

Weir removal in salmonid streams: implications, challenges and practicalities

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Abstract Low-head dams and weirs can greatly limit the distribution and abundance of Atlantic salmon and other migratory salmonids in streams. Weirs can significantly increase the vulnerability of migratory fish to anglers, alter natural migration patterns, and exacerbate the effects of opportunistic predators. Overcrowding of fish at downstream pools can also facilitate the spread of parasites and infectious diseases, magnify the impact of pollution incidents, and increase the risk of mass mortalities, particularly at low flows. Not surprisingly, augmenting the accessible stream area constitutes one of the best ways to restore depleted salmonid populations. In this context, the removal of unused or illegal weirs can be an efficient, cheap solution to increase stream accessibility. Here, I examine some impacts of weirs on Atlantic salmon populations, and document with

case studies the removal and breaching of weirs in several Iberian streams.

Keywords Dam removal · Salmonids · River restoration · Fish movements · Atlantic salmon · River connectivity

Introduction

Along with water abstraction and pollution, damming is probably one of the greatest stressors affecting the integrity of running waters (Pielou, 1998; Heinz Center, 2002). Dams can interfere or even stop the transport of sediment and nutrients along waterways, reduce (or amplify) fluctuations in natural discharge levels, prevent inundation of floodplains and create wider and shallower rivers. Such changes in riverine processes can lead to increased algal blooms, increased bank erosion and reduced water quality (Kondolf, 1997). Impounded waters can also trigger important changes in the composition of stream fauna, favouring lentic over lotic species (Raymond, 1979; Lewis, 2001). Indeed, impounding can result in the loss of native species and their habitats (Vaughn & Taylor, 1999), and facilitate the colonization and spread of invasive species such as water weeds and pest fish (Havel et al., 2005).

Dams can block or delay the movements of migratory fish, and these are responsible for the decline or extirpation of many native salmon

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populations in both the Atlantic (Netboy, 1968; Mills, 1989) and the Pacific (Meehan, 1991; Frisell, 1993; Levin & Tolimieri, 2001). Difficulty of migration also explains the distribution and abundance of other migratory species such as the eel (Ibbotson et al., 2002). However, the effects of low head dams and small weirs (i.e. those that do not represent a permanent or insurmountable barrier to fish migration) are less well understood. Even small weirs (<5 m) can have significant effects on flow and temperature regimes, sediment transport, biogeochemistry, animal movements and stream habitat (Larinier, 2001; Hart et al., 2002), so it should come as no surprise that the modification of flow caused by such weirs can also alter the structure of communities and function of river ecosystems (Baumgartner, 2007). For example, weirs can prevent natural gravel recruitment along the river, leading to a reduction in the quality and extension of downstream gravel spawning areas (Kondolf, 2000, 2001).

Here, I examine the abundance of weirs and other obstacles in rivers of N. Spain and assess some of their impacts upon Iberian Atlantic salmon populations. In particular, I consider the effect of weirs on (1) upstream migrations, (2) exploitation by anglers, (3) predation risk, and (4) spread of infectious diseases. Finally, I document with case studies the practicalities and challenges of weir removal in France and Spain (online supplemental material).

Impact of weirs on salmon populations in the Iberian Peninsula

Abundance and distribution of weirs

The density of artificial obstacles (chiefly weirs) in the salmon rivers of the northern Spanish provinces ranges from 0.15 km^{-1} of accessible stream length to a maximum of $1.16 \text{ obstacles km}^{-1}$ depending on the river (Fig. 1). The average for 31 rivers is $0.46 \text{ weirs km}^{-1}$. In general, there is a higher density of weirs in tributaries than in main stems (Alvarez et al., 2003; Tamés et al., 2003), possibly reflecting the higher gradients of the former. Consequently, a few tributaries are now accessible to salmon and other migratory species in Iberian streams, and even then the length of accessible stream has been greatly reduced. For example, in the R. Asón, 30% of the

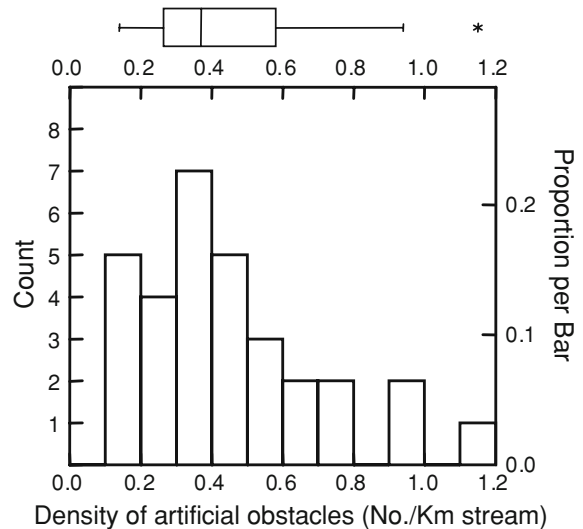


Fig. 1 Density of dams, weirs and other artificial obstacles in salmon streams of N. Spain, expressed as number of weirs per km of accessible stream length. Adapted from data in Alvarez et al. (2003) and unpublished sources

weirs are located within a 10 km radius from the tidal limit, and this can greatly restrict the passage of fish, particularly the weakest swimmers such as the Allis shad (*Alosa alosa* (L.)).

Characteristics of weirs

Most of the barrier that impede or that make difficult the passage of migratory salmonids in Iberian streams are man-made, and only a small percentage (6%) are natural obstacles such as water falls. Artificial obstacles consist of dams (3%), low-head weirs (87%), gauging stations (4%) and culverts or other structures (5%, Alvarez et al., 2003). Over half of the dams and weirs located in the salmon rivers are typically 1–3 m in height (Fig. 2); large dams (>10 m), usually for the production of electricity, are also found in some rivers, especially in the Atlantic rivers of the NW provinces, but these are relatively rare; median weir height is 2.2 m.

Many of the old weirs that are still found in the salmon rivers of the Iberian Peninsula were built to divert water to mills and foundries in the nineteenth century, and some were later reconverted to generate electricity. These were mostly made of masonry and loose slabs and are today in poor condition, constituting a flooding hazard during spates. A survey of 70 weirs in the salmon rivers of Cantabria indicates that

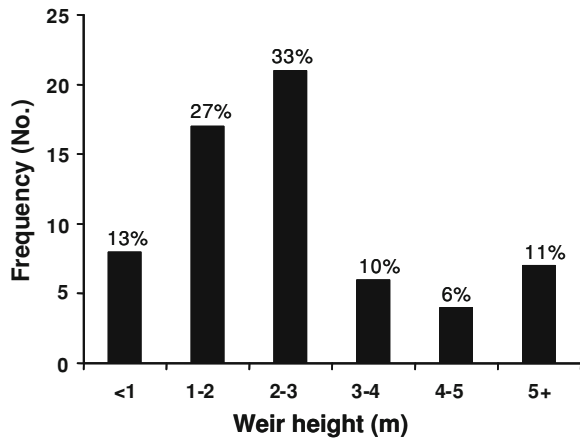


Fig. 2 Height of 62 weirs in four salmon rivers of N. Spain

66% are now abandoned and out of use. A similar proportion of unused weirs was also found in other regions (Alvarez et al., 2003; Tamés et al., 2003). Few, if any, weirs were fitted with a fish pass or with downstream fish screens and during the smolt migration large numbers of smolts may get stranded or delayed in water abstraction canals, this being an additional source of mortality.

Impact of weirs on river connectivity and salmon movements

Weirs can impact upon migratory fish by completely blocking their access to spawning grounds or the sea, but also by delaying their passage or by making it more difficult. The cumulative effect of many small weirs (even those that can be overcome) is particularly insidious (Williams, 1998; Naughton et al., 2005) since small weirs are the most numerous and low-head dams are not necessarily regarded by some fisheries managers as barriers to fish movements. However, weir height is a poor indicator of difficulty of fish passage and low weirs can be as difficult or insurmountable as much higher dams, depending on the hydraulic characteristics, water temperature, river flow and type and size of fish (Larinier, 2001). For example, radio-tracking studies have shown that weirs as small as 0.5 m can delay the passage of adult Atlantic salmon and sea trout, while weirs of only 1.2 m may constitute impassable obstacles, depending on flow and water temperatures (Gerlier & Roche, 1998). Discharge in the salmon rivers of N. Spain follows a marked monthly trend, with flows

typically peaking in March and April (where the largest salmon tend to enter these rivers) followed by severe droughts from July to September (Fig. 3). At least four migratory fish species are present in many of these rivers (Atlantic salmon, *Salmo salar* (L.); sea trout, *Salmo trutta* (L.); European eel, *Anguilla Anguilla* (L.); and Allis shad, *Alosa alosa*) and these can enter the rivers throughout the year. Thus, fish passage must be maintained even during low flows.

Weirs can force adult Atlantic salmon to fall-back and to spawn away from their home river (Gerlier & Roche, 1998; Thorstad & Heggerget, 1998), thereby negating the benefits of homing behaviour. Even when there are provisions for fish passage, adult salmon may take a long time to ascend fish ladders (Gowans et al., 1999; Rivinoja, 2005) or may not ascend at all (Solomon et al., 1999; Solomon & Sambrook, 2004). A lengthened migration period can deplete energy reserves and result in reduced spawning success or increased pre-spawning mortality (Gerlier & Roche, 1998; Geist et al., 2003). This is because injured or exhausted spawners may be forced to spawn in suboptimal areas or to deposit their eggs at too shallow depths (Berg et al., 1986). Since egg

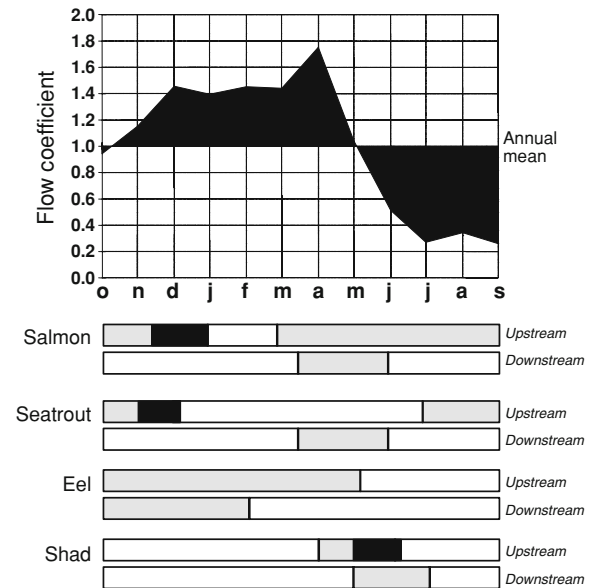


Fig. 3 Seasonal pattern in monthly discharge in the river Asón (Cantabria), typical of many of the salmon streams of northern Spain, expressed as flow coefficients (FC) with respect to the annual mean (FC = 1.0). The migration and spawning periods of several migratory fish are indicated (adapted from Serdio et al., 2001a)

burial in salmonids is directly related to embryo survival (Steen & Quinn, 1999; De Gaudemar et al., 2000), offspring of exhausted females may be more vulnerable to floods, redd overcutting and bed scouring.

Weirs can result in fragmented salmonid populations, decreasing their effective population size (Meldgaard et al., 2003), increasing genetic isolation (Heggenes & Røed, 2006) and compromising their evolutionary potential (Morita & Yamamoto, 2002). Paradoxically, weirs can also increase gene flow among population components. In the case of Atlantic salmon this could affect age at maturity since larger, older multi-seawinter fish tend to enter the rivers earlier and spawn higher upstream than younger grilse, which tend to enter later in the season and spawn lower in the system (Summers, 1996a, b; Youngson & Hay, 1996; Økland et al., 2001). Weirs, hence, can force both age classes to interbreed, thus negating the presumed adaptive benefits of assortative mating (i.e. Taggart et al., 2001) and leading to population homogenization.

Today, Atlantic salmon can only exploit between 5% and 89% of the stream length historically accessible to the species in different Spanish rivers (Alvarez & Lamuela, 2001; Serdio et al., 2001a; Alvarez et al., 2003) and the total loss of salmon habitat due to artificial barriers has been estimated to represent 86% of the stream length historically accessible to the species (Alvarez et al., 2003). Longitudinal profiles of salmon rivers reveal that the cumulative effect of many weirs can be considerable. For example in the R. Asón and its tributaries, the cumulative height of weirs can be in excess of 25 m over a relatively short reach (Fig. 4), making it difficult or even impossible for fish to reach the best spawning grounds located upstream (García de Leaniz et al., 1987). As a result, salmon and sea trout spawners are largely confined to spawn in the lower reaches of the main rivers, where survival of embryos and juveniles is likely to be lower due to increased siltation and greater vulnerability to predation. Radio-tracking of brown trout in the River Bidasoa (Spain) indicates that weirs prevented fish from reaching the spawning grounds, and caused significant reproductive isolation within the watershed (Gosset et al., 2006). In general, weirs in the salmon rivers of N. Spain have disrupted natural community structures and resulted in a significant reduction of fish species diversity (Reyes-Gavilán et al., 1996).

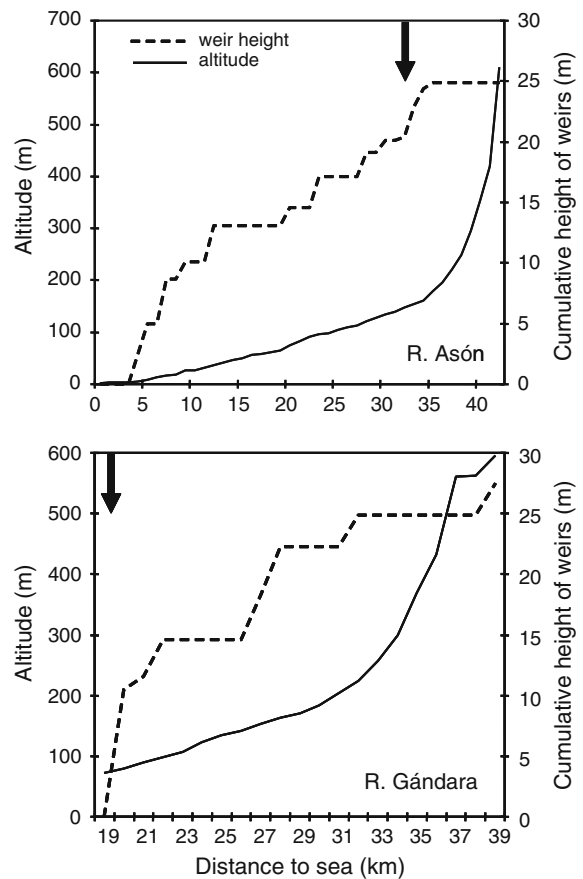


Fig. 4 Longitudinal profiles and cumulative weir heights in the R. Asón and its tributary the R. Gándara, typical of many of the short salmon rivers of N. Spain. Uppermost limits of accessible lengths are indicated by arrows

Although the effects of weirs on upstream fish passage have traditionally received more attention, impacts upon downstream migrants can be just as damaging (O'Connor et al., 2006). Weirs can delay smolt migrations and this can result in increased mortality. For example, Aarestrup & Koed (2003) reported a 53% loss of Atlantic salmon smolts due to weir passage compared to control smolts. They attributed smolt losses to increased predation, and delays that may have resulted in desmoltification. The weirs they studied ranged in height from 0.6 to 2.5 m, indicating that even small structures can negatively impact upon smolt passage. In the Spanish rivers studied, a few abstraction canals were equipped with effective fish screens, and this constitutes an additional source of potential juvenile mortality, particularly among smolts.

Overexploitation

Weirs and other obstacles can greatly increase angling mortality. For example, using data from radio tagged individuals, Karppinen et al. (2002) estimated that anglers fishing downstream of an impassable waterfall fitted with a fish pass exploited 39% of adult Atlantic salmon attempting to swim through the pass. Similarly, in the River Blanda (Iceland) Gudjónsson (1988) estimated exploitation rates by anglers of 36–77% (mean 50%) downstream of an obstacle and fish pass, compared to 21–31% (mean 26%) upstream of the same obstacle, indicating that barriers can almost double fishing mortality induced by anglers, even when they are fitted with a fish pass.

In Spanish rivers, fishing effort for salmon can be high and tends to target the largest females which enter early in the fishing season (Garcia de Leaniz et al., 2001), resulting in significant phenotypic and genetic changes in the populations (Consuegra et al., 2005). Many popular salmon pools in Iberian rivers tend to be located downstream of weirs or other obstacles, and rod catches in these pools can make up more than 30% of the entire river catch (Table 1), despite the existence of daily catch quotas per angler.

Fine-scale analysis of the spatial distribution of catches downstream of one of these weirs (Pte Viesgo weir) on the River Pas, indicates that the barrier effect is most noticeable immediately downstream of the weir, but that its effect can extend up to 1.5 km downstream (Fig. 5). Thus, existing fishing regulations that prohibit fishing within 50 m of weirs may need to be modified to achieve effective protection from over-exploitation, an important factor in the historical decline of Iberian salmon populations (Netboy, 1968, 1974), and one which has been

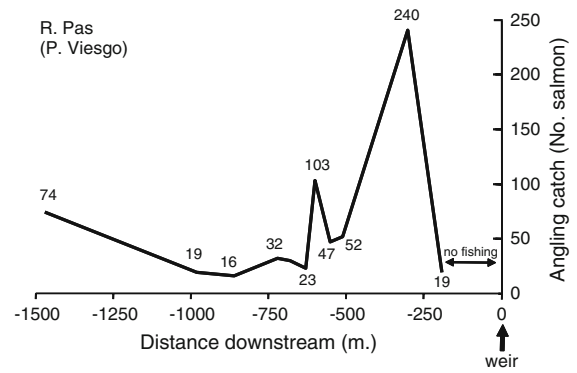


Fig. 5 Spatial distribution of salmon catches in relation to the Pte Viesgo weir (2.9 m) in the R. Pas. Shown are the aggregated rod and line catches in different salmon pools downstream of the weir during the period 1988–2000 (adapted from Serdio et al., 2001a)

evidenced recently by the high concentration of lead sinkers found in traditional fishing pools (Guitart & Thomas, 2005).

Predation

Weirs can facilitate predation in a number of ways. First, crowding of migrants around weirs can increase predation by opportunistic predators such as the otter (*Lutra lutra* (L.)), particularly during the spawning or smolt migrations when salmonids are most vulnerable (e.g. Carss et al., 1990; Garcia de Leaniz et al., 2006). Weirs also force fish to swim over relatively shallow crests and these provide vantage points for bird predators, particularly during low flows. In addition, the existence of still and relatively deep waters upstream of weirs facilitates foraging by diving birds and negates the refuge afforded by the turbulence of riffles. Two important bird predators in the salmon rivers of the

Table 1 Vulnerability of adult salmon to anglers fishing downstream of selected barriers in N. Spain, expressed as percentage of rod catches over the entire river

River	Obstacle	Type	Height (m)	Period	Percentage of salmon rod catches over river total
Ulla	Sinde	Weir	2.0	1982–1988	33.4
Ulla	Couso	Weir	2.0	1982–1988	30.2
Ulla	Ximonde	Weir	2.0	1982–1988	6.3
Ason	Batuerto	Weir	3.0	1990–2000	8.5
Pas	Pte Viesgo	Weir	2.9	1990–2000	38.3
Deva	Matadero	Gorge	–	1990–2000	42.7

Iberian Peninsula include the great cormorant (*Phalacrocorax carbo* (L.)) and the heron (*Ardea cinera* L.), both of which can have a significant effect on salmonid populations (Kennedy & Greer, 1988; Dieperink et al., 2001; Serdio et al., 2003). Data from the R. Asón indicates that the distribution of great cormorants along the river course is closely related to the location of weirs (Fig. 6), suggesting that weirs offer vantage points for bird predators.

Stress and diseases

Infectious diseases represent an important source of adult salmon mortality in Iberian rivers (Martin-Ventura, 1988; Garcia de Leaniz et al., 2001). Delays in upstream passage caused by weirs can result in overcrowding in downstream pools, and this can in turn facilitate the spread of infectious disease especially in the summer months, when temperatures are high and the flows are lowest. Furunculosis (causative agent *Aeromonas salmonicida*) and ERM (causative agent *Yersinia ruckeri*) are two infectious diseases commonly found in Atlantic salmon in Iberian rivers (Marquez, 1999; Garcia de Leaniz et al., 2001; Consuegra et al., 2003) which can cause substantial mortalities in some years. Data from the R. Asón indicates that the distribution of dead and moribund adult salmon (mostly collected before the spawning season) closely matches the location of weirs, perhaps suggesting that both are casually linked (Fig. 7).

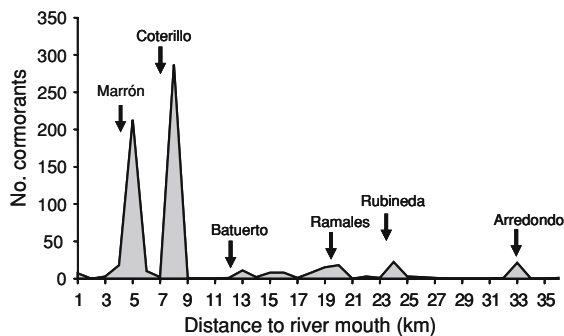


Fig. 6 Spatial distribution of cormorant sightings along the length of the R. Asón during 1996–2000 and location of main weirs (indicated by arrows; adapted from Serdio et al., 2001a)

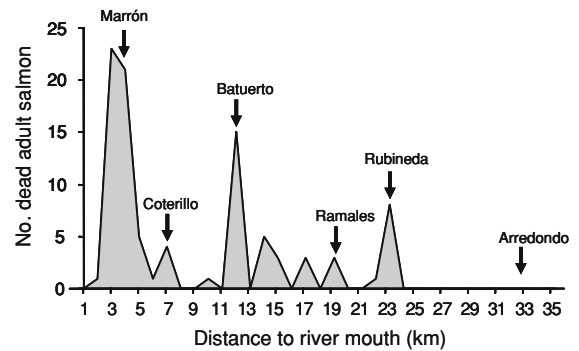


Fig. 7 Spatial distribution of adult salmon mortalities along the length of the R. Asón during 1996 and location of main weirs (indicated by arrows; adapted from Serdio et al., 2001a)

Issues in weir removal

Although dam removal is not new—more than 600 dams have been removed in North America in the last century including 56 during 2005 (Heinz Center, 2002; American Rivers, 2005; <http://www.irn.org>)—it is still a relatively new restoration technique elsewhere. Nevertheless, weir demolition is quickly becoming widespread in Europe (e.g. Finland, Jormola, 2001; Denmark, Riber, 2001; France, van Ast, 2000, Steinbach, 2001; Spain, Garcia de Leaniz et al., 2001, Brufao & Rodriguez, 2003, Brufao, 2006; Germany, Redeker et al., 2004) and Australia (WWF Australia, 2004, 2005). CEMAGREF (<http://www.lyon.cemagref.fr/bea>) provides a useful bibliography on dam removal with more than 60 journal articles, books and reports covering projects on several countries.

Reasons for dam removal

Causes for considering dam removal are numerous, but dam removal was originally driven chiefly by structural and safety reasons, and to minimize flooding hazards (Doyle et al., 2003). For example, rivers in many parts of Southern Europe are particularly prone to droughts and extreme changes in discharge (Nijland & Cals, 2001), which can sometimes result in catastrophic flooding events (e.g. Zacharias, 2001) and which are exacerbated by the presence of weirs and other structures opposing the flow of water. As most dams have an expected life span of c. 50 years (Heinz Center, 2002), ageing is also a major issue in dam decommissioning, and

thousands of dams built during the 1970s ('the dam golden area') will need to be decommissioned in the next few years, offering unprecedented opportunities for river restoration. For this and other reasons, dam removal is rapidly becoming an important management tool in river restoration (Hart & Poff, 2002), though information is still dominated by relative large projects, especially in the United States.

River fragmentation is one of the key impacts of dams on aquatic ecosystems (Nilsson et al., 2005), and restitution of river connectivity is therefore one of the first objectives in dam removal (Pejchar & Warner, 2001; American Rivers, 2002; Roni et al., 2002). In the case of migratory fishes (or those that simply alternate between lentic and riverine habitats), river connectivity is essential for completing their life cycle, and augmenting the area available to these species is tantamount to increasing population numbers (WWF, 2001). For example, 1 year after the Edwards Dam (USA) was demolished, large numbers of migratory fish returned to previously impounded parts of the Kennebec River (Maine), including millions of alewife, a migratory species which had disappeared for 160 years (Meadows, 2001). Likewise, fish diversity in the Baraboo River (Wisconsin) increased from 11 to 24 species less than 2 years following dam removal (Catalano et al., 2001).

Perhaps not surprisingly, the removal of barriers is often the most cost effective instream restoration technique in most situations (Pejchar & Warner, 2001; Roni et al., 2002); in the case of the Atlantic salmon, mathematical models suggest that dam removal and other improvements in freshwater habitats are also the best management options for restoring endangered populations (Robertson, 2005).

Legal framework regulating water concessions and weir removal

Epple (2000) has summarized the legal and regulatory framework governing the concessions of dams in France and most other European nations. Concessions in most European countries last for 40–60 years, a period usually smaller than the expected lifetime of the dam. In the case of Spain, concessions are normally given for 75 years, but these can be easily renewed and Water Authorities have traditionally been reluctant to impose any environmental constraint on water abstraction, let alone for

compensatory flows or fish passage requirements (Zatarain, 2001; Brufao & Rodriguez, 2003). As a consequence, a few dams and weirs built in Spain before the 1970s were fitted with fish passes, and those in existence are notoriously inadequate (Garcia de Leaniz et al., 1987, 2001; Alvarez et al., 2003).

In most countries, concessions granted by the Water Authorities include details of the owner of the dam and the beneficiary of the concession, the type and nature of the water abstraction, the duration of the concession, the methods of exploitation, the power capacity, the minimum flow releases, the fish passage facilities and in general any environmental control measures. In most countries, concession details can be reviewed through public consultation, at least in theory. In practice, however, this can be a difficult and time consuming process, which is a complaint frequently lodged with the European Union (see Zatarain, 2001). Also, concession details of small or very old weirs, are often incomplete or nonexistent (Epple, 2000).

In Spain, weirs can be removed for a variety of reasons (Brufao, 2001; Brufao & Rodriguez, 2003; Brufao, 2006), the most common of which include the following:

- (1) *Lack of concession.* Illegal weirs that lack a water concession are common in many situations, and developers or promoters may fail to provide evidence of a permit to abstract or impound water with a weir.
- (2) *End of concession.* Water concessions are not eternal, and although concessions can be renewed, when a concession expires this allows the authorities to decommission many dams and weirs.
- (3) *Breach of concession terms.* Concessions can be terminated if water is abstracted for a purpose different than that authorized or if it fails to comply with the restrictions imposed in the concession (typically some form of compensatory flow or provisions for fish passage).
- (4) *Lack of use.* A concession can be declared extinct if it has been out of operation for three or more consecutive years for reasons attributed to the concession holder. In theory, this clause allows the public to request from the authorities the removal of any weir which is in ruins, or simply out of use.

In addition the fishery service in Spain can also undertake all the necessary works to facilitate fish

passage in any weir at the weir concession holder's expense.

Considerations for removing weirs

Weir removal can have physical, biological and societal implications that need to be taken into account in the planning process (Doyle et al., 2000; Heinz Center, 2002; Hart et al., 2002), and which include the following:

1. Stability of riparian margins;
2. Sediment and gravel transport;
3. Flood risks;
4. Potential transport of toxic sediments;
5. Reduction of stream width upstream of the weir;
6. Other changes in the river channel;
7. Societal and cultural issues.

Although the long-term consequences of dam removal are still poorly understood (Stanley et al., 2002), particularly in the case of large dams (Grant, 2001; Stanley & Doyle, 2003), the potential impact of sudden sediment mobilization is probably the biggest concern (Doyle et al., 2000, Stanley et al., 2002, Stanley & Doyle, 2003). Bednarek (2001) has summarized the ecological impacts of dam removal and concluded that any increase in sediment load following dam removal is generally short-lived and that the benefits greatly outweigh the temporary impacts, from which the stream quickly recovers (but see Stanley & Doyle, 2003). In most situations, river conditions are little affected by weir removal and appear to return quickly to pre-impoundment conditions (Ashley et al., 2006; Velinsky et al., 2006). However, post-removal monitoring is important (Grant, 2001) since not all dams are likely to have the same effects on the stream ecosystem (Levin & Tolimieri, 2001) and contaminated or toxic sediments may require specific pre-removal studies.

Cultural considerations may also need to be taken into account when considering dam removal (Marmulla, 2001), as some weirs may have high historical or societal value. For example, in S. Europe a number of weirs date back to Roman times (Arenillas & Castillo, 2003) or may have other archaeological interests, and this may prevent their demolition or constrain how they are removed.

People's attitudes to the impact or benefits of weirs in streams can vary markedly between stakeholders

(e.g. Østdahl et al., 2001; Pejchar & Warner, 2001), and these should be incorporated whenever possible into the decision-making process (Babbitt, 2002), particularly in the case of weirs and low-head dams which may not be viewed as detrimental by all (Johnson & Graber, 2002). For example, weirs (some up to 7 m high) continue to be constructed in many streams under the umbrella of 'river restoration', allegedly for sediment retention, reduction of peak flows and creation of fish habitat (e.g. Portugal, Machado & Alves, 2001; Spain, Schmidt et al., 2001; Norway, Østdahl et al., 2001), suggesting that weir removal will always be a contentious issue (Grant, 2001).

Cost of weir removal

Costs of removing old, unused weirs are quite variable but in general are considerably lower than the cost of repairing the structure, or of building fish passages. Costs of removing weirs have been estimated to vary between 20,000 and 90,000 € in several projects in Spain reviewed by Brufao (2006). In the region of Cantabria, actual costs (1999 prices) ranged from just under 2,000 € for small weirs (<1 m) that were removed in a few days to 16,000 € for the demolition of a large weir (6.5 m) that took 3 weeks. In the United States, the cost of removing small weirs (max 10 feet in height) was \$69,000 on average, or \$23,000 per metre height (range \$2,000–\$126,000 per metre height) according to data provided in Heinz Center (2002). In general we have estimated that for small to medium sized weirs (up to 3 m in height), the cost of weir removal was typically less than 20% of the cost of building a Denil fish pass, and less than 12% of the cost of building a pool and weir fish ladder (de la Fuente & Araujo, 2001). Thus, weir removal will often be the most direct, cost-effective option for improving fish passage, and for eliminating the negative effects of low-head dams on stream integrity (Hart et al., 2002).

For some weirs, particularly the highest ones, safety considerations should also be factored in when costing dam removal, as dam removal typically costs only a fraction of the costs of repairing an unsafe dam (Hjorth, 2001). Moreover, even if these costs are comparable, dam removal eliminates the need (and cost) for continued maintenance and repairs in the

future. In Wisconsin (USA), the cost of removing low-head dams was 20–50% of the estimated repair costs (American Rivers, 1999).

Decision-making and prioritisation in the removal of weirs

Not all barriers can be removed easily, thus some form of evaluation criteria and prioritization strategy will be required to optimize weir removal (Pejchar & Warner, 2001). One commonly used prioritizing method employs a scoring and ranking approach (e.g. Roni et al., 2002; Clarkin et al., 2005) which is easily implemented in most situations and which can benefit from the availability of specialized software such as *FishXing* (Love, 1999). An alternative decision-making approach for weir removal which does not rely on subjective scoring has recently been developed by O’Hanley & Tomberlin (2005) based on dynamic programming methods.

A simple decision flow chart adopted to demolish unused weirs in the salmon rivers of N. Spain is shown in Fig. 8. The process begins with a field inventory of all obstacles in target watersheds, including the main stems of river and their tributaries. The inventory provides information on the location, characteristics and impact of each barrier based on expert knowledge combined with an in-situ impact assessment based on weir height, crest profile, existence of a holding pool, distance to river mouth, size of impoundment, weir use, water abstraction and ease of fish passage amongst other criteria (Table 2). From this, weirs are classified as limiting or not limiting depending on their estimated impact. Weirs which are deemed to cause a significant impact on salmon populations are then studied in more detail, and information on their current use and legal status is sought from the relevant authorities. Those weirs which are abandoned or in ruins are singled out and a legal case can be initiated for their decommissioning, and eventually, their removal. Those weirs which lack concessions or those whose concessions have expired can also be singled out for removal. Only in those cases where the weir causes an important impact and cannot be removed are other alternatives explored, typically involving the provision or modification of fish passes or the setting of compensatory flows.

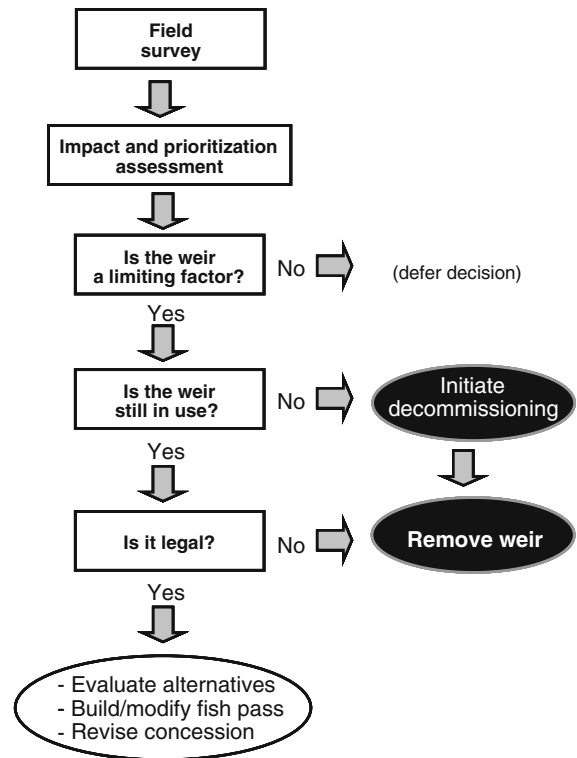


Fig. 8 Decision flow chart for removing unused weirs in N. Spain

Table 2 General criteria used to assess the likely impact of weirs on Atlantic salmon populations from field survey data

Criteria	Likely magnitude of impact	
	Best	Worst
1. Distance to river mouth	Far	Near
2. Crest profile	Vertical	Ramp
3. Deep (>2 m) holding pool	Yes	No
4. Weir height	<1 m	>3 m
5. Use	Out of use	In use
6. Impoundment	Small	Large
7. Canal	No	Yes
8. Ease of upstream passage	Easy	Difficult/ impossible
9. Ease of downstream passage	Easy	Difficult/ impossible

Conclusions

Thousands of low-head dams and weirs, many of them in ruins, litter the salmon rivers of the Iberian Peninsula and probably those elsewhere in Europe.

While a few of these structures are listed and may retain some archaeological value, most do not. They cause a substantial impact on stream ecosystems, particularly amongst migratory fish.

Results from the Iberian Peninsula and elsewhere show that even relatively small weirs can delay or completely block the passage of upstream and downstream migrants. They also facilitate predation, poaching and overexploitation of salmonid populations, and exacerbate the spread of infectious diseases due to overcrowding and stress during low flows.

The removal of weirs offers considerable advantages over other solutions (typically the provision of fish passage facilities) since it solves simultaneously both upstream and downstream fish passage problems, something difficult or impossible to accomplish by other means (Larinier, 2003). In addition, the cost of weir removal is typically a fraction of the cost of building fish passes or repairing unsafe or old weirs. Weir removal is often the most cost effective option for salmonid river restoration, as it achieves direct, integral stream restoration and does not hinder future

options (Peters & Marmorek, 2001; Peters et al., 2001).

However, weir removal also has limitations. It may not always be practical or feasible. Some river systems may take a long time to recover, or may not recover fully, because long-term changes caused by dams may not always be reversible (Doyle et al., 2005). The impact caused by the sudden mobilization of sediments, some potentially toxic, also needs to be taken into account. There is still limited experience in Europe, particularly when compared to the construction of fish passes. Societal and cultural issues need to be considered, while bureaucracy and red tape may mean that the decommissioning process may take a long time. Nevertheless, with many dams in Spain and elsewhere rapidly approaching their life span, increasingly large structures will likely be decommissioned in the next few years (Fig. 9), offering unparalleled opportunities for river restoration at an unprecedented scale.

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Fig. 9 The Palombera dam (23 m) has been blocking the passage of migratory fish in the River Nansa since 1949 (García de Leaniz et al., 1987; Serdio et al., 2001b). As its concession will soon come to an end, conservationists, scientists and anglers alike are campaigning for its decommissioning

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APPENDIX – ONLINE SUPPLEMENTAL MATERIAL

CASE STUDIES IN WEIR REMOVAL

The first dams in Europe that were demolished for purely environmental reasons, chiefly to restore Atlantic salmon and other migratory fish, were found in France. These, along with other pilot experiences of weir removal in Spain, are described below.

THE FRENCH EXPERIENCE

The French pilot experience consisted of the demolition of three dams during 1996-1998 (<http://www.rivernet.org>), one located in the river R. Léguer (Kernansquillec dam), and the other two located in tributaries of the R. Loire (Allier, Vienne) as part of a restoration plan for the Loire watershed (“Plan Loire Grandeur Nature”) developed in 1994. The Kernansquillec dam was built in 1920 in the river Léguer, a small coastal stream in Brittany, to supply electricity to a paper plant. The dam was 15 m high and was demolished in 1996 at a cost of 6.1 million FF to restore the native Atlantic salmon populations and other migratory fish (Larinier, 2001). It was the first hydroelectric dam removed in France, and possibly in Europe, to restore Atlantic salmon populations (ERN 2006).

The St. Etienne de Vigan dam (12 m) was built in 1895 in the headwaters of the R. Allier to supply electricity to the town of Langogne. It was demolished with explosives on 24th June 1998 at a cost of 7 million FF in order to allow salmon to gain access to the traditional spawning grounds of the Allier. The Maisons-Rouges dam (Vienne River, Loire) was also demolished with explosives in 1998 as part of the Loire restoration plan. The Maisons Rouges dam was 3.8 m high and was built in 1922, originally to supply electricity to a paper factory and later incorporated in the French National Grid. Demolition costs amounted to 14 million FF. Plans are also under way to dismantle the Poutès dam, also in the headwaters of the R. Allier (see <http://www.rivernet.org>). More information about dam decommissioning in France can be found in <http://www.dams.org/kbase/submissions/showsub.php?rec=OPT136>

SPANISH CASE STUDIES

At least 20 weirs and low head dams have been removed in 14 Spanish rivers for environmental reasons (chiefly to increase the area accessible to salmon and other migratory fish) during the last decade (Table S1), and many more are due to be removed within the next few years. These have ranged in height from 0.6 to 6.5 m (mean height = 2.4 m). The pattern of weir removal observed in Spain parallels that observed in the United States, where c. 200 dams have been removed in the last few years (Figure S1), and will continue to grow in the future.

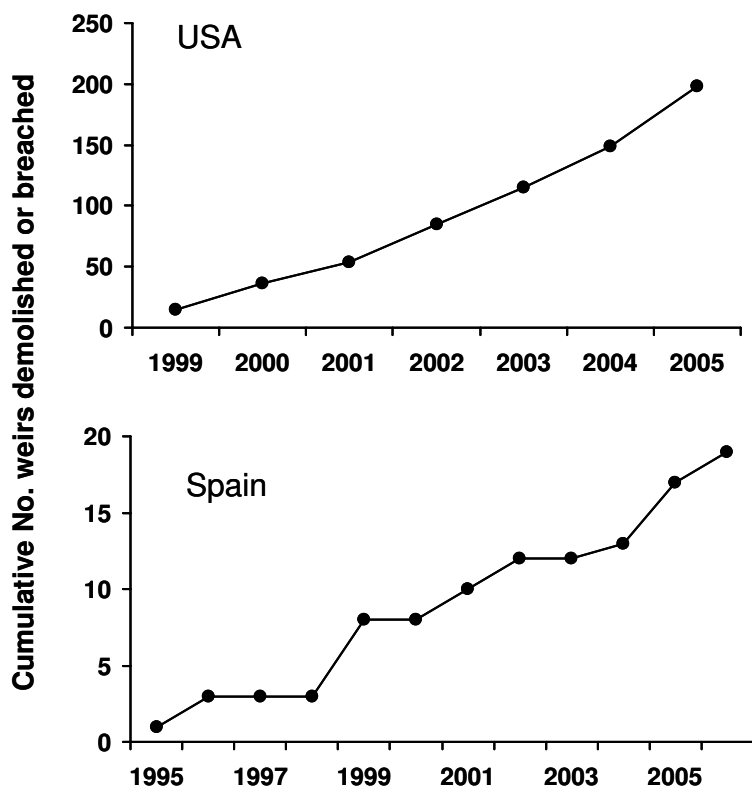


Figure S1. Cumulative trend in the number of dams and weirs demolished or breached in the USA and in Spain during the period 1995-2006. Some 500 dams had been decommissioned in the USA prior to 1999 (data not shown).US data adapted from American Rivers (2005).

Table S1. Removal or breaching of old, unused weirs in Iberian salmonid streams. The list is not exhaustive.

River	Weir/location	Province	Year	Height (m)	Reference
Ulla	Sinde	Pontevedra	1993	2.0	Garcia de Leaniz et al (unpubl)
Tea	Angoares	Pontevedra	1995	2.8	De La Fuente (unpubl)
Lérez	Mercantil	Pontevedra	1996	2.0	De La Fuente (unpubl)
Lérez	Muiño do Manco	Pontevedra	1996	2.5	De La Fuente (unpubl)
Gándara	Trefilerias	Cantabria	1999	6.5	Garcia de Leaniz et al (2001)
Vallino	La Barcena	Cantabria	1999	2.2	Garcia de Leaniz et al (2001)
Asón	Bulco	Cantabria	1999	1.4	Garcia de Leaniz et al (2001)
Asón	La Puntana	Cantabria	1999	2.0	Garcia de Leaniz et al (2001)
Bustablado	El Manzano	Cantabria	1999	0.6	Garcia de Leaniz et al (2001)
Asón	Rubineda	Cantabria	2001	2.5	Garcia de Leaniz et al (unpubl)
Piloña	Villamayor	Asturias	2001	-	Brufao (2006)
Urola	Txiriboga	Guipúzcoa	2002	-	Urrizalki et al (2002)
Urola	Amilibia	Guipúzcoa	2002	-	Rekondo (2004)
Güeña	Cangas de Onis	Asturias	2004	-	Brufao (2006)
Tiétar	Navalmoral de la Mata	Cáceres	2005	-	Brufao (2006)
Oyarzun	Gabierrota	Guipúzcoa	2005	-	Segura (2005)
Oyarzun	Fandería	Guipúzcoa	2005	-	Segura (2005)
Oyarzun	Ergoien	Guipúzcoa	2005	-	Segura (2005)
Oitavén	Ponte Vilán	Pontevedra	2006	1.7	Araújo (unpubl)
Salor	Ladrillar	Cáceres	2006	-	Brufao (pers comm.)

Various benefits were sought from weir removal:

1. To facilitate the upstream passage of fish, particularly to the spawning and nursery grounds of greater quality located in the headwaters and tributaries
2. To ease downstream migration of smolts, particularly at low flows
3. To reduce mortalities caused by stress, spread of infectious diseases, poaching, predation and increased vulnerability to angling

The first weir to be breached in Spain for environmental reasons was possibly the Sinde weir (2.0 m) in the River Ulla, which was breached with hand tools during 1993. This was an abandoned weir which served no other purpose than to increase fishing mortality in a critically endangered Atlantic salmon population. Unfortunately, pressure from anglers forced the local authorities to block the weir again in 2004, despite considerable opposition from conservationists and fishery scientists.

Five unused weirs were demolished or breached in the River Asón during 1999 with the aid of a hydraulic backhoe digger fitted with a hammer/breaker, as detailed below. Work was carried out during the summer months to minimize silt transportation and run off. In some cases, the largest slabs and rocks removed from the weirs were used to stabilize the river banks (Figure S2). In other cases, these were simply left in place and were carried away with the subsequent autumn flows (Figure S3).



Figure S2. Removal of La Puntana weir (2.0 m) in the River Asón.

La Puntana (Figure S2)

This was an old weir made of masonry and natural rocks which used to feed a water mill, long gone. The weir was 2.0 m in height, and was located 28 km from the sea (120 m above sea level). As in the previous case, no concession details were produced by the Water Authority and the weir had been out of use for more than 10 years when it was surveyed in 1988 and again in 1997. It was therefore deemed to have lost the water abstraction rights. The weir did not have any fish pass and posed a small (albeit significant) obstacle for migratory fish, particularly during low flows. Like the rest of the weirs it also provided a vantage point for bird predators and poachers. The weir was removed with a digger, and the largest rocks and slabs were shifted to the right bank, helping to stabilize it.

Bulco weir (Figure S3)

This consisted of the remains of an old masonry weir which formed a headwater pond for a water mill, and later a dairy factory, both long defunct. The weir was 1.4 m in height and extended for c. 51 m into the right margin of the river Asón. It was located 9.7 km from the sea, 28 m above sea level. The weir had been out of operation for more than 10 years when it was surveyed in 1988 and again in 1997, and was deemed to have lost the water abstraction rights; no concession details were produced by the Water Authority. Although the weir no longer constituted an obstacle for the upstream passage of fish (the left hand side had been breached) it nevertheless helped pool water upstream. It also provided a vantage point for bird predators and poachers, and there was always the risk that developers would attempt to rebuild it. The remains of the weir were broken down with a digger, and the largest rocks and slabs were shifted to the right bank.

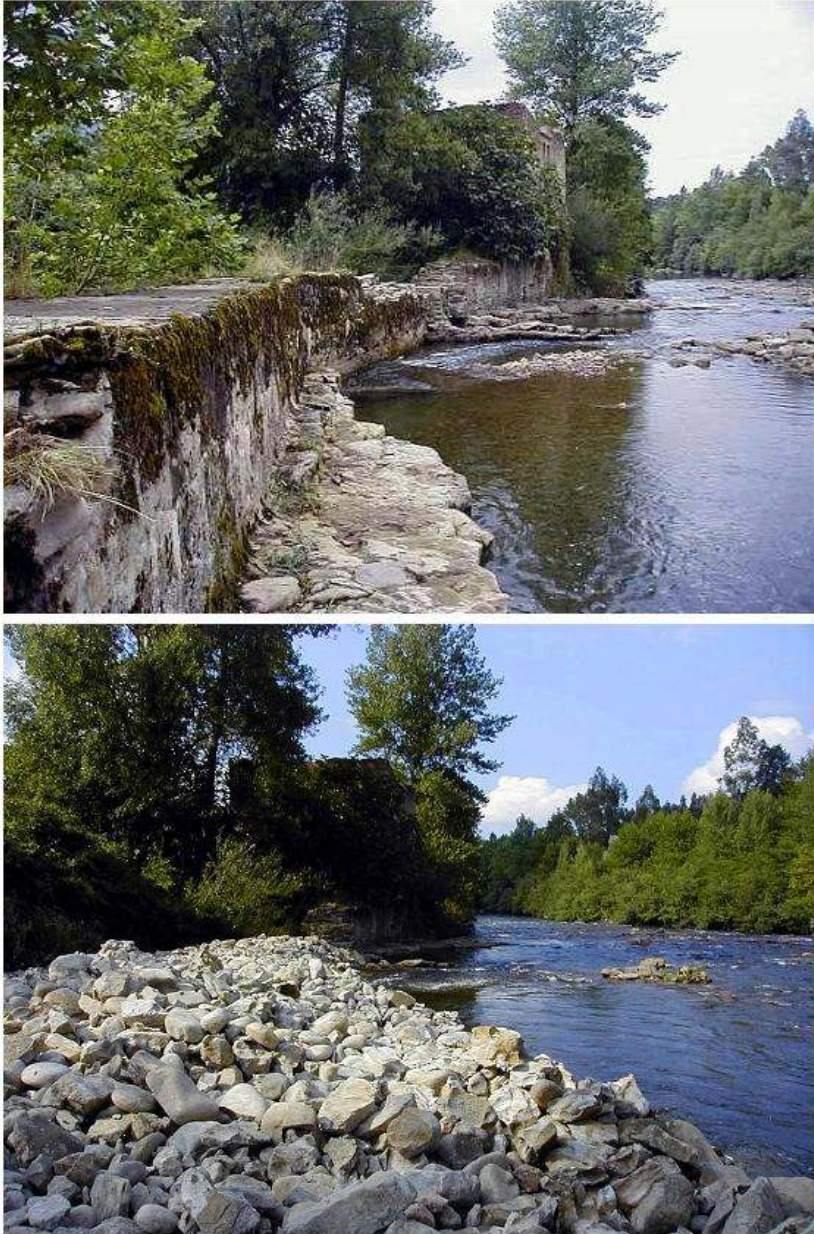


Figure S3. Removal of Bulco weir (1.4 m) in the River Asón.

La Bárcena (Figure S4)

This was an old weir which had been rebuilt with concrete in more recent times. It drew water into a leat (some 200 m long by 1.5 m wide), out of use. The weir was 2.2 m in height, and was located 4.3 km from the sea at 12 m above sea level, in the river Vallino, one of the tributaries of the river Asón. It had also been out of use for more than 10 years when it was surveyed in 1988 and again in 1998, and was therefore deemed to have lost the water abstraction rights. The weir lacked a fish pass and posed a considerable obstacle for migratory fish, making upstream passage into the river Vallino impossible during low flows. Like the rest of the weirs it also provided a vantage point for bird predators and poachers. A digger was used to breach the weir in its left margin, leaving a 2.0 x 2.2 m opening during the summer of 1999.



Figure S4. Breaching of La Barcena weir (2.2 m) in the River Vallino, a tributary of the R. Asón. Note remains of original weir in the right margin.

Trefilerías (Figure S5)

This was an old masonry weir which was used to abstract water into a long canal for the production of electricity for an old cable wire factory, no longer in use. The weir was 6.5 m in height and it was located 19.8 km from the sea (73 m above sea level), very close to the confluence of the river Gándara with the main river (Asón). The weir had been out of operation for more than 10 years when it was surveyed in 1988 and again in 1998, and was therefore deemed to have lost the water abstraction rights. Although the weir had been breached along one margin, it continued to pose a considerable obstacle for migratory fish, making upstream passage difficult during low flows. It had also dammed a considerable reach upstream and was a favourite spot for poachers. During the summer of 1999, a digger fitted with an hydraulic hammer-drill worked for several weeks to cut through the structure and remove the largest rocks and slabs, which were piled along the banks. A few months after its demolition, adult salmon ascended and spawned in the River Gándara (García de Leaniz et al., 2001).



Figure S5. Demolition of Trefilerias weir (6.5 m) in the River Gándara (R. Asón), and aspect of the site immediately after the removal. Note poor condition of the weir and substantial erosion at its base.

El Manzano

This consisted of an old, low weir (0.60 m) made of rocks and masonry which used to draw water into a mill. The weir had been out of use for many years and no canal was found when it was surveyed in 1998. It was located 34.4 km from the sea, at 165 m above sea level and close to the confluence of the river Bustablado with the main river (Asón). Due to its low height, the weir only constituted a small obstacle for the passage of fish at low flows, but it encouraged poaching and there was always the risk that its height would be increased. The weir was removed with a backhoe digger in the summer of 1999.

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