Technical Note 7

FISH PASSES: fish ladders and other pass systems

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Wetlands INTERNATIONAL

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FISH PASSES: fish ladders and other pass systems

1. Introduction

Aquatic environments are habitats where we can find a great number of flora and fauna species. The composition, structure and function of these ecosystems is easily affected by human activity, both in the water and in the surrounding area. Notably from the middle of the 20th century, Man has altered the hydrological and hydraulic system of rivers, with dams, hydropower plants, dredging, rectifications, channelling, tubing, breakwaters, etc., changing the characteristics of the water: current speed, depth, the morphology of the river and its banks, the granulometry of the riverbed and the physical-chemical parameters of the water. These actions have led to substantial alterations in the natural flora and fauna associated with waterways, with a particular impact on fish, as they are more vulnerable than vegetation when the hydraulic environmental conditions vary.

One of the most damaging effects related to the previous activities, results from constructing crossing works over rivers (dams, waterwheels, bridge foundations, prefabricated water crossings, drainage pipes, culverts, gauging stations; see figure 1), which frequently impede or limit the free movement of fish fauna.

The most well-known fish migration is in search of suitable spawning areas: this is true of the trout, the barbel and the Iberian nase, which always move within the same waterway (potamodromous migrators – figure 2), or the salmon, the shad or the sturgeon, which develop in the sea and spawn in rivers (anadromous migrators). The opposite occurs with the eel (catadromous migrator), which reaches adulthood in rivers the returns to the sea to reproduce. However, practically all fish undertake some length of journey in order to find food at times of shortage, to find shelter in the summer, or to find new territories in the event of dense populations.

The current ichthyo-diversity in the Iberian Peninsula is not very high (71 native species and 28 introduced) when compared to other central and northern European countries (Kottelat & Freyhof, 2007). However, the number of genus and endemic species is very high – 41 species – due to the hydrological characteristics of our rivers (with intense seasonal fluctuations) and geographical isolation caused by the Pyrenees (Doadrio, 1988; Elvira 1990). 65% of the native species undertake long migratory journeys (hundreds of km: eel, salmon, sea trout, sturgeon, shad, American shad, lamprey, etc.) or shorter journeys (few km: barbel, nase, chub, gobies, etc.). This percentage increases up to 80% in the case of endemic species (Sanz Ronda et al., 2007). As a result of the drastic increase in crossing works over waterways, the anadromous and catadromous migratory species have seen, the best-case scenario, that their distribution zones are reduced (eel – Anguilla anguilla -, shad – Alosa alosa -, Twait shad – Alosa fallax-). Other species are under serious threat due to the obstacles (salmon – Salmo salar-) and, sadly, two species have already disappeared (the sturgeon – Acipenser sturio – and the River Lamprey – Lampetra fluviatilis-) (Elvira et al., 1998; Martínez de Azagra, 1999; Algarín, 2002). It is worth remembering that all of these species swam the Iberian Peninsula waters only a century ago. With regards to potamodromous species, very few have been studied except for the trout: the reduction in their numbers and

Figure 1. Main obstacles that limit the movement of the fish: dams, irrigation dams, bridge foundations,

Figure 2. Some migratory species in the Duero basin: barbel (Luciobarbus bocagei) and nase (Pseudochondrostoma duriense).

disappearance or population reduction in specific parts of the river, are pressing.

When an impassable crossing infrastructure is constructed on a river, the fish species that need to access upstream to reproduce, inexorably disappear from the inaccessible higher section. This has been the most frequent cause of extinction of certain species in a good number of rivers and peninsular river sections (salmon, eel, sturgeon, etc.). For the rest of the fish, the limited movement means it is impossible to populate new territories, a loss of upstream habitats, a reduction in genetic diversity (isolation of populations), and even the disappearance of the species in the upper section of the structure (the channels may drag fish down – or a polluting spillage can wipe them out – then later the lost section cannot be repopulated).

On the other hand, when the obstacle is very selective, with some fish able to get through, changes occur in the genetic population, and only the strongest specimens reproduce (not necessarily those that are best suited to the environment). Likewise, in their efforts to overcome the obstacle, the fish may injure themselves, and the exertion required uses up their energy reserves that were needed for spawning, weakening them and increasing their chance of becoming ill. Finally, if the fish take longer in their journeys as a result of waiting for suitable conditions to avoid the structure (raised water levels), it may be that the optimum conditions for reproducing (temperature, water depth and speed, maturity of internal organs, etc.) have passed by the time they reach the spawning areas.

Another serious problem to take into account in the event that obstacles can be overcome, is the lack of suitable conditions for reproduction or upstream habitat. Dams and irrigation dams retain the water over several hectometres or kilometres of river, transforming a flowing section, with alternating riffle and pool sections, into a lake (very low or no speed and very deep). Many fish can become disorientated faced with this situation, as they do not know which way to swim in still waters, without the necessary currents. This situation becomes even more complicated when the river is a laddered succession of dams. It is important to remember that our native migratory fish spawn in gravel beds, in shallow, flowing waters. Furthermore, their habitat requirements demand a certain heterogeneity in hydraulic conditions. Therefore the clear question is: will there be enough reproduction in the event that the fish overcome the barrier? Another important aspect to consider is whether, in the event that the journey upstream and spawning have been successful, the adults and young fish will be able to move downstream past the obstacle without any problems. If the answer is yes, the obstacle is considered as passable for fish and has a very low negative impact upon them.

According to the federal and state legislation in force [River Fishing Act, 1942; Waters Act, 1985 (integrated in the Royal Decree 1/2001 and later in 10/2001, 11/2005, etc.) and the Protection of Aquatic Ecosystems Act and the Regulation of Fishing in Castile and Leon (1992)] the movement of fish along rivers should be guaranteed and any structure that impedes or limits this movement, should be adapted to suit this purpose. However, administrative negligence and social apathy with the subsequent failure to adhere to prescribed regulations, have led to the disappearance or reduction in number of many fish species. Fortunately, the Directive 2000/60/EC, better known as the Water Framework Directive, has acknowledged this serious problem. Among many aspects covered, it specifically requires "river continuity" – defined by considering the "non-interference with the migration of aquatic organisms" – as a marker of the superficial water quality (appendix V.1.1.1). European Union Member Countries must adapt their rivers to meet this regulation before 2015 in order to achieve a "good ecological state of continental waters". Will this new act take effect on our rivers, or will it be yet another example of good intentions for waterway nature?

2. Determining factors

The solution to the migratory problem caused by crossing or linear hydro-technics, is to either demolish the obstacle or to construct an additional structure which facilitates the upstream/downstream movement: a fish pass (commonly known as a "fish ladder"). Generally, these are waterways that are passable for fish, guiding them up or down the obstacle.

As clearly explained above, it is vital for anadrome and catadrome species to be able to swim the entire length of rivers. For the remaining migratory species, even for the most sedentary fish, it is essential to maintain healthy populations and prevent reproductive isolation (artificial confinement of population concentrations). This requirement to move should not just be pertinent over the reproductive season of the species, but should be possible throughout the hydrological year.

The general conditions that any fish-way must meet, are as follows (Larinier et al., 1994; Martínez de Azagra, 1999):

● Easily located entrance (due to its location and calling)

● Simple passage (without stresses, injuries or excessive exhaustion)

● Safe exit (avoiding disorientation, dragging towards spillways or dangerous outlets, etc.)

● Passable by all native fish (not just the strongest specimens; not selective passes, they should not be exclusively for one species), preferably throughout the year.

● A minimum migratory delay (no queueing or piling)

● Functional during water level fluctuations

● Maintained and inspected regularly (after flooding and during migrations; cleaned, obstructions removed, damage repaired, illegal fishing prevented)

The conditions of the environment where the structures are installed are also important (Sanz Ronda & Martínez de Azagra, 2009). The following should be adhered to:

● Dimensions of the structure to be overcome, requiring some solutions to be rejected in favour of others

● Easy access to the obstacles and the place where the fish-way will be constructed (cofferdams, machinery crossings)

● Poaching or predation, in this case, access to the fish-way should be made difficult

● Ownership of the adjoining land (wherever possible, land not belonging to Public Hydraulic Territory should not be entered)

● The works environment should be integrated, with the chosen solution fitting aesthetically and socially within the surrounding waterway environment.

Likewise, the volumes of water that circulate throughout fish migration will have an influence on the type of solution to adopt (type of fish pass and its dimensions). Furthermore, the long-term functioning of the solution developed should be considered, with a reasonable financial cost that does not interfere in any way with the structural resistance of the dam. It is worth noting that the cost of a fish pass is considerably reduced if it is planned and carried out at the same time as dam construction, as opposed to constructing it once the hydro-technical work has been finished. Finally, wherever possible, the evacuation capacity of the flow from the obstacle to pass, should not be modified.

3. Solutions

Before focusing on constructive solutions, we should clarify that to achieve a successfully

Figure 3. Example of two correctly located fish ladders in Peñafiel (river Duero) and in Puebla de Lillo (river Porma). Wherever possible, the fish pass entrance should be placed next to the riverbank and near the face of the dam, making it easy to locate for the fish.

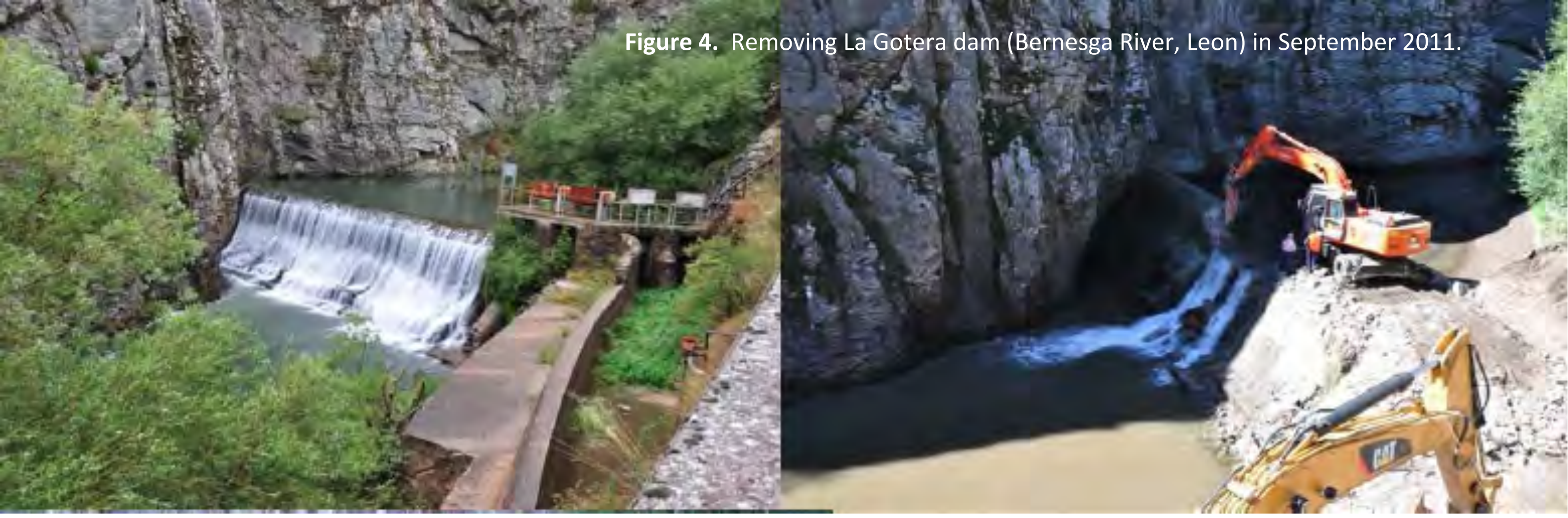


Figure 4. Removing La Gotera dam (Bernesga River, Leon) in September 2011.

functioning fish-way system, four basic premises should be complied with:

- **Location**: all activity should be located correctly within the dam, taking into account the priority migratory trajectory followed by the fish as they go upstream and attracting them towards the fish pass (concentrating greater flows, controlling the speed and exit of the water, adequately locating the entrance to the level system depending on the fluctuating flows, etc.) (Figure 3).
- **Design**: it should be suitable for the characteristics of the fish that will use it and for the determining factors of the works. The project should inexorably include a technical document which hydraulically justifies the solutions adopted, taking into account the different flow scenarios. It should be noted that on many occasions designers lack the necessary knowledge and disregard this basic information, which leads to serious design-flaws in these constructions.
- **Building**: despite projects being well designed and containing a refined definition of the solutions to adopt, the reality is that circumstances and unforeseen events always arise during the works building, which can alter the operation of the fish pass. This is why a specialised works director is required, as well as final verification. "Certificates of correct building" are the guarantee that the fish pas system has been undertaken in accordance with the project and the Government should require this of developers.
- **Assessment**: despite having completed the three previous phases with meticulous detail, unexpected issues frequently arise regarding the biological behaviour of the fish and their reaction to specific unknown flow situations. As such, it is necessary to verify that the fish pass works as it was intended to, and in the event that it does not, to determine the causes of the malfunction and to propose measures to improve its low performance.

Solutions that allow migratory movement, have different degrees of complexity, depending on the dimensions of the obstacle and the circulating flows. They can basically be broken into two methods: continuous operation (they operate without interruption) and discontinued (the movement of the fish is undertaken in phases: wait or capture, ascent, and release upstream). There are also specific solutions for some fish species that have peculiar migratory habits and swimming methods, such as eels and shad. Finally, we should not forget that once the fish has ascended the obstacle, it has only completed half of its objective, as along with the rest of its offspring, it will have to return back downstream to complete its life cycle, return to its original habitat or to disperse.

The most direct and efficient method for overcoming migratory obstacles caused by a dam, is to remove it (Figure 4). Until recently an unthinkable practice due to prevailing mentality, yet increasingly common: for example in North America (USA and Canada) where the environmental and financial benefits provided by river fishing in certain rivers, significantly surpass those produced from hydroelectric energy. In Spain, since the start of this century, some similar activities have been carried out (WWF, 2009) on small dams with expired licences, and they are increasing. However, with any kind of demolition, the environmental effects must be analysed (movement of sediment accumulated in the dam basin, upstream erosion, localised variations of groundwater), the effect on people (loosening of foundations in hydraulic works, taking down of outlet tubing, provisions and irrigation) and on society itself (history, culture and tradition). In any case, the

Figure 5. Traditional construction of rustic fish-ways in small dams in the mountains of Palencia and Leon.

environmental implications of the demolition in the medium and long-term are always positive for the ecosystem (Sanz-Ronda et al., 2011a).

For new facilities or old structures with the intention of adapting to meet current regulations, there are various methods that allow fish to overcome the obstacle. Within the continuous operation methods for small hydro-technics (less than 1m water drop) there are some alternative solutions: a simple adaptation of the spillway – a reduction – optionally accompanied by a ledge which sometimes acts as the channel, and/or maintaining a certain depth at the base of the dams which allows the fish to gain momentum (Figure 5). These are called “rustic fishways”. If the work is for a larger facility, the following options apply:

a) The first group of solutions are called **“nature like fish passes**” (Figure 6), due to their successful integration within the river surroundings. If well-designed and carried out, they permit all types of fish to ascend and descend, regardless of the size or species. Furthermore, they do not interfere with the works they are permeating and require low-maintenance. However, they are only manageable for medium height obstacles (in general < 3m water drop, though there are example with much greater level differences: Makrakis et al., 2011), due to the gradients with which they are designed (≈ 5 %) (FAO/DVWK, 2001, Larinier et al., 2002) and they are vulnerable to variations in water levels at the entrance (a water level reduction of 0.5 m can render the solution useless, unless the design has taken such scenarios into account).

● **Artificial river**: this is a lateral channel with a 3 to 5% gradient divided into riffle-pool sequences, offering an alternative route for fish via one of the river banks, thus avoiding the obstacle. Breakwater stones are placed on the riverbed, either randomly or in order, with the aim of slowing down the hydraulic strength of the current and offering rest and shelter for the fish.

● **Rock-ramps:** these are ridged channels or with internal partitions, with a gradient of 5 to 10%, attached to the dam, slowing down the flow of water and allowing obstacles under 2-3 m to be overcome. When it is carried out along the entire width of the obstacle, the ramps provide a natural rapids effect, successfully imitating the river.

● **Pre-dams:** the obstacle is overcome via small dams which break down the total gradient into smaller jumps, and between them large pools are created. They usually take up a large part (if not all) of the river width. They provide an intermediary solution between stone ramps and traditional fish ladders (which we will discuss later), though on a larger scale.

b) The second group of solutions are usually given the umbrella term of “**technical fish passes”** as they generally have a more complex hydraulic design, and are constructed from concrete and metal. They are not so well integrated within the surroundings, but they are shorter and can work with lower volumes of water.

● **Baffle fish passes (or Denil ramps)**: this is a straight channel with a steep gradient (up to 20%, though they are usually around 10-15%) with some deflectors to reduce the speed of the flow to allow the fish to swim upstream (figure 7). The deflectors (or baffles) have a variety of complexity and are based on prototypes that have been previously tried out on a smaller scale. Their usage is restricted to fish species with strong swimming techniques (salmonids). Further testing is required to ensure that they work with Iberian cyprinids. They are easily obstructed, thus requiring regular

Figure 6. An example of nature like fish passes: artificial river in the River Tormes in El Marín (left); stone ramp in the River Najerilla in Torremontalbo (centre) and pre-dams in the River Pisuerga in San Salvador de Cantamuda (right)

maintenance, and they are also quite sensitive to water level fluctuations at the source.

- **Pool and weir fish ladders** (or successive pools): this is a stairway of water formed with pools of 2-3 m long and 1-2 m wide, connected by 15-30 cm drops (depending on the target species). The water flows through via a series of spillways, vertical slots and/or orifices (figure 8). These are classic fish ladders and their usage has proven to be compatible with all sizes of migratory Iberian fish species (Sanz Ronda et al. 2011b), as by choosing the correct size of drops, the connections between pools and their size, they are scalable by any kind of fish targeted (as long as the fis ladder is sufficiently submerged with regards to the river water levels).

The **building cost** of the aforementioned works varies considerably depending on the accessibility of the works, the need for cofferdams, flood protection, etc. Costs are usually less than 5,000 €/m of gradient to overcome for rustic fish-ways, 10,000 to 15,000 €/m of gradient for baffle systems, and 15,000 to 30,000 €/m of height for nature like fish passes and pool and weir ones (information updated from own projects from 2004-2009).

On the other hand there is a vast difference between the various **discontinued operation** methods. For small, seasonal usage dams (irrigation, recreational use), that do not interfere with fish migration seasons (autumn-winter for salmonids and springtime for cyprinids), the handling or management solution is very interesting. It simply consists of installing a gate to allow the water flow to escape with suitable speed and depth for the target fish, which should be kept open during periods of migration. If this coincides with the dam usage season, it may be opened at specific times whenever migration is evident (dawn, dusk, in the descending phase of a flood, following rains which delays irrigation…Figure 9).

However, when the gradient to overcome is greater (>10 m), more economical and operational alternatives must be sought out than those previously mentioned. These are not very selective and do not require a lot of flow to function, though they do require rigorous handling and follow-up. Notably:

Figure 7. Denil and Alaska type fish passes.

Figure 8. Pool and weir fish ladders: "submerged spillway and bottom orifice" in the River Duero (Guma, Burgos) and "vertical slots" in the River Porma (Vegas del Condado, Leon)

● Capture and transportation of the fish: migrating fish species are captured downstream the dam using fish traps or electrofishing. They are then transported in water tanks to upstream, where they are released. Occasionally, the fish are driven directly upstream with special pump equipment, using the same methods as in fish-farms: specially adapted Archimedes' screws.

● Fish locks (or Borland or García Nájera locks): this device is very similar to a navigation lock (figure 10a), except that it should be designed with the greatest capacity possible to attract fish (technically defined as "attraction").

● Fish elevator/Funicular/Cable car: this consists of a cage (or elevator box where the fish are brought together), which periodically rises and empties its contents into the waters above the obstacle (figure 10b), in keeping with the number of migrating specimens that are trying to overcome the dam at any given time (Martínez de Azagra and García Molinos, 2003).

Finally, it is worth mentioning that all fishways require regular maintenance. In particular following a flood it is essential to check that there are no significant snags or obstacles impeding the flow of water. To carry out these operations it is useful to install a flow control device in the supply entrance (gate), allowing the ladder or capture system to be emptied (in discontinuous methods), thus facilitating maintenance activities.

Once the obstacle has been overcome by upstream migrating fish, another (somewhat less major) issue to address, is that of the downstream migration of the fry and the parent fish. In medium-height dams (4-8 m), fish can descend via the spillway – as long as there is a minimum water depth at the bottom to cushion the impact – or by the fishways itself (Larinier et al., 2002). However, when the dams are very high, and the fish pass used is an elevator or capture and transport system, the problem becomes more serious. In these cases, it is useful to know that the speed the fish reach when they enter the lower water cushion, depends on their size and the height of the drop: fry and juveniles attain a low and tolerable maximum speed, whilst larger, adult fish reach an excessive speed, causing them injuries when entering the water. Currently, special structures are being developed, similar to slides, to resolve this complicated situation (figure 11).

Another adverse situation, in the case of hydroelectric power plants, is that fish enter via the diversion channel and pass through the turbines. Under these circumstances, the mortality rate is extremely high, reaching up to 100% of the fish depending on the turbine type and the size of the fish. Prediction formulae have been produced regarding the mortality rates for the different species, sizes and turbines (Larnier et al., 2002). To prevent this, there are many devices that stop ictiofauna from entering the channels: physical barriers – narrow grating (<15 mm) – sonic barriers, light or electrical barriers.

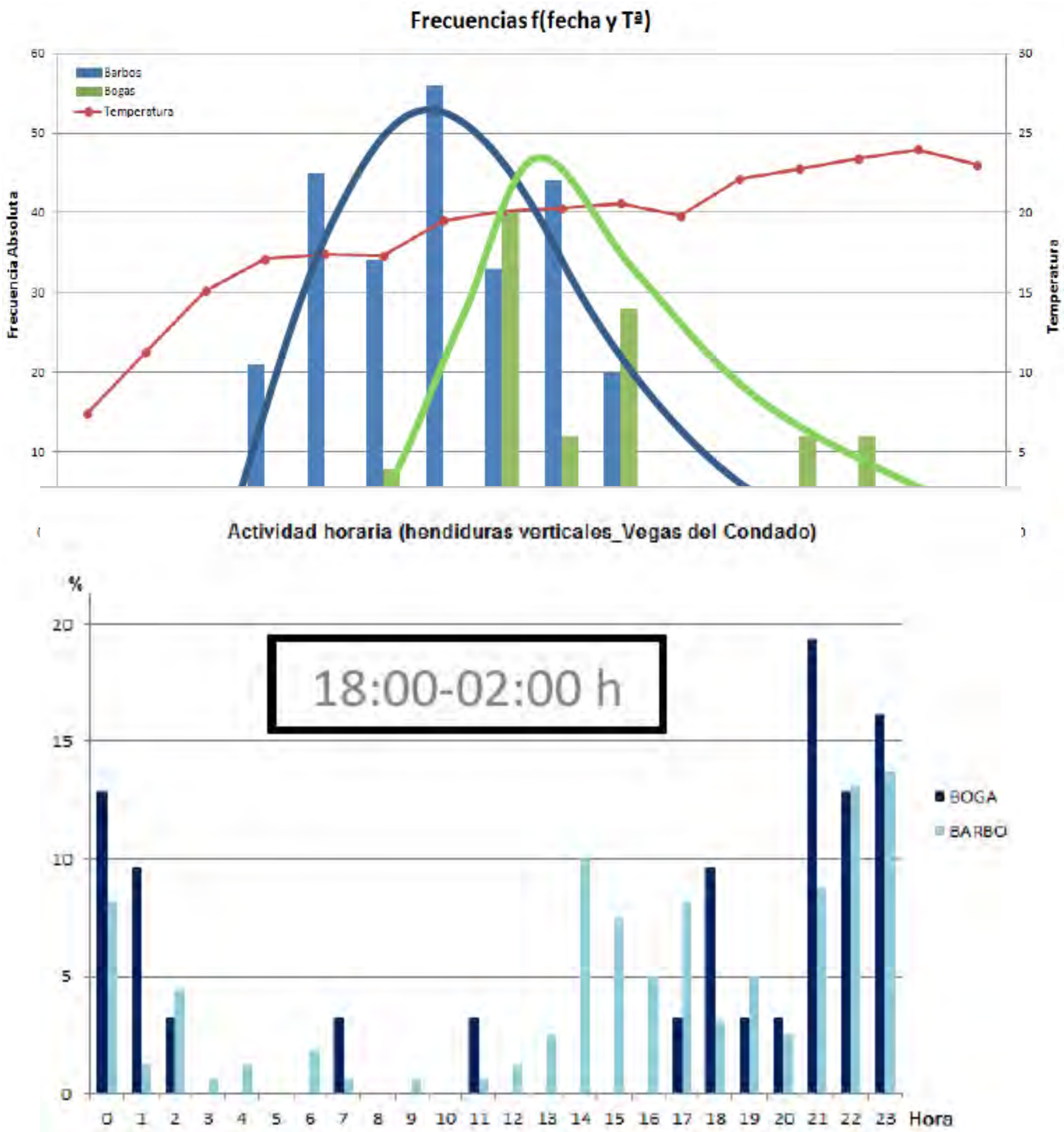


Figure 9. Season and time of upstream migration of Luciobarbus bocagei and Pseudochondrostoma duriense, at the tail of the Santa Teresa reservoir (River Tormes). Own information obtained from trapping and PIT tags in 2012.

4. Assessment

Once the fish pass has been chosen and the works finished, it is worth assessing the operability of the solution used. The technique commonly used in the biological evaluation of fish passes, are limited by the financial and human resources required. The most straightforward methods are the capture of specimens in different pools in the ladder, stopping the flow of water and/or using landing nets, electrofishing or traps (figure 12a and 12b) (Stuart & Mallen Cooper, 1999; Laine et al., 2002). Occasionally, it is also possible to study their ascent by marking captured fish (Knaepkens et al., 2006). All of these systems provide data about the species that use the fishway and their success rate, if they are marked fish or if very consecutive samplings are used (every 24 hours). To achieve truly thorough scientific data, these test need to be repeated, requiring considerable human effort.

An indirect study of the efficiency of the fish pass may be carried out by observing hydraulic variables (figure 12c), checking that it meets the criteria indicated in the project (speed, energy dissipation, drop, etc.), and by comparing it with the swimming capacities of the fish (Sanz Ronda et al., 2011b). Another, more biological system, is based on the procedure of capture-marking-recapture, with a high sampling cost (Burnham et al., 1987), or by analysing the population structures in the waters above and below the obstacle, checking for any size differences, species and number of specimens (Santos et al., 2005).

With modern-day technology, there is even more room for perfecting these assessments. It is even relatively simple to carry out a constant follow-up of the passes. For example, by installing “fish counters” in the fishways (though this is quite expensive) or by undertaking follow-up via radio-frequency systems or electromagnetic markers (PIT tags) (figure 13).

In short, it is essential to find out if the fishway meets its target objectives, to discover the species and size of fish that use it, how easy it is to locate, its success-rate, the periods of operation, etc. (figure 14). When the fish do not overcome the fish pass, the causes must be analysed (often due to insufficient attraction or a poor hydraulic design), and corrected. If serious assessment and follow-up are not performed, we are destined to repeat past mistakes. It is equally as bad to fail to install a fish pass in a dam as it is to install one merely as a gesture. Technically faulty fishways only act to discredit person who design them and building them, and to fuel the arguments of those that do not want to construct them, supporting their view that they are not efficient solutions.

5. Research

Until the start of this century, fish migration was a very under-researched field. In terms of generalised and basic knowledge, it would be useful to understand the migratory habits of our fish species (routes, times, stimuli, etc.) particularly in the case of potamodromous fish. We are also interested in discovering their population activity, how many individuals migrate, when they return, or what is the consequence of a percentage of the population managing (or not) to migrate successfully and reproducing.

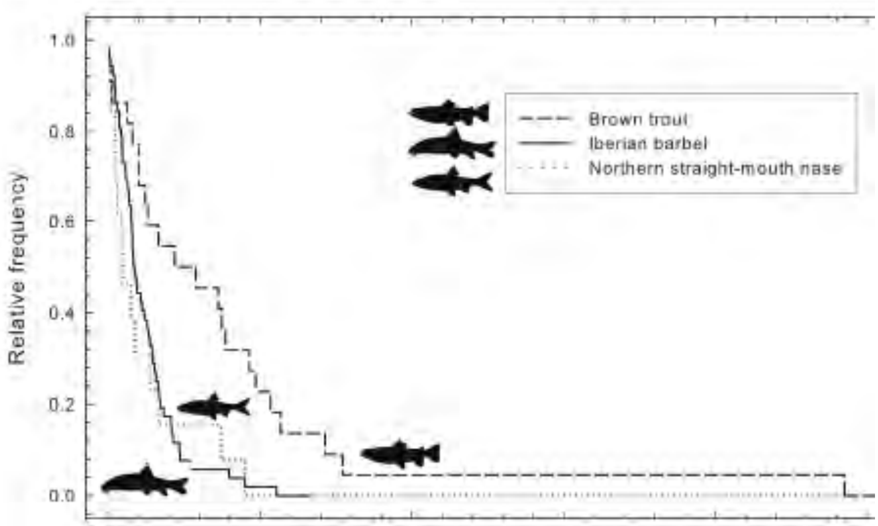
Figure 10.
a) Fish lock in Gormaz (River Duero, Soria)
b) Fish elevator in Vera de Bidasoa (Navarre)

Figure 11. Fish slide for downstream movements in Torquemada (River Pisuerga, Palencia). It is positioned near the turbine outlet and it is occasionally used to add greater volume to the fish ladder entrance, increasing the “attraction”.

Figure 12. Different assessment procedures for fish-ways:
a) Stopping water flow in the fish ladder and capturing fish
b) Trapping via orifices and
c) Hydraulic assessment

Figure 13. Insertion of a PIT tag into the intraperitoneal cavity of a nase and antenna (readers) installed in a fish ladder, which register the passage of marked fish.

Figure 14. IAssessment results: relative frequency and passage times (for 1 m of gradient) of the specimens that were able to ascend a fish ladder of vertical slots following 24 hours of experimentation [Own data].



On the other hand, considering fish pass systems from a more applied perspective, it is essential to discover which are most successful at attracting fish, the behaviour of the species within the ladders, the time it takes for them to scale them, the amount of turbulence they are able to take on, or the speeds that limit them. For example, determining the swimming capacities of ictiofauna (understood as their jumping capacity, maximum swimming speed, fatigue times and the maximum distance covered in different flow speeds), would allow us to define and identify insurmountable obstacles and, in particular, to improve fishway system designs (figure 15).

Epilogue

To summarise and as a final word, we would like to stress that effective and varied technical solutions are available – many have been around for over a century – to solve the challenge of migrating fish (both upstream and downstream). Yet the desire to undertake new projects with understanding is not enough. Existing structures with deficient functionality – or none at all in the majority of cases - must also be maintained and improved. Their operability must be assessed, their faults corrected, and their virtues enhanced. With the greater environmental awareness possessed by today's society, we hope that the attitude of apathy towards the ichthyological situation changes soon for the good of our long-suffering fish, rivers, streams and brooks.

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Figure 15. Fish swimming flume in Vadocondes (River Duero, Burgos), the first voluntary swimming channel in Europe. The swimming capacity at different flow speeds is analysed from the information collected by a PIT tag system and video cameras (see the next page).

More information

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