SOLUTIONS FOR ENSURING FISH MIGRATION IN HYDROPOWER SITES

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Aquatic ecosystems often suffer changes in hydrologic connectivity due to human impacts. In many European countries, hydropower production is one of the main factors affecting the quality of river ecosystems, and altering connectivity in rivers. Many fish species depend on an intact longitudinal connectivity to be able to migrate. This paper presents some aspects regarding the importance of river connectivity in order to be able to maintain or even to increase their biodiversity. Also, this paper aim to provide practical solution solutions of fish ladder design for the most common migrating species in Romania.

Keywords: longitudinal connectivity, fish passes, Romanian rivers

1. Introduction

Hydropower was identified in the Water Framework Directive -WFD report as one of the main drivers of hydro-morphological alterations, loss of connectivity and significant adverse effects on the survival of fish populations. Nowadays, the connectivity is recognized as a fundamental property of ecosystems. In rivers, hydrologic connectivity can be viewed as operating in longitudinal, lateral, and vertical dimensions and over time [1] and refers to the water-mediated fluxes of material, energy, and organisms within and among components of the ecosystem [2]. Longitudinal connectivity refers to the pathway along the entire length of a stream and comprises three elements: water; fish and benthos and solid components as sediment and bedload. Rivers ecosystems, once seen as discrete entities, are now considered as a continuum environment, with gradual changes towards downstream. All ecosystems within a river are linked to those above and below, by the spiraling of nutrients as they move with the current and cycle through the ecosystem or through the movement of energy and nutrients as fish and other taxa migrate upstream.

Illies (1961) introduced a generally accepted international nomenclature for running waters to replace the zonation based on indicator fish species [3]. He

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first divided running waters into two major categories, brooks (rhithron) and rivers (potamon), which are each further subdivided into three. For the waters of Central Europe, ILLIES' nomenclature is synonymous with the classification by indicator fish zones.

The movements of aquatic organisms can be limited by dams which fragment and regulate rivers, and subsequently contribute to the population decline of special status fish species. Passage obstructions have been the reason for the extinction of entire stocks or for the confinement of certain species to a very restricted part of the river basin. Sturgeon stocks have been particularly threatened by hydroelectric dams [4]. Presently, the International Red List mention 801 endangered fish species, which represent almost 3% from the known species. Over 100 species of freshwater migratory, which are known as potamodromous species and usually are moving to spawning and feeding toward upstream, were identified. The percentage of endangered potamodromous species is 15%. These numbers reflect the destruction of breeding habitat and also of the ways to access them, due to hydraulic engineering works on rivers. In Romania there are 23 species of migratory fish in rivers, classified into five orders.

Considering all these aspects, and also the fact that in Romania all of the large dams were constructed without upstream or downstream fish passage, is clearly necessary the tackling of restoring longitudinal connectivity of rivers in Romania.

2. The fish passages

Many types of technologies are available for passing fish upstream or downstream dams. Some of these provide volitional passage which is fish passage made continuously without trap and transport [5]. These types of passage facilities, such as fishways for upstream migrants and fish bypasses for downstream migrants, let the fish choose when to move past a dam by providing a constant hydraulic connection from the reservoir upstream of the dam to the river downstream of the dam. Non-volitional technologies rely on humans or machines to provide assistance in the passing of fish. These technologies does not have a constant hydraulic connection, and may take hours for one load of fish to be moved. There are several types of fish passage facilities: fishways (ladders and nature-like channels), fish lifts and locks, and collection and transport facilities.

2.1 Upstream migration

Dams and weirs may interrupt or even block the upstream migration of fish and aquatic invertebrate species. Upstream fish passage facilities considerably narrow the migration corridor through which organisms move up the river. However, since they constitute the sole, or one of few possibilities of aiding fish

swim past migration barriers, their arrangement in the river must assure the following requirements: 1) the river reaches downstream and upstream of the barrier must be apt for migration of the potentially natural species composition; 2) the entrance must be easy to find by fish.

The following issues must be considered:

- fish individuals must be able to migrate according to their natural behavior;
- invertebrates require a continuous bottom, structured and rugged;
- the maximal water velocity at each particular slope and the energy required to pass the obstacle must be kept within certain limits;
- even low drop differences (approx. 0.1-0.2 m) and smooth bottom areas may act as obstacles.

The dimensions of the facility are to be determined in accordance with the fish species expected to occur in the particular river reaches. As a rule, fish passage facilities must be arranged to guarantee a flawless functioning on at least 300 days per year, i.e. the hydraulic and geometrical dimensions must remain within a frame of $Q_{10\%}$ and $Q_{90\%}$. Table 1 shows, depending on the river zoning, hydraulic dimensions for: maximal velocity, maximal drop difference and maximal power input.

Table.1. Hydraulic dimension of pool type fish passes and migration corridors of fishramps and bypass channels

River zone	Drop difference, pool to pool (m)	Medium velocity within pool (m/s)	Medium velocity in migration corridor (m/s)	Velocity of attraction flow (m/s)	
Epi-rhithron	≤ 0.20	0.5	≤ 1.0	0.3	2.0
Meta-rhithron	≤ 0.18	0.5	≤ 1.0	0.3	1.9
Hypo-rhithron	≤ 0.15	0.5	≤ 0.9	0.3	1.7
Epi-potamon	≤ 0.13	0.5	≤ 0.8	0.3	1.6
Meta-potamon	≤ 0.10	0.5	≤ 0.7	0.3	1.4
Hypo-potamon	≤ 0.09	0.5	≤ 0.6	0.3	1.3

The geometrical dimensions in Table 2 are set in relation to the fish species: minimal length, width, minimal water depth and slot depth.

Table.2. Geometrical dimension for pool type fish passes and migration corridors of fishramps and bypass channels [6] (VSP - Vertical slot pass & NLF - Nature like fishpass)

Fish species	Pool dimensions (m)				Min. slot width (m)		Typical min. discharge (m)	
	Min water depth	Slot depth	Min length	Min width	VSP	NLF	VSP	NLF
Trout	0.4	0.2	1.5– 1.9	1.0–1.2	0.15	0.2–0.4	0.1	0.2
Grayling, chub, roach, dace	0.45	0.2	2.0	1.4	0.17–0.3	0.4– 0.6	0.15–0.25	0.35

Barbel, bream, zander, pike, salmon, sea trout, huchon	0.5	0.3	2.8 –4.0	1.8– 3.0	0.3– 0.6	0.6	0.4 – 1.0	0.5–0.55
Sturgeon	0.8 – 1.0		5.0	3.0	0.8	0.8	0.7 – 1.5	1.2– 2.0

The rhithron has turbulent flow, fairly low temperatures and usually, the water is very well oxygenated. However, during low water periods, the pool - riffle system may split up into a series of pools with anoxic waters. The resident fish species in rhithron zones fall into two main groups. Firstly, there are those species which live on or among the rocks and vegetation of the bottom and are distributed mainly in the riffles (*Chiloglanis*, *Mastacembelus* or *Clariallabes*). Secondly, there are species adapted to swim sufficiently fast as to resist the current and even move against it such as *Barbus* or *Salmo*. Since they cannot do this on a continuous basis, often benefit of cover provided by elements which perturb the current, like: snags, overhangs and so on.

The potamon is globally more complex, containing a precise series of river channels, edged by a floodplain, and both lotic and lentic waters can exists. At low water, areas of slack current form bars downstream of the point, but during high water these features are submerged. Floating and emergent vegetation usually lines the river banks and floating leaved and emergent vegetation may appear in the slacks below the point bars [7]. Also, many water bodies are present in the plain itself, some of them retaining water during the period between floods.

The concentration of the dissolved oxigen decreases in the dry season, in the water bodies of the floodplain. This phenomenon is particularly encountered in the smaller pools which can become completely exhausted of oxygen, toghether with the shrinkage in the volume of the water because of evaporation. Simoultaneously, the temperature and conductivity rise due to the evaporation. The river channels remain relatively cool and well oxygenated, providing flow persists, but if this stops, the channel breaks down into a chain of pools which behave similar to the floodplain water bodies. Furthermore, migrations may be disturbed if the existing corridors cannot be found or if the process of finding requires too much time and energy. Individuals trying to find the migration corridors may be additionally disturbed by different river branches at a specific point of the river. River reaches which, in relation to areas not artificially modified and considering the physiological requirements of the fish fauna, reveal a too low water depth and velocity, may be partially or totally not apt for migration. This applies typically to the original river bed of hydroelectric power stations, if they have a low discharge for a long period of time.

2.2 Downstream migration

The downstream migration of aquatic organisms is not fully interrupted by dams and hydroelectric power stations. In principle, migration is possible even without the construction of special fish passes. Typically downstream migrants can pass a dam by three methods: turbines, spillways, or bypass systems [8]. Juvenile migrants can also pass dams by using the fishways or navigation locks, but the percentage of fish using these methods is very small.

Downstream fish passage facilities are not so advanced like upstream fish passages, and still demand comprehensive research. The downstream migration issues started to be investigated recently, due to the fact that first efforts were focused on upstream fish passages to reestablish the connectivity and to allow free movement of migrating fish. Also, the development of effective downstream migration passages is far more complex.

If the river's discharge flows to a great extent through a hydroelectric power station, downstream migrating fishes swim on this main current and eventually reach its screen. Safe fish downstream migration is only practicable if individuals neither get injured at the screen nor pass through it, but reach tailwater with the help of a suitable bypass.

Two alternatives have been considered during the study of downstream migration at hydroelectric power stations. Alternative 1 aims at enhancing the level of fish protection by installing a screen with small spacing at the entrance to the power station and then a suitable bypass; Alternative 2 consist in a minimal protection, e.g. diversion walls.

Experience has shown that turbine and spillway passage can cause damage to downstream migrants and are major factors affecting these fish [5].

Since early fish passage efforts focused on upstream passage, downstream fish passage technologies are much less advanced. In addition, the development of effective facilities for downstream fish passage is more difficult and complex. Downstream migration issues have only recently come to the forefront [5].

The dams and reservoirs represent danger sources for juvenile fish migrating downstream. In the reservoirs where the water is deep and slow moving, these fish move slower than they do in a typical riverine environment, causing migration delays. In addition, juvenile fish can be exposed to reservoir dwelling fish predators for a significant period of time. At the dam, turbines and spillways can cause injury or death to fish. After juveniles pass the dam, turbulence below the dam increases exposure of juvenile salmon to predatory birds [8].

When considering downstream fish passage at hydropower facilities, one must have three distinct goals: 1) to prevent fish from entering into turbine intakes; 2) to allow fish to move safely downstream past the facility; and 3) to

move fish, in a timely and safe manner, through the reservoir. The first two are applicable to all hydropower facilities, but the third generally applies only to large reservoirs. Compared to upstream passage, there are generally more options available for downstream passage, but no downstream passage method is appropriate for all situations [9].

2.3 Arrangement of fish passage facilities

Fish ladders, also known as pool-type fishways, contain a succession of pools placed at consecutively higher elevations and water flows from one to another over weirs, through orifices, or through slots. Fish must be able to easily overcome the water surface differential between pools by swimming or leaping. The water volume in the pool dissipates the water's energy before reaching the drop to the next downstream pool [9]. The entrance design and attraction flow are significant elements of pool-type fishways. Attraction flow mimics the turbulence and water movement of the river and encourages adults to enter and ascend the ladder [7]. Improper flows delay migration as the fish cannot find the ladder entrance. Flows in these types of fishways can vary from around 0.028 m^3/s to 50 m^3/s and the slope from less than 5% to more than 20%, most frequently ranging from 10% to 12% [5]. The main pool-type fishways are: the pool and weir, pool and chute, and vertical slot.

Pool and weir fishways have been used most often for lower dams. The fishway is an open channel, usually constructed with concrete, with pools that are separated by weirs. A pool pass consists in the division of the channel starting from the headwater to the tailwater with cross-walls, so a succession of stepped pools are obtained.

The weirs are typically horizontal, but can be sloped or notched. The discharge is usually passed through openings in the cross-walls and the potential energy of the water is dissipated, step-by-step, in the pools. Fish migrate from one pool to the next through openings in the cross-walls, struggling in this zone with high flow velocities. The pools can be considered as shelters, assuring the possibility to rest due to their low flow velocities. To make the pool crossable for benthic fauna, a rough bottom is required.

A plunging circulation pattern represent the normal flow regime in the fishway. Water passing over the upstream weir plunges toward the fishway floor, moves downstream along the floor, then rises along the upstream face of the downstream weir and either drops over the weir or moves back upstream along the surface of the pool. As the flow in the fishway increases, the depth of water over the weirs increases and the flow changes to a streaming flow regime. In this case, a continuous surface jet passes over the series of weir crests and skims along

the surface of the pools, creating a circulation pattern opposite to that of the plunging regime [9].

The *pool and chute fishway* is similar to the pool and weir fishway in that water flows over a weir from pool to pool. The difference is that a pool and chute fishway has a center notch and sloping weirs that extend to the fishway walls. At low flows, the fishway behaves like a pool and weir fishway, with water only passing through the center notch and spilling over the horizontal weir. At moderate to high flows, parts of the fishway operate in both plunging and streaming flow regimes simultaneously [9]. Water spreads across the fishway and up the sloping weirs, creating plunging flow at the flow margins. Under this condition, high velocity streaming flow exists in the center of the fishway. The fishway should be designed so that the high fish passage design flow doesn't quite cover the entire width of the sloping weirs (at least 0.5 m from the wall is recommended). Orifices can be included at the floor to help stabilize the flow and provide a submerged swimming option for fish.

The pool and chute fishway has many benefits. For smaller applications, all of the flow can be contained in the fishway and creates a strong jet, making it very attractive to migrants. Also, great fishway flows wash sediment and debris, reducing maintenance. In addition, several passage routes are available to fish moving upstream and the size of the pools can be smaller than a pool and weir fishway for the same range of flows [9].

The pool and chute fishway also has some disadvantages. The fishway must be aligned in a straight line without bends, since it has high velocities. Also, the high velocities can cause erosion downstream of the fishway if the channel is narrow or if the fishway is aligned towards a bank.

In case of *vertical slot fishways,* hydraulic control and fish passage are provided by full-depth slots between the pools. A benefit of the vertical slot design is that it is self-regulating and operates throughout the entire range of design flows without adjustment. That means that the water surface elevation difference between the tailrace and forebay will be divided equally between all of the fishway slots. The fishway automatically compensates for any change in forebay or tailrace water surface elevation. The vertical slot fishway's full depth slots also allow fish passage at any depth [9].

Energy is dissipated by the water jet through the slot mixing with the water in each pool [11]. Pool depths increase as flows increase, creating additional pool volume and thereby maintaining the needed energy dissipation [9]. Since fish must swim the entire length of the fishway, the vertical slot fishway is not the best choice for species that need overflow weirs for passage. For instance, juvenile salmonids will have more passage success leaping over a weir than trying to burst through a slot with a high velocity flow. The vertical slot fishway gives them no opportunity to leap [10].

It is critical to the stability of flow in the vertical slot fishway that the design uses the dimensions described by Bell [11], unless it is known, from studies or experience, which other configurations will work. Changes from the standard dimensions can cause unstable flow conditions and water surging in the fishway. Shallow depths can cause hydraulic problems in the fishway, as the water jet through the slot shoots across the pool and to the next slot. Sills at the bottom of the slot should be added if the pool upstream of the slot is to be operated at depths less than 1.5 m [9].

Rock ramps are continuous roughened channels constructed at a constant slope with no large structural bedforms (e.g., steps, pools). Rock ramps are often limited to slopes less than 4% and are best for overcoming elevation differences of 1.5 m or less. Higher and longer rock ramps may be less stable due to the potential for increasing water velocities in the downstream direction. Additionally, the risk of creating an exhaustion barrier to fish increases as the ramp length increases. To overcome larger elevation differences, rock ramps can be interspersed with large pools to form a sequence of chutes and pools or small pools can be scattered within rock ramps.

Rock ramps and chutes rely on the swimming abilities of the fish, making them better suited for passage of fish species and life stages that have poor or no leaping abilities. However, to achieve adequate water depth for fish passage, a sufficient amount of flow is required, which limits their application. In streams with very low base-flows, rock ramps and chutes may not be able to provide adequate water depth for fish passage during low flows. This concern is increased with increasing slope, channel width, and the likelihood of significant subsurface flow.

4. Fish ladders sizing

The most common migrating fish species in Romania are trout, grayling, chub and roach, while most of the water works affecting the longitudinal continuity have heights below 15m. In the following we intend to determine the hydraulic characteristics for a fish ladder appropriate to this situation. Thus, we consider a dam, placed on a river with a 40‰ slope, and a difference between the upstream and downstream of 15m in height. .

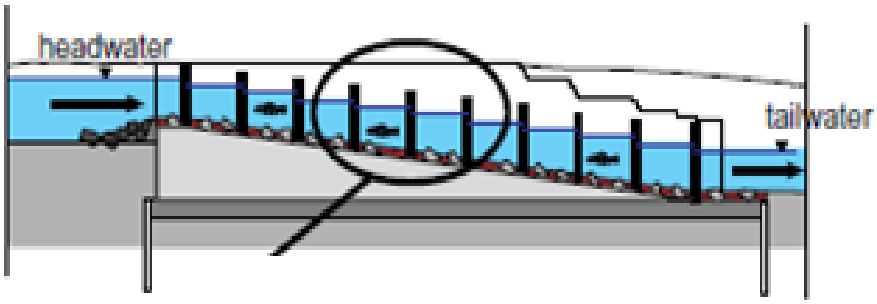

Fig. 1. Projected weir fishways [6]

In order to allow the ichthyofauna transit, a by-pass channel type fish ladder (fig.1.) is studied, under the restrictions imposed for the considered fish species (table 2&3). The ladder has a prismatic shape, made of concrete, with a rectangular section of 1.4m width and 0.014 roughness. Total head is fractioned by weirs of 0.75m heights.

For the chosen channel two possibilities of weirs placement are studied:

a) the first one consider the weirs placed far enough to assure a torrential flow and no hydraulic jump;
b) the second one consider the weirs close, the hydraulic jump reach up to the upstream weir and the torrential flow disappear.

Knowing that the fish species considered cannot pass over an obstacle higher than 0.2m and a flow speed greater than 1m/s does not allow the advancement, the number of weirs needed is determined.

For the first case the solution is not realistic for flow rates greater than 0.026 m^3/s, due to high flow speed in the channel. A lower value of the flow is not permitted since it is smaller than the sanitary discharge.

For the second case we notice that for flow rates between 0.01 and 0.3 the solution is viable, respecting the dimensional input for speed and for total head or spillways distance as well.

The relationship between flow rates and total head is presented in figure 2, in figure 3 the dependence between flow rates and spillways distance and figure 4 presents the dependence between flow rates and the total length of the design channel.

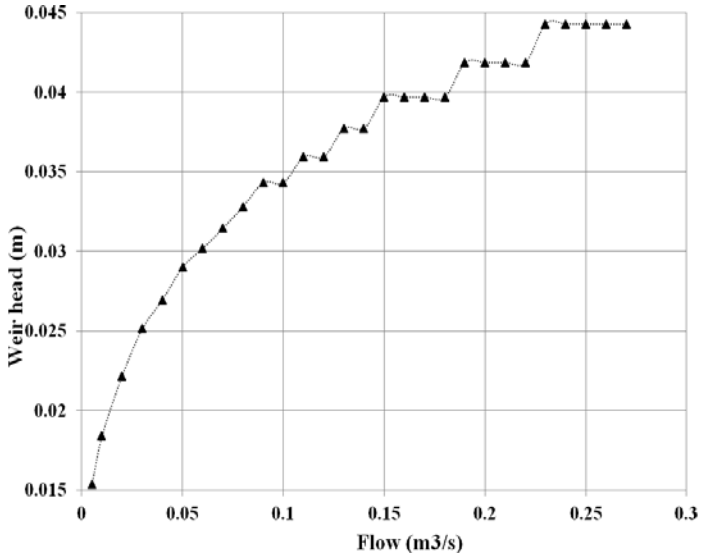

Fig.2. Dependence between flow and weirs head

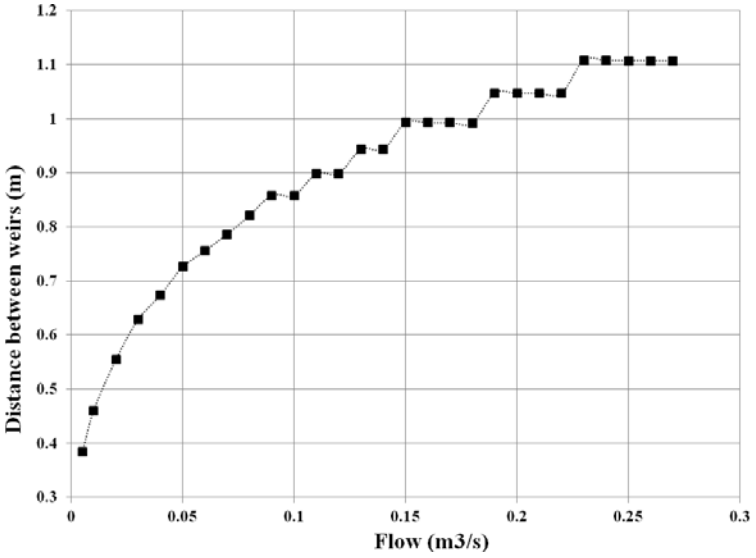

Fig.3. Variation of flow with the distance between weirs

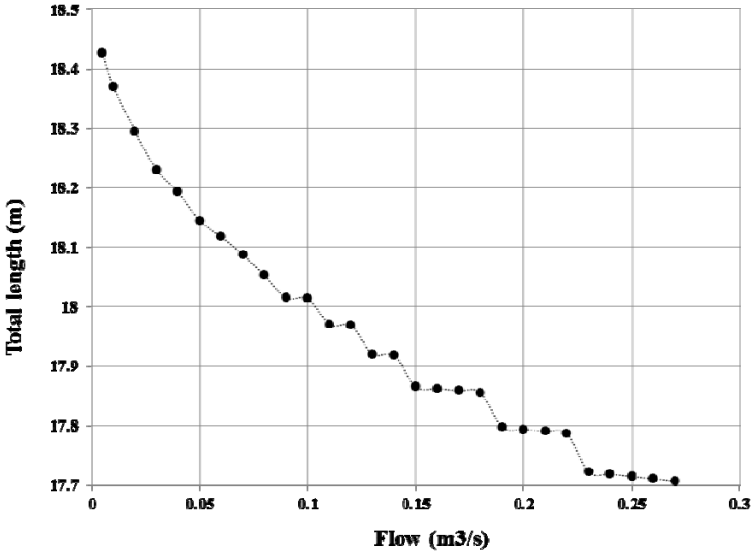

Fig.4. Dependence between flow and total length construction

5. Conclusion

Fish passes are of increasing importance for the restoration of free passage for fish and other aquatic species in rivers as such devices are often the only way to make possible for aquatic fauna to pass obstacles that block their up-river journey. Concluding, they are vital features in improvement of aquatic ecosystems in surface waters and their function must be faultless in order to restore the free passage in rivers.

However, studies of existing devices have shown that many of them does not work correctly. Therefore, nowadays great interest is directed towards the establishment of universal design criteria, corresponding to the present state-of-the-art.

Analyzing the solution presented in this paper, we can state that for the most common fish species in Romania (trout, grayling, chub, roach and dace) the best solution is represented by a fish ladder with the distance between spillways greater than 1 m. The flow rates range between 0.18 and 0.25 m^3/s, and the total length is approximately 17.8 m.

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