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Ecological engineering: from concepts to applications

The importance of design in river fishways

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Abstract

The main objective of this work is showing how numerical simulation and optimal control theory can be useful tools in practical ecological engineering. We take attention into diadromous fish (salmon, trout, eel…) and their river migrations, and particularly, we focus on fishways, hydraulic structures that enable fish to overcome stream obstructions as dams or weirs. We use mathematical modelling to formulate the problems of design and management of a fishway providing a good hydraulic performance for fish. By solving these problems for a standard vertical slot fishway, we can observe that controlling the flux of inflow water is a useful technique for the management of an already built fishway, but a correct shape design is mandatory in order to guarantee a correct hydraulic performance, especially for a new fishway.

1. The engineering problem: design and management of a fishway

Many types of fish undertake migrations on a regular basis, on time scales ranging from daily to annual, and with distances ranging from a few meters to thousands of kilometers. In this work we take attention on diadromous fish which migrate between salt and fresh water. The best known diadromous fish is salmon, which is capable of going hundreds of kilometers upriver.

When people makes a barrier in a river (for example, a dam or a weir) they must install a fishway to allow fish to overcome it. Fishways are hydraulic structures placed on or around man-made barriers to assist the natural migration of diadromous fish. An exhaustive overview on the design and management of river fishways can be found in the book of Clay [1]. In the literature three different types of fishways are studied: the pool and weir type (Rajaratnam et al. [2]), the Denil type (Rajaratnam and Katopodis [3]), and the vertical slot type (Rajaratnam et al. [4]). In this work we deal with vertical slot fishways, which are the more generally adopted for upstream passage of fish in stream obstructions. They consist of a rectangular channel with a sloping floor that is divided into a number of pools (see Fig. 1). Water runs downstream in this channel, through a series of vertical slots from one pool to the next one

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below. The water flow forms a jet at the slot, and the energy is dissipated by mixing in the pool. Fish ascends, using its burst speed, to get past the slot, then it rests in the pool till the next slot is tried (Blake [5]).
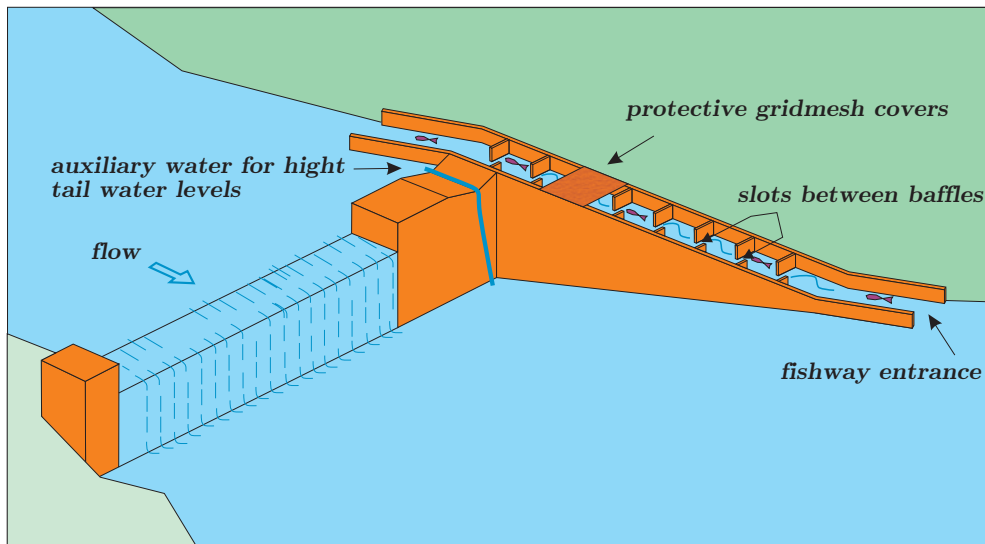

Fig. 1. Schematic drawing of a vertical slot fishway

To allow the fish to get over the dam through the fishway, water velocity in the channel must be controlled. Specifically, the following objectives are looked for:

1. In the zone of the channel near the slots, the velocity must be close to a desired horizontal velocity suitable for fish leaping and swimming capabilities.
2. In the other zones of the fishway, the velocity must be close to zero, to allow the fish to rest.
3. In the entire channel, flow turbulence must be minimized, to avoid fish disorientation and exhaustion.

If a new fishway is going to be built, water velocity can be controlled through the location and length of the baffles determining the slots. On the opposite, if the fishway is already built, it can only be controlled by determining the flux of inflow water. The main goal of this work is to show how mathematical tools can be very useful in this type of problems. Specifically, we use numerical simulation and optimal control theory to study the following problems:

- Problem 1: Optimal design of a new vertical slot fishway (by determining the location and length of the baffles in the channel).

- Problem 2: Optimal management of a fishway already built (by determining the flux of inflow water).

2. Numerical simulation and optimal control of water velocity in a fishway

We consider a standard vertical slot fishway consisting of a rectangular channel dividing into a reduced number of pools with baffles and sloping floor, and two transition pools, one at the beginning and another at the end of the channel, with no baffles and flat floor. A scheme of the fishway used in this paper can be seen in Fig. 2: water enters by the left side and runs downstream to the right side, and fish ascend in the opposite direction. The number of pools (ten) and the dimensions of the full channel correspond to an experimental scale fishway reported by Puertas et al. [6].

For a time interval (0,T), the average horizontal velocity of water $\mathbf{u}(x_1,x_2,t)$ can be obtained by solving the well known shallow water equations (see, for example, Alvarez-Vázquez et al. [7]). Then, for a typical horizontal velocity c (suitable for fish leaping and swimming capabilities), above objectives 1 and 2 for a fishway are equivalent to determine $\mathbf{u}(x_1,x_2,t)$ close to the following target velocity:

$$\mathbf{v}(x_1,x_2,t) = \begin{cases} (c,0) & \text{if } x_2 \le \dfrac{1}{3}0.97 \\ (0,0) & \text{otherwise} \end{cases} \tag{1}$$
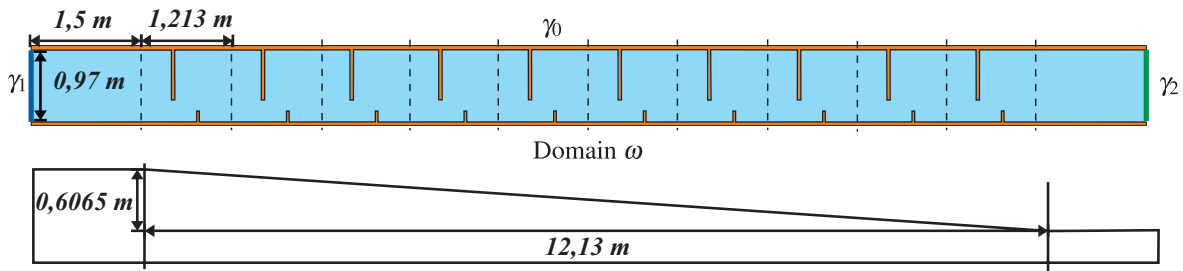

Fig. 2. Ground plan and elevation of the fishway under study

Then, for a fixed weight parameter $\varepsilon \ge 0$ emphasizing the role of turbulence (objective 3), controlling the water velocity in the fishway is equivalent to minimizing the following objective function:

$$J = \frac{1}{2}\int_0^T \int_\omega \| \mathbf{u} - \mathbf{v} \|^2 + \frac{\varepsilon}{2}\int_0^T \int_\omega | curl(\mathbf{u}) |^2 \tag{2}$$

Problem 1.- Optimal design of a new fishway: If we assume that the structure of the ten pools with sloping floor has to be the same, the shape of the complete fishway is given by the shape of the first pool. Then, the control variable is given (see Alvarez-Vázquez et al. [7]) by the two midpoints corresponding to the end of the baffles in the first pool (points $a = (s_1, s_2)$ and $b = (s_3, s_4)$). With this notation, Problem 1 is described by

$$(P_1) \quad \begin{cases} \min J(s) \equiv J \\ s = (s_1, s_2, s_3, s_4) \in S_{ad} \end{cases}$$

where $S_{ad} \subset \Re^4$ collects the design constraints on points a and b.

Problem 2.- Optimal management of a fishway already built: If the fishway is already built, the domain $\omega \subset \Re^2$ is known and fixed, and the control variable is the flux of inflow water (function $q(t)$ in the boundary conditions of shallow water equations, as detailed in Alvarez-Vázquez et al. [8]). So, Problem 2 can be formulated as

$$(P_2) \quad \begin{cases} \min J(q) \equiv J \\ q(t) \in Q_{ad} \end{cases}$$

where $Q_{ad} \subset L^2(0,T)$ collects the technological constraints on the inflow water.

3. Numerical results

Problem 1.- Optimal design of a new fishway: For the sake of simplicity, we have taken a fixed and constant flux of inflow water $q = -0.065/97 \, m^2 s^{-1}$ and, for the standard fishway under study, we look for a shape (that is, points a and b) which minimizes the objective function $J(s)$ giving by (2).

Fig. 3 shows the water velocity at final time of the simulation (representing the stationary situation) in the central pool of the fishway, corresponding to the initial random shape (left) and to the optimal shape (right). We can observe that, in the case of the initial shape, we can identify the standard flow patterns presented in Rajaratnam et al. [4]: a direct flow region where the flow circulates in a curved trajectory at high velocity from one slot to the next downstream, and two recirculation regions - the larger one located between the long baffles and the smaller one located between the short baffles - flowing in opposite directions. In the case of the optimal shape, the horizontal

velocity is close to the target velocity **v** (given by (1) with $c = 0.8ms^{-1}$), and the two large recirculation regions at both sides of the slot are highly reduced.
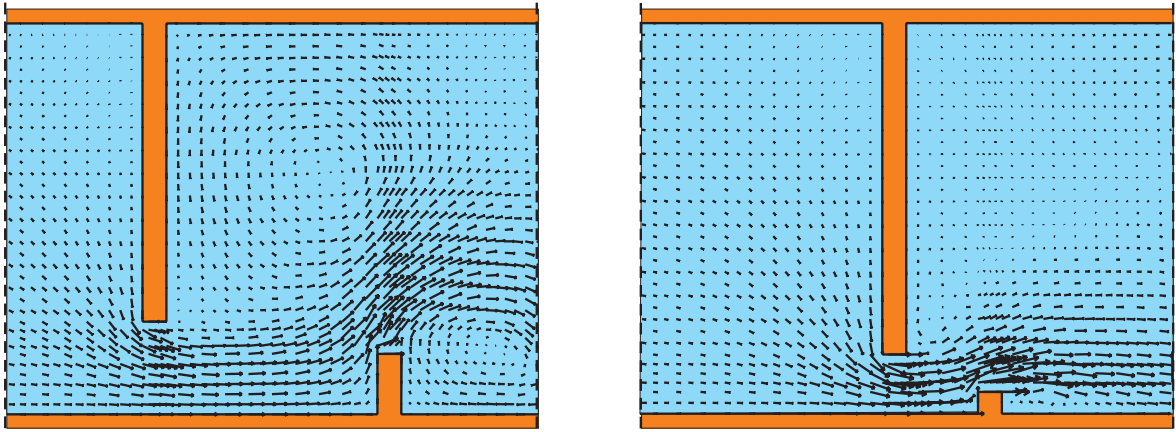

Fig. 3. Problem 1: Velocity fields in the central pool of the fishway at time *t=300s* for the initial shape (left) and the optimal shape (right)

Problem 2.- Optimal management of a fishway already built: We have considered a given standard fishway and we look for the flux of inflow water *q(t)* which minimizes the objective function *J(q)* given by (2). Fig. 4 shows water horizontal velocities at time *t=150s* in the central pools of the fishway, corresponding to the initial random flux (up), and to the optimal flux (down). A clearly best velocity field (more similar to the desired target velocity **v**) is obtained for the controlled case (down). However the small eddy region between the short baffles cannot be completely avoided (in contrast to the results obtained for the optimal shape solution in Problem 1).
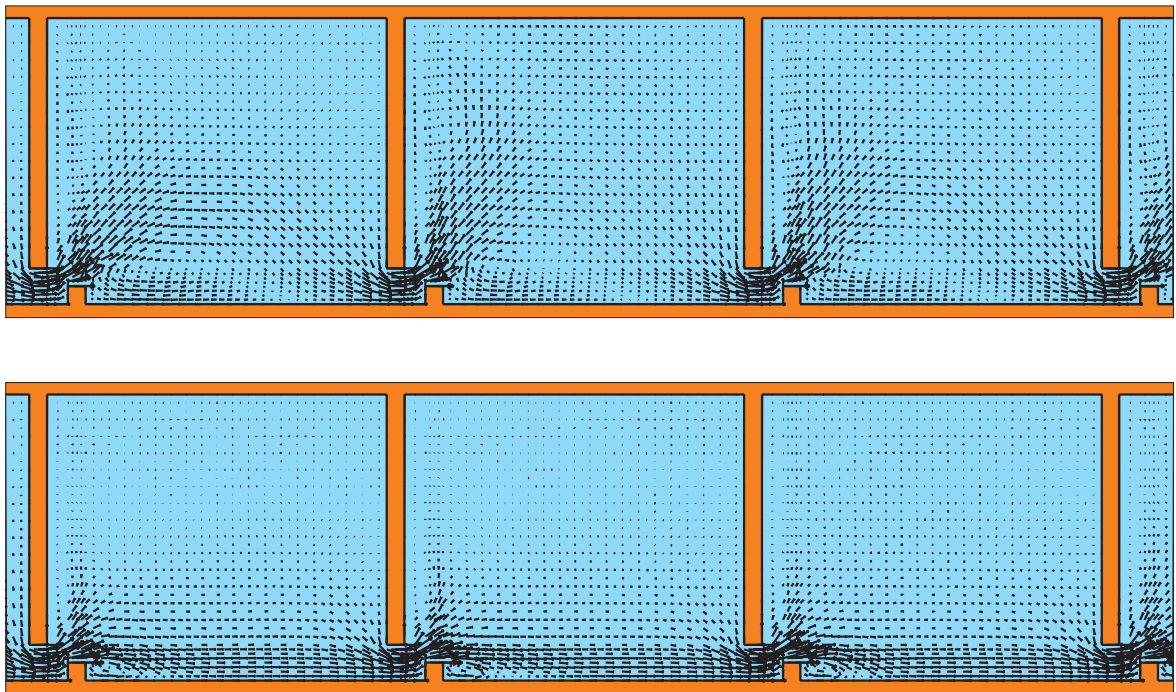

Fig. 4. Problem 2: Initial (up) and optimal (down) velocity fields in the central pools of the fishway at time *t=150s*

4. Conclusions

Mathematical modelling has been used to simulate the height and velocity of the water in a standard vertical slot fishway. Moreover, optimization and optimal control techniques have been employed to control the water velocity in two different problems. From the numerical experiences we observe that:

A. Controlling the water velocity in fishways is mandatory, if we want that these hydraulic structures fulfill their task.
B. Optimal control techniques, joined to numerical simulation, have shown to be very useful tools for this type of hydraulic engineering problems.
C. Controlling the flux of inflow water in a vertical slot fishway can be useful for the management of an already built fishway, but a good shape design is fundamental in order to guarantee a correct hydraulic performance.

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