Criteria for decision-making towards the improvement of river connectivity and dam removal considering the impacts of invasive fish species in the Iberian Peninsula

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Criteria for decision-making towards the improvement of river connectivity and dam removal considering the impacts of invasive fish species in the Iberian Peninsula

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Summary

The Water Framework Directive is the response to the need to unify the actions on water management in the European Union, while the Habitats Directive lays the foundation for the conservation of natural habitats and wild fauna and flora. Both directives, especially the former, prioritize the reestablishment of the longitudinal continuity of rivers to improve and conserve existing water bodies, although the latter also tries to prevent actions that entail the introduction and expansion of invasive alien species. Thus, river connectivity restoration through dam removal or passage improvement could prove to be an erroneous option because of the disastrous consequences of invasive alien species on aquatic organisms, especially on native ichthyofauna. Iberian freshwater ichthyofauna is exceptionally vulnerable to the consequences arising from the introduction of exotic fish species and habitat fragmentation as it is characterized by a high degree of endemism and many species are included in some category of IUCN threat. This report aims to facilitate decision-making mechanisms in those actions of river connectivity recovery affected by the expansion of invasive species. To this end, an evaluation criteria and manual of good practices has been developed to address connectivity recovery projects in Iberian rivers when invasive alien species are present.

1. INTRODUCTION

The Water Framework Directive (Directive 2000/60/EC) is the response to the need to unify the actions on water management in the European Union and defines the basic principles of sustainable water policy throughout the Union. The main purpose is to improve and conserve existing water bodies in order to achieve good ecological status in all the EU countries. The "ecological status" of water bodies is understood as the quality of the structure and functioning of ecosystems. Annex V describes the evaluation criteria used to make this assessment, which includes river continuity as one of the hydro-morphological quality indicators that must be taken into account when evaluating the ecological status of surface water bodies in order to achieve very good ecological status. Rivers cannot be awarded this status while there are elements that interrupt their continuity. In this sense, a connected river, which does not present barriers to the transport of sediments or the displacement of aquatic organisms, or in which the barriers are equipped with devices allowing aquatic species and their propagules to overcome them in both directions, ascent and descent, has a higher level of ecological quality than others of similar characteristics that are affected by barriers, which prevent or hinder ecological connectivity.

An impassable barrier can cause diverse impacts on fish populations, from the disappearance of isolated populations due to loss of viability to the disappearance of a certain species throughout an entire basin due to the infeasibility of access to breeding areas. Even at best, a decrease in genetic diversity can be expected owing to the isolation of populations (Niccola et al., 1996; Morita & Yokota, 2002). If only a few individuals are able to overcome the obstacle, changes in population genetics may occur and the fertility and immune status of individuals could decrease. In addition, for certain Iberian species, the sizes at sexual maturity can be very different for each sex, which produces a different capacity to overcome obstacles according to sex and size. Likewise, if overcoming the barrier is only possible in certain flow conditions, asynchronies can occur, making reproduction impossible (Alonso, 1998; Ordeix et al., 2011).

The implications of longitudinal connectivity recovery in the conservation of fish populations and habitat quality improvement are evident (Doyle et al., 2000; Bednarek, 2001). This factor is especially important in the Iberian Peninsula as it features one of the highest rates of endemic freshwater fish in the EU and 95% of its native species are included in some category of threat by the IUCN (Doadrio et al., 2011b).

However, the alarming increase of invasive alien species in the Iberian water courses is a threat factor for the conservation of Iberian endemisms (Elvira & Almodóvar, 2001), at least as great a threat as habitat fragmentation. Paradoxically, measures specifically designed to recover connectivity for threatened species could also favour the dispersion of invasive species, compromising the viability of the target species (Fausch et al., 2009; McLaughlin et al., 2013; Rahel, 2013).

In this sense, the Habitats Directive (Directive 92/43/EEC), on the conservation of natural habitats and wild fauna and flora, establishes that Member States must ensure that the intentional introduction of alien species is regulated, so that they do not harm the native fauna and flora or their natural habitats and, if it is considered necessary, will prohibit such an introduction. However, this directive also calls for the recovery of the linear and continuous structures—such as rivers—that are essential for the migration, dispersal and genetic exchange of wild species. Therefore, both the Water Framework Directive and the Habitats Directive prioritize the reestablishment of the longitudinal continuity of rivers, although the latter also tries to prevent the actions that entail the introduction and expansion of invasive alien species.

Thus, the choice of the most appropriate alternative between improving the connectivity of an obstacle or removing it should not only include the most appropriate engineering solution, but also an evaluation of its ecological implications. When invasive alien species are present, the most appropriate alternative may be to refrain from acting on the obstacle, or to act partially, due to the negative consequences on the native ichthyofauna. In any case, studies should include alternatives to be analysed prior to formulating the definitive connectivity improvement project, and this must be monitored especially closely when it can compromise the conservation of threatened endemic species.

This report is structured into several sections in an attempt to present an overview of the most relevant information about the object of study, namely: Iberian ichthyofauna; fluvial connectivity and the expansion of invasive alien species, with special reference to the situation in the Iberian Peninsula; a compilation of the main papers and projects about connectivity versus invasive alien species; and, finally, evaluation criteria and a manual of good practices to address the connectivity recovery projects in Iberian rivers when invasive alien species are present.

2. OBJECTIVES

This report aims to facilitate the decision-making mechanisms when assessing actions to recover river connectivity in areas affected by the expansion of invasive species; i.e. the dilemma between compliance with the Water Framework Directive for river connectivity, and the protection of biodiversity as established in other European directives, such as the Habitats Directive. It contains an overview of the current situation and clear and detailed proposals on the evaluation of the type of actions that would serve as guidelines in future programmes on river connectivity in Spain, Portugal and other States of the European Union in order to make the recovery of river connectivity compatible with the conservation of their biodiversity.

Specific objectives are:

a) To show the current situation of the problem of the river connectivity versus the dispersion of invasive species and current solutions through a compilation of recent scientific knowledge and up-to-date technical practices in the countries where the management of invasive species presents great development and extensive experience.

b) To serve as a best practices guide to make decisions, as a fundamental document, and to be used as a reference to unify management criteria at a national level.

c) To analyse the management actions and the studies undertaken in the Iberian Peninsula and other areas during recent years concerning connectivity and invasive species, and to contrast that information with current science-based management criteria.

d) To highlight guidelines on the issues addressed to inform various European institutions about advisable improvements in the national and European legal regulations.

3. IBERIAN FRESHWATER ICHTHYOFAUNA

Currently, the Iberian Peninsula—as part of peri-Mediterranean Europe—is considered to be a 'biodiversity hotspot' for European riverine fish (Smith & Darwall, 2006; Reyjol et al., 2007). Its special geological features have lead to a very particular composition of ichthyofauna (Doadrio & Aldeguer, 2007; Doadrio et al., 2011b), with a high of amount of endemisms (Fig. 1). The Iberian Peninsula has an insular character for continental ichthyofauna, which is unable to cross active geographical barriers such as the Pyrenees or the Strait of Gibraltar and other historical biogeographic barriers, e.g. catchment divides or climatic conditions (Leunda, 2010; Doadrio et al., 2011b). Most of the 61 species present are exclusive to freshwaters (51), while 10 species can carry out part of their life cycle in brackish or marine waters. Among the continental fish, 41 species are Iberian endemics, which represent more than 80% of the continental ichthyofauna. In addition, six other species are Spanish-French endemisms because their distribution includes a small part of southern France (Doadrio et al., 2011b).

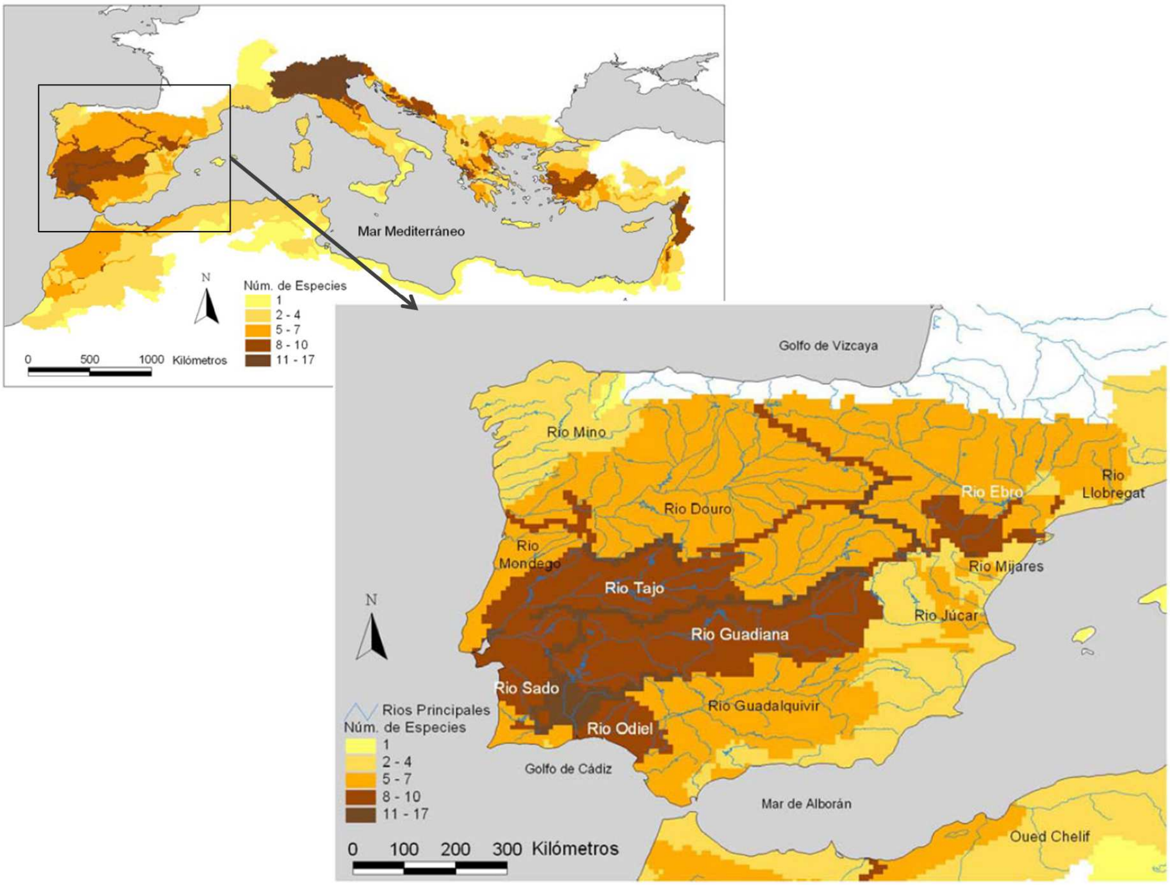


Figure 1. Distribution and richness of autochthonous species of freshwater fish in the Mediterranean region and details of their situation in Spain and Portugal. Source: Smith & Darwall (2006).

The Iberian ichthyofauna is an ancient fauna, dating back to before the configuration of the current hydrographic network, when the geographical barriers between river basins were not yet formed. The ichthyofauna has been isolated for 5.5 million years, starting when the Strait of Gibraltar opened. Several hypotheses indicate that the Iberian ichthyofauna is the result of colonization from Eurasia and from the extension area of the current Mediterranean Sea during several geological periods (Banarescu, 1989; Bianco, 1990; Doadrio & Carmona, 2003; Perea, et al., 2010). In addition, in contrast to most of Europe—where homogenization of the ichthyofauna occurred as a result of the Pleistocene glaciations that led to the disappearance of endemic species—the ancient fauna was conserved in the Iberian Peninsula. Natural selection acted intensely, causing the evolution and speciation of different fish populations restricted to certain river basins in the interior of the peninsula (Doadrio, 2011).

Iberian native freshwater fish comprise a low number of families, with a high degree of diversification at the species level, and the greatest percentage of endemism in Europe (Doadrio, 2001). Most of the species belong to Cyprinidae. As in other Mediterranean peninsulas, the Iberian river network is complex and contains a high number of independent river basins where different species populations are strongly isolated. Most Iberian rivers have a typical Mediterranean cycle: autumn winter floods and severe summer droughts (Gasith & Resh, 1999). This important seasonal instability, coupled with a huge interannual variability in precipitation, are key factors structuring freshwater communities (Pires et al., 1999; Magalhães et al., 2002). A characteristic that is associated with unpredictable aquatic systems, such as Mediterranean rivers, is the notable presence of hybridogenetic fish taxa, constituted by polyploid females, and also species with an extraordinary phenotypic plasticity and zones of hybridization between species (Doadrio, 2011b).

Another feature of the Iberian ichthyofauna is the variability of species according to their need to migrate, excluding dispersion or colonization movements. Thus, several groups of fish are distinguished (MAGRAMA, 2017): large diadromous migratory species (eel, lampreys, sturgeon, shads and salmon), potadromous species with strong migratory requirements (trout, barbels, nases and chubs), potadromous species with low migratory demands (small species of Iberian cyprinids such as bermejuela, sarda, ruivacos, gudgeon and minnow), species that are sedentary or with very small movements (spined loaches, loaches, sculpins, samaruc and Iberian toothcarps), and euryhaline species (e.g. black-striped pipefish or big-scale sand smelt).

Despite the great importance of Iberian freshwater ichthyofauna, their conservation status is very poor (Cabral et al., 2005, Doadrio et al., 2011b). According to the IUCN criteria, more than 95% of the 61 native continental fish species are included in some category of threat: 11 critically endangered species, 13 endangered species, 30 vulnerable species, 2 almost threatened species, and 5 species of minor concern.

The main two causes for the poor state of conservation of the Iberian ichthyofauna are habitat fragmentation (or lack of longitudinal connectivity) and the introduction of exotic fish species, involving a progressive and generalized decline in native species (Doadrio et al., 2011b). The introduced species are widespread and are expanding their ranges. Moreover, many of them are piscivorous species, which is a trophic group that is virtually absent in the indigenous fauna (Aparicio et al., 2000; Elvira & Almodóvar, 2001). In addition, factors such as habitat loss, water pollution (ground water, domestic and urban waste water, industrial effluents, and agricultural and forestry effluents), overfishing and droughts or climate change also affect the native fish populations (Freyhof & Brooks, 2011).

Appendix I lists the Iberian species of continental fish, their endemicity, their degree of threat according to the IUCN, and their migratory requirements. In this report, the common English names for Iberian endemic freshwater fishes have been used, following Leunda et al. (2009).

4. BARRIERS AND FLUVIAL CONNECTIVITY

4.1. Barriers in rivers and their effects

Hydrologic connectivity is the “water-mediated transfer of matter, energy, and/or organisms within or between elements of the hydrologic cycle” (Pringle, 2001) and that connectivity can be assessed in longitudinal, lateral, vertical, temporal, or multiple dimensions (Kondolf et al., 2006). However, rivers have been used by humans more than any other type of ecosystem throughout history, (Arthington & Welcomme, 1995), thus all the connectivity dimensions have been modified. For regulated-flow rivers, dam releases are often timed to meet human demands, such as water supply, navigation, flood control, power production, and recreation (Malmqvist & Englund, 1996). This introduces complex impacts on fluvial ecosystems, among which is the loss of longitudinal continuity in rivers and between their tributaries and the sea.

The loss of longitudinal connectivity in rivers is a major problem worldwide as a result of dam development (Gought et al., 2012). Throughout the world, there are now >50,000 dams with a crest height >15 m and an estimated 16.7 million reservoirs >0.01 ha (Lehner et al., 2011). In addition to the obvious physical modifications of the habitat, the most important effect produced by transversal infrastructures is the barrier effect, compartmentalizing the basins, isolating populations, and preventing or delaying the migratory movements of a good number of species, especially fish. Not only are their reproductive movements modified, but also their movements of colonization or dispersion by drift and movements related to the search for refuge and food (Pess et al., 2005; Poulet, 2007; Fullerton et al., 2010). In addition, the impediment of migrations interrupts the genetic flow between subpopulations of different species, causing the loss of genetic diversity and giving rise to a greater risk of extinction (Rieman & Dunham, 2000; Wofford et al., 2005; Neville et al., 2006).

A transverse barrier also establishes a new arrangement of flow regimes, riffles and pools, which modify sediment transport processes. This increases retention times, thus favouring sedimentation upstream of them and decreasing contributions to low-lying areas (Nilsson & Berggren, 2000; McAllister et al., 2001; Poulet, 2007; Fullerton et al., 2010). These changes in transport processes alter the flows of materials and energy, and produce alterations to a greater or lesser extent in the physical-chemical dynamics of the river, which affects the entire biological community of the waterway, both upstream and downstream. Dams and weirs disrupt a river’s natural course and flow, alter or redirect river channels, transform floodplains, and disrupt river continuity (Ward & Stanford, 1995; Stanford et al., 1996; Poff et al., 1997). The final result is a loss of water quality due to numerous processes: an increase in water temperature, an increase in eutrophication, the clogging of beds, a decrease in pH and dissolved oxygen, a massive proliferation of phytoplankton, the retention of floating materials, the bioaccumulation of toxic substances, and impacts on riparian vegetation, etc. (González et al., 2011; EPA, 2016). The impacts of these obstacles are cumulative and their effects continue up to the estuaries and coastal areas, where the sediments do not reach as they are retained by the barriers.

Furthermore, fish are delayed when trying to cross a partial barrier or a fishway. These delays produce more serious consequences (McLaughlin et al., 2013): at the point of passage, delays can force fish to congregate at high densities, possibly creating an attractive patch of prey for predators and facilitating the transfer of diseases and increased competition for space due to the close proximity of individuals; they can also prolong exposure to supersaturated gases, which can increase the likelihood of stress and injury; they can reduce an individual's ability to complete its migration to a spawning ground or new foraging habitat; they can also mean that individuals arrive at spawning grounds with less energy for reproduction and arrive late, possibly creating a mismatch between offspring hatch and food availability; and fallback can occur, when a fish moving forward through a fishway reverses its course because it is disoriented and moves in the wrong direction. Furthermore, dams and fishways can create an ecological trap, when the fishes select a habitat where their Darwinian fitness is relatively low (Pelicice & Agostinho, 2008). Dams and fishways can create strong selective pressures operating over many generations, thereby selecting for genotypes with traits best suited for an environment with dams and fishways. If these are later removed, the population may have to undergo further evolution to restore the lost fitness associated with the change from a more fragmented to a less fragmented river system (Waples et al., 2007).

Water flows that are reduced by impoundments may instead support non-native habitat generalist species of fish or other aquatic life, and become more conducive to the propagation of invasive aquatic species. Above the dam, slower, deeper, warmer water is often no longer suitable for native riverine species adapted to flowing, shallower, cooler water. (EPA, 2016). In addition to increasing the abundance of standing-water habitats, impoundments are frequently larger and more accessible to humans.

Reservoirs have indirect effects on the decline of native fish assemblages in the Iberian Peninsula through their relationship with invasive species (Hermoso et al., 2011). Propagule pressure is a major factor for predicting the success of invaders in colonizing new ecosystems, and reservoirs play an important role as centres of introduction of invasive species (Kolar & Lodge, 2000; Clavero et al., 2004).

Spain is one of the countries with the largest number of dams in the world, with the documented existence of more than 1,200 large dams, and there is evidence that the current inventories made by the various River Basin Districts in the country have determined the existence of about 26,000 barriers in Spanish rivers (Fig. 2). Nevertheless, it is estimated that the actual number may be closer to more than 50,000 obstacles, as the public information on the inventory of barriers still remains heterogeneous and incomplete (CIREF, 2016).

In Portugal, the loss of habitat resulting from the construction of dams and weirs is a determining factor in the impact on Portuguese ichthyofauna caused by human activities (Bochechas, 2014). According to the Red Book of the Vertebrates of Portugal, the loss of river connectivity constitutes one of the main threat factors for almost 80% of the native fish species (Cabral et al., 2005).

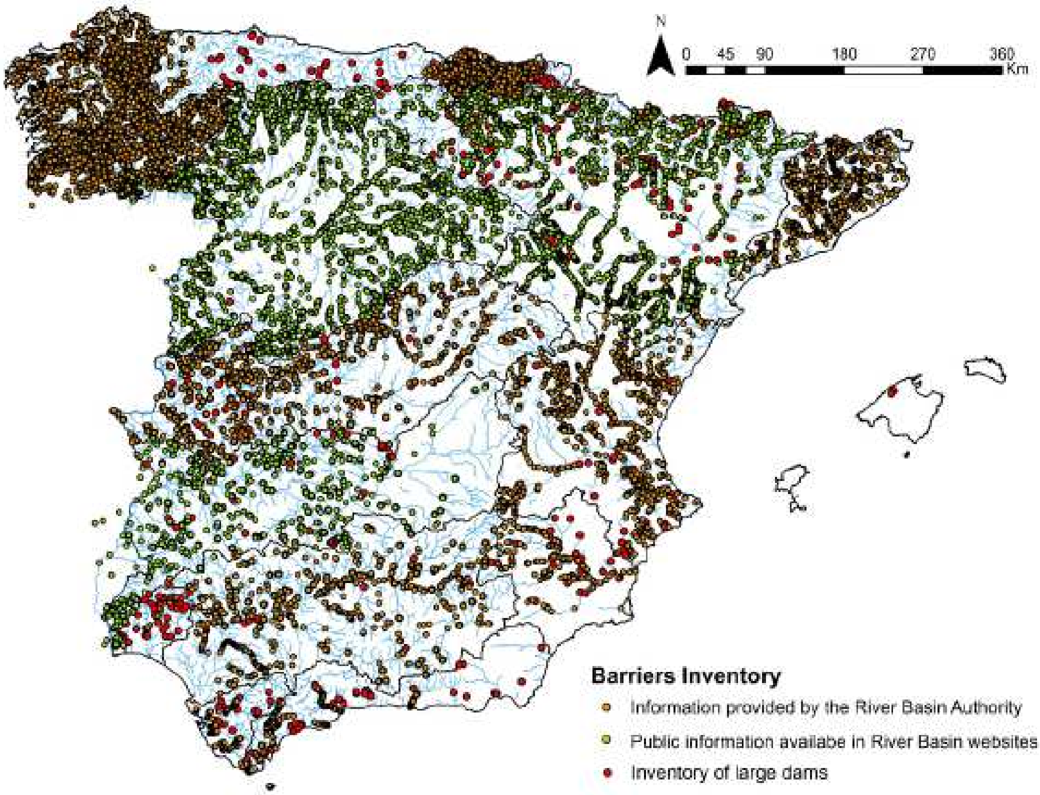


Figure 2. Barriers inventory obtained from the various River Basin Authorities (green and orange points) and those that appear in the inventory of large dams (red points) in Spain. Source: CIREF (2016).

The information obtained on dams and weirs in Portugal, including the official reports from the various river basin organizations, also presents a high variability of criteria, rigor and detail, between the different hydrographic demarcations (Fig. 3) (Bochechas, 2014). There are 256 large dams identified and the total number of barriers that affect the river connectivity of the Portuguese rivers is over 6,000, according to Bochechas (2014), and almost 8,000, as indicated by the Conselho Nacional da Água (CNA, 2017). However, the Agência Portuguesa do Ambiente and the organisms that preceded it almost completely neglected the oldest and smallest infrastructures during the inventories, in particular those to the north of the Tajo basin, where 50% of the water basin agencies did not include dams smaller than 10 m in height in the inventory (Bochechas, 2014). Thus, as in Spain, it is assumed that the total number of barriers in Portuguese rivers has been underestimated and the real number is much higher. In addition, the information available about the characteristics of transversal barriers, ecological flows and the presence of fish passages is still very poor (CNA, 2017).

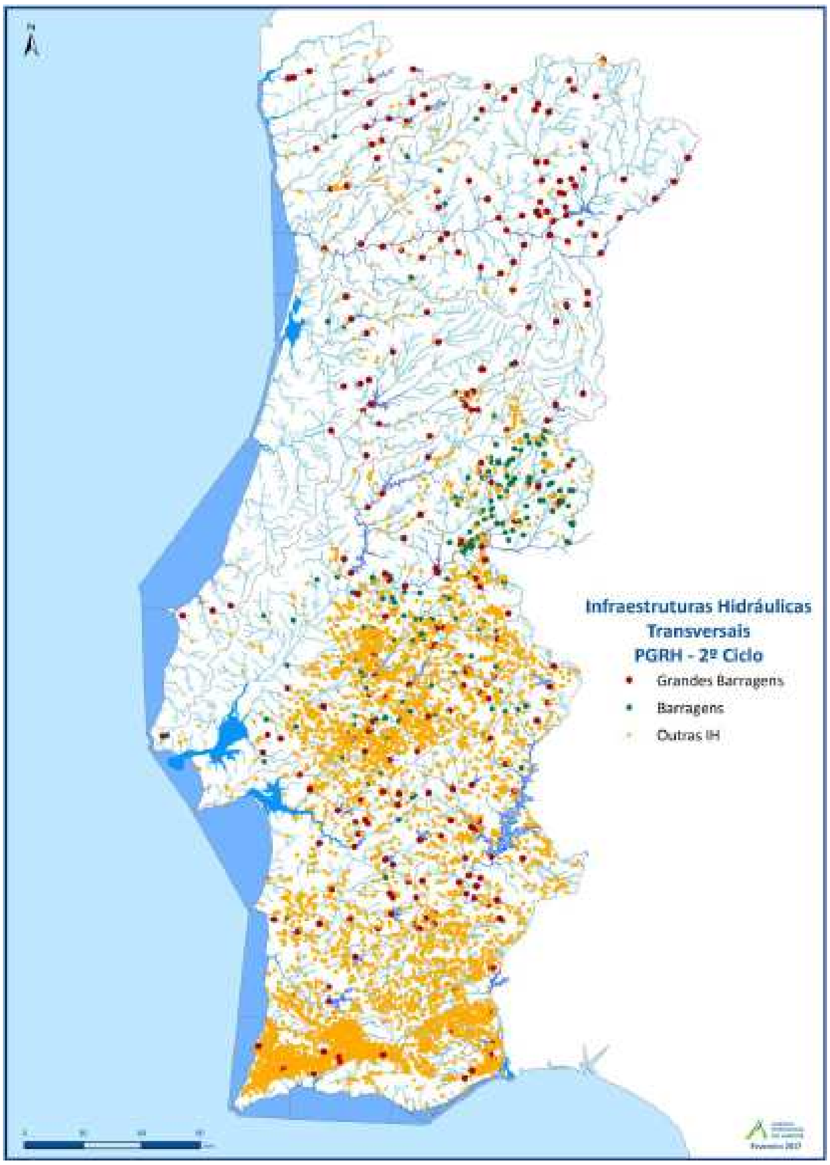


Figure 3. Hydraulic Infrastructures identified in the Management Plans of Hydrographic Regions (2016–2021) obtained from the Agência Portuguesa do Ambiente in Portugal. Red circle: large dams; green circle: dams; and orange circle: other infrastructures and weirs. Source: Agência Portuguesa do Ambiente (2017).

River Basin Management Plans consider the effect of dams and weirs too be one of the main hydromorphological pressures on Portuguese water bodies. However, the data available in these plans does not allow a detailed evaluation of the influence of transversal infrastructures on the ecological status of water bodies, since hydromorphological pressures include other factors, such as dredging, lateral protection levies, occupation and alteration of the bed and of the margins and the transfers and deviations of water. Furthermore, it is questionable that the methods and indicators used are sufficiently sensitive to evaluate aspects such as the degree of fragmentation of water courses caused by consecutive sets of hydraulic uses (CNA, 2017).

4.2. Legislation about river continuity

The restoration of fluvial continuity was first contemplated in two pioneering and important international conventions: in the Bonn Convention on the Protection of Migratory Wild Species (Ap. I and II, 23/6/1979), and in the Bern Convention on the Preservation of Wildlife (Ap. I, II, II and IV, 7/19/1979).

Over a decade later, the **Habitat Directive** (Council Directive 92/43/EEC, dated 21 May 1992) on the conservation of natural habitats and of wild fauna and flora established in Article 10 that Member States shall endeavour to develop policies to "*encourage the management of features of the landscape which are of major importance for wild fauna and flora*. *Such features are those which, by virtue of their linear and continuous structure (such as rivers with their banks or the traditional systems for marking field boundaries) or their function as stepping stones (such as ponds or small woods), are essential for the migration, dispersal and genetic exchange of wild species"*.

Subsequently, the **Water Framework Directive** (Directive 2000/60/EC, dated 23 October 2000) established transversal barriers as part of the anthropic pressures to be considered, river continuity as one of hydromorphological indicators in quality monitoring programmes, and the recovery of longitudinal connectivity as part of good ecological status: *The continuity of the river is not disturbed by anthropogenic activities and allows undisturbed migration of aquatic organisms and sediment transport*.

Currently, many of the guidelines of the Habitat Directive and Water Framework Directive are already reflected in Spanish legislation. Thus, Law 42/2007, dated 13 December 2007, on Natural Heritage and Biodiversity, states in Article 20 that Public Administrations will plan mechanisms to achieve ecological connectivity of the territory for which priority will be given to river courses. Subsequently, the Regulation of the Hydraulic Public Domain (introduced by Royal Decree 1290/2012, dated 7 September 2012), in Article 126, expressly indicates the conditions to guarantee the fluvial continuity and establishes that:

1. The basin authority will promote respect for the longitudinal and lateral continuity of rivers, making it compatible with current water uses and the hydraulic infrastructures included in hydrological planning.

2. In the specifications of the new concessions and authorizations or the modification or revision of existing ones, which include transversal works in the river, the basin authority will require the installation and adequate conservation of devices that guarantee it is crossed by the native ichthyofauna. The same requirement will apply to existing works of this type, linked to concessions and authorizations that include this obligation in their specifications or that must incorporate such devices in the application of current legislation.

3. The basin authority will promote the elimination of infrastructures that, within the public hydraulic domain, are abandoned without fulfilling any function linked to the use of water, taking into consideration the safety of people and goods and assessing the environmental and economic effect of each action.

4. For the granting of new authorizations or concessions for transversal works in the river, which due to their nature and dimensions may significantly affect the transport of sediments, an evaluation of the impact of those works on the sediment transport regime of the river shall be required. In the exploitation of those works, measures to minimize this impact will be adopted.

In the case of an expired concession, Article 89 of the aforementioned Regulation, states that:

5. When the concession right is extinguished, all the works that have been built within the hydraulic public domain will revert to the State, free of liens and encumbrances. If, at that moment, the Hydraulic Administration considers the continuity of the use to be possible and convenient, it may demand from the concessionaire the delivery of the goods subject to reversion under exploitation conditions. If, on the contrary, it considers it unfeasible, or its maintenance is contrary to the public interest, it may demand the demolition of what has been built in the public domain in accordance with article 101 of Law 33/2003, dated 3 November 2003, on the Patrimony of the Public Administrations.

It should be remembered at this point that the aforementioned Article 101 explicitly states that "*when the concession is extinguished, the works, constructions and fixed installations existing on the property shall be demolished by the concession holder or, by subsidiary execution, by the Administration*". Therefore, in these cases, the demolition is a legal obligation of the Administration. (To see more in CIREF, 2017).

Portuguese legislation has also transposed the European directives to its national legal order by the Lei del Áqua nº 58/2005, dated 29 December 2005, modified by four subsequent Decree-Laws since its publication, and the water resources planning instruments: National Water Plan, approved by Decree-Law No. 76/2016, dated 8 November 2016, and the Hydrographic Region Management Plans approved through the Resolution of the Council of Ministers No. 52/2016, dated 20 September 2016. The environmental objectives for surface water are featured in the watershed management plans, including the description of the significant impact of human activity, where the continuity of the river is one of the hydro morphological elements to be considered.

Current legislation in Portugal does not establish the removal of medium- and large-sized dams at the end of the concession period. It foresees their reversion to the State, and legal procedures to this effect exist, in particular in the Regulation of Safety of Dams (Regulamento de Segurança de Barragens), which must be met in cases of abandonment. Decree-Law No. 226-A/2007, dated 31 May 2007, states the demolition of infrastructures in relation to abusive uses, a situation in which demolition may be charged to the offender (Article 2); and in relation to the term of the license (Article 34) according to which the owner has to remove the temporal facilities, demolish the works executed on the riverbed, as well as the fixed installations, unless the competent authority opts for the reversal free of liens and encumbrances. The demolition or elimination of facilities is carried out by the concession holder, who must restore the river to its condition prior to the execution of the works. In spite of the above provisions, for licensed uses, which represent many of the dams and licensed weirs, the legislation stipulates that at the end of the term of the concession, the State takes free possession of the infrastructures and facilities of the concession (article 35), but without any reference to a resulting demolition.

Recently, a working group in this country, the Conselho Nacional da Água, has just drawn up a National Strategy for the Elimination of Obsolete Hydraulic Infrastructures and assess aspects related to the elimination of disused infrastructures, including information on barriers, a diagnosis of the current situation regarding the presence of dams and weirs in the various river basins, and the establishment of the information to be obtained and the criteria for a systematic selection of infrastructures to be eliminated in Portugal (CNA, 2017). The report of this strategy also points out that there are still huge administrative difficulties associated with the dam and weir removal projects in this country.

This Strategy forms part of the Plano Nacional da Água (Decree-Law No. 76/2016, dated 8 November 2016), which establishes the preparation of a Specific Plan for the reconstitution of fluvial continuity, and with the Plans of Gestão de Região Hydrographic

(Resolution of the Council of Ministers No. 52/2016, dated 20 September 2016), which identify hydromorphological pressures in several water bodies and propose measures to reduce them, including the elimination of infrastructures. All these measures would be in line with the Water Framework Directive in its objective of contributing to the achievement of the Good Ecological Condition of all water bodies.

4.3. Benefits of dam removal and improvements in river connectivity

Nowadays, the removal of dams that have lost their function is considered one of the most effective tools for the recovery of the ecological quality of a river in the medium-long term, which, in the majority of cases, would have a significant net positive impact on riverine ecosystems and aquatic biodiversity (Hart et al., 2002; Orr et al., 2004; Perkin et al., 2015; Tonra et al., 2015). Habitat connectivity can prove to be a key determinant of fish species distribution and community composition and there is evidence that dam removal has more ecological benefits on the movement of fish and improvement of water quality than fish ladders (Bednarek, 2001; Slawski et al., 2008). The benefits of dam removal on fish assemblage and distributions were shown over relatively short periods of time; nevertheless, they all indicated or predicted the positive impacts of dam removal on native species and, moreover, that these benefits would be not only upstream of the barrier, but also downstream (Birnie-Gauvin et al., 2017).

In addition, in most cases, the costs involved in removal are lower than those of repair and maintenance, and even in those cases where they are comparable, removal puts an end to the cost of future repairs (Orr et al., 2004). Safety reasons are also vital, especially in cases in which the dams are in bad condition and hold large amounts of water (Stanley & Doyle, 2003). In North America and Europe, more and more old and obsolete dams are being eliminated and, in some countries dam removal now outpaces construction (O'Connor et al., 2015; Beatty et al., 2017). Thus, the literature points out that the benefits that removing unnecessary dams has on rivers and aquatic organisms are evident (Hill et al., 1993; Poff, 1997; Bednarek, 2001; American Rivers & Trout Unlimited, 2002; Graf, 2003; Lytle & Poff, 2004):

- Restoration of fluvial habitat.
- Recovery of the natural flow regime, which significantly favours biodiversity.
- Depending on the size of the dam, recovery of the original morphology of the channel, including the floodplain, the fluvial annexes and the adjacent wetlands.

- Improvement in water quality by reducing hydraulic retention time, which can lead to eutrophication phenomena and, depending on the size and depth of the reservoir, even stratification phenomena.
- Redistribution of sediments and favouring transport and the deposition of solid flows, improving river dynamics and the renewal of habitats.
- Improvement of the distribution of nutrients and of the self-purification capacity of the river.
- Recovery of longitudinal connectivity, enabling migratory movements of fish and other organisms, as well as the rehabilitation of threatened and endangered species.

It is also necessary to consider that complete or partial physical removal of obstacles restores a greater proportion of natural processes (Poff & Hart, 2002), compared with the construction of a fishway, which is at best a mitigation measure (Kemp, 2016). In addition, the difficulty of the fishway being effective for several species of migratory fish in a dam may involve the construction of several fish ladders, in order to adapt to the different characteristics of each species (Silva et al., 2017).

However, before removing or improving the connectivity the obstacles in a basin, it is necessary to take into account further factors, in addition to the ecological benefits of longitudinal connectivity. The action made on a dam is also an ecological disturbance in itself: the mobilization of sediments, erosion, the elimination of the new lentic ecosystems, the impossibility of returning to the original state, etc. (Bednarek, 2001; Stanley & Doyle, 2003; Beatty et al., 2017).

Moreover, there may be negative impacts associated with reconnecting ecosystems related to the spread of invasive species (McKay et al., 2013). This is especially important in the management of watersheds with a dendritic structure. Habitats in dendritic stream systems are highly prone to fragmentation and also the spread of invasive species (Fagan, 2002; McKay et al., 2013). Thus, priority indexes that include the benefits and drawbacks of one or several interventions are developed and this allows decision-making to be facilitated when intervening on the weirs of a specific stretch or mass of water. In the case that concerns the present report, this means prioritizing actions in the stretches of river with native species over those with invaders, or directly discarding the actions if there is a risk of invasion.

There are examples in both Spain and Portugal of this type of index. Branco et al. (2014) provides a methodology for prioritizing the removal of barriers in Portugal for Iberian barbell *Luciobarbus bocagei* and Southern Iberian chub *Squalius pyrenaicus*, but does not take into account the presence of exotic fish. In Spain, the Duero, Tajo and Segura water Authorities use a Priority Index of Intervention, and the Internal Basins of Catalonia Agency has an Obstacle Priority Index (CIREF, 2016). A good example is the Priority Index of Intervention in weirs, which was developed in the Duero basin (González et al., 2011) and also transferred to the Segura and Tajo basins. This index considers eight factors that limit and facilitate the selection of the dams on which to act, namely those with the least possibilities of being overcome, in order to recover the largest barrier-free length of river with a greater number of autochthonous species. One of these factors prioritizes the intervention in weirs that do not include invasive alien species. In fact, the possibility is mentioned that some dams should be maintained as barriers to the expansion of these species. The Obstacle Priority Index develops a sum of parameters associated with the obstacle and in its environment, which are scored according to their representativeness for the execution of actions to improve connectivity (Agència Catalana de l'Aigua, 2010). On the other hand, this index does not assess the presence of invader species, only whether the body of water is declared as a Genetic Reserve of brown trout *Salmo trutta*.

In this respect, during the first years of the twenty-first century there has been an increase in the development of measures to improve the connectivity of obstacles in **Spain**. Increasingly taking into account the elimination of weirs as a practice to improve the longitudinal connectivity of rivers, and also the construction of new fish passages. In line with the objectives set out in the Water Framework Directive, the implementation of the National Strategy of River Restoration has been a strong stimulus in the process of barrier connectivity improvement and dam removal. Thus, during the years 2006–2014, about 200 weirs were removed and about 100 fish passages were built (CIREF, 2016).

However according to this report, there are still many problems to be addressed. For example, there are marked differences with respect to the amount of information available (and its quality) regarding the issue of barrier inventories and the existence of plans to improve the longitudinal connectivity of rivers in each basin, and only a few basins have applied connectivity indices to assess the passability of obstacles in their basins. Furthermore, a large number of fish passages are not operative, so they do not solve the river disconnection problem.

The evaluation of the ecological repercussions associated with the recovery or improvement in connectivity of an obstacle and the expansion of invasive alien species, especially compared with threatened endemic fish species, is still reduced to very few projects.

In **Portugal**, an exhaustive inventory of the hydraulic infrastructures that constitute physical barriers in rivers is in progress—initiated thanks to the Project of Identification and Characterization of Obstacles to Fluvial Continuity, the National Cadaster for River Continuity and the Portuguese National Commission of Large Dams Methodologies—and criteria for evaluating obstacles to fish movements continue to be refined (Bochechas, 2014). The assessment of fluvial continuity has been carried out more exhaustively in two Portuguese rivers, the Sabor River and Ribeira do Vascão. The results advise the recovery of fluvial continuity and the development of priority intervention mechanisms over obstacles (Bochechas, 2016a).

The recent proposal of the Conselho Nacional da Água (CNA, 2017) lays the groundwork for a national strategy for the elimination of obsolete hydraulic infrastructures and aims to recover fluvial ecosystems. It also tries, based on the update of the available information, to establish two types of actions: to either totally or partially removal dams or weirs, or to adopt alternative actions such as the application of ecological flow regimes and passage facilities for fish. The aforementioned strategies call for a complete inventory of dams and weirs, without limitations of information, which would allow their impact to be quantified (mainly the migration of organisms and sediment transport) and the degree of fragmentation of the water bodies to be evaluated. The CNA report (2017) also makes a preliminary assessment of some obstacles that may be eliminated in several Portuguese river basins and that may serve as pilot cases for future implementations of the Hydrographic Region Management Plans.

Given the difficulty in applying the Strategy simultaneously to all existing infrastructures, the application of criteria for the selection of priority action areas has been proposed, in a similar way to the priority indices previously indicated for Spain. In this case, the priority levels focus on the criteria of high biodiversity and those that affect the management plan of the eel, among others, but do not take into account the presence of invasive alien species.

Unlike in Spain, the removal of dams and weirs in Portugal has been very specific and framed within larger projects, although these projects also included the construction of fish ladders and naturalized ramps (CNA, 2017). The Portuguese Administration indicates a recent project to eliminate several infrastructures without socioeconomic function, independent of those that were proposed in the report of the Conselho Nacional da Água (CNA, 2017).

5. THE SPREAD OF INVASIVE ALIEN SPECIES

5.1. What are invasive alien species and how do they affect ecosystems?

An **invasive alien species** is a non-native or non-indigenous species whose introduction (by humans, whether intentional or not), establishment and spread threaten ecosystems, habitats and native species, and have negative impacts on ecosystem services and/or on socio-economic and/or health aspects (Sarat et al., 2015). Moreover, more than half of the animal extinctions in recent centuries list invasive alien species among their causes (Clavero & García-Berthou, 2005). There are almost 11,000 non-native species in Europe, of which 10–15% are expected to have a negative economic or ecological impact. The damage caused by these species and the measures taken to control them are estimated to cost EUR 12 billion annually in the European Union.

Aquatic environments are ecosystems that are very sensitive to the alterations provoked by invasive species because of their strong negative influence on the abundance of aquatic communities, particularly macrophytes, zooplankton and fish, as their dispersion capacity is limited and their distribution is restricted to water bodies (Kolar & Lodge, 2000). Invaded habitats showed increased water turbidity, nitrogen and organic matter concentration, which are related to the capacity of invaders to transform habitats and increase eutrophication (Gallardo et al., 2016).

Species introductions have frequently been cited as an important threat to native freshwater fauna. The presence of invasive alien fish is one of the main causes of the decline in populations and genetic integrity of native freshwater fishes worldwide (Ribeiro et al., 2008), and can cause the extinction of native fish fauna (Clavero & García-Berthou, 2005). The consequences that introductions produce in the environment tend to be very negative and difficult to predict and the possible benefits to be obtained (fishing, extensive aquaculture and vegetation control) do not compensate the presumable losses of biodiversity in the ecosystem (Moyle & Moyle, 1995; Cowx, 1997). Indeed, biotic homogenization of freshwater fish faunas is a reality that has high ecological and economic costs (Rahel, 2000).

In short, the introduction of species changes the composition of communities and reduces the abundance of native species through four mechanisms: trophic relationships, hybridization and genetic alteration, the introduction of parasites and diseases, and global changes in the ecosystem functions. However, prior to this, the alien species must overcome various geographic and/or environmental barriers before they become invasive

(Richardson et al., 2000). These phases are: introduction, adaptation, naturalization, and expansion. The exotic species present in a river that could benefit from the removal or improvement in connectivity of a transversal barrier have already overcome all these phases and can expand in the new area by colonizing new habitats upstream.

In Spain, the acclimatization of exotic fish is also among the main threat factors that negatively affect the survival and conservation of native freshwater fish species (Elvira & Almodóvar, 2001; Doadrio & Aldeguer, 2007), as many of them are invasive and predators of the local ichthyofauna. On a global scale and as a loss of diversity, this fact is important, since the native freshwater fish fauna of the Iberian Peninsula is one of the most endemic in the world (Doadrio et al., 2011b). In Portugal there are also numerous species of introduced fish, some of which are responsible for the decline in numbers of the native species (Pinheiro, 2017).

5.2. Legislation on invasive alien species

The main international agreement on invasive alien species is the Convention on Biological Diversity, formulated in Rio de Janeiro in 1992, which states that each signatory party "*shall prevent the introduction, control or eradication of alien species that threaten ecosystems, habitats or species*". That same year, European legislation exhibited this concern in the **Habitat Directive** (Council Directive 92/43/EEC, dated 21 May 1992) on the conservation of natural habitats and of wild fauna and flora, by stating "*whereas provision should be made for supplementary measures governing the possible introduction of non-native species of fauna and flora".* Article 32 establishes the requirement for Member States to: "*ensure that the deliberate introduction into the wild of any species which is not native to their territory is regulated so as not to prejudice natural habitats within their natural range or the wild native fauna and flora and, if they consider it necessary, prohibit such introduction"*.

In this regard, in 2008, the European Commission issued the communication "Towards an EU strategy on invasive species" [COM (2008) 789 final - Not published in the Official Journal] and to prepare a strategy to tackle this problem, which is one of the major threats to biodiversity. This Commission recommended measures such as control and/or confinement if the invasive species *is already established, as well as the implementation of coordinated action*. This gave rise to Regulation (EU) no 1143/2014 of the European Parliament and of the Council, dated 22 October 2014 on the prevention and management of the introduction and spread of invasive alien species, in addition to several subsequent regulations that adopt a list of invasive alien species, such as EU: Regulation (EU) 2016/1141 and Regulation (EU) 2017/1263.

Regarding Spanish legislation, Article 52 (paragraph 2) in Law 42/2007 of Natural Heritage and Biodiversity prohibits the introduction of species, subspecies or allochthonous geographic races when these are liable to compete with the autochthonous wild species, alter their genetic purity or ecological balances. Some Regional Governments, through their competencies in the field of nature conservation, have also developed additional legislation to prevent the introduction of alien species in their respective territories.

As a development of the previous law, currently in Spain the main tool that regulates exotic species is the Spanish Catalogue of invasive alien species (Royal Decree 630/2013). The catalogue includes exotic species on which scientific and technical information exists to indicate they constitute a serious threat to native species, habitats or ecosystems, agronomy, or to economic resources associated with the use of natural heritage.

Article 7 (section 4) states that: in no case, may actions or behaviour aimed at promoting the species included in the catalogue be considered.

Article 10 details the measures to fight against the invasive alien species in the catalogue, and rivers are specifically referenced in Section 3, which states: The competent authorities will require the promoters of works in water courses to report the presence of species in the catalogue in those water bodies that are to be the source of transferences or temporary or permanent deviations of water. In the event of the presence of these species, the project will be reviewed to study alternatives and preventive measures that do not imply dispersal of these species, or the suspension of the project will be assessed. Similarly, if work is carried out in water courses affected by the species in the catalogue, preventive protocols for the dispersion of species to non-affected courses should be applied.

In Portuguese legislation, the introduction of non-indigenous species into natural environments, as well as their detection, are regulated by Decree-Law No. 565/99, with the modifications provided for in Declaration of Rectification No. 4-E/2000. This legislation regulates the intentional or accidental introduction of non-indigenous species into the continental territory of Portugal and its watersheds. Annexes I and III detail the non-indigenous wildlife species already introduced and those that carry a known ecological risk, respectively. Annex I details the species introduced in each river basin, including fish, and specifies those that have an invasive character. However, it is an older law than the Spanish law and it has not been updated to include new invasive species or the degree of threat they represent. Nevertheless, this legislation was stated to be under review in 2011 (ICNIB, 2012), which included updating the list of non-indigenous species present in Portugal, as well as the associated ecological risk.

Another recent Decree-Law, 112/2017, regulates the management of aquaculture resources in inland waters of Portugal. The only mention it makes of the use of exotic species in aquaculture is to state that it is subject to European Regulations and to the law of introduction of non-indigenous species.

In Appendix II of this report, the invasive exotic species of continental fish in Spain are listed and several of their characteristics are indicated. The catalogue of invasive alien species in Portugal only lists two fish with an invasive character: the Eastern mosquitofish *Gambusia holbrooki*, and the pumpkinseed *Lepomis gibbosus.*

5.3. Invasive alien species in the Iberian Peninsula

In the Iberian Peninsula, exotic fish constitute 45% of all the ichthyofauna present, or 55% if we consider only the strictly freshwater species. Spain is the country in Europe with the fifth largest number of exotic species, after France, Italy, Russia and the Czech Republic (Copp et al., 2005). However, in terms of the proportion of the number of species, Spain is the third country, after France and Italy, which shows the magnitude of the problem. In general, escapes from fish farms, the culture of ornamental fish and especially sport fishing, are the main agents that cause the introduction and dispersion of new exotic species in Spanish continental waters (Doadrio et al., 2011b).

Although there have not been many works that establish a direct relationship between the introduction of exotic species and the extinction of native species, an analysis of the data published by the IUCN allows us to establish that 54% of extinct species have been partially due to the introduction of exotic species, and 20% have occurred specifically due to their presence (Clavero & García-Berthou, 2005). Some studies have revealed local extinctions and strong declines in native species populations (García-Berthou & Moreno-Amich, 2000), along with the decreasing distribution areas of native species (Aparicio et al., 2000), both of which are related to the establishment and expansion of introduced species in the Iberian Peninsula.

In the Iberian Peninsula, the number of introduced fish species is continually rising and established invasive species are spreading through both natural expansion and secondary introductions allowing inter-basin jump dispersal (Clavero & García-Berthou, 2006).

The modification of river characteristics by damming has favoured the establishment of introduced species in Iberian rivers. Natural Mediterranean rivers undergo enormous annual flow variations and lentic habitats are scarce (Elvira & Almodóvar, 2001). In this environment, Iberian freshwater fish are habitat generalists that are very well adapted to survival in constantly changing environments (Magalhães et al., 2002). However, impoundments provide the stable lentic habitats in which introduced species, many of them predatory, can develop thriving populations. It is also commonly assumed that introduced species can more easily become established in altered ecosystems, such as those created by impoundments (Fig. 4). The establishment of new reservoirs is an important threat to the native freshwater fish fauna, through promoting the establishment of introduced species, most of which exhibit a high degree of invasiveness in these artificial ecosystems (Clavero et al., 2004). Nevertheless, there are differences in Iberian reservoirs: those in the Mediterranean area feature more introduced species than native ones, due to the presence of introduced piscivorous species; whereas an opposite pattern is seen in the temperate climate areas (Clavero et al., 2013).

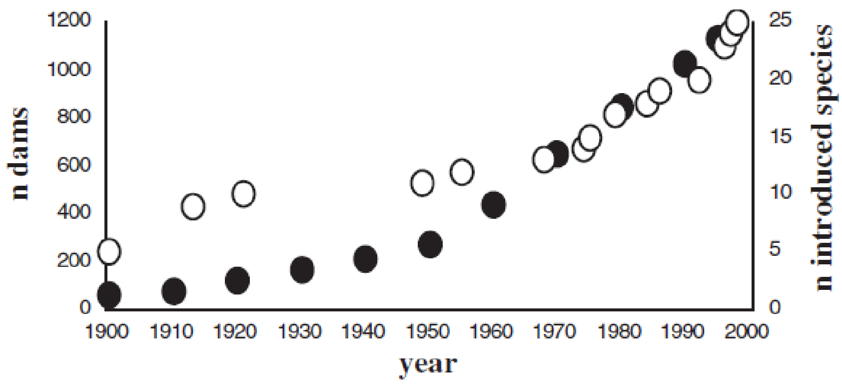


Figure 4. Cumulative numbers of dams (filled circles) and introduced fish species (empty circles) during the twentieth century in Spain. Data on dams from MMA (1998) and data on introduced species from Elvira & Almodóvar (2001). Source: Clavero et al. (2004).

Most of the exotic fish species in the Iberian rivers are characterized by large size, long life spans, late maturity, high fecundity, few spawnings per year, and short reproductive spans. Conversely, Iberian native species predominantly exhibit the opposite suite of traits due to the high hydrological variability of Mediterranean rivers, as well as generalist and opportunistic feeding strategies (Vila-Gispert et al., 2005; Ferreira et al., 2007). The wide-scale damming of Iberian rivers has led to the introduction of game fishes into reservoirs to promote recreational fisheries (Clavero & García-Berthou, 2006). Moreover, most of the invasive species show water quality flexibility and tolerance to pollution and habitat disturbances.

In Portugal it has also been indicated that the expansion of invasive species is favoured by the changes in river systems, especially by the reservoirs themselves, which entail the rupture of the river continuum, an increase in depth, fluctuations in the level of water, and unguarded margins without vegetation. These ecological conditions rarely benefit the native species, which are not ecologically prepared to adapt to these environmental conditions. This means that, in most situations, the artificial lentic systems are dominated, in number and biomass, by exotic species (Godinho, 2000; Pinheiro, 2017). In Spain, it has been highlighted that the proliferation of dams and reservoirs from the 60s caused a profound alteration of the continental aquatic environments due to the regulation of flows, causing a loss of torrentiality and floods and the homogenization of the flow throughout the year, which has favoured the acclimatization and expansion of exotic fish species (Elvira, 1995; Martínez-Capel et al., 2010; Yagüe et al., 2010). The proliferation of weirs also favours the deposition of silts that ends up covering the riverbed, delaying the aeration of the substrate and annulling the interstitial space, both of which have very negative effects on the spawning areas and on the recruitment of young native fish species (Martínez-Capel et al., 2010). Thus, in the Iberian Peninsula, most of the invasive species of fish currently occupy medium and low sections, except for some species of salmonids that are present in high sections.

Furthermore, it is not only exotic species from other countries, outside the scope of the Iberian Peninsula, that can cause impacts on local fauna; the translocation of fish between Iberian basins are another important cause of the loss of biological diversity (Leunda, 2010; Doadrio et al., 2011b). Among the particularities of the Iberian ichthyofauna, in addition to its high number of endemisms, the presence of different fish communities in each river basin is remarkable. The Iberian species of fish also present differences in their reproductive characteristics, size and longevity between populations that live in small streams and those that live in large rivers (Vila-Gispert et al., 2005). Therefore, translocations of fish from one basin to another, within the Iberian Peninsula, are liable to have as negative an impact as the introduction of exotic species (Doadrio et al., 2011b).

Despite its impact, translocation has been studied less and scientific studies in the Iberian Peninsula are especially scarce. The best-studied example is the translocation of *Pseudochondrostoma polylepis* to the Júcar basin, which is threatening the native nase, *Pseudochondrostoma arrigonis* due to its hybridization and the interspecific competition between them (Doadrio et al., 2011a). Also in the Júcar basin, a model on microhabitat selection and habitat suitability was developed. In this model it is shown that the Júcar nase will compete, spatially and temporally, for the few suitable microhabitats with bermejuela *Achondrostoma arcasii* and, to a lesser extent, with small Iberian nase (Muñoz-Mas et al., 2017). The other examples of translocations mentioned by Doadrio et al. (2011b) are: the expansion of Pyrenean gudgeon *Gobio lozanoi* from northern Spain to almost the entire Peninsula; the presence of the Pyrenean minnow *Phoxinus bigerri* in many rivers of the Duero basin, coming from the Ebro basin; the appearance in northern basins of the Southern Iberian spined-loach *Cobitis paludica* when it is typical of central and southern Iberia; or the presence of Ebro nase *Parachondrostoma miegii*, also coming from the Ebro basin, in the rivers of the Catalan internal basins.

6. STUDIES: CONNECTIVITY AND INVASIVE SPECIES

Studies that attempt to relate the removal or connectivity improvement of barriers in rivers with the expansion of invasive alien species are scarce. Most of them only refer to the fact that measures to recover the longitudinal connectivity of a river can favour invasive species, but do not detail or analyse the consequences or measures to be taken to stop their expansion, nor describe how to help conserve the threatened native species. Many of the studies and projects dealing with this problem are based on research carried out with salmonids and very few deal with cyprinids, a group to which many of the most threatened endemic species of the Iberian Peninsula belong. In addition, most of these studies were made in North America, and there have been very few studies carried out in the Iberian Peninsula or in Europe.

Below are examples of these studies, which mention the problem of the restoration of fluvial continuity against the expansion of invasive alien species. In addition, some of them also include internal references about other works or experiences related to the purpose of this report. Some cases of the effects of the restoration of connectivity on hybridization due to translocation and the expansion of exotic crabs are also included. In each bibliographical reference a summary is included that indicates the geographical area of the study, as well as the main proposals or questions that it addresses.

This section only provides a list of the main studies consulted. The subsequent section, evaluation criteria, is where the proposed measures are analysed and discussed. In each of the studies mentioned hereunder, the main ideas are cited in italics:

Calamusso & Rinne, 1999. Native montane fishes of the Middle Rio Grande ecosystem: Status, threats, and conservation.

The primary objective of this paper is to present an overview of the status, threats and conservation strategies for three native species in the Rio Grande, New Mexico, United States. To protect the populations of one of these species, the Rio Grande Sucker (RGS) *Catostomus plebeius*, the use of barriers and dams against the advance of invasive species is highlighted.

Surveys to identify unknown populations of RGS need to continue. The known populations of RGS warrant protection from invasion by the white sucker and non-native salmonids. Instream barriers need to be constructed for tributaries draining to the Rio Grande and Chama River.

While streams within the Jemez drainage are currently safe from intrusion by the white sucker due to Jemez Canyon Dam white sucker may eventually be introduced into this system via bait bucket. Regulations may be warranted to limit any use of non-native bait or to prohibit the use of bait in the Jemez system above the Jemez Canyon Dam. White sucker have been found in the Rio Chama and in its southern tributaries (for example Canones Creek). Here, the only way to prevent white sucker from expanding its range into streams containing RGS would be the placement of barriers. Due to the precarious status of northern populations of RGS protection of populations of RGS in isolated Rio Grande tributaries in southern New Mexico should be considered. Restoration efforts should identify those waters having modest gradients (<2.5 percent) with well developed glide/pool habitat within a mosaic of various habitat types.

Harig et al., 2000. Factors influencing success of greenback cutthroat trout translocations.

This study about the native subspecies of cutthroat trout *Oncorhynchus clarki* compare successful and failed translocations in the wild and in hatcheries in Colorado, United States.

Of the translocations that failed, 48% were reinvaded by non-native salmonids, 43% apparently had unsuitable habitat, and 9% experienced suppression by other factors.

Reinvasion occurred most often because of failed artificial barriers or incomplete removal of non-native salmonids in complex habitats. Of those areas that were not reinvaded, success was highest in receiving waters with at least 2 ha of habitat that had previously supported reproducing trout populations.

Three translocations were thought to have failed when brook trout, brown trout, or rainbow trout breached artificial barriers to fish movement (i.e. the invading species were found just upstream from the barriers). Non-native salmonids breached rock gabions and wooden dams either by surmounting structures (heights ranged 1–3 m) or through channels eroded around or beneath the barrier. Choosing only natural barriers unlikely to fail could reduce the risk of translocation failure. That is, no artificial barrier, except an 18-m high reservoir spillway, successfully prevented upstream movement of non-native salmonids, whereas all other successful greenback cutthroat trout populations were above natural waterfalls or steep cascades.

Lintermans, 2000. Recolonization by the mountain galaxias *Galaxias olidus* of a montane stream after the eradication of rainbow trout *Oncorhynchus mykiss*.

This work about native mountain galaxias in Australia studies the use of barriers and targeted eradication programmes for the management of small, threatened fish species. This author demonstrates that treatment of small streams with rotenone is a rapid and cost-effective technique for removing exotic trout species, and provides a useful management tool for conserving threatened native fish, using weirs as barriers.

The effectiveness of the augmented weir in Lees Creek as a long-term barrier to trout movement indicates that only relatively small structures are required for trout exclusion. The present barrier is an engineered concrete construction, but natural materials such as boulders and logs should prove equally effective. Where there are natural barriers (such as waterfalls) in streams, there is no need to construct barriers. Whatever type of barrier is used, there is an ongoing need to prevent deliberate re-introduction of trout by anglers.

There has been no need for maintenance of the weir during the study, making it an extremely cheap option for trout exclusion. The piped road crossing at the Blundells/Lees creeks confluence has also provided a long-term barrier to trout movement. The piped section of creek provides a 15 m length of relatively fast, unbroken flow with no cover available to provide respite from the current for trout. Although it was not constructed as a barrier to fish movement, it demonstrates that relatively minor works on small streams can prove as effective an upstream barrier as large impoundments. However, care needs to be taken by land and water management agencies when contemplating such works because of their capacity to block native fish movements.

Marchetti & Moyle, 2001. Effects of flow regime on fish assemblages in a regulated California stream.

These authors indicate that native fishes in streams of the western United States exhibit different habitat requirements and respond to temporal variation in flow in a different manner than non-native fishes. The restoration of the natural flow is a very important factor for the restoration of the fish community when a dam is removed.

Restoration of natural flow regimes, in company with other restoration measures, is necessary to conserve the native fish populations. Native fishes tended to cluster in areas with colder temperatures, lower conductivity, less pool habitat, faster streamflow, and more shaded stream surface. Numbers of non-native fish were negatively correlated with increased streamflow, and numbers of native fish were positively correlated with increased flow.

It is widely recognized that a natural hydrograph reduces the invasibility of undammed streams by alien fishes (Baltz & Moyle, 1993; Stanford et al., 1996). Understanding how a more natural flow regime favors native fishes and other organisms can help to establish favorable flow regimes in regulated streams with minimal costs in additional releases of water from dams (Power et al., 1996). The improvement of habitats for native fishes while simultaneously decreasing the abundance of alien fishes are synergistic actions because alien species can limit native species through competition and predation.

American Rivers & Trout Unlimited, 2002. Exploring dam removal: A decision-making guide.

This report about dam removal in United States exposes some benefits reported by not removing a dam, both by the effect of the works and by the barrier effect for invasive fish, parasites and toxins.

Scientists have found that when river habitat and natural flow fluctuations are restored to a river, natural diversity and populations of river and riparian species increase. Higher species diversity is typically an indicator of better river health, and riverine species typically require less in management costs than non-native species.

In some cases, dams and other blockages in a stream can provide benefits to fish populations. For example, a dam may serve as a barrier to undesirable non-native species, preventing them from moving upstream or downstream and reaching vulnerable native species and habitats. A dam may also prevent downstream fish contaminated with parasites or toxins from infiltrating the river's upper reaches. In these situations, dam removal may not be advisable, or a smaller barrier may need to be constructed after removal to prevent undesired migrations. In addition, conducting dam removal activities when fish are migrating can cause harm. Scheduling the removal at a time when fish are not migrating up or downstream can avoid this harm.

Several question tables are also presented, detailing the effects of keeping or removing the dam with regard to upstream and downstream flows, wildlife populations (Box 1), the habitat, passage and movement of fish and other species (Box 2), sediment movement, water quality, riparian areas, wetland areas, and location of the dam within the watershed. Some interesting questions about the problematic dam removal versus the spread of invasive alien species are included in these tables:

EFFECT OF KEEPING THE DAM

1. What fish and wildlife species benefit from the dam? Are these species of concern?
2. What fish and wildlife species does the dam negatively affect? Are these species of concern?
3. Can riverine species reproduce at a sustainable rate in the impoundment? Are they threatened by non-native species?
4. Are contaminated sediments built up behind the dam currently harming fish and wildlife or likely to in the future?
5. Is the current condition of fish and wildlife consistent with published river or fisheries management plans applicable to the area?

EFFECT OF REMOVING THE DAM

1. What fish and wildlife species will benefit from dam removal? Are these species of concern?
2. What fish and wildlife species will suffer from dam removal? Are these species of concern?
3. Will the process of removing the dam negatively impact fish and wildlife populations in the short-term? Long-term?
4. If any contaminated sediments are built up behind the dam, will their release be harmful to fish and wildlife?
5. Will dam removal be consistent with published river or fisheries management plans applicable to the area?
6. Could any negative impacts to fish and wildlife that are attributed to the removal process be reduced or eliminated by altering the project's timing or design?

Box 1. Questions about fish and wildlife. Is the net impact of dam removal on fish and wildlife populations positive or negative? Image taken from American Rivers & Trout Unlimited (2002).

EFFECT OF KEEPING THE DAM

1. Does the dam prevent undesirable, non-native, diseased, or contaminated species from spreading throughout the river system?
2. Does the dam block movement or migration of fish or other wildlife (such as shrimp or mussels)? Are any of these species of concern?
3. Does the dam have effective fish passage devices, or could they be installed, to aid passage of fish and wildlife species? Will the devices be effective at passing all species and "life stages" of concern? What species mortality rates are associated with these devices? What is the cost of installing and maintaining the fish passage devices?
4. What kind of impact does the impoundment have on fish migration (e.g., affecting upstream and/or downstream migration as the species navigates a lake-like as opposed to a river environment)? Can this impact be reduced or eliminated?
5. What is the cumulative impact of all of the river's dams on fish migration? Can these impacts be reduced or eliminated?

EFFECT OF REMOVING THE DAM

1. Will dam removal result in an increased survival rate for species of concern by allowing these species to reach appropriate spawning, rearing, and foraging habitat?
2. Will dam removal restore access to any species' historic range?
3. Will removing the dam encourage the spread of undesirable species? Could measures be taken (e.g., building another smaller barrier) to prevent the spread of undesirable species?
4. Will removing the dam allow contaminated or diseased fish to move into sections of the river not currently contaminated?
5. Will the physical deconstruction of the dam have a negative impact on the movement of fish and other aquatic species (e.g., mussels)? Can the removal process be timed to avoid negative impacts or will temporary fish passage be necessary?

Box 2. Questions about the passage and movement of fish and other species. Will dam removal improve the safe passage of migrating fish and the movement of resident fish and wildlife? Is dam removal necessary to accomplish this? Can dam removal be undertaken without enabling the spread of undesirable species? Image taken from American Rivers & Trout Unlimited (2002).

American Rivers, 2002. The ecology of dam removal: a summary of benefits and impacts.

This report, also in the United States, summarizes some limited short-term ecological consequences of dam removal and the long-term ecological benefits of dam removal—as measured in improved water quality, sediment transport, and native resident and migratory species recovery—which demonstrate that dam removal can be an effective long-term river restoration tool.

The slower water flow and larger surface area created by dams can alter the species composition of organisms in the river, favoring slower-moving aquatic species that are better adapted to lake-like bodies of water, in many cases invasive species.

Dam removal often displaces warm-water species that prefer a lake-like environment, while promoting the recovery of fish populations that prefer colder-water rivers.

Removing a dam on a contaminated river can have a negative impact on the stream community. In some cases, dams create a useful barrier between fish populations up- and downstream of a dam. For example, if fish populations are contaminated with toxins *downstream of a dam, the dam may prevent these same populations from migrating upstream and contaminating fish populations above the dam. Additionally, dams can prevent the invasion of exotic species either above or below the structure.*

Hart & Poff, 2002. A special section on dam removal and river restoration.

These two authors with extensive experience in studies in North America, only reflect the complexity and the multitude of factors that affect a river where a dam is removed, including the effects on invasive species.

The successful repair of damaged systems will require a deep understanding of the processes that determine their structure and function. Biologists have a critical role to play in creating this knowledge because of their expertise in such varied phenomena as the role of microbes in detoxifying anthropogenic contaminants, the effects of disturbance on population persistence, and the factors influencing competitive interactions between native and exotic species.

Hart et al., 2002. Dam removal: challenges and opportunities for ecological research and river restoration.

This paper only mentions the case of sea lamprey as an invasive species in the lakes and rivers of North America.

Despite the recommended usage of dam removal to eliminate barriers to fish movement, there are some situations where removal could potentially increase the chances that exotic species presently blocked by dams could invade upstream habitats. For instance, dam removal could permit sea lamprey Petromyzon marinus *to invade various rivers that drain into the Great Lakes or flathead upstream in various rivers of the Atlantic coastal plain.*

Reaser, 2003. Closing the pathways of aquatic invasive species across North America: Overview and Resource Guide.

This report analyses the problems and adverse effects of invasive species in North America.

A means of introduction is a release of organisms upstream and/or downstream when dams are removed. Under some circumstances, the removal of dams might release invasive alien species formerly held in reservoirs into the associated watershed.

Graf, 2003. Dam removal research: Status and Prospects.

This scientific work describes several aspects regarding small dam removal. Two of the introductory sections are about prey and invasive aliens:

Dams as Facilitators and Supporters of Species Invasions:

Dams sometimes facilitate the process of biological invasion by creating an attractive habitat for recreational activities that can result in the purposeful or accidental introduction of non-native species. Dams can also change the general environment in such a way that it becomes more hospitable to certain types of invasive alien species. Dam removal may restore conditions that are more favourable to native species, but it may also increase disturbance regimes, which can often favour invasive alien species because they are typically rapid and strong colonizers.

Using Dams to Impede the Spread of Invasions:

Although dams are barriers to the passage of native populations, they can also serve as barriers to certain alien species. Dam removal therefore may have the undesired effect of providing a greater range for invasive alien species. In the Great Lakes regions, dams on streams entering the lakes have prevented the upstream migration of sea lampreys and thus have restricted their ability to prey on native fishes.

Invasive alien species must be considered in any analysis undertaken to assess the potential environmental and socioeconomic consequences of dam removal. The removal of some dams may reduce the effects of biological invasion, but the removal of others may facilitate the process of invasion and ultimately result in environmental and economic harm.

The potential thermal change highlights an important distinction between large and small dams. Some large dams with impoundments of sufficient depth that release water from the bottom of the impoundment can create a population of cold-water fish downstream. Small dams do not have impoundments with sufficient depth to release cold water if the system was not previously cold-water. Therefore, small dam removals will either have no effect on the thermal regime or will make the water colder in the summer by removing the slow-moving, exposed, high surface-area impoundments that were previously warmed under the sun. Furthermore, their removal can improve the dissolved oxygen regime.

Novinger & Rahel, 2003. Isolation management with artificial barriers as a conservation strategy for cutthroat trout in headwater streams.

This study evaluated the effectiveness of isolation management and stocking to meet protection and enhancement goals for the native Colorado River cutthroat trout *Oncorhynchus clarki pleuriticus* in Wyoming, United States. As a management strategy, cutthroat trout were isolated upstream of artificial barriers in small headwater streams.

Isolation management provided only short-term benefits by minimizing the risks of hybridization and allowed populations to persist during the study. The removal of non-native trout and stocking did not enhance wild cutthroat trout populations, however, this was likely because the isolated reaches lacked critical habitat such as the deep pools necessary to sustain large fish. Furthermore, barriers disrupt migratory patterns and prevent seasonal use of headwater reaches by adult cutthroat trout. Longer-term consequences of isolation include vulnerability to stochastic processes and loss of genetic diversity. Where non-native species pose an immediate threat to the survival of native fishes, isolation in headwater streams may be the only conservation alternative. In such situations, isolated reaches should be as large and diverse as possible, and improvements should be implemented to ensure that habitat requirements are met.

Despite potentially serious drawbacks, isolation management may offer the only immediate solution for the protection of native fishes that cannot withstand predation, hybridization, or competition with non-native species (Shafer, 1995). For example, native galaxiid fishes in New Zealand remain abundant only upstream of barriers that prevent colonization by non-native, piscivorous brown trout (Townsend, 1996). Populations of genetically pure Yellowstone cutthroat trout may owe their persistence to irrigation diversion dams that prevent invasion by non-native trout (Kruse et al., 2001). The recovery of threatened greenback cutthroat trout has relied on establishing new populations isolated from non-native trout by natural or artificial barriers (Harig et al., 2000).

Jackson et al., 2004. Alien salmonids in Australia: impediments to effective impact management, and future directions.

This article about fish conservation in Australia includes management options that feature the use of dams and weirs as barriers against invasive salmonids.

Existing methods of control where salmonids are already present or may invade have been applied on a relatively small scale. They include the construction of barriers followed by trout removal by poisoning and/or electrofishing for recovery of galaxiids populations (e.g. Lintermans, 2000). Barriers used to prevent upstream movement of trout include culvert pipes and concrete weirs, log weirs, rock filled gabions, and natural falls enhanced with rocks and concrete.

Kerby et al., 2005. Barriers and flow as limiting factors in the spread of an invasive crayfish (*Procambarus clarkii*) in southern California streams.

This report indicates that invasive crayfish *Procambarus clarkii* mainly spread downstream from a point of colonization and are restricted in their movement to adjacent upstream sections by both natural and artificial barriers in streams of southern California, United States. The authors suggest management strategies for removing invasive crayfish and reducing their spread by focusing on smaller stream segments that are bounded by a downstream barriers and by timing removal efforts to follow large flow events.

Restoration efforts are important in re-establishing natural communities but must also be executed with caution in riparian systems. However, allowing the upstream passage of fish may also allow non-native crayfish to move upstream into reaches that had been formerly blocked. The alteration or removal of barriers for restoration could actually reduce biodiversity if the impacts from newly introduced crayfish are considered. The removal or replacement of barriers that increase water velocity, such as culverts, must be carefully considered for the same reasons. Water flow over a smooth surface sweeps out crayfish more easily than those over a rocky substrate. Although the loss of connectivity in stream habitats may negatively impact some native species, the introduction of crayfish may prove more damaging. Further research should be done on the construction of barriers that allow passage by some species but prohibit invasive crayfish movement upstream.

Van Houdt et al., 2005. Migration barriers protect indigenous brown trout (*Salmo trutta*) populations from introgression with stocked hatchery fish.

In this case, the authors studied hybridizations of brown trout populations in Belgian rivers. These populations have been intensively stocked in the past decades, often with material of uncertain origin. Moreover, the species habitat has become increasingly fragmented, preventing gene flow between neighbouring populations. The paper analyses the impact this has had on genetic diversity and population structure in wild and hatchery stock populations.

Gene pools present in most downstream sections from tributaries of the Meuse were similar to each other and to the hatchery samples, despite the presence of migration barriers. Assignment analyses indicated that the contribution of hatchery material to the upstream parts was limited or even completely absent in populations separated by a physical barrier. Intensive stocking and exchange between hatcheries has homogenized the downstream sections of the Meuse River, whereas the migration barriers preserved the indigenous upstream populations. As such, the uncontrolled removal of barriers may result in an irreversible loss of the remnant indigenous gene pools.

Currently, migration barriers are being removed from Belgian rivers. This may have a pronounced impact on the small indigenous populations currently protected by these barriers from introgression with hatchery material present in the stocked downstream populations. Nevertheless, it is obvious that long-term goals should focus on the removal of barriers in order to allow natural migrations and restore the ecosystem and to connect the pristine populations with non-indigenous populations might lead to the loss of authentic genetic material and adaptive traits. However, prior to removing migration barriers the status and relationship between the adjacent populations should be assessed, to prevent additional loss of indigenous brown trout populations and homogenization of the diversity.

McLaughlin et al., 2007. Research to guide use of barriers, traps, and fishways to control sea lamprey.

This paper provides a research framework for fostering innovations in the design, implementation, and operation of barriers, traps, and fishways used to control the sea lamprey *Petromyzon marinus*, with minimal deleterious effect on non-target fishes, in the Laurentian Great Lakes.

Barriers that restrict the movements of non-native species represent a potentially important tool for reducing the potential population growth rate of invasive species and for protecting and restoring native populations and ecosystems from the negative effects invasive species can cause; however, these barriers remain controversial because of concerns regarding habitat fragmentation and reduced connectivity for non-target species and because of limited, broad evaluations of both the advantages and disadvantages of barriers and corridors.

The configuration of the control device(s) implemented on any given tributary consists of one to three components: a barrier, a trap, and a fishway. Various design options exist within each component. The objective will be pursued through a transition from using barriers to deny spawning-phase sea lampreys access to spawning habitats, to using barriers to block and selectively trap sea lampreys, and, ultimately, to the development and deployment of barriers that are transparent to non-target fishes and of novel, barrier-free traps effective enough for control purposes.

Rahel, 2007. Biogeographic barriers, connectivity and homogenization of freshwater faunas: It's a small world after all.

This paper analyses how, through a variety of mechanisms, humans have increased the connectivity among aquatic systems that were historically isolated by biogeographic barriers to movement. This human-aided breaching of biogeographic barriers has led to the significant homogenization of aquatic biotas, which can be compounded by restoration through the removal of dams.

River restoration can influence biotic homogenization through two major mechanisms: by removing barriers to movement and by restoring natural habitat conditions. Barriers to movement can involve physical obstructions such as dams or highway culverts or river reaches with poor physical or chemical habitat conditions such as low oxygen or chemical contaminants. Removing such obstructions would allow native species to recolonize areas within their historic range, which most biologists would consider beneficial. However, the removal of barriers may also facilitate the upstream expansion of non-native species, which would contribute to the homogenization of biotas (Freeman et al., 2002). In fact, the construction of barriers is a common approach for protecting isolated populations of native *fishes when it is impractical to eliminate non-native fishes from an entire catchment. For example, barriers are important for the conservation of native trout in North America (Novinger & Rahel, 2003) and native galaxiids in Australia (Jackson et al., 2004). Barriers formed by low-head dams also prevent the expansion of non-native sea lampreys into new spawning areas in tributary streams of the United States Great Lakes.*

Whereas enhancing biotic connectivity is likely to increase biotic homogenization, restoring natural habitat conditions, including natural flow regimes, may reduce biotic homogenization by favouring native regional species over widespread and often non-native species (Travnichek et al., 1995; Marchetti & Moyle, 2001). This is especially true when impoundments are restored to free-flowing stream reaches and non-native lake fishes are replaced by native stream fishes. Restoration of natural habitat conditions can involve eliminating stressors such as low oxygen or high contaminant levels. Streams with degraded habitat and poor water quality typically have simplified fish assemblages dominated by a few tolerant species that are often non-native (Paul & Meyer, 2001). Restoring historic habitat conditions will often allow regionally distinctive native species to return to these areas.

Spens et al., 2007. Network connectivity and dispersal barriers: using geographical information system (GIS) tools to predict landscape scale distribution of a key predator (*Esox lucius*) among lakes.

The aim of this study was to create a model to anticipate the presence or absence of *Esox lucius* in individual lakes within watersheds with interconnecting lotic and limnetic networks. The study area was situated in the northern boreal region of Sweden.

Generally, when restoring lake habitat by liming programmes or pollution control, for example, managers often need to assess the intrinsic potential for the natural recovery of eradicated species. In the case of fishes, managers can estimate connectivity as demonstrated in this study to predict which habitats will be recolonized from natural populations. For example, the eradications examined in our study show that many extirpations of pike are reversible, and that no reintroduction is necessary, provided that connectivity is sufficient. The UC model worked well even without taking anthropogenic barriers (such as impassable road culverts) into account, when pike were not limited by in-lake habitat. This may be because the model incorporates the historical (e.g. pre-culvert) access that pike had already used to colonize lakes, and that pike are capable of completing their entire life-cycle within a lake. However, if the in-lake habitat becomes unsuitable and leads to extinction (e.g. in our specific case, eliminated by rotenone), contemporary connectivity would then be crucial for recolonization, in which case anthropogenic barriers must also be taken into account.

Related measurements of natural connectivity (SVimax) should be a useful tool to estimate natural connectivity for different species. With this new tool, managers will be able to estimate the potential for introductions to affect new lakes and streams, as well as objectively classify those areas that are more resistant to invasion. The mapping of *connectivity in drainage networks can indicate pro-active priorities needed for managers to protect communities vulnerable to future invasions that risk damaging local economies and ecosystems. There is also an obvious need for managers to master methods to measure natural connectivity in order to help define the ecological importance of adding or removing anthropogenic barriers at specific locations, considering the effects of existing natural barriers. Just as drainage-divides are now used widely as management boundaries (e.g. 'river basin districts' in the European Water Framework Directive), connectivity related variables such as SVimax should also be useful in certain cases for setting ecologically appropriate aquatic management units in sub-basins. This is because high SVimax between two waterbodies can indicate isolation and separate species populations, needing separate management. Our study suggests that measures of slope in relation to a fixed interval of smaller rises in elevation will provide managers with substantially higher resolution when judging fish passage possibilities.*

Stanley et al., 2007. Effects of dam removal on brook trout in a Wisconsin stream.

Fish community composition are examined two years before, and two years after the removal of a pair of low-head dams from Boulder Creek, in Wisconsin, United States. This article determined whether the removal of these potential barriers affected the resident population of native brook trout *Salvelinus fontinalis* faced with the presence of brown trout *Salmo trutta* in the downstream reaches.

In conclusion, we observed a mixture of brook trout changes associated with the removal of the Boulder Creek dams. Given the nature of our sampling regime, we cannot exclude the possibility that these changes reflected normal spatial and temporal variation in the creek, but the amplified responses in the reaches immediately upstream and downstream of the dam provided good support for a removal effect. Although the removals appeared to have a negative effect on the adults, on a more basic level we noted that two years after the removals, the brook trout population in the Boulder Creek has remained in place, has not been supplanted by other taxa, and has a large juvenile population indicative of ongoing recruitment. In turn, these observations suggested that, thus far, the adverse effects of the removal on brook trout have been relatively small.

Peterson et al., 2008. Analysis of trade-offs between threats of invasion by nonnative brook trout *(Salvelinus fontinalis*) and intentional isolation for native westslope cutthroat trout *(Oncorhynchus clarkia lewisi).*

The goal of this work was to formalize an evaluation of trade-offs between intentional isolation and invasion, relevant to the conservation of native salmonids in streams in the central and northern Rocky Mountains, United States. They focused on the persistence of native west slope cutthroat trout *Oncorhynchus clarkii lewisi*, the potential invasion and subsequent effects of non-native brook trout, and the primary environmental and anthropogenic factors influencing both species and their interactions.

The conundrum is that removal of migration barriers to connect native populations to larger stream networks could allow upstream invasions of non-native fishes, while installing migration barriers to preclude these invasions may exacerbate the effects of habitat fragmentation and population isolation. Both actions could threaten native species and the integrity of aquatic systems, but fish biologists may employ both barrier installation and barrier removal strategies across the western USA without evaluation of the opposing threats. The potential conflicts highlight a challenge in native fish conservation. Because resources for conservation management are limited, effective prioritization is important. Trade-offs may be relatively clear to biologists and managers with intimate knowledge of a particular system, and their efforts can be focused effectively. Elsewhere, the trade-offs may be more ambiguous or the data and experience more limited, and the result may be a decision that is influenced more by personal philosophy or public pressure than by knowledge. Nevertheless, existing knowledge, then, provides a foundation to consider the risks inherent in intentional isolation or continuing species invasions.

The assumptions inherent in the evaluation method and subsequent analyses suggest two generalizations for the management of barriers and invasions. First, a barrier will be more likely to increase the probability of persistence for a west slope cutthroat trout population as the expression of migratory life histories becomes limited, demographic links to other populations are reduced, and invasion by brook trout becomes more likely. The relative benefits associated with any barrier, however, can primarily depend on habitat quality and the size of the isolated stream network, and secondarily on other environmental effects. Intentional migration barriers could be important tools to reduce any additional threat of invasion in these systems, but priorities may favour isolation of the largest populations and best habitats. Second, the maintenance or restoration of fish passage appears to most strongly influence the persistence of west slope cutthroat trout when the full expression of life histories and strong connection with other populations are anticipated, even if brook trout are expected to invade. The relative benefit of maintaining or restoring passage was again principally dependent on the size and quality of the available habitat.

Propst et al., 2008. Natural flow regimes, nonnative fishes, and native fish persistence in arid-land river systems.

The study predicted that the annual variation in native fish assemblage structure would be associated with the annual variation in the flow regime, that native fish assemblages would not change appreciably (despite pressures by non-native fishes) in a natural flow regime setting, and that evidence of interactions between native and non-native fishes would be most apparent during years with low flows. The study area was the Gila River in the United States.

We tested how natural flow regimes and the presence of non-native species affected the long-term stability of native fish assemblages. Overall, we found that native fish density was greatest during a wet period at the beginning of our study and declined during a dry period near the end of the study. Non-native fishes, particularly predators, generally responded in opposite directions to these climatic cycles. Our data suggested that chronic presence of non-native fishes coupled with naturally low flows reduced the abundance of individual species and compromised the persistence of native fish assemblages. We also found that a natural flow regime alone was unlikely to ensure the persistence of native fish assemblages. Rather, active management that maintains natural flow regimes while concurrently suppressing or excluding nonnative fishes from remaining native fish strongholds is critical to conservation of native fish assemblages in a system, such as the upper Gila River drainage, with comparatively little anthropogenic modification.

Conserving native populations of fishes in the upper Gila River drainage will require mitigating human activities that block or impede movement of native fishes and reversing the genetic and demographic consequences of isolation through population augmentation.

Daugherty et al., 2009. Suitability modeling of lake sturgeon habitat in five Northern Lake Michigan tributaries: Implications for population rehabilitation.

One of the objectives of this study on the conservation of lake sturgeon *Acipenser fulvescens* in Lake Michigan tributaries, United States, is to use information to determine the most appropriate rehabilitation strategies in each system.

Management approaches that favour the rehabilitation of one species often negatively affect the management of others. For example, dams that currently impede lake sturgeon access to spawning and nursery habitats in upper river reaches also function to block spawning migrations of the non-native sea lamprey Petromyzon marinus *(Lavis et al. 2003). Providing access to upstream reaches for lake sturgeon, either through the construction of fish passage structures or dam removal, would likely result in improved conditions for lake sturgeon rehabilitation (i.e. increased habitat) and negative consequences for sea lamprey control efforts. Dam removal may negatively affect publicly desirable reservoir fisheries and recreational use patterns and result in disturbances to downstream aquatic communities due to temporarily increased sediment loads (Bednarek 2001) or unpredictable changes in river morphology. Therefore, lake sturgeon rehabilitation strategies should be implemented as part of an integrated, multiscale approach to Lake Michigan fishery management.*

Our study suggests that efforts to rehabilitate lake sturgeon populations should consider providing fish passages and creating supplemental spawning habitats to increase reproductive and recruitment potential.

Fausch et al., 2009. Invasion versus isolation: trade-offs in managing native salmonids with barriers to upstream movement.

The report reviews the problems of invasion versus isolation for native stream salmonids in the United States, and proposes a framework for decisions about installing or removing barriers to conserve these fishes. They first define the problem, and then outline four questions to guide the analysis of the trade-off.

(1) Are native populations of important conservation value present? Considering evolutionary legacies, ecological functions, and socioeconomic benefits as distinct values.

(2) Are the populations threatened by invasion and displacement by non-native species?

(3) Would these populations be threatened with local extinction if isolated?

(4) How does one prioritize among several populations of conservation value?

They also develop a simple conceptual model of opportunities for strategic decisions regarding the joint trade-off of invasion and isolation threats. These priorities are important because constructing or removing barriers is expensive and logistically difficult. They combine considerations about the degree of invasion threat with those for the degree of isolation to propose a conceptual model that allows biologists to consider the joint trade-off for their particular basin and set of salmonid populations of conservation value (Fausch et al. 2006).

The trade-off space is defined by two axes, the degree of invasion threat and the degree of isolation (Fig. 10). If most native salmonid populations in a given basin are remnants in headwater habitats and invaders are advancing upstream rapidly and displacing them (Fig. 10, upper left), the main focus of management will be to intentionally isolate populations above barriers to protect them and to translocate these populations in other patches to replicate them. For managers in this situation, strategic decisions for conserving the remaining evolutionary legacy involve optimizing the number, size, and spatial distribution of patches to buffer against local extinctions and correlated catastrophic disturbances. Other strategic decisions include removing or controlling invaders, and restoring habitat quality to enhance population resilience.

At the opposite end of the spectrum, if native trout occupy a large stream network of interconnected habitats and the invasion threat is distant or invader effects are weak (Fig. 4, lower right), then options include preventing invasions at their source, preventing fish movement barriers and management activities that fragment habitat, monitoring the spread of non-natives and habitat degradation, and maximizing the opportunity for natural ecological processes to create and maintain habitat. For example, managers could minimize sources of non-native fishes (e.g. streamside ponds) for unauthorized or accidental introductions and vectors such as roads that foster introductions.

Other circumstances will require different strategies. Some basins are under little threat from invasion or the effects are weak because the native salmonids resist invasion, but the habitat is fragmented by many barriers that restrict movement (Fig. 10; upper right). Here, strategic decisions include restoring habitat quality in the small patches to minimize local extinctions, and removing barriers or providing fish passages to restore connectivity and ecological function, perhaps by allowing large spawning fish to migrate into tributaries. In contrast, other basins may have large networks of relatively intact habitat, but non-native trout have invaded and are widespread (Fig. 10, lower left). Strategic decisions here involve prioritizing sub-basins for the difficult task of removing non-native trout, which may require constructing temporary barriers and working successively downstream. Therefore, within this trade-off space the overall goal should be to move toward the lower-right corner, where interconnected populations can function and evolve in intact stream networks free of invaders, and to keep from being pushed into the upper-left corner, where only a few small populations remain in habitat fragments at risk of invasion and options for managing them are limited.

Unauthorized introductions above barriers require other strategic decisions not considered in this tradeoff space. If native populations are restricted to many small patches above barriers (Fig. 10, upper left), managers could construct several barriers spaced near the downstream end of the most accessible ones and monitor these buffer zones to guard against invasions, but the original stream fragments are usually too short to justify other measures. In contrast, in large remote basins with intact habitat (Fig. 10, lower right), it would be strategic to place barriers in inaccessible locations some distance upstream from access points to minimize unauthorized introductions.

Although each combination of threats from isolation and invasion favours particular actions, managers may select a mixed strategy to hedge against uncertainty. For example, many cutthroat trout subspecies consist of multiple small populations isolated above barriers to prevent invasion, each at relatively high risk of extinction from stochastic environmental factors. The current management strategy is to find and conserve these many small populations, translocate fish to found new populations or restore those lost to local extinctions, and simultaneously work to develop networks of interconnected metapopulations in larger basins that are remote or protected. In the worst case, if downstream barriers that protect these metapopulations from invasions are breached and invasions proceed quickly, fish from the smaller replicate populations can be used to refound them.

Pratt et al., 2009. Balancing aquatic habitat fragmentation and control of invasive species: Enhancing selective fish passage at sea lamprey control barriers.

The study about invasive sea lamprey *Petromyzon marinus* and native species in Great Lakes provides an approach to assessing fishway performance that can be employed widely and successfully to assess initial fishway design and subsequent modifications, and can help mitigate the effects of low-head barriers for some native species.

Providing fish passage at barriers to restore river connectivity and ecosystem function is recognized as a critical challenge for fisheries resource managers. Therefore, the ability to successfully mitigate barrier effects would have important conservation implications. Dams and other barriers have been constructed on tributaries to the Laurentian Great Lakes since the beginning of European settlement. Of more recent concern are low-head barriers specially built as part of an integrated management programme to control the invasive sea lamprey. Low-head sea lamprey barriers complement the larger lampricide control efforts by denying maturing sea lampreys access to suitable riverine spawning areas. There are currently 61 barriers built or modified for sea lamprey control in the basin (Lavis et al., 2003). Low-head sea lamprey barriers are a weir-and-pool design, which allows the passage of jumping fishes, but restricts the movements of non-jumping fishes.

Concerns about the effects on non-target fishes have led to the construction of specially designed vertical-slot trap-and-sort fishways to mitigate potential barrier effects. To improve passage at these fishways, we used passive integrated transponder technology to assess the performance of two fishways located on low-head sea lamprey barriers. Fishways on the Big Carp River (which flows into Lake Superior) and Cobourg Brook (which flows into Lake Ontario) were assessed for attraction efficiency, trap attraction and retention, and passage efficiency. Based on the results of these assessments, fishways were modified by increasing the trap volume and altering the funnel characteristics to reduce escapement from the trap and then reassessed. Attraction efficiency for all tagged fish was high (≥80%) at both sites in all years. Fishway modifications improved passage from 35% in 2003 to 88% and 64% in 2004 and 2005, respectively, at the Big Carp River. As expected, white suckers Catostomus commersonii*, an obligate migrant, had higher attraction and passage efficiency, fewer passage attempts, and shorter migration delay than did rock bass* Ambloplites rupestris*, a facultative migrant. No improvements were seen at Cobourg Brook, where passage efficiency remained low (7% in 2003, 10% in 2005), probably because of the loss of attraction flow. At both fishways, individual fish averaged 3–10 attempts to pass through the fishways and had their migrations delayed by 1–2 weeks. The observed improvements to the Big Carp River fishway, which resulted in high fishway attraction and passage rates for white suckers, suggest that vertical-slot fishways can help mitigate the effects of low-head barriers for some species. Our study provides a rigorous quantifiable approach to assessing fishway performance that can be employed widely and successfully to assess initial fishway design and subsequent modifications.*

Lejon et al., 2009. Conflicts associated with dam removal in Sweden.

In this paper, the authors studied incentives and conflict associated for dam removal such as safety issues, law and policies, and economic as well as ecological incentives. The study is based on their own experience with recently debated and implemented dam removals in Sweden.

Dams work as barriers that block the migration and dispersal of invasive as well as native species. Removal of a dam exposes a large area of reservoir sediment that is highly conducive to plant colonization, especially of invasive species. Aggressive plant colonists may dominate for several years if natives fail to survive because of strong competition. On the other hand, by removing these barriers, river restoration may increase the homogenization of aquatic biotas by spreading non-native species. However, by restoring former impoundments to free-flowing stream reaches, fish composition will shift from lentic to lotic, thus increasing biotic diversity and allowing native species to return to their habitats (Rahel, 2007). Some faunal changes may occur rapidly, whereas other long-term changes occur as species adjust to changes in the channel (Hart et al., 2002).

Riverine organisms are always more or less affected by dam removal before the state in the channel has stabilized. Freshwater mussels are generally the most negatively affected. Studies in Koshkonong Creek, Wisconsin, USA, showed that 95% of the mussels in the previously inundated area died because of exposure and dehydration, and one species disappeared entirely. Also, the mussels downstream from the dam were affected by the removal, and their density decreased because of increased sedimentation (Sethi et al., 2004). The freshwater pearl mussel Margaritifera margaritifera *is a red-listed and threatened species in Swedish streams. This species lives its larval stage on the gills of salmonid fish species, mainly brown trout* Salmo trutta*, and would likely benefit in the long term from dam removal because this facilitates trout migration. However, it is important to consider the amount of sediment that could affect populations located downstream. Despite the obvious benefits of removing the Örby sawmill in Ljungån, Sweden, this could potentially harm populations of freshwater pearl mussels in the stream, because of both increased sedimentation and the leakage of toxic waste from the former sawmill. Removal should not be undertaken without a thorough investigation of the harm it could potentially cause.*

Jackson & Pringle, 2010. Ecological benefits of reduced hydrological connectivity developed landscapes.

Here the authors provide examples illustrating how reduced hydrologic connectivity can provide greater ecological benefits than enhanced connectivity does in highly developed, human-modified ecosystems. They conclude by emphasizing the importance of adaptive management and balancing trade-offs associated with further alterations of hydrologic connectivity in human-modified landscapes. They also give several examples of studies in the United States.

How can managers manipulate hydrologic connectivity to protect native species from invasive species in river drainages? One such effort involves protection of the endangered native greenback cutthroat trout Oncorhynchus clarki stomias*. Strategic placement of small dams in stream headwaters allows this fish species to persist. In order to protect greenback cutthroat trout, permanent physical barriers are maintained at the downstream end of headwater drainages where this endangered species has established populations.*

Barriers prohibit the upstream passage of non-native species. Whether this strategy will be successful in the long term is unclear.

Similarly, west slope cutthroat trout Oncohynchus clarki lewiii *populations in the Rocky Mountains are threatened by invasions of brook trout introduced from the Appalachian Mountains. However, west slope cutthroat is also threatened by habitat fragmentation. Peterson et al. (2008) found that management actions to ameliorate one of these threats could exacerbate the other, and that "trade-off between isolation and invasion were strongly influenced by size and habitat quality of the stream network to be isolated and existing demographic linkages within and among populations". Novinger & Rahel (2003) found that artificial passage barriers provided benefits for protecting native cutthroat from hybridization with invasive brook trout, but the benefits were limited in their study by the lack of deep pool habitat in the small streams that were isolated. They concluded: "Where non-native species pose an immediate threat to the survival of native fishes, isolation in headwater streams may be the only conservation alternative. In such situations, isolated reaches should be as large and diverse as possible".*

Another management example that involves maintaining reduced hydrologic connectivity is the decision to retain dams that are blocking the passage of exotic fishes that would otherwise transport bioaccumulated toxic chemicals into upstream habitats in tributaries of the Laurentian Great Lakes in the Midwestern United States (Freeman et al., 2002). Consequent cascading ecological effects throughout the food chain (that are predicted to occur if certain dams are removed) include impaired reproduction of bald eagles feeding on fishes contaminated with PCBs (polychlorinated biphenyls) and other persistent organic chemicals.

How can managers effectively manipulate hydrologic connectivity to restrict the dispersal of exotic species and to protect native species? One example is the installation of powerful electric aquatic nuisance species dispersal barriers designed to prevent the upstream migration of exotic bighead carp Aristichthys nobilis *and silver carp* Hypophthalmichthys molitrix*, which are threatening to invade Lake Michigan through the Chicago Sanitary and Ship Canal.*

Kornis & Vander-Zanden, 2010. Forecasting the distribution of the invasive round goby (*Neogobius melanostomus*) in Wisconsin tributaries to Lake Michigan.

In the Great Lakes region, dams block upstream movements of the round goby *Neogobius melanostomus* into tributary streams and are therefore important for controlling the spread of this invasive fish species.

Efforts to increase stream connectivity by removing dams can also open new habitats to the natural dispersal of aquatic invasive species. Increasingly, decision-makers are choosing to remove rather than repair aging and obsolete dams (Stanley & Doyle, 2003). Although the ecological benefits of dam removals are well documented (Hart et al., 2002), invasive species add a level of complexity to improving stream connectivity. The removal *of dams that are the first barrier between a Great Lake and its upstream watershed, for example, would open up new stream habitats not only to desirable fish species (Bednarek 2001), but also to aquatic invasive species. The general issue of stream connectivity facilitating invasive species spread is likely to be relevant in other regions of the world, though perhaps with a different set of invasive species.*

Marks et al., 2010. Effects of flow restoration and exotic species removal on recovery of native fish: Lessons from a dam decommissioning.

The authors used a dam decommissioning in Fossil Creek, Arizona, United States, to compare the responses of native fish to exotic fish removal and flow restoration, using a before-after control-impact design with three impact treatments.

Despite the positive intent of restoration projects for native species, it is possible that interventions reverse one disturbance but create or exacerbate others pointing to the need to view interventions from an ecosystem perspective. For example, studies from other dam decommissioning projects showed that sediments released from behind the dam can reduce densities of native filter feeders such as mussels (Sethi et al., 2004), and drained reservoirs can be vulnerable to the invasion of exotic plants (Orr & Stanley, 2006).

The project studied flow restoration and invasive species removal in helping native fish. They found that while both measures improved native fish populations, the impact of invasive species removal was much greater and less expensive. The need for an ecosystem perspective in planning and conducting habitat restoration is important. Implications for practice:

- *Flow restoration and exotic fish removal are both powerful tools for increasing native fish populations.*
- *In some southwestern United States streams exotic fish likely pose bigger threats than habitat deterioration to native fish.*
- *Habitat improvements alone may do little for native fish recovery where exotic fish dominate the fish assemblage.*

Raadik et al., 2010. National Recovery Plan for the Barred Galaxias *Galaxias fuscus.*

This report is an action plan for barred galaxias in Australia. The objective to ensure all important populations and their habitat are protected and managed appropriately includes Action 1.4: Construct or modify, and maintain, barriers to prevent the upstream access of alien predators:

Barred Galaxias are highly susceptible to predation from, and competition with, the much larger alien trout species Brown Trout and Rainbow Trout, which have been introduced into Australia and are widespread in the upper Goulburn River system. At all newly detected Barred Galaxias populations where the population needs to be protected from *the upstream incursion of predators (trout), and where no sufficiently effective instream barrier exists, an artificial barrier(s) should be constructed if feasible, or modifications undertaken to an ineffective existing barrier. Where instream barriers (e.g. natural or artificial) preventing the incursion of predators into Barred Galaxias habitat exist, annual inspection of barrier integrity should be conducted, and maintenance undertaken when required, ensuring the effectiveness of the barrier.*

Lieb et al., 2011. Conservation and management of crayfishes: Lessons from Pennsylvania.

This article analyses the role of barriers (e.g. dams), environmental protection, and regulations in preventing crayfish invasions and conserving native crayfishes, and presents management initiatives centred on these factors. The study area was Pennsylvania, United States.

Because dams can block the dispersal of crayfish, their removal may facilitate crayfish invasions in some systems, with the potential for negative effects on native communities. Despite this possibility, the potential for such effects is rarely discussed in the scientific literature, or empirically tested, and is typically not considered by regulatory agencies charged with managing dam removals.

Continuing to ignore the potential influence of dams on crayfish invasions could have serious consequences, particularly for imperiled crayfishes. For example, in Pennsylvania, dams are located downstream of most of the known populations of an extremely rare crayfish and may be protecting them from invasion. At a minimum, surveys should be conducted prior to dam removal to ensure that removal will not facilitate the upstream migration of introduced crayfish. Ironically, dams that are protecting upstream areas from invasion may need to be left in place for conservation reasons. In areas prone to invasion, dams located downstream of imperiled crayfish should probably not be removed, regardless of whether exotics are present in the system or not.

Vélez-Espino et al., 2011. Demographic analysis of trade-offs with deliberate fragmentation of streams: Control of invasive species versus protection of native species.

This study evaluates the efficacy of seasonally operated barriers and fishways for controlling non-native sea lamprey *Petromyzon marinus* in the Laurentian Great Lakes while minimizing the effects on non-target fishes. The movements of invasive species and habitat fragmentation for native species are complex examples of how actions taken to address one environmental concern can hinder the efforts to address another.

Our study provides an explicit, generalizable method for assessing the population consequences of management tools used to restrict or facilitate the movements of animals in light of the control of a harmful, non-native species and reduction of habitat fragmentation. It further applies this method to assess the efficacy of seasonally operated barriers and fishways used to control sea lamprey in the Great Lakes. We first quantified overlap in the migration phenology of sea lamprey and seven migratory non-target teleost fishes that co-occur with sea lamprey. We then used stage-structured matrix population models to project how blocking the reproductive migrations of sea lamprey was expected to affect the production of sea lamprey and the non-target fishes. Lastly, we projected how population sizes of non-target species change proportionally over time under different levels of fish passage.

Without a fishway, seasonally operated barriers are unlikely to be more effective than permanent barriers at passing non-target fishes exhibiting spring spawning migrations, while blocking sea lamprey. The migration phenology of migratory, non-jumping fishes overlap considerably with the migration phenology of sea lamprey and projected population growth rates of some non-target fishes are as sensitive as sea lamprey to reductions in reproduction due to blocking. Even under density-dependent compensation, providing a fishway is advisable and passage of non-target fishes may have to be highly effective to avoid population declines in non-jumping species that migrate between a Great Lake and its tributaries.

Clarkson et al., 2012. Population prioritization for conservation of imperilled warmwater fishes in an arid-region drainage.

This article was based on the literature on warm water fish species of the Gila River basin in Arizona-New Mexico, USA and Sonora, Mexico. The authors studied the isolation management for segregating non-native fishes.

Isolation management (segregation of native from non-native fishes) is considered the primary recovery action for the native fauna. Protection via such isolation management (Novinger & Rahel, 2003) includes situations where (1) barriers such as waterfalls or other natural blockages to fish movements are present and non-natives have not invaded, or (2) artificial fish passage barriers have been constructed in conjunction with non-native fish removal or suppression.

Is the population free of non-native fishes? This considers other impacts of non-native species introductions on native populations. Although some non-native species are perceived as less problematic for native fishes than others, accounting for such nuances confounds the analytical approach, and the impacts of all non-native species on natives are not fully understood. Although native populations that are sympatric with non-native fishes are more vulnerable to loss, the reality is that the costs necessary to manage against extant non-natives is high even in those places where such management is logistically feasible. Therefore, typically it is easier to protect a population without non-

natives than to rid one of existing non-natives, and thus the conservation priority is greater for a population free of non-natives.

Question: Is the population free of non-natives, or can non-natives be controlled or eliminated with reasonable effort? Scoring criteria: Scored 'yes' if no non-native fishes have been recorded from within the range of the population, or if the stream is small and non-natives might be controlled by mechanical means.

The status of the largely endemic native fish fauna has deteriorated to the point that most populations of the six imperilled remnant species require protection and/or replication. No further degradation can be tolerated if the evolutionary legacy of the fauna is to be preserved, and the major goal of Gila basin recovery programmes is to protect remaining populations before they disappear. Given the present state of technology, emplacement of fish exclusion barriers followed by restoration of the native fish assemblage upstream seems the only viable and sustainable means to accomplish the segregation of natives and non-natives.

Cooke et al., 2012. Endangered river fish: Factors hindering conservation and restoration.

The objective of this paper is to identify and discuss general factors (which can also be viewed as research and implementation needs) that may hinder the ability to enable effective conservation action for endangered river fish.

A biological challenge is that reconnecting riverine networks may allow migration of aquatic invasive species, the release of upstream contaminants trapped in sediments, or excess nutrients. Therefore, managers may need to consider the cost and benefit of reconnections of large rivers as this may provide opportunities for native fish migration, but will also allow the transfer of undesirable products and organisms.

Restoring natural flow regimes has been proposed as a useful measure for dealing with non-native fish invasions. Although mimicking the natural flow regime may enhance native fish recruitment, it does not necessarily reduce non-native fish recruitment, particularly for highly fecund small-bodied non-native fishes. Therefore, identifying the mechanisms and specific aspects of flow that help maintain native river fishes may be needed to maintain these native populations.

Marr et al., 2012. An assessment of a proposal to eradicate non-native fish from priority rivers in the Cape Floristic Region, South Africa.

Non-native fish are considered the most important threat to the survival of the indigenous freshwater fishes in the Cape Floristic Region. This Mediterranean-climate region is a recognized biodiversity hotspot with high levels of endemicity, including freshwater fishes.

This study assesses a pilot project evaluating the use of the piscicide rotenone to eradicate non-native fish in four selected rivers in South Africa.

Each river has unique characteristics and challenges to achieving the eradication of non-native fish and the restoration of its indigenous fish assemblage. In several cases they use weirs as limits of action. For example, a derelict weir just above the confluence with the Matjies River is the potential lower boundary for the non-native fish eradication, but would require refurbishment to be an effective barrier to non-native fish. Or in Krom River, the eradication project proposes to remove bass from between the waterfall and the Working for Wetlands weirs and from the farm dams upstream to prevent re-invasion.

Olaya-Marín et al., 2012. Modelling native fish richness to evaluate the effects of hydromorphological changes and river restoration (Júcar River Basin, Spain).

Part of this study was to evaluate the effectiveness of two restoration actions in the Júcar River, Eastern Iberian Peninsula, through the removal of two abandoned weirs. This measure would allow the progressive increase in the proportion of riffles that favour the richness of native Mediterranean fish. Furthermore, this model at the basin scale was a first step for further research on the effects of water scarcity and global change on Mediterranean fish communities.

The proposal for removing weirs is based on the current knowledge of the river reaches, which contain abandoned and obsolete structures whose water rights are not in use. Weir removal and the legal process of water rights cessation are important tools for river restoration at the basin scale, and they should be widely applied to improve the status of Mediterranean aquatic communities.

One limitation of the study was that it did not consider the biological interactions (e.g. food availability and inter-species competition). The target segment contained four exotic species of fish (Gobio gobio, Alburnus alburnus, Lepomis gibbosus and Micropterus salmoides), which could interfere with the recovery of the NFSR because they can compete with or predate on the native fish. The importance of habitat and exotic species for the recovery of native populations is undoubtedly an important issue that must be considered in these Mediterranean rivers.

Frings et al., 2013. A fish-passable barrier to stop the invasion of non-indigenous crayfish.

This study aimed to determine whether native crayfish can be protected by physical barriers that do not hinder fish migration, but prohibit the upstream migration of non-native crayfish.

Some residual populations of native crayfish have been able to survive in river headwaters. These remaining populations now are in great danger due to the implementation of the European Water Framework Directive (EU, 2000), a legally-binding agreement that requires the restoration of the ecological continuity of water bodies by 2015. This implies that anthropogenic barriers that hinder fish migration must be removed or provided with a fish ladder. It may be clear that this is beneficial for migratory fish species (e.g. salmon) and gene flow in residential species populations, but threatening to native crayfish, because it promotes the invasion of signal crayfish.

The only alternative solution is the management and confinement of native crayfish populations in isolated 'ark sites', free from non-native crayfish and the threat of colonization by non-native crayfish. Crayfish barriers can protect native crayfish in such ark sites in the hope that acceptable eradication methods against invaders will be developed soon.

Gangloff, 2013. Taxonomic and ecological tradeoffs associated with small dam removals.

This author makes a critically important review of the potential positive and negative effects of removing small dams on both resident and migratory stream species. He examines the literature describing some effects of small dams, the trade-offs associated with removing small dams from stream ecosystems, and compares the tradeoffs associated with dam removal projects in streams in the Midwestern and Southeastern United States.

To managers concerned with invasive species, increased connectivity of linear ecosystems may not always be a desirable goal. Jackson and Pringle (2010) provide an excellent, if counter-intuitive review of the management benefits of decreased hydrologic connectivity including reduced movement of exotic species (Kerby et al., 2005). Dams have long been a component of invasive fish management strategies and are important barriers to invasive apex predators.

Many agencies and researchers have begun to devise prioritization metrics for dam removals. These project goals frequently include restoration of diadromous fishes but just as frequently ignore the effects on other stream organisms (in particular the effects associated with increasing stream access to invasive or non-native game fishes). In addition, managers content to let failing or breached dams become degraded are operating with the erroneous assumption that passage in any form is beneficial. Increasingly, evidence suggests that the technological obsolescence and abandonment of many small dams may have profound ecological implications in the long term that may ultimately require more hands-on management. Although intact small dams are relatively easy and inexpensive to remove, the removal of breached small dams can be even more cost-effective.

McLaughlin et al., 2013. Unintended consequences and trade-offs of fish passage.

These authors made a broad study the trade-offs that arise when passage decisions intended to benefit native species interfere with management decisions intended to control the unwanted spread of non-native fishes and aquatic invertebrates, or genes, diseases and contaminants carried by hatchery and wild fishes. These consequences and trade-offs will vary in importance from system to system and can result in large economic and environmental costs.

Table 4 of this report relates examples where dams are being used purposely or incidentally to restrict the upstream movement of introduced or undesirable native fishes, aquatic invertebrates, and contaminants. Most of these affect native salmonids and the geographical location of the study is the rivers and Laurentian Great Lakes of North American.

Fish passage and dam removal can allow unwanted movement of invasive and introduced species, and even native species, into upstream river reaches formerly isolated by the dam or barrier. These introductions can become the source of unwanted consequences from new predator-prey and competitive interactions, from hybridization and introgression within and between species, or between wild and hatchery fish, and from exposure to new diseases and contaminants. Barriers to movement represent a recognized method of restricting invasions (Sharov & Liebhold, 1998). There are numerous examples where barriers are being used, intentionally or unintentionally, or being considered as a method of restricting the movements of invasive fishes and crayfishes, and native predatory fishes, to protect biological communities upstream of the barrier.

Dams and barriers can be considered a temporary solution for addressing invasive species, to be abandoned once better control options become available, because these obstructions represent an impediment to restoring the native fishes that were impacted negatively following dam construction. On the other hand, the consideration and use of dams and barriers as a management tool is likely to increase, particularly in ecosystems prone to problems with invasive species. The broader consequences of the unwanted effects of fish passage and dam removal are restoration outcomes that are incomplete or unintended when compared to the management objectives set for the watershed or river. Objectives should include the conserving native and valued non-native fishes by minimizing habitat fragmentation or using fragmentation to limit the harm caused by an invasive species.

Incomplete and unintended outcomes can be expected because some of the unwanted effects, such as the introduction of invasive species, can create biological trade-offs between different ecosystem components (e.g. abundances of the fishes affected positively and negatively by any decision taken and create corresponding management trade-offs between different restoration objectives (conserving native and valued non-native fishes by minimizing habitat fragmentation or using fragmentation to limit the harm caused by an invasive species) (e.g. Fausch et al., 2009; Pratt et al., 2009; Vélez-Espino *et al., 2011). When fish passage or dam removal decisions are motivated by narrow interests, such as the enhanced angling opportunities for a specific species, the biological and management trade-offs can further reveal disagreements in how scientists, managers and stakeholders value the species that stand to benefit from the different management options available (value trade-offs).*

Rahel, 2013. Intentional fragmentation as a management strategy in aquatic systems.

In this paper, the author makes a broad examination of fluvial connectivity versus fragmentation.

Maintaining or restoring connectivity in aquatic systems can enhance migratory fish populations; maintain genetic diversity in small, isolated populations; allow organisms to access complementary habitats to meet life-history needs; and facilitate recolonization after local extirpations. However, intentional fragmentation may be beneficial when it prevents the spread of non-native species or exotic diseases, eliminates hybridization between hatchery and wild stocks, or stops individuals from becoming entrapped in sink environments. Strategies for fragmenting aquatic systems include maintaining existing natural barriers, taking advantage of existing anthropogenic features that impede movement, severing artificial connectivity created by human actions, and intentionally creating new barriers. Future challenges for managing fragmentation include maintaining hydrologic connectivity while blocking biological connectivity in water development projects; identifying approaches for maintaining incompatible taxa, such as sport fishes and small non-game species; and developing selective barriers that prevent the passage of unwanted species while allowing normal life-history movements of other species.

Restoring connectivity is a major theme in the management of aquatic systems. The benefits of maintaining or restoring connectivity are well documented and include the enhancement of migratory fish populations; increased genetic diversity and reduced extirpation risk in small, isolated populations; increased access to a range of complementary habitats needed at different life-history stages; and recolonization after local extirpations (Fullerton et al., 2010). Discussions of how biodiversity can be maintained in a changing climate often include recommendations to increase landscape connectivity, so that species can migrate to new habitats as current ones become unsuitable (Kostyack et al., 2011). As a result of the focus on connectivity, removing dams and improving fish passage at road culverts have become common activities in watershed restoration efforts (Kemp & O'Hanely 2010).

Nevertheless, connectivity can have a downside in some situations. Most biologists would agree that connecting waterways that were naturally isolated is not a good idea. Less clear cut are situations that involve restoring connectivity in waterways that were historically connected or fragmenting currently connected systems (Fausch et al. 2009, Jackson & Pringle, 2010). In fact, maintaining isolation or even intentionally fragmenting systems may be beneficial. The benefits fall into four main categories: preventing the *spread of non-native species, preventing the spread of exotic diseases, preventing hybridization between hatchery and wild populations, and preventing organisms from entering attractive human-created habitats that act as ecological traps. Therefore, natural resource managers face a tension in balancing the pros and cons of connectivity in aquatic systems (Fig. 11).*

At the earliest stage, preventing a species from colonizing a region means reducing the likelihood that it will cross natural biogeographic barriers. Intentional fragmentation is used when non-native species are such strong competitors or predators that coexistence with the native species is unlikely (Clarkson et al., 2012; Marr et al., 2012). Typically, a barrier is constructed, non-native species are removed, and native species are returned to upstream segments in a strategy known as isolation management (Novinger & Rahel, 2003). This approach has been widely used in the conservation of native fish populations in United States. Once an invasive species is established and elimination is unfeasible, the management goal changes to reducing its effect through population control. One strategy is to disrupt the connectivity between habitats needed for the species to complete its life cycle. Examples of this strategy include the use of low-head dams to block access to spawning tributaries for sea lampreys in the Great lakes of North America (Pratt et al., 2009) and the use of screens to prevent the common carp from reaching wetland spawning areas in Australia (Hillyard et al. 2010).

Once it becomes clear that isolation is an important goal, there are four major strategies for managing fragmentation in aquatic systems:

a) The simplest strategy is to use existing natural barriers to prevent intrusion by unwanted taxa.

b) A second strategy for managing fragmentation is to eliminate human-induced connectivity between formerly disconnected waterways. To prevent the dispersal of undesirable organisms, managers face the difficult challenge of disrupting biological connectivity while retaining hydrological connectivity.

c) A third strategy for managing fragmentation is to take advantage of existing anthropogenic features that already create isolation. For example, dams originally built for hydroelectric generation or water storage can be repurposed as colonization barriers for undesirable species.

d) The fourth approach for managing fragmentation is to intentionally create movement barriers in waterways that are naturally connected. The isolation management is a common approach when non-native species are such voracious predators or superior competitors that coexistence with native species is not possible. Despite the potential problems, intentional fragmentation is a major conservation strategy for situations in which native and non-native taxa are considered immiscible.

A few examples of the third strategy are: In New Mexico, a dam was constructed to store irrigation water, but it has also prevented upstream intrusion by the non-native white sucker Catostomus commersonii *into river reaches occupied by the Rio Grande sucker* Catostomus plebeius*, that is a native species with conservation concern (Calamusso & Rinne, 1999). The state of Iowa has identified a set of dams that could be retained as* *barriers to upstream colonization by Asian carp living in the Missouri and Mississippi Rivers (Hoogeveen, 2010). In the Great Lakes region, dams block upstream movements of the round goby* Neogobius melanostomus *into tributary streams and are therefore important for controlling the spread of this invasive fish species (Kornis & Vander-Zanden, 2010). Therefore, retaining these dams, even if they are no longer needed for hydropower, may be justified because these structures prevent encroachment by non-natives that can displace native species.*

However, dams are not the only human-created features that can fragment systems: drainages, reaches with poor water quality or reaches that were dewatered because of agricultural water withdrawal, dry stream reaches, road culvert pipes, paved culverts with high water velocity, etc. served as barriers to the upstream movement of undesired aquatic species in streams, mainly fishes and crayfishes. Restoring lateral connectivity between main channels and floodplains is another focus of watershed restoration efforts, but restoring this connectivity may not always be beneficial for native species.

Isolation by barriers does have several drawbacks. First, it may result in small populations that are subject to the loss of genetic variation or to demographic fluctuations that can lead to extirpation (Fausch et al., 2009). These problems can be minimized if the amount of isolated habitat is as large as is possible. Second, barriers can prevent individuals from moving to refuges during periods of high temperature, low oxygen, or stream desiccation and then returning when conditions improve (Winston & Taylor, 1991). Therefore, managers would need to be vigilant in rescuing populations facing stressful conditions. Finally, intentional isolation might remove a population from the constellation of geographically separated but interacting populations that form a metapopulation. Such populations occasionally exchange individuals through long-distance dispersal, which allows for genetic exchange among populations and which can reestablish populations that have been extirpated by environmental catastrophes. With the loss of natural dispersal, managers may need to play a more active role in reestablishing populations through translocation (Olden et al., 2011). With climate change, some aquatic species may need to be moved to new areas if they are unable to migrate on their own or to adapt fast enough to changing conditions.

Therefore, the relative value of the connectivity versus the fragmentation of aquatic habitats needs to be evaluated on a case-by-case basis, through which the beneficial effects of limiting the spread of invasive species or diseases, preventing hybridization with hatchery fish, or keeping organisms out of ecological traps are weighed against the potential detrimental effects on the movement patterns of native species.

Crook et al., 2015. Human effects on ecological connectivity in aquatic ecosystems: Integrating scientific approaches to support management and mitigation.

In this review, the authors examine the effects of anthropogenic activities on ecological connectivity regarding the movement and dispersal of aquatic organisms. They identify and describe the main anthropogenic effects on ecological connectivity in aquatic ecosystems, and explore their consequences for biota both within and between populations. It includes a section concerning dams and weirs and another on the spread of invasive species. The management examples are salmonids of the genus *Salvelinus* in the United States.

As disparate areas are artificially linked via canals, inter-basin diversions and other human activities, previously restricted aquatic species can disperse to new areas, leading to a homogenization in the species composition of aquatic biota, reduced local biodiversity, and the spread of noxious invasive species (Rahel, 2007). The invasions of the Great Lakes region in Northern America by the sea lamprey Petromyzon marinus *and zebra mussel* Dreissena polymorpha *are graphic examples of the ability of invasive species to utilize artificial connectivity pathways, and the devastating consequences this can have on native biota and human values.*

Once invasive species have become established in open systems such as the ocean, little can generally be done to manage connectivity pathways in order to limit their spread. In river networks, a series of management interventions is available, including the installation of artificial barriers at key locations (e.g. Pratt et al., 2009). However, the establishment of invasive species in river networks often creates a conundrum with regard to the management of ecological connectivity. This is particularly the case for populations in small, headwater streams where invasive predators have colonized downstream river reaches (Fig. 5) (Fausch et al., 2009). Small and isolated populations face an inherent extinction risk that could be reduced by removing barriers and re-establishing dispersal and gene flow throughout river networks. However, artificial barriers can prevent invasive predators and/or competitors from interacting with isolated native populations in headwaters (Rahel, 2013) (Fig. 5). Consequently, management decisions must weigh the invasion threat against the demographic and genetic risks of the isolation of native populations (Fausch et al., 2009).

In Section 3.3 of the article, concerning native and invasive trout in western North America, two very clear situations are presented on the conservation of the same species.

Research on the threatened bull trout Salvelinus confluentus *in the western USA illustrates how demographic and genetic methods complement one another to provide a full picture of the importance of connectivity for species persistence:*

a) In an Idaho watershed, analytical models based on a temporal sequence of redd (spawning nests laid in gravel) counts determined that isolated headwater populations were too small to prevent impending extinction and that all populations were strongly isolated from one another. The invasive species of greatest concern across the bull trout's native range is the brook trout Salvelinus fontinalis*. In the Idaho system, however, the harmful effects of brook trout appear to be minimal, according to two key observations. First, evidence showed some bull trout juveniles from populations upstream of dams out-migrate through the dams to overwinter in downstream lakes. Genetic analysis also demonstrated minimal hybridization of bull and brook trout in this system. Second, these* *observations, achieved by a combination of methods, suggest that increasing connectivity is a worthy conservation objective for bull trout in this watershed.*

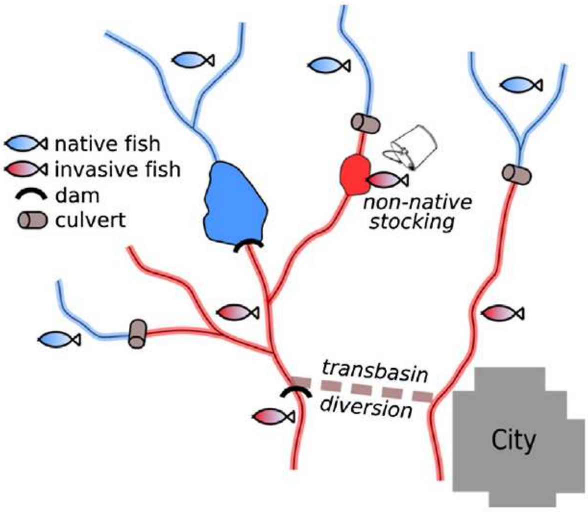


Figure 5. Schematic of the interactive effects of artificial increases in aquatic connectivity. 1) Stocking of non-native game fish in a lake (indicated by the bucket), 2) inter-basin diversion of stream flow to a city in a neighbouring basin (indicated by broken red/grey line). The introduced species has become invasive in both networks (red-shaded streams and lakes), driving native species to fragment into a series of isolated populations in headwaters (blue-shaded streams) above movement barriers. In this case all barriers are artificial, culverts and dams. Source: Crook et al. (2015).

b) In stark contrast to the Idaho system, reducing brook trout encroachment from downstream reaches was critical to the recovery of a bull trout population in Crater Lake National Park, Oregon. A remnant population of bull trout in Sun Creek was studied, a second-order headwater stream, which was found to be threatened with extinction due to competition and hybridization with brook trout. To save the bull trout population, managers used artificial barriers, electrofishing, and piscicide applications. In combination, this body of work shows the value of multiple methods not only for assessing the role of connectivity in species conservation, but also for actively managing connectivity to promote recovery.

Amat-Trigo et al., 2016. Effects of flow regulation along longitudinal gradient on size-related metrics of fish populations from a Mediterranean basin.

The main goal of this study was to assess the influence of flow regulation on the size structure of fish populations along a longitudinal river gradient. They focused on four species present in an area of the Segura River basin (SE Spain): a native species

Luciobarbus sclateri, a translocate species *Gobio lozanoi*, and two invasive species *Lepomis gibbosus* and *Alburnus alburnus*.

Flow regulation and the presence of flow-related artificial habitats affected the variability in several size metrics of fish populations. L. gibbosus *and* G. lozanoi *populations showed higher size diversity and larger sizes in sectors influenced by Impact 2 (high flow peaks and temperatures, as well as constant and high flows throughout the year).* L. gibbosus *attained its maximum sizes in stretches with bypass refuges, where there are flow dispersion and artificial structures to guard against peaks of flow. Size metrics of* A. alburnus *were not affected by the studied factors, although higher somatic condition was observed in populations affected in Impact 1 sectors (similar inter-year flow patterns), in which this species with preference for large lakes and fast-flowing rivers could be benefitted. The opposite effect was observed on the condition in the individuals of* G. lozanoi. L. sclateri *had lower mean size and less size classes (due to the absence of large sizes) in the most natural sectors, in agreement with previous studies.*

The regulation of flows by dams affects the structure and functionality of fish assemblages, making the establishment of non-native species easier (Alexandre et al., 2013). Our results suggest that flow regulation might be contributing the establishment of the invasive alien fish species. The knowledge about expected size structures of native fish populations under natural flow regime could be used to detect flow disturbances and to improve the design of management programmes. For example, an increase of mean length together with a decrease in size classes could be caused by a loss of small sizes, which could be in turn driven by drag effect in areas where high peaks of flow are released. Consequently, the effect of flow regulation on fish population structure should be studied further, since it can be a useful tool in the fish population management.

EPA, 2016. Frequently asked questions on removal of obsolete dams.

This report only mentions the risk of invasive alien species when a dam is going to be eliminated:

Can there be adverse impacts associated with the removal of a dam? Invasive and/or exotic plant or animal species may be released into the riverine system after the dam is removed, which can lead to the displacement of native species.

Factors that may be considered include: the presence of invasive or exotic plant or animal species whose distribution is restricted to only the upstream or downstream side of the dam.

Morcillo et al., 2016. Evaluation of the fish passage design and suitability in the Pareja limno-reservoir (Guadalajara, Spain).

The Pareja limno-reservoir is an infrastructure located in one of the Entrepeñas Reservoir branches (upper Tajo River, Spain). This limno-reservoir was built for hydro environmental recovery and economical promotion in the area, and has a fish passage which is evaluated in this study.

The current fish passage was not operational, and three alternative interventions were proposed. The first one involves the repair of the current fish passage dealing with the aforementioned critical points. The second one implies a new design for a new fishway, dealing with the critical points and other features such as the entry location, the dimensions of the pools, among others. The last alternative is the "non-intervention" option, which is established as consequence of the presence of exotic and/or invasive fish species downstream, upstream, and in the dam.

The results suggest, on one hand, the potential function of limno-reservoirs as fish-passable barriers to stop the invasion of exotic and/or invasive species and, on the other, the need of a risk assessment case by case for the different fish passage options to evaluate the trade-offs between invasive and native species.

Van der Walt et al., 2016. Spatial extent and consequences of black bass (*Micropterus* spp.) invasion in a Cape Floristic Region river basin.

This article studies the effects of invasive black bass *Micropterus* spp. on the communities of threatened native fishes in the Cape Floristic Region of South Africa, where physical barriers in the form of waterfalls define the upper limit of black bass and other alien fish distributions in tributaries studied of the Olifants-Doorn River basin.

The study demonstrates the critical role physical barriers play in preventing the extinction of native fish species and provides a basis for the planning of conservation interventions such as the construction of in-stream invasion barriers.

Natural barriers to upstream movement play a critical role in mitigating the impacts of invasions by alien fishes (Rahel, 2007). These barriers, however, can present a conservation dilemma, in that while protecting headwater stream species from invasive fish incursions, they could also hamper conservation if the threatened species require access to the invaded reaches for part of their life cycles (Fausch et al., 2009; Gangloff, 2013; Rahel, 2013). Information on what constitutes effective barriers for invasive fishes is therefore important for identifying approaches for developing selective barriers that prevent the passage of unwanted alien species while potentially allowing movements of native biota (Rahel, 2013).

In the Olifants-Doorn River basin, black bass invasions are the primary conservation concern facing native species, so the barriers restricting their upward expansion represent indisputable tools for conservation management. Understanding what constitutes a natural barrier for invasive black bass in this system will assist in assessing invasion risk and identifying priorities for conservation action in other streams.

The information on what constitutes a natural barrier to black bass invasions in the Olifants-Doorn River basin should therefore be incorporated in the planning of conservation interventions such as the construction of instream invasion barriers.

Beatty et al., 2017. Rethinking refuges: Implications of climate change for dam busting.

This article uses a model region in the Southern Hemisphere, Australia and South Africa, to study the potential influence of climate change on the impact of dam removals. They highlight that artificial lentic habitats created by dams can act as refuges for increasingly imperilled freshwater fishes, and that dams may also prevent the upstream spread of invasive alien species in rivers.

Invasive species and the exotic diseases that they introduce represent a considerable threat to aquatic ecosystems throughout the world. There is an increased likelihood of novel invasions by aquatic species that possess physiological thresholds mismatched to current environmental conditions, but matched to conditions likely to prevail under future climatic scenarios (Rahel & Olden, 2008). Warmer water temperatures may also increase the transmission and virulence of exotic parasites and pathogens to native fish species (Marcogliese, 2008). We may therefore expect more invasive aquatic species, and greater impacts from these species, in many regions due to climate change.

While the reservoirs created by dams are often hotspots of alien fish species, particularly predatory sportfish, there are also several examples of dams (both intentionally and unintentionally) limiting the spread of invasive species (Rahel, 2013). Moreover, while often difficult, eradicating alien species from reservoirs is possible (Meronek et al., 1996) and can directly facilitate their use as refuges by native fishes (Beatty & Morgan, 2016).

The relative value of restoring connectivity for native species versus limiting the spread of invasive species requires careful consideration in decisions to remove dams or install fishways. There may be trade-offs between the benefits to lotic ecosystems of removing a dam (such as reinstating migratory pathways for diadromous or potamodromous fishes) against potentially facilitating the spread of invasive species by removing barriers. The dispersal of invasive species following barrier removal is not always predictable (Stanley et al., 2007), highlighting the desirability of a sound biological and ecological understanding of the fauna (both native and alien) that will be impacted. In some cases, retaining or even creating new barriers may help offset the increasing threats that invasive alien species pose to native biodiversity in changing climates (Rahel, 2013).

More research is required to quantify the existing ecological values of artificial impoundments and to predict how these values may change in the future. Most notably, in drying temperature streams where natural surface water refuges will be lost, the implication of climate projections on the value of dams and the impacts of their removal need much greater consideration by researchers and policy-makers.

Therefore, with active management, many dams and strategic instream barriers could be used to offset the impact of climate change and other stressors, particularly invasive fish species.

Muñoz-Mas et al., 2017. Microhabitat competition between Iberian fish species and the endangered Júcar nase (*Parachondrostoma arrigonis*; Steindachner, 1866).

Muñoz-Mas, et al., 2016. Risk of invasion predicted with support vector machines: A case study on northern pike (*Esox Lucius*, L.) and bleak (*Alburnus alburnus*, L.)

The main goal of these articles was, firstly, to analyse the potential habitat competition between the critically endangered Júcar nase *Parachondrostoma arrigonis*, and two translocated fish species: the Iberian nase *Pseudochondrostoma polylepis* and the bermejuela *Achondrostoma arcasii*. Secondly, to assess the risk of invasion of two invasive fish species: the northern pike *Esox Lucius* and bleak *Alburnus alburnus.* These studies were carried out in the upper part of the Cabriel River, Eastern Iberian Peninsula.

Muñoz-Mas et al., 2017: *The Júcar nase will compete, spatially and temporally, for the few suitable microhabitats with bermejuela and, to a lesser extent, with small Iberian nase; conversely, large Iberian nase was of minor concern, due to increased differences in habitat preferences.*

Finally, we would like to reiterate the need to maintain the Cristinas weir in its current condition, avoiding measures to improve connectivity, as it is the only barrier impeding the colonization of the uppermost part of the Cabriel River; which we consider should be preserved, despite the negative impact that it exerts on the river continuum.

Muñoz-Mas, et al., 2016: *Northern pike and bleak proved able to colonize the upper part of the Cabriel River but the habitat suitability for bleak indicated a slightly higher risk of invasion. Altogether may threaten the endemic species that currently inhabit that stretch, especially the Júcar nase, which is one of the most critically endangered Iberian freshwater fish species.*

Therefore, we strongly highlight the importance of these existing barriers, and especially the conservation of the Cristinas weir, which is currently impeding the invasion of the non-indigenous Iberian nase to the last significant stronghold of the Júcar nase.

Sánchez Monleón, 2017. Estrategia de actuaciones de demolición de azudes en desuso para la mejora de la conectividad longitudinal de los ríos de la Demarcación Hidrográfica del Júcar.

This study defines a general methodology to prioritize actions of connectivity improvement for dams and their application to the Hydrographic Demarcation of Júcar (Spain).

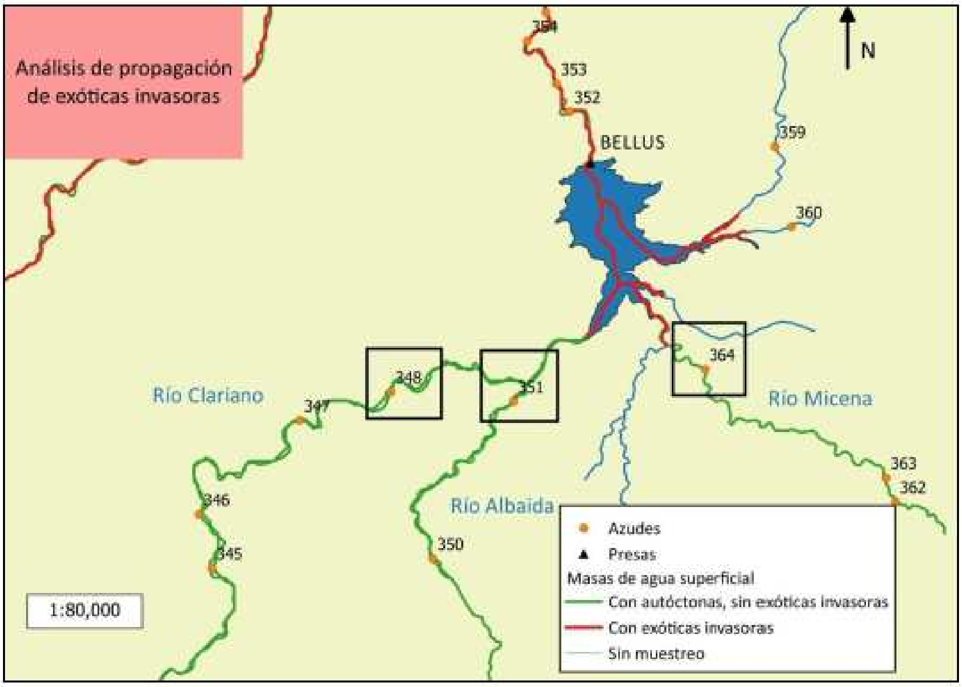


Figure 6. Example of a weir that it is recommended not to improve connectivity or eliminate, located upstream of the Bellus reservoirs (Júcar Basin, Spain), as a brake on the upstream expansion of invasive alien species. Orange point: weir; black triangle: dam; green line: rivers only with native species; red line: river with exotic invasive species. Source: Sánchez (2017).

The result of this study is the action on the dams in disuse, impassable, without pressure by exotic invasive species of fish and without patrimonial value. A priority coefficient of fish species is developed that excludes invasive aliens and translocated species. Therefore, it discards from the outset those dams whose connectivity improvement or removal favours the propagation of invasive alien species towards isolated areas of native species, or the colonization of the distribution area of the threatened Júcar nase *Parachondrostoma arrigonis* by the translocated *Parachondrostoma polylepis*.

Dams were analysed whose connectivity should not be improved due to the presence of invasive alien species. For this purpose, the composition of the fish community in the Júcar Basin was studied, analysing the obstacles that serve as a border between sections with native species and free of invaders, and sections with the presence of invasive or translocated species (Fig. 6 and Fig. 7).

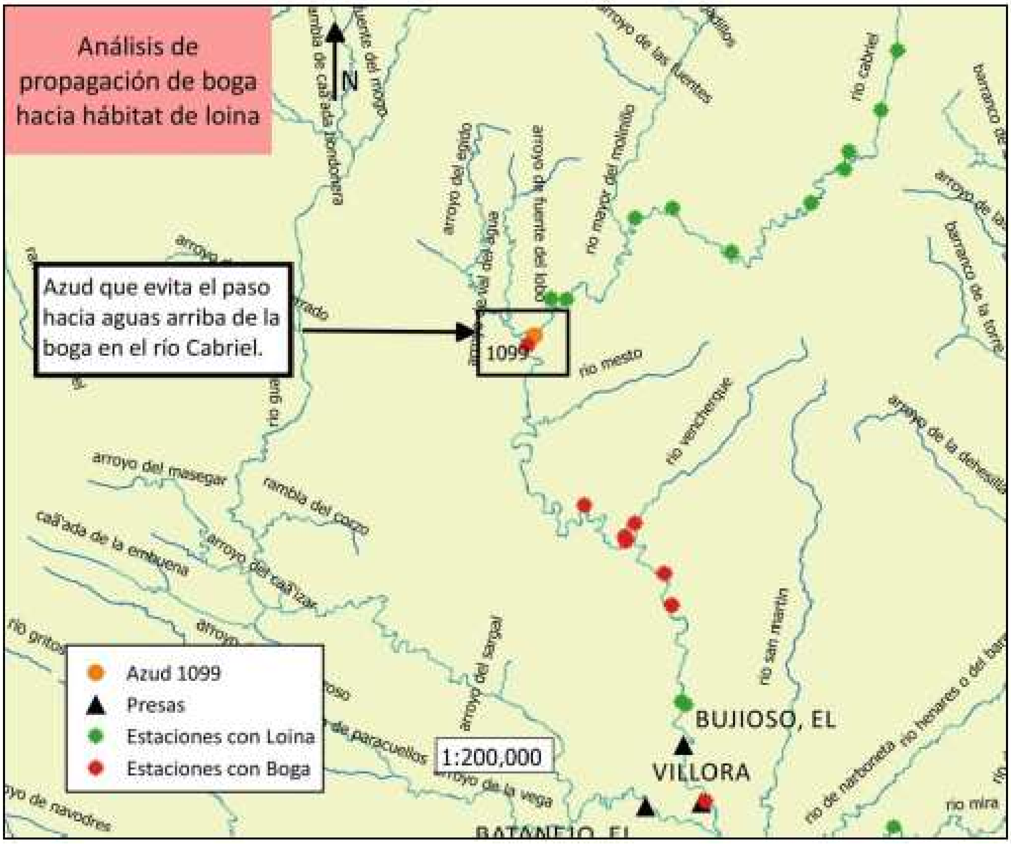


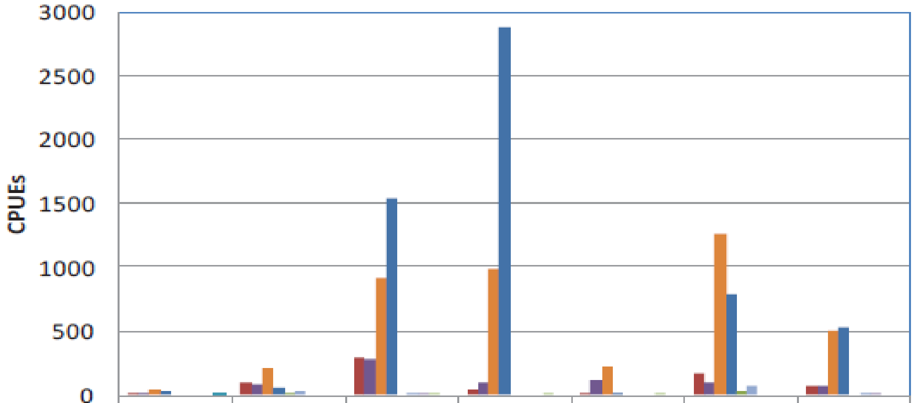
Figure 7. Weirs that are not recommended to be improved in terms of connectivity, or eliminated, in the river Cabriel (Júcar Basin, Spain) as a brake to the upstream expansion of a translocated species. Orange point: weir; black triangle: dam; green point: station with Júcar nase (*Parachondrostoma arrigonis*); red point: station with Iberian straight-mouth nase (*Parachondrostoma polylepis*). Source: Sánchez (2017).

Oliva-Paterna et al., 2017. Programa de seguimiento de indicadores biológicos: comunidades y poblaciones de peces.

Sánchez-Pérez et al., 2017. Uso de pasos para peces por EEIs en el contexto del proyecto Life+ Segura-Riverlink: datos preliminares.

These two works collect preliminary data from the same project, Life + Segura-Riverlink (Segura River Basin, Spain). Through regular samplings the movements of four sentinel: native species (Southern Iberian barbel *Luciobarbus sclateri*), translocated species (Pyrenean gudgeon *Gobio lozanoi* and Iberian nase *Pseudochondrostoma polylepis*), and invasive species (common bleak *Alburnus alburnus*) are analysed in several fish passages, technical fishways and nature-like bypass fishways. These fish passages were implemented over several artificial barriers to improve and restore fish movements.

Oliva-Paterna et al., 2017: *The monitoring programme has made it possible to detect the use of fish passes carried out by the fish community and the populations of sentinel species and, consequently, their effectiveness in increasing connectivity between populations. In addition, the temporary patterns of the use of each sentinel species which have been obtained should be useful in future management and a differential efficiency of different types of implemented fish passes has been observed, which should also be a tool for the future selection of new infrastructures.*



	INV	PRIM	VER	OTO	INV	PRIM	VER
Lscla	4	93	291	38	3	172	67
Ppol	4	81	273	105	116	101	73
Gloz	50	204	920	987	226	1265	495
Aalb	34	58	1539	2880	2	785	524
Ccar	0	15	0	0	0	37	0
Lgib	0	31	10	0	0	66	2
Msal	0	0	1	0	0	0	4
Sluc	0	0	1	2	1	0	0
Eluc	1	0	0	0	0	0	0

Figure 8. Seasonal abundance for each species captured inside fishways during 2016–2017. Source: Oliva-Paterna et al. (2017).

The first approach to data analysis, the higher captures inside fish passes were obtained in the El Jarral (technical fish pass). However, the more natural fish passes of Hoya-García and El Menjú (bypass) also showed high values. The use of the different fish passes by sentinel species showed significant differences in the temporal pattern (Fig. 8). The pattern observed in Luciobarbus sclateri *and* Pseudochondrostoma polylepis *was more correlated to its reproductive movements during an annual cycle, all of types of fish passes have been shown to be effective for displacing schools of* Alburnus alburnus, *and* Gobio lozanoi *may be the sentinel species that shows a best adaptation to new microhabitats created inside the fish passes showing a constant in time use.*

Sánchez-Pérez et al., 2017**:** *94.2% of captures belong to nine foreign species, with 41.8% being native species from other Iberian river basins (*Pseudochondrostoma polylepis *and* Gobio lozanoi*). Other species have their origin in the north of Europe, America and Asia, among this group* Alburnus alburnus, Lepomis gibbosus *and Ciprinus* carpio *were* *dominant in terms of relative abundance. Furthermore, the presence inside fishways of ichthyophages species like* Exos lucius*,* Micropterus salmoides *and* Sander lucioperca *was detected, and also other species like* Gambusia holbrooki*.*

Cipriber, 2017. Life +: Actions towards the protection and conservation of Iberian cyprinids of community interest.

One of the objectives of the Life Cipriber project is to improve habitat conditions in order to achieve a better distribution of populations of threatened fish by removing existing pressures in the river courses and restoring habitats, thus achieving a good ecological status. The target species are: Iberian straight-mouth nase *Pseudochondrostoma polylepis,* Northern straight-mouth nase *Pseudochondrostoma duriense,* sarda *Achondrostoma salmantinum,* bermejuela *Achondrostoma arcasii,* calandino *Squalius alburnoides,* Southern Iberian spined-loach *Cobitis paludica* and Vettonian spined-loach *Cobitis vettonica.*

Two of the main actions of this project have been the drafting of an action protocol against invasive alien species and the connectivity improvement of obstacles that modify the fluvial continuity of eight riverine LICs of the SW Salamanca province (Duero and Tajo basin, Spain). With the aim of improving longitudinal connectivity, a list of weirs to act on was prepared under several premises. The first, that the dam prevents the dispersion of invasive alien species, that its administrative status is in disuse, and that the type of work to be carried out contributes to the achievement of the objectives set out in the LIFE project. The second is that the connectivity improvement works of the obstacle contribute significantly to the improvement of fluvial continuity. Thus, the actions were prioritized in highly impassable, out of service or abandoned infrastructures and with works that imply their connectivity improvement or demolition, but excluding obstacles that would serve as a brake on the expansion of invasive aliens.

Based on the existing data on fish distribution in the basins, two groups of invasive alien species were established, a group with a higher negative influence on the community of the target cyprinids of the project, and another group that due to their distribution or lower interaction with the target species were considered less relevant. The invasive alien species were mainly fish: Northern pike *Esox lucius*, pumpkinseed *Lepomis gibbosus*, back-bass *Micropterus salmoides* and common bleak *Alburnus alburnus*. Nevertheless, other species were also included: American mink, alien crabs, terrapins and plants. Most of these species are adapted to stretches of slow water and reservoirs, so the actions were aimed at favouring the areas of running water; to benefit native species to the detriment of the natural reproduction of invasive alien species, especially piscivorous ones.

Thus, to stop the expansion of populations of invasive alien species within the scope of the project, containment zones were established in each river, identifying the obstacles that should not be eliminated in order to avoid upstream expansion of invasive alien species into stretches that still retained good endemic fish populations (Fig. 9). In addition, in areas with the presence of invasive species, actions were focused on artificial reservoirs, removing dams or reducing their height to prevent their expansion.

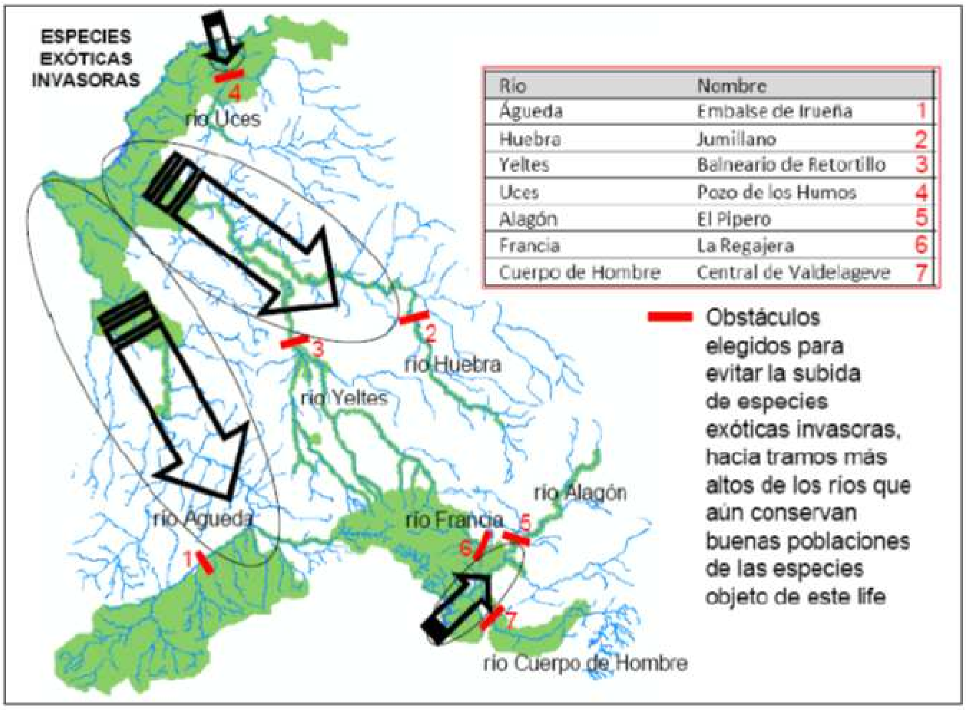


Figure 9. Barriers chosen (red lines) to avoid upstream expansion of invasive alien species towards higher reaches of rivers that conserve good populations of endemic species (Duero and Tajo basins, Spain). In green, the Natura 2000 Network. Source: Life Cipriber, Conservation action C1 (Cipriber, 2017).

7. EVALUATION CRITERIA

This section tries to understand and summarize all the information from the previous sections and adapt it to the problem of fluvial connectivity and expansion of invasive species in the Iberian Peninsula. Dividing the information into several subsections provides a clearer understanding of the various aspects that are addressed.

7.1. Literature search

Most of the scientific literature gathered here (in section six) is focused on studying the pros and cons of the recovery of fluvial connectivity against the expansion of exotic species in areas of North America. Several species of invasive salmonids and sea lamprey are the main threats to native salmonids in this region, which are increasingly relegated to small fragments of river headwaters, where management of the isolation or recovery of river continuity is very important to conserve native species. There are also several works on the effect of invasive fish on native populations of Galaxiids in Australia and New Zealand. In general, the oldest articles basically mention the problem of the advance of invasive species when a dam is removed or when water bodies are connected. However, the increase in experiences of dam demolitions in recent years has allowed publication of works that increasingly deal with the consequences of this problem in more depth.

Over the last few years, there has been a growing focus on the potential value of dam removal in river restoration on the part of ecological researchers, watershed managers, and policy-makers. The growing number of scientific studies provides an important opportunity to learn how to better manage watersheds and improve our understanding of the science of river restoration. This knowledge can begin to understand and predict how dam removal can be used most effectively to achieve watershed restoration goals (Hart et al., 2002). However, the maintenance of dams and other types of barriers used to protect native biological communities is generally less valued than dam removal (McLaughlin et al., 2013).

In the Iberian Peninsula, studies that deal with the recovery of fluvial connectivity versus the threat to biodiversity conservation due to the expansion of invasive aliens are still very scarce and are located in small areas of a few river basins. In Spain, most dam removals in recent years have been concentrated in the Duero and Cantábrico basins (CIREF, 2016), although there are very few monitoring reports of these fluvial actions. Even more striking is the lack of information on connectivity recovery versus invasive species, when there are numerous studies that have revealed a significant decline in endemic species of fish in the Iberian Peninsula and, at the same time, an alarming increase in the distribution of invasive alien species (Elvira & Almodóvar, 2001; Martínez-Capel et al., 2010).

For this reason, we must consider the potential contribution of transferring practices developed in other regions of the globe to the Iberian Peninsula. The main reference publications on this subject are Fausch et al. (2009), McLaughlin et al. (2013), Rahel (2013) and Crook et al. (2015), whose management conclusions may be used to evaluate the guidelines for action against the elimination or connectivity improvement of obstacles and the expansion of invasive species in any region, including the Iberian Peninsula.

7.2. River connectivity versus invasive species

As noted above, habitat destruction and biological invasions are the two main factors that affect the conservation of ecosystems, causing the decline and disappearance of species worldwide (Dirzo & Raven, 2003). At present, the main purposes of managers are to conserve natural environments, biodiversity and the landscape. When managers try to solve the problems of fluvial connectivity and invasive species, they are often faced with the trade-off that managing ecosystems to address one problem precludes solving the other (Fausch et al., 2009): on the one hand, habitat fragmentation isolates populations and increases their risk of extinction, so it may be proposed to improve hydrological connectivity between fragments; on the other hand, connectivity increases the risk of expansion of invasive species, so it may be decided to isolate those habitats.

In the aquatic environment this invasion-isolation trade-off is most acute. The dendritic system, or corridors of river systems, greatly favours the movements of aquatic organisms, whether they are native or exotic; however, it also makes them very vulnerable to fragmentation (Fagan, 2002, Fausch et al., 2009). For example, in some cases a single dam can prevent the migration of a community of native fish over a large area, but it can also prevent the advance of invasive fish species. Therefore, the barriers designed to protect native populations from invasions may also contribute to their extinction by creating small populations isolated in habitat fragments; managers are faced with the trade-off between restricting the movement of invasive species and facilitating the movement of native species (Novinger & Rahel, 2003, Fausch et al., 2006).

With regard to the application of the Habitat Directive to aquatic ecosystems, the Water Framework Directive is an important support for the management and monitoring of the Natura 2000 network and water bodies (Kettunen et al., 2007). Both directives share the common aim of recovering the fluvial continuity as a tool for the conservation of aquatic ecosystems and their native species. Nevertheless, it has already been pointed out that the presence and expansion of invasive alien species in many Iberian river basin districts jeopardizes the compliance with the environmental objectives established by the Habitats Directive in terms of biodiversity conservation.

Although the Water Framework Directive does not contain specific requirements for the application of the provisions of the Habitats Directive, the definition of good ecological status within the framework of this Directive includes aspects related to the maintenance or restoration of hydromorphological characteristics and structure of aquatic ecosystems, including fish community composition and abundance, which must correspond totally or nearly totally to undisturbed conditions. However, the controversy of connectivity versus invasion appears again and the directives contradict each other in some aspects, as the preservation of the fluvial continuity that allows natural migration of autochthonous species, like fish, can also entail a serious risk of propagating the invasive species that put them in danger.

In other words, aquatic ecosystems would ideally have to be managed to maintain viable populations of all native species, increase the habitat and numbers of individuals in threatened and endangered species, and also prevent the introduction or spread of non-native invasive species (Jackson & Pringle, 2010). The development of effective conservation and restoration strategies is critical, given the magnitude of land-use change and alterations to connectivity regimes (Crooks & Sanjayan, 2006). However, rivers and their restoration are complex, and any effort to rehabilitate a river system needs to be based on a sound understanding of the ecological benefits and drawbacks of a proposed restoration plan. The invasion of exotic species, for example, may block recovery or set it off along a different trajectory. The effects of invasive exotic species should be integrated in project plans, either to minimize the impact of exotics, or to modify the expected outcome of the restoration (Rahel, 2007). Any decision to remove or improve a dam must include a careful examination of all the potential ecological impacts of dam removal, as well as the continued ecological impacts of a standing dam.

Before barrier removal or placement can be recommended, it is necessary to undertake the following actions: study how new tools and methodologies are improved with enhanced knowledge of fish passage criteria, habitat requirements, life history and population dynamics for a wider range of aquatic species; promote validation studies to assess the accuracy of assigned barrier passability values; perform further tests to investigate the cumulative effects of multiple barriers on passability, habitat connectivity and population responses (Kemp & O'Hanley, 2010), for native organisms as well as invaders.

Wherever invasive species have already become established, active management is needed to reduce their harmful effects and prevent the further spread of invasive species. Control programmes should focus on the areas of highest value for native biodiversity and most at risk from non-native invaders. In this sense, further efforts should be devoted to the identification of these areas.

The Iberian Peninsula is not removed from this controversy regarding isolation in the face of the expansion of invasive species. Thus it is clear that the introduction of exotic species in aquatic environments has a remarkable impact on the native fauna of Iberian fish and, furthermore, that the loss of fluvial continuity also constitutes one of the main threat factors (Elvira & Almodóvar, 2001; Cabral et al. al., 2005; Doadrio & Aldeguer, 2007). In addition, the alterations in hydrologic connectivity associated with interbasin transfers have resulted in new pathways for the invasion of exotic and translocated species (Jackson & Pringle, 2010, Doadrio, et al., 2011a; Muñoz-Mas et al., 2017).

7.3. Framework to analyse the trade-off according to Fausch et al. (2009)

The degree of threat of invasions and the degree of threat of isolation can differ enormously between fish populations within watersheds due to differences in evolutionary history, habitat and other abiotic factors, and the time since isolation began. Therefore, the strategies to follow may be different in each case. Fausch et al. (2009) developed a conceptual framework to analyse the trade-off. It is based on four key questions that can be transferred to the Iberian Peninsula:

1. Is a native population of important **conservation value** present?

The first step is to consider whether the stream concerned supports a native population of important conservation value. This study suggests three conservation elements to be evaluated: evolutionary, ecological and socioeconomic. It is important to define which sets of values to conserve in which locations, and select those of highest value in order to analyse the invasion-isolation trade-off:

- Evolutionary values encompass the traditional goals of conservation biology and are focused on elements of biological diversity including native species, phenotypes, and genes. Most of the Iberian native fish species are endangered and endemic—some are even circumscribed within a single river basin—so this element of conservation is usually very important.
- Ecological values are focused on ecological patterns, processes, and functions at the population, community, or ecosystem levels. In the case of Iberian fish, the distribution in metapopulations is common in many species, which helps them to persist despite

environmental disturbances or changes, so that resilient and self-sustaining populations have a greater ecological value than others.

- Socioeconomic values include other ecosystem services, such as commercial and sport fishing or tourism from wildlife watching. The socioeconomic values of the Iberian fish are mainly focused on the two species of native salmonids, eel and some large cyprinids.

2. Is a native population **threatened by invasion and displacement by non-native species**?

In the Iberian Peninsula, the introduction and expansion of invasive species is growing alarmingly, especially due to the deliberate release of sport fishing and the growing number of reservoirs or impoundments that serve both as a sink and as a focus for the introduction and expansion of new species of invaders. Whether these invasive species manage to invade or displace indigenous fish populations depends on competition for the same food resources and the need for refuges, or on predation or hybridization. The threat of invaders after a demolition or connectivity improvement action of a dam can be established by sampling in the reservoir and/or downstream to verify the risk both downstream and upstream. The Iberian ichthyofauna virtually lacks native predators, only the eel and the salmonids, making it extremely vulnerable to invasive piscivorous species. In addition, the low number of species present in the same stretch of river also makes them very vulnerable to competition for food against invasive species.

3. Would this native population be **threatened with local extinction if isolated**?

The negative effects of the isolation of fish populations in small river segments or in their headwaters have already been mentioned in chapter 4 of this report. As a whole, there is a wide variety of movement needs to cover the life cycle in Iberian ichthyofauna species, from sedentary individuals which only perform movements on a small scale to large diadromous and potamodromous migrants. In addition, the needs of metapopulations for the persistence and maintenance of the genetic diversity of Iberian fish, as well as the re-establishment of extinct populations in other areas or river stretches, are still unknown. Nor is it known what is the minimum length of fluvial network necessary to maintain an effective population size, and to maintain the long-term evolutionary potential of Iberian species. This large network may not only include a greater population size, but also more internal complexity and diversity of habitats, which reduces its vulnerability to catastrophic events.

4. How does one **prioritize among several native populations** of conservation value?

On many occasions there are conflicting objectives within the same river basin regarding the intervention on an obstacle. In this way, all fish populations must be taken into account, as well as their interactions, movements and migrations, and the factors that threaten them. Conservation actions must prioritize four aspects:

- Representation: The selection of populations should include the full range of ecological and evolutionary diversity within a region (unique alleles, life-history types and species assemblages).
- Redundancy: This is important because no local population is immune to extinction. Accordingly, it is prudent to conserve multiple populations to minimize the possibility of all of them being lost simultaneously, and also to provide a source for recolonization if some are extinguished. One strategy is to select widely distributed populations to minimize their vulnerability to the same disturbance.
- Resilience: This refers to populations that persist despite natural or human-caused disturbances or environmental changes. Resilience is higher in large populations, with adequate space, with productive habitats and with the presence of adequate shelters.
- Feasibility: Conservation actions should be cost-effective, sustainable, and socially and environmentally acceptable. This point also considers that barriers affect all the aquatic and riparian communities, so these communities should be taken into account before deciding whether to eliminate an obstacle or not.

Therefore, it seems obvious that in some cases artificial barriers in rivers are one of the means of isolating native fish populations, preventing or delaying the expansion of invasive alien species, mainly fish, but also invertebrates such as crabs, gastropods or bivalves. However, in other cases, the best decision may be to reconnect native populations because the risk of invasion is low and the migratory needs of native species are high. According to the model of Fausch et al. (2009), strategic decisions must be taken according to different management priorities, it being necessary to weigh the threat of invasion against the demographic and genetic risks of the isolation of native populations and, above all, act with a vision of the entire watershed. In any case, dams and weirs as barriers can be considered to be a temporary solution to restrict the expansion of some invasive species, which can be abandoned and removed once better control options become available (McLaughlin et al., 2013).

7.4. Action strategies for isolation versus invasion

The general measures and alternatives regarding the problems of isolation versus invasion of exotic fish are aptly summarized in two diagrams mentioned in section 6 of the compiled bibliography. The first diagram, from Fausch et al. (2009), is composed of two axes: one assesses the degree of threat of an invasion and the other assesses the degree of isolation or fragmentation of the habitat (Fig. 10). The second diagram is from Rahel (2013) and only has one axis in terms of the optimal level of connectivity (Fig. 11). The information in both diagrams, although mainly oriented to the conservation of salmonids, can be transferred to the conservation area of the Iberian ichthyofauna in order to examine the possibilities of an action, either demolition or improvement in connectivity, in a dam or weir.

Next, the four possible situations are described, as explained by Fausch et al. (2009):

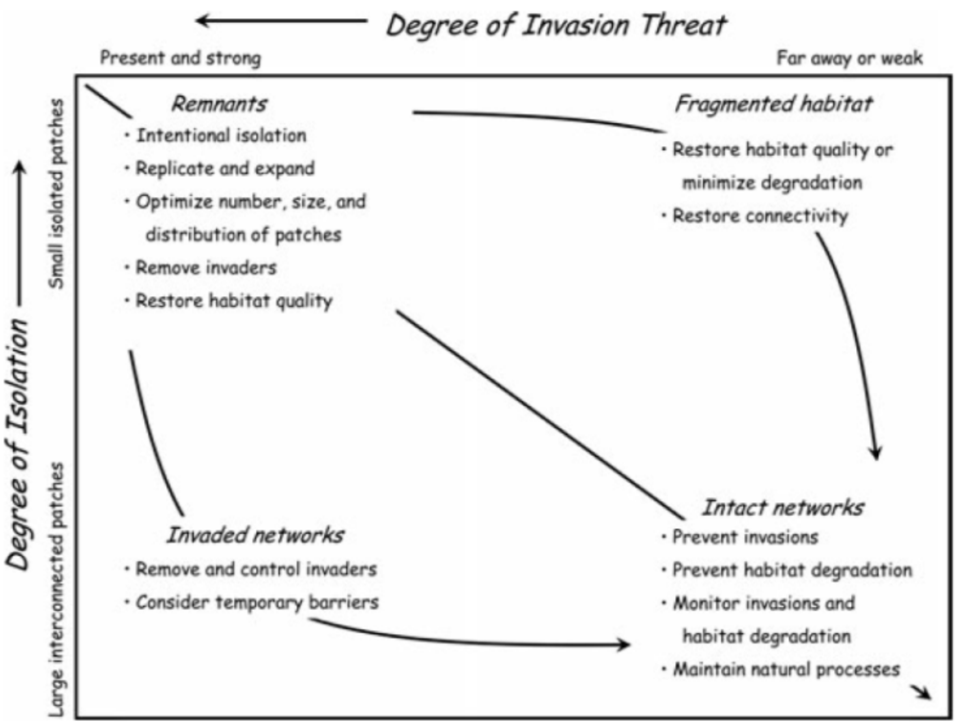


Figure 10. A conceptual model of the opportunities for strategic decisions when managing the joint invasion-isolation trade-off for native salmonid populations of conservation value. Examples of strategic decisions to maximize the conservation of remaining populations under different degrees of invasion and isolation threat are shown. Arrows pointing toward the lower right show the overall goal of management, which is to conserve interconnected populations in stream networks free of invaders. Source: Fausch et al. (2009).

Situation 1: High risk of isolation and high risk of invasion (top left)

This is the worst possible situation, it occurs when threatened populations are in vulnerable habitats where invasive fish species are advancing, displacing them by competition, depredation or hybridization. In this case, management measures aim to keep native populations of fish isolated above artificial barriers. Therefore, the maintenance of barriers in strategic locations can serve to stop the advance of invasive aliens. However, it is necessary to undertake other measures of isolation management oriented towards the long-term preservation of native populations; in such situations, isolated reaches should be as large and diverse as possible (Novinger & Rahel, 2003; Jackson & Pringle, 2010).

In the case of highly restricted distributions of native species, it is necessary to deliberately translocate some individuals between populations every few generations to maintain genetic variability and replicate genetically distinct populations to avoid local extinctions. Habitat improvement measures would act to increase the number of individuals of populations and their distribution; in this way, their resilience and capacity to recover after potential disturbances, catastrophes or extinctions would be greater.

Other studies conclude that the emplacement of fish barriers together with the restoration of native fish assemblages upstream of such barriers seems to be the only viable and sustainable means of achieving the segregation of native and non-native fish (e.g. Clarkson et al., 2012). The possibility of developing campaigns to eliminate or control the populations of invasive species can also be evaluated.

Situation 2: Low risk of isolation and high risk of invasion (bottom left).

This situation implies a network of well-connected streams or sub-basins, but the threat of invasive species expansion is extremely high. In this case, the strategy to follow is to stop the advance of invaders through temporary or seasonal barriers and work on their control and disposal downstream. Another possibility is to reach a level of partial connectivity by installing barriers for certain taxa or life stages.

Situation 3: High risk of isolation and low risk of invasion (top right).

When the threat of invasion is low or fish populations resist invasions, but fluvial continuity is very low due to the presence of artificial barriers, action measures should be aimed at restoring connectivity and habitat quality. These measures include removing barriers or making improvements with fish passage devices. In this way, the genetic flow is reconnected between isolated populations and movement is enabled in species with high migratory requirements.

Situation 4: Low risk of low isolation and low risk of invasion (bottom right).

When fish populations occupy a wide network of interconnected habitats and the effects of invaders are low or the threat is distant or unlikely, management options should focus on prevention. In this case, weir or dam removal or improving road crossings would not represent a problem, generally speaking. However, early warning programmes must be implemented to prevent the establishment of invasive species at their origin, as well as to prevent the presence of source areas of exotic fish that serve as vectors for the entry of new invaders. Examples of prevention measures are the removal of artificial reservoirs or keeping strategic barriers that may stop a future unauthorized introduction. These measures must be accompanied by others that maximize natural ecological processes in rivers and prevent habitat degradation.

In the first three situations, the general objective is to move forward until Situation 4 is reached, in which the native fish populations are interconnected and can function and evolve in fluvial networks free of invasive species.

Some further ecological considerations for a species that are achieved with an optimum level of connectivity are considered by Rahel (2013): the possibility of reaching an adequate population size, moving to complementary habitats, increasing the potential recolonization capacity, and improving migratory life history. In any case, reaching the extreme scenario in Situation 1 must be avoided—when small isolated populations survive at a high risk of invasion and in small fragments of habitat—as future management options would be very limited and the risk of disappearance would be very high. In this sense, Peterson et al. (2008) found that management actions to ameliorate one of these threats could exacerbate the other, and that trade-offs between isolation and invasion were strongly influenced by the size and habitat quality of the stream network to be isolated and the existing demographic linkages within and between populations.

The measures against the advance of invasive alien species through the restriction of connectivity are the same for three other fish conservation problems, which Rahel (2013) points out in other ecological considerations. First, low connectivity allows the expansion of diseases or parasites associated with exotic species to be halted simultaneously. Second, unwanted genetic exchanges are avoided, such as hybridization between individuals that have escaped from fish farms or from poorly managed repopulations carried out with wild stocks (for example, the consequences of stocking the Iberian Peninsula with brown trout from Central Europe). Hybridization between an autochthonous species and a translocated species from a nearby watershed (such as the case of Iberian straight-mouth and Júcar nase) can also be avoided. Both lead to the loss of authentic genetic material and adaptive traits (Van Houdt et al., 2005). Third, barriers could prevent organisms from entering human-created habitats that act as ecological traps. Related to the first point, another management example that involves maintaining reduced hydrologic connectivity is the decision to conserve dams that are blocking the passage of exotic fish that would, otherwise, transport bioaccumulated toxic chemicals into upstream habitats (Freeman et al., 2002).

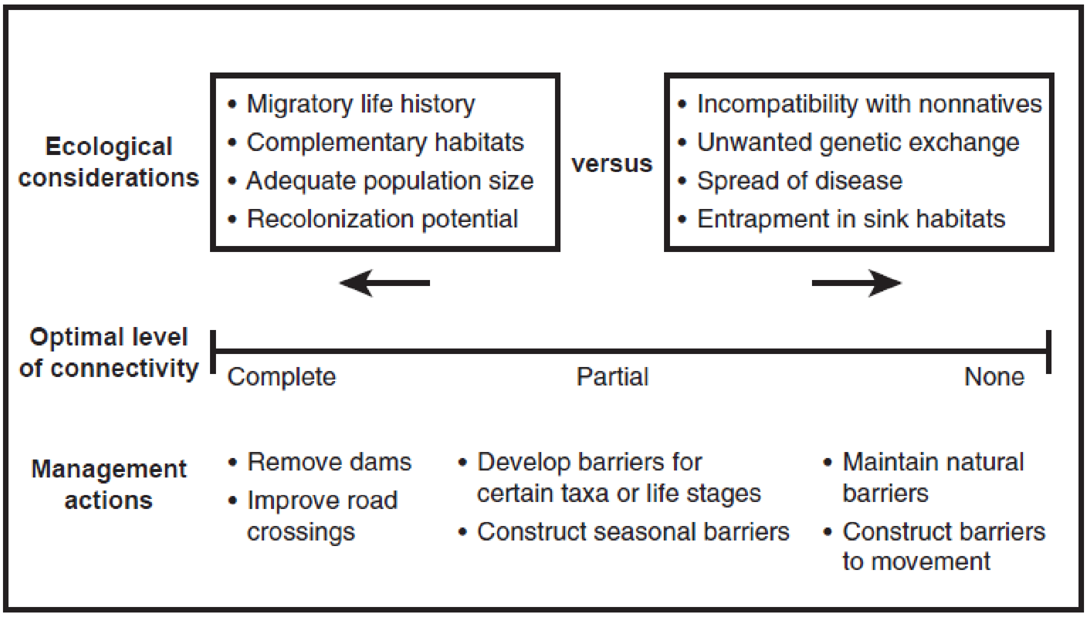


Figure 11. Tension between factors that support complete connectivity in aquatic systems (left) and factors that support no connectivity (right) in aquatic systems. Source: Rahel (2013).

Concerning the balance between isolation and connectivity, some indices of prioritisation that are proposed in Iberian hydrographic districts (González et al., 2011; Sánchez, 2017) can produce fundamental information about the naturalness, mobility and vulnerability of the species in river basins. Fish communities and invasive species are some of the factors that are taken into account in these indexes to make decisions easier, but they are not the only ones. There are other factors that should be taken into account to prioritise the dams or weirs on which to act, such as: those that represent insurmountable barriers or which allow for the recovery of the greatest barrier-free length of river, prioritizing those that are in protected areas, those that cause droughts downstream, or those with a poor state of conservation or that are in disuse.

7.5. Other active strategies

In essence, as McLaughlin et al. (2013) indicated, the objectives of improvements to fish passage and dam removal should include the conservation of native and valued non-native fishes by minimizing habitat fragmentation or using fragmentation to limit the harm caused by invasive species. To these ends, some other factors that affect the community of aquatic organisms present in the river basin, and therefore the decision-making process, must also be considered:

Reservoir as attractive habitat for alien species. Reservoirs created by dams and weirs maintain large surfaces of slow water. These reservoirs facilitate the process of biological invasion by creating attractive habitats for recreational activities that can result in the purposeful or accidental introduction of non-native species. Reservoirs, also, can change the general environment in such a way that it becomes more hospitable to certain types of invasive alien species that are better adapted to lake-like water bodies (American Rivers, 2002; Graf, 2003; Alexandre & Almeida, 2010). Thus, total dam removal may reduce the effects of biological invasion by controlling both the invaders adapted to the warm and slow waters, and the appeal of these places as an entry point for exotic species, leading to a situation where non-native lake fishes are replaced by native stream fishes (Rahel, 2007). Moreover, the restoration of natural habitat conditions can involve eliminating stressors such as low oxygen or high pollutant levels. The option of partial connectivity improvement should at minimum eliminate the reservoir area, as the source of these introductions, and at the same time maintain a barrier to stop the advance of exotic species from downstream river segments. Given the special role that reservoirs seem to play in the dispersion of invasive species, these environments should be a focus of attention in future management programmes (Saunders et al., 2002; Hermoso et al., 2011). It is also necessary to take into account that interventions could possibly create or exacerbate disturbances, for example drained reservoirs could be vulnerable to the invasion of exotic plants (Orr & Stanley, 2006). In many cases, the option of total or partial dam removal will depend on the invasion risk, represented by the invasive alien fish species present downstream.

Regular flow regime. Many species of alien fish develop better in stretches of regulated rivers, that is, with a regular flow regime all or almost all year (for example, species from Central Europe, such as pike or pike perch, in the Iberian Peninsula). Hydro electrical and agricultural regulation cause changes or inversion of the hydrological cycle and create a more homogeneous community that benefit the introduced fish, which are generalist and more tolerant species (Alexandre et al., 2013; Amat-Trigo et al., 2016).

Many Iberian rivers have cycles that alternate periods of water stress with periods of high rainfall and floods, especially in the Mediterranean climate areas. Native species that naturally inhabit Iberian rivers are well adapted to these flow variations, having developed strategies to deal with the harsh low-flow periods (Magalhães et al., 2007), which probably does not happen with the introduced fish species (Rodriguez-Ruiz, 1998). Dam removal would allow natural flow regime and natural habitat conditions to be restored, which could reduce biotic homogenization by favouring the recolonization of native fish that are better adapted to the irregular and unpredictable nature of the Mediterranean hydrology, thus halting the proliferation of non-native fish that are better adapted to fluvial courses of regulated flow (Baltz & Moyle, 1993; Stanford et al., 1996; Marchetti & Moyle, 2001; Olaya-Marín et al., 2012).

Other authors, such as Marks et al. (2010), suggest that in order to increase native fish populations, flow restoration should be accompanied by the removal of exotic fish, as habitat improvements alone may do little for native fish recovery where exotic fish dominate the fish assemblage. Cooke et al. (2012) indicated that imitating the natural flow regime may enhance native fish recruitment; however, it does not necessarily reduce non-native fish recruitment, particularly for highly fecund small-bodied non-native fish species. Moreover, streams with degraded habitats and poor water quality typically have simplified fish assemblages dominated by a few tolerant species that are often non-native (Paul & Meyer, 2001). When dam removal is not possible (for technical or financial reasons) and connectivity would not be recovered, the restoration of the natural flow alone would also help to fight against the introduction and advance of some exotic species (Power et al., 1996) and would favour native species completing their natural biological cycles.

In fact, most of the introductions of alien fish species in the Iberian Peninsula were made downstream of large reservoirs. Colonization upstream would depend on the time elapsed since introduction and the capacity for colonization of alien species (Vila-Gispert et al., 2005), but many of these introduced and currently invasive species have not yet colonized the upper part of rivers. In some cases, artificial barriers serve as a brake on expansion, but in others, invasive species do not adapt to the unpredictable Mediterranean hydrological regimes that exist upstream the reservoirs or regulated sections, a fact already described in other regions such as California (Baltz & Moyle, 1993).

Potential thermal change. Regulated rivers cause a potential thermal change downstream. Large dams, which normally release water from the bottom of the reservoir, supply very cold water downstream. On the other hand, weirs favour large insolation periods and contribute to a warming of the water, including flow that is released downstream (Graff, 2003). Both situations can favour, downstream, the development of alien fish populations adapted to water temperature conditions that are different to the natural ones. The demolition of these dams and weirs would restore the natural thermal condition of the water and would allow these stretches to be recolonized by displaced native ichthyofauna, to the detriment of exotic species that are not adapted to the seasonality patterns of flow and temperature of unregulated rivers.

Selection of strategic weirs or dams as barriers. In the case of projects or plans at the river basin scale, in which a general assessment of the weirs to be eliminated can be carried out, such as the Spanish LIFE Cipriber project and the report about dam removal in the Júcar Basin (Cipriber, 2017; Sánchez, 2017), a good tactic is to analyse the distribution of all native and exotic species and try to select the strategic dams that serve as a barrier to the expansion of invasive species in each of the sub-basins studied.

Effect of demolition. Works to improve connectivity should be avoided in the periods in which fish are migrating, both in upstream and downstream movements (American Rivers & Trout Unlimited, 2002). The effect of demolition works may harm the species of fish that are intended to be conserved, such as the release of contaminants trapped in sediments or excess nutrients (Cooke et al., 2012), and they can affect species from other groups with a greater threat status, such as large freshwater mussels (Sethi et al., 2004). In the Iberian Peninsula, freshwater mussels *Margaritifera margaritifera* or *M. auricularia* would benefit in the long term from the removal of some obstacles, since it would facilitate the migration of the fish that serve as hosts during their glochid larval stage, although an increase in sedimentation and toxic products from the reservoir could cause huge short-term mortality following the removal of a dam (Lejon et al., 2009).

Presence of aquatic invasive species other than fishes. Efforts to increase stream connectivity by removing dams can also open new habitats to the natural dispersal of aquatic invasive species other than fishes. For example, the introduction and expansion of invasive bivalves are one of the main causes of the disappearance of **Iberian freshwater mussels** (Araujo et al., 2009). In addition, some alterations that are produced on native ichthyofauna by exotic fish, which affect through competition, predation or hybridization of the fish species that host their gloquidia, represent a serious threat to the conservation of Iberian freshwater mussels (GTAR, 2009). Another example is dams that are protecting upstream areas from the invasion of non-native crayfishes. Some studies recommend that dams located downstream of endangered native crayfish should probably not be removed (Kerby et al., 2005, Lieb et al., 2011), and others also recommend modifying weirs so that native crayfish can be protected by barriers that do not hinder fish migration, but can block upstream migration of non-native crayfish (Frings et al., 2013). On the other hand, Adams & Marks (2016) pointed out that the restoration of natural flow together with other factors may help prevent further upstream invasion by an exotic crayfish *Orconectes virilis* in Fossil Creek, United States. All these management experiences could be transferred to conservation strategies for **native crayfish** *Austropamobius pallipes* in the Iberian Peninsula, which is extremely threatened by two invading crayfishes of North American origin, *Procambarus clarkii* and *Pacifastacus leniusculus*.

Piscicide treatments. In other cases, dams and weirs serve not only as barriers to the expansion of invasive species, but are also used as potential limits for piscicide treatments to achieve the eradication of non-native fish and the restoration of its indigenous fish assemblage. There are experiences in the Cape region (South Africa), which has a Mediterranean climate and high levels of endemicity (as in the Iberian Peninsula), where there are weirs and farm dams upstream to prevent re-invasions (Marr et al., 2012). In California, exotic salmonids were controlled by gill netting and using barriers as limit to protect an endangered frog (Vredenburg, 2004). In the same line, in Australia there are studies on the use of barriers and targeted eradication programmes for the management of small, threatened fish species (Lintermans, 2000). Nevertheless, the region where there are most experiences of this type is in the Laurentian Great Lakes, with the invasive sea lamprey (e.g. McLaughlin et al., 2007; Daugherty et al., 2009; Pratt et al., 2009).

Needs of migratory movements. The restoration, or not, of fluvial continuity must take into account the different needs of migratory movements and the jump capacity of native and invasive species. In fact, the hydromophological characterization protocol of rivers in Spain (MAGRAMA, 2017) establishes values to calculate the barrier effect of obstacles for each species depending on the naturalness (native, introduced or invasive), mobility (according to their migratory needs) and vulnerability (depending on the IUCN categories). In the appendices I and II of this document, these parameters are detailed for the Iberian native and invasive species respectively. Moreover, in low-head barriers there is a strong body-length effect on passage success (e.g. Forty et al., 2016). Furthermore, in some Iberian species, the size of the fish at sexual maturity can differ greatly depending on the sex. Both factors, length and size, at maturity determine the capability to overcome obstacles, which sometimes also depends on certain flow conditions, causing asynchronies that affect reproduction (Alonso, 1998; Ordeix et al., 2011).

Improvement connectivity. Another means of action is the improvement in connectivity, e.g. enhancing or rehabilitating ramps and fish ladders, which favour migratory movements and the connectivity of the entire fish community, native, translocated and exotic (Oliva-Paterna et al., 2017; Sánchez-Pérez et al., 2017). It would be necessary to develop improvements in fish passages to protect native fish with barriers that do not impede their migrations, but at the same time prevent upstream movements of the invasive species. In this sense, there are many experiences in the Laurentian Great Lakes region, where some fish ladders have been designed to only impede the migration of the invasive sea lamprey (e.g. McLaughlin et al., 2007; Daugherty et al., 2009).

Successful fish passage through obstacles, including artificial barriers, is governed by a combination of swimming capacity, behaviour, and motivation, which allow fish to swim faster than the speed of flow (Castro-Santos, 2005; Sanz-Ronda et al., 2015). For this reason, designing efficient and selective fishways, with minimal passage delay and post passage impacts, requires adaptive management and continued innovation, especially in advances towards fish passage at community scale and in selective fishways, which are also needed to manage invasive fish colonization (Pratt et al., 2009; McLaughlin et al., 2013; Rahel, 2013; Silva et al., 2017). In fact, for most Iberian fish species (except for salmon, trout, eel and a few cyprinids) their jumping ability, swimming speed, fatigue time, etc., are unknown, and these are the characteristics that would enable the design of these structures or selective steps. Moreover, these artificial passages should function as a pass for a wide range of aquatic species, not only fish, and help in species restoration plans (Louca et al., 2014).

Climate change. It is also necessary to include climate change issues in the prioritization processes for dam removal, especially when climate change leads to an increase in both the environmental and economic value of the stored water resources (Beatty et al., 2017). Climate change exacerbates the negative effects of dams: temperature increases and flow declines create more suitable conditions for alien species in reservoir and upstream habitats, and are also liable to negatively affect fish migrations and increase the fragmentation of populations. However, reservoirs and other artificial lentic systems could also act positively against climate change as an aquatic refuge for threatened viable endemic fish populations when they have low migratory requirements and are free of invasive species (Beatty & Morgan, 2016); at the same time, in a situation of climate change, dams help to prevent the spread of existing or novel alien species. Beatty et al. (2017) point out that as the increasingly dry climate continues in some Australian and South African regions, the potential ecological value of artificial reservoirs may increase in dry regions, especially if the eradication of invasive species and repopulation of native fish are combined. In these regions, some native species could benefit from the use of artificial lentic habitats during prolonged low water periods, and they can then restock rivers when flows resume. Therefore, in Mediterranean regions, such as a large part of the Iberian Peninsula, it is necessary to evaluate the potential ecological value of a dam as a vital refuge for some Iberian endemisms in the face of predictions of a decrease in surface runoff.

Another common factor in these regions is that the number of invasive species with the possibility of expanding their distribution and affecting endangered Iberian endemic populations is high and varied. The higher the number of invasive species, the greater the probability of choosing to maintain an artificial barrier in the river, since its removal would increase the possibility of risks or threats to the native ichthyofauna.

Another aspect to take into account within the scope of the Iberian Peninsula is the existence of two large bio-geographic regions, the Mediterranean and the temperate region. Some of the most important differences in the fluvial courses of both regions are the composition of their ichthyofauna, hydrological regimes and threats. In the temperate region, especially in rivers that flow into the Cantabrian Sea, flows are more stable or more homogeneous throughout the year, the level of endemism is low, and incidences of invasive species are lower. On the other hand, flows in the Mediterranean rivers are subject to more seasonal fluctuations, with alternating periods of drought and high flows or floods. The number of endemic species is very high in these rivers, and the number of invasive species and their effects are higher. Therefore, the varying characteristics of Iberian rivers between Mediterranean and temperate climates, mean that fluvial fragmentation and the expansion of invasive species have differing effects on communities of native Iberian species.

The typical Mediterranean characteristics regarding climate and natural flow are increased by the impact of climate change on Iberian rivers. The problems of fluvial connectivity and invasive alien species combined with the effect of climate change and over exploitation of many aquifers is liable to exacerbate the present ecological problems, especially in Mediterranean rivers subject to periods of prolonged low water and unpredictable rainy periods. For example, studies on climate change in the Júcar basin (NE Spain) have already indicated a reduction in water resources that is much higher than the current water plan projections; in addition, these studies reveal a greater decrease in the precipitation in the headwater and inland areas than in the coastal areas, and between different seasons (Marcos-García & Pulido-Velázquez, 2017).

7.6. Future action strategies

Proposals to restore rivers via dam removal or improvements in connectivity raise many issues that require broad discussion and teamwork (Hart & Poff, 2002). Future dam removal decisions can be enhanced by developing a more complete scientific understanding of processes that determine how rivers are affected by different types of dams and how they respond to dam removal. There is an equally important need to understand the social, economic, engineering, and legal factors that influence dam removal decisions. Babbitt (2002) emphasizes the critical need for strong science, not only to predict what will happen when dams are removed, but also to monitor dam removal outcomes, so that is important to learn how to maximize the effectiveness of this restoration method.

A proactive approach, which combines a good knowledge of invasive species, can help us target our limited resources towards species of high potential threat to the ecosystem integrity and biodiversity of a given area of concern. Although extinction is often the final result of invasions, there are other ecological and evolutionary impacts of biotic homogenization that are less understood, thus prevention and precautionary principles are of particular relevance to invasive species (Clavero & García-Berthou, 2005). A new powerful tool, eDNA, can be applied to monitor the presence of invasive fish species through an analysis of DNA extracted from water samples in a variety of situations, for example checking upstream colonization after the removal of river barriers or monitoring potential escapes from fish farms (Clusa et al., 2017).

When fish passage or dam removal decisions are motivated by narrow interests, such as the enhancement of angling opportunities for a specific species, the biological and management trade-offs can further reveal disagreements in how scientists, managers and stakeholders value the species that stand to benefit from the different management options available (McLaughlin et al., 2013). One of these disagreements concerns the magnitude of climate change in terms of water resources (reductions), which are expected to alter river discharge in every major river basin in the world (Palmer et al., 2008).

For fish passage and dam removal decisions, uncertainty about the consequences exist because our understanding of the unwanted effects remains limited, the responses of populations and ecosystems can be complex, and uncertainties and responses can differ from one river system to another due to differences in geomorphology, climate, dam structure and operation, and the biota inhabiting river sections below and above individual dams (McLaughlin et al., 2013). Efficiency and selectivity in the design of fishways are key to controlling the expansion of invasive alien species (Silva et al., 2017).

During the last three years, several LIFE + projects have started in the Iberian Peninsula: Cipriber, Irekibai, Migratoebre, Segura-Riverlink, LimnoPyrineus, Miera and Águeda. Among their objectives and actions are the restoration of longitudinal connectivity by eliminating artificial barriers or improving passage systems. In a few years, their monitoring programmes, which in some cases including invasive fish species, will enable management programmes to be established in these areas. Subsequently, these programmes may be extended to other areas of the Iberian Peninsula and other countries, especially those in the Mediterranean area.

8. BEST PRACTICES GUIDE

This section attempts to summarize all the information compiled in the previous sections and to serve as a guidance document of best practices to take decisions and to be used as a reference to unify management criteria, especially when applied to the Iberian Peninsula.

Although the action of removing, maintaining or improving the connectivity of a dam or weir may appear to be a specific or isolated action, it is very important to always maintain a global vision of the whole basin. From the perspective of the fish community, and with knowledge of all the communities of living beings and also the hydraulic conditions, different factors influence the decision whether or not to restore a river section affected by a barrier. In any case, among the many factors that intervene in the criteria on whether or not to modify a fluvial obstacle, this good practice guide gives particular importance to aspects of fluvial connectivity related to the risk of expansion of invasive alien species.

Thus, when making the decision of whether or not to restore the fluvial continuity in a waterway, due to the risk of expansion of invasive alien species, it is important to answer a series of questions regarding certain criteria on the removal of a dam, as follows, which can be transferred to a table of pros and cons (Table 1):

- What is the degree of threat of the native species that are intended to be conserved? Are they endemic?
- What are the main threat factors? Fluvial fragmentation, invasive species, habitat loss, climate change, etc.

- What are the migratory requirements of the native species? Are they diadromous species, or potamodromous with strong or low migratory, sedentary or euryhaline needs?
- What is the importance of metapopulations of the native species? Does the viability of the populations of native species depend on the colonization of new river stretches and the dispersion of specimens between these metapopulations? Will isolation produce its disappearance in the medium or long term?
- Where are invasive species? Upstream of the dam or in the reservoir itself, or downstream?
- Which species live in the reservoir, native or invasive? Do only invaders live in the reservoir? Are they adapted to lentic, deep waters, with fluctuations in water level and margins without vegetation? Or are these habitats also important for some native species?
- Does the reservoir have a potential ecological value as a refuge for native species? Would the lentic waters of the reservoir help to preserve endemic populations of threatened fish in the face of the situation of the scarcity of precipitations due to climate change?
- What are the migratory requirements of invasive species?
- What kind of trophic interactions exist between invasive and native species? Are the invaders piscivorous predators? Do they compete for the same food, space and shelter?
- What kind of reproductive interactions exist between invasive and native species? Is there a sexual competence on the part of the invasive species that causes hybrids or genetic contamination with native fish populations?
- Are invasive species carriers of diseases or parasites that can be transmitted and affect native species?
- How could the restoration of natural flow affect native and invasive species? Would the restoration of the natural flow, the temperature of the water and the concentration of dissolved oxygen favour native and/or invasive species?
- Do invasive species present bioaccumulable toxic substances, or would the barrier removal favour the mobility of some types of pollutant in the upstream or downstream direction?
- After a potential dam removal, would river continuity be favoured throughout the basin? Would the elimination of the dam greatly favour connectivity in the basin or would it not contribute anything? Is there a cumulative impact of river fragmentation

with other obstacles? Dams generate a synergistic effect where the effect of two or more dams is higher than the sum of their individual effects.

- Faced with the impossibility of removing the obstacle, what options to recover connectivity and/or restore the natural flow regime exist? Is it possible to carry out improvement works on the obstacle such as ramps, ladders, height reduction, elimination of the reservoir, etc. without favouring the expansion of invasive species?
- What other complementary measures are going to be adopted? The use of piscicides against invaders, habitat restoration, direct elimination or control of invaders, translocations between isolated native metapopulations, etc.
- Are other threatened species affected, other than fish? In the case of the Iberian Peninsula, examples are the presence of species of *Margaritifera* sp. or of the autochthonous crayfish.
- Are other invasive species, other than fish, present? For example, species of terrapins, crayfish and other invertebrates such as snails or bivalves.
- Could the reservoir be a focus of attraction for new invasive species?

When faced with the decision to maintain river fragmentation or restore connectivity, four elements or issues can be considered as determining factors:

First, the degree of threat of the native species that are to be conserved is paramount. If the **state of conservation of native species** is very unfavourable to a high risk of invasion there are two options depending on the stretch of river they occupy: if native species are upstream, the *a priori* option would be to choose isolation or to maintain the obstacle. On the other hand, if the threatened native species are downstream, the best option is to remove the dam so that native species can recolonize upstream sections (for example, in the cases of eel and salmon).

The second factor is **adaptation of invasive species to lentic or lotic water**. In the case of the presence of invasive alien species adapted to slow waters, which carry out their life cycle in the reservoir's own body of water or in the downstream regulated flows, the elimination of the reservoir and restoration of natural conditions, regarding flow or water temperature, would allow natural control of many invasive species. On the other hand, if invaders are adapted to lotic waters, the decision on the intervention on the dam may be more difficult to take.

Another important issue is the **type of feeding of invasive species**, primarily if they are piscivorous or not. In the case that invasive species are piscivorous, it is most likely to affect some Iberian endemisms. Iberian fish, from the evolutionary point of view, have developed with an almost total absence of predatory fish, for this reason they are very vulnerable to the presence of invasive piscivorous species.

Finally, the **migratory needs of native species and invasive species** are fundamental to make a decision. The migratory requirements of the Iberian ichthyofauna are diverse, although a good part of them need to move to complete their biological cycles. Therefore, it is very important to assess the migratory needs of the whole fish community of a basin as a whole before considering the possibility of removing an obstacle.

The pros and cons criteria for removing an obstacle posed above can be transferred to a decision table that includes the four situations raised by Fausch et al. (2009) and the intermediate intervention option of carrying out improvement works in an obstacle (Box 3). However, this last possibility could require the construction of selective passages, and information and studies on the characteristics that the passage structures would have to meet in order to adapt to the passage characteristics of most Iberian species are lacking.

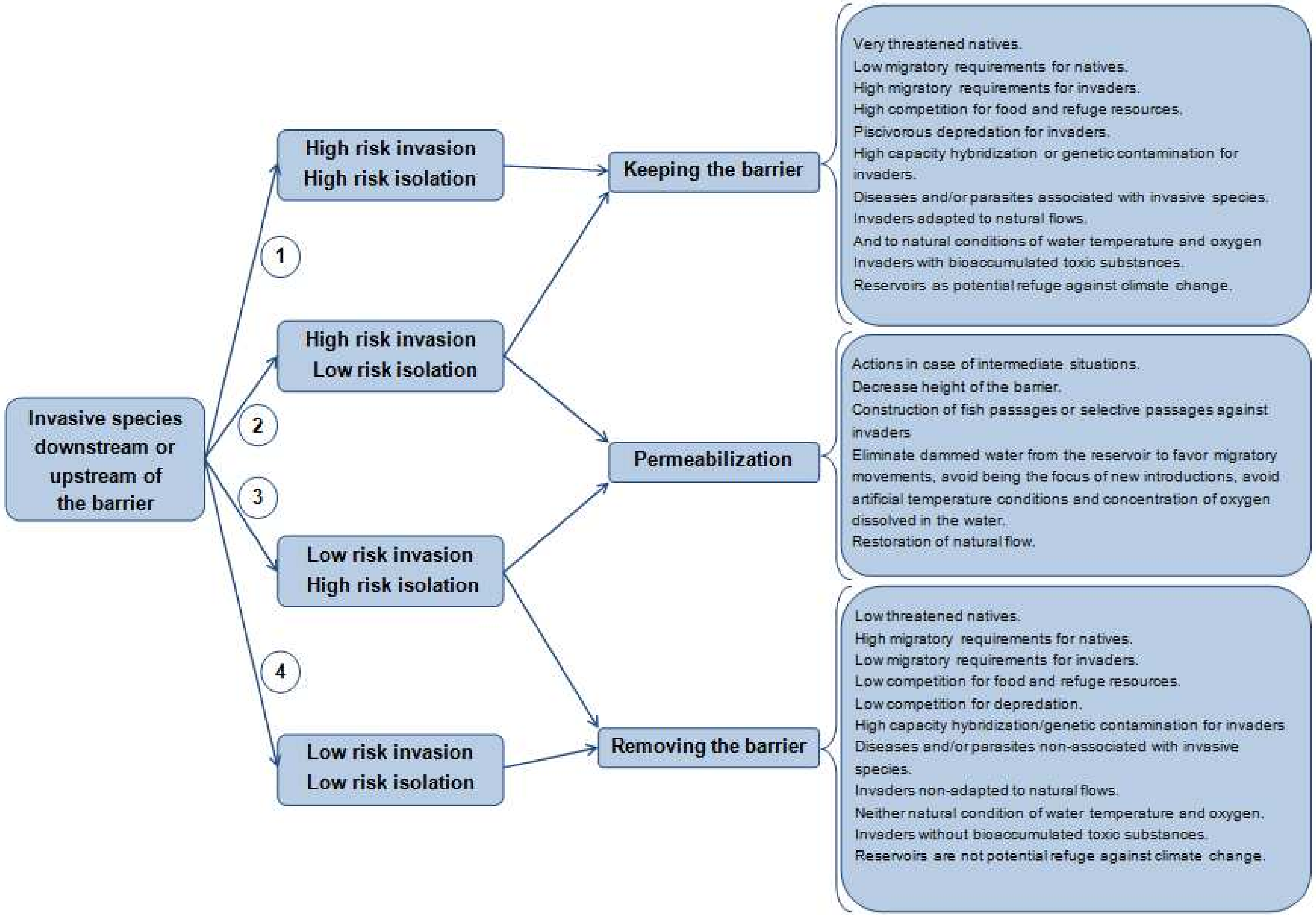
Table 1. General criteria in favour of removing or keeping a barrier or dam in a river. The most decisive criteria are in bold.

Question?	check	Remove the dam	Keep the dam	check
What is the degree of threat of the native species?		**Natives little threatened upstream or highly threatened downstream**	**Natives highly threatened upstream or little threatened downstream**	
What are the migratory requirements of native species?		**High migratory requirements**	**Low or no migration requirements**	
What is the importance of metapopulations of native species?		High isolation. High need of contact or genetic flow.	Low isolation. Low need of contact or genetic flow.	
Where are the invasive fish species?		Upstream	Downstream	
What are the migratory requirements of invasive species?		Low migratory requirements	High migratory requirements	
What kind of trophic interactions exist between invasive and native species?		Low competition for food resources, space and/or refuge between native and invasive species	High competition for food resources, space and/or refuge between native and invasive species	
What kind of predation interactions exist between invasive and native species?		**Invaders low or no predation on eggs, juveniles and/or adults of native fish species**	**Invaders high predation on eggs, juveniles and/or adults of native fish species**	
What kind of reproductive interactions exist between invasive and native species?		Invaders with low hybridization capacity or genetic contamination	Invaders with high capacity for hybridization or genetic contamination	
		Invaders with low sexual competence	Invaders with high sexual competence	
Are invasive species carriers of diseases or parasites?		No diseases or parasites associated with invasive species	Presence of diseases and/or parasites associated with invasive species	
How does the recovery of natural conditions affect invasive species?		**Invaders not adapted to natural flows**	**Invaders adapted to natural flows**	
		Invaders not adapted to natural conditions of water temperature and oxygen	Invaders adapted to natural conditions of water temperature and oxygen	
Are there toxic substances in the reservoir? or Do invasive species present bioaccumulable toxic substances?		No toxic substances in the reservoir neither Invaders transport bioaccumulated toxic substances	Toxic substances in the reservoir or invaders transport bioaccumulated toxic substances	

Question?	check	Remove the dam	Keep the dam	check
Does the reservoir have a potential ecological value as a refuge for native species under drought conditions?		The lentic waters of the reservoir cannot preserve populations of threatened endemic fish against climate change	Reservoir can preserve populations of threatened endemic fish against to climate change	
Does the removal of the dam significantly increase connectivity in the basin?		The obstacle causes a high synergic effect and its elimination would be very beneficial for the entire basin	There are no synergistic effects or obvious benefits	
Faced with the impossibility of removing the obstacle, what options to recover connectivity and/or restoration of natural flow exist?		No possibility of improvements in the passage of the obstacle	It is possible to improve connectivity and to safeguard a necessary isolation	
Are other, non-fish, invasive species present?		No risk of expansion of other, non-fish, invasive species	Risk of expansion of other invasive species.	
Are other, non-fish, threatened species affected?		It favours other highly threatened, non-fish, native aquatic species	It harms other highly threatened native aquatic species	
What other complementary measures are going to be adopted?		Habitat restoration, control of invaders, translocations between isolated native metapopulations, etc.	None	
Is the reservoir a focus of attraction for new introductions?		Yes	No	

Total checks		**Checks in favour to remove**	**Checks in favour to keep**	

Box 3. Decision flowchart for the evaluation of a transversal barrier with an impact on fluvial continuity and on the risk of expansion of invasive alien species. The numbers indicate the four possible situations pointed out by Fausch et al. (2009).



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10. APPENDICES

Appendix I. Iberian freshwater ichthyofauna (Doadrio et al., 2011b; MAGRAMA, 2017). Threat category UICN: LC least concern; NT near threatened; VU vulnerable; EN endangered; CR critically endangered. Mov: movement requirements: 5 diadromus, 4 potamodromus of strong migration requirements, 3 potamodromus of low migration requirements, 2 sedentary, 1 euryhaline. ki: priority coefficient of the Iberian ichthyofauna $ki = N \times (Mov + Vn)^2$ where *N* is the naturally, *Mov* the movement and *Vn* the IUCN vulnerability.

Species	Threat category UICN	Iberian endemism	Spanish-Franco endemism	Mov	Ki
Petromyzon marinus Linnaeus, 1758	VU				
Lampetra fluviatilis (Linnaeus, 1758)	EN			3	22,56
Lampetra planeri (Bloch, 1784)	CR			2	16,00
Acipenser sturio Linnaeus, 1758	CR			5	49,00
Anguilla anguilla (Linnaeus, 1758)	CR			5	45,56
Alosa alosa (Linnaeus, 1758)	VU			5	42,25
Alosa fallax (Lacepède, 1803)	VU			5	42,25
Atherina boyeri Risso, 1810	VU			1	6,25
Platichthys flesus (Linnaeus, 1758)	LC			1	4,00
Syngnathus abaster Risso, 1827	LC			1	4,00
Salmo salar Linnaeus, 1758	EN			5	45,56
Salmo trutta Linnaeus, 1758	VU			4	30,25
Cottus aturi Freyhof, Kottelat y Nolte, 2005	CR		x	2	16,00
Cottus hispanoliensis Bacescu & Bacescu-Mester, 1964	CR		x	2	16,00
Gasterosteus aculeatus Linnaeus, 1758	EN			2	14,06
Barbatula quignardi Bacescu-Mester, 1967	VU		x	2	12,25
Cobitis calderoni Bacescu, 1962	EN	x		2	14,06
Cobitis paludica (De Buen, 1930)	VU	x		2	12,25
Cobitis vettonica Doadrio & Perdices, 1997	EN	x		2	14,06
Cobitis cf. victoriae	VU	x			
Achondrostoma arcasii (Steindachner, 1866)	VU	x		3	20,25
Achondrostoma oligolepis (Robalo, Doadrio, Almada & Kottelat, 2005)	VU	x		2	12,25
Achondrostoma occidentale Robalo, et al., 2005	VU	x		2	12,25
Achondrostoma salmantinum Doadrio & Elvira, 2007	EN	x		3	22,56
Anaecypris hispanica (Steindachner, 1866)	EN	x		3	22,56
Barbus haasi Mertens, 1924	VU	x		3	20,25
Barbus meridionalis Risso, 1827	VU		x	4	30,25
Gobio lozanoi Doadrio y Madeira, 2004	LC		x	3	16,00
Iberochondrostoma almacai (Coelho, Mesquita & Collares-Pereira, 2005)	VU	x		3	20,25
Iberochondrostoma lemmingii (Steindachner, 1866)	VU	x		3	20,25
Iberochondrostoma lusitanicum (Collares-Pereira, 1980)	VU	x		2	12,25

Appendix I (cont.). Iberian freshwater ichthyofauna (Doadrio et al., 2011b; MAGRAMA, 2017). Threat category UICN: LC least concern; NT near threatened; VU vulnerable; EN endangered; CR critically endangered. Mov: movement requirements: 5 diadromus, 4 potamodromus of strong migration requirements, 3 potamodromus of low migration requirements, 2 sedentary, 1 euryhaline. ki: priority coefficient of the Iberian ichthyofauna $ki = N \times (Mov + Vn)^2$ where *N* is the naturally, *Mov* the movement and *Vn* the IUCN vulnerability.

Species	Threat category UICN	Iberian endemism	Spanish-Franco endemism	Mov	Ki
Iberochondrostoma olisiponensis Gante, Santos & Alves, 2007	EN	x		3	22,56
Iberochondrostoma oretanum (Doadrio & Carmona, 2003)	CR	x		3	25,00
Luciobarbus bocagei (Steindachner, 1865)	VU	x		4	30,25
Luciobarbus comizo (Steindachner, 1865)	VU	x		4	30,25
Luciobarbus graellsii (Steindachner, 1866)	VU	x		4	30,25
Luciobarbus guiraonis (Steindachner, 1866)	VU	x		4	27,56
Luciobarbus microcephalus (Almaça, 1967)	VU	x		4	30,25
Luciobarbus sclateri (Günther, 1868)	NT	x		4	27,56
Parachondrostoma arrigonis (Steindachner, 1866)	CR	x		4	36,00
Parachondrostoma miegii (Steindachner, 1866)	VU	x		4	30,25
Parachondrostoma turiense (Elvira, 1987)	EN	x		4	33,06
Phoxinus bigerri Kottelat, 2007	LC		x	3	16,00
Pseudochondrostoma duriense (Coelho, 1985)	VU	x		4	30,25
Pseudochondrostoma polylepis (Steindachner, 1865)	VU	x		4	30,25
Pseudochondrostoma willkommii (Steindachner, 1866)	VU	x		3	20,25
Squalius alburnoides (Steindachner, 1866)	NT	x		3	18,06
Squalius aradensis (Bogutskaya, Rodrigues & Collares-Pereira, 1998)	VU	x		2	12,25
Squalius carolitertii (Doadrio, 1987)	EN	x		4	33,06
Squalius castellanus Doadrio, Perea & Alonso, 2007	CR	x		4	36,00
Squalius laietanus Doadrio, Kottelat & Sostoa, 2007	VU	x		4	30,25
Squalius malacitanus Doadrio & Carmona 2006	EN	x		3	22,56
Squalius palaciosi (Doadrio, 1980)	CR	x		3	25,00
Squalius pyrenaicus (Günther, 1868)	VU	x		4	30,25
Squalius torgalensis (Bogutskaya, Rodrigues & Collares-Pereira, 1998)	VU	x		2	14,06
Squalius valentinus Doadrio & Carmona, 2006	VU	x		3	18,06
Tinca tinca (Linnaeus, 1758)	LC			2	9,00
Aphanius baeticus Doadrio, Carmona & Fernández-Delgado, 2002	CR	x		2	16,00
Aphanius iberus (Valenciennes, 1846)	EN	x		2	14,06
Valencia hispanica (Valenciennes, 1846)	CR	x		2	16,00
Salaria fluviatilis (Asso, 1801)	EN			2	14,06

Appendix II. Exotic species of fish introduced in Spain and their characteristics (Doadrio et al., 2011b; MAGRAMA, 2017). Mov: movement requirements: 5 diadromus, 4 potamodromus of strong migration requirements, 3 potamodromus of low migration requirements, 2 sedentary, 1 euryhaline. In purpose introduction Lake of Bañolas is to improve the natural populations Lake of Bañolas.

Species	Introduction date	Origin	Purpose introduction	Distribution	Spanish invasive catalogue	Mov	Ki
*Cyprinus carpio**	s. XVII	Asia	Ornamental	Broad		2	0
Carassius auratus	s. XVII	Asia	Ornamental	Broad		2	4,5
Oncorhynchus mykiss	s. XIX	North America	Sport fishing	Broad		4	0
Salvelinus fontinalis	s. XIX	Europe	Sport fishing	Narrow	Yes	3	0
*Salmo trutta ** (central European populations)	s. XIX	Europe	Sport fishing	Broad		4	
Rutilus rutilus	1910–1913	Europe	Lake of Bañolas	Narrow	Yes	2	0
Scardinius erythrophthalmus	1910–1913	Europe	Lake of Bañolas	Narrow	Yes	2	0
*Ameiurus melas **	1910–1913	North America	Lake of Bañolas	Broad	Yes	2	0
*Lepomis gibbosus **	1910–1913	North America	Lake of Bañolas	Broad	Yes	3	0
*Gambusia holbrooki **	1921	North America	Malaria control	Broad	Yes	2	0
*Esox lucius **	1949	Europe	Sport fishing	Broad	Yes	3	0
*Micropterus salmoides **	1955	North America	Sport fishing	Broad	Yes	2	0
Hucho hucho	1968	Europe	Sport fishing	Narrow		4	0
Fundulus heteroclitus	1970–1973	North America	Aquarist?	Broad	Yes	2	0
*Silurus glanis **	1974	Europe	Sport fishing	Broad	Yes	2	0
Perca fluviatilis	1970–1979	Europe	Sport fishing	Narrow	Yes	3	0
*Sander lucioperca **	1970–1979	Europe	Sport fishing	Broad	Yes	4	0
Oncorhynchus kisutch	1983–1984	North America	Aquaculture	Narrow		4	12,5
*Australoheros facetus **	1980–1986?	South America	Aquarist	Narrow	Yes	2	0
*Alburnus alburnus **	1992	Europe	Sport fishing	Broad	Yes	2	0
Acipenser baeri	1995	Europe	Aquaculture	Narrow			
Blicca bjoerkna	1995	Europe	Sport fishing	Narrow		2	4,5
Ictalurus punctatus	1995	North America	Aquaculture	Narrow	Yes	3	0
Barbatula barbatula	1997	Europe	Sport fishing	Narrow		2	4,5
Aphanius fasciatus	1997	Europe	Aquarist	Narrow		2	4,5
Poecilia reticulata	2000	North America	Aquarist	Narrow		2	4,5
Cobitis bilineata	2000	Europe	Sport fishing	Narrow			
Misgurnus anguillicaudatus	2001	Asia	Aquarist	Narrow	Yes	2	0
Pseudorasbora parva	2002	Asia	Aquarist	Narrow	Yes	2	0
Channa spp.		Asia	Aquarist		Yes		

* Invasive species especially worrying for aquatic ecosystems.