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Design and assessment of weirs for fish passage under drowned conditions

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ABSTRACT

In aquatic systems, in-stream structures such as dams, weirs and road crossings can act as barriers to fish movement along waterways. There is a growing array of technological fish-pass solutions for the movement of fish across large structures such as weirs and dams. However, most existing weir structures lack dedicated fishways, and fish often have to rely on drowned conditions to move upstream.

In order to assess the adequacy of a given or proposed weir for upstream fish passage under drowned conditions, it is necessary to determine, firstly, the hydraulic properties of the drowned weir with respect to the requirements of the fish community and, secondly, the duration and timing of drowning flows with respect to the hydrograph for the site and the likely timing of fish movements. This paper primarily addresses the first issue.

A computer program has been developed and incorporated in a simple-to-operate spreadsheet for the determination of the hydraulic characteristics of a drowned weir which are important to fish movement. The program is based on a theoretical analysis of drowned weirs and subsequent extensive verification in laboratory experiments. Inputs to the program include site information comprising channel cross-section data, channel slope, and channel roughness, and weir information comprising weir height and the required minimum drowned depth over the weir for migrating fish passage. The program then calculates the flow rate at which the required level of drowning occurs, the velocity characteristics above the weir (including transverse distributions), and flow depths and velocities upstream and downstream of the weir.

The paper discusses (briefly) the theoretical background of the program and its experimental verification. A case study is then presented that illustrates the use of the program in the field to assess fish passage opportunities at an existing weir and to develop a case for retrofitting a fishway. Some discussion is also provided on the contribution of a modelled drownout volume to the assessment of how significant a barrier a weir is to fish passage. It is shown that the program is an important new additional tool in the assessment of the adequacy of weir structures in providing for fish movement and informing associated fish passage solutions.

1. Introduction

The objective of this paper is to describe the basis of a computer program which has been developed and incorporated in a simple-to-operate spreadsheet for the determination of the hydraulic characteristics of a drowned weir that are important to fish movement. The key output of the program is the flow rate under drowned conditions. The program has been verified through laboratory experiments.

In aquatic systems, in-stream structures such as dams, weirs and road crossings can act as barriers to fish movement, particularly upstream movements, along waterways (Baxter, 1977; Cadwallader, 1978; Kingsford, 2000; Frazier and Page, 2006; Koehn and Harrington, 2006; Sternberg et al., 2008; Lyon et al., 2010). There is a growing array of technological fish passage solutions for the movement of fish across structures such as weirs and dams (Clay, 1996; Larinier and Marmulla, 2004; Stuart et al., 2004; Barrett and Mallen-Cooper, 2007).

However, for the majority of existing weirs in Australia, fishways have not been installed and fish have to rely on drowned conditions to move upstream (Faragher and Harris, 1994;

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Baumgartner et al., 2008). A weir is considered drowned when the tail water level rises above the height of the barrier and the barrier becomes submerged.

There are limited data on upstream fish movement across barriers under drowned conditions (Harris et al., 1992; Mallen-Cooper and Thorncraft, 1992). However, based on what is known about fish passage through culverts and fishways, important parameters affecting the success of an individual fish moving across a weir are likely to include the depth and velocity above the weir under drowned conditions, the head difference across the weir, and the surface roughness and roughness around the edges of the weir (Katopodis, 1977; Rajaratnam et al., 1988; Bates and Powers, 1998; Morrison et al., 2009; Doehring et al., 2011).

New weir proposals, or fish passage rehabilitation programs often need to determine the impact of a new or existing weir on fish movement. This may then be used to evaluate whether a fishway should be installed on the weir, or whether fish passage at the site is likely to be sufficiently catered for by the weir drowning out (Bennett, 1997; O'Brien et al., 2006).

In order to assess the adequacy of a given or proposed weir for upstream fish passage under drowned conditions, it is necessary to determine, firstly, the frequency, duration and timing of drowning flows (and hence fish passage opportunities) and how they accord with fish movement requirements. These include the frequency in a fish's lifespan to allow completion of critical lifecycle migrations such as spawning runs; the duration in comparison to how long migratory populations take to move through a site; and timing in respect of water temperature, daylength or other seasonal fish migration cues (e.g. Roberts et al., 2008; Sternberg et al., 2008; Lyon et al., 2010). And in particular, how fish passage opportunities vary in comparison to no barrier at the site.

Secondly, the hydraulic properties of the drowned weir need to be identified with respect to the capabilities and requirements of the fish community at the site, such as the depth and velocity at the crest of the weir, combined with headloss across the crest, turbulence and roughness or lack of roughness at the abutments (e.g. Bice and Zampatti, 2005; Kilsby, 2008), which can all impact on the capacity of a structure to provide passage at drownout.

It is also important to acknowledge that some fish species and size classes may primarily move on low flows (Balcombe and Arthington, 2009; Lyon et al., 2010) and passage across a weir during drownout flows would be unlikely for these fish.

This paper includes a case study where the key output of the program, the flow rate at drownout (Q) was used to assess fish passage opportunities at an existing weir (without a fishway) and to lobby for a fishway to be retrofitted. The application of modelled results in the field, together with their limitations in light of the availability and scale of hydrological and biological data are discussed. Conclusions on the suitability of the program in the assessment of fish passage at weirs under drowned conditions and recommendations for further in situ validation complete the paper.

2. Methods

2.1. Theoretical analysis of drowned weir and computer solution

The theory was developed by Keller (1995) for flow over a weir in a rectangular channel as part of a study of the reinstatement of river meanders. The theory is similar to that used for drowned sluice gates and described by Henderson (1966). The extension of the theory to channels of a completely general cross-section involves no change in concept – only an increase in the degree of difficulty of the equations to be solved.

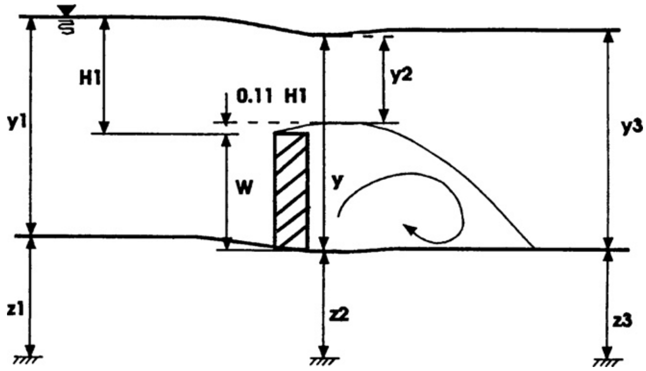

Fig. 1. Schematic of flow over a weir under drownout conditions.

Fig. 1 shows a schematic of flow over a weir under drownout conditions. Flow is from left to right. Typically, the flow separates from the top of the weir with a recirculating zone downstream. The required depth over the weir to allow fish passage is identified as y_2.

With reference to Fig. 1, the true depth over the weir is $y_2 + 0.11H_1$. However, the additional component is due to the separation of the flow from the upstream top corner of the weir. This component is part of the recirculating flow zone where significant levels of turbulence and energy loss can be expected. Accordingly, fish would normally be expected to remain within the depth y_2.

Again with reference to Fig. 1, in comparison with other linear depth measurements, differences in bed elevation upstream and downstream of the weir are negligibly small. Accordingly, the bed of the channel can be considered to be horizontal over the short length involved in the analysis.

In a given design or assessment situation, the following site and weir information would be available:

- Channel cross-section geometry, specified by transverse distance and bed elevation coordinates
- Channel slope
- Channel roughness parameter (Manning's n)
- Weir height, w, – specified by designer to provide required level of storage upstream
- Required drownout depth over weir, y_{weir}, – specified with regard to migrating fish depth requirements

Following the analysis, the following information would be required from the program to enable an assessment of the weir design:

- Flow rate at which required level of drownout occurs
- Velocity over the weir
- Flow depths upstream and downstream of the weir.

The equation set that must be solved is listed in the following, with brief explanations. A notation is provided at the end of this section.

The situation of a drowned weir is analogous to that of a drowned sluice gate. The analysis of the latter has been presented by Henderson (1966) and was based on the assumption that there was no energy loss across the gate (analogous to the flow volume between Sections 1 and 2 in Fig. 1). This assumption was validated by subsequent experimental data. The same approach is followed herein.