Biological Conservation 256 (2021) 109043

Contents lists available at ScienceDirect

Biological Conservation

journal homepage: www.elsevier.com/locate/biocon

Offsetting connectivity loss in rivers: Towards a no-net-loss approach for barrier planning☆

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A R T I C L E I N F O

Keywords:
Dam
Weir
Longitudinal
Movement
Prioritisation
Removal

A B S T R A C T

Biodiversity offsetting is a popular conservation tool to reduce the impact of human activities. This is especially relevant in freshwater ecosystems, under the increasing threat posed by the development of infrastructure to store freshwater or produce energy that break longitudinal connectivity and modify the structure and functioning of these systems.

We demonstrate how to plan offset of connectivity loss in rivers derived from the construction of new barriers, by using the Tagus River (Iberian Peninsula) as a model. We simulate the construction of new barriers, measure the impact they would have on connectivity for each species individually, and identify an optimal set of existing barriers that should be removed to counterbalance the loss of connectivity caused for all species collectively.

We found that loss in connectivity could be offset for most of species when a single new barrier was simulated at a time, by removing a small number of existing barriers. However, there was a group of species with very restricted ranges that could undergo irreversible loss of connectivity even when all existing barriers were made available as an offset option. The list of species that could not be offset and the cost of barrier removals increased as the number of new barriers simulated increased.

The approach presented here could be used to plan offset actions for other types of impacts in freshwater systems or elsewhere, or to assess the vulnerability of particular species or processes to potential future impacts by identifying the boundaries of development that can be offset.

1. Introduction

Freshwater ecosystems are heavily impacted by habitat modification and fragmentation, invasive species, pollution and overexploitation (Tickner et al., 2020), due to the dependence of human development on freshwater resources and the intensive use they are subjected (Vörösmarty et al., 2010). As a consequence of the poor conservation status of freshwater ecosystems, populations of freshwater species have declined 83% in the last decades, well over the patterns observed in other realms (WWF, 2018). River regulation by dams and weirs deserves special attention, among other threats to freshwater ecosystems, due to the widespread impact of these infrastructure (e.g., >1.2 million instream barriers, Belletti et al., 2020) and strong impacts posed to the ecology and functioning of these systems (Fagan et al., 2002; Campbell-Grant et al., 2007). Two-thirds of the World's major rivers are highly regulated and only 1/4 of the global runoff is not intercepted by dams (Grill et al., 2019). This impact is expected to continue to increase, for example with 3700 new hydropower dams projected (Zarfl et al., 2015), many receiving support as part of the transition towards arguably greener sources of energy (Hermoso, 2017), declining freshwater resources and raising demands for water uses (Tickner et al., 2020). The future persistence of freshwater biodiversity and ecosystem services that these systems provide will, therefore, depend on our capacity to halt or minimise the impacts of human pressures.

Biodiversity offsetting has become a popular conservation approach to try to reduce the impact of new development on biodiversity and

☆ Acknowledgements: VH was funded by the Spanish Government through a Ramon y Cajal contract (RYC-2013-13979). AFF was funded by FRESHING project of Portuguese Foundation for Science and Technology (FCT) and COMPETE (PTDC/AAGMAA/2261/2014–POCI-01-0145-FEDER-356016824).

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https://doi.org/10.1016/j.biocon.2021.109043
Received 3 October 2020; Received in revised form 22 January 2021; Accepted 18 February 2021
Available online 8 March 2021

move towards a no-net-loss scenario (Marshall et al., 2020). Under biodiversity offsetting schemes, biodiversity loses derived from new project developments, that cannot be avoided, need to be counterbalanced by generating an equivalent biodiversity benefit somewhere else (IUCN, 2014). Offsetting should only be evaluated whenever biodiversity loses cannot be avoided or minimised following the mitigation hierarchy steps (Kiesecker et al., 2011). Moreover, biodiversity offsetting has been questioned because it is unclear how effective offsetting policies are in practice (Bull et al., 2013) or how to operationalise the trade between impacts and benefits to ensure the desired no-net-loss (Maron et al., 2018).

In this sense, one of the main challenges that biodiversity offsetting faces is how to measure both the biodiversity loss caused by the new development and the gain derived from the implementation of an offset action (Ives and Bekessy, 2015). Ideally, the indicators used for measuring biodiversity loss and gain should reflect not only biodiversity patterns, but also key processes that determine its persistence, such as connectivity between populations. However, biodiversity offsetting literature focuses mainly on measuring biodiversity patterns through coarse surrogates, such as habitat attributes, which does not necessarily capture the processes that drive biodiversity patterns, survival or persistence (Marshall et al., 2020). The inadequate characterisation of biodiversity loss and gain could be behind the lack of documented successful offset results in scientific literature (Coker et al., 2018). Therefore, the integration of improved indicators that better convey information on the ecological processes important to the persistence of biodiversity is a key challenge in biodiversity offsetting schemes (Marshall et al., 2020).

Although biodiversity offsetting was pioneered in freshwater systems, especially in wetlands (Maron et al., 2018), and has rooted on policy such as in the Wetland Mitigation Banking in the USA, or the European Water Framework Directive (Theis et al., 2020), it has been less implemented in stream ecosystems, especially considering whole catchments (Coker et al., 2018). The strong longitudinal connectivity within river networks adds complications to the difficulty of quantifying biodiversity loss-gain when the direct and indirect impacts of new developments propagate and accumulate along the stream network beyond the actual location where the impact occurs (Coker et al., 2018). However, accounting for the connected nature of rivers is essential to ensure the success of offsetting schemes in these systems. Projects planned and implemented at catchment scale (regardless their size), tend to be more successful at achieving offset targets compared to projects that only account for local conditions and overlook the state of the rest of the catchment (Theis et al., 2020). This is especially important for species that need to move along river systems, such as long-distance migrators (e.g., eels or shads), or species with restricted distribution very sensitive to disruption of connectivity between remaining small populations. Therefore, careful planning at the catchment scale is key to ensure the effectiveness of offsetting programs in river systems.

Another important feature that biodiversity offsetting in rivers must account for is the key role that longitudinal connectivity plays at maintaining ecological processes that sustain freshwater biodiversity (e.g., migrations, gene exchange), but also the propagation of threats along the system. No-net-loss of connectivity at catchment scale could help maintain ecological processes and the persistence of biodiversity they hold (Fagan et al., 2002). Planning for connectivity offsetting at catchment scale is, therefore, a key issue under the global context of increasing anthropogenic pressure to assure energy and water resources. Despite the importance of developing tools to offset freshwater barrier impacts, it has received little attention in scientific literature (but see recent study by O'Hanley et al., 2020).

Here, we demonstrate how to systematically plan offset of connectivity loss in river systems derived from the construction of new barriers, by using the Tagus River catchment (Portugal and Spain) and its fish community as a case study. We simulate the construction of new barriers along the catchment, measure the impact that these barriers would have on connectivity for each species individually, and identify an optimal set of existing barriers that should be removed to counterbalance the loss of connectivity caused by the new barriers for all species collectively. We compare two alternative scenarios: locking-out existing barriers that were assessed as non-removable, and making all barriers available as offset options. These scenarios aim to explore whether the impacts of new barriers on connectivity could be fully offset with the group of existing barriers assessed as removable or if some of the larger ones, assessed as non-removable, would be needed. We also explore the cost and achievement of offsetting targets for increasing numbers of new barriers. The data and tools used here are publicly available, demonstrating how to plan the offset of proposed future infrastructure development in rivers systems worldwide, to help achieve a no-net-loss of connectivity in these systems and contribute to halting the steep biodiversity loss they currently experience.

2. Methods

2.1. Study area and fish data compilation

The Tagus River is the largest in the Iberian Peninsula, with a length of more than 1000 km east-west direction and an average annual flow of 300 m^3 s^{-1}, and one of the largest catchments in the European Atlantic coast with more than 80,000 km^2 of catchment area, of which 55,800 km^2 are in Spanish territory. The Tagus streamflow is strongly regulated by several large dams, some supplying drinking water to population centres of central Spain and Portugal, hundreds of small hydropower plants, and weirs (Fernandes et al., 2020; Hermoso et al., 2021).

We gathered information on the distribution of 28 fish species (Table 1) across the whole Tagus River catchment at 10 km^2 resolution, based on the Portuguese Red Book of Vertebrates (Rogado et al., 2005), the Spanish Atlas of freshwater fishes (Doadrio, 2002) and updates from the database by Filipe et al. (2009). This data represents the most complete information on the distribution of fish for the Tagus River catchment. This dataset included the distribution of species with a wide range of life-histories and movement needs (Table 1). We assessed the capacity of each species to pass different types of barriers based on their swimming and jumping abilities (see also Rincon et al. 2017), and classified them into three broad categories: high, medium and low (Table 1).

2.2. Barrier mapping and impact assessment

We used the distribution of barriers described in Hermoso et al. (2021) for the Tagus River catchment, identified and mapped using Google Earth Pro 7.3. The potential impact of each of these barriers was assessed as a combination of the physical characteristics of the barrier and each species' swimming and jumping capacities (Rincón et al., 2017). Following this approach we classified each barrier into a broad passability class, according to estimates of the height of the infrastructure, presence of water spilling over it, or presence of barrier breaks that could facilitate some species to pass and each species' assessment described above. In this way, a barrier was considered i) impassable by all species when it occupied the whole section of the stream and was high enough as to prevent any species from jumping over it, such as large dams and weirs; ii) passable by species with high swimming and jumping capacity when the height would allow species with high jumping ability to jump over it and with water flowing over the barrier, such as medium-small weirs with water flowing over them; iii) passable by species with medium swimming and jumping capacity when the barrier had a small height and water flowing over it, or barriers with narrow water ways with water flowing at high velocity, such as gauging stations; and finally iv) barriers passable by all species when the barrier occupied only part of the stream's section with water flowing, had a wide water way, and/or small height with water flowing in most of its length. This assessment aims to roughly classify barriers into broad

Table 1
List of species included in this study, their conservation status (IUCN, 2020), life-history, capacity to overcome obstacles based on their swimming and jumping abilities, and indication (x) if the species could not be completely offset for at least one new barrier, upstream or donstream, in this study.

Species	Conservation status (IUCN)	Life-history	Capacity to pass obstacles*	Upstream	Downstream
Achondrostoma oligolepis	LC	Local	Medium		
Alosa alosa	LC	Diadromous	High	x	x
Alosa fallax	LC	Diadromous	High	x	x
Anguilla anguilla	CR	Diadromous	High		
Atherina boyeri	LC	Local¶	Low		
Chelon labrosus	LC	Diadromous	Medium		
Chelon ramada	LC	Diadromous	Medium		
Cobitis calderoni	EN	Local	Low		
Cobitis paludica	VU	Local	Low		
Cobitis vettonica	EN	Local	Low		
Dicentrarchus labrax	LC	Local¶	Medium		
Iberochondrostoma lemmingii	VU	Local	Low		
Iberochondrostoma lusitanicum	CR	Local	Low		
Iberochondrostoma olisiponense	CR	Local	Low		x
Lampetra fluviatilis	LC	Diadromous	Medium		
Lampetra planeri	LC	Local	Low		x
Luciobarbus bocagei	LC	Freshwater migrant	High		
Luciobarbus comizo	VU	Freshwater migrant	High		
Luciobarbus steindachneri	VU	Freshwater migrant	High		
Parachondrostoma miegii	LC	Local	High	x	x
Petromyzon marinus	LC	Diadromous	Medium		
Pomatoschistus microps	LC	Local	Low		
Pomatoschistus minutus	LC	Local	Low		
Pseudochondrostoma polylepis	LC	Local	High		
Salmo trutta	LC	Local/freshwater migrant	High		
Squalius alburnoides	VU	Local	Low		
Squalius castellanus	EN	Local	Medium		x
Squalius pyrenaicus	NA	Local	Medium		

* Estimates sourced fromfrom: Fishbase (www.fishbase.de), Carta Piscícola Española (http://www.sibic.org/carta-piscicola-espanola), and Rincón et al. (2017).
¶ Denotes species that are mainly residents in brackish waters near the estuary but that can move opportunistically into freshwaters.

passability classes for a demonstration exercise, and it was limited by satellite data available. Further assessments, with on the ground validation would be required for a comprehensive passability assessment.

We classified barriers into four broad cost categories: low, medium, high, very high cost based on size, construction material and maintenance status (Hermoso et al., 2021). We then translated this qualitative assessment into a semi-quantitative value using the low cost class as the reference for cost-units, and applied a logarithmic increase in cost-units as we escalated in categories. In this way, removal cost of a small weir would be one cost-unit, while removal of a large dam would be 1000 cost-units. These broad estimates of cost were used for demonstration purposes only, and further assessments on real costs for each barrier would be needed to better inform an accurate barrier removal plan for this catchment. We also classified barriers as removable or not, to further account for potential constraints of restoration plans to tackle removal of large or strategic infrastructure which could not be realistically implemented. Under the not-removable category we included all large dams and hydropower stations mapped by Lehner et al. (2011) that we complemented with a set of 14 additional large dams after visual inspection from Google Earth.

2.3. Planning offset of new barriers

To demonstrate how to plan offsetting the impact on connectivity of new barriers, we first allocated these new barriers along the catchment, then estimated the loss of connectivity for each species that would be caused by these new barriers, and finally identified which of the existing barriers should be removed to compensate for the loss in connectivity.

To simulate the allocation of new barriers we used the existing network of barriers described above as a baseline. This was done for illustration purposes only, making the most of the wide coverage of barriers mapped across the catchment. We iteratively selected the location of each of these barriers (excluding barriers assessed as not removable) as the potential location of a barrier that would block movement of all fish species. We then calculated the loss of connectivity that this simulated new barrier would cause by assuming that the barrier would become impassable to all species. We considered the potential asymmetrical impact of new barriers in both directions, upstream and downstream movement (Rincón et al., 2017), by creating two pseudo-species for each species, one for each direction of movement. We measured the impact of each new barrier as the length of river occupied by each species in both directions (upstream and downstream), until the next not passable barrier if the new barrier was allocated between two other barriers, or the headwaters or estuary in case new barriers had no other barriers upstream or downstream respectively. This measure of impact resembles the length of river that was initially connected allowing movement of all fish species that inhabited it. For example, a new barrier located close to the mouth of the river would impact downstream movement, measured as the length of river occupied by each species (or pseudo-species) in the downstream segment of river between the barrier and the mouth. The upstream impact would be the length of river occupied by each species in the upstream stretch between the new barrier and the next upstream barrier that was not passable by the species or headwaters, in case no other barrier was present. We followed the same approach to measuring the offsetting benefits associated with the removal of a given existing barrier, as the length of river occupied by each species upstream and downstream the location of the barrier, that would eventually get connected. In this case, we also accounted for the passability of each barrier by each species, to avoid overestimating the benefit of removing the barrier as part of the offset project (Fig. 1). For example, an existing barrier could not contribute to offsetting the impact of the new barrier if it was already passable for a given species.

To identify an optimal set of barriers to offset the loss of connectivity caused by the new one, we used the software Marxan (Ball et al., 2009) and recommendations in Hermoso et al. (2021). Marxan is a spatial planning tool, commonly used for identifying priority areas for conservation of biodiversity, aiming to identify a minimum set of areas that cover the distribution of all conservation features under consideration (e.g., species, habitats, ecoregions, or ecosystem services) at minimum

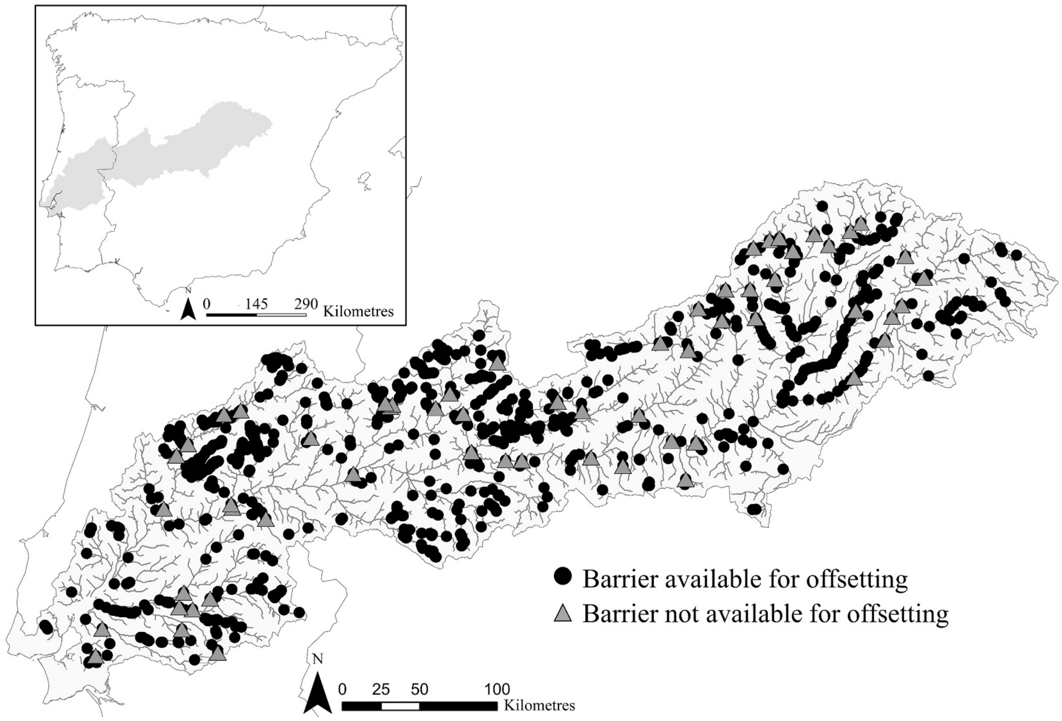

Fig. 1. Tagus River catchment and spatial distribution of the 934 barriers mapped for this study. Barriers were assessed as available (black dots) or not available for offsetting (grey triangles), based on their size and strategic value.

cost. To do that, Marxan uses a heuristic optimisation algorithm to minimise an objective function (3) that includes the cost of planning units in the solution and other penalties for not achieving the desired spatial coverage (conservation targets) for all the conservation features and spatial constraints, such as connectivity among selected planning units (Hermoso et al., 2011).

In our case, the optimisation problem that we addressed was:

$$\text{minimise} \sum_{i=1}^{m} c_i x_i + b \sum_{i1=1}^{m} \sum_{i2=1}^{m} x_{i1}(1 - x_{i2}) cv_{i1,i2} \text{ for i} \in \{1, 2, \ldots, m\} \tag{1}$$

$$\text{subject to} \sum_{i=1}^{m} a_i x_i \geq t_j \forall j \text{ for j} \in \{1, 2, \ldots, n\} \tag{2}$$

where, x_i is a control variable that takes a value of 1 when the barrier i is selected and 0 otherwise; i belongs to the group of m barriers available for removal in the Tagus River catchment; c_i is the cost-units of removing barrier i; a_i is the benefit for each pseudo-species j provided by each barrier if it was removed i (measured as detailed above); $cv_{i1,\ i2}$ is normally the penalty for missing the connection between a given pair of planning units, or barriers in our case (i_1 and i_2) in the solution, and weighted by b, a connectivity strength modifier (CSM); and t_j is the

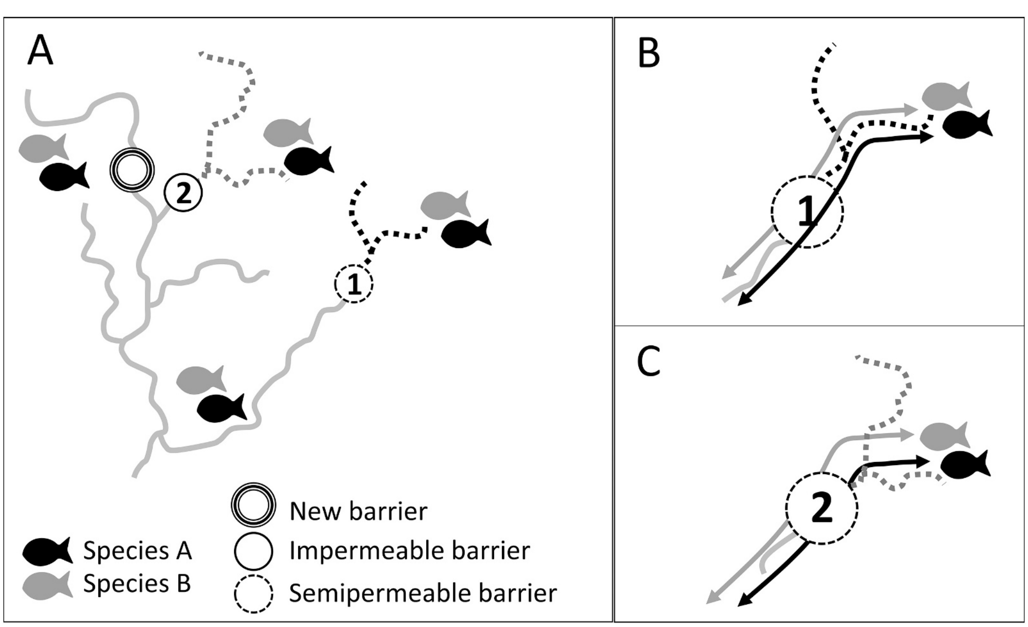

Fig. 2. Illustration of a new barrier in a hypothetical river network and two existing barriers that could be removed to offset the loss of connectivity for two species (A). This new barrier is assumed to completely block movement for both species, so the barrier or group of barriers used to compensate for the loss of connectivity must provide the same gain in connectivity somewhere else in the river network. In this case, barrier #1 (B) is semipermeable, so only effective for species B. If selected alone to offset the impact of the new barrier, there would be a net loss of connectivity, as the impact for species A would not be replaced. For this reason, the selection of barrier #2 (C), impassable for both species, would be the best option in this case.

target for each pseudo-species. Targets for each pseudo-species were determined by the impact of each new barrier, as detailed above.

We used the connectivity penalty feature in Marxan to aggregate barrier removal projects along the river network as a way to maximise connectivity of fish populations. Whenever more than one barrier was necessary to compensate for the loss of connectivity caused by the new barrier, we aimed to group them along the river network. In this way, we wanted to favour groups of connected barriers treated, and therefore, create long new stretches of river connected that resemble and offset the lost ones. For this, we used Hermoso et al. (2011) recommendations on how to address longitudinal connectivity in Marxan for river applications. In our case, we built a connectivity matrix containing all connections of barriers along the river network (Fig. 2). In traditional Marxan applications in rivers, these connections have a penalty associated that is calculated as a function of the inverse of the distance between each pair of planning units. In our case, instead of distance between planning units, we used the number of barriers in between each pairwise combination of barriers as a penalty. We calculated the penalty between each pair of barriers as the inverse of the squared number of barriers in between plus one (to avoid 0 s for contiguous barriers) [penalty = 1 / (number of barriers in between + 1)^2]. Therefore, for two contiguous barriers, the penalty was one, while for two barriers with a third one in between the penalty was 0.25. In this way, we tried to avoid potential conflicts between the benefit and connectivity penalty in Marxan's objective function. Distant, but consecutive barriers along a river reach could pose a long stretch of river with continuous habitats for fish (high benefit), but low connectivity penalty if calculated based on distance and, therefore, low priority for connectivity. This would end up in contradictory decisions, such as selecting barriers that release long river reaches, but not their contiguous neighbours. By only considering the number of barriers in between, we made them virtually "closer" to each other, and therefore, fostered the selection of consecutive barriers regardless their distance. We calibrated the CSM as recommended in Ardron et al. (2010).

Under these premises the objective function that we tried to minimise was as follows:

$$\text{Obj.function} = \sum_{i=1}^{m} c_i x_i + b \sum_{i1=1}^{m} \sum_{i2=1}^{m} x_{i1}(1 - x_{i2}) cv_{i1,i2} + \sum_{j=1}^{n} SPF_j H(s) \left(\frac{s}{t_j} \right) \tag{3}$$

where there are n pseudo-species under consideration; SPF_j is a Species Penalty Factor or weighting factor that applies for not achieving the desired representation target for each pseudo-species j; $H(s)$ is a Heaviside function that takes a value of 0 when $s/t_j \leq 0$ and 1 otherwise; s is the shortfall in targets not achieved and is measured as t_j-representation achieved; the ratio s/t_j equals 1 when the pseudo-species j is not represented within the solution and approaches 0 as the level of representation approaches the target amounts (t_j). We used a constant SPF = 100 for all pseudo-species to ensure they all achieved the desired targets. With this configuration we ran Marxan 100 times, 10 million iterations each across all analyses and kept for subsequent comparison the best solution out of those 100.

2.4. Offsetting scenarios

We tested two alternative offsetting scenarios: considering only barriers assessed as removable (locked-out scenario) and considering all barriers as available for removal (all barriers scenario). Under the locked-out scenario, all barriers that were assessed as not removable for their strategic value were locked out from Marxan's solutions. Given that this hard constraint could compromise the achievement of full offset targets for some species, we tested the second scenario where all barriers were available. In all cases, the barrier used iteratively as the new barrier to be offset was discarded from the optimisation analyses (locked out), so a barrier cannot offset itself. We checked whether all pseudo-species fully achieved the target throughout the iterative analyses of new barriers and scenarios and identified those locations for new barriers that could not be fully offset by removing existing barriers.

Finally, we identified offsetting options for more than one barrier simultaneously under the lock-out scenario, compared to the single new barrier at a time in previous analyses. For this, we selected 100 random combination of barriers (2, 5, 10, 25 and 50 barriers) and repeated the same analyses explained above: we calculated the impact on connectivity of each combination of new barriers and then identified a set of optimal existing barriers needed to offset the loss of connectivity caused by the new ones. We checked whether all pseudo-species could be fully offset and the cost of solutions. As the number of barriers increased, we would expect costs and loss of connectivity that cannot be offset to also increase.

3. Results

We found that under the locked-out scenario most of new barriers needed the removal of between one and three barriers to offset their impact (e.g., Fig. 3). Only a small number of barriers needed more than 10 barriers as part of their optimal offset plan (Fig. 4). From the total 873 barriers available for removal in this scenario, only 194 were selected at least once. A small group of barriers, though, located in some headwater streams in the upper Tagus River and tributaries close to the estuary were selected more frequently (Fig. 5).

Not all new barriers could be completely offset by removing existing barriers (Supplementary Figure). We found that 17 barriers had between one and two pseudo-species that could not be offset by removing barriers somewhere else, under the locked-out scenario. There were six species (nine pseudo-species) with at least one new barrier that could not be fully offset (Table 1). These were mainly species with very restricted distribution ranges in the Tagus River catchment, such as *Iberochondrostoma olisiponense* or *Squalius castellanus* restricted to headwater streams, or species with a wider distribution extent, but constrained to areas close to the estuary, such as *Alosa fallax*.

The results from the all-barriers scenario were very similar to the locked-out scenario. There were no differences in number of barriers selected on average to offset new ones (Fig. 4). However, there were less new barriers that could not be fully offset (Fig. 6), and consequently the number of species that could not be fully offset declined to five, all of them related to downstream connectivity (i.e., all previously reported for the locked-out barriers scenario, but *I. olisiponensis*). This shows that the impossibility to achieve the offset targets for some new barriers, although all current barriers were available for removal regardless their cost, was probably related to the weak overlap of the distribution ranges of these species with currently observed barriers, or high removal cost of some of the barriers. Therefore, there are some new barriers that would inevitably cause loss of connectivity for these species that cannot be offset anywhere else in the catchment, or would be too expensive as to be a realistic option (e.g., need to remove a large hydropower dam in use).

When increasing the number of new barriers to be offset simultaneously, we found an increase in the number of barriers that would need to be removed and cost-units associated to the solutions, and an increase in the number of combinations of new barriers that could not be fully offset (Fig. 6).

4. Discussion

Here we have demonstrated how to plan offset priorities for connectivity loss for multiple species simultaneously at the catchment scale. Offset of a single barrier could be achieved in most of cases through the removal of a small number of existing barriers. However, there were some species that would face irreversible connectivity loss even if a single new barrier was planned. This is especially the case for long-term migratory species that need to move between rivers and the estuary or

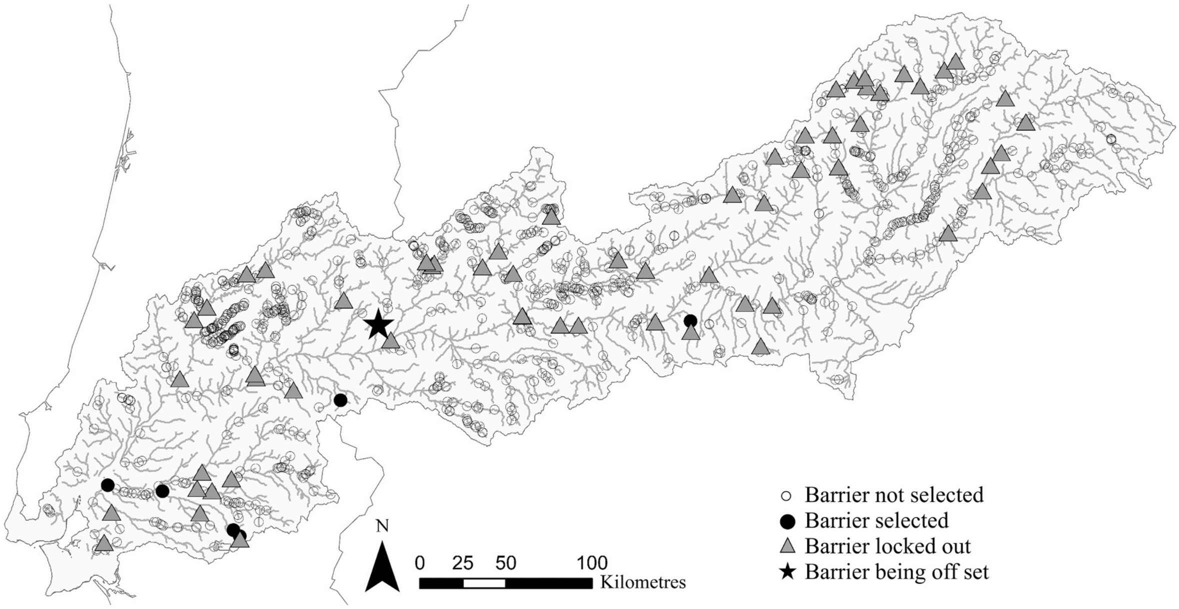

Fig. 3. Example of selected barriers (black dots) to offset loss of connectivity caused by a new barrier (black star), not passable by any species.

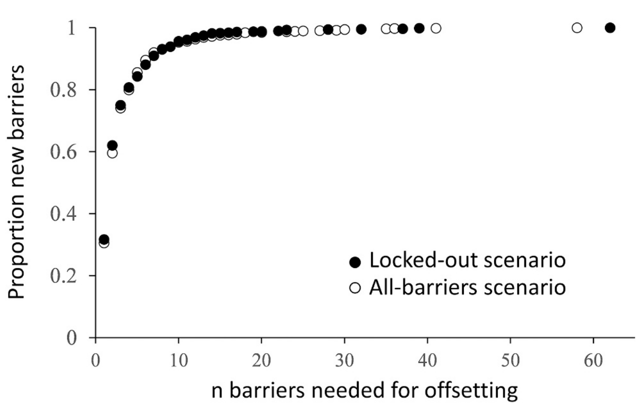

Fig. 4. Proportion of new barriers (N = 873) according to the number of existing barriers that would be needed to offset the loss of connectivity caused by the those new barriers. Under the 'locked-out scenario', all barriers that were assessed as not available for offsetting purposes (e.g., large dams) were excluded from the set of offsetting options, while all barriers were made available for offsetting purposes under the 'all barriers scenario'scenario.

the ocean, and species with restricted distribution ranges that cannot be found anywhere else in the catchment apart from where they are impacted. This situation became more common when we simulated the construction of more than one barrier at the same time, highlighting the need for addressing cumulative impact assessments at catchment scale and adequate prioritisation of offsetting efforts. The methodology that we demonstrate here could be used elsewhere, to plan at the adequate scale (e.g., catchment), for multiple objectives (e.g., multiple species, ecosystem services, or functions), and help overcome traditional opportunistic decision-making at local scale in river management (Hermoso et al., 2012).

The increasing pressure on freshwater ecosystems under global change due to the higher demand on diminishing and less predictable water resources (Hermoso, 2017) could aggravate the steep decline of freshwater biodiversity and ecosystem services. Adequate planning is urgently needed to avoid or minimise further impacts and whenever these cannot be avoided at least counterbalanced through offsetting schemes (Brown and Veneman, 2001). Experience in offsetting projects in river systems shows that planning at catchment scale leads to more effective results (Theis et al., 2020), as we can account for the condition of the whole catchment that might undermine local offsetting efforts (Coker et al., 2018). Planning at the catchment scale is also needed to account for the cumulative impacts of new barriers and existing ones and the cumulative benefits of multiple barrier removals (O'Hanley and Tomberlin, 2005; Kemp and O'Hanley, 2010; Segurado et al., 2013). However, planning at this large scale is challenging (Mckay et al., 2017), and decisions are usually driven by opportunities (e.g., removal of obsolete barriers that might not be the best option) or ranking approaches that fail to account for multiple barriers collectively (Kemp and O'Hanley, 2010). For example, the number of combinations for relatively simple barrier removal planning exercises needs picking a solution from billions of combinations (Mckay et al., 2017). The magnitude of the problem increases when accounting for multiple species or the spatial dependencies among barriers (O'Hanley and Tomberlin, 2005, Branco et al., 2014, Erős et al., 2018). For this reason, the use of optimisation methods, like we demonstrate here, are highly recommended when planning offsetting actions at catchment scale.

There is an extended literature around barrier removal optimisation (Kemp and O'Hanley, 2010), but planning for biodiversity offsetting in rivers has received less attention (Coker et al., 2018). O'Hanley et al. (2020) recently developed a mixed integer linear programming model to prioritise allocation of new hydropower dams, that is also suitable for identifying offsetting actions for these new dams if desired. However, this model only minimises the impact of new hydropower dams on species richness, and therefore, is not able to account for species-specific habitat or connectivity loss, or other processes. Integrating indicators of ecological processes that better convey the impacts of development projects on the persistence of biodiversity has been identified as a key challenge to enhance the effectiveness of biodiversity offsetting schemes (Coker et al., 2018; Maron et al., 2018; Marshall et al., 2020). Most of offsetting projects rely on area-based measures of impacts that do not necessarily reflect the processes driving biodiversity patterns and persistence. When the objective of offsetting is to avoid loss of species in a region, offset metrics should incorporate measures that better convey the persistence of populations, such as species-specific connectivity needs (Marshall et al., 2020). The hierarchical geometry of freshwater ecosystem makes them different from other spatially structured habitats and especially sensitive to fragmentation (Campbell-Grant et al., 2007). Consequently, population stability and local extinction risk are highly sensitive to the asymmetric connectivity among branches in riverine

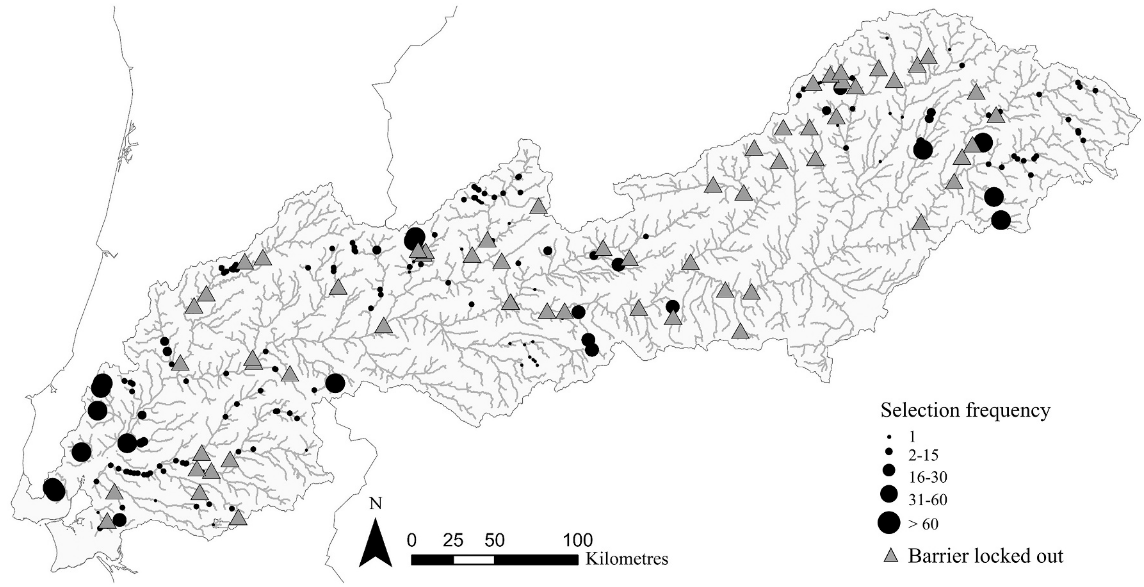

Fig. 5. Selection frequency of barriers as offset options after the iterative upgrade of all barriers present in the Tagus River catchment to impassable. Size of circles shows selection frequency, with large circles indicating barriers that were selected more often to offset. Grey triangles indicate barriers that were not available as offset option under the lock-out scenario.

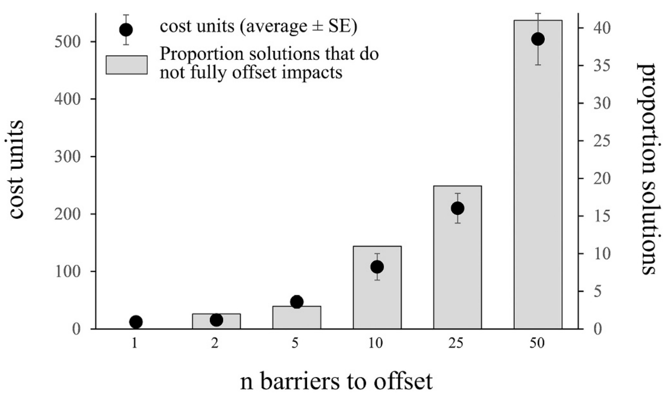

Fig. 6. Cost units of solutions (average ± SE) for different number of new barriers to be offset simultaneously, and proportion of solutions that could not fully achieve the offset targets for at least one pseudo-species. Tests of increasing number of new barriers to be offset simultaneously were ran on 100 combination of randomly selected barriers, apart from the test with a single barrier that was ran iteratively on each of the existing barriers (n = 873).

ecosystems (Labonne et al., 2008). Therefore, the maintenance of longitudinal connectivity is vital to ensure the long-term persistence of metapopulation in these systems (Fagan et al., 2002), and represents a suitable offsetting objective in these systems.

Here, we measured the impact of new barrier development on connectivity loss between populations of each species, and the gain in connectivity if existing barriers were removed. In this later case, we accounted for barrier passability by each species, to avoid overestimating the gain in connectivity if that barrier was removed as part of an offset action. We considered that if a barrier was passable by a given species, it cannot contribute to replacing the loss of connectivity for that species somewhere else. Otherwise, there would be a net loss of connectivity for the species, and therefore the offset would fail. By using population connectivity as our metric for offsetting, we accounted for important processes for the persistence of freshwater fish in the Tagus River catchment, such as migrations between river and estuary or ocean (e.g., *Anguilla anguilla*), and seasonal migrations within the river network (e.g., *Luciobarbus* sp.). However, barriers cause other multiple impacts, such as strong habitat transformations from lotic to lentic system or the proliferation of invasive species (Januchowski-Hartley et al., 2020; Turgeon et al., 2019) with implications for the persistence of local populations. A more comprehensive assessment of the full range of impacts associated with barriers, would benefit future applications of the methodology we present here, and ensure that the impact of the new barrier would be fully offset. For example, the loss of lotic habitat for a given species caused by a new barrier would have to be compensated by restoring suitable habitat for this species somewhere else in the catchment.

We found that a small group of barriers located in some headwater streams in the upper Tagus River and tributaries close to the estuary were selected more frequently, which shows the importance of these areas for offsetting purposes. These were mainly located in river reaches with critical conservation value for some long-migratory species (e.g., eels) or species with very restricted distribution ranges (e.g., *I. olisiponensis* and *S. castellanus*). However, we also found that some of these species would face irreplaceable loss of connectivity even if only one new not passable barrier was added, or large dams, initially assessed as non-removable, were allowed as offsetting options. For example, impacts on populations of species with restricted distribution ranges, such as *S. castellanus*, are difficult to offset anywhere else in the catchment, at least through removal of existing barriers. In these cases, drastic measures, such as not granting construction permits or considering translocating the species somewhere else in the catchment would be needed (Olden et al., 2011). In other cases, species life history makes them very vulnerable to connectivity loss, such as long-term migratory species that need to move between freshwater and marine realms (e.g., the eel, shads). Impacted by past river regulation, these species already show a reduced distribution (Clavero and Hermoso, 2015), constrained to the final river reaches, in close contact with the estuary, and are considered threatened according to UICN criteria (IUCN, 2020). These reaches have a high conservation value and cannot be offset anywhere else in the catchment. In these cases, the use of current distribution as reference for the no-net-loss scenario would not be enough and more ambitious objectives towards a net-gain (Maron et al., 2018) would be needed to ensure the long-term persistence of these species in the catchment.

The implementation of offsetting projects in the Tagus River catchment, like in the rest of the EU, is mainly enforced through compensatory measures for development projects located within the Natura 2000 network (European Commission, 2007). There are also offsetting opportunities for impacts outside protected areas through new initiatives, such as the habitat banking that aims to deliver compensation for development projects outside the Natura 2000 network by implementing compensatory measures in advance, enabling developers to purchase credits from established compensation schemes (habitat banks) to offset their impacts (Maestre-Andrés et al., 2020). However, the full implementation of this system still needs policy development, currently under consideration.

The approach that we present here could accommodate more objectives and indicators of loss/gain, such as water quality, quantity or lotic habitats favourable to the fish species studied (Coker et al., 2018), complementary to longitudinal connectivity used as indicator in this study. The integration of multiple objectives helps to address the complexity of natural systems and cover more processes on which its functioning depends and produces more effective offsetting results (Theis et al., 2020). Given the strategic value of freshwater resources, offsetting should not only balance ecological trade-offs, but also socio-economic trade-offs, especially in transboundary basins as Tagus. The removal of existing barriers that are used for water storage or hydropower production does only report a potential ecological benefit that helps offset the impact caused by new developments elsewhere, but also a socio-economic impact. Such impact can be indirectly addressed through the removal cost of each barrier (e.g., opportunity cost associated to each barrier), or directly as additional objectives in the spatial prioritisation of offset actions. In the first case, the objective would be to minimise the socio-economic impact of offset actions, while in the second there would be to incorporate explicit socio-economic targets (e.g., retain a given water storage capacity or minimise loss of hydropower productivity; see O'Hanley et al., 2020).

Although focused on barrier offsetting to maintain structural connectivity of freshwater fish populations, the approach demonstrated here could be used to plan offsetting of any other impact elsewhere, including other realms. Moreover, these types of analyses can be useful when assessing the vulnerability of particular species or processes to potential future impacts, even when best practise protocols, such as the mitigation hierarchy (Kiesecker et al., 2011), are into place. As we found, the construction of new barriers in some areas of the Tagus River catchment would inevitably pose an irreplaceable damage to connectivity for some species with restricted distribution ranges or migratory behaviours. Careful attention needs to be paid to the indicators used, that must fit for purpose, so the offsetting results identified are a suitable option to avoid further loss.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2021.109043.

CRediT authorship contribution statement

Virgilio Hermoso: Conceptualization, Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **Ana Filipa Filipe:** Data curation, Validation, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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