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Identifying River Corridors for the Implementation of the Network of Green Infrastructure in Spain

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ABSTRACT

1. Spatial–temporal connectivity plays a key role in freshwater ecosystems by maintaining processes such as the transfer of materials and energy, gene exchange, and migratory movements necessary for the maintenance of functional ecosystems. However, connectivity in these systems has undergone severe modifications over the last century, threatening the persistence of biodiversity and the ecosystem services they provide. The European Union (EU) acknowledges the value of freshwater ecosystems as important connectivity elements of the landscape and the need to recover their functionality, not only for freshwater biodiversity, in policy instruments such as the European Biodiversity Strategy for 2030 or the Green Infrastructure Strategy. Priority areas need to be designated and managed as corridors. However, given the widespread impacts to connectivity, balancing the functionality of corridors and socio-economic constraints will be key.

2. We demonstrate how to design a network of river corridors in Spain to connect populations of freshwater fish species, while minimising the impact of barriers that compromise the functionality of the corridor or make its restoration expensive. We integrated information on the spatial distribution of 40 fish species and more than 30.000 barriers along 80.000 km of rivers and streams to identify priority corridors that connect at least 50% of the populations for all species. We ran three different scenarios that depict alternative planning interests and constraints: (i) an unconstrained scenario, where all river reaches were equally available to be part of the corridor; (ii) a Natura 2000 scenario (N2K), where corridors connected protected areas; and (iii) a no dam allowed scenario (NDA), where we avoided selecting reaches with dams as part of the network of corridors. We measured four different indicators to compare scenarios: number of planning units selected, the number of dams included, the length of continuous units selected and the length of continuous units selected for each species individually.

3. We found that the optimal network of corridors always contained reaches with barriers. However, the network was more spatially continuous (22% and 26% more continuity) and was always less impacted by barriers (6.9 and 2.6 fewer barriers) under the unconstrained scenario than under the N2K and NDA scenarios. The network of corridors was free from dams only under the NDA scenario, although the average connectivity across all species was always lower than under the other two scenarios.

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4. Our results demonstrate that the design and management of a coherent network of freshwater corridors in Spain will need to integrate reaches impacted by barriers. Securing the functionality of such a network by restoring the lost connectivity will pose a socio-economic challenge. Spatial planning can help address this challenge by identifying priority corridors that minimise restoration efforts.

5. The approach demonstrated here could be extended to other components of connectivity, such as lateral and vertical connectivity, as well as biodiversity and ecosystem services features to address other dimensions and functionality of freshwater corridors. However, implicit decisions that contextualise the planning exercise, exemplified by the differences across the three alternative scenarios we tested, lead to very different spatial priorities. Therefore, defining the planning objectives and constraints to deliver solutions that fit for purpose is critical.

1 | Introduction

Spatial and temporal connectivity play key roles in maintaining functional and well-structured river ecosystems. The longitudinal (from headwaters to the mouth), lateral (between the river channel and the floodplain) and vertical connectivity (between surface and groundwater), as well as their temporal components, are essential to maintain key ecological processes such as the transfer of matter and energy throughout the system or seasonal migratory movements (Ward 1989). All these ecological processes are decisive for the maintenance of biodiversity and the ecosystem services associated with these environments. Moreover, the value of rivers and streams as connectors goes beyond freshwater ecosystems and biodiversity, as they also facilitate the movement of other nonaquatic species (Gillies and St. Clair 2008; Sánchez-Montoya et al. 2016; Zimbres et al. 2017).

However, all these components of connectivity in rivers have been deeply transformed. The proliferation of barriers such as dams, weirs, and culverts has fragmented river networks longitudinally (Januchowski-Hartley et al. 2020); the drainage and occupation of floodplains with intensive uses (e.g., agriculture, urban and industrial) have disconnected riverbeds from their associated wetlands (Reis et al. 2017); the overexploitation of aquifers has transformed the vertical component of connectivity (e.g., Wang 2023; Green et al. 2024); and the flow regulation has transformed natural flow patterns (minimum, maximum and seasonality of flow) and flood frequency, modifying freshwater ecosystems and the temporal dimension of connectivity (Jaeger et al. 2014). These modifications are common in river networks worldwide and have deeply transformed the structure and functioning of these ecosystems (Grill et al. 2019). For this reason, the restoration of connectivity, in all its dimensions, is key to recovering these ecosystems and the biodiversity and services they sustain.

The poor conservation status of freshwater ecosystems has triggered global responses and commitments towards restoration efforts. Although freshwater ecosystems have been traditionally treated in international policy as part of terrestrial systems (Golçalves and Hermoso 2022), recent policy advancements like the Kunming-Montreal Global Biodiversity Framework (Conference of the Parties to the Convention on Biological Diversity 2022; Cooke et al. 2023), or the EU Biodiversity Strategy for 2030 and EU Nature Restoration Law (European Commission 2024; European Commission 2020; Stoffers et al. 2024) explicitly recognise the need for specific efforts to these ecosystems. The European policy goes a step forward and set quantitative targets for the recovery of connectivity in river systems in the EU, aiming to recover at least 25,000 km of free-flowing rivers by 2030. To help operationalise these objectives in a standardised way, guideline documents to assess connectivity and identify free-flowing conditions have also been developed (e.g., European Commission et al. 2024). Additional opportunities to restore freshwater ecosystems and connectivity arise at a continental scale from the EU Green Infrastructure Strategy (European Commission 2013; Portela et al. 2021) and the Water Framework Directive (European Commission 2000). Green Infrastructure is conceived as a tool 'for providing ecological, economic and social benefits through natural solutions' and 'mobilise investments to sustain and enhance the value of the benefits that nature provides to human society' (Maes et al. 2015). The network of Green Infrastructure aims, among other objectives, to enhance the connectivity among protected areas, contributing to a better and more coherent and effectively connected network of protected areas (European Commission 2020). Therefore, an opportunity exists to integrate freshwater ecosystems in the overall design of this network of Green Infrastructure and improve their degraded connectivity status under current policy. However, this recovery needs to be supported by adequate planning to overcome the limitations of traditional opportunistic decisions, which have dragged the effectiveness of past river restoration efforts (Hermoso et al. 2012a; Roni and Beechie 2013).

For example, the Spanish Green Infrastructure Strategy was approved in 2021 (MITERD 2021) and acknowledged the value of freshwater ecosystems as providers of important services, such as flood mitigation (disaster reduction) or carbon sequestration and the key role of freshwater ecosystems in articulating a well-connected, coherent and functional network of Green Infrastructure. For this reason, rivers, wetlands and freshwater habitats at risk of disappearance must be given special consideration when designing the network of Green Infrastructure. Additional support for the inclusion of freshwater ecosystems in the design of corridors comes from the Spanish Law 42/2007, on Natural Heritage and Biodiversity. This law gives priority to river courses, among other linear and continuous elements of the territory such as traditional livestock trails, to be considered as corridors, particularly between the protected Natura 2000 network sites. This Natura 2000 is the European network of protected areas designated under the Habitats and birds Directives. Given the importance of freshwater ecosystems in this context, and the need for adequate planning stated above, novel methods are needed to help design river corridors that could be integrated into the overall management context defined under current policy.

Here, we aim to contribute to the process of designing river corridors that should be considered when designing the network of

Green Infrastructure; we focus on the contribution that freshwater ecosystems could make to articulating a well-connected network. We develop a novel methodology to support the design of networks of river corridors to respond to the growing needs for adequate spatial planning under the current policy context. Given the current fragmentation status of rivers, we gave special attention to the spatial distribution of barriers in our approach to minimise the impact of these barriers on the network of corridors to ensure their functionality. Integrating a network of river corridors that connect populations of freshwater fish species in the future network of Green Infrastructure will contribute to the conservation and recovery of freshwater biodiversity. We tested this approach under three alternative planning scenarios: (i) an unconstrained scenario, where all river reaches were equally available to be part of the corridor; (ii) a Natura 2000 scenario (N2K), where we connected protected areas; and (iii) a no dam allowed scenario (NDA), where we avoided selecting reaches with dams as part of the network of corridors. Because of the widespread occurrence of barriers, we expected restoration efforts to be necessary to recover the functionality of the corridors identified. The approach that we demonstrate here could be used elsewhere to design river corridors, even beyond the focus on Green Infrastructure, and to plan future restoration efforts.

2 | Methods

2.1 | Spatial Framework for the Analyses

We used a hydrologic network derived from a 100-m resolution digital elevation model available from the Spanish Ministry for the Ecological Transition and Demographic Challenge (MITERD; 2007) as the spatial framework for the analyses. To delineate our minimum planning units, we overlapped this hydrologic network with the most updated inventory of transversal barriers, also available from the same Ministry. These included all dams ($N = 1364$; MITERD 2024a) and smaller barriers including weirs, culverts, and gauging stations ($N = 29{,}287$; MITERD; 2024b) present in the study area. Therefore, our basic planning units corresponded to the hydrologic network in between two consecutive transversal barriers (Figure 1). To ensure spatial coherence between the hydrologic network and barriers, we first selected all barriers within a 1-km buffer along the hydrologic network and then snapped the barriers selected to the hydrologic network. In this way, we discarded barriers that could be allocated in streams not included in this study (e.g., barriers in small headwater streams not mapped at the spatial resolution of the network used here). We then split the hydrologic network into stretches between consecutive barriers (Figure 1). We constrained the analyses to the catchments with complete and standardised data on barriers in continental Spain (Figure 2). These included all major rivers and 88% of the river network in Spain (Figure 2). The final dataset resulted in 30,082 planning units spanning 70,312 km of rivers and streams, 2.6 km long on average (80% of planning units ranged between 63 m and 5.5 km).

2.2 | Distribution of Species

We sourced the distribution of 40 native freshwater fish species (Table 1) from Lanzas et al. (2024). These distributions were derived from Species Distribution Models developed using Biomod2 (Thuiller et al. 2024) on a database of 10,035 field observations and 9 environmental variables covering climate, topographic, and land use variables at three different spatial scales: local, reach and upstream catchment. These

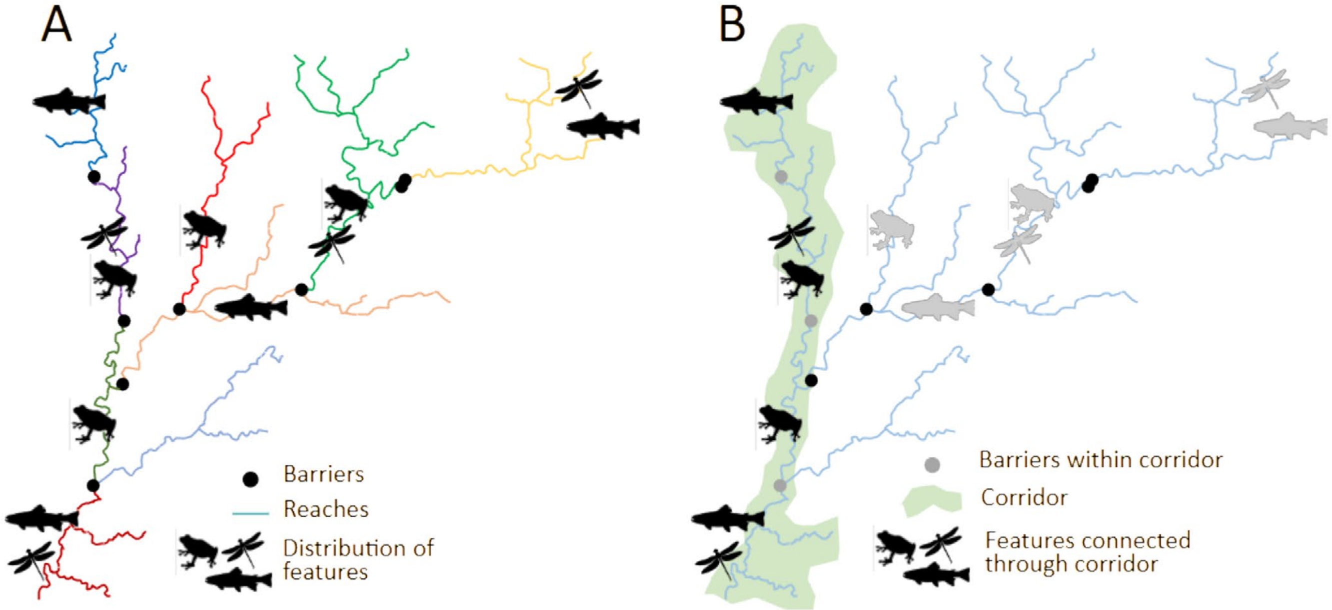

FIGURE 1 | Conceptual representation of the approach proposed in this study to the design of an optimal network of freshwater corridors. (A) The approach is based on the distribution of features and barriers in a stream network. The network is divided into reaches between consecutive barriers, where the populations of the different features are internally connected but disconnected from the populations in other reaches. (B) The optimal network of corridors, identified to connect at least two populations of the three features while minimising the number of barriers within the network.

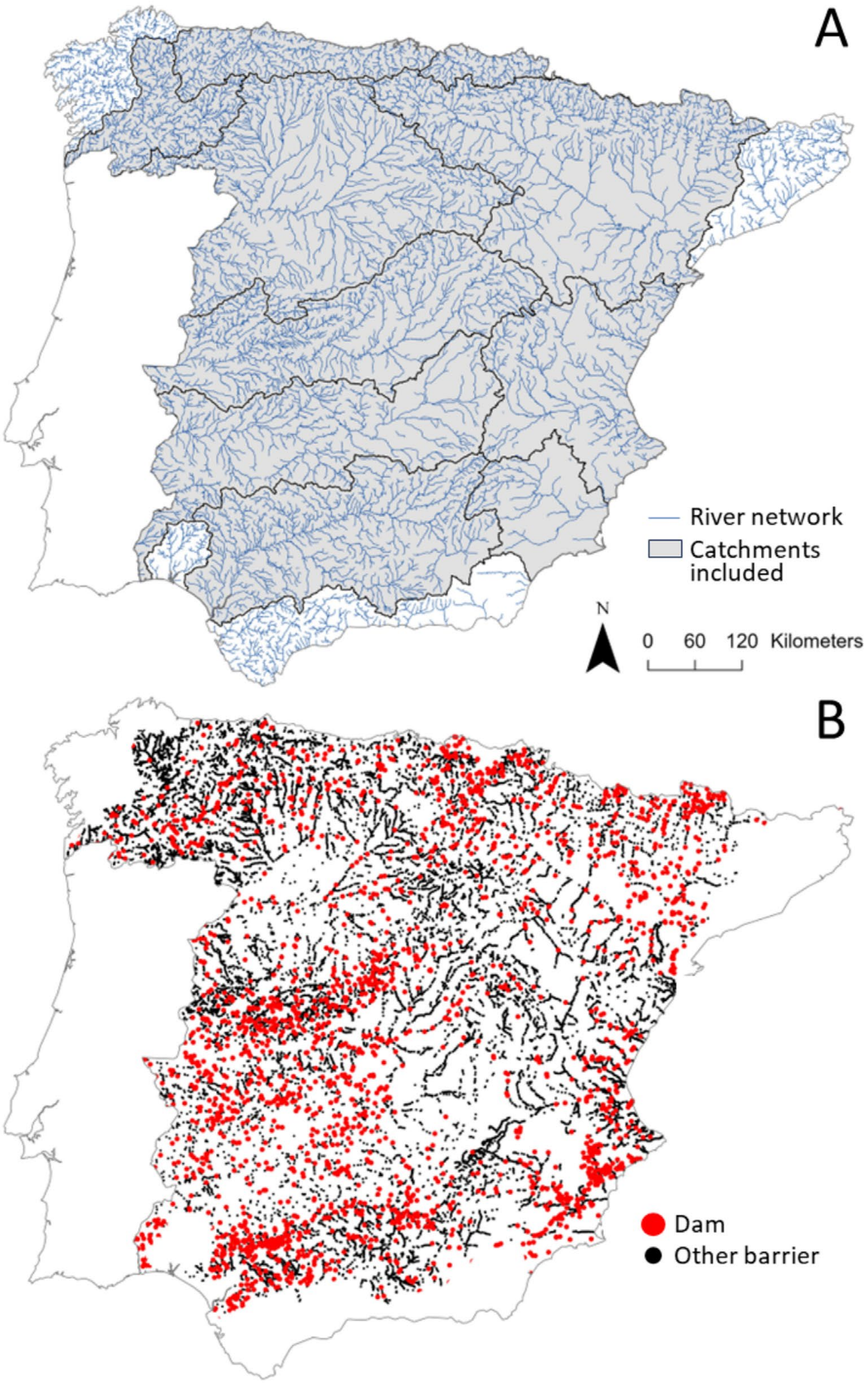

FIGURE 2 | Study area showing (A) the river network and the distribution of the catchments included in this study (grey), and (B) the distribution of the barriers (dams = red dots, black = other smaller barriers).

models showed a strong capacity to correctly predict presence and absence for all species, with an Area Under the ROC Curve (AUC) > 0.7 in all cases (see Lanzas et al. 2024 for more details on the species distribution models). The continuous habitat suitability values were then transformed into presence–absence binary distributions by setting a threshold for each species individually that maximised the sensitivity and specificity of the models using the *presenceabsence* R package (Freeman and Moisen 2008). These binary distributions were translated into the network of planning units described above, resulting in occupancy maps with the length of each planning unit occupied by each species.

TABLE 1 | Summary of number of planning units, number of dams, length of continuous planning units selected and average length of continuous planning units selected for each species in % related to the full distribution range of the species in the best solutions of the three alternative scenarios.

	Unconstrained (CSM = 2.6)	Natura 2000 (CSM = 0.1)	No dams allowed (CSM = 30)
Number of planning units selected	7716	7731	7617
Number of dams included in solutions	374	424	0
Length continuous planning units selected	20,885	16,347	15,445
Average length continuous planning units selected across all species	0.29	0.18	0.21

2.3 | Design of the Network of Corridors

We used the software Marxan (Ball et al. 2009) to design an optimal network of corridors that maximised the connectivity among the populations of the species described above. Marxan uses a heuristic optimisation algorithm to find an optimal set of planning units that collectively achieve a defined representation target (coverage of species), while minimising the cost of the selected units and connectivity penalties for fragmented solutions (objective function Equation (1)).

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

where, x_i is a control variable that takes a value of 1 when the planning unit i is selected and 0 otherwise; i belongs to the group of m planning units; c_i is the cost of planning unit i; $cv_{i1,i2}$ is the penalty for missing the connection between a given pair of planning units (i_1 and i_2) in the solution, and weighted by b, a connectivity strength modifier (CSM hereafter; high CSM values give more weight to connectivity, heavily penalising solutions that result in fragmented corridors, while low CSM values may result in more fragmented corridors); t_j is the target for each species; n is the group of species under consideration; SPF_j is a Species Penalty Factor or weighting factor that applies for not achieving the desired representation target for each species j; FR_j is a feature representation cost computed as the representation cost of meeting the target of feature j; s is the shortfall in targets not achieved and is measured as t_j-representation achieved; the ratio $\frac{s_j}{t_j}$ equals 1 when the species j is not represented within the solution and approaches 0 as the level of representation approaches the representation target (t_j); $H(s)$ is a Heaviside function that takes a value of 0 (cancelling out this parameter of the objective function) when $\frac{s_j}{t_j} \leq 0$ and 1 otherwise.

We used a constant $SPF = 100$ for all species to ensure that they all achieved the desired targets. We set a representation target of 50% of the distribution extent for each species, subject to a maximum of 1000 km to avoid the overrepresentation of very common species and the excessive extent of the network of corridors. Whenever a species was present in multiple catchments, we created pseudo species (species × catchment) and split the overall target for the species evenly among those pseudo species, emulating the relative contribution of a catchment's distribution to the whole distribution extent of the species. So, if a species was present in two catchments and both contributed equally to the distribution of the species, the targets for the two pseudo species were split equally between both catchments (Table S1). In this way, we aimed to distribute the network of corridors evenly across all catchments, avoiding the concentration of corridors in any of them. On average, each species was present in 3.3 catchments (range 1–10), which resulted in a total of 121 pseudo species (Table S1).

We used a constant cost for all planning units (cost = 1), given the lack of economic estimates of management cost. In this way, the optimisation problem that we addressed translated into identifying a minimum set of longitudinally connected planning units to collectively achieve the targets for all species. Given that planning units were defined as longitudinally connected river reaches between barriers, by using a unitary cost in combination with the distribution extent of each species/planning unit to minimise the number of planning units selected, we prioritised the selection of long reaches that were largely occupied by species and minimised the barriers included in the network of corridors (Figure 1b). We ran Marxan 100 times with 1 million iterations each and kept the solution with the lowest objective function value out of those 100 runs as our best solution for subsequent analyses.

2.4 | Planning Scenarios

We tested three alternative planning scenarios for the design of the network of corridors, all following the same representation targets described above. These scenarios aimed to depict different planning objectives and constraints: (i) an unconstrained scenario, where all planning units were equally available (all planning units had a status = 0 in the planning units file), (ii) a Natura 2000 scenario (N2k), where we used the distribution of the network of protected areas as the backbone of the network of corridors and (iii) a no dams allowed scenario (NDA), where we aimed to avoid the selection of planning units with dams as part of the network of corridors. To operationalise the last two scenarios, we locked in all planning units currently covered in more than 75% of their extent (> 75% of the length) by the Natura 2000 network by setting the status of those planning units to 2 ($N = 6984$ planning units; see Serra et al. 2020 for more detail on Marxan's input parameters) under the N2k scenario, and locked out all planning units that were isolated from their downstream neighbour by a dam, by setting the status of those planning units to 3 ($N=1195$ planning units) under the NDA scenario. We carried out a sensitivity analysis on CSM values for each scenario individually to explore differences in the connectivity that could be achieved and the number of planning units selected.

We measured four different indicators to compare the best solutions obtained for each scenario: number of planning units needed to achieve the target, the number of dams included in the solution, the length of continuous units selected for the solution and the length of continuous units selected for each species individually. The number of planning units was used as a surrogate for the efficiency of the solutions, assuming that the lower the number of planning units needed, the more efficient would be the solution. Given that planning units were defined using barriers as spatial breaks, this indicator also shows how many barriers would be included in the network of corridors. Out of those barriers, some could be dams so we also measured the number of dams included in the solution. The length of continuous units selected was measured as the sum of the length of planning units that had at least one contiguous neighbour (either upstream or downstream) selected as part of the best solution. In this way, isolated planning units with no neighbour selected did not contribute to this indicator. We also measured this indicator, restricted only to planning units where each species was present. In this case, we summed the length of planning units with contiguous neighbours selected when both had populations of a particular species and reported as the proportion of the full distribution range of each species. This indicator could be interpreted as the proportion of the distribution extent of a given species that would be included in neighbouring planning units selected in the best solution.

3 | Results

We found that the connectivity that could be achieved and the efficiency of solutions (measured as the number of planning units selected for achieving a given representation target) were always better under the unconstrained scenario than the other two that we tested (Figure 3). We also found important differences in the spatial allocation of priority corridor areas, although some areas appeared persistently across scenarios (Figure 4).

The sensitivity analysis on the CSM values showed that for a given number of planning units selected (cost in Figure 3), the connectivity that could be achieved (inverse of connectivity penalty in Figure 3) was always better under the unconstrained scenario. For example, the connectivity penalty of the network of corridors derived from a selection of 7500 planning units was 11 and 1.7 times higher under the N2K and no dam allowed (NDA) scenarios respectively than the unconstrained scenario. The impact of scenario planning on the achieved connectivity was especially remarkable in the NDA scenario, where the maximum achievable connectivity was limited, regardless of the CSM used (Figure 3). While better connectivity could be achieved by increasing CSM values in the unconstrained and N2K scenarios, both the connectivity and cost reached a maximum value that could not be exceeded above $\text{CSM}=5$ ($\text{connectivity penalty}=7937.25$ and $\text{cost}=6208$). This maximum limit was derived from the hard constraint of the selection of all planning units with a dam.

The constraints applied in each scenario also impacted the efficiency of solutions. For example, to achieve similar connectivity to the unconstrained scenario at low CSM values (e.g., $\text{CSM}=0.8$, $\text{connectivity penalty}=7414.3$), the number of

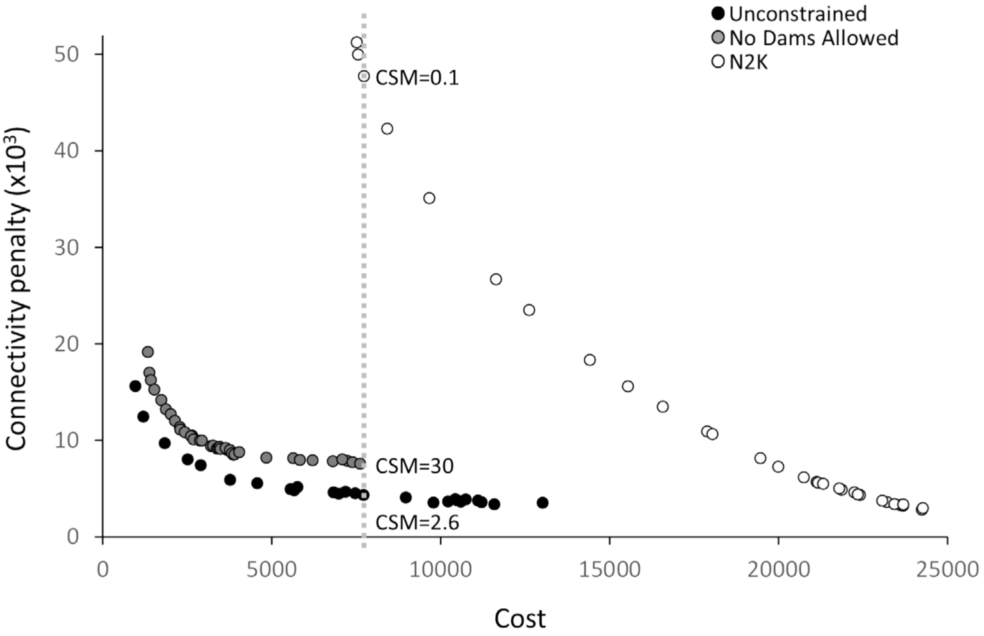

FIGURE 3 | Connectivity strength modifier (CSM) calibration curves for the three alternative scenarios tested in this study. Each dot represents an optimal solution obtained after 100 runs and 1 million iterations each for different CSM values. Lower connectivity penalty values indicate better connected solutions. The dotted vertical line shows the equivalent CSM value used to compare best solutions across scenarios. Although connectivity penalty plateaus in all three calibration curves, so little connectivity improvement can be achieved even at large cost increases, the minimum connectivity penalty achievable differed across scenarios, being highest (so less achievable connectivity) under the NDA scenario (grey dots). Trying to connect protected areas under the N2K scenario comes at the highest cost of all scenarios (line of white dots displaced towards the higher values of cost).

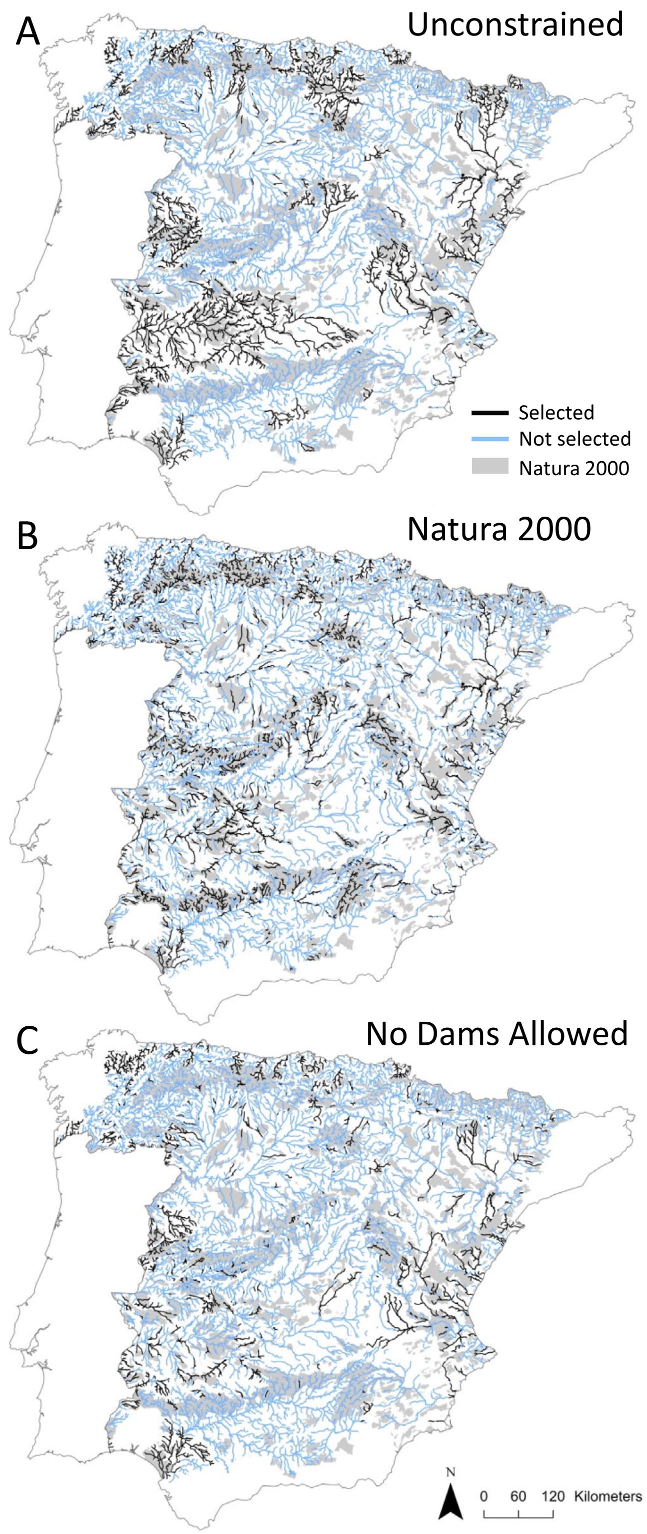

FIGURE 4 | Best solutions under the three alternative scenarios tested. Dark blue shows the reaches to be selected as part of the optimal network of corridors to achieve the representation target and minimise connectivity penalties and number of reaches selected. Light grey shows the distribution of the Natura 2000 network in continental Spain for the catchments included in this study.

planning units necessary was 6.9 and 2.6 times higher. This difference was more remarkable for larger CSM values (Figure 3), increasing from 2.6 to 3.9 more planning units needed under the N2K scenario to reach a similar connectivity to the unconstrained scenario at CSM = 1.4 (connectivity penalty = 4939; Figure 3).

The spatial continuity of corridors, measured as the length of continuous units selected in each solution, was also highest under the unconstrained scenario. For a similar number of planning units selected, the spatial continuity of corridors was 22% and 26% larger under the unconstrained scenario than under the N2K and NDA scenarios respectively (Table 1). However, this spatial continuity did not relate to effective continuity within corridors, given that these corridors were impacted by dams, except for the NDA scenario (Table 1).

Finally, the average spatial continuity of corridors also differed under each scenario for the populations of all the species considered in the analyses (Table S2). These differences also translated into efficiency: to achieve the same average spatial continuity for all species achieved under the unconstrained scenario with a CSM = 0.1), 25% more planning units had to be selected under the N2K scenario (BLM = 2.6). A similar average spatial continuity could not be achieved under the NDA scenario. The maximum average continuity value achieved was 0.21 at CSM = 30. But even at these high CSM values, some species could not achieve the connectivity target required. This was the only scenario where not all species achieved the connectivity targets.

4 | Discussion

In this study, we developed a novel methodology to support the design of networks of river corridors, to respond to the growing needs for adequate spatial planning under the current policy context. Our method takes into account key aspects of river ecology, such as longitudinal connectivity and impacts, such as the distribution of barriers, to deliver management recommendations that strike the balance between functionality and feasibility. Given the widespread distribution of barriers, with a barrier every 2.6 km of river on average, we were unable to identify a well-connected network of river corridors without a single barrier. The unconstrained planning scenario produced the most spatially comprehensive network of corridors, with lengths of continuously selected reaches between 20% and 26% longer than the other scenarios tested. However, although the selection of barriers was minimised, these solutions overlooked the potential impact of barriers that were necessarily included in the network of corridors. Therefore, restoration of connectivity within corridors would be needed to ensure their functionality. When a more conservative approach was taken by avoiding the selection of reaches with dams (NDA scenario), the network of corridors appeared more spatially disaggregated and had a limited capacity to connect populations of the target species. We found a similar effect when we forced the inclusion of reaches covered by protected areas (N2K scenario), although in this case led by the isolated distribution of protected areas mainly allocated in headwater streams. These scenarios demonstrate the relevance of defining the context and objectives of a planning exercise (Possingham et al. 2000; Halpern et al. 2013) and the limitations derived from those planning decisions. The approach that we demonstrate here could be used elsewhere and expanded to other taxonomic groups or components of connectivity, to address further functionality expected from river corridors.

Rivers and streams are natural connectors within landscapes, serving as potential corridors for both aquatic and terrestrial biodiversity. However, the widespread distribution of barriers, a common problem to river networks worldwide (Grill et al. 2019), poses a challenge to designing functional river corridors. For example, a barrier every 3.7 km of rivers was found in the UK (Jones et al. 2019) or more than 1.2 million barriers have been identified in European rivers (Belletti et al. 2020). Spatial optimisation tools can help identify priority rivers and streams of exceptional value for the maintenance of biodiversity and the ecological processes that sustain it (O'Hanley 2011; O'Hanley et al. 2013; Hermoso et al. 2021). In this study, we paid special attention to the longitudinal component of connectivity and the barriers that impact its continuity, to try to identify a network of functional river corridors. Although we used the reaches between consecutive barriers as our planning units, we did not focus the prioritisation on the length of those reaches alone, but the length of suitable habitat within each reach for each species. In this way, long reaches with very little suitable habitat for the species would not contribute much to the achievement of the targets. The selection of the longest occupied reaches was additionally reinforced using a null cost, which did not penalise the selection of large reaches as commonly done (Linke et al. 2012). This was done as we were mainly interested in the connectivity value of corridors. We overlooked additional management costs in the reaches selected as part of the network of corridors that could also be necessary (Garcia de Leaniz and O'Hanley 2022), but associated with management actions other than securing connectivity.

Here, we have considered all barriers as equal elements: they all are impassable structures for all species and all would pose a similar cost or impediment to restoring connectivity. However, the inventory of barriers that we used is quite heterogeneous and included small weirs to large dams. Therefore, differences in passability and restoration costs associated with each barrier could have also been considered. For example, Hermoso and Filipe (2021) estimated the relative passability of each barrier by different species, as a combination of each barrier's size and capacity of each species to jump/swim, and only considered as effective barriers those that actually impeded the movement of fish (Rincón et al. 2017). They also estimated the relative effort needed to remove each barrier, derived from its size and current use (e.g., large dams with strategic value for water provisioning or energy production would be more expensive than small weirs that are not currently in use). Both estimates were then included when identifying priority barriers to be removed to offset losses in connectivity due to new barrier construction. When we tested a more restrictive planning scenario, where reaches with dams were not allowed (NDA scenario) as part of corridors, we found that the resulting network was the least connected when looking at the number of continuously selected lengths of streams and that some species could not achieve the connectivity target. These results show the complexity of planning for river corridors and the need to integrate restoration measures that facilitate the design of well-connected and functional networks (e.g., long stretches), overcoming the limitations posed by the widespread impacts of barriers. These limitations could also be imposed by planning decisions, like the one tested under the N2K scenario. We found that if the network of corridors was designed to connect protected areas, the resulting network would be worse at connecting the distributions of species even more than the NDA scenario, and in all cases more costly in terms of lengths selected. The limitations to the design of the network imposed by this scenario originate in the spatial distribution of protected areas, mostly covering headwater streams (Hermoso et al. 2015). From a dendritic network point of view, the distribution of protected areas makes addressing freshwater connectivity and the design of the network of corridors complex, given that protected areas are effectively isolated headwater streams that would be too complex to connect following the river network.

Our approach can be expanded to include other components of connectivity and species for a more comprehensive definition of river corridors. For example, longitudinal and lateral connectivity were integrated when priority areas were identified for freshwater biodiversity in the Amazon and Northern Australia (Reis et al. 2019 and Hermoso et al. 2012a respectively) by including the connection between the river channel and its floodplain or surrounding wetlands; the vertical component of connectivity has been addressed by considering the relationships between superficial freshwater ecosystems and the groundwater systems that sustain them (Linke et al. 2019); and the temporal dimension of connectivity has been included by integrating measures of water residence time and effective connectivity when identifying priority river reaches for freshwater conservation in temporal systems of Northern Australia (Hermoso et al. 2012b). In all these cases, the different components of connectivity were addressed through the connectivity file used in Marxan (named boundary file in Marxan's terminology). This boundary file contains an estimate of the connectivity strength between each pair of reaches, or planning units as called in Marxan's terminology. The pairwise combinations of connections included in this boundary file can be characterised using longitudinal relationships between pairs of reaches, convening the dendritic structure of river systems as we did here (following Hermoso et al. 2011), or an estimate of the length of time during which water flows between both reaches in the case of temporal connectivity, for example. These advances could be integrated in future applications of the approach that we demonstrate here to address additional functionality of river corridors, beyond longitudinal connectivity. These broader applications to designing networks of river corridors could also include the distribution of additional species that benefit from those other components of connectivity (e.g., amphibians that benefit from lateral connectivity). This would result in a network of more comprehensive corridors (than if designed for a single species or taxa) encompassing the needs of multiple taxa, not only strictly aquatic and with that also a broader variety of functions.

Addressing connectivity restoration is needed to ensure that these corridors are functional regardless of the planning approach used. The current policy context supports this much needed restoration with clear goals and financial assistance. For example, the objective of recovering 25,000 km of free flowing rivers or the restoration priority given to habitats that contribute to climate change mitigation, such as wetlands in floodplains, as stated in the EU Biodiversity Strategy for 2030 and the EU Nature Restoration Regulation (European Commission 2020;

European Commission 2024) could help improve connectivity and the condition of these river corridors. The Spanish National Strategy of Green Infrastructure and connectivity and ecological restoration (MITERD 2021) and the National Strategy for River Restoration (2023–2030; MITERD 2023) also support the implementation of restoration to 'ensure ecological connectivity and ecosystem functionality, mitigation and adaptation to the effects of climate change, defragmentation of strategic areas for connectivity and restoration of degraded ecosystems'. However, despite the policy support for connectivity restoration, the capacity to undertake it is limited. Given the widespread impacts to connectivity some sort of prioritisation is also inevitable. Defining clear objectives will be important when deciding how to distribute the restoration efforts in the future, to ensure that the limited resources are placed in those areas and corridors that best contribute to achieving the desired objectives. Otherwise, opportunistic decisions, based on criteria like tenureship or potential conflict with other uses, could result in an inadequate distribution of efforts and deficient achievement of objectives (Hermoso et al. 2012c). Spatial prioritisation examples focused on river connectivity restoration could also help inform how to operationalise these future restoration efforts by finding the best barriers to be removed at lowest cost or socio-economic impact (Garcia de Leaniz and O'Hanley 2022). For example, a budget constrained optimisation model was used to decide which barriers to repair or remove to maximise habitat availability for freshwater fish species in the Pine-Popple Watershed (Wisconsin, USA; O'Hanley et al. 2013), or a simulated annealing optimisation algorithm was used to identify priority barriers to be removed to reconnect populations of freshwater fish in the Tagus River catchment (SW Spain and Portugal; Hermoso et al. 2012a).

5 | Conclusion

Overall, we demonstrated that ambitious goals can be pursued with adequate planning. However, the widespread incidence of barriers made it impossible to design a network of corridors completely free from these infrastructures. There are tools and information publicly available, like the ones used in this demonstration, to help design a comprehensive network of river corridors to be integrated in a future network of Green Infrastructure. However, the implicit decisions that contextualise the planning exercise, exemplified here by three alternative scenarios, can lead to very different spatial priorities and provide recommendations that are more or less functional (e.g., long corridors including dams vs. networks composed of smaller disconnected portions). Therefore, defining the planning objectives and constraints to deliver purposeful solutions is critical. The unconstrained scenario delivered the most connected network of corridors, falling closer to the needs of the Spanish case. However, the functionality of these corridors needs to be secured through adequate restoration measures.

Author Contributions

Conceptualisation: V.H., J.S.R., F.M., F.C., M.O., R.H., G.M., J.R.S.G. Developing methods: V.H., J.S.R., M.L. Data analysis: V.H. Preparation of figures and tables: V.H. Conducting the research, data interpretation, writing: V.H., J.S.R., F.M., F.C., M.O., R.H., G.M., J.R.S.G.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.