be possible to build an ideal culvert that has the same width and bed characteristics as the natural river where natural low velocity swimming zones and/or an abundance of resting areas are provided (Fig. 1a). Although installation of culverts which are obviously impassable such as those with an overhanging outlet (Fig. 1b) can usually be avoided, invariably, the culvert roughness will be smaller, the slope higher and the cross section narrower than that of the original channel. In such structure, if water velocities and travel distance are above the swimming ability of the target fish and if no resting places are available, the fish will not be able to surmount the obstacle.

In this study a computational fluid dynamic (CFD) model has been used to design circular culverts with barrel features that maximise the upstream passage of small fish species such as *G. maculatus*, a southern hemisphere diadromous species with swimming performances characteristics of many small migratory fish (Stevenson et al., 2008).

2. Preliminary laboratory and field tests

Several designs have been proposed to reduce water velocity and provide resting areas for fish within culverts (Fig. 2). To better understand the hydraulic characteristics of these designs and determine which has the best hydraulic effect on water velocity a review of the literature has been undertaken. This revealed that from a purely hydraulic perspective, the weir and slotted weir baffle systems appeared to provide the best means of reducing water velocities and increasing water depth within culverts (e.g. Ead et al., 2002). However, as few studies tested the success of the different arrangements for providing fish passage the authors carried out preliminary field and laboratory trials on the most promising designs.

The preliminary laboratory trials consisted of visual and video recording of 50–70 mm long *G. maculatus* released at the base of a 7 m long open steel pipe of 0.48 m diameter set at a slope of 3%. The pipe was fitted successively with one of the four baffle designs depicted in Fig. 2. The observations obtained indicated that fish passage issues could not be solved by simple examining the hydraulic characteristic of the structure and that the best way to reduce water velocity was not necessarily the best solution for fish. For example, video footage taken of fish attempting to negotiate the structure fitted with Alberta fish weirs clearly indicated that fish were confused by the arrangement and would not pass easily over the weirs (Fig. 3). In the majority of the trials it could be observed that fish became stuck between the first two weirs where they remained swimming back and forth between the weirs. Only occasionally and always after considerable time did fish pass upstream and then only to repeat the same searching behaviour at the next weir. Similar observations were made with the weir baffle and slotted weir baffle arrangements.

In contrast, laboratory trials with spoiler baffles indicated that fish had no problems finding their way through the culvert thus fitted. With this arrangement, fish were able to quickly progress upstream and negotiated the entire length of the culvert with little effort or stress (Fig. 4).

Field tests using spoiler baffles attached to the base of a medium (1.35 m diameter) sized culvert subsequently indicated that these baffles created sufficient low velocity zones and resting areas to facilitate the passage of 50–70 mm fish (Boubée and McGuckin, 2004). The results have since been confirmed by MacDonald and Davies (2007).

Besides the positive effect on upstream fish migration spoiler baffles are also easy to install either by using individual wooden blocks screwed in the concrete or as prefabricated plastic plates of several baffles (Fig. 5).

3. Numerical model – theory

After determining that spoiler baffles were the most promising way of providing an upstream migration friendly environment for fish, the effect of spoiler baffles on the flow field within culverts has been examined in more detail. In this analysis to test geometry variations of the design, the commercially available, three dimensional (3D) numerical software Flow-3D produced by Flow Science Inc. has been used. With this tool it is possible to compute the flow field in three dimensions and to determine water surface elevation very accurately. The program resolves the Reynolds-Averaged Navier–Stokes (RANS) equations (continuity Eq. (1), momentum Eq. (2)) using a finite difference (control volume) method.

$$\frac{\partial}{\partial x_i}(U_i A_i) = 0 \tag{1}$$

$$\frac{\partial U_i}{\partial t} + \frac{1}{V_F}\left(U_j A_j \frac{\partial U_i}{\partial x_j}\right) = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + G_i + f_i \quad \text{with} \quad i, j = 1, 2, 3 \tag{2}$$

where U_i is the velocity averaged over time t in the subscript direction, x is the spatial geometrical scale, A_i is the fractional area open to flow across each cell face, V_F is the fraction of fluid in each cell, ρ is the water density, P is the pressure, G_i is the gravitational force and f_i represents the Reynolds stresses added by Reynolds averaging.

For solving f_i the Renormalised Group (RNG) k–ε turbulence model (Yakhot and Orszag, 1986) was applied. For calculating the turbulent eddy viscosity following equation has been used.

$$\upsilon_T = C_\mu \frac{k^2}{\varepsilon} \tag{3}$$